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Measurement and Prediction of the Airflow Caused by Free-Convection in Stored Grain

by

Michael P. Booy

A thesis

presented to the University of Manitoba

in partial fulfillment of the

requirements for the degree of

Master of Science

in

the Department of Agricultural Engineering

Winnipeg, Manitoba

1985

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a Master's thesis entitled: Measurement and prediction of the airflow caused by free convection in stored grain

submitted by Michael Philip Booy

in partial fulfilment of the requirements for the degree of Master of Science

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Date 5 September 1985 ....

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MEASUREMENT AND PREDICTION OF THE AIRFLOW CAUSED BY FREE-CONVECTION IN STORED GRAIN

BY

MICHAEL P. BOOY

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

The purpose of this research was to develop a method of predicting the rate of free-convective air movement through stored grain. Predictions were based on the temperature difference within the grain and on an empirical equation relating pressure gradient to airflow through grain. The method of prediction was verified by comparing predicted airflow rates to airflow rates measured using a tracer gas in a closed loop laboratory apparatus. The airflows were measured in wheat having porosities of 44 and 47% and in rapeseed having a porosity of 44%, for temperature differences which ranged from 10 to 45°C. Airflow rates ranged from 0.000057 to 0.00033 $(m^3/s)/m^2$. The predicted airflow rates ranged from 0.000022 $(m^3/s)/m^2$ lower than measured airflow rates to 0.00007 $(m^3/s)/m^2$ higher than measured airflow rates. The disagreement between measured and predicted airflow rates was greatest at the low airflow rates, but, the method of prediction was suitable for estimating the higher airflow rates. It was concluded that this method was not suitable for predicting airflow rates in actual storage bins since more research is required concerning the resistance of grain to low airflows, the effects of variable airflow resistance within bins and the effects of wind pressure on the airflow patterns within the bin.

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ACKNOWLEDGEMENTS

I would like to acknowledge the patience and support of my family during the writing of this thesis. I would also like to acknowledge the support of Mr. and Mrs. I. Cruson and thank them for providing the time required to finish the work. I would also like to thank Anita for helping with the typing.

1. INTRODUCTION

1.1 Subject

The subject of this thesis is the investigation of free-convection heat transfer in stored grain. Convection is the transfer of heat in a gas or a liquid resulting from unequal temperatures and consequent unequal densities (Funk and Wagnalls 1980). Convective heat transfer in stored grain is considered to be the primary cause of moisture migration from warmer to colder regions of the bin (Friesen et al. 1982). The migration of moisture within a grain mass removes small amounts of water from a large part of the grain and deposits the water in small regions, thereby forming pockets of damp grain (Stewart 1975). These pockets of damp grain are primary locations for spoilage to start. The amount of moisture migration is a function of time and the rate at which air in the bin is circulated by convection currents. This thesis investigates the rate of air movement in stored grain resulting from free-convection heat transfer.

In particular, this project examines the rate at which convection currents circulate air through grain and its relationship to the forces that drive and resist that air movement. The driving force behind convective heat transfer arises from the temperature difference between the cold and warm regions of the bin. The force that resists the air movement is the friction between the air and the grain which results from the reduction in the area of the passage through which the air flows; this resistance force can be described by the permeability of the grain mass. The purpose of this thesis is to determine the relationship between the rate of air movement, the temperature difference

causing convection and the permeability of the grain.

1.2 Mechanism of Moisture Migration

To understand how moisture migration occurs, it is necessary to first examine the grain storage practices of western Canada. Grain is usually harvested shortly after reaching maturity in late August or early September. The temperature of the harvested grain is approximately equal to or greater than the ambient air temperature when harvesting occurs. In a study conducted in Manitoba, the grain temperature at harvest was found to be 5 to 8°C above the ambient air temperature when harvesting was done on a sunny day (Prasad et al. 1978). Thus, when grain is placed in storage, its temperature is usually between 25 and 35°C. The grain storage structures commonly in use for on-farm storage are circular corrugated steel bins, having volumes that range from 50 to 1000 m^3. These bins are filled in the fall and usually remain filled until the following spring or summer. The low ambient temperatures that accompany winter create temperature differences between the grain and the surrounding air (Figure 1). Heat transfer through the grain is slow; so, for many months, the grain near the center of the bin remains at the temperature at which it was when placed in the bin. The grain near the walls, floor and grain surface, cool faster because it is in contact with the bin walls, floor or headspace air, and within a few weeks comes into equilibrium with the ambient air temperature. Thus, by December or January, when the ambient temperature is approximately -20°C the temperature differences within the bin may be 40 to 50°C.

