# APPARENT DIFFUSION COEFFICIENTS OF CARBON DIOXIDE THROUGH GRAIN BULKS

BY

SHUNMUGAM GANAPATHY

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

# APPARENT DIFFUSION COEFFICIENTS OF CARBON DIOXIDE THROUGH GRAIN BULKS

BY

SHUNMUGAM GANAPATHY

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree of DOCTOR OF PHILOSOPHY

## ABSTRACT

The diffusion coefficient of carbon dioxide ($CO_2$) through grain bulks was determined with the following variables: 1) grain bulk (wheat, barley, and canola); 2) moisture content (a dry, a wet, and a damp condition for each grain bulk); 3) temperature (5, 15, 25, and 40°C); 4) direction of flow of gas (upward, horizontal, and downward); 5) porosity (two levels for each grain bulk); 6) grain kernel orientation (vertical and horizontal); 7) initial concentration in the gas chamber (20, 40, and 60%); and 8) dockage (0, 4, 8, and 12%).

Experiments on transient diffusion of $CO_2$ through grain bulks were conducted using a diffusion cell placed inside a temperature- and humidity- controlled chamber. The $CO_2$ concentrations along the grain column were measured at 0.5 h, 1h, and every hour until 6 h from the start of diffusion. The diffusion process was modeled as one-dimensional transient diffusion solved using Crank-Nicholson's implicit finite difference method. The $CO_2$ concentrations along the grain column predicted by the model were compared with the measured values for different diffusion coefficients. The diffusion coefficient which gave the least mean relative error between the predicted and measured $CO_2$ concentrations was considered the diffusion coefficient for the given conditions.

A sink term 'q' was introduced in the diffusion equation to account for the sorption of $CO_2$ in the grain bulk. For canola and barley, experiments were conducted at 15 and 25°C and at three moisture levels (dry, damp, and wet conditions) to determine the sorption of $CO_2$. Sorption values reported in the literature were used for wheat.

The diffusion coefficients of $CO_2$ through wheat bulks ranged from $5.9 \times 10^{-6}$ to $7.6 \times 10^{-6}$ $m^2s^{-1}$; through barley bulks ranged from $5.1 \times 10^{-6}$ to $8.4 \times 10^{-6}$ $m^2s^{-1}$; and

through canola bulks ranged from $3.7 \times 10^{-6}$ to $5.3 \times 10^{-6}$ $m^2s^{-1}$ for the test conditions studied. Increasing the moisture content from the dry to the damp condition decreased diffusion coefficients for all three grain bulks. A further increase in moisture content did not affect the diffusion coefficient in wheat and canola whereas in barley a decrease in the diffusion coefficient was observed as the moisture content was increased from the damp to the wet condition.

An increase in temperature generally increased the diffusion coefficient of $CO_2$ in all three grain bulks. Diffusion in the downward direction resulted in higher diffusion coefficients in all the grain bulks. No significant difference in diffusion coefficients was observed between upward and horizontal directions of flow. An increase in porosity resulted in a higher diffusion coefficient in all the grain bulks tested. The diffusion coefficient of $CO_2$ was higher for vertical grain kernel orientation than horizontal grain kernel orientation for all the three grain bulks for upward gas flow, although the difference between the two kernel orientations for canola bulks was not significant because the seeds are round. No significant change in diffusion coefficients through grain bulks was detected as the initial $CO_2$ concentration was varied between 20 and 60%. The diffusion coefficient of $CO_2$ increased linearly as the foreign material content was increased from 0 to 12% in all the grain bulks.

## ACKNOWLEDGEMENTS

I express my sincere gratitude to my advisor Dr. D.S. Jayas for his invaluable guidance, inspiration, and support during the course of this study. I could not have prepared this thesis staying thousands of miles away without his consistent support and periodical direction since I left Winnipeg.

I thank Dr. W.E. Muir and Dr. N.D.G. White for their constructive criticisms and encouragement throughout this study. I also thank Dr. A.C. Trupp and Dr. D. Abramson for having served on my thesis committee.

I thank the Natural Sciences and Engineering Research Council of Canada for providing financial assistance.

I thank Messrs. Jack G. Putnam, and Rob Ataman for their technical assistance. I gratefully acknowledge the encouragement and support extended by Dr. T. Nitheanandan, Dr. R. Srinivasan, and Dr. C. Divaker Durairaj. Special thanks are due to Dr. K. Alagusundaram, my colleague both in Canada and in India, whose guidance was of immense help all through the study.

I thank my wife Rema and my daughter Swathika for their co-operation and my parents, brothers, and sisters for their support.

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF SYMBOLS

| | |
|---|---|
| a, b, c, d | - empirical constants, (eq. 6.1) |
| $C_{ij}$ | - $CO_2$ concentration in the 'i'$^{th}$ node and 'j'$^{th}$ time step, (mole fraction) |
| D | - Diffusion coefficient of $CO_2$ through grain bulk, ($m^2s^{-1}$) |
| $D_{AB}$ | - Diffusion of gas 'A' into gas 'B', ($m^2s^{-1}$) |
| q | - sorption of $CO_2$ into the grain mass, (mole fraction/s) |
| $\varnothing(t)$ | - $CO_2$ concentration in the gas chamber at time 't', (mole fraction) |
| f(x) | - initial nodal $CO_2$ concentration, (mole fraction) |
| k | - time step, (s) |
| h | - lenth of element, (m) |
| L | - length of the grain chamber, (m) |
| x | - distance of the node from the level of the wiremesh screen in the difusion cell, (m) |
| t | - time elapsed since the start of the experiment, (s) |

# 1. INTRODUCTION

Harvested grain is stored on farms in Canada for a few months to 3 years before being passed on to the grain handling system and then the processor or the overseas customer. Most grain, however, is stored for less than 1 year. In Canada, approximately 26.6 million tonnes of wheat, 12.5 Mt of barley, and 4.7 Mt of canola are stored on farms annually (Anonymous 1997).

Stored grain is a man-made ecosystem where the interaction of abiotic and biotic factors is responsible for the growth and survival of insects, mites, rodents, and fungi in the grain mass (Sinha 1973). The important abiotic factors are: temperature, moisture, and intergranular gases such as carbon dioxide ($CO_2$), oxygen ($O_2$), and nitrogen ($N_2$). The biotic factors include microorganisms such as fungi and bacteria, insects, mites, and vertebrates such as rodents and birds. Uncontrolled infestations in a grain bulk lead to quantity and quality losses of grain. Moisture migration due to convective mass transfer in a grain bin may create an ideal environment for fungal growth, which in turn may lead to growth and development of certain insects. Hot spots may develop in a grain bin due to the respiration of fungi and insects. Infested grain shows visual deterioration, has damaged kernels that become "caked" together and occasionally mycotoxins develop unwanted odours. Insect incidence is reported frequently in farm storages on the Prairies. Of the 2919 primary grain elevators surveyed in Western Canada in 1969-71, 15% of the elevators had stored-grain insect infestations (Sinha 1972). Nearly 42% of the farms in the same areas had infested stored grain. In a survey of country elevators and commercial facilities in southern Ontario in 1990, 48% of the managers reported infestation of grain

bulks. In another survey conducted in granaries of Manitoba, low levels of infestation of cereals were observed in 8% of the granaries in the fall of 1986, 13% in the summer of 1987 and 46% in the fall of 1987 (Madrid et al. 1990). As Canada is maintaining a reputation of exporting insect-free grain in the world grain market, grain storages in Canada need to be monitored at regular intervals for infestation and if infestations are detected they must be eradicated.

The methods employed to control pests on Canadian farm stores include lowering the temperature of the grain by aeration, or turning the grain mass at regular intervals, lowering the moisture content of grain by drying, maintaining good sanitation by cleaning and burning the debris and residual grain in the vicinity of grain bins before filling with newly harvested grain, and applying chemicals. Chemical control methods include the use of the fumigant phosphine to eliminate infestations from grain, and occasionally contact pesticides to protect the grain against invasion by insects and mites.

In recent years, pesticides used as grain protectants are subjected to rigorous regulatory review by government agencies as they can be harmful to human health in the form of grain residues. Many of the contact insecticides have been restricted from use on food materials. The popularly used malathion may not be used in grain storages in the near future because many of the commonly occurring stored-product insects are developing resistance to it. Phosphine is the only fumigant presently used on commodities in grain storages and methyl bromide is used as a space fumigant in flour mills and ship holds. The USA, Canada and most countries of the world have decided to eliminate the use and production of methyl bromide by the year 2005 because methyl bromide depletes the ozone layer in the atmosphere. Farmers cannot rely on phosphine indefinitely because

there are reports about the incidence of resistance in stored-product insects to phosphine (Price 1991). Among the alternatives and substitutes for methyl bromide and phosphine, controlled atmosphere (CA) storage using carbon dioxide is an effective and low cost technique (Anonymous 1993).

In CA storage, the intergranular gas composition is altered either by adding nitrogen ($N_2$) to reduce oxygen ($O_2$) or by adding carbon dioxide ($CO_2$). Atmospheres depleted of $O_2$ or high in $CO_2$ kill stored-product insects. The action of gases in killing the insects is through the respiratory system unlike the synthetic insecticides, which are neurotoxins. The technique is residue free and less likely for the insects to develop resistance.

Studies on the CA storage of grain bulks have been carried out in Australia, Israel, Canada, the USA (Bailey and Banks 1980; Banks and Annis 1980; Jay et al. 1971; White et al. 1990; Ramesh babu et al. 1991; Navarro and Calderon 1974) and other countries. The potential of the CA storage technique to control insects was confirmed in these studies. However, in these studies $CO_2$ dosage for a 100% kill of insects in a given storage situation was not calculated. To do so, knowledge on the principles governing the gas movement in grain storages is necessary which is presently not available. Gas movement in a bulk grain is due to one or more of the following mechanisms: ordinary diffusion into the porous grain bulk, diffusion caused by temperature gradients within the grain bulk, convection currents set up by temperature differences within the grain bulk, bulk flow caused by pressure differences within the grain mass, diurnal variations in atmospheric pressure, and sorption and desorption of gases by the grain.

In CA storages involving $CO_2$ applications, $CO_2$ is applied in a gaseous or a solid form into the grain bulk. This may induce a transient bulk flow due to pressure difference within the grain bulk followed by transient diffusion and other mechanisms of gas transport. As diffusion is an important factor in gas movement, knowledge on the diffusion coefficient of $CO_2$ gas through grain bulks is necessary to understand the diffusion process. This and understanding of other factors of gas movement will help in the development of guidelines to estimate the dosage of $CO_2$ required in a given situation.

Few studies are reported in the literature on the determination of the diffusion coefficient of $CO_2$ through a grain bulk (Henderson and Oxley 1944; Bailey 1959; Haugh and Isaccs 1967; Singh(Jayas) 1985; Alagusundaram et al. 1996a). They are preliminary in nature and were carried out for an objective different from CA treatments. The objectives in most of these studies were to identify spoilages inside grain bulks based on $CO_2$ gas concentration in the intergranular spaces. Many important factors such as dockage, temperature, grain kernel orientation, and concentration dependence of the diffusion coefficient were not studied in the above studies. Dockage is a critical factor controlling gas movement in a grain bulk. Jay and Pearman (1973) reported that it takes a longer time for $CO_2$ to reach the average concentration in the areas of higher dockage inside a silo. Grain kernel orientation could be an important factor in controlling the movement of $CO_2$ molecules similar to affecting air flow (Kumar and Muir 1986). The effect of sorption of $CO_2$ by grain was neglected in the above studies on diffusion of $CO_2$ through grain bulks. It was reported that a significant amount of $CO_2$ in grain bulks is sorbed by the grain (Mitsuda and Yamamoto 1980; Cofie-Agblor et al. 1993). Therefore, this work was undertaken to determine the diffusion coefficient of $CO_2$ from the

standpoint of CA storage application for three commercially important crops of Canada namely wheat, barley, and canola.

The diffusion coefficients of gases through porous media such as a grain bulk can be measured by two methods, namely steady state and transient methods. In the steady state method, continuous flushing of $CO_2$ along the grain column is necessary and the time required for reaching the steady state is usually greater than 24 h (Slaterry and Bird 1958). To avoid these disadvantages, I chose a transient method for diffusion tests. Several studies on diffusion of $N_2$ through soil were reported by the transient technique (e.g., Pritchard and Currie 1982; Troeh et al. 1982; Dowdell and Smith 1974). The technique is simple, quick, and reliable. The diffusion coefficient of $CO_2$ through a grain bulk was estimated using Crank-Nicholson's implicit finite difference method.

## 2. OBJECTIVES

The objectives of this study were:

1. to develop a model for the one-dimensional, transient-diffusion problem;
2. to determine the sorption of $CO_2$ in barley and canola bulks;
3. to determine the diffusion coefficient of $CO_2$ through grain bulks; and
4. to determine the effects of moisture content, temperature, direction of flow of gas, porosity, grain kernel orientation, initial concentration of gas, and dockage, on the diffusion coefficient of $CO_2$ through bulks of wheat, barley, and canola.

# 3. LITERATURE REVIEW

## 3.1 CA Storage

### 3.1.1 General

Only a limited number of contact insecticides and fumigants are registered for use on stored grain in the United States and Canada (White and Leasch 1996). Grain protectants used in grain storages are under the threat of elimination because of stringent tolerance levels stipulated by regulatory agencies in many countries around the world. Malathion was decertified in the United States in 1992 because many economically important stored-product insects developed resistance to it. Resistance to the fumigant phosphine was reported for some strains of stored-product insects (Mills 1983; Price 1991). Methyl bromide is a depleting chemical for ozone in the atmosphere and hence its use and production will be eliminated except for quarantine purposes in the United States and Canada by the year 2005. Controlled atmosphere (CA) storage is one of the potential alternatives to insecticides and fumigants to control stored-product insects and is also a low cost technique (Anonymous 1993). Unlike the synthetic insecticides, the CA storage technique is residue free. The insects are less likely to develop resistance to CA storage because the mode of action of the gases is through the respiratory system (White and Jayas 1991).

### 3.1.2 Laboratory Scale Studies

Controlled atmospheres can be created either by lowering the interstitial $O_2$ content by flushing the grain bulk with $N_2$ or by elevating the $CO_2$ content by flushing the

grain bulk with $CO_2$. A typical CA storage of the first type will have an $O_2$ composition of $\leq$ 1%; and of the second type will have a $CO_2$ composition of $\geq$ 40%. Low $O_2$ atmospheres can be generated in a grain bulk by flushing it with $N_2$ gas (Banks and Fields 1995). High $CO_2$ atmospheres can be generated by introducing dry ice into the grain bulk or by flushing the bulk with $CO_2$ gas from cylinders (Alagusundaram et al. 1996b and 1996c; Jay and Pearman 1973).

Knowledge on mortality responses of stored-product insects and their life stages is essential to apply controlled atmospheres successfully in a grain storage. The mortality response to controlled atmospheres differs from species to species and could be different among life stages of a species. While exposure time was critical for some species, low $O_2$ content was important in killing some other species (Krishnamurthy et al. 1986). Therefore, it is not advisable to generalise the response of controlled atmospheres to insects.

The results of pilot scale studies on the mortality response of various stored-product insects to controlled atmospheres have been reviewed periodically. Jay and D'Orazio (1984) recommended that $CO_2$ concentration of 60% if maintainted for 5 to 6 d in a grain bulk at or below 14% moisture content (mc) wet mass basis (wb) and at or above 27°C will kill all the infestations except Trogoderma spp. Annis (1987) in a review of studies on mortality of insects exposed to CA storage concluded that $CO_2$ levels held at 80% for 8.5 d, 60% for 11 d, or 40% for 17 d at or above 20°C is effective against all stages of common stored-product insects. Also, $O_2$ levels maintained at less than 1.0% for longer than 20 d at or above 20°C would kill most of the stored-product insects. There is disagreement as to what is the limiting concentration for effective kill when using low $O_2$

atmospheres. Bailey (1965) concluded that the lethal level of $O_2$ in hermetic storage systems is about 2%. Reichmuth (1987) suggested that the $O_2$ level must be kept at < 3% for effective control of stored-product insects. Bailey and Banks (1980) suspected that the lethal level of $O_2$ to Sitophilus granarius(L.) cultures at 18 to 24°C must be < 1.3%.

High $CO_2$ atmospheres generally work well with internal grain feeders whereas low $O_2$ atmospheres work well with external feeders. Press and Harein (1966) found that pure $N_2$ was more effective than $CO_2$ atmospheres against Tribolium castaneum (Herbst) and Plodia interpunctella (Hubner) while Lindgren and Vincent (1970) found no difference in action between the two atmospheres against all stages of the granary weevil, S. granarius (L.), and the rice weevil, Sitophilus oryzae (L.) Zakladnoi (1976) as cited by Bailey and Banks (1980) concluded that pure $CO_2$ is more effective than pure $N_2$ atmospheres in controlling the adults of S. granarius, S. oryzae, Rhyzopertha dominica (F.), and T. castaneum at 20, 25, and 35°C. Aliniazee (1971) found synergistic effect of high $CO_2$ gas with low $O_2$ atmospheres on Tribolium confusum (I. du Val) and T. castaneum adults at 27°C and 38% relative humidity (rh). Bailey and Banks (1980) reported that although there is some advantage in introducing $CO_2$ in low $O_2$ atmospheres, there is no significant reduction in exposure time when Sitophilus species is present.

Rameshbabu et al. (1991) studied the mortality response of rusty grain beetle Cryptolestes ferrugineus (Stephens) adults and eggs to controlled atmospheres. They found that 96 h of exposure to 88-91.7% $CO_2$, 0-0.5% $O_2$, at 19.5-20.5°C, and 60-64% rh killled 99% of adults and 85% of eggs. Shunmugam et al. (1993) studied the mortality response of all the four stages of C. ferrugineus to various gas compositions of $CO_2$ and found that 40% $CO_2$ at 30°C killed all the immature stages in 4 d and adults in 8 d .

Many researchers, after studying the mortality response of a variety of stored-product insects, concluded that S. granarius is the most tolerant and S. oryzae is equally or less tolerant among the stored-product insects to controlled atmosphere gases.

Increasing the temperature generally increases the speed of action of high $CO_2$ and low $O_2$ atmospheres although conflicting results were obtained by Harein and Press 1968, and Zaklodnoi (1976) as cited by Bailey and Banks (1980). Harein and Press (1968) reported little change in T. castaneum larvae mortality at 16, 27 or 39°C to 48% $CO_2$ in air. Zakladnoi (1976) found little temperature dependence on adults of Tribolium species.

Controlled atmospheres achieve better control at low relative humidities because of enhanced desiccation of insects, when $CO_2$ causes the respiratory spiracles to open and water loss occurs.

### 3.1.3 Field Studies

In the USA, Canada, Australia, and several other countries, some researchers have studied CA storage in farm bins, elevators, and rail cars during transport (Jay and D'Orazio 1984, Alagusundaram et al. 1996c, Banks and Annis 1980). These studies revealed the practical difficulties for successful application of CA storage. First, whether the desired gas can be produced on the farm itself or transported to it through tankers has to be decided based on the cost. Second, if the gas can be applied from liquid, or solid source. Application in liquid form will necessitate additional equipments like vaporisers, flow meters, and pressure regulators, while the solid form will require proper storage facilities to reduce significant loss due to sublimation.

Wooden bins or bolted or welded metal bins are commonly used to store grain on the farm. These bins and elevator bins are not airtight to gases. For successful application of CA storage, these structures require modification. Some researchers attempted to apply CA storage technique in the existing storage bins and found that frequent application of gases is necessary as there were leakages from the bin and an adequate concentration could not be maintained throughout the bin (e.g. Jay 1980; Alagusundaram et al. 1996c). This led to partial or no control of insects in storages and also to a high dosage requirement. Banks and Annis (1980) attempted to seal the existing storage structures using a variety of materials like acrylic paste, silicon rubber, and bitumen emulsion. They also estimated the cost of converting the existing storages into sealed storages for CA application in Australia. A standard for gas tightness in a storage structure was also stipulated by Banks and Annis (1980) for applying CA treatment. A decay in pressure from 1500 Pa to 750 Pa in 3.5 min is stated to be the required level of gas tightness for a grain bin.

Jay et al. (1970) applied $CO_2$ gas into inshell-peanut bulks of 2262 $m^3$ stored in concrete bins 9.1 m diameter and 34.4 m tall. They achieved a $CO_2$ concentration of 35% and 14% $O_2$ at the end of all the three treatments of 48, 96, and 168 h. The $CO_2$ requirement was high in these studies. About 2.162 kg of $CO_2/m^3$ of grain was applied for a test with a longest exposure of 168 h.

Jay and Pearman (1973) studied the effectiveness of CA storage on corn (maize) bulks infested with insects including Sitophilus spp., in a 7.3 m diameter and 24.7 m tall silo. Carbon dioxide at the rate of 4.3 $kg/m^3$ of grain was applied to obtain an average concentration of 60-70%. They reported complete control of insects in 96 h.

Jay and D'Orazio (1984) applied $CO_2$ gas from vaporised liquid into non-airtight concrete and steel bins containing wheat, sorghum, maize, and rice. Complete control of insects was achieved in wheat with a $CO_2$ application rate of 2.6-3.8 $kg/m^3$.

Alagusundaram et al. (1996b and 1996c) studied the distribution of $CO_2$ in pilot scale bins and 83 tonne capacity bolted metal bins on a research farm in Manitoba, Canada. Mortality response of insects to $CO_2$ was determined in bolted metal bins only. They found that the existing bolted metal bins do not have the required airtightness and are unsuitable for CA treatments even with an impermeable plastic sheet covering the top of the grain bulk. In the bolted metal bins, $CO_2$ tended to accumulate at the bottom and accordingly the mortality of insects was higher at the bottom of the bins than at the top. For example, at a location 0.55 m above the floor 90% mortality was achieved whereas at a location 2.05 m above the floor near the top surface only 38% mortality was achieved at the end of 10 d.

### 3.2 Gas Movement Through a Grain Bulk

Atmospheric air in the head space of a grain bin, and intergranular air within the grain bulk constitute the gaseous phase inside the grain bulk. Since the existing grain bins are not completely sealed, air exchange takes place between the atmosphere and grain in the bin due to atmospheric pressure fluctuations. Barker (1974) calculated that in a typical grain bin in Manitoba, approximately 3% of the air inside a grain bin is exchanged in a day due to pressure changes in the atmosphere.

Because grain is a poor conductor of heat, temperature gradients between the centre and near the walls of a grain bin is a common phenomenon in North American farm

bins (Muir 1973). Convection currents of intergranular air are established between warmer and cooler parts of the grain bin. In winter, the grain at the centre below the surface remains warmer than the reminder of the bin and in summer, the grain at the centre near the bottom remains cooler than the rest of the bin. Air and moisture transport between different parts of the grain bulk takes place due to convection currents. Bundus et al. (1996) reported a convective pore velocity of $8.24 \times 10^{-4}$ m/s for $CO_2$ gas introduced in a wheat bulk having a temperature gradient of 20°C.

Respiration of insects, mites, fungi, and also, to a limited extent, grain produce $CO_2$, however $CO_2$ production is due to insects or microorganisms in a spoiling grain bulk. The $CO_2$ thus produced will remain in the interstitial spaces of the grain until it diffuses out of the granary. White et al. (1982) suggessted that in a grain bulk, spoilage can be detected by measuring the $CO_2$ concentration in the intergranular air. Muir et al. (1980) reported that high $CO_2$ levels could be detected at a considerable distance from the point of spoilage in polyethylene, steel, and wooden bins that were used to store wheat temporarily. Similarly, cumulative production of $CO_2$ has been used to measure deterioration of grain by other researchers (Steele et al. 1969; White et al. 1982). In the above studies, the $CO_2$ produced in the spoiling grain was probably transported by diffusion and convection currents.

Mechanisms of gas movement inside a grain bulk during fumigation trials have been studied by Gilby (1983). Gas movement in CA treatments of a stored grain bulk has also been studied by researchers (Jay et al. 1970; Calderon and Carmi 1973; Wilson et al. 1980). Inside the grain bulk, carbon dioxide being heavier than air sinks due to gravity. Jay (1980) and Wilson et al. (1980) stated that recirculation of intergranular air is very

useful in CA treatments to create an uniform distribution of gas. Alagusundaram et al. (1996c) reported that irrespective of the point of application of $CO_2$ into the grain bin, higher $CO_2$ concentrations were observed near the bottom of the bin when gases were not recirculated.

In field trials of a CA treatment conducted in welded steel bins using dry ice as the $CO_2$ source, Alagusudaram et al. (1996c) noted that sublimation of dry ice caused a slight increase in pressure inside the grain bulk which lasted for a few minutes. They assumed that the principal mechanism for $CO_2$ transport inside the grain mass in CA applications was molecular diffusion.

Pressure flow of gases may happen in two ways inside a grain bin. In many field trials of CA applications, $CO_2$ gas was introduced in the overhead space above the grain bulk or below the plenum through the duct used for a cooling fan (Jay 1980; Alagusundaram et al. 1996c). At the overhead space or at the plenum chamber, pressure may increase above atmospheric level and induce viscous flow into the grain bulk. Also through leaks in the grain bin, atmospheric pressure fluctuations can cause pressure flow of air into and intergranular air out of the bin.

## 3.3 Diffusion of Gases Through a Grain Bulk

### 3.3.1 Problem Formulation and Solution Techniques

Although a grain bulk with intergranular air constitutes a porous medium, properties of porous media are not taken into account in the analysis of diffusion of gases through a grain bulk. Such a treatment at the macro level can be justified for the levels of porosity encountered in grain bulks. Because the resistance to diffusive flow of gases by

grains is assumed to be insignificant and the intergranular pore spaces are larger than the mean flow path of the molecules allowing free movement of molecules through them. However, few studies were reported in the literature which had taken into account the properties of porous media at the micro level (Thorpe et al. 1991a and 1991b). Many researchers have treated the diffusion of gas or gases into porous media, like soil and grain bulks, similar to ordinary diffusion and have determined apparent diffusion coefficients (McHenry et al. 1957; Troeh et al. 1982).

Experiments on diffusion problems are basically of two kinds namely steady state and transient. In the steady state method, the ends of a grain bulk are exposed to gas flows of constant but different concentrations. After reaching the steady state, the changes in gas concentration across the grain column are noted. Using Fick's law of diffusion, the diffusion coefficient is calculated. Since this is a time consuming and wasteful method, some researchers have tried the transient method to determine the diffusion coefficient of various gases (Pritchard and Currie 1982; Troeh et al. 1982). In this method, one end of the grain column is exposed to the gas at high concentration. After a lapse of time, gas concentrations are measured along the grain column. By applying Fick's law of diffusion and the continuity principle, the governing equation of the diffusion process is obtained. The diffusion equation is solved analytically or using the finite difference method by imposing the appropriate boundary and initial conditions.

### 3.3.2 Diffusion Coefficient of Gases Through Grain Bulk

Studies on diffusion of gases through grain bulks are few, and had varying purposes. They were based on steady state and transient methods and different methods were used to measure gas concentration.

Henderson and Oxley (1944) determined the diffusion coefficient (D) of $CO_2$ through a wheat bulk at 12% moisture content as $4.15 \times 10^{-6}$ $m^2$ $s^{-1}$ at room temperature.

Bailey (1959) determined the diffusion coefficient of $O_2$ through wheat, corn, barley, and oats at 23°C as 6.7, 5.58, 6.42, and $7.21 \times 10^{-6}$ $m^2 s^{-1}$, respectively. They also reported a quadratic relationship between the diffusion coefficient and temperature.

Haugh and Isaccs (1967) reported a dependence of the diffusion coefficient of $O_2$ on initial gas concentration. By conducting transient state experiments for initial $O_2$ concentrations of 5, 8, 10, 14, and 21%, they obtained the following relationship between a diffusion coefficient and concentration:

$$D = 0.791 - 0.420\,(CR) + 0.136\,(CR^2) \qquad (3.1)$$

where:

D = diffusion coefficient $\times 10^{-6}$, $m^2 s^{-1}$,

CR = concentration ratio $C_o/C$, dimensionless,

C = concentration of $O_2$ $\times 10^{-3}$, kg $m^{-3}$,

$C_o$ = initial concentration in the gas chamber $\times 10^{-3}$, kg $m^{-3}$

Singh ( Jayas) et al. (1984) assumed a steady state condition over a short period during transient diffusion of $CO_2$ through canola, wheat, maize, and oats and determined the diffusion coefficient of $CO_2$ through grain bulks. They reported that the diffusion

coefficient of $CO_2$ through the grain bulks was not affected significantly by flow directions (upward, horizontal, and downward), and porosity. It decreased with an increase in moisture and increased with an increase in temperature in a quadratic fashion. The sorption of $CO_2$ in grain was neglected in this study.

Alagusundaram et al. (1996a) determined the apparent flow coefficient of $CO_2$ through wheat using a method similar to the one used by Singh (Jayas) et al. (1984). The source of $CO_2$ was dry ice. Because mass flow of $CO_2$ was suspected to dominate at the start of the experiment, the apparent flow coefficient did not have a definite relationship with moisture content of the grain and it increased linearly with an increase in temperature of the grain.

### 3.4 Diffusion of Gases Through Porous Media.

Studies (e.g. McHenry et al. 1957; Dowdell and Smith 1974; Troeh et al. 1982) have been reported in the literature on the diffusion of gases like $N_2$, $O_2$, hydrogen ($H_2$), and ethylene ($C_2H_4$) through porous media like soil, sand, and artificial medium made of glass beads . McHenry et al. (1957) studied the movement of $H_2$-$N_2$, and $C_2H_4$-$N_2$, through packed beds of spheres made of glass beads. Diffusion of gases through the porous medium was described by Fick's law in this study.

Bird et al. (1960) stated that diffusion inside the tortuous void passages of a porous medium is too complex to describe. The pore dimensions may be smaller than the mean free path of the diffusing molecules. Instead, an average diffusion of the chemical components in terms of an effective diffusion coefficient can be described. Diffusion as suggested by Fick's law can be applied for diffusion through a porous medium.

### 3.5 Sorption of $CO_2$ by Grain.

Researchers in grain storage studies have observed the sorption of gases by grains (Yamamoto and Mitsuda 1980; Mitsuda and Yamamoto 1980). In a CA treatment sorption of $CO_2$ by grains may render the treatment ineffective. A sink term is included in the governing differential equation of mass transfer through bulk grains subjected to $CO_2$ treatment. Although $CO_2$ is produced by the respiration of grain and associated microorganisms, this component is usually considered negligible in experiments because of their short duration (< 6 h).

Mitsuda and Yamamoto (1980) observed that the pressure change in a 200 L airtight can containing rice, measured over a period of 10 d, followed the same curve as that of the amount of $CO_2$ sorbed. They concluded that $CO_2$ sorption is the reason for the change in pressure inside the vessel. Yamamoto and Mitsuda (1980) studied the $CO_2$ sorption phenomenon in many agricultural grains such as rice, wheat, corn, peanuts, soyabean, sugarcane, red bean, coffee bean, and tea. They observed that the velocity of sorption varies with the type of grain. Among the grains studied, $CO_2$ sorption was maximum for peanuts (560 mL $kg^{-1}$) and minimum for red beans (64 mL $kg^{-1}$) at 20°C for 3h of treatment. Maximum sorption takes place within the first 6 h of treatment for rice. Equilibrium was achieved in 24 h for all the crops tested. They also found that the amount of gas sorbed decreased with an increase in moisture content for paddy whereas it increased with a increase in moisture content for brown rice. The amount of $CO_2$ sorbed by grains increases with a decrease in temperature. However, the rate of sorption is not affected much by temperature. When the $CO_2$ sorbed grain is allowed to stand in free air

desorption of $CO_2$ takes place and the desorption curve looks like a mirror image of sorption curve with respect to the time.

Cofie-Agblor et al. (1993) measured the sorption of $CO_2$ in wheat at 0, 10, 20, and 30°C temperature and at 12, 14, 16, and 18% m.c. (w.b.). For moisture contents tested, there was a decrease in the amount of gas sorbed with an increase in temperature. At 20°C, the amount of $CO_2$ sorbed into the grain kernels increased with an increase in moisture content. They reported a maximum value of sorption of 0.42 g of $CO_2$ per kg of wheat in 24 h at 0°C and 18% m.c.(w.b.).

The actual mechanism underlying sorption is not yet understood completely by researchers. However, the studies conducted by Mitsuda and Yamamoto (1980) showed that diffusion of gas molecules through the grain pores could be the major mechanism involved in sorption.

### 3.6 Production of $CO_2$ by Grain

#### 3.6.1 Respiration of Grain

In stored grain, $CO_2$ is produced due to the respiration of grain, insects, mites, and fungi. Several researchers have studied the production of $CO_2$ in grain bulks and reported that moisture content and temperature are the important factors affecting the production of $CO_2$ (Bailey 1940; Milthorpe and Robertson 1948; White et al. 1982; Srour 1988).

Bailey (1940) reported that as the moisture content of wheat was increased from 11% to 17%, $CO_2$ production per kilogram of dry matter increased from 0.2 mg to 11.0 mg. White et al. (1982) found that the rate of production of $CO_2$ increased with an increase in temperature and moisture content. In a 35 d period, 1 kg wheat at 16.5%

moisture content and 10° C produced 28 mg of $CO_2$ and when the temperature was raised to 40° C, 793 mg of $CO_2$ were produced in 21 days. They reported that for wheat at < 14% moisture content the $CO_2$ production is negligible.

### 3.6.2 Respiration of Insects and Microorganisms.

A high concentration of $CO_2$ in a grain bulk can be an indication of an insect infestation especially when the grain is relatively dry. Oxley and Howe (1944) have tried to detect insect infestation based on $CO_2$ concentration in the grain bulk.

Sinha et al. (1986a) detected 2% $CO_2$ inside infested bins containing corn, barley, and wheat and found the $CO_2$ concentration remained unchanged at the atmospheric level of 0.035% in control bins. Sinha et al. (1986b) estimated the rates of $CO_2$ production of T. castaneum and C. ferrugineus at 27.5°C and 33°C. They found a relationship between the insect life stages and amount of $CO_2$ produced.

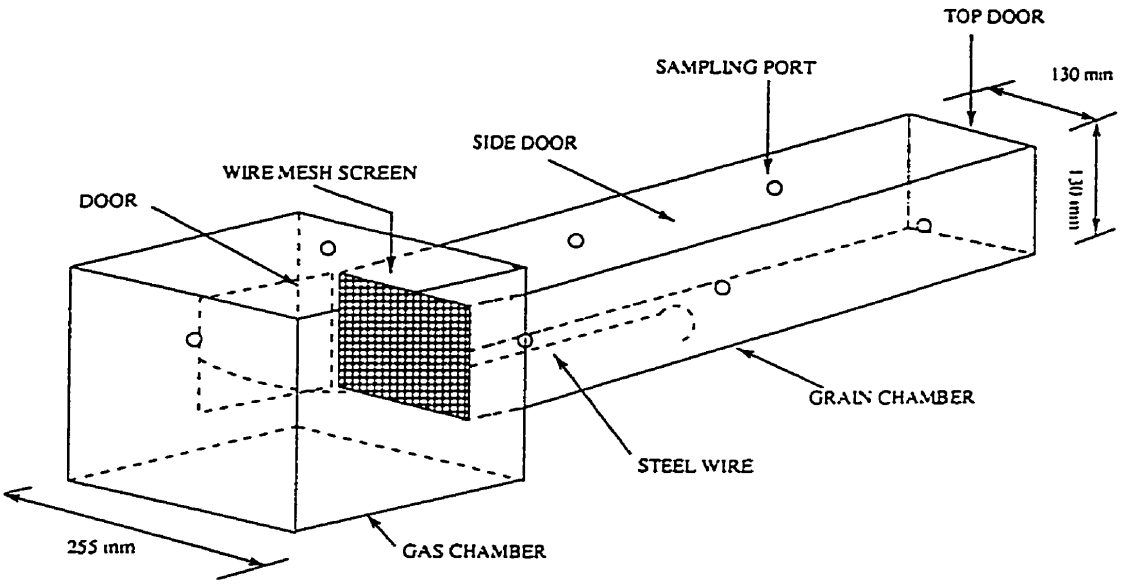
Respiration of microflora could cause $CO_2$ production in stored grain. Sauer et al. (1954) stated that about 90% of the respiration in corn with about 15-16% moisture could be due to microflora. White et al. (1982a and 1982b) reported that significant amount of $CO_2$ is produced by the respiration of microflora in damp wheat and canola. They found that when the moisture content and temperature were increased further, the amount of $CO_2$ produced by microflora in the grain also increased.