The temperature differences within the grain mass cause convec-

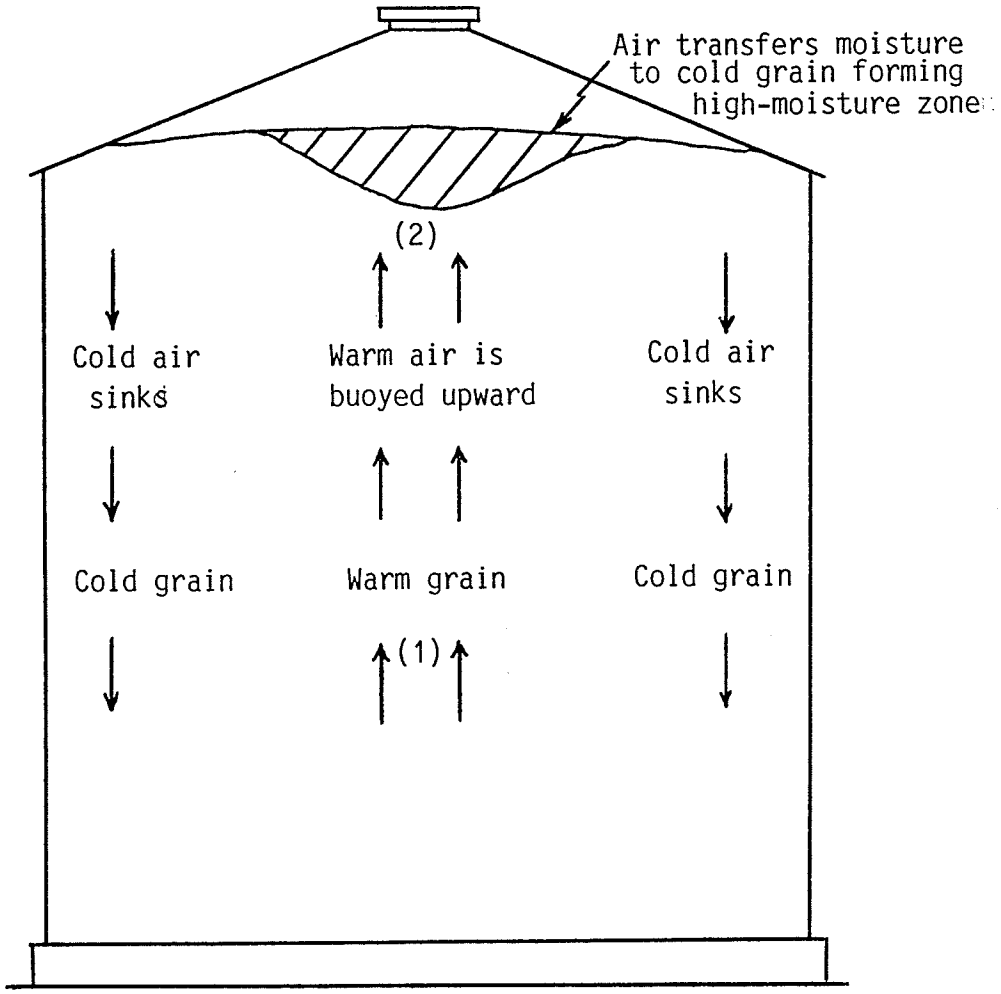

FIGURE 1: Presumed pattern of convection currents in a grain bin during winter with resulting moisture migration (Friesen et al. 1982).

tive heat transfer within the grain bin. A grain mass is porous; the spaces between the kernels occupied by air. This intergranular air is in equilibrium with the grain temperature and moisture content. The cold dense air near the bin walls tends to sink, while the less dense warm air in the center of the bin is buoyed upward, thus creating convective air currents. The air movement transfers heat from the center of the bin, but because air has a low specific heat and the rate of air movement is slow, the quantity of heat transferred by convection is insignificant compared with that transferred by conduction (Scott and Shipp 1973).

The convective circulation of air in a bin provides the primary mechanism for moisture movement in large grain storage structures (Stewart 1975). The relative humidity of the intergranular air is a function of the grain temperature and moisture content. Consider the intergranular air near the center of the bin in Figure 1. It is assumed that the equilibrium relative humidity of the grain at (1) is 70%. The convective heat transfer causes the air at (1) to move to (2) where it comes into contact with the colder grain. The heat transfer from the warm air to the grain reduces the air temperature and causes a vapour pressure difference between the air and the surrounding grain. This vapour pressure difference is shown by an increase in relative humidity on the psychrometric chart in Figure 2. For the previously warm air to reach vapour pressure equilibrium with the grain, moisture must be transferred from the air to the grain (Figure 2). This process continues until the air reaches equilibrium with its surroundings. Although this process is shown in large, discrete steps for the purpose of explanation, the process is a continuous one; the heat and

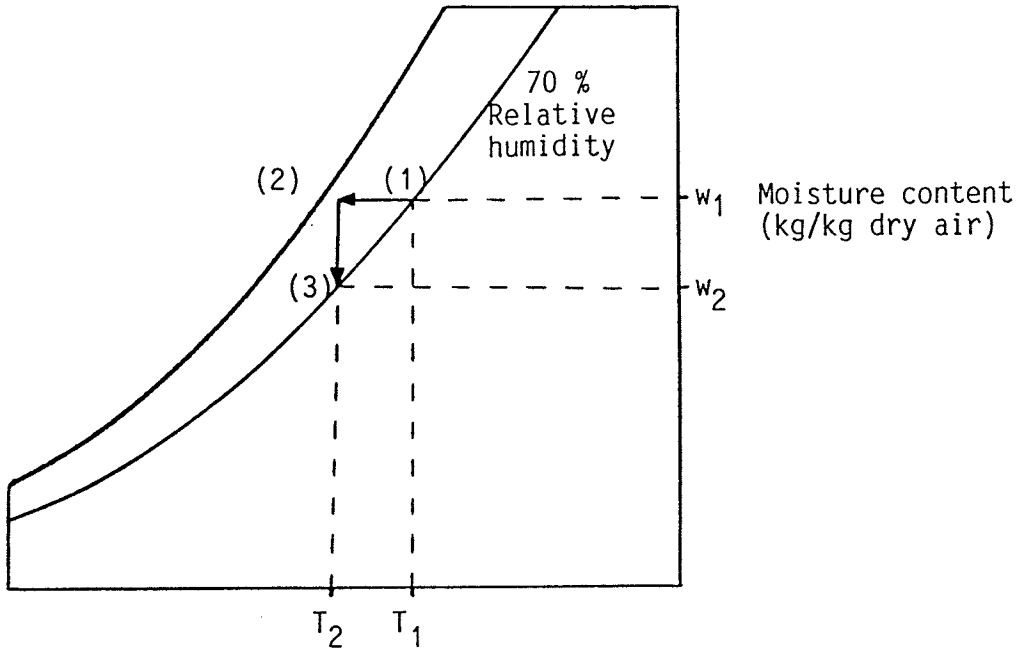

FIGURE 2: Psychrometric chart: Air at (1) arrives at (2) when heat loss from the air results in a temperature drop (T_1-T_2) and a consequent increase in relative humidity. Air at (2) arrives at (3) by releasing moisture (w_1-w_2).

moisture transfer is gradual and probably proceeds along the 70% relative humidity line from point (1) to point (3). This process, carried on over a long period of time, results in the development of regions of high-moisture grain where the warm air from a convective cell flows into cooler grain.

Grain which is initially at a moisture content low enough to be stored safely, may develop pockets of spoiled grain as a result of moisture migration (Greig and Matouk 1977). Spoilage results from the interaction of certain physical, chemical and biological variables. Important variables are: grain temperature, grain moisture content, physical properties of the grain, oxygen concentrations, microorganisms, insects, mites, rodents, birds, climatic conditions and characteristics of the storage facility. These variables interact either alone or in groups with the grain to cause spoilage (Sinha and Wallace 1979). Moisture migration may lead to spoilage in the following way: grain is placed in a steel bin after harvest, its moisture content is uniform at 14% and the average temperature is 30°C. As winter comes, temperature differences are established within the bin and convective air currents cause moisture to migrate to the top of the bin. The formation of a region of damp grain allows the development of specialized microorganisms that are able to function at low temperatures and high relative humidities. As they grow and reproduce, these microorganisms generate heat; this heat generation raises the temperature of the grain to levels where other microorganisms, mites and insects can become active. These organisms, in turn cause grain spoilage. Thus, grain can spoil as a result of moisture migration.

1.3 Previous Investigations Into Moisture Migration

The mathematical models developed to simulate moisture migration resulting from convective heat transfer are not completely satisfactory. A model developed to predict moisture and temperature distributions in stored corn by Williams (1973) provided predictions that were only approximately correct. It was concluded that more knowledge concerning the physical properties of the grain along with an expanded knowledge of the patterns and magnitudes of the free-convection airflow was required to permit a more precise determination of the moisture migration. In another model (Scott and Shipp 1973), temperature and moisture variations in stored grain were predicted fairly accurately, but the simulation of vapour transport required closer specification. Greig and Matouk (1977) indicated that their model lacked data to support the approximate values used and suggested that future work concentrate on providing information on grain properties and on airflow rates caused by convection. A paper by Fraser et al. (1980) described two-dimensional heat transfer in grain bins. A finite-difference model was developed to simulate the conductive heat transfer in both the radial and vertical directions in cylindrical bins. The model was verified by comparing the predicted temperatures to actual measurements. The inclusion of a model of convective heat transfer did not improve the accuracy of the temperature predictions and caused the amount of moisture migration to be over-estimated. It was concluded that under the conditions of the experiment, free-convection was not important in transferring either heat or moisture.

One of the causes of inaccuracy in the previously mentioned models may be the lack of information about the airflow rate through

grain resulting from temperature differences within the bin. Accurate predictions of moisture migration require accurate estimates of the convective airflow rate since the rate of convective heat and mass transfer depends upon the heat and mass transfer coefficients respectively and both these coefficients are a function of the airflow rate (Wang et al. 1979).

1.4 Objectives

The objective of this research was to improve the accuracy with which moisture migration might be predicted by developing a method of predicting the rate of convective air movement in stored grain from the temperature difference within the grain and the resistance of the grain to airflow. Temperature differences and the resistances of grain to airflow were measured in a laboratory apparatus to provide the information required for predicting the airflows. The method of prediction was verified by measuring the airflow in the apparatus directly using carbon dioxide as a gaseous tracer. Having measured the airflow rate for several temperature differences, grain permeabilities and grain types, an additional objective of this research was to develop a method of predicting the rate of air movement resulting from convection for situations normally occurring in grain storage.

The importance of this research will be in the application of this method of prediction to mathematical models of free-convection heat and moisture transfer. As discussed previously, most attempts to model the process of moisture migration have failed to provide satisfactory results. One of the problems with these models was the lack of information on the magnitudes of convective airflow rates. This research is

important since it provides quantitative information concerning the rate of air movement resulting from convection. This information will also be useful in predicting the effects of convection currents on the movement of fumigants, carbon dioxide and other gases in stored grain.

2. LITERATURE REVIEW

2.1 Moisture Migration In Stored Grain

In 1941 the formation of pockets of damp grain within dry wheat stored in country elevator annexes was reported in western Canada. Grain which was initially uniformly dry was placed into storage in the fall, but by spring a layer of damp grain had developed close to the surface (Anderson et al. 1943). Mature soybeans stored in the fall at a uniform moisture content of 11.5% were found to have developed layers in which the moisture content ranged from 16 to 20%; these layers were formed in the upper part of the bin within a few weeks of storage (Carter and Farrar 1943). In both cases, it was concluded that this accumulation of moisture was the result of moisture movement within the grain rather than from wetting by rain or snow.

Anderson et al. (1943) reported that the primary cause of moisture movement was a temperature differential that existed within the grain mass. This conclusion was based on the results of an experiment in which a temperature difference of 35°C was maintained across 2.0 m of grain for 316 days. The grain, which was initially at a uniform moisture content of 14.6%, was observed to increase in moisture content to 20% near the cold end. Thus, it was shown that moisture migration occurred when a temperature differential was present within the grain mass.

2.2 Contribution of Diffusion vs. Convection In Moisture Migration

Laboratory experiments have been conducted by several researchers to determine which mechanism was mainly responsible for moisture migration, diffusion or convection.

Pratt (1951) conducted an experiment using three columns of wheat; these columns were heated at one end and cooled at the other. The columns were plywood boxes, each 0.197 m by 0.197 m by 1.829 m long. The temperature difference was maintained at 33.4°C. One column was positioned horizontally, one positioned vertically and heated at the top such that conditions were favourable to moisture migration by diffusion only resulting from a vapour pressure difference, and the last column was positioned vertically and heated at the bottom creating conditions that were favourable to moisture migration by convection. The temperature and moisture content of the grain was measured at many points in each column and recorded over a period of 62 days. The temperature patterns in the columns did not provide conclusive evidence of convection within any of the columns; therefore, in this experiment, convective heat transfer was considered to be negligible. However, the moisture distribution in the column heated at the bottom indicated that convective air currents were present. In this column, the grain increased in moisture content at the cold end and down one side while decreasing in moisture content at the warm end and up the other side. In all three columns, moisture migration was observed but the effect that convection currents had on the rate of moisture migration was not determined. On the basis of this experiment, Pratt concluded that both diffusion and convection were responsible for moisture migration in stored grain, but the contributions of each mechanism was unknown.

Pixton and Griffiths (1971) examined the rate at which moisture diffused through grain at two temperatures, 22.5°C and 5°C. Small quantities of wheat at 22.1% moisture content were embedded in larger volumes of wheat at 13.7% moisture content and then allowed to reach

equilibrium. It required 65 days for the warm wheat and 140 days for the cold wheat to reach equilibrium, demonstrating that moisture changes caused by diffusion are extremely slow.

To determine the relative importance of convection and diffusion, Stewart (1975) investigated the migration of moisture in high-moisture corn. Stewart compared the amount of moisture transferred in three jars containing whole-kernel corn, rolled corn and ground corn. Convection currents are diminished by reducing the particle size since the resistance of the grain to airflow is increased. However, the reduction of particle size does not affect the rate of diffusion significantly. In the rolled and ground corn, convection was assumed to have been essentially eliminated. The moisture content of the corn was initially uniform at 28% and a temperature difference of 10°C was maintained across each jar; the diameter of each jar was 0.305 m and each jar was 0.457 m high. After 240 h all three jars experienced moisture migration from the warm to the cold side, but the moisture migration was reduced by 38% in the rolled corn and by 51% in the ground corn. In this experiment, diffusion contributed as much or more to moisture migration than convection, based on measured average losses in moisture content. However, in this laboratory study, the temperature gradient was considerably larger than would be expected under field conditions. To achieve the same diffusion mass flux in a 6.100 m diameter bin subjected to similar temperature gradients and containing similar grain would have required 1000 h. Convection rather than diffusion was concluded by Stewart to be primarily responsible for moisture migration.