# 4. MATERIALS AND METHODS

## 4.1 Diffusion of $CO_2$ Through Grain Bulk

### 4.1.1 Diffusion Cell

A temperature- and humidity- controlled chamber was used to conduct diffusion experiments. Inside the chamber, a set of three humidifying fans were located at the top left when viewed on entering the chamber. On preliniminary investigation, I found non-uniform airflow inside the chamber. Therefore, I suspected that if an open diffusion cell was used, airflow inside the chamber could interfere with and alter the diffusion study. To minimise the influence of the surroundings inside the chamber on the diffusion process, I chose a closed diffusion cell. The diffusion cell is similar in concept to the cell used by Singh (Jayas) et al. (1984) and consisted of two parts: a cubical gas chamber of size 255 x 255 x 255 mm and a cylindrical grain chamber of size 130 x 130 x 500 mm (Fig. 4.1). The cell was constructed using 6.4 mm thick acrylic sheets. A wire mesh screen having 1.7 mm diameter holes was fitted at the joint of the grain column and gas chamber. The screen was covered from beneath by a door made of acrylic sheet. The door can be actuated manually from outside using a flexible steel wire. Along the joints of both the grain and gas chambers and also on the inner side of the door, foam tape weather stripping was used as a sealant. On checking for the effectiveness of sealing, the diffusion cell maintained a given concentration of $CO_2$ for more than 12 h (Fig. 4.2). Gas sampling ports were situated along two sides of the grain chamber with a spacing of 100 mm. Eight sampling ports covered with rubber septums installed in the gas chamber. The apparatus was placed on a table inside the chamber.




DIFFUSION CELL

Fig. 4.1 Schematic diagram of the diffusion cell

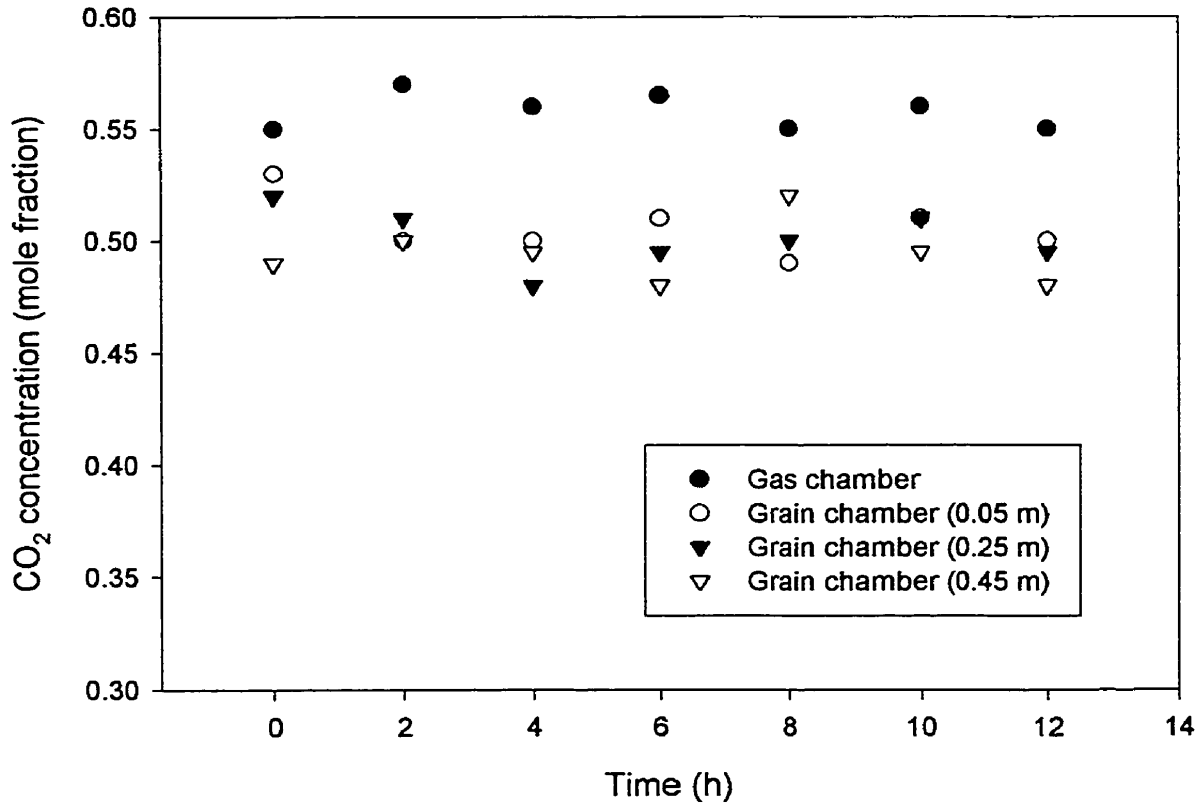



Fig. 4.2 Effectiveness of sealing the diffusion cell

All the four long sides of the grain chamber and the end cover (farthest from the gas chamber) can be removed and refitted with screws allowing grain to be filled either through the end or side of the grain chamber and thus two extreme grain kernel orientations (horizontal and vertical) to the direction of diffusion of $CO_2$ can be obtained. To study the downward direction of flow of $CO_2$, the gas chamber was above the grain chamber. Similarly horizontal movement of $CO_2$ was studied by placing suitable supports beneath the grain chamber and keeping the grain chamber horizontal. A spirit level was used to level the grain chamber and gas chamber.

### 4.1.2 Calibration of the Apparatus

Three tests each were conducted using the diffusion apparatus to measure the diffusion coefficient of carbon dioxide ($CO_2$) in nitrogen ($N_2$) and air. The environmental controlled chamber was set at the required temperature and humidity. The gas chamber was filled with $CO_2$ and the grain chamber was filled with $N_2$ or left with atmospheric air. A U- tube manometer was connected between the gas chamber and the grain chamber to check if both the chambers were at atmospheric pressure before the start of diffusion. The door separating the chambers was opened from outside using a steel wire to start the experiment. The gas samples of size 2 mL were withdrawn from each port of the chambers at the same time intervals as that for the experiments on diffusion of $CO_2$ through grain bulk and were analysed.

### 4.1.3 Sample Preparation

Wheat, barley, and canola (referred to a grains hereafter) were used for this study. Seed quality grains were purchased from United Grain Growers Ltd., Winnipeg (Table 4.1). Grain samples were moistened to the required moisture content by adding distilled water to the grain and mixing in a rotary concrete mixer for 30 min. The samples were then transferred to a plastic bag, sealed and placed at 24 °C inside the temperature- and humidity- controlled chamber for 48 h to allow equilibration of moisture with the grain kernels.

### 4.1.4 Experimental Design

The variables studied were grain moisture content, grain temperature, direction of flow of gas, porosity, grain kernel orientation to the gas flow, initial gas concentration, and dockage. I chose a partial factorial design because of the large number of variables. The details of the experiments conducted using wheat, barley, and canola bulks are given in Tables 4.2, 4.3, and 4.4, respectively. For each test, three replications were carried out.

### 4.1.5 Experimental Procedure

The diffusion cell was placed inside the temperature- and humidity- controlled chamber. The required temperature for the test was set in the chamber. The equilibrium relative humidity for the temperature and moisture content of the grain under test was set as the desired relative humidity in the chamber. About 1 h was allowed for the chamber to attain the required conditions of temperature and humidity. The hinged door separating

**Table 4.1 Details of grain used in the experiments**

| No. | Grain Type | Variety | Harvested in | Initial Moisture Content (% w.b.) |
|---|---|---|---|---|
| 1 | Wheat | Katepwa | 1992 | 10.0 |
| 2 | Barley | Bedford | 1993 | 9.5 |
| 3 | Canola | Jackpot | 1993 | 6.0 |

**Table 4.2 Experimental details of diffusion of $CO_2$ through a wheat bulk**

| No. | Moisture content (% w.b) | Temper-ature °C | Direction of gas flow | Porosity (%) | Kernel orien-tation* | Initial gas concent-ration (%) | Dockage (%) |
|---|---|---|---|---|---|---|---|
| 1 | 12.5 | 25 | upward | 40 | horizontal | 40 | 0 |
| 2 | 15.5 | 25 | upward | 43 | horizontal | 40 | 0 |
| 3 | 18.0 | 25 | upward | 46 | horizontal | 40 | 0 |
| 4 | 15.0 | 5 | upward | 43 | horizontal | 40 | 0 |
| 5 | 15.0 | 15 | upward | 43 | horizontal | 40 | 0 |
| 6 | 15.0 | 40 | upward | 43 | horizontal | 40 | 0 |
| 7 | 15.0 | 25 | downward | 43 | horizontal | 40 | 0 |
| 8 | 15.0 | 25 | horizontal | 43 | horizontal | 40 | 0 |
| 9 | 15.0 | 25 | upward | 38 | + | 40 | 0 |
| 10 | 15.0 | 25 | upward | 43 | vertical | 40 | 0 |
| 11 | 15.0 | 25 | upward | 43 | horizontal | 20 | 0 |
| 12 | 15.0 | 25 | upward | 43 | horizontal | 60 | 0 |
| 13 | 15.0 | 25 | upward | 45 | horizontal | 40 | 4 |
| 14 | 15.0 | 25 | upward | 47 | horizontal | 40 | 8 |
| 15 | 15.0 | 25 | upward | 49 | horizontal | 40 | 12 |

*To obtain horizontal kernel orientation, grain chamber was filled from the top, whereas to obtain vertical kernel orientation, the grain chamber was filled from the side.
+Shaking of grain chamber affected the grain kernel orientation.

**Table 4.3 Experimental details of diffusion of $CO_2$ through a barley bulk**

| No. | Moisture content (% w.b) | Temper-ature °C | Direction of gas flow | Porosity (%) | Kernel orien-tation* | Initial gas concent-ration (%) | Dockage (%) |
|---|---|---|---|---|---|---|---|
| 1 | 12.5 | 25 | upward | 51 | horizontal | 40 | 0 |
| 2 | 15.5 | 25 | upward | 54 | horizontal | 40 | 0 |
| 3 | 18.0 | 25 | upward | 57 | horizontal | 40 | 0 |
| 4 | 15.0 | 5 | upward | 54 | horizontal | 40 | 0 |
| 5 | 15.0 | 15 | upward | 54 | horizontal | 40 | 0 |
| 6 | 15.0 | 40 | upward | 54 | horizontal | 40 | 0 |
| 7 | 15.0 | 25 | downward | 54 | horizontal | 40 | 0 |
| 8 | 15.0 | 25 | horizontal | 54 | horizontal | 40 | 0 |
| 9 | 15.0 | 25 | upward | 48 | + | 40 | 0 |
| 10 | 15.0 | 25 | upward | 54 | v ertical | 40 | 0 |
| 11 | 15.0 | 25 | upward | 54 | horizontal | 20 | 0 |
| 12 | 15.0 | 25 | upward | 54 | horizontal | 60 | 0 |
| 13 | 15.0 | 25 | upward | 56 | horizontal | 40 | 4 |
| 14 | 15.0 | 25 | upward | 58 | horizontal | 40 | 8 |
| 15 | 15.0 | 25 | upward | 60 | horizontal | 40 | 12 |

*To obtain horizontal kernel orientation, grain chamber was filled from the top, whereas to obtain vertical kernel orientation, the grain chamber was filled from the side.
+Shaking of grain chamber affected the grain kernel orientation.

**Table 4.4 Experimental details of diffusion of $CO_2$ through a canola bulk**

| No. | Moisture content (% w.b) | Temper-ature °C | Direction of gas flow | Porosity (%) | Kernel orien-tation* | Initial gas concent-ration (%) | Dockage (%) |
|---|---|---|---|---|---|---|---|
| 1 | 8.0 | 25 | upward | 31 | horizontal | 40 | 0 |
| 2 | 10.5 | 25 | upward | 34 | horizontal | 40 | 0 |
| 3 | 13.0 | 25 | upward | 37 | horizontal | 40 | 0 |
| 4 | 15.0 | 5 | upward | 34 | horizontal | 40 | 0 |
| 5 | 15.0 | 15 | upward | 34 | horizontal | 40 | 0 |
| 6 | 15.0 | 40 | upward | 34 | horizontal | 40 | 0 |
| 7 | 15.0 | 25 | downward | 34 | horizontal | 40 | 0 |
| 8 | 15.0 | 25 | horizontal | 34 | horizontal | 40 | 0 |
| 9 | 15.0 | 25 | upward | 31 | + | 40 | 0 |
| 10 | 15.0 | 25 | upward | 34 | vertical | 40 | 0 |
| 11 | 15.0 | 25 | upward | 34 | horizontal | 20 | 0 |
| 12 | 15.0 | 25 | upward | 34 | horizontal | 60 | 0 |
| 13 | 15.0 | 25 | upward | 36 | horizontal | 40 | 4 |
| 14 | 15.0 | 25 | upward | 37 | horizontal | 40 | 8 |
| 15 | 15.0 | 25 | upward | 39 | horizontal | 40 | 12 |

*To obtain horizontal kernel orientation, grain chamber was filled from the top, whereas to obtain vertical kernel orientation, the grain chamber was filled from the side.
+Shaking of grain chamber affected the grain kernel orientation.

the grain chamber from the gas chamber was closed by pulling the steel wire and screwing a bolt on to the wire. The grain chamber was filled with grain by filling grain from the top for most experiments (Tables 4.2, 4.3, and 4.4). The grain was levelled off using the top plate and the chamber top was closed. The gas chamber was flushed with $CO_2$ from a compressed gas cylinder after conditioning the gas to the desired relative humidity using a saturated salt solution (Greenspan 1977). Preliminary tests showed that 3 h were required for the $CO_2$-flushed gas chamber to attain a uniform concentration after the $CO_2$ flow was turned off. Therefore, the gas chamber was left undisturbed for 3 h to get a uniform gas mixture.

Three sample ports were randomly chosen in the gas chamber and one gas sample was withdrawn from each of the ports selected. Also, one gas sample was withdrawn for each of the five ports of the grain chamber. The gas samples were stored in syringes covered with rubber septa. At this stage of the experiment, a U- tube manometer was connected between the gas chamber and grain chamber to check if there was a pressure difference. Then the separation door was opened to start the diffusion process. Eight gas samples were collected at 0.5 h and at every hour for 6 h from the start of the diffusion. Preliminary tests indicated that the gas concentration along the grain chamber as well as the gas chamber levelled off after 6-7 h and the diffusion process comes to an end.

The gas samples were analysed using a gas chromatograph (Hewlett-Packard model HP 9850, Avondale, PA) equipped with a thermal conductivity detector and a fixed sample loop of 1 mL. The carrier gas used was helium (50 mL/min). The oven temperature was programmed at 70°C and the detector temperature at 150°C. The steel column was packed with Porapak N.

The mass of grain put into the grain chamber was measured and used to calculate the in situ bulk density of the grain. The particle density of the grain used in each test was measured using an air comparison pycnometer (Model 930, Beckman Instruments, Inc., Fullerton, CA). Three samples were used for each test. To achieve the desired porosity, the measured grain mass was filled into the chamber in four equal increments and after each increment, the diffusion cell was shaken 15 times by hand.

To study the effect of dockage on the diffusion coefficient of $CO_2$, 10 bags of dockage were collected as samples from a primary elevator belonging to United Grain Growers Ltd., Winnipeg. The distribution of chaff and fines in the dockage were estimated by sieve analysis. The material not passing through sieve number 10 was considered as chaff. Generally more chaff by mass was found than fines in a sample of dockage. The average size distribution of fines and chaff is given in Table 4.5.

To study the effect of kernel orientation on the diffusion of $CO_2$, the cell was placed such that the grain chamber was held horizontally on the table. One of the side walls (top side wall) of the grain chamber was opened and used for filling. After filling the chamber, the side-wall was closed and the diffusion cell was turned to the upright position.

## 4.2 Sorption of $CO_2$ by Grain

### 4.2.1 Sorption Apparatus

The sorption apparatus used in this study was similar to the one used by Cofie-Agblor et al. (1993). The apparatus consisted of two conical flasks of 500 mL volume closed by rubber stoppers. Each flask was fitted with two plastic tubes (Fig 4.3). One of the tubes was connected to one end of a U-tube manometer, and the other tube was closed

**Table 4.5 Size distribution of dockage in typical samples**

| No. | Sieve size | Apperture (mm) | Classification | Mass retained (g)# | % Total |
|---|---|---|---|---|---|
| 1 | Pan | | Dust | 6.0 | 0.39 |
| 2 | 20 | 0.85 | Fines | 18.0 | 1.18 |
| 3 | 16 | 1.19 | Fines | 307.0 | 20.05 |
| 4 | 10 | 2.00 | Fines | 190.0 | 12.41 |
| 5 | >10 | > 2.00 | Chaff | 1010.0 | 65.97 |
| | | | | 1531.0 | 100.00 |

# Average of 6 samples.

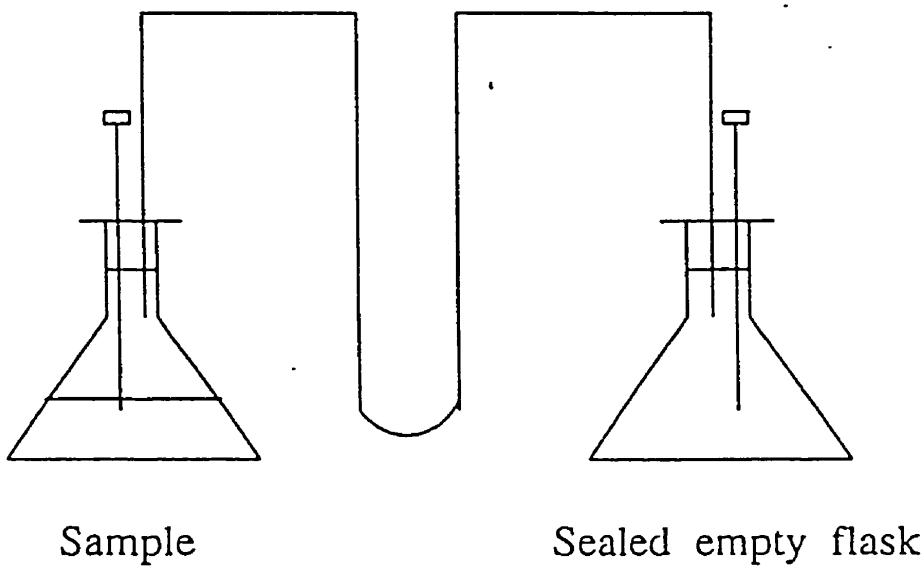



Fig. 4.3. Schematic diagram of sorption apparatus (Cofie-Agblor et al. 1993)

with a rubber septum for taking gas samples. One of the flasks was filled with grain and the other was left empty. The empty flask eliminated the effects of variations in atmospheric pressure on manometer readings by maintaining a constant atmospheric pressure during experiments.

### 4.2.2 Experimental Procedure

The details of sorption tests are listed in Table 4.6. The tests were replicated three times. Grain samples were conditioned to the desired moisture levels using the procedure in section 4.1.4.

In one flask, 200 g of grain at the specified moisture content was placed and it was flushed with $CO_2$ gas. The dry gas from the $CO_2$ cylinder was bubbled through saturated salt solutions to have the required relative humidity before being allowed to flush the grain at a gas pressure of 2 ksc. After 3 min of flushing, the flask was sealed with the stopper. One of the tubes was connected to the U-tube manometer. A gas sample of 2 mL was taken from the septum of the other tube and analysed to check if 100% $CO_2$ concentration was achieved.

The empty flask was then connected to the other side of the U-tube manometer. Initially the mercury levels in both sides of the U-tube were at the same level. The difference in mercury levels was noted at every hour from the start of the experiment. Because the diffusion experiment lasted for 6 h, sorption experiments were also conducted for the same time period. The atmospheric pressure reading for Winnipeg was obtained from Environment Canada at the time of starting the experiment. The particle densities of grains measured during diffusion tests were used in calculations for $CO_2$ sorption.

**Table 4.6 Experimental details of sorption of $CO_2$ by barley and canola**

| Test No. | Grain Type | Moisture content (%) | Temperature (°C) |
|---|---|---|---|
| 1 | Barley | 12.5 | 15 |
| 2 | Barley | 15.0 | 15 |
| 3 | Barley | 18.0 | 15 |
| 4 | Barley | 12.5 | 25 |
| 5 | Barley | 15.0 | 25 |
| 6 | Barley | 18.0 | 25 |
| 7 | Canola | 8.0 | 15 |
| 8 | Canola | 10.5 | 15 |
| 9 | Canola | 13.0 | 15 |
| 10 | Canola | 8.0 | 25 |
| 11 | Canola | 10.5 | 25 |
| 12 | Canola | 13.0 | 25 |

Because the total time of the experiments was only 6 h, and most of the experiments were carried out at temperatures < 25°C and moisture contents < 15% for wheat; < 15% for barley; and < 10.5% for canola, I assumed that the $CO_2$ production due to respiration of the grain was negligible and hence did not include a source term in the governing differential equation for diffusion.

# 5. MODEL DEVELOPMENT

## 5.1 Governing Equation and Boundary Conditions

The partial differential equation describing the diffusion of carbon dioxide ($CO_2$) into intergranular air in the diffusion apparatus is given as (Bird et al. 1960):

$$\partial C/\partial t = D\,\partial^2 C/\partial x^2 + q \qquad \text{for } 0 < x < L; \text{ and } 0 < t \qquad (5.1)$$

where:

C = concentration of $CO_2$, mole fraction,

D = diffusion coefficient of $CO_2$ through a grain bulk, $m^2\ s^{-1}$,

q = sorption of $CO_2$ into the grain mass; mole fraction/s,

The boundary and initial conditions for the governing equation are:

1. $\partial C/\partial x = 0$ at $x = L$

2. $C(x,t) = \varnothing(t)$ at $x = 0$

3. $C(x,0) = f(x)$ $0 < x < L$

Although the $CO_2$ movement through a grain bulk is a three dimensional problem, the diffusion apparatus was designed in such a way that the movement was treated as one-dimensional problem. Any direction dependence of the diffusion coefficient was to be studied separately. To isolate the effect of the fans inside the temperature- controlled chamber from influencing the diffusion process, the apparatus was completely closed.

**5.2 Solution Technique**

Eq. 5.1 along with the associated boundary and initial conditions was solved using the finite difference method. The technique proposed by Crank-Nicholson was adopted because of its reliability and ease (Smith 1985).

The grain mass inside the diffusion apparatus was divided into 10 spatial elements, 50 mm each. The time step was chosen as 180 s. The approximation used for $\partial C/\partial t_{(x, t+k/2)}$ was from the central difference formula.

$$\partial C/\partial t_{(x,t+k/2)} = \{C_{(x, t+k)} - C_{(x,t)}\}/ k \qquad (5.2)$$

where 'k' is the time step.

The approximation used for $\partial^2 C/ \partial x^2_{(x, t+k/2)}$ is the average of approximations

$$\partial^2 C/ \partial x^2_{(x, t)} \text{ and } \partial^2 C/ \partial x^2_{(x, t+k)}.$$

$$\partial^2 C/ \partial x^2_{(x, t+k/2)} = 0.5h^2[C_{(x-h, t+k)} - 2C_{(t+k)} + C_{(x+h, t+k)} + C_{(x-h, t)} - 2C_{(x, t)} + C_{(x+h, t)}] \qquad (5.3)$$

where 'h' is the element length.

Substituting Eqs. 5.2 and 5.3 in Eq. 5.1 and employing the notation $C_{ij} = C_{(xi, tj)}$

$$[C_{i\,j+1,} - C_{ij}]/k = D[C_{i-1\ j+1} - 2C_{i\,j+1} + C_{i+1\,j+1} + C_{i-1\,j} - 2C_{ij} + C_{i+1\,j}]/ 2h^2 \qquad (5.4)$$

Rearrangement of the terms in Eq. 5.4 results in

$$-rC_{i-1\,j+1} + (2+2r)\, C_{i\,j+1} - rC_{i+1\,j+1} = (2-2r)\, C_{ij} + r\,(C_{i-1\,j} + C_{i+1\,j}) \text{ for } i= 2, 3,.....10 \qquad (5.5)$$

where $r = Dk/h^2$

The Eq. 5.5 forms a linear system of equations, $[A]X = \{B\}$ which can be solved by iteration using the Guass Elimination Method.

The diffusion coefficient of $CO_2$ through the grain bulk was determined as follows:

With an arbitrary 'D' value, $CO_2$ concentrations were predicted at the five sampling locations of the grain chamber for the sampling time intervals of the experiment (t = 0, 0.5, 1, 2, 3, 4, 5, and 6 h) using the model. For each time interval, the differences between the observed and predicted concentrations in all the sampling locations were calculated. The percent error in concentration values were obtained for all the sampling points in all the time intervals as follows:

$$\text{Percent error} = \frac{(\text{Observed } CO_2 \text{ concentration-Predicetd } CO_2 \text{ concentration})}{\text{Observed } CO_2 \text{ concentration}} \times 100$$

For each experimental set of observations, mean percent error was calculated and minimised by an iterative process with either incremented or decremented 'D' value. The desired value of 'D' was found based on the minimum error between the predicted and measured $CO_2$ concentrations along the grain column.

A program coded in Fortran for the one dimensional transient diffusion model is included in Appendix A. The program was tested as follows to ensure that it accurately solves the diffusion equation:

Carbon dioxide concentration profiles were obtained at a specific location in the grain chamber by solving the diffusion equation analytically and also by running the model. Same test conditions were maintained for both the cases. A common 'D' value and an initial gas concentration in the gas chamber were used to generate the concentration profiles. The grain chamber was assumed to hold no grain. The shapes of both the concentration profiles were same which indicated that the model solves the diffusion

equation. When the size of the spatial element and the time step were reduced, the solution curve of the model approached the solution curve of the analytical method.

# 6. RESULTS AND DISCUSSION

## 6.1 Calibration of the Apparatus

The diffusion coefficients of $CO_2$ in air and $CO_2$ in $N_2$ were determined using the finite difference model described in Chapter 5. During these calculations the sorption term was included.

The measured diffusion coefficients of $CO_2$ in air and $CO_2$ in $N_2$ are given in Table 6.1 along with the values reported by Sissom and Pitts (1972), and Pitchard and Currie (1982). Theoretical values calculated from the kinetic theory of gases are also given in Table 6.1. The measured diffusion coefficient of $CO_2$ in air was 6.5% less than the value of Sissom and Pitts (1972), and 10% less than the value of Pitchard and Currie (1982). No reported value of the diffusion coefficient of $CO_2$ in $N_2$ is available for comparison. The measured diffusion coefficient of $CO_2$ in air is 17% less than the theoretically calculated value and that of $CO_2$ in $N_2$ is 9% less than the theoretical value.

Slattery and Bird (1958) discussed the deviations of measured diffusion coefficients from values calculated based on Chapman-Enskog's kinetic theory of gases. They concluded that the discrepancy is probably due to the inadequacy of the Lennard-Jones potential. They also stated that the Lennard-Jones potential is generally inadequate for large complex molecules and wherever possible, experimental values must be relied upon rather than the theoretical values. As diffusion of $CO_2$ in air involves tri-atomic molecules, probably the discrepancy resulted from an inadequate Lennard-Jones parameter, because the Chapman-Enskog's theory was developed for mano-atomic molecules.

**Table 6.1 Comparison of diffusion coefficients of $CO_2$ through air and $N_2$**

| Test | Measured ($\times 10^{-6} m^2 s^{-1}$) | Predicted using kinetic theory ($\times 10^{-6} m^2 s^{-1}$) | Sissom and Pitts(1972) ($\times 10^{-6} m^2 s^{-1}$) | Pritchard and Currie(1982) ($\times 10^{-6} m^2 s^{-1}$) |
|---|---|---|---|---|
| $CO_2$ in air | 12.51 | 15.16 | 13.38 | 13.90 |
| $CO_2$ in $N_2$ | 15.06 | 16.52 | - | - |

### 6.2 Sorption of $CO_2$ by Barley and Canola

There is a relationship between sorption of $CO_2$ and moisture content of grain at 25°C (Figures 6.1, and 6.2). Cofie-Agblor et al. (1993) obtained similar results for sorption of $CO_2$ in wheat. They reported that in the middle range of temperatures studied (10 and 20°C), the variation of sorption of $CO_2$ by the grain was insignificant at all moisture levels (12, 14, 16, and 18%), but at 30°C the sorption of $CO_2$ increased with moisture content. Increased sorption at higher moisture contents could be due to increased bulk porosity and dissolution of $CO_2$ in water molecules filled in the pore spaces of grains. Yamamoto and Mitsuda (1980), however, found a linear dependence of sorption on the temperature of grain. For the temperature range studied, there were no significant differences ($p > 0.05$) in the amounts of $CO_2$ sorbed by barley at 15% m.c. (Fig. 6.3) and also for canola at 10.5% m.c. (data not shown).

I used the data of Cofie-Agblor et al. (1993) for sorption of $CO_2$ by wheat to determine the diffusion coefficient in wheat. The temperature dependence of sorption was negligible and therefore it was not considered in calculating the diffusion coefficient of $CO_2$ through grain bulks.

The results of $CO_2$ sorption for wheat, barley and canola were fitted to a polynomial of the form:

$$q = a + b\,(t) + c\,(t^2) + d\,(t^3) \qquad (6.1)$$

where:

q = amount of $CO_2$ sorbed at time 't', ($mg \cdot kg^{-1}$),

t = time elapsed since the start of experiment, (h),

a, b, c, and d are constants.

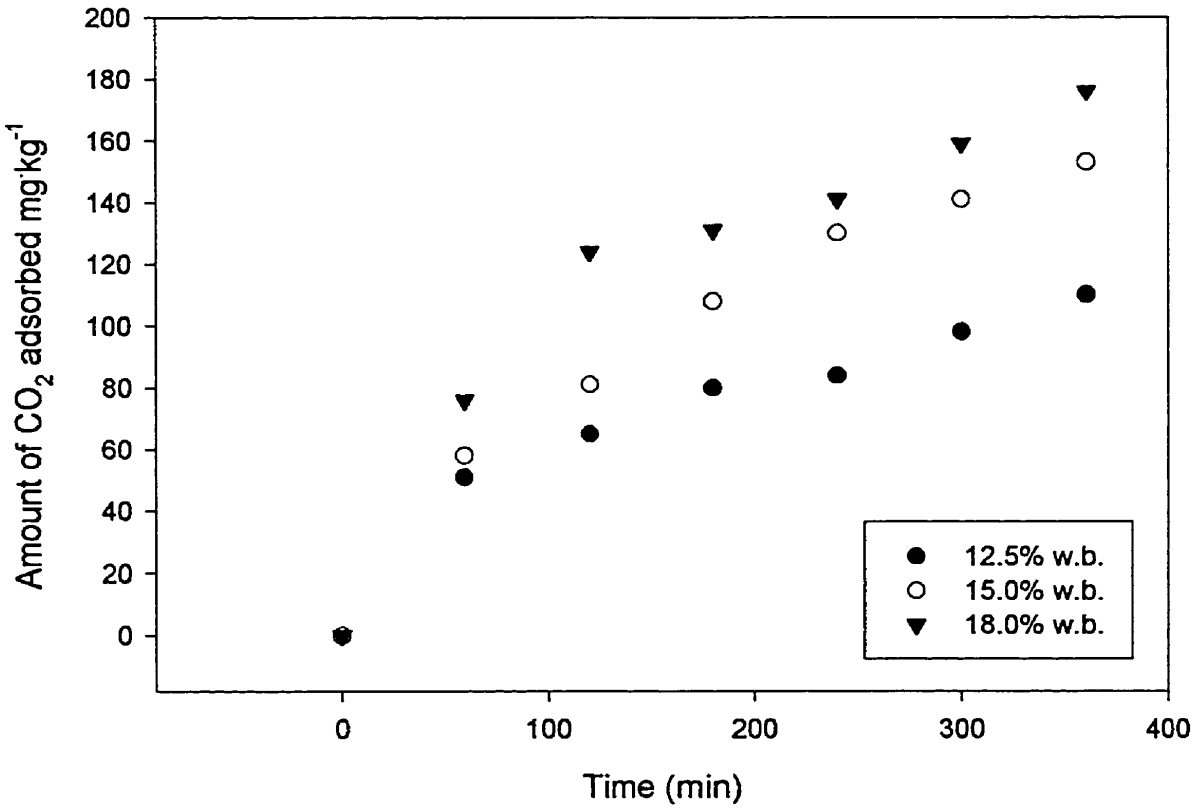



Fig. 6.1 Effect of moisture content on sorption of $CO_2$ by barley at 25°C

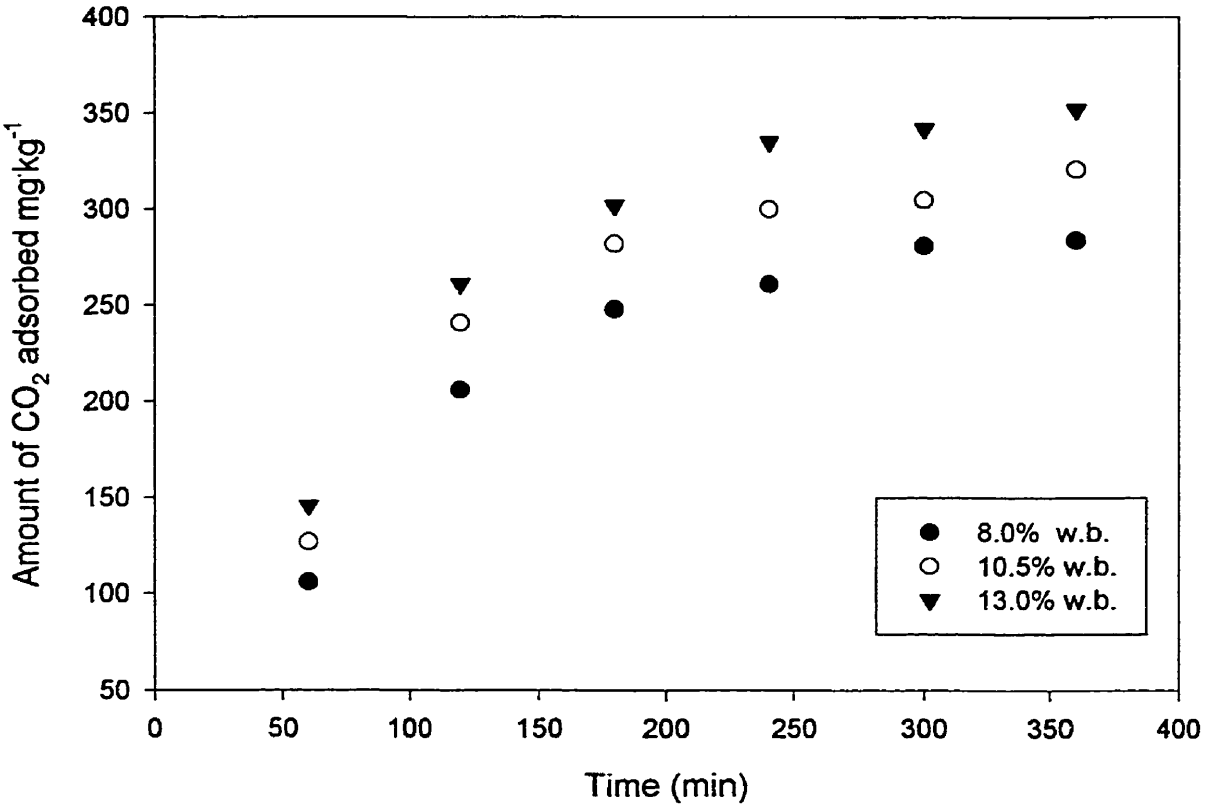



Fig. 6.2 Effect of moisture content on sorption of $CO_2$ by canola at 25°C

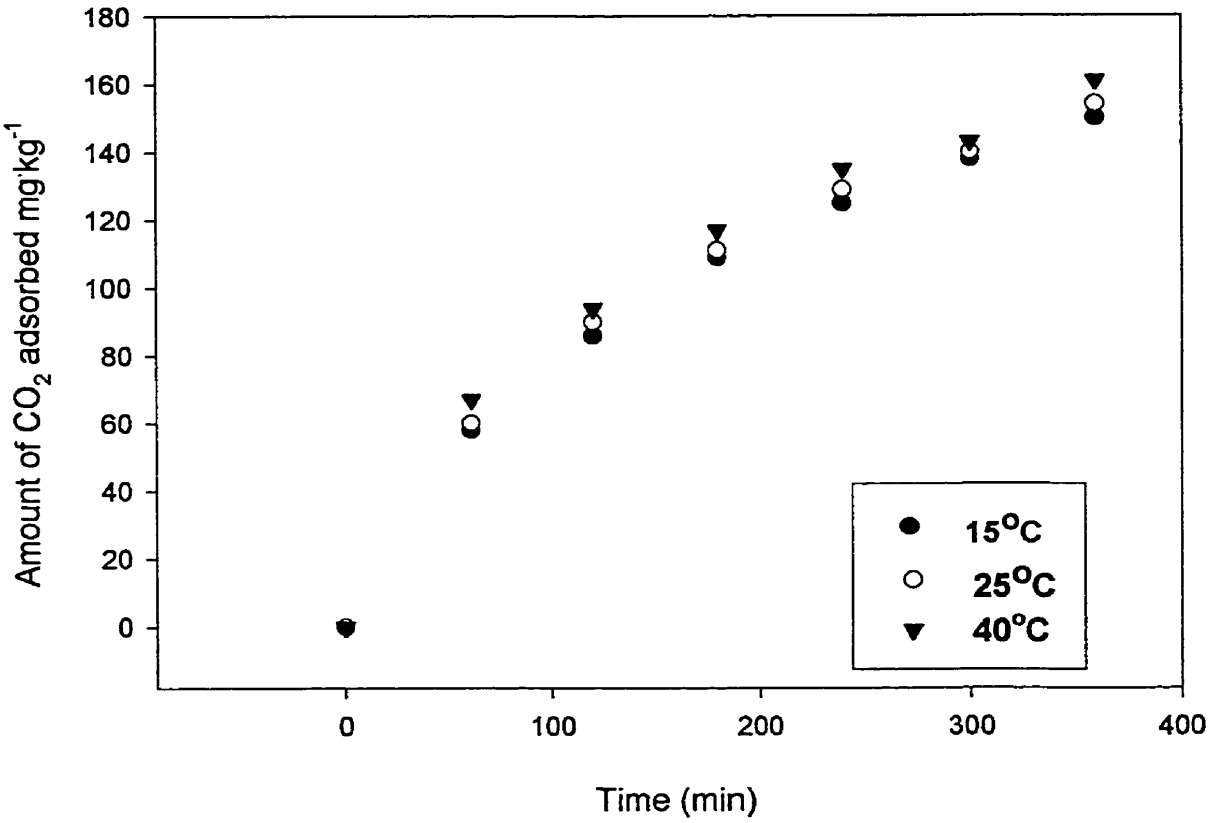



Fig. 6.3 Effect of temperature on sorption of $CO_2$ by barley at 15% m.c.

The values of a, b, c, and d are given in Table 6.2 for wheat, barley, and canola.

Cofie-Agblor et al. (1993) stated that the amount of $CO_2$ sorbed in grain is dependent on initial gas concentration in the flask. This result was assumed to extend to barley and canola and in calculating the diffusion coefficient the amount of $CO_2$ sorbed was adjusted for the initial gas concentration in the gas chamber.

### 6.3 Diffusion Coefficient of $CO_2$ Through Grain Bulks

The diffusion coefficients of $CO_2$ through wheat bulks were in the range of 5.9 x $10^{-6}$ to 7.6 x $10^{-6}$ $m^2s^{-1}$ and through barley bulks they were in the range of 5.1 x $10^{-6}$ to 8.4 x $10^{-6}$ $m^2s^{-1}$ and that of canola bulks they were in the range of 3.7 x$10^{6}$ to 5.3 x $10^{-6}$ $m^2s^{-1}$. These values were generally higher (63% higher for wheat and 43% higher for canola) than the values obtained by Singh (Jayas) et al. (1985). In multi-component diffusion in a closed system such as the one used in this study, a viscous flux is generated in addition to the molecular flux because of the difference in molecular mass of the component molecules. This may account for the increase in flow and hence for a higher coefficient (Cunningham and Williams 1980).

The effects of the variables (i.e., moisture content, temperature, direction of flow of gas, porosity, grain kernel orientation, initial gas concentration, and dockage) on the diffusion coefficients of $CO_2$ through the grain bulks followed similar trends for all three grain bulks.

The average absolute errors between the predicted and measured nodal $CO_2$ concentrations were in the range of 10-17%. Typical plots of predicted and determined $CO_2$ concentrations at 0.15 and 0.35 m in the grain chamber are shown in Fig. 6.4. The

**Table 6.2 Regression coefficients of sorption curves (Eq. 6.1)**

| Grain Type | Moisture content (% w.b.) | a | b | c | d | $r^2$ |
|---|---|---|---|---|---|---|
| Wheat [+] | 12.0 | 0.0410 | 0.0161 | 0.0004 | $3.085 \times 10^{-6}$ | 0.926 |
| | 14.0 | 0.0437 | 0.0209 | 0.0005 | $4.706 \times 10^{-6}$ | 0.931 |
| | 16.0 | 0.0630 | 0.0253 | 0.0007 | $6.5978 \times 10^{-6}$ | 0.917 |
| | 18.0 | 0.0856 | 0.0260 | 0.0008 | $7.4792 \times 10^{-6}$ | 0.955 |
| Barley | 12.5 | 0.0012 | 0.0540 | 0.0108 | 0.0008 | 0.963 |
| | 15.0 | 0.0009 | 0.0659 | 0.0114 | 0.0007 | 0.928 |
| | 18.0 | 0.0011 | 0.0879 | 0.0183 | 0.0014 | 0.903 |
| Canola | 6.5 | 0.0007 | 0.0920 | 0.0212 | 0.0014 | 0.914 |
| | 8.0 | 0.0006 | 0.1241 | 0.0220 | 0.0012 | 0.891 |
| | 10.5 | 0.0013 | 0.1534 | 0.0271 | 0.0029 | 0.924 |

[+] Sorption data for wheat was adopted from Cofie-Agblor et al. (1993)

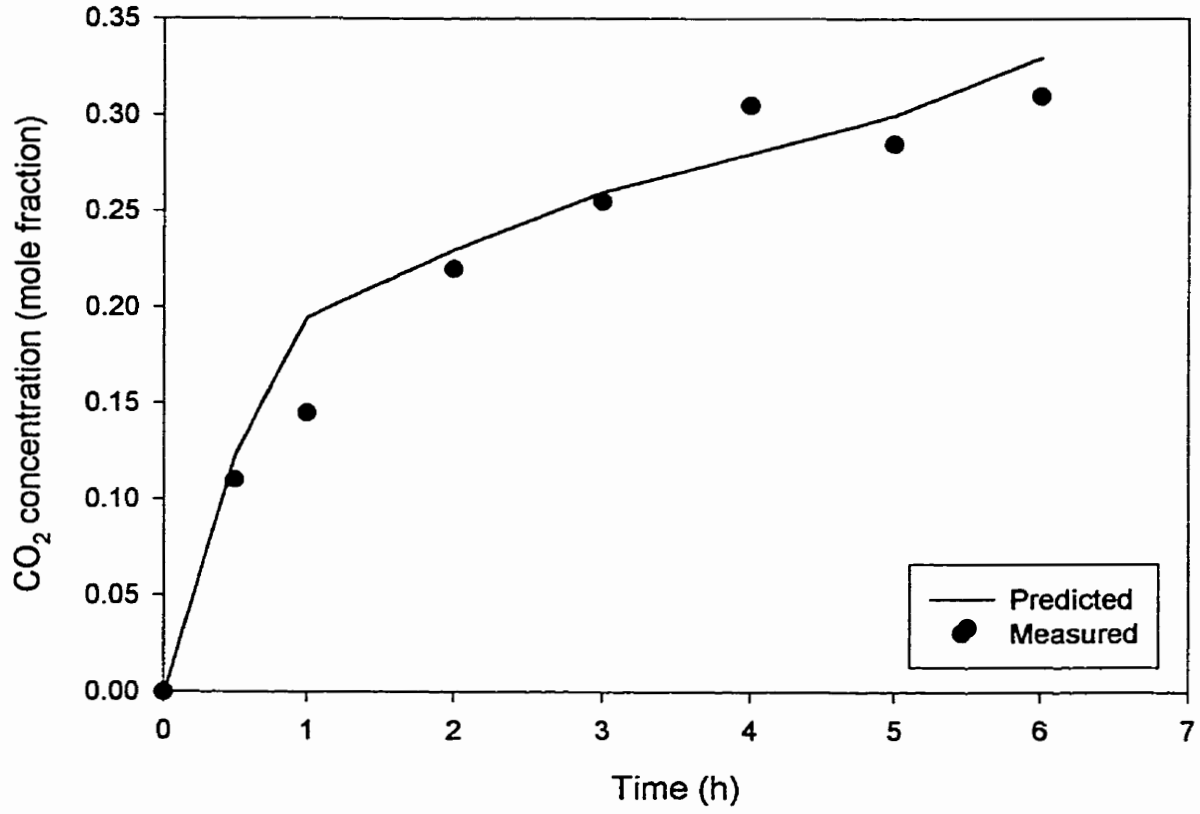



Fig. 6.4 Comparison of predicted and measured $CO_2$ concentrations in the grain chamber at a point 0.15 m from the top

method used to determine the diffusion coefficient of $CO_2$ has an accuracy of about 20%. The measured $CO_2$ concentrations in the diffusion cell are given in Appendix B.

A sensitivity analysis of the model was carried out to study the effect of 20% variation in 'D' on the changes in $CO_2$ concentrations inside a grain bulk. A simulation study was done to predict the $CO_2$ concentrations due to diffusion along a pilot scale bin (1.42 m diameter and 1.00 m height) containing wheat at 12.5% m.c. and 25°C using the three dimensional finite element model developed by Alagusundaram et al. (1996b). An initial concentration of 60% was provided at the bottom of the bin and the top was left open. For a diffusion coefficient value of $6.5 \times 10^{-6}$ $m^2s^{-1}$, the average increase in nodal concentrations was 14% for a 20% increase in 'D' value and the average decrease in nodal concentrations was 9% for a 20% decrease in 'D' value.

The model can be used to develop a three dimensional model with direction dependent diffusion coefficients. The three dimensional model could then be used to predict the $CO_2$ concentrations in a grain bulk treated with controlled atmospheres. The developed model is an useful tool to ensure the effectiveness of CA treatment in a farm bin. Alternatively, the quantity of $CO_2$ required for generating a specific $CO_2$ concentration inside the grain bulk can be estimated using the model.

## 6.4 Diffusion Coefficient of $CO_2$ Through Wheat Bulks

### 6.4.1 General

The diffusion coefficients of $CO_2$ through wheat bulks for the variables tested in this study are given in Table 6.3.

**Table 6.3 Diffusion coefficient of $CO_2$ through a wheat bulk**

| Experiment* | Diffusion coefficient (x $10^{-6}$ $m^2s^{-1}$) | | | Mean (x $10^{-6}$ $m^2s^{-1}$) | Standard deviation (x $10^{-6}$ $m^2s^{-1}$) |
|---|---|---|---|---|---|
| | $r_1^{\Psi}$ | $r_2^{\Psi}$ | $r_3^{\Psi}$ | | |
| 1 | 6.9 | 6.6 | 5.9 | 6.5 | 0.4 |
| 2 | 5.3 | 6.2 | 6.8 | 6.1 | 0.6 |
| 3 | 5.2 | 7.1 | - | 6.2 | 1.0 |
| 4 | 6.1 | 5.6 | 6.2 | 6.0 | 0.3 |
| 5 | 6.2 | 5.8 | 6.1 | 6.0 | 0.2 |
| 6 | 6.7 | 6.3 | 8.0 | 7.0 | 0.7 |
| 7 | 9.3 | 7.1 | 6.2 | 7.5 | 1.3 |
| 8 | 6.7 | 6.0 | 6.3 | 6.3 | 0.2 |
| 9 | 5.6 | 6.6 | 5.6 | 5.9 | 0.5 |
| 10 | 6.6 | 8.6 | 7.7 | 7.6 | 0.8 |
| 11 | 6.5 | 6.8 | 6.2 | 6.5 | 0.3 |
| 12 | 6.6 | 6.3 | 5.9 | 6.3 | 0.3 |
| 13 | 6.5 | 6.3 | 6.2 | 6.3 | 0.1 |
| 14 | 6.8 | 6.5 | 6.5 | 6.6 | 0.1 |
| 15 | 7.2 | 6.9 | 6.9 | 7.0 | 0.2 |

$^{\Psi}$ $r_1$, $r_2$ , $r_3$ are three replicates.
* Refer to Table 5.2 for the details of the experimental conditions.

### 6.4.2 Effect of Moisture Content

The diffusion coefficient of $CO_2$ through a wheat bulk decreased from 6.5 x $10^{-6}$ $m^2s^{-1}$ to 6.1 x $10^{-6}$ $m^2s^{-1}$ with an increase in grain moisture content from 12.5 to 15.0% and then remained constant with an increase in the moisture content to 18%. This result is similar to the observation by Singh (Jayas) et al. (1984) who reported that the diffusion coefficient decreases with an increase in moisture content from 13 to 15%. No change in diffusion coefficient was observed as the moisture content was increased further to 18%. The reduction in diffusion coefficient despite a 3% increase in porosity at higher moisture contents (Table 4.2) indicated that the resistance to diffusive flow is higher in wet grains. The $CO_2$ molecules adsorbed on the surface of wet grain may offer more resistance to diffusion at increasing moisture contents up to 15%. As the moisture content was increased further, the effect of sorption of $CO_2$ molecules on moist grain may have been nullified by the effect of increased bulk porosity which led to the stabilisation of diffusion coefficient values.

### 6.4.3. Effect of Temperature

As the temperature was increased from 5°C to 40°C, the diffusion coefficient increased from 6.0 x $10^{-6}$ $m^2s^{-1}$ to 7.0 x $10^{-6}$ $m^2s^{-1}$ (Table 6.3 and Table 4.2). According to the kinetic theory of gases, temperature is a critical factor controlling the molecular motion of a gas. An increase in temperature increases the velocity of the gas molecules inside the wheat bulk and hence an increase in diffusion rate. Singh (Jayas) et al. (1984) observed an increase in diffusion coefficient in a quadratic fashion as the temperature increased from -10°C to 30°C. The mass diffusivity ($D_{AB}$) for a binary system of gases is

a function of temperature and it increases with increase in temperature (Bird et al. 1960). Alagusundaram et al. (1996a) observed that for wheat the apparent diffusion of $CO_2$ had a linear dependence on temperature. The increase in the diffusion coefficient of $CO_2$ in air with an increase in temperature was calculated using Chapman-Enskog's kinetic theory of gases and compared with the rates of increase of diffusion coefficient of $CO_2$ through a wheat bulk. For the temperature range 5°C-40°C, theoretically calculated and experimentally determined diffusion coefficients compared very well.

### 6.4.4 Effect of Direction of Gas Flow

The diffusion coefficient of $CO_2$ through wheat was 23% higher in the downward direction than in the upward direction (Table 6.3 and Table 4.2). Carbon dioxide, being 1.3 times denser than air sinks from the gas chamber as soon as the diffusion process starts and that could be the reason for a higher coefficient in the downward direction than in the upward direction. Penetration of $CO_2$ deep into the grain bulk due to gravity forces was observed by several researchers. Wilson et al. (1980) conducted pilot scale studies on a CA storage of bulk wheat using $CO_2$. In a bin containing 1.9 t of wheat, intergranular $CO_2$ gas composition was raised to 81% and 10 d later the gas concentration dropped to 20% at the top and to 60% at the bottom. They observed a similar difference in another experimental bin holding 2.13 t of wheat. In the same bins when recirculation was installed, the difference in $CO_2$ concentrations between top and bottom was reduced to < 5% in bin 1 and < 3% in bin 2. Earlier, Jay et al. (1970) in their study of $CO_2$ treatment of 2203 $m^3$ of inshell peanuts in a 9.1 m diameter by 34.4 m tall concrete silo, observed that the $CO_2$ introduced at the top of the silo sank to the bottom as it was denser than air.

Therefore, they devised a recirculation system to maintain $CO_2$ concentration at the required level. Later, Calderon and Carmi (1973) used a mixture of methyl bromide and $CO_2$ to fumigate a wheat bulk stored in a 17 m high by 4 m diameter concrete vertical bins. Their results suggest that $CO_2$ was responsible for penetration of the fumigant down 17 m. A similar result of increased penetration of halogenated fumigants when mixed with $CO_2$ was obtained by Gilby (1983). Alagusundaram et al. (1996c) in their CA storage studies in farm bins, observed a higher concentration of $CO_2$ near the floor plenum compared with the top of the bulk which was covered with a gas-proof plastic sheet. Singh (Jayas) et al. (1984) did not find a significant difference between $CO_2$ concentration between upward, horizontal, and downward directions of flow through grain bulks. However, when $CO_2$ was allowed to diffuse through air, $CO_2$ movement was considerably faster in the downward direction than flow sideways or upward. No change in diffusion coefficient was observed for horizontal direction of flow of gas compared with upward flow of gas.

### 6.4.5. Effect of Porosity

Keeping all the other variables constant, as the porosity of the wheat bulk was reduced from 43% to 38% there was a 3.4% decrease in the diffusion coefficient. This can be explained from the reduction in the available interstitial space for $CO_2$ transport with a decrease in porosity.

Henderson and Oxley (1944) determined the diffusion coefficient of $CO_2$ through a wheat bulk using a steady state method. They concluded that the diffusion coefficient of

$CO_2$ through a wheat bulk was 1/3 of the diffusion coefficient of $CO_2$ through air. They correlated this result to porosity of the grain bulk which was approximately 39%.

### 6.4.6. Effect of Grain Kernel Orientation

There was an increase (24%) in the diffusion coefficient when the grain kernels were oriented parallel to the gas flow direction. When a farm bin is filled with grain, the grain kernels tend to fall with their major axes horizontal and hence the likely orientation of kernels of the bulk is towards horizontal. In these experiments, because all the other factors such as moisture content, temperature, direction of flow, porosity, initial concentration, and dockage were kept constant, the only factor responsible for the difference in diffusion coefficient may be due to differences in flow path offered by the media to $CO_2$ flow. Tortuosity of a porous medium is defined as the ratio of the actual path of gas molecules to the theoretical shortest flow path in the medium (Troeh et al. 1982). Horizontal kernel orientation may result in a higher tortuosity than vertical kernel orientation for upward flow direction of gas.

### 6.4.7 Effect of Initial Concentration of Gas in the Gas Chamber

The diffusion coefficient of $CO_2$ through wheat was not dependent on initial concentration. The values do not differ significantly from each other. Pritchard and Currie (1982) measured the diffusion coefficients of $CO_2$, nitrous oxide, ethylene, and ethane in air by a steady state method. They found that the diffusion coefficients of the tested gases in air were unaffected by a two-fold change in initial gas concentration. Bird et al. (1960) analysed the binary diffusion of gases and concluded that the diffusion

coefficient of gas pairs is independent of gas concentration at low densities. Because the present study was done at a pressure of 1 atm, non-dependence of diffusion coefficient on initial gas concentration was expected.

### 6.4.8 Effect of Dockage

The dockage added to the wheat bulk affected the diffusion rate of $CO_2$ through the wheat bulk. The diffusion coefficient increased with increasing amounts of dockage in the grain bulk.

Non uniform distribution of applied fumigant in a grain bulk due to the presence of dockage was reported by several researchers. Jay and Pearman (1973) studied $CO_2$ storage of infested corn in concrete silos containing 958 $m^3$ of shelled corn. They reported that the $CO_2$ gas distribution on purging the bin with 144 kg $h^{-1}$ of $CO_2$ for 8 h was uniform everywhere except where a large amount of dust and dockage were detected. They did not attempt to correlate the type and density of dockage at a location inside a grain bulk to the level of gas concentration achieved.

No study was found in the literature on the effect of dockage on the movement of gases and fumigants.

Dockage which includes chaff and fines will alter the structure of a porous medium for gas flow. The porosity and tortuosity of the medium will be altered. The samples collected at a grain elevator (grain handling facility) in Winnipeg contained more chaff than fines by mass. Therfore, in my study on the effect of dockage on diffusion coefficients, the porosity of grain with dockage was generally more than for clean grain. The increased porosity may have resulted in a higher diffusion coefficient when dockage

was added to the grain bulk. The diffusion coefficient increased almost linearly with the dockage.

## 6.5 Diffusion Coefficient of $CO_2$ Through Barley Bulks

### 6.5.1 General

The diffusion coefficients of $CO_2$ through barley bulks for the variables tested in this study are given in Table 6.4.

### 6.5.2 Effect of Moisture Content

The diffusion coefficient decreased with an increase in grain moisture content in the range of moisture contents studied (12.5-18% w.b.) (Table 6.4 and Table 4.3). The reduction in the diffusion coefficient despite the increase in porosity at higher moisture contents indicated that the resistance to diffusive flow is higher in wet grains. This result is different from the one obtained for wheat in which no change in the diffusion coefficient was observed as the grain moisture content was increased from damp (15%) to wet (18%) conditions. Alagusundaram et al. (1996a) reported that for wheat, no definite relationship between grain moisture content and apparent flow coefficient of $CO_2$ through the bulk existed. The complex interactions among the factors, namely; grain moisture content, $CO_2$ sorption, and grain kernel geometry; determines the diffusive flow path for $CO_2$ molecules inside the grain bulk. In this study, the reduction in diffusion rate was not caused by the sorption of $CO_2$ because its effect was accounted for in the data analysis.

**Table 6.4 Diffusion coefficient of $CO_2$ through barley bulk**

| Experiment* | Diffusion coefficient (x $10^{-6}$ $m^2s^{-1}$) | | | Mean (x $10^{-6}$ $m^2s^{-1}$) | Standard deviation (x $10^{-6}$ $m^2s^{-1}$) |
|---|---|---|---|---|---|
| | $r_1^{\Psi}$ | $r_2^{\Psi}$ | $r_3^{\Psi}$ | | |
| 1 | 7.1 | 7.0 | 7.1 | 7.1 | 0.0 |
| 2 | 6.2 | 7.0 | 6.3 | 6.5 | 0.9 |
| 3 | 4.5 | 5.5 | 5.4 | 5.1 | 1.3 |
| 4 | 6.3 | 6.2 | 6.1 | 6.2 | 0.1 |
| 5 | 6.8 | 6.3 | 5.3 | 6.1 | 0.6 |
| 6 | 6.3 | 7.1 | 8.4 | 7.3 | 1.1 |
| 7 | 9.4 | 8.5 | 7.1 | 8.4 | 1.4 |
| 8 | 6.1 | 7.3 | 6.7 | 6.7 | 0.5 |
| 9 | 5.4 | 6.7 | 6.0 | 6.1 | 0.6 |
| 10 | 7.4 | 7.7 | 7.5 | 7.5 | 0.2 |
| 11 | 6.2 | 6.7 | 6.1 | 6.3 | 0.5 |
| 12 | 5.8 | 6.2 | 6.4 | 6.1 | 0.2 |
| 13 | 7.0 | 6.8 | 6.5 | 6.7 | 0.2 |
| 14 | 6.5 | 7.6 | 7.4 | 7.1 | 0.5 |
| 15 | 8.1 | 7.7 | 7.0 | 7.6 | 0.5 |

$^{\Psi}$ $r_1$, $r_2$ , $r_3$ are three replicates.
* Refer to Table 4.3 for the details of the experimental conditions.

### 6.5.3 Effect of Temperature

As the temperature was increased from 15°C to 40°C, the diffusion coefficient generally increased. The relative increase corresponded with the amount of increase predicted by Chapman-Engskok's theory for the diffusion of $CO_2$ in air (Chapman and Cowling 1951). This is expected because as the temperature increases, the energy level of the molecules increases which results in increased random molecular motion. However the relative increase in the diffusion coefficient for a temperature increase of 25°C to 40°C did not agree with the trend predicted by Chapman-Engskok's theory. Inconsistency in the temperature dependence of the diffusion coefficient of $CO_2$ in nitrogen ($N_2$) was reported by Holsen and Strunk (1964). Deviations from the values predicted by kinetic theory is expected because the theory is derived based on certain assumptions relative to the real process which may not be valid during experimentation. Bird et al. (1960) also stated the need to consider the diffusion coefficient values of gases, calculated based on kinetic theory only in situations where actual values are not available from experiments.

### 6.5.4 Effect of Direction of Gas Flow

The diffusion coefficient was 29% higher when the direction of flow was downward than when it was upward. This may be due to the action of gravity forces on the heavier $CO_2$ molecules into the intergranular air as reported by several researchers (Jay et al. 1970; Calderon and Carmi 1973; Gilby 1983; Alagusundaram et al. 1996c).

### 6.5.5 Effect of Porosity

As the porosity was reduced from 54% to 48% there was a 6.6% decrease in the diffusion coefficient. This can be explained by the reduction in the available interstitial space for $CO_2$ transport with a decrease in porosity (Van Brakel and Heertjes 1974). Troeh et al. (1982) in their review of diffusion studies for porous materials stated that the diffusion coefficient of gases through a porous medium varies almost linearly with the porosity in the porosity range studied (20-60%).

### 6.5.6 Effect of Grain Kernel Orientation

There was a 15% increase in the diffusion coefficient when the grain kernels were oriented parallel to the direction of flow of $CO_2$. . This is similar to the results obtained in the case of airflow resistance studies with bulk grain (Kumar and Muir 1986). They observed that at an airflow of 0.077 $m^3s^{-1}m^{-2}$), the resistance to airflow through barley with horizontally oriented kernels was up to 115% higher than when the kernels were oriented parallel to the direction of gas flow.

### 6.5.7 Effect of Initial Concentration of Gas in the Gas Chamber

The diffusion coefficient was not dependent on the initial $CO_2$ concentration in the 20-60% range. This is in agreement with the results obtained by Pritchard and Currie (1982) who found that diffusion coefficient of gases through porous media could be treated as constant and independent of the concentration of gases.

### 6.5.8 Effect of Dockage

For the range of dockages (0, 4, 8, and 12%) studied in barley, the diffusion coefficient of $CO_2$ were 6.48, 6.72, 7.11, and 7.62 x $10^{-6}$ $m^2s^{-1}$ respectively. Addition of dockage loosened the bulk which may have increased the porosity. For example, the grain with 12% dockage had approximately about 468 g of chaff and 252 g of fines in 6700 g of clean grain.

## 6.6 Diffusion Coefficient of $CO_2$ Through Canola Bulks

### 6.6.1 General

The diffusion coefficients of $CO_2$ through a canola bulk for the variables tested in this study are given in Table 6.5.

### 6.6.2 Effect of Moisture Content

Diffusion tests were conducted on dry, wet, and damp canola bulks. The diffusion coefficient was highest at 5.3 x $10^{-6}$ $m^2s^{-1}$ for dry grain at 8% m.c.(w.b.) and decreased with increase in moisture content to 4.1 x $10^{-6}$ $m^2s^{-1}$ for damp grain at 10.5% m.c.(w.b.) (Table 6.5 and Table 4.4). No change in diffusion coefficient was observed when the moisture content was increased from damp to wet condition. The results are similar to that obtained for a wheat bulk (Fig. 6.5).

### 6.6.3 Effect of Temperature

With increase in temperature, the diffusion coefficient increased generally. There was a 21% increase in the diffusion coefficient as the temperature was increased from 5°C

**Table 6.5 Diffusion coefficient of $CO_2$ through a canola bulk**

| Experiment* | Diffusion coefficient ($\times 10^{-6}$ $m^2s^{-1}$) | | | Mean ($\times 10^{-6}$ $m^2s^{-1}$) | Standard deviation ($\times 10^{-6}$ $m^2s^{-1}$) |
|---|---|---|---|---|---|
| | $r_1^{\Psi}$ | $r_2^{\Psi}$ | $r_3^{\Psi}$ | | |
| 1 | 4.8 | 4.6 | 4.4 | 4.6 | 0.1 |
| 2 | 4.0 | 4.0 | 4.2 | 4.1 | 0.1 |
| 3 | 3.7 | 4.3 | 4.1 | 4.0 | 0.2 |
| 4 | 3.5 | 3.6 | 4.0 | 3.7 | 0.2 |
| 5 | 3.8 | 3.6 | 4.2 | 3.9 | 0.3 |
| 6 | 4.3 | 4.5 | 5.3 | 4.7 | 0.4 |
| 7 | 4.6 | 5.7 | 5.6 | 5.3 | 0.5 |
| 8 | 4.1 | 3.9 | 4.5 | 4.2 | 0.3 |
| 9 | 3.6 | 3.7 | 3.9 | 3.7 | 0.2 |
| 10 | 4.2 | 4.6 | 4.2 | 4.3 | 0.2 |
| 11 | 4.0 | 4.1 | 4.6 | 4.2 | 0.3 |
| 12 | 4.7 | 4.6 | 4.4 | 4.6 | 0.2 |
| 13 | 4.2 | 4.4 | 4.3 | 4.3 | 0.3 |
| 14 | 4.7 | 4.7 | 4.5 | 4.6 | 0.1 |
| 15 | 4.6 | 5.0 | 5.1 | 4.9 | 0.2 |

$^{\Psi}$ $r_1$, $r_2$ , $r_3$ are three replicates.

* Refer to Table 4.4 for the details of the experimental conditions.

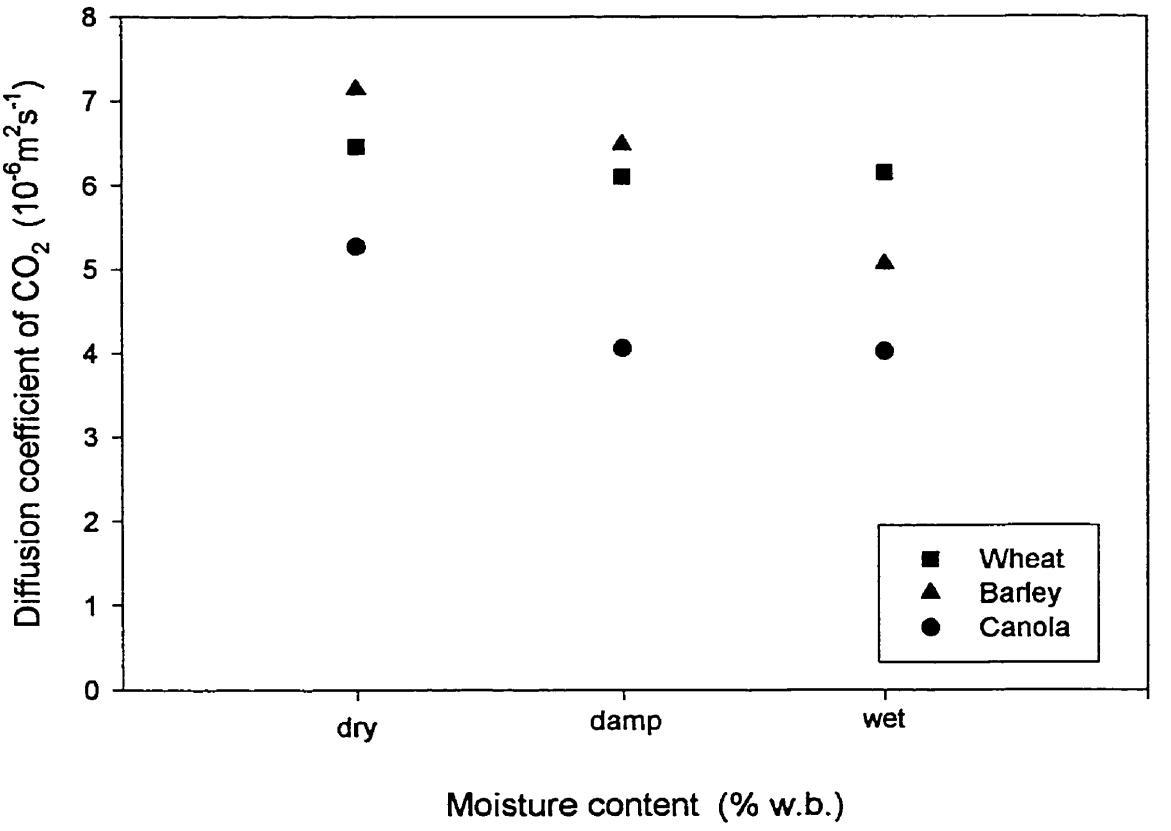



Fig. 6.5 Effect of moisture content on diffusion coefficient of $CO_2$ through grain bulk.

Wheat- 12.5, 15.0, and 18.0%; Barley- 12.5, 15.0, and 18.0%; Canola- 8.0, 10.5, and 13.0%

to 40°C. It compares well with the increase in diffusion coefficient suggested by Chapman and Engskok's kinetic theory of gases.

### 6.6.4 Effect of Direction of Gas Flow

The downward diffusion of $CO_2$ was 29% higher than the upward and the horizontal flows. The diffusion coefficient was 5.3 x $10^{-6}$ $m^2s^{-1}$ for the downward flow; 4.2 x $10^{-6}$ $m^2s^{-1}$ for horizontal flow; and 4.1 x $10^{-6}$ $m^2s^{-1}$ for upward flow of $CO_2$ (Table 6.5 and Table 4.4).

### 6.6.5 Effect of Porosity

Two porosity levels (34 and 31%) were obtained by compacting the grain in the grain chamber. The diffusion coefficient decreased proportionately with a decrease in porosity because the diffusion process is dependent on the intergranular pore spaces. The diffusion coefficient of $CO_2$ through a canola bulk was 4.1 x $10^{-6}$ $m^2s^{-1}$ at 40% porosity and decreased to 3.7 x $10^{-6}$ $m^2s^{-1}$ as the porosity was decreased to 38% (Table 6.5 and Table 4.4).

### 6.6.6 Effect of Grain Kernel Orientation

Although the shape of canola grains was spherical, the diffusion coefficient obtained when filling the grain chamber through the top door was different from that of filling the grain chamber through the side door. It was higher (6.9%) when grain was filled through the top door.