2.3 Observations of Convection Heat and Moisture Transfer

An experimental study into heat and moisture transfer in stored

grain resulting from convection was conducted by Multon et al. (1979). Corn was placed in a 42 m^3 steel bin and a hot spot was artificially created in two separate trials. In the first trial, an electric heater that maintained a temperature of 60°C was placed in the center of the bin, in a second trial a 7 kg spherical mass of wet grain was used. Grain temperatures and moisture contents were monitored throughout the bin and recorded for a period of 60 days. In both trials, temperature and moisture changes were only observed above the hot spot, thereby providing evidence of convective heat and moisture transfer. It was observed that moisture changes moved in a front, followed by a front of temperature changes. Convective air movement caused the warm moist air to rise, the air came into contact with the cooler grain where the air cooled and released moisture to the grain, thereby increasing the grain moisture content. The grain then gained heat by conduction and convection. This phenomenon was propogated step by step, resulting in moisture migration. A mathematical model of the process was not attempted.

2.4 Mathematical Models of Convection In Stored Grain

Williams (1973) investigated moisture migration in high-moisture shelled corn. He developed a model that simulated the heat and mass transfer in corn for a 6 month storage period using daily mean ambient temperature data. The bin was divided into small elements and heat and moisture balance equations were used to calculate the temperature and moisture content of each grain element at each time interval. It was assumed that all convective air currents passed through the center-most grain column in the bin and at least part of the top and bottom layers

of grain. The pressure difference between two columns of grain in the model was found by summing the weights of the intergranular air in each column; this difference was then converted to a pressure gradient and the airflow was approximated from the following:

$$Q = 0.002714\ (\nabla P) \tag{2.1}$$

where:

Q = airflow $((m^3/s)/m^2)$,

∇P = pressure gradient (Pa/m grain depth).

The storage model was found to be sufficiently accurate to predict temperature and moisture distributions throughout the grain; simulated temperatures were within ±5°C of measured temperatures and simulated moisture contents were generally within ±1% moisture content of measured moisture contents. It was concluded that an increased knowledge of the patterns and magnitudes of airflow within the bulk corn resulting from natural convection would permit a more precise determination of moisture migration. It was also concluded that bins having diameters less than 2.5 m would not experience any significant moisture migration since temperature gradients would not exist for a long enough period of time.

Temperature and moisture variations in shelled corn were examined by Scott and Shipp (1973). This study used a finite-difference approach to model the heat and mass transfer within shelled corn stored in Minnesota for 2 years. The initial moisture content of the corn was 13%. The equation used to describe momentum in the axial direction was as follows:

$$\frac{\partial P}{\partial x} = -\left(\rho g + \frac{\mu \epsilon u}{\kappa}\right) \tag{2.2}$$

where:

$\frac{\partial P}{\partial x}$ = pressure gradient (Pa/m grain depth),

ρ = air density (kg/m^3),

g = gravitational constant (m/s^2),

μ = dynamic viscosity ($kg/m \cdot s$),

u = velocity (m/s),

ϵ = porosity,

K = permeability (m^2).

The Boussinesq approximation was applied and Darcy resistances were inserted. Thus, the air velocity was a function of the density differences between elements, modified by the resistance of the grain to the airflow. Calculations of heat and mass transfer were made in which convective terms were both present and absent in the energy equation. The results indicated that the effects of convection on temperatures within the bin were minimal. However, it was found that convection had to be considered for accurate predictions of moisture migration.

Experiments conducted by Holman and Carter (1952) involved comparing the mass flow rate of convective cells for different resistances to airflow. Soybeans stored at an initially uniform moisture content of 12.5% developed a region where the moisture content reached 24%. This region was near the top of the 70 m^3 steel bin containing the soybeans. In a similar storage bin containing wheat initially at a uniform moisture content of 12.5%, the highest moisture content found was 14.5% again at the top of the bin. Both products were stored for 30 months. The soybeans, offering less resistance to airflow than the wheat, had more convection and consequently more moisture migration.

This relationship between particle size and airflow was described by Leva (1957) in the following equation for laminar flow through a bed of fixed solid particles:

$$G = \frac{\nabla P \, D_p^2 \, \phi_s^2 \, \rho \, g_c \, \epsilon^3}{M \, \mu \, L \, (1-\epsilon)^2} \qquad (2.3)$$

where:

G = fluid mass velocity (kg/m²·s),

∇P = pressure gradient (Pa/m grain depth),

D_p = particle diameter (m),

ϕ_s = shape factor,

M = constant = 200 (1/m),

ρ = air density (kg/m³),

g_c = proportionality factor,

ϵ = porosity,

μ = dynamic viscosity (kg/m·s),

L = height (m).

Another mathematical model describing the heat and moisture movement in stored corn was developed by Greig and Matouk (1977). The grain at the hot and cold sides was thought of as begin a deep bed with the air drying the hot region and placing the moisture on the cold side. The simulation method used was based on the stepwise solution in time and distance of a set of differential equations describing the heat and mass transfer within each element of the bed. The convective airflow rate was calculated from the following empirical equations which do not have homogeneous units of measurement:

$$\Delta P = 0.581 \, L \, B_p \, (1/T_c - 1/T_h) \qquad (2.4)$$

where:

ΔP = pressure difference (Pa),

L = height (m),

B_p = barometric pressure (Pa),

T_c = temperature of cold grain (°C),

T_h = temperature of hot grain (°C),

and

$$G = 7995\ \rho\ \Delta P^{0.68} \tag{2.5}$$

where:

G = fluid mass velocity ($kg/m^2 \cdot s$),

ρ = air density (kg/m^3).

In this simulation model, the effects of three initial moisture content levels and three levels of temperature difference across the grain volume were investigated. It was found that as the initial moisture content increased, the amount of moisture transferred also increased. As the temperature difference increased, the amount of moisture transferred also increased. The researchers found that, while their model correctly predicted trends in moisture migration, more information was required concerning the rate of heat transfer between the air and the grain, and the rate of drying and rewetting under conditions of low airflow.

Beukema (1980) investigated the heat and mass transfer during cooling and storage of agricultural products as influenced by natural convection. The product under investigation was potatoes. The model used by Beukema was derived from the governing equations of natural convection. The natural convection velocity was calculated from the following relation:

$$u = \frac{\kappa \rho g [B(T - T_o) + B_c(c - c_o)]}{\mu} \quad (2.6)$$

where:

u = velocity (m/s),

κ = permeability (m^2),

μ = dynamic viscosity (kg/m·s),

ρ = air density (kg/m^3),

g = gravitational constant (m/s^2),

B = thermal expansion coefficient (1/°C),

T = temperature of potatoes (°C),

T_o = temperature of air (°C),

B_c = concentration expansion coefficient (m^3/kg),

c = moisture concentration of air near potatoes (kg/m^3),

c_o = moisture concentration of air (kg/m^3),

and

$$l = \frac{\epsilon^3 D_p^2}{K(1-\epsilon)} \frac{1}{[150(1-\epsilon) + 1.75 Re]} \quad (2.7)$$

where:

ϵ = porosity,

D_p = particle diameter (m),

K = dimensionless constant for product,

Re = Reynolds number.