### 6.6.7 Effect of Initial Concentration of Gas in the Gas Chamber

There was no change in the diffusion coefficient of $CO_2$ through a canola bulk for the range of initial gas concentrations studied. This result verified our assumption of treating the diffusion coefficient as a constant in the model developed.

### 6.6.8 Effect of Dockage

The effect of dockage on the diffusion coefficient of $CO_2$ for a canola bulk were similar to those obtained for wheat and barley bulks (Fig. 6.6). Because the addition of dockage increased the porosity of the bulk, there was linear increase in diffusion coefficient with an increase in dockage in the range tested in this study (0, 4, 8, and 12%).

Results of effects of dockage and porosity on the diffusion coefficient of $CO_2$ through wheat, barley, and canola bulks indicate that porosity is the most important factor in controlling the diffusive flow through porous media.

## 6.7 Comparison of Diffusion Coefficients of $CO_2$ Through Grain Bulks

An increase in grain moisture content from dry to damp conditions decreased the diffusion coefficient of $CO_2$ through all the grain bulks studied. As the grain moisture content is increased further to a wet condition, the diffusion coefficient decreased in the barley whereas it did not change in the wheat and canola bulks.

An increase in grain temperature increased the diffusion coefficient of $CO_2$ through wheat, barley, and canola bulks. The relative increase in diffusion coefficient with an increase in grain temperature generally followed the trend predicted by the kinetic theory of gases in all three grain bulks tested.

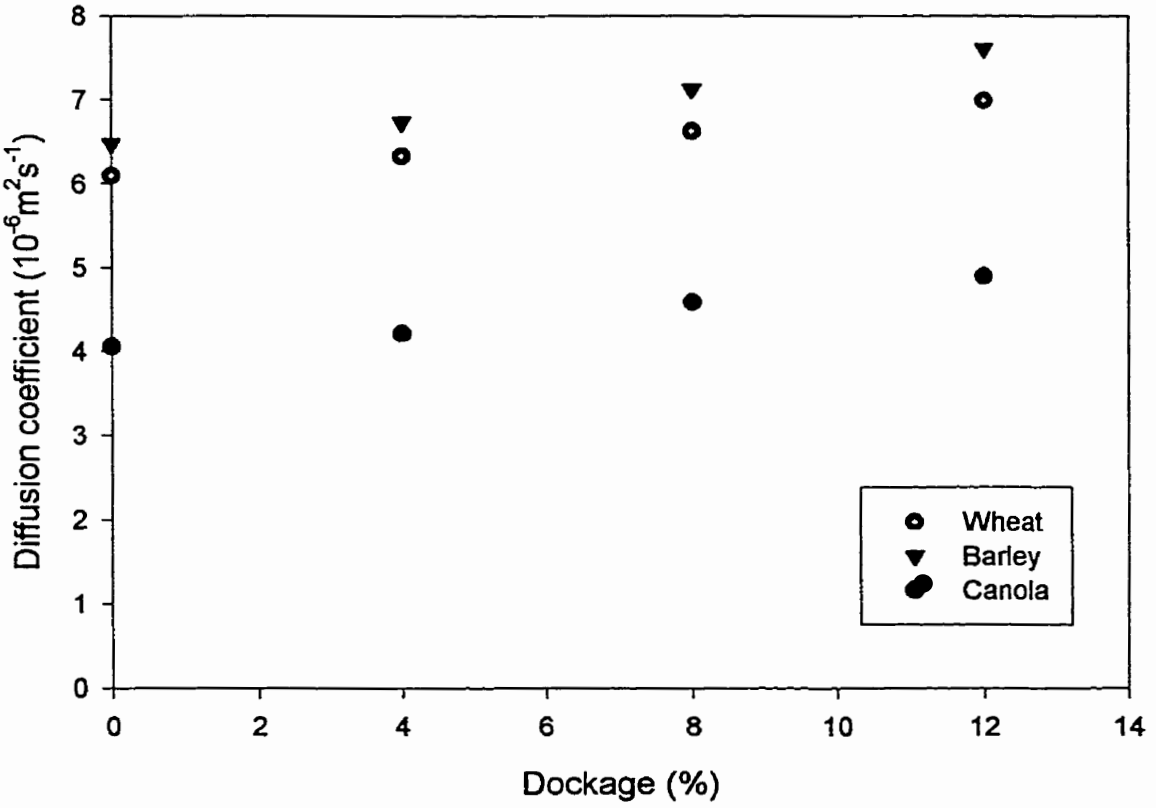



Fig. 6.6 Effect of dockage on the diffusion coefficient of $CO_2$ through grain bulks

The downward direction of gas flow resulted in a higher diffusion coefficient than the horizontal and upward gas flows in all the three grain bulks studied. The diffusion coefficient, however, did not change between horizontal and upward gas flows in wheat, barley, and canola bulks.

A decrease in porosity in the range of 3 to 6% resulted in a decrease in diffusion coefficient of $CO_2$ through wheat, barley, and canola bulks.

Gas flow parallel to the orientation of kernels increased the diffusion coefficient in wheat and barley bulks while in canola bulks, there was no difference in diffusion coefficient between gas flow parallel and perpendicular to the orientation of kernels.

The diffusion coefficient of $CO_2$ through wheat, barley, and canola bulks did not change with change in initial gas concentration.

The addition of dockage to the grain bulks loosened the bulks and increased the diffusion coefficients of $CO_2$ through all the grain bulks.

Among the variables studied, temperature, direction of gas flow, porosity, initial gas concentration, and dockage affected the diffusion process uniformly in wheat, barley and canola bulks. The effect of moisture content and grain kernel orientation on the diffusion coefficient of $CO_2$ were different among all the grain bulks studied. This may be because these variables are related to the grain properties like shape, composition, and moisture movement into the pores of the kernel which are unique for a grain type.

# 7. CONCLUSIONS

The following conclusions can be drawn from this study.

1. Diffusion of $CO_2$ through a grain bulk can be modelled at the macroscopic level similar to the inter-diffusion of gases without a porous media.
2. Carbon dioxide sorption in barley and canola bulks increased with an increase in moisture content of the grain between dry and wet conditions. It was not significantly affected ($p > 0.10$) by a change in grain temperature.
3. The diffusion coefficients of $CO_2$ through wheat bulks ranged from $5.9 \times 10^{-6}$ to $7.6 \times 10^{-6}$ $m^2s^{-1}$; through barley bulks they ranged from $5.1 \times 10^{-6}$ to $8.4 \times 10^{-6}$ $m^2s^{-1}$; and through canola bulks they ranged from $3.7 \times 10^{-6}$ to $5.3 \times 10^{-6}$ $m^2s^{-1}$ for the range of storage conditions commonly found in Canada.
4. There is some indication that the diffusion coefficient of $CO_2$ through the grain bulks decreases with increasing moisture content from dry to damp range. No change in diffusion coefficient was observed between damp and wet conditions for wheat and canola bulks whereas the diffusion coefficient decreased further for the barley bulk.
5. The diffusion coefficient of $CO_2$ through the grain bulks seem to increase with an increase in temperature.
6. The diffusion coefficient of $CO_2$ through the grain bulks was higher for a downward direction of flow than the upward and horizontal flow. No difference in diffusion coefficient was observed between the upward and horizontal flow.

7. There is some indication that the diffusion coefficient of $CO_2$ through the grain bulks decreases with decrease in porosity in the range of porosities studied.
8. The diffusion coefficient of $CO_2$ through wheat and barley bulks is higher for vertical grain kernel orientation than horizontal kernel orientation for upward direction of gas flow.
9. The diffusion coefficient of $CO_2$ through all three grain bulks did not change with a change in initial $CO_2$ concentration in the gas chamber. This result validates the assumption used in the model development that the diffusion coefficient is constant.
10. There is very strong evidence that the presence of dockage in grain bulks affects the molecular diffusion and the diffusion coefficient increases linearly with increase in coarse dockage in a grain bulk.

# 8. SUGGESTIONS FOR FUTURE RESEARCH

In this laboratory study, a one dimensional transient diffusion model was used to determine the diffusion coefficient of $CO_2$ through grain bulks. Field experiments should be conducted to measure the $CO_2$ concentration distribution along a grain column and compare it with the predictions made by a three-dimensional, transient-diffusion model.

More studies on sorption of $CO_2$ by grain bulks are needed in the future to enable effective CA treatments in grain bulks. Presently, information on sorption of $CO_2$ by grain bulks is not available for all the crops stored on Canadian farms. Moreover, for crops like wheat, barley, and canola, $CO_2$ sorption data for initial $CO_2$ concentrations in the range 20-80% need to be collected.

In this study, the dockage added to the grain bulks contained more chaff than fines. Studies on the effect of dockage with more fines than chaff on the diffusion coefficient of $CO_2$ through grain bulks should be carried out in the future. This information will be useful to deal with situations inside grain bins where the fines accumulate (i.e. in the centre of the bin).

The effect of thermal gradients along a grain column on the diffusion of $CO_2$ through grain column may be studied in the future. Knowledge of thermal diffusion through a grain bulk is necessary because temperature differences inside large grain bulks are common phenomena on North American farms.

## 9. REFERENCES


Alagusundaram, K., D.S. Jayas, W.E. Muir, N.D.G. White, and R.N. Sinha. 1996a. Apparent flow coefficient of carbon dioxide through wheat bulks. Can. Agric. Eng.. 38: 69-74.

Alagusundaram, K., D.S. Jayas, W.E. Muir, N.D.G. White, and R.N. Sinha. 1996b. Distribution of introduced carbon dioxide through stored wheat bulks-A pilot scale study. Can. Agric. Eng.. 38: 83-90.

Alagusundaram, K., D.S. Jayas, W.E. Muir, and N.D.G. White. 1996c. Convective-diffusive transport of carbon dioxide through stored-grain bulks. Trans. ASAE 39(4): 1505-1510.

Aliniazee, M.T. 1971. The effect of carbon dioxide gas alone or in combinations on the mortality of Tribolium castaneum (Herbst) and T. Confusum du Val (Coleoptera Tenebrionidae). J. Stored Prod. Res. 7: 243-252.

Anonymous. 1993. Methyl bromide, alternatives, substitutes, and recovery systems. Interim Report. Agriculture and Agri-Food Canada. Ottawa, ON 39 p.

Anonymous. 1997. Statistical handbook-97. Canada Grains Council, Winnipeg, MB. 261 p.

Annis, P.C. 1987. Towards rational controlled atmosphere dosage schedules: a review of current knowledge. Pages 128-148 in: Donahaye, E. and S. Navarro (eds.) Proceedings of the Fourth International Working Conference on Stored-Product Protection. Tel Aviv, Israel.

Bailey, E.A. 1940. Respiration of cereals and flax seed. Plant Physiol. 15(2): 257-274.

Bailey, E.A. 1959. The rate of diffusion of oxygen through grain. J. Sci. Food. Agric. 26(9): 501-506.

Bailey, S.W. 1965. Airtight storage of grain: its effects on insect pests. IV. Rhyzopertha dominica (F.) and some other Coleoptera that infest stored grain. J. Stored Prod. Res. 1: 25-33.

Bailey, S.W. and H.J. Banks. 1980. A review of recent studies of the effects of controlled atmospheres on stored-product pests. Pages 101-118. in: Shejbal, J. (ed.) Controlled atmosphere storage of grains. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Banks, H.J. and P.C. Annis. 1980. Conversion of existing grain storage structures for modified atmosphere use. Pages 461-474. in: Shejbal, J. (ed.) Controlled atmosphere storage of grains. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Banks, H.J. and P. Fields. 1995. Physical methods for insect control in stored grain ecosystems. Pages 353-410 in: Jayas, D.S. White, N.D.G. and W.E. Muir. (eds.) Stored-grain ecosystems. Marcel Dekker Inc., New York, NY.

Barker, P.S. 1974. A theoretical consideration of the behaviour of air-fumigant mixtures in stored grain in relation to the loss of gases. Manitoba Entomol. 8: 80-84.

Bird, R.B., W.E. Stewart, and E.N. Lightfoot. 1960. Transport phenomena. John Wiley and Sons, New York, NY. 780 p.

Bundus, C.L., D.S. Jayas, W.E. Muir, N.D.G. White, and D. Ruth. 1996. Average convective-pore velocity of carbon dioxide gas through grain bulks. Can. Agric. Eng. 38: 91-98.

Calderon, M. and Y. Carmi. 1973. Fumigation trials with mixture of methyl bromide and carbon dioxide in vertical bins. J. Stored Prod. Res. 8: 315-321.

Chapman, S. and T.G. Cowling. 1951. Mathematical theory of non-uniform gases. Cambridge University Press, UK. 423 p.

Cofie-Agblor, R., W.E. Muir, S. Cenkowski, and D.S. Jayas. 1993. Carbon dioxide gas sorption by wheat. Pages 261-269 in: Navarro, S. and E. Donahaye, (eds.) Proc. of Int. Conf. on Controlled Atm. and Fumig. Grain Storages. Caspit Press Ltd., Jerusalem, Israel.

Cunningham, W. and J. Williams. 1980. Diffusion in gases and porous media. Plenum Press, New York, NY. 275 p.

Dowdell, R.J. and K.A. Smith. 1974. Field studies of the soil atmosphere. II. Occurrence of nitrous oxide. J. Soil Sci. 25: 231-238.

Gilby, A.R. 1983. Movement of halogenated fumigants through wheat. J. Stored. Prod. Res. 19: 199-202.

Greenspan, L. 1977. Humidity fixed points of binary saturated aqueous solutions. J. Res. National Bureau Standards-A. Physics and Chem. 81: 89-96.

Harein, P.K., and A.F. Press Jr. 1968. Mortality of stored-peanuts exposed to mixtures of atmospheric gases at various temperatures. J. Stored Prod. Res. 4: 77-82.

Haugh, C.G. and G.W. Isaacs. 1967. Isothermal diffusion of oxygen in grain masses. Trans. ASAE 10: 175-181.

Henderson, F.Y. and T.A. Oxley. 1944. The properties of grain in bulk- II. The coefficient of diffusion of carbon dioxide through wheat. J. Soc. Chem. Ind. 63: 52-53.

Holsen, J.N. and M.R. Strunk. 1964. Binary diffusion coefficients in non polar gases. Ind. Eng. Chem. Fund. 3:143-146.

Jay, E. 1980. Methods of applying carbon dioxide for insect control in stored grain. Pages 225-234. in: Shejbal, J. (ed.) Controlled atmosphere storage of grains. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Jay, E.G., L.M. Redlinger, and H. Laudani. 1970. The application and distribution of carbon dioxide in a peanut (groundnut) silo for insect control. J. Stored Prod. Res. 6: 247-254.

Jay, E.G. and G.C. Pearman. 1973. Carbon dioxide for control of an insect infestation in stored corn (maize). J. Stored Prod. Res. 9:25-29.

Jay, E.G. and D'Orazio. 1984. Progress in the use of controlled atmosphere in actual field situations in the United States. Pages 3-13, in: Ripp. B.E. (ed.) Controlled atmosphere and fumigation in grain storages. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Krishnamurthy, T.S., E.C. Spratt, and C.H. Bell. 1986. The toxicity of carbon dioxide to adult beetles in low oxygen atmospheres. J. Stored Prod. Res. 22: 145-151.

Kumar, A. and W.E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. Trans. ASAE 29: 1423-1426.

Lindgren, D.L. and L.E. Vincent. 1970. Effect of atmospheric gases alone or in combination on the mortality of granary and rice weevils. J. Econ. Entomol. 63: 1926-1929.

Madrid, F.J., N.D.G. White, and S.R. Loschiavo. 1990. Insects in stored cereals, and their association with farming practices in southern Manitoba. Can. Entomol. 122: 515-523.

Mchenry, K.W. Jr. and R.H. Wilhelm. 1957. Axial mixing of binary gas mixtures flowing in a random bed of spheres. A.I. Ch. E. J. 3: 83-91.

Mills, K.A. 1983. Resistance to the fumigant hydrogen phosphide in some stored-product species associated with repeated inadequate treatments. Pages 98-101. in Proc. of the second European Congress of Entomology, Kiel,

Milthorpe, T. and R.N. Robertson. 1948. Respiration of dry grain, insect respiration and temperature and moisture effects. CSIRO Bulletin No. 237. Comm. Sci. Ind. Res. Org., Canberra, Australia.

Mitsuda, H. and A. Yamamoto. 1980. Advances in grain storage in a carbon dioxide atmosphere in Japan. Pages 235-246, in: Shejbal, J. (ed). Controlled atmosphere storage of grains. Elsevier Scientific Pub. Co., Amsterdam, The Netherlands.

Muir, W.E. 1973. Temperature and moisture in grain storages. Pages 49-70 in: Sinha, R.N. and W.E. Muir. (eds.) Grain storage- part of a system. The AVI Publishing Company Inc., Westport, CT.

Muir, W.E., R.N. Sinha., H.A.H. Wallace, and P.L. Sholberg. 1980. Emergency farm structures for storing grain- a multi disciplinary evaluation. Trans. ASAE 23: 208-217.

Oxley, T.A. and R.W. Howe. 1944. Factors influencing the course of an insect infestation. Ann. Appl. Biol. 31: 76-81.

Press, A.F. Jr. and P.K. Harein. 1966. Mortality of red flour beetle adults and Indian -meal moth larvae in nitrogen and carbon dioxide. J. Ga. Entomol. Soc. 1:15-17.

Price, N.R. 1991. Enzymic factors in the resistance of stored-product pests to insecticides. Biochem. Soc. Trans. 19: 759-762.

Pritchard, D.T. and J.A. Currie. 1982. Diffusion coefficients of carbon dioxide, nitrous oxide, ethylene, and ethane in air and their measurement. J. Soil Sci. 33: 175-184.

Rameshbabu, R., D.S. Jayas, and N.D.G. White. 1991. Mortality of Cryptolestes ferrugineus (Stephens) adults and eggs in elevated carbon dioxide and depleted oxygen atmospheres. J. Stored Prod. Res. 27: 163-170.

Reichmuth, C. 1987. Low oxygen content to control stored product insects. Pages 194-207 in: Donahaye, E. and S. Navarro (eds.) Proc. Fourth Intern. Working Conf. Stored-Prod. Prot. Tel Aviv, Israel.

Sauer, D.B., R.A. Meronuck, and C.M. Christensen. 1954. Microflora. Pages 313-340 in: Sauer, D.B. (ed) Storage of cereal grains and their products. Am. Assoc. Cereal Chem. Inc., St. Paul, MN.

Shunmugam, G., D.S. Jayas, and N.D.G. White. 1993. Effects of controlled atmospheres on all life stages of the rusty grain beetle. J. Appl. Zool. Res. 4(2): 114-117.

Singh, D. (Jayas, D.S.), W.E. Muir, and R.N. Sinha. 1980. Transient method to

determine the diffusion coefficient of gases. Can. Agric. Eng. 27: 69-72.

Singh, D (Jayas), W.E. Muir, and R.N. Sinha, 1984. Apparent coefficient of diffusion of carbon dioxide through cereals and rapeseed. J. Stored Prod. Res. 20: 169-175.

Sinha, R.N. 1972. Grain storage and associated problems: a report on elevator surveys 1967-71. Cereal Research Centre, Agriculture and Agri-Food Canada. Winnipeg, MB. 30 p.

Sinha, R.N. 1973. Interrelations of physical, chemical, and biological variables in the deterioration of stored grains. Pages 15-48 in: Sinha, R.N. and W.E. Muir. (eds.) Grain storage: Part of a system. The AVI Pub. Co., Inc., Westport, CT.

Sinha, R.N., D.Waterer, and W.E. Muir. 1986a. Carbon dioxide concentrations associated with insect infestations of stored grain. 1- Natural infestation of corn, barley, and wheat in farm granaries. Sci. des Aliments 67: 91-98.

Sinha, R.N., D.Waterer, and W.E. Muir. 1986b. Carbon dioxide concentrations associated with insect infestations of stored grain. 1- Infestation in wheat filled jar. Sci. Des Aliments 67: 99-106.

Sissom, L.E. and D.R. Pitts. 1972. Elements of transport phenomena. McGraw-Hill Book Company, New York, NY. 814 p.

Steele, J.L., R.A. Saul., and W.F. Hukill. 1969. Deteriorations of shelled corn as measured by carbon dioxide production. Trans. ASAE. 12: 685-689.

Srour, S. 1988. Thermic properties of grains-production of heat and carbon dioxide. Pages 189-202 in: Multon, J.L., Reimbert, A.M., Nash, D., and A.J. Eydt (eds.) Preservation and storage of cereal grains, seeds, and their by-products. Lavoisier Publishing Company Inc., New York, NY.

Slattery, J.C. and R.B. Bird. 1958. Calculation of the diffusion coefficient of dilute gases and of the self diffusion coefficient of dense gases. A. I. Ch. E. J. 4(2): 137-142.

Smith, G.D. 1985. Numerical solution of partial differential equations: finite difference method. (3rd ed.). Oxford University Press, Oxford, UK. 337 p.

Thorpe, G.R. and S. Whitaker. 1992a. Local mass and thermal equilibria in ventilated grain bulks. Part I: The development of heat and mass conservation equations. J. Stored Prod. Res. 28: 15-27.

Thorpe, G.R. and S. Whitaker. 1992b. Local mass and thermal equilibria in ventilated grain bulks. Part II: The development of constraints. J. Stored Prod. Res. 28: 29-51.

Troeh, F.R., J.D. Jabro, and D. Kirkham. 1982. Gaseous diffusion equations for porous materials. Geoderma 27: 239-253.

Van Brakel, J. and P.M. Heertjes. 1974. Analysis of diffusion in macroporous media in terms of a porosity, a tortuosity, and a constrictivity factor. Int. J. Heat Mass Transfer 17: 1093-1103.

White, N.D.G., R.N.Sinha, and W.E. Muir. 1982a. Intergranular carbon dioxide as an indicator of biological activity associated with the spoilage of stored wheat. Can. Agric. Eng. 24: 35-42.

White, N.D.G., R.N.Sinha, and W.E. Muir. 1982b. Intergranular carbon dioxide as an indicator of deterioration in stored rapeseed. Can. Agric. Eng. 24: 43-50.

White, N.D.G. and D.S. Jayas. 1991. Control of insects and mites with carbon dioxide in wheat stored at cool temperatures in nonairtight bins. J. Econ. Entomol. 84(6): 1933-1942.

White, N.D.G. and J.G. Leesch. 1996. Chemical control. Pages 287-330, in: Bh. Subramanyam and D.W. Hagstrum. (eds.) Integrated management of insects in stored-products. Marcel-Dekker Inc., New York, NY.

Wilson, A.D., H.J. Banks, P.C. Annis, and V. Guiffre. 1980. Pilot commercial treatment of bulk wheat with $CO_2$ for insect control: the need for gas recirculation. Aust. J. Agric. Anim. Husb. 20: 618-624.

Yamamoto, A. and H. Mitsuda. 1980. Characteristics of carbon dioxide gas sorption by grain and its components. Pages 247-258, in: Shejbal, J. (ed). Controlled atmosphere storage of grains. Elsevier Scientific Pub. Co., Amsterdam, The Netherlands.

Zakladnoi, G.A. 1976. Regulation of the gas composition of the atmosphere for eliminating insects in grain. USSR Ministry of procurement, Moscow. 3 pp (in Russian) (cited by Bailey, S.W. and H.J. Banks. 1980). A review of recent studies of the effects of controlled atmospheres on stored-product pests. Pages 101-118. in: Shejbal, J. (ed.) Controlled atmosphere storage of grains. Elsevier Scientific Pub. Co., Amsterdam, The Netherlands.

# APPENDIX A

## COMPUTER CODING OF ONE DIMENSIONAL MODEL OF TRANSIENT DIFFUSION EQUATION

# PROGRAM TO DETERMINE THE DIFFUSION COEFFICIENT BY NUMERICAL METHOD

```
C*************************************************************************
C               CARBON      = CO2 concentration data
C               DELX        = Increment in x 'm'
C               DELT        = Increment in t 's'
C               DIFCO       = Diffusion coefficient, m2/s
C               COEFF       = Coefficients of Nicholson's equations
C               CONST       = Right hand side coefficients
C               INIT        = Initial concentration values in mole fraction
C               GEE         = Multiplier
C               BEE         = Constant in the initial concentration function
C               CNOT        = Co'
C               CCAL        = Calculated concentration matrix
C               CALCAR      = Calculated concentration that can be compared with the
C                             measured ones
C               DIFF        = Difference between CARBON and CCAL
C*************************************************************************
C
C   INPUT THE VALUES OF x, t, D AND CONCENTRATIONS
C
      REAL DIFCO, DELX, DELT, CARBON(5,5), COEFF(9,9), CONST(9), INIT(10), CONC(9),
     +  GEE, CNOT, CCAL(9,120), CALCAR(5,5), TIME, DIFF(5,5), ERROR(5,5), TERROR(5),
     +  TERROR1(5), ERRUN(50), START(10), FCA, FCB, BDENS, DIST(9), CN(1), CN(2), CN(3)
      INTEGER I, J, K, L
      OPEN(5, FILE ='94JULY13')
      OPEN(6,FILE ='94JYOT13)
C
      READ(5,*) ((CARBON(I,J), J=1,5), I=1,5)
 5    READ(5,*) DELAX, DELT, FCA, FCB, FCC
      READ(5,*) AA, BB, CC, DD
      READ(5,*) BDENS, CODENS, POROS
      READ(5,*) CN1, CN2, CN3
C
C     CALCULATING THE INITIAL CONCENTRATION VALUES
C
            START(1)      = CN1
            DO 10 I       = 1,9
            DIST(I)       = 0.05*I
      START(I+1) = FCA-FCB*(DIST(I)**FCC)
 10   CONTINUE
C
C     GENERATE THE COEFFICIENTS OF CRANK NOCHOLSON'S EQUATION
C
            DIFNOT = 3.0
            STEP = 0.5
            DO 115 L = 1, 25
                  DO 20 I = 1,10
            INIT(I) = START(I)
 20         CONTINUE

      DIFDAS = DIFNOT + STEP
      DIFCO = (DIFDAS)*1E-06
```

```
              K = 1
 25     TIME = K*DELT
        TIME1 = TIME/3600
        TIME2 = (K+1)*DELT/3600
        SORP1 = AA+BB*TIME1-(CC*TIME1**2)+(DD*TIME1**3)
        SORP2 = AA+BB*TIME2-(CC*TIME2**2)+(DD*TIME2**3)
        ASORP = (SORP2-SORP1)
        CLOSS = (ASORP*BDENS)/CODENS
        CLOSS2 = CLOSS/POROUS
        CLOSS2 = 0.0
        CNOT = CN1- (CN2TIME**CN3)
  7     GEE = (DIFCO*DELT)/(2*DELX**2)
C
C       THE LEFT HAND SIDE CONSTANTS
C
        CONST(1) = (1-2*GEE)*INIT(2)+GEE*(INIT(3)+INIT(1)+GEE*CNOT+INIT(2)*CLOSS2
                   DO 30 I = 2,8
        CONST (I) = (1-2*GEE)*INIT(I+1)+GEE*(INIT(I+2)+INIT(I)+ INIT(I+1)*CLOSS2
 30                 CONTINUE
        CONST(9) = (1-GEE)*INIT(10)+GEE*INIT(9)+INIT(10)*CLOSS2
C
C       THE RIGHT HAND SIDE COEFFICIENTS
C
        COEFF(1,1) = 1+ 2*GEE
        COEFF(1,2) = -1*GEE
              DO 35 I = 2,8
              COEFF(I, I-1) = -1*GEE
              COEFF(I,I)    =  1+2*GEE
              COEFF(I, I+1) = -1*GEE
 35           CONTINUE
        COEFF(9,8) = -1*GEE
        COEFF(9,9) = 1+GEE
        CALL GUASS(COEFF, CONC, CONST)
C
C       FEED THE INITIAL CONCENTRATION VALUES
C
              DO 45 I = 2, 10
              INIT(I) = CONC(I-1)
 40           CONTINUE
              INIT(1) = CNOT
C
C       STORE THE CONCENTRATION VALUES
C
              DO 45 I = 1,9
              CCAL(I,K) = CONC(I)
 45           CONTINUE
              K = K+1
        IF (K.EQ.121) THEN
        GO TO 50
        ELSE
        GO TO 25
        END IF
C
```

```
C       SORTING OUT THE CONCENTRATION
C
   50   CALCAR(1,1) = CCAL(1,10)'
        DO 55 I = 1,4
        DO 55 J = 1,4
        CALCAR(1,J+1) = CCAL(1,20*J)
        CALCAR(I+1, 1) = CCAL)2*I+1, 10)
        CALCAR(I+1, J+1) = CCAL(2*I+1, 20*J)
   55   CONTINUE
C
C       FINDING THE DIFFERENCE IN CONCENTRATION
C
        DO 60 I = 1.5
        DO 65 J = 1,5
        DIFF(I,J) = CARBON(I,J)-CALCAR(I,J)
   65   CONTINUE
        WRITE (6,70) (DIFF(I,J), J=1,5)
   70   FORMAT (1X, 5(2X, F6.4))
   60   CONTINUE
        WRITE (6,75) ((CALCAR(I,J) J =1,5), I = 1,5)
   75   FORMAT (/1X, 5(2X, F8.4))
        DO 80 I = 1.5
        DO 85 J = 1.5
        ERROR(I,J) = (DIFF(I,J)/CARBON(I,J))*100
   85   CONTINUE
        WRITE (6,90) (ERROR(I,J), J=1,5)
   90   FORMAT (1X, 5(2X, e10.2))
   80   CONTINUE
C
C       CALCULATING THE AVERAGE ERROR
C

        ERROR = 0.0
        DO 100 J = 1.5
        TERROR(J) = 0.0
        DO 105 (I) = 1.5
        TERROR(J) = TERROR(J) + ABS(ERROR(I,J))
  105   CONTINUE
        TERROR1(J) = TERROR/5
        ERTOT = ERTOT + TERROR1(J)
  100   CONTINUE
        ERTOT = ERTOT/5
        ERRUN(L) = ERTOT
        WRITE(6.110) ERTOT, DIFCO
  110   FORMAT(/1X, F10.5, 2X, E12.4)
        IF (L. GT. 1) THEN
        TEST = ERRUN(L)- ERRUN(L-1)
        END IF
        IF (TEST. GT.0) THEN
                DIFNOT = (DIFDAS-STEP)
                STEP = STEP/10
        ELSE
                DIFNOT = DIFDAS
```

```
      END IF
  115 CONTINUE
      IF (STEP. LT. 0.0005) THEN
            GO TO 120
      END IF
  120 WRITE (6,125) DIFCO
  125 FORMAT(1X/, /F15.9/)
      END
C
C     SUBROUTINE TO CALCULATE THE UNKNOWN CONCENTRATION VALUES
C
      SUBROUTINE GAUSS(COEFF1, CONC1, CONST1)
      PARAMETER (IPATH=1, LDA=9, N=9)
      REAL COEFF1(LDA, LDA), CONST1(N), CONC1(N)
      CALL  LSARG (N, COEFF1, LDA, CONST1, IPATH, CONC1)
      END
```

# APPENDIX B

## EXPERIMENTAL DATA OF CARBON DIOXIDE CONCENTRATIONS IN THE GRAIN CHAMBER

Table B.1. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4296 | 0.4210 | 0.4304 | 0.4934 | 0.1657 | 0.0454 | 0.0194 | 0.0152 | 0.0084 |
| 1 | 0.4482 | 0.4020 | 0.4361 | 0.45483 | 0.3279 | 0.2124 | 0.0481 | 0.0151 | 0.0066 |
| 2 | 0.2954 | 0.3271 | 0.3989 | 0.4382 | 0.2844 | 0.2654 | 0.1286 | 0.1303 | 0.0733 |
| 3 | - | - | 0.3404 | - | 0.3184 | 0.2991 | 0.1627 | 0.2127 | 0.1818 |
| 4 | 0.4101 | 0.3210 | 0.3718 | 0.3570 | 0.3429 | 0.3281 | 0.1901 | 0.2314 | 0.2167 |
| 5 | 0.3438 | 0.3725 | 0.3380 | 0.4076 | 0.3393 | 0.3059 | 0.2226 | 0.2304 | 0.2168 |
| 6 | 0.3691 | 0.3872 | 0.3430 | 0.3022 | 0.2376 | 0.2646 | 0.1939 | 0.2497 | 0.2467 |

Table B.2. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; horizontal direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4416 | 0.5008 | 0.3773 | 0.4299 | 0.0719 | 0.0216 | 0.0069 | 0.0053 | 0.0031 |
| 1 | 0.4968 | 0.4331 | 0.4090 | 0.4361 | 0.2435 | 0.23452 | 0.0698 | 0.2117 | 0.1115 |
| 2 | 0.3701 | 0.3714 | 0.3479 | 0.3808 | 0.2814 | 0.2812 | 0.1652 | 0.2687 | 0.2519 |
| 3 | 0.3575 | 0.3683 | - | - | 0.3408 | 0.3091 | 0.2268 | 0.2603 | 0.2264 |
| 4 | 0.3307 | 0.3742 | 0.3470 | 0.3484 | 0.3162 | 0.2936 | 0.2883 | 0.2602 | 0.2284 |
| 5 | 0.2908 | 0.3844 | 0.2659 | 0.3330 | 0.2414 | 0.3159 | 0.2942 | 0.2585 | 0.2887 |
| 6 | 0.3047 | 0.2929 | 0.2726 | 0.3396 | 0.2670 | 0.2772 | 0.2775 | 0.2786 | 0.2621 |

Table B.3. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; downward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4774 | 0.5362 | 0.4764 | 0.5160 | 0.1014 | 0.0307 | 0.0267 | 0.0220 | 0.0161 |
| 1 | 0.4549 | 0.5232 | 0.4467 | 0.4862 | 0.2442 | 0.2336 | 0.1361 | 0.0795 | 0.0239 |
| 2 | 0.4400 | 0.5049 | 0.3658 | 0.4537 | 0.3543 | 0.3580 | 0.1289 | 0.2393 | - |
| 3 | 0.4157 | 0.4751 | 0.3159 | 0.3630 | 0.3042 | 0.3482 | 0.1801 | 0.2420 | 0.2601 |
| 4 | 0.3912 | 0.4055 | 0.4175 | 0.3588 | 0.2956 | 0.3425 | 0.2291 | 0.2561 | 0.2587 |
| 5 | 0.3789 | 0.3881 | 0.3923 | 0.3612 | 0.3194 | 0.3419 | 0.2797 | 0.2619 | 0.2691 |
| 6 | 0.3512 | 0.3619 | 0.3771 | 0.3781 | 0.3012 | 0.3122 | 0.2829 | 0.2841 | 0.2723 |

Table B.4. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 18% moisture content; 25°C; upward direction of flow; 46% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4825 | 0.4984 | 0.4402 | 0.4969 | 0.0624 | 0.0115 | 0.0034 | 0.0021 | 0.0014 |
| 1 | 0.4775 | 0.4640 | 0.4503 | 0.5064 | 0.3847 | 0.2572 | 0.1099 | 0.1035 | 0.0470 |
| 2 | 0.4664 | 0.4881 | 0.4166 | 0.4612 | 0.3993 | 0.3210 | 0.1873 | 0.1623 | 0.12033 |
| 3 | 0.3146 | - | - | - | 0.2569 | 0.3212 | 0.2067 | 0.2042 | 0.15201 |
| 4 | 0.3154 | - | 0.3980 | - | 0.4147 | 0.3492 | 0.2576 | 0.2506 | 0.19464 |
| 5 | 0.3854 | - | 0.4175 | | 0.2969 | 0.3180 | 0.2855 | 0.2562 | 0.21087 |
| 6 | 0.4165 | - | 0.4427 | | 0.3667 | 0.3538 | 0.2232 | 0.2745 | - |

Table B.5. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 18% moisture content; 25°C; upward direction of flow; 46% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4865 | 0.6264 | 0.4987 | 0.5260 | 0.3814 | 0.3609 | 0.2224 | 0.1972 | 0.1114 |
| 1 | 0.4965 | 0.5593 | 0.4927 | 0.5163 | 0.4203 | 0.4154 | 0.2650 | 0.2575 | 0.1959 |
| 2 | 0.4485 | - | 0.4598 | - | 0.4239 | 0.3809 | 0.1954 | 0.3363 | 0.3386 |
| 3 | 0.3933 | - | 0.3108 | - | 0.2988 | 0.3904 | 0.2141 | 0.3731 | 0.2868 |
| 4 | 0.4445 | - | 0.4685 | - | 0.3641 | 0.3729 | 0.2522 | 0.3651 | 0.3371 |
| 5 | 0.4183 | - | 04656 | - | 0.4091 | 0.3598 | 0.3558 | 0.3638 | 0.3673 |

Table B.6. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; downward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4094 | - | 0.4747 | 0.4408 | 0.0729 | 0.0153 | 0.0073 | 0.0031 | 0.0082 |
| 1 | 0.4048 | - | 0.4712 | 0.4363 | 0.4899 | 0.3962 | 0.2438 | 0.2225 | 0.1284 |
| 2 | 0.4332 | - | 0.4239 | - | 0.4473 | 0.4228 | 0.2204 | 0.2739 | 0.2463 |
| 3 | 0.2094 | - | 0.3252 | - | 0.2680 | 0.3501 | 0.1944 | 0.2230 | 0.1913 |
| 4 | 0.3250 | - | 0.3361 | - | 0.3148 | 0.4265 | 0.2754 | 0.3672 | 0.3641 |
| 5 | 0.3366 | - | 0.3534 | - | 0.3999 | 0.4121 | 0.3101 | 0.3782 | 0.2646 |
| 6 | 0.3267 | - | 0.3329 | - | 0.3900 | 0.3666 | 0.3551 | 0.3854 | 0.3422 |

Table B.7. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 5°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4657 | - | 0.4663 | - | 0.0193 | 0.0066 | 0.0021 | 0.0021 | 0.0016 |
| 0.5 | 0.4451 | - | 0.4557 | - | 0.3478 | 0.1457 | 0.0843 | 0.0402 | 0.0122 |
| 1 | 0.3910 | - | 0.4856 | - | 0.2829 | 0.2249 | 0.1360 | 0.0755 | 0.0380 |
| 2 | 0.3776 | - | 0.4471 | - | 0.2788 | 0.2791 | 0.1487 | 0.1346 | 0.1103 |
| 3 | 0.2708 | - | 0.3826 | - | 0.2880 | 0.3156 | 0.2351 | 0.2091 | 0.1459 |
| 4 | 0.3577 | - | 0.3346 | - | 0.2701 | 0.3030 | 0.2148 | 0.1763 | 0.1192 |
| 6 | 0.3328 | - | 0.3240 | | 0.2870 | 0.3052 | 0.2408 | 0.1956 | 0.1423 |

Table B.8. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6094 | 0.6555 | 0.6247 | 0.5408 | 0.0729 | 0.0153 | 0.0073 | 0.0036 | 0.0082 |
| 1 | 0.5748 | - | 0.5712 | 0.5363 | 0.4899 | 0.3962 | 0.2438 | 0.2225 | 0.1284 |
| 2 | 0.5332 | - | 0.5239 | - | 0.4473 | 0.4228 | 0.2204 | 0.2739 | 0.2463 |
| 3 | 0.3094 | - | 0.3252 | - | 0.2680 | 0.3501 | 0.1944 | 0.2230 | 0.1913 |
| 4 | 0.4250 | - | 0.4361 | - | 0.3148 | 0.4265 | 0.2754 | 0.3672 | 0.3641 |
| 5 | 0.4366 | - | 0.4534 | - | 0.3999 | 0.4121 | 0.3101 | 0.3782 | 0.2646 |
| 6 | 0.4267 | - | 0.4329 | - | 0.3900 | 0.3666 | 0.3551 | 0.3854 | 0.3422 |

Table B.9. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4846 | - | 0.4506 | - | 0.0575 | 0.0162 | 0.0083 | 0.0057 | 0.0037 |
| 0.5 | 0.4965 | - | 0.4927 | 0.5163 | 0.4203 | 0.4154 | 0.2650 | 0.257 | 0.1953 |
| 1 | 0.4485 | - | 0.5598 | - | 0.4239 | 0.3809 | 0.1954 | 0.3363 | 0.3386 |
| 2 | 0.4865 | - | 0.5287 | 0.5260 | 0.3814 | 0.3609 | 0.2224 | 0.1972 | 0.1114 |
| 3 | 0.4965 | - | 0.4927 | 0.5163 | 0.4203 | 0.4154 | 0.2650 | 0.2575 | 0.1953 |
| 4 | 0.4485 | - | 0.5598 | - | 0.4239 | 0.3809 | 0.1954 | 0.3363 | 0.3386 |
| 5 | 0.3933 | - | 0.3108 | - | 0.2988 | 0.3904 | 0.2141 | 0.3731 | 0.2868 |
| 6 | 0.4445 | - | 0.4685 | - | 0.3641 | 0.3729 | 0.2522 | 0.3651 | 0.3371 |

Table B.10. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4783 | - | 0.4546 | - | 0.0641 | 0.0117 | 0.0047 | 0.0032 | 0.0058 |
| 0.5 | 0.4498 | - | 0.4715 | - | 0.2755 | 0.1666 | 0.0624 | 0.0319 | 0.0552 |
| 1 | 0.3884 | - | 0.4392 | - | 0.3155 | 0.1921 | 0.1360 | 0.1229 | 0.0785 |
| 2 | 0.3776 | - | 0.4471 | - | 0.2788 | 0.2791 | 0.1487 | 0.1346 | 0.1103 |
| 3 | 0.3783 | - | 0.3971 | - | 0.3459 | 0.3103 | 0.2401 | 0.1713 | 0.0996 |
| 4 | 0.3820 | - | 0.3459 | | 0.2923 | 0.2111 | 0.1547 | 0.1209 | 0.0769 |
| 5 | 0.2701 | | 0.3598 | | 0.3469 | 0.2560 | 0.2549 | 0.2663 | 0.2510 |
| 6 | 0.0.340 | - | 0.3330 | - | 0.3342 | 0.3065 | 0.2226 | 0.2339 | 0.2278 |

Table B.11. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 15°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4151 | - | 0.4169 | - | 0.0776 | 0.0102 | 0.0057 | 0.0038 | 0.0059 |
| 0.5 | 0.3671 | - | 0.4254 | - | 0.3089 | 0.2214 | 0.1110 | 0.0984 | 0.0409 |
| 1 | 0.2476 | - | 0.4067 | - | 0.3253 | 0.2272 | 0.1403 | 0.1173 | 0.0621 |
| 2 | 0.3177 | - | 0.3612 | - | 0.3767 | 0.2696 | 0.2030 | 0.1887 | 0.1294 |
| 3 | 028867 | - | 0.3790 | - | 0.3104 | 0.2661 | 0.1816 | 0.2316 | 0.1635 |
| 4 | 0.2929 | - | 0.3654 | - | 0.3420 | 0.2564 | 0.1954 | 0.1629 | 0.1432 |
| 5 | 0.2810 | - | 0.3275 | - | 0.3066 | 0.2711 | 0.2044 | 0.1728 | 0.2084 |
| 6 | 0.3181 | - | 0.3478 | - | 0.3159 | 0.2661 | 0.2296 | 0.1904 | - |

Table B.12. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 40°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3631 | - | 0.3907 | - | 0.0368 | 0.0109 | 0.0041 | 0.0029 | 0.0008 |
| 0.5 | 0.3274 | - | 0.3442 | - | 0.2889 | 0.1703 | 0.0670 | 0.0373 | 0.0206 |
| 1 | 0.3070 | - | 0.2639 | - | 0.2756 | 0.1849 | 0.1162 | - | 0.0443 |
| 2 | 0.2218 | - | 0.3121 | - | 0.2894 | 0.2335 | 0.1552 | 0.1417 | 0.0995 |
| 3 | 0.2409 | - | 0.2686 | - | 0.2020 | 0.2119 | 0.1586 | 0.0920 | 0.1226 |
| 4 | - | - | 0.2729 | | 0.2411 | 0.2248 | 0.1690 | 0.2048 | 0.1866 |
| 5 | 0.3094 | | 0.2436 | | 0.2667 | 0.2634 | 0.2030 | 0.2000 | 0.1423 |
| 6 | - | - | 0.2896 | - | 0.2262 | 0.2348 | 0.2020 | 0.2248 | 0.1408 |

Table B.13. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 12.5% moisture content; 25°C; upward direction of flow; 40% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4651 | - | 0.4785 | - | 0.0536 | 0.0110 | 0.0068 | 0.0023 | 0.0026 |
| 0.5 | 0.3637 | - | 0.4028 | - | 0.3607 | 0.1543 | 0.0787 | 0.0391 | 0.0106 |
| 1 | 0.2504 | - | 0.4789 | - | 0.3617 | 0.1750 | 0.1084 | 0.0663 | 0.0252 |
| 2 | 0.2722 | - | 0.4158 | - | 0.3746 | 0.2863 | 0.1952 | 0.1244 | 0.0777 |
| 3 | 0.3238 | - | 0.3560 | - | 0.2870 | 0.2451 | 0.1617 | 0.1178 | 0.0611 |
| 4 | 0.3659 | - | 0.3620 | | 0.3536 | 0.2381 | 0.2306 | 0.2639 | 0.2134 |
| 5 | 0.3018 | | 0.3830 | | 0.3649 | 0.3146 | 0.2092 | 0.1406 | 0.1639 |
| 6 | 0.3250 | - | 0.3239 | - | 0.3915 | 0.3440 | 0.2697 | 0.3220 | 0.2911 |

Table B.14. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3454 | - | 0.3782 | - | 0.1921 | 0.0853 | 0.0527 | 0.0312 | 0.0090 |
| 0.5 | 0.2684 | - | 0.3100 | - | 0.2100 | 0.1457 | 0.0748 | 0.0545 | - |
| 1 | - | - | - | - | 0.2403 | 0.2540 | 0.1722 | 0.0609 | 0.0107 |
| 2 | 0.2348 | - | 0.3125 | - | 0.2551 | 0.2075 | 0.1382 | 0.1484 | 0.1034 |
| 3 | 0.1517 | - | 0.2831 | - | 0.2369 | 0.2105 | 0.1316 | 0.0816 | 0.0309 |
| 4 | 0.2929 | - | 0.3654 | - | 0.3420 | 0.2564 | 0.1954 | 0.1629 | 0.1432 |
| 5 | - | - | 0.3070 | - | 0.2369 | 0.2504 | 0.2054 | 0.1326 | 0.1854 |
| 6 | 0.2763 | - | 0.2699 | - | 0.2461 | 0.2365 | 0.2082 | 0.1810 | 0.2435 |

Table B.15. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 15°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3852 | - | 0.3271 | - | 0.0383 | 0.0066 | 0.0022 | 0.0019 | 0.0015 |
| 0.5 | 0.4146 | - | 0.4289 | - | 0.2815 | 0.1604 | 0.0643 | 0.0327 | 0.0068 |
| 1 | 0.3737 | - | 0.3747 | - | 0.3323 | 0.1794 | 0.1143 | 0.017 | 0.0421 |
| 2 | 0.3162 | - | 0.3982 | - | 0.3313 | 0.2331 | 0.1638 | 0.1270 | 0.0942 |
| 3 | 0.3079 | - | 0.3260 | - | 0.3170 | 0.2217 | 0.1834 | 0.1795 | 0.1118 |
| 4 | 0.2492 | - | 0.3062 | - | 0.2507 | 0.2171 | 0.1876 | 0.2006 | 0.1483 |
| 5 | 0.3071 | | 0.3485 | - | 0.3384 | 0.2916 | 0.2319 | 0.2342 | 0.1899 |
| 6 | 0.2797 | - | 0.3334 | - | 0.3282 | 0.2631 | 0.2188 | 0.2864 | 0.1507 |

Table B.16. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 15°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3752 | - | 0.3701 | - | 0.0460 | 0.0072 | 0.0037 | 0.0023 | 0.0017 |
| 0.5 | 0.4364 | - | 0.4141 | - | 0.3356 | 0.1611 | 0.0647 | 0.0302 | 0.0084 |
| 1 | 0.4158 | - | 0.3586 | - | 0.2826 | 0.2358 | 0.1338 | 0.0787 | 0.0314 |
| 2 | 0.3452 | - | 0.4494 | - | 0.3842 | 0.1826 | 0.2038 | 0.1291 | 0.1292 |
| 3 | 0.3352 | - | 0.3198 | - | 0.2355 | 0.2539 | 0.1760 | 0.2037 | 0.0893 |
| 4 | 0.3663 | - | 0.3260 | - | 0.3683 | 0.3151 | 0.2390 | 0.2555 | 0.1907 |
| 5 | 0.4000 | - | 0.4172 | - | 0.4018 | 0.3416 | 0.2602 | 0.2743 | 0.2297 |
| 6 | 0.3936 | - | 0.4475 | - | 0.3851 | 0.3968 | 0.2858 | 0.3091 | 0.3002 |

Table B.17. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 18% moisture content; 25°C; upward direction of flow; 46% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4745 | - | 0.4715 | - | 0.0604 | 0.0154 | 0.0089 | 0.0055 | 0.0045 |
| 0.5 | 0.4446 | - | 0.4009 | - | 0.2934 | 0.1759 | 0.0705 | 0.0439 | 0.0160 |
| 1 | 0.4619 | - | 0.4157 | - | 0.3855 | 0.2000 | 0.1486 | 0.0995 | 0.0461 |
| 2 | 0.4507 | - | 0.4459 | - | 0.4050 | 0.3230 | 0.2106 | 0.1634 | 0.1330 |
| 3 | 0.5110 | - | 0.4360 | - | - | 0.2827 | - | 0.2013 | 0.2211 |
| 4 | 0.3680 | - | 0.4085 | - | 0.3023 | 0.2677 | - | 0.2289 | 0.0982 |
| 5 | 0.3494 | - | 0.3266 | - | 0.3244 | 0.2731 | 0.2103 | 0.2662 | 0.2472 |
| 6 | 0.3317 | - | 0.3277 | - | 0.3365 | 0.2744 | 0.2718 | 0.2899 | 0.2765 |

Table B.18. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 38% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4785 | - | 0.4389 | - | 0.0584 | 0.0221 | 0.0100 | 0.0072 | 0.0032 |
| 0.5 | 0.4653 | - | 0.5310 | - | 0.3827 | 0.1722 | 0.0828 | 0.0369 | 0.0124 |
| 1 | 0.4604 | - | .04900 | - | 0.4470 | 0.2653 | 0.1503 | 0.1387 | 0.0817 |
| 2 | 0.4887 | - | 0.4460 | - | 0.3791 | 0.3923 | 0.2343 | 0.2863 | 0.2489 |
| 3 | - | - | - | - | - | - | - | - | - |
| 4 | 0.4509 | - | 0.4390 | - | 0.3646 | 0.2830 | 0.2189 | 0.2827 | 0.2016 |
| 5 | 0.4969 | - | 0.4764 | - | 0.4030 | 0.3877 | 0.2791 | 0.3379 | 0.3278 |
| 6 | 0.3789 | - | 0.3584 | - | 0.4015 | 0.2943 | 0.2930 | 0.3198 | - |

Table B.19. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 38% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3927 | - | 0.4842 | - | 0.0590 | 0.0097 | 0.0035 | 0.0023 | 0.0010 |
| 0.5 | 0.3413 | - | 0.4209 | - | 0.2891 | 0.1644 | 0.0621 | 0.0315 | 0.0082 |
| 1 | 0.3861 | - | 0.3464 | - | 0.3420 | 0.1554 | 0.1282 | 0.0911 | 0.0485 |
| 2 | 0.3935 | - | 0.3937 | - | 0.3676 | 0.2825 | 0.1881 | 0.1459 | 0.0979 |
| 3 | 0.4042 | - | 0.2991 | - | 0.3174 | 0.2900 | 0.1845 | 0.1896 | 0.1334 |
| 4 | 0.3504 | - | 0.3625 | - | 0.3546 | 0.2396 | 0.2134 | 0.2276 | 0.2096 |
| 5 | 0.3698 | - | 0.3953 | - | 0.3326 | 0.3193 | 0.2342 | 0.2565 | 0.1508 |
| 6 | 0.3827 | - | 0.3949 | - | 0.3747 | 0.2772 | 0.2526 | 0.2879 | 0.2564 |

:

Table B.20. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 5°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4534 | - | 0.4682 | - | 0.0474 | 0.0091 | 0.0035 | 0.0023 | 0.0023 |
| 0.5 | 0.5056 | - | 0.4304 | - | 0.3692 | 0.1520 | 0.0713 | 0.0346 | 0.0078 |
| 1 | 0.4525 | - | 0.4162 | - | 0.3880 | 0.2139 | 0.1336 | 0.0769 | 0.0563 |
| 2 | 0.4497 | - | 0.4788 | - | 0.3800 | 0.2761 | 0.2108 | 0.1705 | 0.0891 |
| 3 | 0.3336 | - | 0.2884 | - | 0.2909 | 0.2261 | 0.1951 | 0.1763 | 0.1554 |
| 4 | 0.3409 | - | 0.3403 | - | 0.3799 | 0.2550 | 0.2468 | 0.2398 | 0.2165 |
| 5 | 0.4102 | - | 0.4342 | - | 0.3459 | 0.3133 | 0.2694 | 0.2827 | 0.2306 |
| 6 | 0.4006 | - | 0.4049 | - | 0.4180 | 0.3417 | 0.2517 | 0.3154 | 0.2646 |

Table B.21. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; downward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4683 | - | 0.4639 | - | 0.0773 | 0.0136 | 0.0053 | 0.0041 | 0.0028 |
| 0.5 | 0.4490 | - | 0.4300 | - | 0.3396 | 0.2677 | 0.2553 | 0.2174 | 0.0919 |
| 1 | 0.3842 | - | 0.4139 | - | 0.4118 | 0.2619 | 0.2424 | 0.2050 | 0.1636 |
| 2 | 0.3338 | - | 0.2594 | - | 0.2574 | 0.2207 | 0.1804 | 0.2342 | 0.0610 |
| 3 | 0.4133 | - | 0.3687 | - | 0.3952 | 0.3160 | 0.2845 | 0.3096 | 0.2397 |
| 4 | 0.4315 | - | 0.3536 | - | 0.3769 | 0.1658 | 0.2699 | 0.2833 | 0.2582 |
| 5 | 0.3706 | - | 0.3871 | - | 0.3035 | 0.3096 | 0.2500 | 0.2757 | 0.1794 |
| 6 | 0.3860 | - | 0.4103 | - | 0.3824 | 0.3559 | 0.2919 | 0.3502 | 0.2579 |

Table B.22. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 5°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4742 | - | 0.4016 | - | 0.0360 | 0.0073 | 0.0030 | 0.0025 | 0.0019 |
| 0.5 | 0.3916 | - | 0.3715 | - | 0.3026 | 0.1565 | 0.0667 | 0.0294 | 0.0083 |
| 1 | 0.3424 | - | 0.3664 | - | 0.3399 | 0.1829 | 0.1156 | 0.0707 | 0.0359 |
| 2 | 0.2364 | - | 0.2421 | - | 0.2972 | 0.2103 | - | - | - |
| 3 | 0.3255 | - | 0.3296 | - | 0.3185 | 0.2729 | 0.2056 | 0.2078 | 0.1702 |
| 4 | 0.2587 | - | 0.3557 | - | 0.3271 | 0.2853 | 0.2213 | 0.2158 | 0.2052 |
| 5 | 0.3607 | - | 0.3543 | - | 0.3259 | 0.2913 | 0.2427 | 0.2176 | 0.1508 |
| 6 | 0.3390 | - | 0.3514 | - | 0.3463 | 0.3240 | 0.2168 | 0.2749 | 0.2442 |

Table B.23. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 40°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4220 | - | 0.4881 | - | 0.0423 | 0.0075 | 0.0041 | 0.0021 | 0.0016 |
| 0.5 | 0.4462 | - | 0.4490 | - | 0.2971 | 0.1397 | 0.0564 | 0.0325 | 0.0086 |
| 1 | 0.4514 | - | 0.4507 | - | 0.3552 | 0.2125 | 0.1368 | 0.0815 | 0.0478 |
| 2 | 0.3870 | - | 0.4356 | - | 0.4127 | 0.2839 | 0.2006 | 0.1675 | 0.1194 |
| 3 | 0.4362 | - | 0.4263 | - | 0.2587 | 0.3867 | 0.1818 | 0.1582 | 0.1670 |
| 4 | 0.3914 | - | 0.3893 | - | 0.3663 | 0.3017 | 0.2747 | 0.2438 | 0.2313 |
| 5 | 0.3680 | - | 0.3990 | - | 0.3320 | 0.2923 | 0.2314 | 0.2296 | 0.2272 |
| 6 | 0.3757 | - | 0.3340 | - | 0.4145 | 0.3508 | 0.2593 | 0.3012 | 0.3083 |

Table B.24. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 12.5% moisture content; 25°C; upward direction of flow; 40% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4838 | - | 0.4828 | - | 0.0747 | 0.0163 | 0.0065 | 0.0035 | 0.0023 |
| 0.5 | 0.4769 | - | 0.4609 | - | 0.3742 | 0.1830 | 0.0893 | 0.0435 | 0.0145 |
| 1 | 0.4704 | - | 0.4838 | - | 0.4026 | 0.2204 | 0.1392 | 0.0931 | 0.0531 |
| 2 | 0.4673 | - | 0.4795 | - | 0.2848 | 0.2065 | 0.1762 | 0.1586 | 0.1295 |
| 3 | 0.4397 | - | 0.3847 | - | 0.3847 | 0.3054 | 0.2521 | 0.2497 | 0.2178 |
| 4 | 0.4207 | - | 0.4118 | - | 0.3536 | 0.2597 | 0.2577 | 0.2514 | 0.2503 |
| 5 | 0.3949 | - | 0.4353 | - | 0.3899 | 0.3319 | 0.2521 | 0.2299 | 0.2673 |
| 6 | 0.4182 | - | 0.3469 | - | 0.3824 | 0.3462 | 0.3060 | 0.2823 | 0.2675 |

Table B.25. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 12.5% moisture content; 25°C; upward direction of flow; 40% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4612 | - | 0.4555 | - | 0.0349 | 0.0160 | 0.0052 | 0.0022 | 0.0019 |
| 0.5 | 0.4459 | - | 0.3864 | - | 0.3413 | 0.1471 | 0.0718 | 0.036 | 0.0154 |
| 1 | 0.3903 | - | 0.4427 | - | 0.3449 | 0.2183 | 0.1160 | 0.0512 | 0.0427 |
| 2 | 0.4299 | - | 0.3628 | - | 0.2647 | 0.2246 | 0.1284 | 0.1194 | 0.1108 |
| 3 | 0.4169 | - | 0.3807 | - | 0.3667 | 0.2582 | 0.1919 | 0.1599 | 0.1765 |
| 4 | 0.3853 | - | 0.3787 | - | 0.3745 | 0.3084 | 0.2181 | 0.1971 | 0.2309 |
| 5 | 0.4048 | - | 0.4013 | - | 0.3847 | 0.3349 | 0.2403 | 0.2766 | 0.2633 |
| 6 | 0.4012 | - | 0.3929 | - | 0.3939 | 0.3510 | 0.2719 | 0.2843 | 0.2712 |

Table B.26. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4860 | - | 0.4760 | - | 0.0479 | 0.0087 | 0.0033 | 0.0022 | 0.0780 |
| 0.5 | 0.4757 | - | - | - | 0.3884 | 0.1948 | 0.1551 | 0.0817 | 0.0444 |
| 1 | 0.4456 | - | - | - | 0.4012 | 0.2314 | 0.2098 | 0.1564 | 0.1131 |
| 2 | 0.3663 | - | 0.3887 | - | 0.3554 | 0.2659 | 0.1980 | 0.1065 | 0.1515 |
| 3 | 0.4030 | - | 0.1239 | - | 0.3555 | 0.3094 | 0.2615 | 0.2304 | 0.2281 |
| 4 | - | - | - | - | - | - | - | - | - |
| 5 | 0.3828 | - | 0.4141 | - | 0.3636 | 0.3289 | 0.2561 | 0.2151 | 0.2391 |
| 6 | 0.3871 | - | 0.3884 | - | 0.3936 | 0.3466 | 0.2294 | 0.3213 | 0.2995 |

Table B.27. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 38% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4874 | - | 0.4357 | - | 0.0680 | 0.0111 | 0.0029 | 0.0021 | 0.0025 |
| 0.5 | 0.4776 | - | 0.4795 | - | 0.3839 | 0.1645 | 0.0776 | 0.0314 | 0.0063 |
| 1 | 0.4517 | - | 0.4264 | - | 0.3722 | 0.1951 | 0.1270 | 0.1018 | 0.0478 |
| 2 | - | - | - | - | 0.3216 | 0.2071 | 0.1536 | 0.0550 | 0.1083 |
| 3 | 0.4373 | - | 0.3748 | - | 0.4317 | 0.3193 | 0.2522 | 0.2402 | 0.1987 |
| 4 | 0.4363 | - | 0.4355 | - | 0.3865 | 0.2909 | 0.2553 | 0.2460 | 0.2421 |
| 5 | 0.4140 | - | 0.4468 | - | 0.4044 | 0.3089 | 0.2950 | 0.2978 | 0.2839 |
| 6 | 0.4001 | - | 0.4321 | - | 0.4005 | 0.3212 | 0.3183 | 0.3056 | 0.3021 |

Table B.28. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 40°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4575 | - | 0.4944 | - | 0.0698 | 0.0108 | 0.0042 | 0.0027 | 0.0021 |
| 0.5 | 0.3746 | - | 0.3898 | - | 0.2887 | 0.2145 | 0.0703 | 0.0336 | 0.0093 |
| 1 | 0.3978 | - | 0.3942 | - | 0.3275 | 0.2119 | 0.1596 | 0.1017 | 0.0556 |
| 2 | 0.3798 | - | 0.3793 | - | 0.3318 | 0.2922 | 0.2290 | 0.1519 | 0.1497 |
| 3 | 0.3045 | - | - | - | 0.3000 | 0.2630 | 0.2900 | 0.2596 | 0.2108 |
| 4 | 0.3732 | - | 0.3205 | - | 0.3459 | 0.2281 | 0.2447 | 0.2235 | 0.2888 |
| 5 | 0.3357 | - | 0.3520 | - | 0.3159 | 0.2307 | 0.2336 | 0.2489 | 0.2462 |
| 6 | 0.3207 | - | 0.3452 | - | 0.2847 | 0.2495 | 0.2337 | 0.1993 | 0.1678 |

Table B.29. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4609 | - | 0.4770 | - | 0.0512 | 0.0106 | 0.0037 | 0.0036 | 0.0017 |
| 0.5 | 0.4148 | - | - | - | 0.3521 | 0.1746 | 0.0842 | 0.0428 | 0.0092 |
| 1 | 0.3271 | - | 0.3944 | - | 0.3167 | 0.2623 | 0.1505 | 0.1031 | 0.0490 |
| 2 | 0.3631 | - | - | - | 0.3398 | 0.2800 | 0.2328 | 0.1851 | 0.1509 |
| 3 | 0.3134 | - | 0.3231 | - | 0.2445 | 0.2328 | 0.2462 | 0.2049 | 0.2224 |
| 4 | 0.2945 | - | 0.3056 | - | 0.3145 | 0.2266 | 0.2492 | 0.2820 | 0.2593 |
| 5 | 0.3011 | - | 0.3472 | - | 0.3150 | 0.2308 | 0.2886 | 0.3081 | 0.1662 |
| 6 | 0.2815 | - | 0.3425 | - | 0.2878 | 0.2323 | 0.2500 | 0.2398 | 0.2143 |

Table B.30. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4220 | - | 0.4558 | - | 0.1011 | 0.0287 | 0.0108 | 0.0056 | 0.0038 |
| 0.5 | 0.4246 | - | 0.4309 | - | 0.2759 | 0.1567 | 0.0888 | 0.0427 | 0.0150 |
| 1 | 0.4164 | - | 0.3757 | - | 0.3299 | 0.2507 | 0.1607 | 0.1061 | 0.0574 |
| 2 | 0.3618 | - | 0.3969 | - | 0.3412 | 0.2525 | 0.1829 | 0.1592 | 0.1364 |
| 3 | 0.3624 | - | 0.3493 | - | 0.3558 | 0.2867 | 0.2359 | 0.2146 | 0.1567 |
| 4 | 0.3498 | - | 0.3488 | - | 0.3277 | 0.2841 | 0.1813 | 0.2397 | 0.2136 |
| 5 | 0.3725 | - | 0.3591 | - | 0.3410 | 0.2954 | 0.2121 | 0.2533 | 0.2380 |
| 6 | 0.3163 | - | 0.3533 | - | 0.3429 | 0.2790 | 0.2522 | 0.2535 | 0.2671 |

Table B.31. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4944 | - | 0.4417 | - | 0.0948 | 0.0215 | 0.0061 | 0.0030 | 0.0062 |
| 0.5 | 0.3908 | - | 0.3853 | - | 0.3352 | 0.1687 | 0.0816 | 0.0397 | 0.0136 |
| 1 | 0.3917 | - | 0.3976 | - | 0.3446 | 0.2292 | 0.1443 | 0.0969 | - |
| 2 | - | - | - | - | 0.3420 | 0.2658 | 0.1712 | 0.1720 | 0.1387 |
| 3 | 0.3492 | - | 0.3717 | - | 0.3495 | 0.3033 | 0.2323 | 0.2015 | 0.1774 |
| 4 | 0.3720 | - | 0.3718 | - | 0.3539 | 0.3000 | 0.2451 | 0.2323 | 0.2257 |
| 5 | 0.3744 | - | 0.3775 | - | 0.3482 | 0.3089 | 0.2629 | 0.2471 | 0.2207 |
| 6 | 0.3595 | - | 0.3288 | - | 0.3565 | 0.2958 | 0.2736 | 0.2627 | 0.2330 |

Table B.32. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4016 | - | 0.4074 | - | 0.1069 | 0.0269 | 0.0072 | 0.0020 | 0.0031 |
| 0.5 | 0.3788 | - | 0.4264 | - | 0.3230 | 0.1586 | 0.0927 | 0.0400 | 0.0102 |
| 1 | 0.3419 | - | 0.3791 | - | 0.3260 | 0.1968 | 0.1248 | 0.0848 | 0.0367 |
| 2 | 0.3937 | - | 0.4030 | - | 0.3468 | 0.2644 | 0.2111 | 0.1650 | 0.0726 |
| 3 | 0.3461 | - | - | - | 0.2872 | 0.3605 | 0.2405 | 0.2003 | 0.0907 |
| 4 | 0.3568 | - | 0.3650 | - | 0.3583 | 0.2676 | 0.2053 | 0.1857 | 0.1167 |
| 5 | 0.3355 | - | 0.3796 | - | 0.3568 | 0.2490 | 0.2463 | 0.1922 | 0.1170 |
| 6 | 0.3633 | - | 0.3746 | - | 0.3040 | 0.2737 | 0.2258 | 0.2103 | 0.1133 |

Table B.33. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6586 | 0.6614 | 0.6837 | 0.6289 | 0.0918 | 0.0231 | 0.0112 | 0.0070 | 0.0033 |
| 0.5 | - | - | - | - | - | - | - | - | - |
| 1 | 0.6037 | 0.6323 | 0.5761 | 0.5913 | 0.4807 | 0.3333 | 0.1890 | 0.1312 | 0.0753 |
| 2 | 0.5919 | 0.6001 | 0.6010 | 0.5663 | 0.5207 | 0.4013 | 0.2691 | 0.2343 | 0.1859 |
| 3 | - | - | - | - | - | - | - | - | - |
| 4 | 0.5442 | 0.5500 | 0.5425 | 0.5207 | 0.4816 | 0.4085 | 0.3216 | 0.3307 | 0.2896 |
| 5 | 0.5281 | 0.5430 | 0.5361 | 0.5299 | 0.5099 | 0.3950 | 0.34297 | 0.3563 | 0.3125 |
| 6 | 0.5304 | 0.5261 | 0.5321 | 0.4893 | 0.4599 | 0.4337 | 0.3466 | 0.3680 | 0.3241 |

Table B.34. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6808 | 0.6136 | 0.6604 | 0.6239 | 0.1066 | 0.0355 | 0.0347 | - | - |
| 1 | 0.5924 | 0.6276 | 0.5556 | 0.5956 | 0.5040 | 0.3774 | 0.2497 | 0.1501 | 0.0937 |
| 2 | 0.5964 | 0.5471 | 0.5992 | 0.5538 | 0.5241 | 0.4385 | 0.3443 | 0.2600 | 0.2122 |
| 3 | 0.5644 | - | - | 0.5248 | 0.5369 | 0.4656 | 0.3856 | 0.3395 | 0.3154 |
| 4 | 0.5665 | 0.5404 | 0.5420 | - | 0.5001 | 0.4855 | 0.4055 | 0.3814 | 0.3812 |
| 5 | 0.5338 | 0.5430 | 0.4952 | - | 0.5050 | 0.4619 | 0.4271 | 0.3826 | 0.4166 |
| 6 | 0.5213 | 0.4572 | 0.5216 | - | 0.4789 | 0.4684 | 0.4584 | 0.3899 | 0.4340 |

Table B.35. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4716 | 0.4924 | 0.4847 | 0.4982 | 0.0376 | 0.0293 | 0.0048 | 0.0021 | 0.0016 |
| 1 | 0.4515 | 0.4930 | 0.4643 | - | 0.3860 | 0.2704 | 0.1801 | 0.1011 | 0.0579 |
| 2 | 0.4540 | 0.4403 | 0.4642 | - | 0.4066 | 0.3227 | 0.2516 | 0.1994 | 0.1694 |
| 3 | 0.4353 | - | 0.4380 | - | 0.4170 | 0.3129 | 0.3033 | 0.2593 | 0.2205 |
| 4 | 0.4042 | - | - | - | 0.4007 | 0.3676 | 0.3300 | 0.2848 | 0.2935 |
| 5 | 0.4062 | 0.3949 | 0.3931 | - | 0.3731 | 0.3608 | 0.3369 | 0.3306 | 0.3010 |
| 6 | 0.3810 | 0.4054 | 0.4064 | - | 0.3648 | 0.3252 | 0.3523 | 0.3091 | 0.3177 |

Table B.36. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4883 | 0.4858 | 0.4960 | - | 0.0579 | 0.0109 | 0.0056 | 0.0030 | 0.0024 |
| 1 | 0.4693 | 0.4856 | 0.4590 | - | 0.3595 | 0.2228 | 0.2108 | 0.1221 | 0.0649 |
| 2 | - | - | - | - | - | - | - | - | - |
| 3 | 0.4109 | 0.4210 | 0.3854 | - | 0.3754 | 0.2796 | 0.2236 | 0.1737 | 0.1567 |
| 4 | 0.4000 | 0.4134 | 0.3801 | - | 0.3621 | 0.2882 | 0.2709 | 0.2225 | 0.1856 |
| 5 | 0.3664 | 0.3823 | 0.3627 | - | 0.3221 | 0.3224 | 0.3005 | 0.2689 | 0.2386 |
| 6 | 0.3551 | 0.3321 | 0.3621 | - | 0.3312 | 0.3287 | 0.2923 | 0.2771 | 0.2556 |