Beukema reported that the model accurately predicted temperature and moisture changes within the experimental bin.

Fraser et al. (1980) simulated the heat transfer in cylindrical steel grain bins. The primary objective was to model the conductive

heat transfer using initial grain temperatures, mean daily temperatures, solar radiation, wind velocities and thermal properties of the grain, the grain bin and the soil. The predicted temperatures reflected those measured fairly accurately; standard errors of estimate being less than 2.0°C. A model of the natural convection currents was included as an additional refinement. The driving force behind the air movement was assumed to be the differences in the gravitational force on equal volumes of air of differing densities. The air density in each element was calculated from the predicted temperature, the air was assumed to move vertically within the columns of the elements and horizontally through the bottom layer only. The pressure at the base of each column was calculated by summing the forces of gravity on the air masses in each element; the air velocity was determined from the pressure gradient-airflow relationships reported in the American Society of Agricultural Engineers Yearbook of Standards (1983), hereafter referred to as ASAE. The inclusion of the convection model did not increase the accuracy of the temperature predictions and, therefore, it was concluded that the convection heat transfer under those conditions was negligible. Also, the amount of moisture migration predicted by the convection model was greater than that measured. It was concluded from this study that under these conditions, convection was not important in transferring either heat or moisture through stored grain.

The purpose of the present investigation was to determine why a discrepancy existed between the measured and predicted rates of moisture migration in the study conducted by Fraser et al. (1980). Since temperature predictions were quite accurate, the error was either in the assumption of the rate of air movement resulting from convective heat

transfer or in the model of moisture transfer between the air and the grain. The purpose of this project was to investigate the rate of air movement resulting from convective heat transfer in stored grain; therefore, this literature review also examines fluid flow through porous media.

2.5 Fluid Flow Through Porous Media

Ergun (1952) reviewed the existing information on the flow of fluids through beds of granular material. It was concluded that pressure losses were caused by simultaneous viscous and kinetic energy losses. The following equation was found to be applicable to all types of flow:

$$\frac{\Delta P\ g_c}{L} = \frac{150(1-\epsilon)^2}{\epsilon^3}\frac{\mu\ u}{D_p^2} + \frac{1.75(1-\epsilon)}{\epsilon^3}\frac{G\ u}{D_p} \qquad (2.8)$$

where:

ΔP = pressure difference (Pa),

g_c = proportionality factor,

L = height (m),

ϵ = porosity,

μ = dynamic viscosity (kg/m·s),

u = velocity (m/s),

D_p = particle diameter (m),

G = fluid mass velocity (kg/m²·s).

Schwartz and Smith (1953) investigated flow distribution in packed beds. This work was initiated when results of heat transfer studies indicated that, contrary to popular belief, the velocity across the diameter of a packed bed was not uniform. Data obtained in this inves-

tigation showed that a maximum velocity occurred approximately one particle diameter away from the pipe wall. For pipe diameters less than 30 times greater than the particle diameter, this maximum velocity was found to range from 30 to 100% greater than the velocity at the center of the tube. It was concluded that unless the ratio of the pipe diameter to the particle diameter exceeds 30, then important variations in velocity exist across the packed bed.

Shedd (1953) presented data relating the pressure difference to airflow through various grains. These measurements were made in columns of grain in which the airflow paths were parallel. Hukill and Ives (1955) examined Shedd's data and found that the following equation accurately expressed the relation between velocity and pressure difference when the constants were chosen for a particular system:

$$\Delta P = \frac{a\,Q^2}{\log_e (1+bQ)} \tag{2.9}$$

where:

ΔP = pressure difference (Pa),

Q = airflow ($(m^3/s)/m^2$),

a,b = dimensional constants for a particular system.

Matthies and Petersen (1974) presented an equation relating pressure to airflow through agricultural products. This equation was based on Reynolds' law and previous research by the authors:

$$P = \frac{\phi_s\, k_s\, L\, \rho\, u^2}{D_p\, \epsilon^4} \tag{2.10}$$

where:

P = pressure (Pa),

ϕ_s = shape factor,

k_s = coefficient of air resistance of spheres,

L = height (m),

ρ = air density (kg/m^3),

u = velocity (m/s),

D_p = particle diameter (m),

ϵ = porosity.

A large number of experiments were conducted to provide constants for most agricultural products.

2.6 Measurements of Convective Airflow Through Grain

Intergranular air movement resulting from free-convection in stored grain was measured by Berck (1975). Sulphur hexafluoride was used as a gaseous tracer to measure the air velocity. The velocity was found to be dependent on the grain type and the magnitude of the temperature difference within the grain. Air velocities ranged from 0.020 to 0.763 mm/s for temperature differences ranging from 8.6 to 20.6°C in hard spring wheat at 12.2% moisture content. No attempt was made to relate the experimental results to the magnitude of the temperature difference or to the characteristics of the grain.

Gunasekaran et al. (1983) measured the resistance of rough rice to airflow for airflows ranging from 0.001 to 0.300 $(m^3/s)/m^2$. These airflows which are similar to those resulting from free convection were measured using a transistor anemometer. The relation between airflow rate and pressure gradient was as follows (R^2 = 0.9860):

$$\log(Q) = \log(0.0008) + 0.87[\log(\nabla P)] \qquad (2.11)$$

where:

Q = airflow $((m^3/s)/m^2)$,

∇P = pressure gradient (Pa/m grain depth).

The data obtained from forced air movement were found to be best described by the following equation, where Q and ∇P are as in equation (2.11):

$$\log(Q) = -0.031[\log(\nabla P)]^2 + 0.920[\log(\nabla P)] - 3.042, \quad (2.12)$$

no explanation was given for the differences between the results of free and forced convection. It is thought that the differences in densities due to temperature, relative humidity and total air pressure may be factors (personal communication, W.E. Muir). The pressure gradient of the rice was found to increase proportionately with the grain bed depth up to 0.300 m, confirming the observations of other researchers. However, the increase in pressure gradient was disproportionate with the increase in airflow. The results of the experiments were used to develop an equation relating airflow to the magnitude of the temperature gradients and the characteristics of the grain bin:

$$Q = 0.0000381\ (\Delta T \cdot H/h)^{0.87} \quad (2.13)$$

where:

Q = airflow $((m^3/s)/m^2)$,

ΔT = temperature difference (°C),

H = height of hot air column (m),

h = grain bed thickness (m).

The accuracy of this equation in predicting airflows and the relationship of this equation to the data of Gunasekaran et al. (1983) was not reported.

2.7 Summary of Literature Review

The equations that have been presented in this literature review may be divided into two categories: the first are empirical equations of the form:

$$Q = f(\nabla P) \tag{2.14}$$

where:

Q = airflow,

∇P = pressure gradient.