Table B.37. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; horizontal direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4701 | 0.4659 | 0.4559 | - | 0.0700 | 0.0131 | 0.0045 | 0.0027 | 0.0023 |
| 1 | 0.4407 | 0.4787 | 0.4568 | - | 0.3810 | 0.2677 | 0.2254 | 0.1948 | 0.1549 |
| 2 | 0.4017 | 0.4405 | 0.4418 | - | 0.4112 | 0.3452 | 0.2824 | 0.2791 | 0.2422 |
| 3 | 0.4065 | 0.4265 | 0.4397 | - | 0.4014 | 0.3782 | 0.3464 | 0.3256 | 0.2993 |
| 4 | 0.4057 | 0.4230 | 0.4107 | - | 0.4015 | 0.3452 | 0.3139 | 0.3354 | 0.3280 |
| 5 | 0.4001 | 0.4227 | 0.4101 | - | 0.4178 | 0.3723 | 0.3221 | 0.3319 | 0.3199 |
| 6 | 0.3945 | 0.3923 | 0.3978 | - | 0.3991 | 0.3824 | 0.3521 | 0.3112 | 0.3001 |

Table B.38. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; horizontal direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4706 | 0.5147 | 0.4967 | - | 0.0556 | 0.0095 | 0.0032 | 0.0018 | - |
| 1 | 0.4476 | 0.4417 | 0.4600 | - | 0.4210 | 0.3316 | 0.2806 | 0.2271 | 0.1877 |
| 2 | 0.4172 | 0.4327 | - | - | 0.4002 | 0.3749 | 0.3280 | 0.2994 | 0.2433 |
| 3 | 0.3860 | - | 0.4103 | - | 0.3864 | 0.3777 | 0.3370 | 0.3164 | 0.3180 |
| 4 | 0.3817 | 0.3882 | 0.4005 | - | 0.3757 | 0.3498 | 0.3392 | 0.3205 | 0.3116 |
| 5 | 0.3846 | 0.3923 | 0.3857 | - | 0.3721 | 0.3742 | 0.3440 | 0.3476 | 0.3409 |
| 6 | 0.3822 | 0.3394 | 0.3991 | - | 0.3777 | 0.3721 | 0.3521 | 0.3512 | 0.3555 |

Table B.39. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4556 | 0.4846 | 0.4681 | - | 0.0371 | 0.0328 | 0.0021 | 0.0031 | 0.0021 |
| 1 | 0.4370 | 0.4243 | 0.42991 | - | 0.4091 | 0.1485 | 0.0582 | 0.0383 | 0.0251 |
| 2 | 0.4000 | - | 0.4723 | - | 0.3934 | 0.2280 | 0.1390 | 0.0777 | 0.0491 |
| 3 | 0.3883 | - | - | - | 0.3189 | 0.2347 | 0.2018 | 0.1186 | 0.1206 |
| 4 | 0.3337 | 0.3187 | 0.3492 | - | 0.3105 | 0.2632 | 0.2053 | 0.1833 | 0.1327 |
| 5 | 0.2999 | 0.3305 | 0.2992 | - | 0.3095 | 0.2668 | 0.2357 | 0.2227 | 0.1765 |
| 6 | 0.2889 | 0.3120 | 0.3001 | - | 0.3021 | 0.2967 | 0.2632 | 0.2343 | 0.1934 |

Table B.40. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4841 | 0.4871 | 0.4709 | - | 0.0741 | 0.0146 | 0.0057 | 0.0043 | 0.0038 |
| 1 | 0.4231 | 0.3976 | 0.4184 | - | 0.4220 | 0.1844 | 0.0673 | 0.1072 | 0.0352 |
| 2 | 0.4309 | 0.4333 | 0.4317 | - | 0.4017 | 0.2401 | 0.1579 | 0.1119 | 0.0556 |
| 3 | 0.4111 | - | - | - | 0.4223 | 0.2785 | 0.2086 | 0.1714 | 0.1535 |
| 4 | 0.3777 | 0.3758 | 0.3707 | - | 0.4083 | 0.2370 | 0.2298 | 0.2231 | 0.1634 |
| 5 | 0.3598 | 0.3410 | 0.3413 | - | 0.4045 | 0.1890 | 0.2536 | 0.2265 | 0.1923 |
| 6 | 0.3216 | 0.3279 | 0.3249 | - | 0.3043 | 0.2122 | 0.2542 | 0.2397 | 0.2358 |

Table B.41. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4441 | 0.4871 | 0.4709 | - | 0.0648 | 0.0146 | 0.0055 | 0.0061 | 0.0027 |
| 1 | 0.3731 | 0.3976 | 0.4184 | - | 0.3228 | 0.3844 | 0.0674 | 0.0072 | 0.0039 |
| 2 | 0.3709 | 0.3833 | 0.3817 | - | 0.3017 | 0.2409 | 0.1572 | 0.1128 | 0.0538 |
| 3 | 0.3511 | 0.3429 | 0.3329 | - | 0.3225 | 0.2782 | 0.2087 | 0.1768 | 0.1519 |
| 4 | 0.3277 | 0.3158 | 0.3107 | - | 0.3086 | 0.2378 | 0.2299 | 0.2225 | 0.1629 |
| 5 | 0.3098 | 0.3310 | 0.3213 | - | 0.3042 | 0.2890 | 0.2533 | 0.2238 | 0.1985 |
| 6 | 0.3016 | 0.3279 | 0.3149 | - | 0.2845 | 0.2627 | 0.2541 | 0.2376 | 0.2393 |

Table B.42. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4283 | 0.3858 | 0.3960 | - | 0.0579 | 0.0109 | 0.0056 | 0.0030 | 0.0024 |
| 1 | 0.3693 | 0.3856 | 0.3590 | - | 0.2595 | 0.1228 | 0.1108 | 0.0221 | 0.0649 |
| 2 | - | - | - | - | - | - | - | - | - |
| 3 | 0.3109 | 0.3210 | 0.2854 | - | 0.2754 | 0.1796 | 0.1236 | 0.1737 | 0.0567 |
| 4 | 0.3000 | 0.3134 | 0.2801 | - | 0.2621 | 0.1882 | 0.1709 | 0.2225 | 0.0856 |
| 5 | 0.2881 | 0.2952 | 0.2821 | - | 0.2492 | 0.1992 | 0.1882 | 0.1992 | 0.1221 |
| 6 | 0.2664 | 0.2823 | 0.2627 | - | 0.2221 | 0.2224 | 0.2005 | 0.1689 | 0.1386 |

Table B.43. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2296 | 0.2210 | 0.2304 | 0.2234 | 0.0657 | 0.0454 | 0.0194 | 0.0152 | 0.0084 |
| 1 | 0.2482 | 0.2420 | 0.2361 | 0.2483 | 0.1279 | 0.0124 | 0.0081 | 0.0051 | 0.0676 |
| 2 | 0.1954 | 0.2271 | 0.1989 | 0.2382 | 0.03844 | 0.1654 | 0.0286 | 0.0303 | 0.0733 |
| 3 | 0.2008 | 0.2113 | 0.1404 | 0.2287 | 0.1184 | 0.1991 | 0.0627 | 0.0127 | 0.0818 |
| 4 | 0.2101 | 0.2210 | 0.1718 | 0.1570 | 0.1429 | 0.2281 | 0.0901 | 0.0314 | 0.0317 |
| 5 | 0.1438 | 0.1725 | 0.1380 | 0.2076 | 0.1393 | 0.2059 | 0.1226 | 0.0404 | 0.0368 |
| 6 | 0.1691 | 0.1872 | 0.1430 | 0.1022 | 0.0376 | 0.1646 | 0.0939 | 0.0597 | 0.0467 |

Table B.44. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2752 | - | 0.1701 | - | 0.0460 | 0.0072 | 0.0037 | 0.0023 | 0.0017 |
| 0.5 | 0.2364 | - | 0.2141 | - | 0.1356 | 0.0611 | 0.0647 | 0.0302 | 0.0084 |
| 1 | 0.2158 | - | 0.1586 | - | 0.0826 | 0.0358 | 0.0338 | 0.0787 | 0.0314 |
| 2 | 0.1452 | - | 0.2494 | - | 0.1842 | 0.0826 | 0.0038 | 0.1291 | 0.1292 |
| 3 | 0.1352 | - | 0.1198 | - | 0.0355 | 0.0539 | 0.0760 | 0.1037 | 0.1293 |
| 4 | 0.1663 | - | 0.1260 | - | 0.1683 | 0.1151 | 0.1090 | 0.1555 | 0.1307 |
| 5 | 0.2000 | - | 0.2172 | - | 0.2018 | 0.1416 | 0.1202 | 0.1743 | 0.1297 |
| 6 | 0.1936 | - | 0.2475 | - | 0.1851 | 0.1968 | 0.1858 | 0.1091 | 0.16002 |

Table B.45. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with wheat for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 43% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2301 | 0.2259 | 0.2559 | - | 0.0700 | 0.0131 | 0.0045 | 0.0027 | 0.0023 |
| 1 | 0.1407 | 0.1787 | 0.1668 | - | 0.0810 | 0.0067 | 0.0054 | 0.0048 | 0.0549 |
| 2 | 0.1017 | 0.1405 | 0.1418 | - | 0.1112 | 0.0452 | 0.0024 | 0.0091 | 0.0422 |
| 3 | 0.1065 | 0.1265 | 0.1397 | - | 0.1014 | 0.0782 | 0.0464 | 0.0256 | 0.0993 |
| 4 | 0.1057 | 0.1230 | 0.1107 | - | 0.1015 | 0.0852 | 0.0639 | 0.0354 | 0.0380 |
| 5 | 0.1120 | 0.1332 | 0.1000 | - | 0.1001 | 0.0721 | 0.0621 | 0.0412 | 0.0518 |
| 6 | 0.1210 | 0.1235 | 0.1063 | - | 0.0991 | 0.0778 | 0.0791 | 0.0631 | 0.0629 |

Table B.46. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4732 | 0.4897 | - | 0.0302 | 0.0085 | 0.0049 | 0.0037 | 0.0033 |
| 0.5 | 0.4552 | 0.4530 | - | 0.3299 | 0.1709 | 0.0748 | 0.0249 | 0.0101 |
| 1 | 0.4317 | 0.4348 | - | 0.3614 | 0.2516 | 0.1415 | 0.0770 | 0.0459 |
| 2 | 0.4545 | 0.4560 | - | 0.3760 | 0.3133 | 0.2181 | 0.1617 | 0.1285 |
| 3 | 0.3975 | 0.4203 | - | 0.4167 | 0.2977 | 0.2670 | 0.2065 | 0.1840 |
| 4 | 0.4077 | 0.4116 | - | 0.3806 | 0.3253 | 0.3047 | 0.2578 | 0.2399 |
| 5 | 0.3991 | 0.3934 | - | 0.3793 | 0.3373 | 0.3148 | 0.2920 | 0.2837 |
| 6 | 0.3870 | 0.4185 | - | 0.4013 | 0.3393 | 0.3155 | 0.2979 | 0.3008 |

Table B.47. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4612 | 0.4825 | - | 0.0555 | 0.0094 | 0.0037 | 0.0023 | - |
| 0.5 | 0.4188 | 0.4140 | - | 0.2920 | 0.1880 | 0.0560 | 0.0670 | 0.0860 |
| 1 | 0.3589 | 0.3744 | - | 0.2599 | 0.1475 | 0.0378 | 0.0751 | 0.0417 |
| 2 | 0.3698 | 0.3832 | - | 0.2978 | 0.1908 | 0.1165 | 0.0823 | 0.0400 |
| 3 | 0.3454 | 0.3637 | - | 0.2657 | 0.2210 | 0.1752 | 0.1408 | 0.1111 |
| 4 | 0.3225 | 0.3988 | - | 0.2841 | 0.2242 | 0.2049 | 0.1656 | 0.1508 |
| 5 | 0.3232 | 0.3167 | - | 0.2668 | 0.2398 | 0.2095 | 0.1960 | 0.1629 |
| 6 | 0.3026 | 0.3090 | - | 0.2810 | 0.2719 | 0.2223 | 0.1984 | 0.2363 |

Table B.48. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4804 | 0.4893 | - | 0.0517 | 0.0098 | 0.0245 | - | - |
| 0.5 | 0.4654 | 0.4403 | - | 0.3127 | 0.1924 | 0.0825 | 0.0272 | 0.0218 |
| 1 | 0.3812 | 0.3645 | - | 0.3137 | 0.2025 | 0.1260 | 0.0680 | - |
| 2 | 0.4188 | 0.4375 | - | 0.3426 | 0.2787 | 0.2276 | 0.1740 | 0.1309 |
| 3 | 0.4117 | 0.3904 | - | 0.3250 | 0.2944 | 0.2575 | 0.2248 | 0.1921 |
| 4 | 0.3769 | 0.3888 | - | 0.3236 | 0.3011 | 0.2753 | 0.2361 | 0.2308 |
| 5 | 0.3697 | 0.3879 | - | 0.3308 | 0.2872 | 0.2727 | 0.2792 | 0.2480 |
| 6 | 0.3371 | 0.3765 | - | 0.3445 | 0.3139 | 0.2848 | 0.2795 | 0.2948 |

Table B.49. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4894 | 0.4711 | - | 0.0556 | 0.0085 | 0.0040 | 0.0027 | 0.0024 |
| 0.5 | 0.4190 | 0.4398 | - | 0.3357 | 0.3178 | 0.2212 | 0.1840 | 0.1387 |
| 1 | 0.4197 | 0.4398 | - | 0.3539 | 0.3168 | 0.2263 | 0.1894 | 0.1856 |
| 2 | 0.4205 | 0.4092 | - | 0.4021 | 0.3160 | 0.2893 | 0.2281 | 0.2004 |
| 3 | 0.3856 | 0.4195 | - | 0.3950 | 0.3091 | 0.2850 | 0.2750 | 0.2968 |
| 4 | 0.3850 | 0.4024 | - | 0.3489 | 0.3196 | 0.3231 | 0.2837 | 0.3155 |
| 5 | 0.3580 | 0.3953 | - | 0.3532 | 0.3203 | 0.3074 | 0.3035 | 0.3058 |
| 6 | 0.3654 | 0.3900 | - | 0.3502 | 0.3317 | 0.3199 | 0.3039 | 0.3478 |

Table B.50. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; downward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4783 | 0.4665 | - | 0.0424 | 0.0068 | 0.0032 | - | - |
| 0.5 | 0.4526 | 0.4504 | - | 0.3124 | 0.2705 | 0.1811 | 0.1326 | 0.0815 |
| 1 | 0.3938 | 0.3978 | - | 0.3426 | 0.2792 | 0.1974 | 0.1741 | 0.1507 |
| 2 | 0.4493 | 0.4497 | - | 0.3471 | 0.3096 | 0.2910 | 0.2466 | 0.1950 |
| 3 | 0.4080 | - | - | 0.3781 | 0.3220 | 0.2931 | 0.2679 | 0.2747 |
| 4 | 0.4060 | 0.3865 | - | 0.3655 | 0.3300 | 0.3059 | 0.2853 | 0.2883 |
| 5 | 0.4008 | 0.3643 | - | 0.3465 | 0.3395 | 0.3233 | 0.3056 | 0.3392 |
| 6 | - | - | - | - | - | - | - | - |

Table B.51. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 12.5% moisture; 25°C; upward direction of flow; 51% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4831 | 0.4137 | - | 0.0706 | 0.0172 | 0.0071 | 0.0033 | 0.0024 |
| 0.5 | 0.4156 | 0.3707 | - | 0.3422 | 0.2164 | 0.1216 | 0.0729 | 0.0158 |
| 1 | 0.3788 | 0.3624 | - | 0.3094 | 0.2401 | 0.1468 | 0.1218 | 0.0784 |
| 2 | 0.3651 | 0.3412 | - | 0.3192 | 0.2634 | 0.1964 | 0.1463 | 0.1399 |
| 3 | 0.3465 | 0.3334 | - | 0.3069 | 0.2949 | 0.2214 | 0.2345 | 0.2075 |
| 4 | 0.3162 | 0.3183 | - | 0.2781 | 0.2528 | 0.2262 | 0.2121 | 0.2269 |
| 5 | 0.3164 | 0.3380 | - | 0.2729 | 0.2810 | 0.2486 | 0.2427 | 0.2505 |
| 6 | 0.2962 | 0.2735 | - | 0.2804 | 0.2823 | 0.2570 | 0.2368 | 0.2275 |

Table B.52. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 12.5% moisture content; 25°C; upward direction of flow; 51% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4885 | 0.4613 | - | 0.0535 | 0.0076 | 0.0022 | - | - |
| 0.5 | 0.4762 | 0.4472 | - | 0.3420 | 0.1739 | 0.0649 | 0.0203 | 0.0620 |
| 1 | 0.4741 | 0.4798 | - | 0.3821 | 0.2038 | 0.1322 | 0.0701 | 0.0429 |
| 2 | 0.4390 | 0.4189 | - | 0.3518 | 0.2802 | 0.1984 | 0.1433 | 0.1377 |
| 3 | 0.4202 | 0.4060 | - | 0.3680 | 0.2948 | 0.2434 | 0.2011 | 0.2115 |
| 4 | 0.3885 | 0.4003 | - | 0.3665 | 0.2718 | 0.2719 | 0.2195 | 0.2460 |
| 5 | 0.3664 | 0.3972 | - | 0.3513 | 0.3147 | 0.2893 | 0.2595 | 0.2649 |
| 6 | 0.3693 | 0.3733 | - | 0.3618 | 0.2834 | 0.2784 | 0.2591 | 0.2956 |

Table B.53. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 12.5% moisture; 25°C; upward direction of flow; 51% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5011 | 0.4849 | - | 0.0571 | 0.0080 | 0.0030 | 0.0020 | 0.0015 |
| 0.5 | 0.4965 | - | - | 0.3751 | 0.1667 | 0.0606 | 0.0189 | 0.0068 |
| 1 | 0.4779 | 0.4558 | - | 0.3925 | 0.2350 | 0.1152 | 0.0695 | 0.0387 |
| 2 | 0.4653 | 0.4329 | - | 0.3539 | 0.2741 | 0.1692 | 0.1365 | 0.1222 |
| 3 | 0.4259 | 0.4074 | - | 0.4022 | 0.3118 | 0.2254 | 0.2318 | 0.2085 |
| 4 | 0.4285 | 0.4179 | - | 0.3472 | 0.3088 | 0.2700 | 0.2656 | 0.2136 |
| 5 | 0.4035 | 0.4258 | - | 0.3761 | 0.3175 | 0.2874 | 0.2591 | 0.2914 |
| 6 | 0.3884 | 0.3762 | - | 0.3722 | 0.3083 | 0.2708 | 0.2864 | 0.3237 |

Table B.54. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4573 | - | - | 0.0997 | 0.0409 | - | - | - |
| 0.5 | - | - | - | - | - | - | - | - |
| 1 | 0.4802 | 0.4756 | - | 0.3813 | 0.3246 | 0.1786 | 0.1146 | 0.0668 |
| 2 | 0.4926 | 0.4456 | - | 0.4404 | 0.3686 | 0.2521 | 0.2076 | 0.1292 |
| 3 | 0.4435 | 0.4576 | - | 0.4524 | 0.3579 | 0.3117 | 0.2431 | 0.1574 |
| 4 | 0.4354 | 0.4600 | - | 0.4139 | 0.3901 | 0.3176 | 0.2577 | 0.1971 |
| 5 | 0.4424 | 0.4057 | - | 0.3824 | 0.3307 | 0.3214 | 0.2323 | 0.1915 |
| 6 | 0.4227 | 0.4135 | - | 0.3751 | 0.3320 | 0.3187 | 0.2453 | 0.2143 |

Table B.55. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4402 | - | 0.0646 | 0.0194 | 0.0092 | 0.0046 | 0.0036 |
| 0.5 | 0.4550 | 0.4631 | - | 0.3562 | 0.2171 | 0.1097 | 0.0405 | 0.0169 |
| 1 | 0.4146 | 0.4303 | - | 0.3494 | 0.2640 | 0.1725 | 0.1050 | 0.0041 |
| 2 | 0.4039 | 0.4194 | - | 0.3791 | 0.3141 | 0.2487 | 0.1715 | 0.1654 |
| 3 | 0.3625 | 0.3979 | - | 0.3436 | 0.3159 | 0.2698 | 0.2404 | 0.2104 |
| 4 | 0.3771 | 0.3861 | - | 0.3447 | 0.3215 | 0.3078 | 0.2453 | 0.2644 |
| 5 | 0.3657 | 0.3615 | - | 0.3605 | 0.3096 | 0.2818 | 0.2928 | 0.2810 |
| 6 | 0.3266 | 0.3515 | - | 0.2972 | 0.2854 | 0.2784 | 0.2550 | 0.2929 |

Table B.56. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3940 | 0.4962 | - | 0.0546 | 0.0076 | 0.0041 | 0.0029 | 0.0095 |
| 0.5 | 0.4414 | 0.4471 | | 0.3221 | 0.1994 | 0.0937 | 0.0384 | 0.0127 |
| 1 | 0.4272 | 0.4388 | - | 0.3085 | 0.2406 | 0.1468 | 0.1015 | 0.0512 |
| 2 | 0.4149 | 0.4274 | - | 0.3571 | 0.2754 | 0.2269 | 0.2060 | 0.1497 |
| 3 | 0.3937 | 0.4029 | - | 0.3685 | 0.2977 | 0.2540 | 0.2556 | 0.2380 |
| 4 | 0.3535 | 0.3838 | - | 0.3478 | 0.3235 | 0.3204 | 0.2860 | 0.2583 |
| 5 | 0.3763 | 0.3812 | - | 0.3426 | 0.3235 | 0.3694 | 0.2997 | 0.2793 |
| 6 | 0.3281 | 0.3603 | | 0.3673 | 0.3135 | 0.3365 | 0.2907 | 0.2885 |

Table B.57. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6331 | 0.6688 | - | 0.0846 | 0.0127 | 0.0041 | 0.0027 | 0.0021 |
| 0.5 | 0.6231 | 0.6336 | - | 0.4825 | 0.2191 | 0.0986 | 0.0308 | 0.0108 |
| 1 | 0.5281 | 0.6145 | - | 0.5170 | 0.3355 | 0.2023 | 0.1061 | 0.0591 |
| 2 | 0.5968 | 0.5729 | - | 0.4633 | 0.3464 | 0.2724 | 0.2342 | 0.1783 |
| 3 | 0.5401 | 0.5337 | - | 0.5021 | 0.4318 | 0.3322 | 0.3000 | 0.2514 |
| 4 | 0.5114 | 0.5253 | - | 0.4892 | 0.3943 | 0.3678 | 0.3653 | 0.3182 |
| 5 | 0.4913 | 0.4964 | - | 0.4357 | 0.3995 | 0.4152 | 0.4155 | 0.3756 |
| 6 | 0.4762 | 0.4998 | - | 0.4551 | 0.4225 | 0.3964 | 0.4296 | 0.4246 |

Table B.58. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5746 | 0.6383 | - | 0.1342 | 0.0156 | 0.0067 | 0.0047 | 0.0034 |
| 0.5 | 0.5581 | 0.5838 | | 0.4446 | 0.2502 | 0.1090 | 0.0391 | 0.0150 |
| 1 | 0.5510 | 0.5766 | - | 0.4800 | 0.3291 | 0.2052 | 0.1136 | 0.0683 |
| 2 | 0.5162 | 0.5478 | - | 0.4882 | 0.3707 | 0.2949 | 0.2286 | 0.1747 |
| 3 | 0.4901 | 0.5027 | - | 0.4497 | 0.3964 | 0.3423 | 0.2931 | 0.2699 |
| 4 | 0.3841 | 0.4940 | - | 0.4523 | 0.4021 | 0.3660 | 0.3395 | 0.3203 |
| 5 | - | - | - | - | - | - | - | - |
| 6 | 0.4142 | 0.4538 | - | 0.4165 | 0.4024 | 0.4058 | 0.3933 | 0.3723 |

Table B.59. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 18% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4959 | 0.5024 | - | 0.0811 | 0.0420 | 0.0333 | 0.0317 | 0.0318 |
| 0.5 | 0.4834 | 0.4944 | - | 0.3636 | 0.2071 | 0.1070 | 0.0750 | 0.0652 |
| 1 | 0.4798 | 0.4958 | - | 0.4282 | 0.3150 | 0.1929 | 0.1267 | 0.1006 |
| 2 | 0.4792 | 0.4563 | - | 0.4525 | 0.3680 | 0.2423 | 0.2235 | 0.1953 |
| 3 | 0.4684 | 0.4713 | - | 0.3885 | 0.3342 | 0.2878 | 0.2909 | 0.2707 |
| 4 | 0.4035 | 0.4334 | - | 0.4387 | - | 0.3304 | 0.3225 | 0.3216 |
| 5 | 0.3843 | 0.4348 | - | 0.4397 | 0.3762 | 0.3481 | 0.3521 | 0.3574 |
| 6 | 0.3928 | 0.4392 | - | 0.4374 | 0.4158 | 0.4021 | 0.3876 | 0.3833 |

Table B.60. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5510 | 0.6118 | - | 0.0904 | 0.0161 | 0.0068 | 0.0046 | 0.0042 |
| 0.5 | 0.5412 | 0.5643 | - | 0.3845 | 0.2131 | 0.0900 | 0.0378 | 0.0135 |
| 1 | 0.4953 | 0.5351 | - | 0.4679 | 0.3074 | 0.1902 | 0.1049 | 0.0620 |
| 2 | 0.4922 | 0.5111 | - | 0.4678 | 0.3598 | 0.2725 | 0.1996 | 0.1631 |
| 3 | 0.4610 | 0.4843 | - | 0.3726 | 0.3268 | 0.2925 | 0.2814 | 0.2461 |
| 4 | 0.4284 | 0.4540 | - | 0.3830 | 0.3844 | 0.3424 | 0.3239 | 0.3085 |
| 5 | 0.3961 | 0.4085 | - | 0.4297 | 0.3717 | 0.3600 | 0.3475 | 0.2920 |
| 6 | 0.4022 | 0.4184 | - | 0.3826 | 0.3883 | 0.3884 | 0.3469 | 0.3387 |

Table B.61. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 48% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4967 | 0.4841 | - | 0.0775 | 0.0117 | 0.0035 | 0.0021 | 0.0021 |
| 0.5 | 0.3938 | 0.4622 | - | 0.3577 | 0.1713 | 0.0736 | 0.0269 | 0.0095 |
| 1 | 0.4468 | 0.4425 | - | 0.3595 | 0.2625 | 0.1516 | 0.0852 | 0.0508 |
| 2 | 0.4390 | 0.4550 | - | 0.3558 | 0.2896 | 0.2030 | 0.1806 | 0.1496 |
| 3 | 0.3943 | 0.4021 | - | 0.3086 | 0.2760 | 0.2390 | 0.21980 | 0.4095 |
| 4 | 0.4157 | 0.4128 | - | 0.3654 | 0.3162 | 0.2747 | 0.2890 | 0.2659 |
| 5 | 0.3868 | 0.3830 | - | 0.3357 | 0.3211 | 0.2793 | 0.3156 | 0.2625 |
| 6 | 0.3630 | 0.3956 | - | 0.3305 | 0.3231 | 0.2900 | 0.2967 | 0.3254 |

Table B.62. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; vertical kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4786 | 0.4817 | - | 0.0693 | 0.0233 | 0.0150 | 0.0127 | 0.0122 |
| 0.5 | 0.4106 | 0.4166 | - | 0.3250 | 0.1810 | 0.0895 | 0.0497 | 0.0376 |
| 1 | 0.3743 | 0.3812 | - | 0.2949 | 0.2007 | 0.1450 | 0.0897 | 0.0714 |
| 2 | 0.3721 | 0.3502 | - | 0.3531 | 0.2838 | 0.2355 | 0.1950 | 0.1718 |
| 3 | 0.3444 | 0.3644 | - | 0.3432 | 0.3196 | 0.2894 | 0.2685 | 0.2466 |
| 4 | 0.3412 | 0.3569 | - | 0.3547 | 0.3291 | 0.3177 | 0.2777 | 0.2668 |
| 5 | 0.3398 | 0.3039 | - | 0.3401 | 0.3222 | 0.3209 | 0.2912 | 0.3087 |
| 6 | 0.3271 | 03182 | - | 0.3336 | 0.3275 | 0.3419 | 0.3362 | 0.3255 |

Table B.63. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 48% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4969 | 0.4895 | - | 0.0854 | 0.0188 | 0.0065 | 0.0030 | 0.0023 |
| 0.5 | 0.4650 | 0.4773 | - | 0.3178 | 0.1812 | 0.0793 | 0.0340 | 0.0111 |
| 1 | 0.4398 | 0.4570 | - | 0.3931 | 0.2643 | 0.1645 | 0.0969 | 0.0492 |
| 2 | 0.4263 | 0.4191 | - | 0.3818 | 0.2791 | 0.2026 | 0.1732 | 0.1441 |
| 3 | 0.3566 | 0.4069 | - | 0.3855 | 0.3257 | 0.2672 | 0.2370 | 0.2144 |
| 4 | 0.3809 | 0.3763 | - | 0.3271 | 0.3212 | 0.2751 | 0.2787 | 0.2655 |
| 5 | 0.3580 | 0.3780 | - | 0.3698 | 0.3238 | 0.2922 | 0.3071 | 0.2569 |
| 6 | 0.3437 | 0.3677 | - | 0.3323 | 0.3107 | 0.3119 | 0.3238 | 0.3139 |

Table B.64. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 48% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3633 | 0.3663 | - | 0.0519 | 0.0107 | 0.0056 | 0.0039 | 0.0031 |
| 0.5 | 0.2206 | 0.3376 | - | 0.2393 | 0.1344 | 0.0561 | 0.0273 | 0.0156 |
| 1 | 0.2916 | 0.2982 | - | 0.2263 | 0.1827 | 0.1129 | 0.0634 | 0.0441 |
| 2 | 0.3037 | 0.2710 | - | 0.2044 | 0.1669 | 0.1468 | 0.1229 | 0.0941 |
| 3 | 0.2899 | 0.2988 | - | 0.2504 | 0.2346 | 0.2092 | 0.1661 | 0.1513 |
| 4 | 0.2814 | 0.2926 | - | 0.2812 | 0.2303 | 0.2245 | 0.2129 | 0.1923 |
| 5 | - | - | - | - | - | - | - | - |
| 6 | 0.2058 | 0.2717 | - | 0.2157 | 0.1974 | 0.1950 | 0.1849 | 0.2079 |

Table B.65. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 40°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4169 | 0.4634 | - | 0.1052 | 0.0103 | 0.0079 | 0.0057 | 0.0044 |
| 0.5 | 0.4550 | 0.4427 | - | 0.3648 | 0.2173 | 0.0998 | 0.0394 | 0.0166 |
| 1 | 0.4294 | 0.4377 | - | 0.4361 | 0.2769 | 0.1645 | 0.1058 | 0.0673 |
| 2 | 0.4198 | 0.4141 | - | 0.3777 | 0.2940 | 0.2667 | 0.1829 | 0.1686 |
| 3 | 0.4008 | 0.4099 | - | 0.3929 | 0.3635 | 0.3056 | 0.2702 | 0.2462 |
| 4 | 0.3995 | 0.3986 | - | 0.3461 | 0.3515 | 0.3505 | 0.3399 | 0.2996 |
| 5 | 0.3844 | 0.3893 | - | 0.3927 | 0.3407 | 0.3551 | 0.3076 | 0.3156 |
| 6 | 0.3711 | - | - | 0.3264 | 0.3541 | 0.3528 | 0.3044 | 0.3033 |

Table B.66. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 40°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4953 | 0.4832 | - | 0.0651 | 0.0113 | 0.0052 | 0.0035 | 0.0471 |
| 0.5 | 0.4777 | 0.4725 | - | 0.3997 | 0.2273 | 0.1059 | 0.0417 | 0.0164 |
| 1 | 0.4636 | 0.5236 | - | 0.4425 | 0.2590 | 0.1210 | 0.0662 | - |
| 2 | 0.4547 | 0.4527 | - | 0.4487 | 0.3455 | 0.2958 | 0.2064 | 0.1732 |
| 3 | 0.4114 | 0.4740 | - | 0.4092 | 0.3978 | 0.3005 | 0.2663 | 0.2817 |
| 4 | 0.4504 | 0.4275 | - | 04397 | 0.3693 | 0.3325 | 0.3067 | 0.2912 |
| 5 | 0.3889 | 0.4592 | - | 0.3787 | 0.4270 | 0.3968 | 0.3697 | 0.3226 |
| 6 | 0.4149 | 0.4340 | - | 0.4257 | 0.3927 | 0.3703 | 0.3585 | 0.3730 |

Table B.67. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 40°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4211 | 0.3837 | - | 0.0660 | 0.0136 | 0.0059 | 0.0064 | 0.0047 |
| 0.5 | 0.3748 | 0.3646 | - | 0.3015 | 0.12371 | 0.1039 | 0.0408 | 0.0082 |
| 1 | 0.3430 | 0.3448 | - | 0.3240 | 0.2023 | 0.1772 | 0.05003 | 0.0232 |
| 2 | 0.3525 | 0.3665 | - | 0.3199 | 0.2394 | 0.1485 | 0.0891 | 0.0611 |
| 3 | 0.3371 | 0.3174 | - | 0.3173 | 0.2507 | 0.2256 | 0.1639 | 0.1198 |
| 4 | 0.2946 | 0.3484 | - | 0.3309 | 0.2947 | 0.2567 | 0.1804 | 0.2004 |
| 5 | 0.2500 | 0.3324 | - | 0.3118 | 0.3045 | 0.2781 | 0.2496 | 0.1852 |
| 6 | 0.3058 | 0.3335 | - | 0.2963 | 0.2668 | 0.2893 | 0.2794 | 0.2401 |

Table B.68. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 5°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4727 | 0.4673 | - | 0.0036 | 0.0146 | - | 0.0052 | 0.0042 |
| 0.5 | 0.4443 | 0.4371 | - | 0.3452 | 0.1573 | 0.0729 | 0.0286 | 0.0115 |
| 1 | 0.4177 | 0.4258 | - | 0.3585 | 0.2390 | 0.1418 | 0.0717 | 0.0408 |
| 2 | 0.4028 | 0.3969 | - | 0.3654 | 0.2664 | 0.2063 | 0.1610 | 0.1190 |
| 3 | 0.3100 | 0.3620 | - | 0.3400 | 0.2718 | 0.2478 | 0.2087 | 0.1705 |
| 4 | 0.3462 | 0.3576 | - | 0.3139 | 0.2672 | 0.2617 | 0.2358 | 0.2203 |
| 5 | 0.3316 | 0.3539 | - | 0.3226 | 0.2987 | 0.2823 | 0.2663 | 0.2494 |
| 6 | - | - | - | - | - | - | - | - |

Table B.69. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 5°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3352 | 0.3461 | - | 0.0522 | 0.0088 | 0.0030 | 0.0026 | 0.0021 |
| 0.5 | 0.2864 | 0.2774 | - | 0.2204 | 0.1126 | 0.0465 | 0.0171 | 0.0166 |
| 1 | 0.2810 | 0.2628 | - | 0.2285 | 0.1543 | 0.0861 | 0.0388 | 0.0223 |
| 2 | 0.2552 | 0.2694 | - | 0.2383 | 0.1705 | 0.1211 | 0.0922 | 0.0708 |
| 3 | 0.2511 | 0.2553 | - | 0.2233 | 0.1969 | 0.1609 | 0.1265 | 0.1106 |
| 4 | 0.2096 | 0.2292 | - | 0.2143 | 0.1978 | 0.1726 | 0.1335 | 0.1351 |
| 5 | 0.2161 | 0.2236 | - | 0.2293 | 0.2038 | 0.1801 | 0.1576 | 0.1591 |
| 6 | 0.2170 | 0.2292 | - | 0.2142 | 0.1963 | 0.1873 | 0.1761 | 0.1722 |

Table B.70. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 5°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4150 | 0.4038 | - | 0.0975 | 0.0222 | 0.0059 | 0.0038 | - |
| 0.5 | 0.3205 | 0.3696 | - | 0.2254 | 0.0139 | 0.0760 | 0.0040 | 0.0006 |
| 1 | 0.3329 | 0.3598 | - | 0.2668 | 0.1064 | 0.0686 | 0.0080 | 0.0407 |
| 2 | 0.2938 | 0.3147 | - | 0.2723 | 0.1518 | 0.1338 | 0.0879 | 0.1373 |
| 3 | 0.2629 | 0.3159 | - | 0.2525 | 0.1878 | 0.1140 | 0.0434 | 0.1298 |
| 4 | 0.2444 | 0.2755 | - | 0.2537 | 0.2004 | 0.1257 | 0.1097 | 0.1767 |
| 5 | 0.2451 | 0.2532 | - | 0.2110 | 0.2005 | 0.1616 | 0.1276 | 0.1024 |
| 6 | 0.2425 | 0.2383 | - | 0.2217 | 0.1979 | 0.1583 | 0.1566 | 0.1512 |

Table B.71. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 18% moisture; 25°C; upward direction of flow; 57% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2722 | 0.3006 | - | 0.0606 | 0.0136 | 0.0094 | 0.0080 | 0.0075 |
| 0.5 | 0.2356 | 0.2566 | - | 0.1945 | 0.1081 | 0.0514 | 0.0235 | 0.0162 |
| 1 | 0.2492 | 0.2534 | - | 0.2043 | 0.1189 | 0.0868 | 0.0534 | 0.0357 |
| 2 | 0.2389 | 0.2465 | - | 0.2100 | 0.1676 | 0.1275 | 0.0919 | 0.0764 |
| 3 | 0.2226 | 0.2314 | - | 0.2075 | 0.1804 | 0.1468 | 0.1420 | 0.1186 |
| 4 | 0.2176 | 0.2148 | - | 0.2018 | 0.1802 | 0.1683 | 0.1452 | 0.1389 |
| 5 | 0.2110 | 0.2064 | - | 0.1943 | 0.1878 | 0.1696 | 0.1618 | 0.1556 |
| 6 | 0.1999 | 0.2170 | - | 0.2058 | 0.2236 | 0.1774 | 0.1973 | 0.1848 |

Table B.72. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 18% moisture content; 25°C; upward direction of flow; 57% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4783 | 0.4738 | - | 0.1038 | 0.0449 | 0.0366 | 0.0303 | 0.0279 |
| 0.5 | 0.4484 | 0.4496 | - | 0.3355 | 0.1532 | 0.0468 | 0.00801 | 0.0056 |
| 1 | 0.3979 | 0.4414 | - | 0.3552 | 0.1968 | 0.0758 | 0.0346 | 0.0014 |
| 2 | 0.3648 | 0.4122 | - | 0.3701 | 0.2332 | 0.1950 | 0.1468 | 0.0825 |
| 3 | 0.3511 | 0.3544 | - | 0.3385 | 0.3035 | 0.3038 | 0.2188 | 0.1761 |
| 4 | 0.3569 | 0.3878 | - | 0.3225 | 0.3046 | 0.2844 | 0.2661 | 0.2382 |
| 5 | 0.3120 | 0.3468 | - | 0.3429 | 0.3130 | 0.2393 | 0.2853 | 0.2725 |
| 6 | 0.3125 | 0.3296 | - | 0.3149 | 0.3211 | 0.3009 | 0.2825 | 0.2724 |

Table B.73. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4684 | 0.4811 | - | 0.0565 | 0.0094 | 0.0031 | 0.0020 | 0.0018 |
| 0.5 | 0.4280 | 0.4223 | - | 0.3107 | 0.1869 | 0.0764 | 0.0271 | 0.0090 |
| 1 | 0.4058 | 0.4216 | - | 0.3408 | 0.2402 | 0.1063 | 0.0762 | 0.0430 |
| 2 | 0.3935 | 0.3889 | - | 0.3441 | 0.2544 | 0.2162 | 0.1442 | 0.1202 |
| 3 | 0.3646 | 0.3810 | - | 0.3497 | 0.2876 | 0.2336 | 0.2013 | 0.1512 |
| 4 | 0.3241 | 0.3205 | - | 0.3213 | 0.3124 | 0.2528 | 0.2546 | 0.2337 |
| 5 | 0.3249 | 0.3537 | - | 0.3237 | 0.2810 | 0.2839 | 0.2882 | 0.2591 |
| 6 | 0.3347 | 0.3323 | - | 0.3212 | 0.3055 | 0.3023 | 0.2773 | 0.2564 |

Table B.74. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2472 | 0.2624 | - | 0.0300 | - | - | - | - |
| 0.5 | 0.2241 | 0.2335 | - | 0.1845 | 0.0977 | 0.0474 | 0.0191 | 0.0124 |
| 1 | 0.2316 | 0.2301 | - | 0.1913 | 0.1289 | 0.0826 | 0.0543 | 0.0328 |
| 2 | 0.2120 | 0.2271 | - | 0.1896 | 0.1707 | 0.1342 | 0.0923 | 0.0760 |
| 3 | 0.2170 | 0.2194 | - | 0.1963 | 0.1732 | 0.1624 | 0.1446 | 0.1257 |
| 4 | 0.2067 | 0.2128 | - | 0.1699 | 0.1848 | 0.1789 | 0.1518 | 0.1376 |
| 5 | 0.2006 | 0.1996 | - | 0.1956 | 0.1813 | 0.1530 | 0.1528 | 0.1043 |
| 6 | 0.1634 | 0.2050 | - | 0.1999 | 0.1900 | 0.1890 | 0.1858 | 0.1446 |

Table B.75. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2263 | 0.2352 | - | 0.0310 | 0.0055 | 0.0024 | 0.0017 | - |
| 0.5 | 0.2067 | 0.2060 | - | 0.1522 | 0.0825 | 0.0300 | 0.0114 | 0.0044 |
| 1 | 0.1968 | 0.1994 | - | 0.1560 | 0.1161 | 0.0688 | 0.0348 | 0.0174 |
| 2 | 0.1860 | 0.1925 | - | 0.1667 | 0.1336 | 0.0863 | 0.0721 | 0.0438 |
| 3 | 0.1744 | 0.1834 | - | 0.1629 | 0.1240 | 0.1028 | 0.0660 | 0.0515 |
| 4 | 0.1620 | 0.1695 | - | 0.1432 | 0.1299 | 0.0687 | 0.1067 | 0.0960 |
| 5 | 0.1647 | 0.1644 | - | 0.1558 | 0.1441 | 0.1179 | 0.1205 | 0.0980 |
| 6 | 0.1557 | - | - | 0.1385 | 0.1408 | 0.1205 | 0.1260 | 0.1277 |

Table B.76. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; downward direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6394 | 0.6683 | - | 0.1803 | 0.0988 | 0.0495 | 0.0192 | 0.0060 |
| 0.5 | 0.5950 | 0.5789 | - | 0.4862 | 0.2722 | 0.1515 | 0.0702 | 0.0417 |
| 1 | 0.5565 | 0.5529 | - | 0.4849 | 0.3591 | 0.2283 | 0.1434 | 0.0930 |
| 2 | 0.5322 | 0.5176 | - | 0.4594 | 0.4061 | 0.3152 | 0.2593 | 0.2137 |
| 3 | 0.5201 | 0.5105 | - | 0.4602 | 0.4018 | 0.3547 | 0.3262 | 0.2684 |
| 4 | 0.4666 | 0.4850 | - | 0.4366 | 0.3872 | 0.3657 | 0.3351 | 0.3300 |
| 5 | 0.4682 | 0.4572 | - | 0.4440 | 0.4269 | 0.4038 | 0.3891 | 0.3648 |
| 6 | 0.4461 | 0.4393 | - | 0.4282 | 0.4215 | 0.3903 | 0.3954 | 0.3924 |

Table B.77. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; downward direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5436 | 0.5528 | - | 0.0782 | 0.0137 | 0.0055 | 0.0043 | 0.0033 |
| 0.5 | 0.4853 | 0.5068 | - | 0.3775 | 0.1969 | 0.0899 | 0.0363 | 0.0155 |
| 1 | 0.4816 | 0.4762 | - | 0.4039 | 0.2851 | 0.1739 | 0.1047 | 0.0611 |
| 2 | 0.4484 | 0.4540 | - | 0.3917 | 0.3195 | 0.2149 | 0.1823 | 0.1457 |
| 3 | - | - | - | - | - | - | - | - |
| 4 | 0.3793 | 0.3701 | - | 0.3534 | 0.3236 | 0.2780 | 0.2725 | 0.2608 |
| 5 | 0.3766 | 0.3483 | - | 0.3325 | 0.3223 | 0.3082 | 0.2889 | 0.2726 |
| 6 | 0.3582 | 0.3228 | - | 0.3382 | 0.3151 | 0.3202 | 0.3130 | 0.2860 |

Table B.78. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4853 | 0.4813 | - | 0.0646 | 0.0102 | 0.0041 | 0.0023 | 0.0036 |
| 0.5 | 0.4639 | 04758 | - | 0.3698 | 0.1898 | 0.0866 | 0.0295 | - |
| 1 | 0.4601 | - | - | 0.3987 | 0.2687 | 0.1647 | 0.0918 | 0.0513 |
| 2 | 0.3804 | 0.4370 | - | 0.3798 | 0.2891 | 0.2019 | 0.1588 | 0.1274 |
| 3 | - | - | - | - | - | - | - | - |
| 4 | 0.3793 | 0.3689 | - | 0.3653 | 0.3317 | 0.2848 | 0.2678 | 0.2645 |
| 5 | 0.3573 | 0.3450 | - | 0.3520 | 0.3356 | 0.3002 | 0.3021 | 0.2975 |
| 6 | 0.3276 | 0.3398 | - | 0.3561 | 0.3497 | 0.3189 | 0.2998 | 0.2934 |

Table B.79. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4081 | 0.4032 | - | 0.0720 | 0.0112 | 0.0051 | 0.0033 | 0.0038 |
| 0.5 | 0.3418 | 0.2759 | - | 0.1944 | 0.1483 | 0.0371 | 0.0021 | 0.0038 |
| 1 | 0.3017 | 0.3186 | - | 0.2001 | 0.1359 | 0.0944 | 0.0652 | 0.0211 |
| 2 | 0.2425 | 0.2490 | - | 0.1924 | 0.1922 | 0.1336 | 0.1217 | 0.0831 |
| 3 | 0.2524 | 0.2318 | - | 0.2528 | 0.2236 | 0.1652 | 0.1440 | 0.1257 |
| 4 | 0.2478 | - | - | 0.2336 | 0.2421 | 0.2019 | 0.1867 | 0.1645 |
| 5 | 0.2218 | - | - | 0.2218 | 0.2319 | 0.2217 | 0.2013 | 0.1856 |
| 6 | 0.2187 | - | - | 0.2087 | 0.2100 | 0.2012 | 0.1845 | 0.1778 |

Table B.80. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; horizontal direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4219 | 0.4430 | - | 0.0484 | 0.0075 | 0.0015 | 0.0009 | 0.0017 |
| 0.5 | 0.3902 | 0.3873 | - | 0.3501 | 0.2780 | 0.1938 | 0.1207 | 0.0739 |
| 1 | 0.3793 | 0.4039 | - | 0.3699 | 0.2981 | 0.2439 | 0.1734 | 0.1613 |
| 2 | 0.3726 | 0.3633 | - | 0.3684 | 0.3130 | 0.2534 | 0.2193 | 0.2257 |
| 3 | 0.3451 | 0.3606 | - | 0.3580 | 0.3304 | 0.2958 | 0.2403 | 0.2673 |
| 4 | 0.3438 | - | - | - | 0.3265 | 0.3283 | 0.3166 | 0.2952 |
| 5 | 0.3508 | 0.3005 | - | 0.3117 | 0.3248 | 0.2915 | 0.2808 | 0.2304 |
| 6 | 0.3315 | 0.3017 | - | 0.3112 | 0.3767 | 0.3012 | 0.2756 | 0.2482 |

Table B.81. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; horizontal direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4316 | - | 0.0473 | 0.0028 | 0.0046 | - | - |
| 0.5 | 0.4187 | 0.4269 | - | 0.2492 | 0.1488 | 0.1489 | 0.0367 | 0.0182 |
| 1 | 0.3985 | 0.4379 | - | 0.2476 | 0.1805 | 0.1991 | 0.0437 | 0.0238 |
| 2 | 0.3836 | 0.3859 | - | 0.2504 | 0.2173 | 0.2154 | 0.1512 | 0.0461 |
| 3 | 0.3735 | 0.3936 | - | 0.2598 | 0.2676 | 0.2196 | 0.1628 | 0.1454 |
| 4 | 0.3375 | 0.3485 | - | 0.2294 | 0.2236 | 0.2011 | 0.1748 | 0.1396 |
| 5 | 0.3015 | 0.3324 | - | 0.2746 | 0.2306 | 0.2055 | 0.1734 | 0.1483 |
| 6 | 0.2912 | 0.2945 | - | 0.2412 | 0.2195 | 0.3123 | 0.2721 | 0.1567 |

Table B.82. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4581 | 0.4537 | - | 0.0635 | 0.0089 | 0.0038 | 0.0020 | 0.0002 |
| 0.5 | 0.4033 | 0.3900 | - | 0.2864 | 0.1100 | 0.0788 | 0.0026 | 0.0007 |
| 1 | 0.4316 | 0.3942 | - | 0.3305 | 0.1796 | 0.0689 | 0.0089 | 0.0051 |
| 2 | 0.3660 | 0.3774 | - | 0.3194 | 0.2134 | 0.1238 | 0.0712 | 0.0121 |
| 3 | 0.3633 | 0.3244 | - | 0.3301 | 0.2466 | 0.2014 | 0.1313 | 0.1185 |
| 4 | 0.3493 | 0.2775 | - | 0.2971 | 0.2766 | 0.2402 | 0.1724 | 0.1817 |
| 5 | 0.3289 | 0.2782 | - | 0.2792 | 0.2343 | 0.2148 | 0.2124 | 0.2164 |
| 6 | 0.2837 | 0.3096 | - | 0.2474 | 0.2524 | 0.1966 | 0.1771 | - |

Table B.83. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 15°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4349 | 0.4309 | - | 0.0489 | 0.0067 | - | - | - |
| 0.5 | 0.4338 | 0.4060 | - | 0.2824 | 0.1097 | 0.0026 | 0.0015 | 0.0009 |
| 1 | 0.4172 | 0.3625 | - | 0.3246 | 0.1676 | 0.0559 | 0.0045 | 0.0043 |
| 2 | - | - | - | - | - | - | - | - |
| 3 | 0.3420 | 0.3398 | - | 0.2673 | 0.2310 | 0.1730 | 0.1170 | 0.0922 |
| 4 | 0.3236 | 0.3145 | - | 0.2894 | 0.2652 | 0.1909 | 0.1621 | 0.1703 |
| 5 | 0.3405 | 0.3024 | - | 0.3058 | 0.2431 | 0.2332 | 0.2109 | 0.1749 |
| 6 | 0.3173 | 0.2667 | - | 0.2635 | 0.2416 | 0.2542 | 0.2226 | 0.2161 |

Table B.84. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 15°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4234 | 0.4112 | - | 0.0684 | 0.0088 | 0.0032 | 0.0021 | 0.0017 |
| 0.5 | 0.4172 | 0.3572 | - | 0.2240 | 0.1291 | 0.0555 | 0.0042 | 0.0079 |
| 1 | 0.3699 | 0.2214 | - | 0.2608 | 0.1896 | 0.0668 | 0.0077 | 0.0077 |
| 2 | 0.3522 | - | - | 0.2774 | 0.1637 | 0.1709 | - | 0.0082 |
| 3 | 0.3333 | 0.2818 | - | 0.2319 | 0.1910 | 0.1311 | 0.0419 | 0.0289 |
| 4 | 0.3282 | 0.2553 | - | 0.2720 | 0.2098 | 0.1635 | 0.0793 | 0.0520 |
| 5 | 0.3110 | 0.2655 | - | 0.2070 | 0.2061 | 0.1783 | 0.1307 | 0.1357 |
| 6 | 0.2847 | 0.2281 | - | 0.2350 | 0.2170 | 0.2045 | 0.1330 | 0.0919 |

Table B.85. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 15°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4534 | 0.4449 | - | 0.0462 | 0.0074 | 0.0023 | 0.0025 | - |
| 0.5 | 0.3891 | 0.4285 | - | 0.4002 | 0.2900 | 0.2158 | 0.1384 | 0.0901 |
| 1 | 0.3989 | 0.3219 | - | 0.3906 | 0.2986 | 0.2652 | 0.1969 | 0.1794 |
| 2 | 0.3660 | 0.3833 | - | 0.3504 | 0.3110 | 0.2299 | 0.1848 | 0.1817 |
| 3 | 0.3726 | 0.3870 | - | 0.3710 | 0.3494 | 0.3167 | 0.2750 | 0.2781 |
| 4 | 0.3510 | 0.3396 | - | 0.3664 | 0.3447 | 0.3129 | 0.3058 | 0.2756 |
| 5 | 0.3680 | 0.330 | - | 0.3397 | 0.3511 | 0.3441 | 0.3115 | 0.3157 |
| 6 | 0.3540 | 0.3110 | - | 0.3348 | 0.3115 | 0.3291 | 0.2854 | 0.3224 |

Table B.86. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 15°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 20% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2064 | 0.2256 | - | 0.0345 | 0.0041 | 0.0022 | 0.0021 | 0.0020 |
| 0.5 | 0.2087 | 0.2189 | - | 0.1671 | 0.0772 | 0.0300 | 0.0111 | 0.0056 |
| 1 | 0.1967 | 0.1989 | - | 0.1589 | 0.1187 | 0.0644 | 0.0321 | 0.0193 |
| 2 | 0.1845 | 0.1994 | - | 0.1645 | 0.1421 | 0.0865 | 0.0724 | 0.0453 |
| 3 | 0.1745 | 0.1926 | - | 0.1629 | 0.1261 | 0.0686 | 0.1065 | 0.0945 |
| 4 | 0.1624 | 0.1856 | - | 0.1476 | 0.1454 | 0.1189 | 0.0967 | 0.0945 |
| 5 | 0.1678 | 0.1756 | - | 0.1558 | 0.1423 | 0.1156 | 0.1245 | 0.0967 |
| 6 | 0.1567 | 0.1623 | - | 0.1421 | 0.1408 | 0.1287 | 0.1276 | 0.1278 |

Table B.87. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; horizontal direction of flow; 54% porosity; horizontal kernel orientation; 60% initial concentration of gas; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.6363 | 0.6445 | - | 0.0805 | 0.0133 | 0.0048 | 0.0012 | 0.0024 |
| 0.5 | 0.6161 | 0.5276 | - | 0.4973 | 0.2756 | 0.1326 | 0.0436 | 0.0186 |
| 1 | 0.5696 | 0.5736 | - | 0.4920 | 0.3629 | 0.2250 | 0.1328 | 0.0777 |
| 2 | 0.5397 | 0.5435 | - | 0.5042 | 0.4013 | 0.3198 | 0.2277 | 0.1938 |
| 3 | 0.5368 | - | - | 0.4751 | 0.4417 | 0.3882 | 0.3225 | 0.3061 |
| 4 | 0.4871 | 0.4936 | - | 0.4547 | 0.4420 | 0.3730 | 0.3276 | 0.3061 |
| 5 | 0.5035 | 0.4755 | - | 0.4071 | 0.3562 | 0.2743 | 0.3303 | - |
| 6 | 0.4582 | 0.4748 | - | 0.4154 | 0.4482 | 0.4069 | 0.3849 | 0.3615 |

Table B.88. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3476 | 0.3032 | | 0.0382 | 0.0071 | 0.0027 | 0.0048 | 0.0000 |
| 0.5 | 0.3230 | 0.2948 | | 0.2489 | 0.1411 | 0.0523 | 0.0167 | 0.0152 |
| 1 | 0.2304 | 0.2738 | | 0.3010 | 0.1892 | 0.1093 | 0.0588 | 0.0313 |
| 2 | 0.3259 | 0.2845 | | 0.2394 | 0.1866 | 0.1629 | 0.0976 | 0.0771 |
| 3 | 0.3278 | - | | 0.2792 | 0.2350 | 0.1949 | 0.1593 | 0.1419 |
| 4 | 0.2441 | 0.2388 | | 0.2503 | 0.2095 | 0.1984 | 0.1723 | 0.1903 |
| 5 | 0.2964 | 0.2369 | | 0.2026 | 0.2260 | 0.2179 | 0.1648 | 0.1549 |
| 6 | 0.2639 | 0.2318 | | 0.2670 | 0.2453 | 0.2379 | 0.1949 | 0.1802 |

Table B.89. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4086 | 0.4158 | - | 0.0584 | 0.0075 | 0.0038 | 0.0024 | 0.0019 |
| 0.5 | 0.3275 | 0.3783 | - | 0.2204 | 0.1171 | 0.0098 | 0.0009 | 0.0012 |
| 1 | 0.3339 | 0.3576 | - | 0.2396 | 0.1050 | 0.0729 | 0.0004 | 0.0028 |
| 2 | 0.3210 | 0.3246 | - | 0.2292 | 0.1353 | 0.1100 | 0.0404 | 0.0183 |
| 3 | 0.2845 | 0.2987 | - | 0.2511 | 0.1848 | 0.1802 | 0.1573 | 0.1019 |
| 4 | 0.2608 | 0.3136 | - | 0.2076 | 0.1663 | 0.2524 | 0.1712 | 0.1530 |
| 5 | 0.2565 | 0.2808 | - | 0.2093 | 0.1586 | 0.2491 | 0.1806 | 0.1868 |
| 6 | 0.2571 | 0.2646 | - | 0.2269 | 0.2128 | 0.2567 | 0.2287 | 0.1530 |

Table B.90. Measured carbon dioxide concentrations in the diffusion cell filled with barley for the following experimental conditions: 15% moisture content; 25°C; upward direction of flow; 54% porosity; horizontal kernel orientation; 40% initial concentration of gas; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4501 | 0.4446 | - | 0.0568 | 0.0078 | 0.0029 | 0.0019 | 0.0017 |
| 0.5 | 0.3780 | 0.4106 | - | 0.3761 | 0.1631 | 0.1016 | 0.0279 | 0.0088 |
| 1 | 0.3876 | 0.4091 | - | 0.3075 | 0.1856 | 0.1916 | 0.0922 | 0.0502 |
| 2 | - | - | - | - | - | - | - | - |
| 3 | 0.3373 | 0.3559 | - | 0.3323 | 0.2101 | 0.2208 | 0.1685 | 0.1260 |
| 4 | 0.2837 | - | - | 0.3491 | 0.3310 | 0.2710 | 0.2183 | 0.2121 |
| 5 | 0.2773 | 0.3147 | - | 0.3275 | 0.2904 | 0.2647 | 0.2216 | 0.2400 |
| 6 | 0.2206 | 0.2168 | - | 0.3151 | 0.3374 | 0.2880 | 0.2383 | 0.2318 |

Table B.91. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 60% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5164 | 0.5425 | - | 0.0588 | 0.0088 | 0.0029 | 0.0020 | 0.0018 |
| 0.5 | 0.5006 | 0.5402 | - | 0.3978 | 0.2327 | 0.1170 | 0.0459 | 0.0204 |
| 1 | 0.4248 | - | - | 0.3610 | 0.2732 | 0.2122 | 0.1259 | 0.0744 |
| 2 | 0.4436 | 0.4463 | - | 0.4286 | 0.3361 | 0.2485 | 0.1877 | 0.1685 |
| 3 | 0.4270 | 0.4872 | - | 0.4389 | 0.3409 | 0.2823 | 0.2849 | 0.2418 |
| 4 | 0.4071 | - | - | 0.3796 | 0.3820 | 0.3660 | 0.3066 | 0.2712 |
| 5 | 0.4328 | 0.3819 | - | 0.3996 | 0.3593 | 0.3398 | 0.3268 | 0.2813 |
| 6 | 0.3816 | 0.3749 | - | 0.4002 | 0.3995 | 0.3507 | 0.3865 | 0.3305 |

Table B.92. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 60% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5895 | 0.5846 | - | 0.0577 | 0.0100 | 0.0021 | 0.0004 | 0.0033 |
| 0.5 | 0.4827 | 0.5901 | - | 0.4065 | 0.2178 | 0.1081 | 0.0519 | 0.0224 |
| 1 | 0.4557 | 0.5472 | - | 0.4114 | 02776 | 01737 | 0.1107 | 0.0571 |
| 2 | 0.4249 | 0.4697 | - | 0.4256 | 0.3187 | 0.2076 | 0.1763 | 0.1419 |
| 3 | 0.3791 | 0.4644 | - | 0.4324 | 0.3546 | 0.2728 | 0.2559 | 0.2065 |
| 4 | 0.4339 | - | | 0.3635 | 0.3813 | 0.3129 | 0.2900 | 0.2113 |
| 5 | 0.3410 | 0.4273 | - | 0.3916 | 0.3368 | 0.3025 | 0.2877 | 0.2596 |
| 6 | 0.3759 | 0.4137 | - | 0.4097 | 0.3501 | 0.3319 | 0.3115 | 0.2887 |

Table B.93. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 60% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.5031 | 0.6117 | - | 0.0581 | 0.0098 | 0.0046 | 0.0022 | 0.0020 |
| 0.5 | 0.5248 | 0.5444 | - | 0.4298 | 0.2679 | 0.1244 | 0.0543 | 0.0245 |
| 1 | 0.4779 | 0.4954 | - | 0.4059 | 0.3089 | 0.1992 | 0.1202 | 0.0699 |
| 2 | 0.4479 | 0.4342 | - | 0.4175 | 0.3545 | 0.2409 | 0.2075 | 0.1695 |
| 3 | 0.4218 | 0.4115 | - | 0.4378 | 0.3449 | 0.3050 | 0.2705 | 0.2319 |
| 4 | 0.3810 | - | - | 0.3441 | 0.3617 | 0.2997 | 0.2736 | 0.2503 |
| 5 | 0.3657 | 0.3813 | - | 0.3440 | 0.2718 | 0.2801 | 0.2575 | 0.2609 |
| 6 | 0.3293 | 0.3607 | - | 0.3544 | 0.3390 | 0.3148 | 0.2971 | 0.2842 |

Table B.94. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4225 | - | - | 0.0562 | 0.0099 | 0.0045 | 0.0028 | - |
| 0.5 | 0.3612 | - | - | 0.3166 | 0.2006 | 0.0743 | 0.0381 | 0.0170 |
| 1 | 0.3292 | - | - | 0.3452 | 0.2314 | 0.1529 | 0.0978 | 0.0579 |
| 2 | 0.3519 | - | - | 0.3383 | 0.2371 | 0.2000 | 0.1489 | 0.1056 |
| 3 | 0.3928 | - | - | 0.3524 | 0.3037 | 0.2134 | 0.1854 | 0.1495 |
| 4 | 0.3033 | - | - | 0.3494 | 0.2580 | 0.2385 | 0.1986 | 0.1782 |
| 5 | 0.2771 | - | - | 0.3291 | 0.2825 | 0.2292 | 0.2191 | 0.1476 |
| 6 | 0.2931 | - | - | 0.3215 | 0.2615 | 0.1883 | 0.1855 | 0.1631 |

Table B.95. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3595 | 0.3672 | - | 0.0684 | 0.0275 | 0.0106 | 0.0036 | 0.0020 |
| 0.5 | 0.3302 | 0.3489 | - | 0.2890 | 0.1935 | 0.0816 | 0.0395 | 0.0216 |
| 1 | 0.3249 | 0.3167 | - | 0.3232 | 0.2437 | 0.1252 | 0.0908 | 0.0625 |
| 2 | 0.2765 | 0.2867 | - | 0.2675 | 0.2378 | 0.1768 | 0.1577 | 0.1323 |
| 3 | 0.2386 | 0.2421 | - | 0.2636 | 0.2350 | 0.1560 | 0.1569 | 0.1671 |
| 4 | 0.2289 | 0.2271 | - | 0.2244 | 0.2023 | 0.2111 | 0.1843 | 0.1864 |
| 5 | 0.2184 | 0.2167 | - | 0.2099 | 0.2119 | 0.1876 | 0.1797 | 0.1723 |
| 6 | 0.1935 | 0.2101 | - | 0.2026 | 0.1920 | 0.1505 | 0.1664 | 0.1727 |

Table B.96. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3916 | - | - | 0.1304 | 0.0382 | 0.0299 | 0.030143 | 0.030640 |
| 0.5 | 0.4072 | - | - | 0.3521 | 0.1709 | 0.1360 | 0.0523 | 0.0530 |
| 1 | 0.3898 | - | - | 0.3574 | 0.2316 | 0.1585 | 0.0845 | 0.0757 |
| 2 | 0.3451 | - | - | 0.3092 | 0.2841 | 0.1679 | 0.1135 | 0.0826 |
| 3 | 0.2836 | - | - | 0.3566 | 0.2511 | 0.1573 | 0.1282 | 0.0976 |
| 4 | 0.3268 | - | - | 0.2699 | 0.2746 | 0.2008 | 0.1915 | 0.1770 |
| 5 | 0.2894 | - | - | 0.2940 | 0.2539 | 0.2199 | 0.1722 | 0.1659 |
| 6 | 0.2812 | - | - | 0.2865 | 0.2734 | 0.2514 | 0.2423 | 0.2387 |

Table B.97. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 13% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4825 | 0.4721 | - | 0.0588 | 0.0069 | 0.0026 | 0.0018 | 0.0020 |
| 0.5 | 0.3978 | 0.4217 | - | 0.3566 | 0.2267 | 0.0956 | 0.0486 | 0.0199 |
| 1 | 0.4098 | 0.4402 | - | 0.3466 | 0.2595 | 0.1819 | 0.1213 | 0.0623 |
| 2 | 0.3872 | - | - | 0.3217 | 0.2874 | 0.2318 | 0.1792 | 0.1452 |
| 3 | 0.3621 | 0.3721 | - | 0.3643 | 0.3258 | 0.2764 | 0.2547 | 0.3352 |
| 4 | 0.3880 | 0.3692 | - | 0.3908 | 0.3391 | 0.3126 | 0.3109 | 0.2769 |
| 5 | 0.3594 | 0.3489 | - | 0.3313 | 0.3466 | 0.3241 | 0.3242 | 0.2864 |
| 6 | 0.3317 | 0.3219 | - | 0.3287 | 0.3267 | 0.3199 | 0.3208 | 0.2914 |

Table B.98. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 13% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4778 | 0.4963 | - | 0.0674 | 0.0149 | 0.0051 | 0.0031 | 0.0024 |
| 0.5 | 0.4175 | 0.4132 | - | 0.3525 | 0.1927 | 0.0951 | 0.0400 | 0.0168 |
| 1 | 0.3854 | 0.4071 | - | 0.3257 | 0.2520 | 0.1639 | 0.1085 | 0.0582 |
| 2 | 0.3913 | 0.4172 | - | 0.3615 | 0.2744 | 0.1932 | 0.1571 | 0.1303 |
| 3 | 0.3515 | 0.3750 | - | 0.3462 | 0.2740 | 0.2082 | 0.2098 | 0.1720 |
| 4 | 0.3346 | 0.3358 | - | 0.3169 | 0.2832 | 0.2399 | 0.2082 | 0.1587 |
| 5 | 0.3345 | 0.3237 | - | 0.3161 | 0.2817 | 0.2299 | 0.2300 | 0.1920 |
| 6 | 0.3214 | 0.3119 | - | 0.3016 | 0.2943 | 0.2678 | 0.2513 | 0.2443 |

Table B.99. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 13% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4075 | 0.4469 | - | 0.0752 | 0.0361 | 0.0341 | 0.0310 | 0.0304 |
| 0.5 | 0.3651 | 0.4325 | - | 0.3353 | 0.1911 | 0.1228 | 0.0960 | 0.0784 |
| 1 | 0.3702 | 0.3747 | - | 0.2959 | 0.2317 | 0.1630 | 0.1347 | 0.0873 |
| 2 | 0.3694 | 0.4025 | - | 0.3627 | 0.2919 | 0.1931 | 0.1752 | 0.1350 |
| 3 | 0.3478 | 0.3412 | - | 0.3496 | 0.2939 | 0.2596 | 0.2344 | 0.2092 |
| 4 | 0.3259 | - | - | 0.3628 | 0.3014 | 0.2695 | 0.2693 | 0.2105 |
| 5 | - | - | - | - | - | - | - | - |
| 6 | 0.2802 | 0.3160 | - | 0.3328 | 0.3106 | 0.3003 | 0.3308 | 0.3000 |

Table B.100. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 8.0% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4561 | 0.5040 | - | 0.0568 | 0.0061 | 0.0038 | 0.0026 | 0.0058 |
| 0.5 | 0.3754 | 0.4667 | - | 0.3339 | 0.2152 | 0.0958 | 0.0484 | 0.0176 |
| 1 | 0.3696 | 0.3910 | - | 0.3449 | 0.2260 | 0.1633 | 0.0955 | 0.0508 |
| 2 | 0.3740 | 0.4026 | - | 0.3179 | 0.2634 | 0.1681 | 0.1499 | 0.1174 |
| 3 | 0.3289 | - | - | 0.3234 | 0.3006 | 0.2286 | 0.1915 | 0.1510 |
| 4 | 0.3277 | 0.3331 | - | 0.3140 | 0.2898 | 0.2144 | 0.2117 | 0.1438 |
| 5 | 0.3134 | 0.3445 | - | 0.3168 | 0.2562 | 0.1994 | 0.2132 | 0.1991 |
| 6 | 0.3010 | 0.3245 | - | 0.2995 | 0.2714 | 0.2135 | 0.2143 | 0.1730 |

Table B.101. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 8.0% moisture; 25°C; upward direction of flow; 31% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4784 | 0.4863 | - | 0.0703 | 0.0334 | 0.0096 | 0.0067 | 0.0050 |
| 0.5 | 0.4010 | 0.4123 | - | 0.3836 | 0.1967 | 0.1452 | 0.0523 | 0.0366 |
| 1 | 0.3256 | 0.3387 | - | 0.3524 | 0.2314 | 0.1904 | 0.0967 | 0.0682 |
| 2 | 0.3473 | 0.4053 | - | 0.3688 | 0.2627 | 0.1691 | 0.1725 | 0.1221 |
| 3 | 0.3324 | 0.3741 | - | 0.3382 | 0.2924 | 0.2520 | 0.2229 | 0.1500 |
| 4 | 0.3317 | 0.3347 | - | 0.3205 | 0.3033 | 0.2689 | 0.2096 | 0.2220 |
| 5 | 0.3126 | 0.3148 | - | 0.3012 | 0.2846 | 0.2523 | 0.2058 | 0.1988 |
| 6 | 0.2967 | 0.2976 | - | 0.3087 | 0.3023 | 0.2643 | 0.2288 | 0.2662 |