Equations (2.1), (2.5) and (2.6) are of this form. The second type of equation are those derived from Reynolds' law:

$$\frac{\Delta P}{L} = a\,u + b\,\rho\,u^2 \tag{2.15}$$

where:

ΔP = pressure difference (Pa),

L = height (m),

u = velocity (m/s),

ρ = density (kg/m^3),

a,b = product constants,

or

$$\frac{\Delta P}{L\,u} = a + b\,G \tag{2.16}$$

where:

$G = \rho\,u$.

From equation (2.16), it can be seen that as the velocity approaches zero, the ratio of pressure gradient to velocity will become constant:

$$\lim_{u \to 0} \left(\frac{\Delta P}{L\,u} \right) = a \tag{2.17}$$

which is a condition for viscous flow, thus 'a' is proportional to the viscosity of the fluid. At high flow rates, the constant 'a' is negligible and kinetic energy losses constitute the entire resistance (Ergun 1952). Viscous energy losses and kinetic energy losses are proportional to $(1-\epsilon)^2/\epsilon^3$ and $(1-\epsilon)/\epsilon^3$, respectively, where ϵ is the porosity:

$$a = a'' \frac{(1-\epsilon)^2}{\epsilon^3} \tag{2.18}$$

$$b = b'' \frac{(1-\epsilon)}{\epsilon^3} . \tag{2.19}$$

The resulting equation proposed by Ergun (1952) was equation (2.8). Equation (2.3) is the first term of equation (2.8):

$$G = \frac{\nabla P \, D_p^2 \, \phi_s^2 \, \rho \, g_c \, \epsilon^3}{M \mu \, L \, (1-\epsilon)^2} \tag{2.3}$$

becomes:

$$\frac{\nabla P \, g_c}{L} = \frac{M \mu \, u \, (1-\epsilon)^2}{D_p^2 \, \phi_s^2 \, \epsilon^3} \tag{2.20}$$

Similarly, the equation (2.7) is a modification of equation (2.8). Equations (2.9) and (2.10) are both derived from Reynolds' law directly.

The two remaining equations, (2.2) and (2.6), were derived from the theory of natural convection. The governing equation for momentum is as follows (Bird et al. 1960):

$$\frac{\partial(\rho u)}{\partial t} + u[\nabla(\rho u)] = \rho g - \nabla P - \mu V^2 u \tag{2.21}$$

where:

ρ = air density (kg/m^3),

u = velocity (m/s),

g = gravitational constant (m/s^2),

P = pressure (Pa),

μ = dynamic viscosity (kg/m·s),

t = time (s).

This equation is simplified by ignoring the inertia term and applying the Boussinesq approximation which implies constant fluid properties except density in the term where density differences create buoyant forces. Equation (2.21) is reduced to the following:

$$\rho \frac{\partial u}{\partial t} = \rho g - \nabla P + \mu \nabla^2 u. \tag{2.22}$$

From this differential form, Whitaker (1966) showed that in an incompressible isotropic porous medium, the viscous term may be given by the following:

$$\mu \nabla^2 u = -\frac{\mu}{K} u \tag{2.23}$$

so that the equation for motion becomes the following:

$$\rho \frac{\partial u}{\partial t} = \rho g - \nabla P - \frac{\mu}{K} u \tag{2.24}$$

where:

K = permeability (m^2).

Under steady state conditions, equation (2.24) can be simplified to the following:

$$0 = \rho g - \frac{dP}{dz} - \frac{\mu}{K} u \tag{2.25}$$

or

$$u = \frac{K}{\mu}\left(\rho g - \frac{dP}{dz}\right). \qquad (2.26)$$

Equation (2.25) is very similar to equation (2.2) which was the basis for calculating the airflow rates in the mathematical model of Scott and Shipp (1973):

$$\frac{\partial P}{\partial z} = \rho g - \frac{\mu \epsilon u}{K}. \qquad (2.2)$$

Equation (2.26) was also the basis of equation (2.6) which was the equation used by Beukema (1980) for calculating the velocity of the air resulting from free-convection in stored potatoes:

$$u = \frac{K}{\mu}\rho g [B(T - T_o) + B_c(c - c_o)]. \qquad (2.6)$$

Darcy's law gives the following equation for pressure gradient resulting from flow through porous media:

$$\frac{P}{L} = -\frac{\mu}{K} u \qquad \text{or} \qquad u = -\frac{K}{\mu}\left(\frac{P}{L}\right). \qquad (2.27)$$

Thus, the velocity of the air movement resulting from free-convection in stored grain can be determined from the density differences of the air (caused by temperature differences) minus the pressure gradient due to friction, equation (2.26). The differences in pressures provides the driving force and the velocity of the air depends on the permeability of the porous medium and the properties of the air (Beukema 1980).

While many investigations have been conducted into free-convection, there is still a lack of quantitative information concerning the relationship between airflow and the conditions of the grain in a bin; there are still discrepancies between measured and predicted rates of moisture migration that have not yet been resolved.

3. MATERIALS AND METHODS

3.1 Free-Convection Apparatus

The airflow caused by free-convection heat transfer in stored grain was measured in a laboratory apparatus. This laboratory apparatus was designed to provide the optimum compromise between two conflicting objectives:

1. accurate simulation of the process of free-convection heat transfer that occurs in actual storage facilities and

2. provision of sufficient control over the variables that affect free-convection heat transfer to permit extensive investigation of the process.

Free-convection heat transfer in stored grain occurs when temperature gradients are formed within the grain mass. Warm air in the center of the bin is buoyed upward while cold air near the wall sinks. This situation was approximated by a loop consisting of a warm and a cold column, connected at the top and bottom by air ducts (Figure 3). This approximation represents the compromise achieved in the design of the laboratory apparatus.

The free-convection apparatus consists of a closed loop (Figure 4). The loop was made of polyvinyl chloride (PVC) plastic pipe and fittings: the internal diameter was 203 mm. The two vertical columns and the upper and lower air ducts were joined together by tee sections. The loop was closed by plugs that were inserted into the open end of the lower tee sections and by removeable caps that closed the open ends of the upper tee sections. Rubber rings and silicone sealant were used at each connection to ensure that the loop was completely airtight. The apparatus was tested for leakage by filling it with carbon

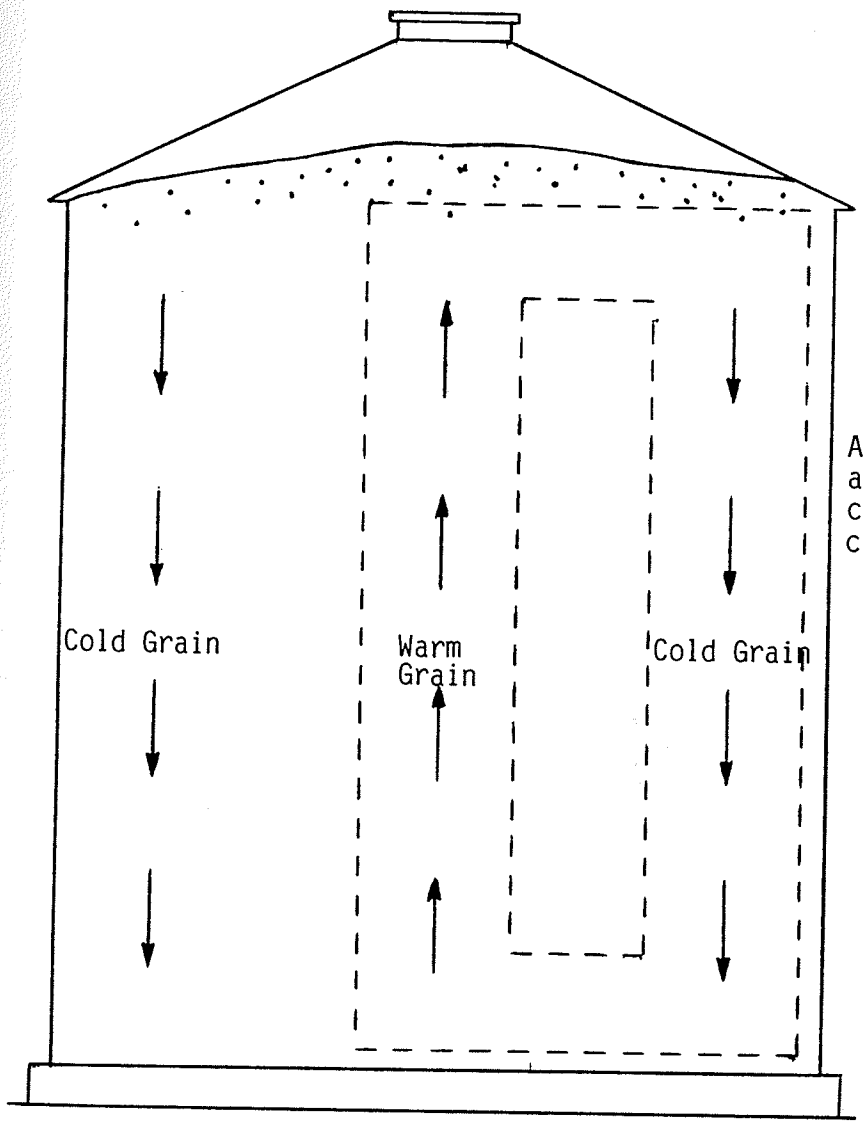

FIGURE 3: Actual storage conditions approximated by a closed loop.

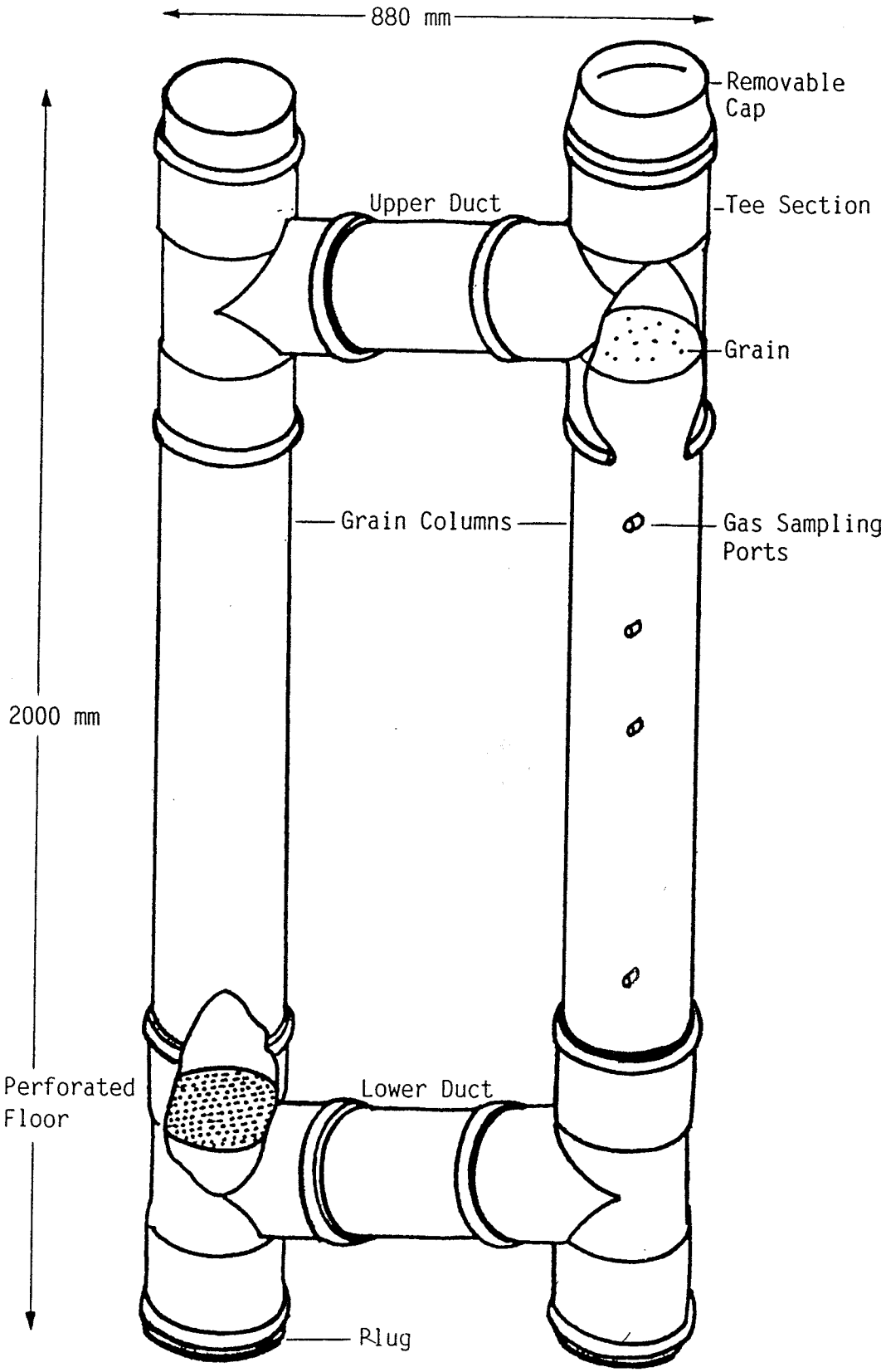

FIGURE 4: Free-convection apparatus.

dioxide and checking each connection with a carbon dioxide detection device. Ensuring that no leaks were present was essential for accurate measurement of convective airflow, since airflow rates are very low and a slight external pressure change could affect the air movement. A perforated floor was placed at the base of each column. The air ducts were not filled with grain so that the conductive heat transfer between the columns was minimized. Both columns were filled with grain, the grain in each column increased the heat transfer area within the column so that the intergranular air was of a uniform temperature in the radial direction. The column height was made as large as possible to maximize the pressure difference between the columns for a given temperature difference, thereby maximizing the airflow rate. The column diameter was made over 30 times as large as the largest particle diameter so that the assumption of uniform velocity across the diameter of the column was valid (Schwartz and Smith 1953).