Table B.102. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; downward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4873 | 0.4716 | - | 0.0866 | - | 0.0122 | - | 0.0056 |
| 0.5 | 0.5017 | 0.5123 | - | 0.4032 | - | 0.1308 | - | 0.0243 |
| 1 | 0.4459 | 0.5497 | - | 0.4798 | 0.3364 | 0.2042 | 0.1123 | 0.0743 |
| 2 | 0.4122 | 0.5187 | - | 0.4443 | 0.3074 | 0.2168 | 0.1825 | 0.1572 |
| 3 | 0.4237 | 0.4208 | - | 0.4158 | 0.3983 | 0.2777 | 0.2436 | 0.2338 |
| 4 | 0.3945 | 0.3925 | - | 0.4245 | 0.3999 | 0.3270 | 0.2590 | 0.2538 |
| 5 | 0.3955 | 0.3978 | - | 0.3964 | 0.3301 | 0.2790 | 0.2414 | 0.2584 |
| 6 | 0.3867 | 0.3856 | - | 0.3924 | 0.3821 | 0.3512 | 0.3129 | 0.3021 |

Table B.103. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 5°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4728 | 0.4759 | - | 0.0442 | 0.0221 | 0.0074 | 0.0045 | 0.0038 |
| 0.5 | 0.3827 | 0.3916 | - | 0.3584 | 0.2101 | 0.1136 | 0.0747 | 0.0252 |
| 1 | 0.3990 | 0.3989 | - | 0.3843 | 0.2737 | 0.1697 | 0.0919 | 0.0537 |
| 2 | 0.3345 | 0.3249 | - | 0.3610 | 0.2875 | 0.1871 | 0.1328 | 0.1196 |
| 3 | 0.3667 | 0.3560 | - | 0.3343 | 0.2804 | 0.2239 | 0.1994 | 0.1803 |
| 4 | 0.3054 | 0.3080 | - | 0.3205 | 0.2644 | 0.2633 | 0.1935 | 0.1528 |
| 5 | 0.3001 | 0.3007 | - | 0.2919 | 0.2231 | 0.2203 | 0.1914 | 0.1932 |
| 6 | 0.2881 | 0.2771 | - | 0.2818 | 0.2645 | 0.2662 | 0.2356 | 0.2313 |

Table B.104. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 5°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4441 | 0.4560 | - | 0.0554 | 0.0234 | 0.0065 | 0.0035 | 0.0027 |
| 0.5 | 0.4128 | 0.4170 | - | 0.3687 | 0.2089 | 0.1027 | 0.0621 | 0.0207 |
| 1 | 0.3941 | 0.3534 | - | 0.3844 | 0.2431 | 0.1618 | 0.0945 | 0.0627 |
| 2 | 0.4012 | 0.4082 | - | 0.3912 | 0.2668 | 0.2047 | 0.1414 | 0.1232 |
| 3 | 0.3645 | 0.3704 | - | 0.3548 | 0.2999 | 0.2203 | 0.1873 | 0.1699 |
| 4 | 0.3689 | 0.3761 | - | 0.3597 | 0.3098 | 0.2672 | 0.2211 | 0.1768 |
| 5 | 0.3087 | 0.3090 | - | 0.3194 | 0.3247 | 0.2241 | 0.1879 | 0.1970 |
| 6 | 0.2998 | 0.2956 | - | 0.3032 | 0.3127 | 0.2991 | 0.2712 | 0.2412 |

Table B.105. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 15°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4677 | - | 0.0673 | 0.0106 | 0.0034 | 0.0025 | - |
| 0.5 | - | 0.3377 | - | 0.3596 | 0.2108 | 0.1152 | 0.0732 | 0.0218 |
| 1 | - | 0.3798 | - | 0.4252 | 0.2778 | 0.1765 | 0.0987 | 0.0654 |
| 2 | - | 0.4525 | - | 0.4277 | 0.3087 | 0.2371 | 0.1515 | 0.1183 |
| 3 | - | 0.4078 | - | 0.4244 | 0.3431 | 0.2824 | 0.2112 | 0.1417 |
| 4 | - | 0.0413 | - | 0.3905 | 0.3541 | 0.3089 | 0.2620 | 0.2005 |
| 5 | - | 0.3285 | - | 0.3346 | 0.2850 | 0.2355 | 0.2336 | 0.2258 |
| 6 | - | 0.3412 | - | 0.3854 | 0.3205 | 0.2804 | 0.2815 | 0.2594 |

Table B.106. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 15°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4123 | - | 0.0508 | 0.0234 | 0.0077 | 0.0045 | 0.0030 |
| 0.5 | - | 0.3693 | - | 0.4057 | 0.2398 | 0.0738 | 0.0523 | 0.0133 |
| 1 | - | 0.3264 | - | - | - | - | - | - |
| 2 | - | 0.2932 | - | 0.2857 | 0.2247 | 0.1609 | 0.1115 | 0.0945 |
| 3 | - | 0.2751 | - | 0.3151 | - | 0.1920 | 0.1682 | 0.1240 |
| 4 | - | 0.2721 | - | 0.2924 | 0.2286 | 0.1889 | 0.1564 | 0.1309 |
| 5 | - | 0.2782 | - | 0.2679 | 0.1949 | 0.1877 | 0.1729 | 0.1402 |
| 6 | - | 0.2645 | - | 0.2771 | 0.2567 | 0.2378 | 0.2113 | 0.1910 |

Table B.107. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 40°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4148 | - | 0.0550 | 0.0356 | 0.0089 | 0.0023 | 0.0050 |
| 0.5 | - | 0.3442 | - | 0.3290 | 0.1732 | 0.1090 | 0.0698 | 0.0335 |
| 1 | - | 0.3201 | - | 0.3083 | 0.2387 | 0.1362 | 0.0934 | 0.0668 |
| 2 | - | 0.3658 | - | 0.3810 | 0.2762 | 0.1978 | 0.1227 | 0.1247 |
| 3 | - | 0.3618 | - | 0.3667 | 0.3138 | 0.2374 | 0.2085 | 0.1597 |
| 4 | - | 0.3514 | - | 0.3463 | 0.2815 | 0.2525 | 0.2341 | 0.2316 |
| 5 | - | 0.2828 | - | 0.3330 | 0.2057 | 0.2484 | 0.2043 | 0.2255 |
| 6 | - | 0.2778 | - | 0.2896 | 0.2734 | 0.2534 | 0.2661 | 0.2438 |

Table B.108. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 40°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4191 | - | 0.0353 | 0.0117 | 0.0136 | 0.0078 | 0.0066 |
| 0.5 | - | 0.3922 | - | 0.3665 | 0.2728 | 0.1198 | 0.0734 | 0.0392 |
| 1 | - | 0.3852 | - | 0.3400 | 0.2499 | 0.1518 | 0.1036 | 0.0679 |
| 2 | - | 0.3475 | - | 0.3524 | 0.2494 | 0.1787 | 0.1467 | 0.1248 |
| 3 | - | 0.3475 | - | 0.3519 | 0.3088 | 0.2335 | 0.1858 | 0.1707 |
| 4 | - | 0.3486 | - | 0.3329 | 0.2700 | 0.2426 | 0.2186 | 0.2284 |
| 5 | - | 0.2889 | - | 0.3086 | 0.2723 | 0.2381 | 0.2391 | 0.2404 |
| 6 | - | 0.2798 | - | 0.3010 | 0.2934 | 0.2756 | 0.2642 | 0.2521 |

Table B.109. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 20% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.2805 | - | 0.0584 | 0.0255 | 0.0192 | 0.0234 | 0.0188 |
| 0.5 | - | 0.2288 | - | 0.1896 | 0.0734 | 0.0171 | 0.00743 | 0.0057 |
| 1 | - | 0.1695 | - | 0.2035 | 0.1687 | 0.0310 | 0.0056 | 0.0082 |
| 2 | - | 0.2009 | - | 0.1700 | 0.1112 | 0.0715 | 0.0185 | 0.0120 |
| 3 | - | 0.2134 | - | 0.2295 | 0.1648 | 0.1119 | 0.0856 | 0.0656 |
| 4 | - | 0.1559 | - | 0.2077 | 0.1438 | 0.1268 | 0.1073 | 0.0794 |
| 5 | - | 0.1471 | - | 0.1655 | 0.1195 | 0.1091 | 0.1196 | 0.0925 |
| 6 | - | 0.1518 | – | 0.1996 | 0.1619 | 0.1308 | 0.1048 | 0.1118 |

Table B.110. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 20% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | | 0.2457 | | 0.0461 | 0.0256 | 0.0195 | 0.0156 | 0.0147 |
| 0.5 | - | 0.2397 | - | 0.2490 | 0.1643 | 0.0932 | 0.0756 | 0.0521 |
| 1 | - | 0.2626 | - | 0.2445 | 0.1491 | 0.1124 | 0.0905 | 0.0730 |
| 2 | - | 0.2350 | - | 0.2459 | 0.1803 | 0.1498 | 0.1122 | 0.1035 |
| 3 | - | 0.2354 | - | 0.2629 | 0.2046 | 0.1707 | 0.1366 | 0.1366 |
| 4 | - | 0.2266 | - | 0.2224 | 0.2092 | 0.1895 | 0.1510 | 0.1525 |
| 5 | - | 0.1827 | - | 0.2105 | 0.1766 | 0.1527 | 0.1410 | 0.1536 |
| 6 | - | 0.1945 | - | 0.2056 | 0.1934 | 0.1845 | 0.1823 | 0.1689 |

Table B.111 Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 31% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4488 | - | 0.0704 | 0.0153 | 0.0167 | 0.0058 | 0.0045 |
| 0.5 | - | 0.4264 | | 0.4170 | 0.3267 | 0.1473 | 0.0657 | 0.0366 |
| 1 | - | 0.4084 | - | 0.3756 | 0.2967 | 0.1386 | 0.0945 | 0.0576 |
| 2 | - | 0.3439 | - | 0.3229 | 0.2492 | 0.1642 | 0.1320 | 0.1011 |
| 3 | - | 0.3479 | - | 0.3977 | 0.2872 | 0.2392 | 0.1490 | 0.1443 |
| 4 | - | 0.3095 | - | 0.3475 | 0.2808 | 0.2509 | 0.1959 | 0.1825 |
| 5 | - | 0.3263 | - | 0.2888 | 0.2550 | 0.2260 | 0.2099 | 0.1941 |
| 6 | - | 0.3398 | - | 0.3678 | 0.3220 | 0.2796 | 0.2418 | 0.2296 |

Table B.112. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 31% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.3329 | - | 0.0460 | 0.0367 | 0.0119 | 0.0056 | 0.0032 |
| 0.5 | - | 0.2890 | - | 0.2608 | 0.1998 | 0.0813 | 0.0416 | 0.0213 |
| 1 | - | 0.2611 | - | 0.2485 | 0.1544 | 0.0940 | 0.0526 | 0.0387 |
| 2 | - | 0.2307 | - | 0.2337 | 0.1437 | 0.1077 | 0.0910 | 0.0695 |
| 3 | - | 0.2318 | - | 0.2255 | 0.1876 | 0.1425 | 0.1175 | 0.0920 |
| 4 | - | 0.2289 | - | 0.2188 | 0.1854 | 0.1465 | 0.1226 | 0.1256 |
| 5 | - | 0.2039 | - | 0.1813 | 0.1703 | 0.1606 | 0.1553 | 0.1341 |
| 6 | - | - | - | - | - | - | - | - |

Table B.113. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 40C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | - | 0.4811 | - | 0.0714 | 0.0123 | 0.0063 | 0.0043 | 0.0034 |
| 0.5 | - | 0.3986 | - | 0.4364 | 0.3723 | 0.1341 | 0.0834 | 0.0266 |
| 1 | - | 0.3976 | - | 0.3858 | 0.3119 | 0.1679 | 0.1232 | 0.0704 |
| 2 | - | 0.3656 | - | 0.3293 | 0.3000 | 0.1902 | 0.1457 | 0.1194 |
| 3 | - | 0.4020 | - | 0.3822 | 0.3025 | 0.1848 | 0.1813 | 0.1702 |
| 4 | - | 0.3799 | - | 0.3516 | 0.3105 | 0.2701 | 0.2202 | 0.2213 |
| 5 | - | 0.3123 | - | 0.3085 | 0.3212 | 0.2490 | 0.2365 | 0.1959 |
| 6 | - | 0.3065 | - | 0.3028 | 0.3219 | 0.2723 | 0.2634 | 0.2013 |

Table B.114. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; horizontal direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | -. | 0.3469 | - | 0.0564 | 0.0312 | 0.0112 | 0.0045 | 0.0047 |
| 0.5 | - | 0.3473 | - | 0.3280 | 0.2798 | 0.1280 | 0.0745 | 0.0269 |
| 1 | - | 0.3670 | - | 0.3785 | 0.2558 | 0.1689 | 0.1045 | 0.0741 |
| 2 | - | 0.3577 | - | 0.3300 | 0.3086 | 0.1919 | 0.1732 | 0.1442 |
| 3 | - | 0.3416 | - | 0.3691 | 0.2630 | 0.1859 | 0.1966 | 0.1924 |
| 4 | - | 0.3483 | - | 0.3304 | 0.2975 | 0.2508 | 0.2108 | 0.2226 |
| 5 | - | 0.2923 | - | 0.2902 | 0.2958 | 0.2489 | 0.2436 | 0.1943 |
| 6 | - | 0.2843 | - | 0.2927 | 0.2945 | 0.2734 | 0.2531 | 0.2120 |

able B.115. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 8.0% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4225 | - | - | 0.0562 | 0.0099 | 0.0045 | 0.0028 | - |
| 0.5 | 0.3612 | - | - | 0.3166 | 0.2006 | 0.0743 | 0.0381 | 0.0170 |
| 1 | 0.3292 | - | - | 0.3452 | 0.2314 | 0.1529 | 0.0978 | 0.0579 |
| 2 | 0.3519 | - | - | 0.3383 | 0.2371 | 0.2000 | 0.1489 | 0.1056 |
| 3 | 0.3928 | - | - | 0.3524 | 0.3037 | 0.2134 | 0.1854 | 0.1495 |
| 4 | 0.3033 | - | - | 0.3494 | 0.2580 | 0.2385 | 0.1986 | 0.1782 |
| 5 | 0.2771 | - | - | 0.3291 | 0.2825 | 0.2292 | 0.2191 | 0.1476 |
| 6 | 0.2931 | - | - | 0.3215 | 0.2615 | 0.1883 | 0.1855 | 0.1631 |

Table B.116. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through side door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3595 | - | - | 0.0684 | 0.0275 | 0.0106 | 0.0036 | 0.0020 |
| 0.5 | 0.3302 | - | - | 0.2890 | 0.1935 | 0.0816 | 0.0395 | 0.0216 |
| 1 | 0.3249 | - | - | 0.3232 | 0.2437 | 0.1252 | 0.0908 | 0.0625 |
| 2 | 0.2765 | - | - | 0.2675 | 0.2378 | 0.1768 | 0.1577 | 0.1323 |
| 3 | 0.2386 | - | - | 0.2636 | 0.2350 | 0.1560 | 0.1569 | 0.1671 |
| 4 | 0.2289 | - | | 0.2244 | 0.2023 | 0.2111 | 0.1843 | 0.1864 |
| 5 | 0.2184 | - | - | 0.2099 | 0.2119 | 0.1876 | 0.1797 | 0.1723 |
| 6 | 0.1935 | - | - | 0.2026 | 0.1920 | 0.1505 | 0.1664 | 0.1727 |

Table B.117. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 31% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3916 | - | - | 0.1304 | 0.0382 | 0.0299 | 0.0301 | 0.0306 |
| 0.5 | 0.4072 | - | - | 0.3521 | 0.2634 | 0.1360 | 0.0923 | 0.0530 |
| 1 | 0.3898 | - | - | 0.3574 | 0.2516 | 0.1585 | 0.1121 | 0.0757 |
| 2 | 0.3451 | - | - | 0.3092 | 0.2841 | 0.1679 | 0.1135 | 0.0826 |
| 3 | 0.2836 | - | - | 0.3566 | 0.2511 | 0.1573 | 0.1282 | 0.0976 |
| 4 | 0.3268 | - | - | 0.2699 | 0.2746 | 0.2008 | 0.1915 | 0.1770 |
| 5 | 0.2894 | - | - | 0.2940 | 0.2539 | 0.2199 | 0.1722 | 0.1659 |
| 6 | 0.2934 | - | - | 0.2967 | 0.2845 | 0.2566 | 0.2110 | 0.2001 |

Table B.118. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; downward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4294 | - | - | 0.1000 | 0.0683 | 0.0375 | 0.0112 | 0.0056 |
| 0.5 | 0.3772 | - | - | 0.3423 | 0.1587 | 0.0409 | 0.0056 | 0.0080 |
| 1 | 0.4119 | - | - | 0.3811 | 0.2160 | 0.1048 | 0.0272 | 0.0400 |
| 2 | 0.3481 | - | - | 0.3310 | 0.2671 | 0.1829 | 0.0976 | 0.0812 |
| 3 | 0.3460 | - | - | 0.3616 | 0.2995 | 0.1584 | 0.1234 | 0.1297 |
| 4 | 0.3460 | - | - | 0.3526 | 0.2790 | 0.1889 | 0.1872 | 0.1609 |
| 5 | 0.3068 | - | - | 0.3321 | 0.2629 | 0.1841 | 0.1648 | 0.1389 |
| 6 | - | - | - | - | - | - | - | - |

Table B.119. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through side door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4698 | - | - | 0.0821 | 0.0247 | 0.0123 | 0.0078 | 0.0048 |
| 0.5 | 0.4970 | - | - | 0.2890 | 0.4000 | 0.3287 | 0.1927 | 0.0484 |
| 1 | 0.4337 | - | - | 0.3285 | 0.2712 | 0.2530 | 0.1723 | 0.0927 |
| 2 | - | - | - | - | - | - | - | - |
| 3 | 0.2892 | - | - | 0.3465 | 0.2808 | 0.1861 | 0.1700 | 0.1474 |
| 4 | 0.3821 | - | | 0.3849 | 0.3321 | 0.2266 | 0.2208 | 0.1869 |
| 5 | 0.2723 | - | - | 0.2507 | 0.2425 | 0.2020 | 0.1781 | 0.1226 |
| 6 | 0.2634 | - | - | 0.2797 | 0.2634 | 0.2523 | 0.2212 | 0.2045 |

Table B.120. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through side door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4400 | - | | 0.0464 | 0.0412 | 0.0079 | 0.0023 | 0.0042 |
| 0.5 | 0.4517 | - | - | 0.4126 | 0.2812 | 0.1656 | 0.0875 | 0.0302 |
| 1 | 0.4078 | - | - | 0.4037 | 0.2768 | 0.1761 | 0.1200 | 0.0881 |
| 2 | 0.3617 | - | - | 0.3326 | 0.3455 | 0.2504 | 0.1722 | 0.1108 |
| 3 | 0.3147 | - | - | 0.2396 | 0.2538 | 0.2027 | 0.1956 | 0.2156 |
| 4 | 0.3887 | - | - | 0.3239 | 0.3285 | 0.2479 | 0.251637 | 0.2378 |
| 5 | 0.3199 | - | - | 0.2958 | 0.3150 | 0.2420 | 0.219594 | 0.1453 |
| 6 | 0.3110 | - | - | 0.3029 | 0.3076 | 0.2944 | 0.2534 | 0.2015 |

Table B.121. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 5°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3937 | - | - | 0.0710 | 0.0421 | 0.0117 | 0.0067 | 0.0021 |
| 0.5 | 0.2782 | - | - | 0.3456 | 0.2631 | 0.1031 | 0.0634 | 0.0215 |
| 1 | 0.3283 | - | - | 0.2651 | - | 0.1202 | - | 0.0382 |
| 2 | 0.3391 | - | - | 0.2952 | 0.2304 | 0.1262 | 0.0765 | 0.0462 |
| 3 | 0.3446 | - | - | 0.3669 | 0.2516 | 0.1261 | 0.1098 | 0.0831 |
| 4 | 0.3549 | - | - | 0.2886 | 0.2429 | 0.1593 | 0.1223 | 0.0982 |
| 5 | 0.3255 | - | - | 0.2453 | 0.1288 | 0.1923 | 0.1195 | 0.0953 |
| 6 | 0.3187 | - | - | 0.2856 | 0.2991 | 0.2534 | 0.1923 | 0.1523 |

Table B.122. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 15°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3976 | - | - | 0.0564 | 0.0367 | 0.0099 | 0.0047 | 0.0041 |
| 0.5 | 0.3688 | - | - | 0.3551 | 0.2318 | 0.1078 | 0.0610 | 0.0210 |
| 1 | 0.4277 | - | - | 0.3421 | 0.2452 | 0.1376 | 0.0856 | 0.0586 |
| 2 | 0.3335 | - | - | 0.2972 | 0.2423 | 0.1651 | 0.1309 | 0.0741 |
| 3 | 0.3199 | - | - | 0.3375 | 0.2494 | 0.1486 | 0.1689 | 0.1513 |
| 4 | 0.3440 | - | | 0.2957 | 0.2463 | 0.1893 | 0.1801 | 0.1867 |
| 5 | 0.2943 | - | - | 0.2793 | 0.1926 | 0.1901 | 0.1724 | 0.1420 |
| 6 | - | - | - | - | - | - | - | - |

Table B.123. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3784 | - | | 0.04574 1 | 0.00331 2 | 0.0243 | 0.0017 | 0.002849 |
| 0.5 | 0.1974 | - | - | 0.2834 | - | 0.0948 | - | 0.0308 |
| 1 | 0.2136 | - | - | 0.2414 | - | 0.1228 | - | 0.0547 |
| 2 | 0.1540 | - | - | 0.2225 | 0.1710 | 0.1461 | 0.1120 | 0.0671 |
| 3 | 0.1735 | - | - | 0.2528 | 0.2283 | 0.1718 | 0.1434 | 0.1212 |
| 4 | 0.2399 | - | - | 0.2351 | 0.1995 | 0.1667 | 0.1458 | 0.1341 |
| 5 | 0.1845 | - | - | 0.1917 | 0.1289 | 0.1624 | 0.1028 | 0.0947 |
| 6 | 0.1923 | - | - | 0.1929 | 0.1723 | 0.1721 | 0.1623 | 0.1521 |

Table B.124. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4508 | - | - | 0.1873 | 0.0812 | 0.0127 | 0.0088 | 0.0023 |
| 0.5 | 0.3077 | - | - | 0.3837 | 0.2319 | 0.0972 | 0.0612 | 0.0214 |
| 1 | 0.4009 | - | - | 0.3285 | 0.2296 | 0.1260 | 0.0715 | 0.0438 |
| 2 | - | - | - | - | - | - | - | - |
| 3 | 0.3586 | - | - | 0.3552 | 0.3430 | 0.1803 | 0.1453 | 0.1291 |
| 4 | 0.3476 | - | - | 0.3018 | 0.2438 | 0.1774 | 0.1731 | 0.1469 |
| 5 | 0.3219 | - | - | 0.2276 | 0.2276 | 0.1785 | 0.1272 | 0.0753 |
| 6 | 0.3056 | - | - | 0.3019 | 0.3001 | 0.2612 | 0.2059 | 0.1421 |

Table B.125. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 31% porosity; filled through top door; 40% initial concentration; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3976 | - | - | 0.0564 | 0.0428 | 0.0099 | 0.0056 | 0.0041 |
| 0.5 | 0.3688 | - | - | 0.3551 | - | 0.1078 | - | 0.0210 |
| 1 | 0.4277 | - | - | 0.3421 | 0.2452 | 0.1376 | 0.0856 | 0.0586 |
| 2 | 0.3335 | - | - | 0.2972 | 0.2423 | 0.1651 | 0.1309 | 0.0741 |
| 3 | 0.3199 | - | - | 0.3375 | 0.2494 | 0.1486 | 0.1689 | 0.1513 |
| 4 | 0.3440 | - | | 0.2957 | 0.2463 | 0.1893 | 0.1801 | 0.1867 |
| 5 | 0.2943 | - | - | 0.2793 | 0.1926 | 0.1901 | 0.1724 | 0.1420 |
| 6 | 0.2978 | - | - | 0.2956 | 0.2331 | 0.2319 | 0.2110 | 0.2006 |

Table B.126. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3786 | - | | 0.0457 | 0.0033 | 0.0243 | 0.0017 | 0.0028 |
| 0.5 | 0.1974 | - | - | 0.2834 | - | 0.0948 | - | 0.0308 |
| 1 | 0.2136 | - | - | 0.2414 | 0.1829 | 0.1228 | 0.8521 | 0.0547 |
| 2 | 0.1542 | - | - | 0.2225 | 0.1710 | 0.1461 | 0.1120 | 0.0671 |
| 3 | 0.1735 | - | - | 0.2528 | 0.2283 | 0.1718 | 0.1434 | 0.1212 |
| 4 | 0.2399 | - | - | 0.2351 | 0.1995 | 0.1667 | 0.1458 | 0.1341 |
| 5 | 0.1845 | - | - | 0.1917 | 0.1289 | 0.1624 | 0.1028 | 0.0947 |
| 6 | 0.1829 | - | - | 0.1889 | 0.1712 | 0.1729 | 0.1528 | 0.1498 |

Table B.127. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; horizontal direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4225 | - | - | 0.0562 | 0.0099 | 0.0045 | 0.0028 | 0.0021 |
| 0.5 | 0.3612 | - | - | 0.3166 | 0.2006 | 0.0743 | 0.0381 | 0.0170 |
| 1 | 0.3292 | - | - | 0.3452 | 0.2314 | 0.1529 | 0.0978 | 0.0579 |
| 2 | 0.3519 | - | - | 0.3383 | 0.2371 | 0.2000 | 0.1489 | 0.1056 |
| 3 | 0.3928 | - | - | 0.3524 | 0.3037 | 0.2134 | 0.1854 | 0.1495 |
| 4 | 0.3033 | - | - | 0.3494 | 0.2580 | 0.2385 | 0.1986 | 0.1782 |
| 5 | 0.2771 | - | - | 0.3291 | 0.2825 | 0.2292 | 0.2191 | 0.1476 |
| 6 | 0.2931 | - | - | 0.3215 | 0.2615 | 0.1883 | 0.1855 | 0.1631 |

Table B.128. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; downward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3595 | - | - | 0.0684 | 0.0275 | 0.0106 | 0.0036 | 0.0020 |
| 0.5 | 0.3302 | - | - | 0.2890 | 0.1935 | 0.0816 | 0.0395 | 0.0216 |
| 1 | 0.3249 | - | - | 0.3232 | 0.2437 | 0.1252 | 0.0908 | 0.0625 |
| 2 | 0.2765 | - | - | 0.2675 | 0.2378 | 0.1768 | 0.1577 | 0.1323 |
| 3 | 0.2386 | - | - | 0.2636 | 0.2350 | 0.1560 | 0.1569 | 0.1671 |
| 4 | 0.2289 | - | | 0.2244 | 0.2023 | 0.2111 | 0.1843 | 0.1864 |
| 5 | 0.2184 | - | - | 0.2099 | 0.2119 | 0.1876 | 0.1797 | 0.1723 |
| 6 | 0.1935 | - | - | 0.2026 | 0.1920 | 0.1505 | 0.1664 | 0.1727 |

Table B.129. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; horizontal direction of flow; 34% porosity; filled through top door; 40% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3916 | - | | 0.1304 | 0.0382 | 0.0299 | 0.0301 | 0.0306 |
| 0.5 | 0.4072 | - | - | 0.3521 | - | 0.1360 | - | 0.0530 |
| 1 | 0.3898 | - | - | 0.3574 | - | 0.1585 | - | 0.0757 |
| 2 | 0.3451 | - | - | 0.3092 | 0.2841 | 0.1679 | 0.1135 | 0.0826 |
| 3 | 0.2836 | - | - | 0.3566 | 0.2511 | 0.1573 | 0.1282 | 0.0976 |
| 4 | 0.3268 | - | - | 0.2699 | 0.2746 | 0.2008 | 0.1915 | 0.1770 |
| 5 | 0.2894 | - | - | 0.2940 | 0.2539 | 0.2199 | 0.1722 | 0.1659 |
| 6 | 0.2845 | - | - | 0.3012 | 0.2734 | 0.2634 | 0.2149 | 0.2068 |

Table B.130. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 20% initial concentration; and no dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| h | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.2231 | 0.2421 | - | 0.0421 | 0.0223 | 0.0195 | 0.0152 | 0.0147 |
| 0.5 | 0.2356 | 0.2391 | - | 0.2414 | 0.1821 | 0.0932 | 0.0423 | 0.0521 |
| 1 | 0.2549 | 0.2621 | - | 0.2423 | 0.1491 | 0.1124 | 0.0914 | 0.0728 |
| 2 | 0.2498 | 0.2351 | - | 0.2434 | 0.1803 | 0.1498 | 0.1122 | 0.1026 |
| 3 | 0.2391 | 0.2352 | - | 0.2627 | 0.2046 | 0.1707 | 0.1367 | 0.1364 |
| 4 | 0.2285 | 0.2263 | - | 0.2222 | 0.2092 | 0.1895 | 0.1527 | 0.1521 |
| 5 | 0.1918 | 0.1821 | - | 0.2112 | 0.1821 | 0.1527 | 0.1413 | 0.1528 |
| 6 | 0.1721 | 0.1735 | - | 0.1821 | 0.1723 | 0.1698 | 0.1674 | 0.1593 |

Table B.131. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 4% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4108 | 0.4234 | - | 0.0873 | 0.0521 | 0.0127 | 0.0087 | 0.0087 |
| 0.5 | 0.4077 | 0.4172 | - | 0.3837 | 0.2432 | 0.0972 | 0.0532 | 0.0314 |
| 1 | 0.4019 | 0.4128 | - | 0.3285 | 0.2296 | 0.1260 | 0.0715 | 0.0638 |
| 2 | 0.3725 | 0.3843 | - | 0.3112 | 0.2854 | 0.1632 | 0.0932 | 0.0898 |
| 3 | 0.3556 | 0.3665 | - | 0.3552 | 0.3430 | 0.1803 | 0.1453 | 0.1291 |
| 4 | 0.3286 | 0.3356 | - | 0.3018 | 0.2438 | 0.1774 | 0.1731 | 0.1469 |
| 5 | 0.3178 | 0.3231 | - | 0.2276 | 0.2276 | 0.1785 | 0.1672 | 0.1753 |
| 6 | 0.3008 | 0.3007 | - | 0.2664 | 0.2443 | 0.2532 | 0.2312 | 0.2219 |

Table B.132. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 8% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3645 | 0.3754 | - | 0.0674 | 0.0235 | 0.0122 | 0.0026 | 0.0022 |
| 0.5 | 0.3292 | 0.3387 | - | 0.2847 | 0.1955 | 0.0817 | 0.0385 | 0.0217 |
| 1 | 0.3159 | 0.3213 | - | 0.3262 | 0.2477 | 0.1255 | 0.0918 | 0.0623 |
| 2 | 0.2567 | 0.2617 | - | 0.2845 | 0.2358 | 0.1764 | 0.1537 | 0.1325 |
| 3 | 0.2312 | 0.2846 | - | 0.2456 | 0.2370 | 0.1563 | 0.1559 | 0.1632 |
| 4 | 0.2218 | 0.2519 | | 0.2234 | 0.2063 | 0.2112 | 0.1853 | 0.1865 |
| 5 | 0.2167 | 0.2363 | - | 0.2179 | 0.2139 | 0.1871 | 0.1787 | 0.1722 |
| 6 | 0.1935 | 0.2012 | - | 0.2036 | 0.1922 | 0.1501 | 0.1634 | 0.1717 |

Table B.133. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.3575 | 0.3441 | - | 0.0664 | 0.0255 | 0.0116 | 0.0046 | 0.0034 |
| 0.5 | 0.3322 | 0.3387 | - | 0.2870 | 0.1945 | 0.0826 | 0.0385 | 0.0227 |
| 1 | 0.3239 | 0.3301 | - | 0.3252 | 0.2477 | 0.1232 | 0.0918 | 0.0678 |
| 2 | 0.2785 | 0.2698 | - | 0.2685 | 0.2328 | 0.1778 | 0.1557 | 0.1341 |
| 3 | 0.2356 | 0.2421 | - | 0.2626 | 0.2360 | 0.1550 | 0.1549 | 0.1654 |
| 4 | 0.2299 | 0.2302 | | 0.2224 | 0.2083 | 0.2121 | 0.1823 | 0.1865 |
| 5 | 0.2174 | 0.2108 | - | 0.2079 | 0.2129 | 0.1856 | 0.1787 | 0.1725 |
| 6 | 0.1925 | 0.2023 | - | 0.2016 | 0.1960 | 0.1515 | 0.1654 | 0.1727 |

Table B.134. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture content; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4076 | 0.4041 | - | 0.0632 | 0.0276 | 0.0146 | 0.0039 | 0.0024 |
| 0.5 | 0.3723 | 0.3788 | - | 0.3340 | 0.2045 | 0.0926 | 0.0583 | 0.0327 |
| 1 | 0.3537 | 0.3502 | - | 0.3252 | 0.2477 | 0.1232 | 0.0919 | 0.0693 |
| 2 | 0.2983 | 0.2997 | - | 0.2685 | 0.2328 | 0.1778 | 0.1558 | 0.1342 |
| 3 | 0.2658 | 0.2623 | - | 0.2626 | 0.2360 | 0.1550 | 0.1547 | 0.1657 |
| 4 | 0.2594 | 0.2506 | - | 0.2224 | 0.2083 | 0.2121 | 0.1821 | 0.1864 |
| 5 | 0.2472 | 0.2405 | - | 0.2079 | 0.2129 | 0.1856 | 0.1787 | 0.1739 |
| 6 | 0.2329 | 0.2322 | - | 0.2216 | 0.2060 | 0.1915 | 0.1854 | 0.1873 |

Table B.135. Measured carbon dioxide concentrations (mole fraction) in the diffusion cell filled with canola for the following experimental conditions: 10.5% moisture; 25°C; upward direction of flow; 34% porosity; filled through top door; 40% initial concentration; and 12% dockage.

| Time | Gas chamber | | | Grain chamber | | | | |
|---|---|---|---|---|---|---|---|---|
| (h) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 0 | 0.4595 | - | 0.4426 | 0.0684 | 0.0275 | 0.0106 | 0.0036 | 0.0020 |
| 0.5 | 0.4302 | - | 0.4521 | 0.3890 | 0.2935 | 0.1816 | 0.1395 | 0.1216 |
| 1 | 0.4249 | - | 0.4198 | 0.4032 | 0.3437 | 0.2252 | 0.1908 | 0.1625 |
| 2 | 0.3765 | - | 0.3987 | 0.3675 | 0.3378 | 0.2768 | 0.2577 | 0.2323 |
| 3 | 0.3386 | - | 0.3772 | 0.3636 | 0.3350 | 0.2560 | 0.2569 | 0.2671 |
| 4 | 0.3289 | - | 0.3421 | 0.3244 | 0.3023 | 0.3111 | 0.2843 | 0.2864 |
| 5 | 0.3184 | - | 0.3287 | 0.3099 | 0.3119 | 0.2876 | 0.2797 | 0.2723 |
| 6 | 0.2935 | - | 0.2987 | 0.3026 | 0.2920 | 0.2654 | 0.2664 | 0.2727 |