The free-convection airflow rates were measured for various treatments of temperature differences and grain permeabilities. The temperature differences in the closed loop were established by heating one column and cooling the other. Heat was transferred to and from the columns by water jackets which enclosed each column (Figure 5). A mixture of water and antifreeze was circulated through the water jackets by constant-temperature circulators. The circulator supplying hot water was a Haake model FJ equipped with a heater in its reservoir. The circulator supplying cold water was a Haake model NB, connected to a PSC model KR 30 refrigerated chiller. Both circulators were equipped with reservoirs and thermostats, the thermostats were specified to maintain the fluid temperature within ±0.01°C. The water jackets were

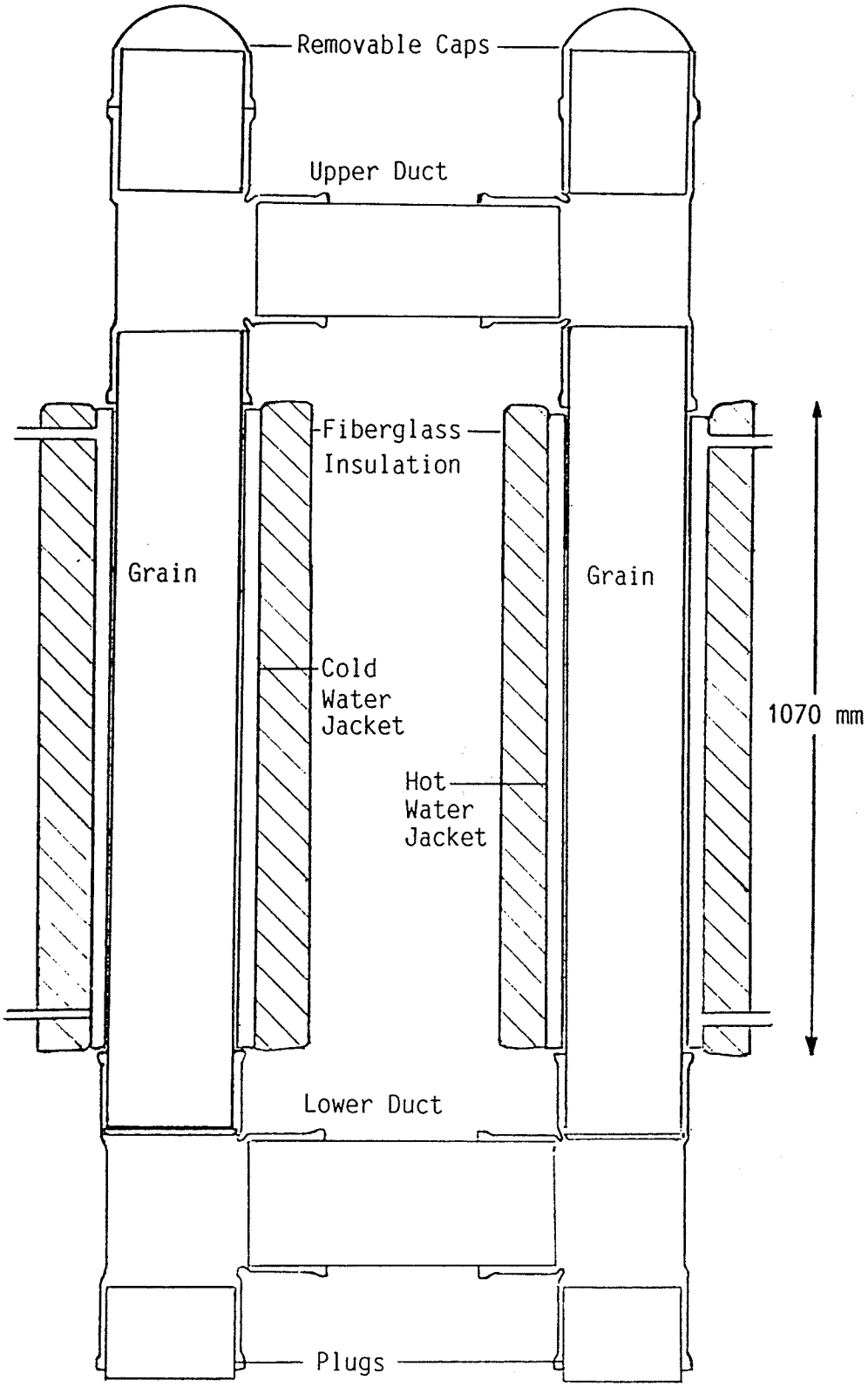

FIGURE 5: Cross-section of free-convection apparatus.

insulated with 100 mm of fiberglass insulation to minimize the heating and cooling loads.

Temperatures in the apparatus were measured using thermocouples (Figure 6). Temperatures were recorded during the experiments with an HP 3497A data acquisition system which was controlled by an HP 85 computer. The thermocouples used were Type T (copper-constantan), 26-gauge, having an accuracy of ±1°C. The thermocouples were placed throughout the apparatus for the purpose of providing sufficient information for predicting the airflow rate on the basis of temperature differences within the grain. Thermocouples were placed closely together where sharp temperature gradients were expected and farther apart where the temperatures were expected to be uniform; typical temperature distributions throughout the apparatus are presented in Appendix A.

Grain properties were determined for each grain tested in the free-convection experiments, the two grains used were hard red spring wheat (Cultivar: Neepawa) and Argentine-type rapeseed (Cultivar: Westar). Both grains were purchased as certified seed and therefore contained no significant amount of dockage. The grain moisture content was determined by the oven-drying method in accordance with ASAE Standard S352; the results were expressed as percentage wet basis (ASAE 1983). The moisture content of the wheat was approximately 10% while the moisture content of the rapeseed was approximately 8%. The purpose of measuring moisture content was to determine the equilibrium relative humidity of the intergranular air so that the density of the air could be determined. A Beckman Instruments model 930 pycnometer was used to measure the volume of a known mass of seeds; porosities were calculated

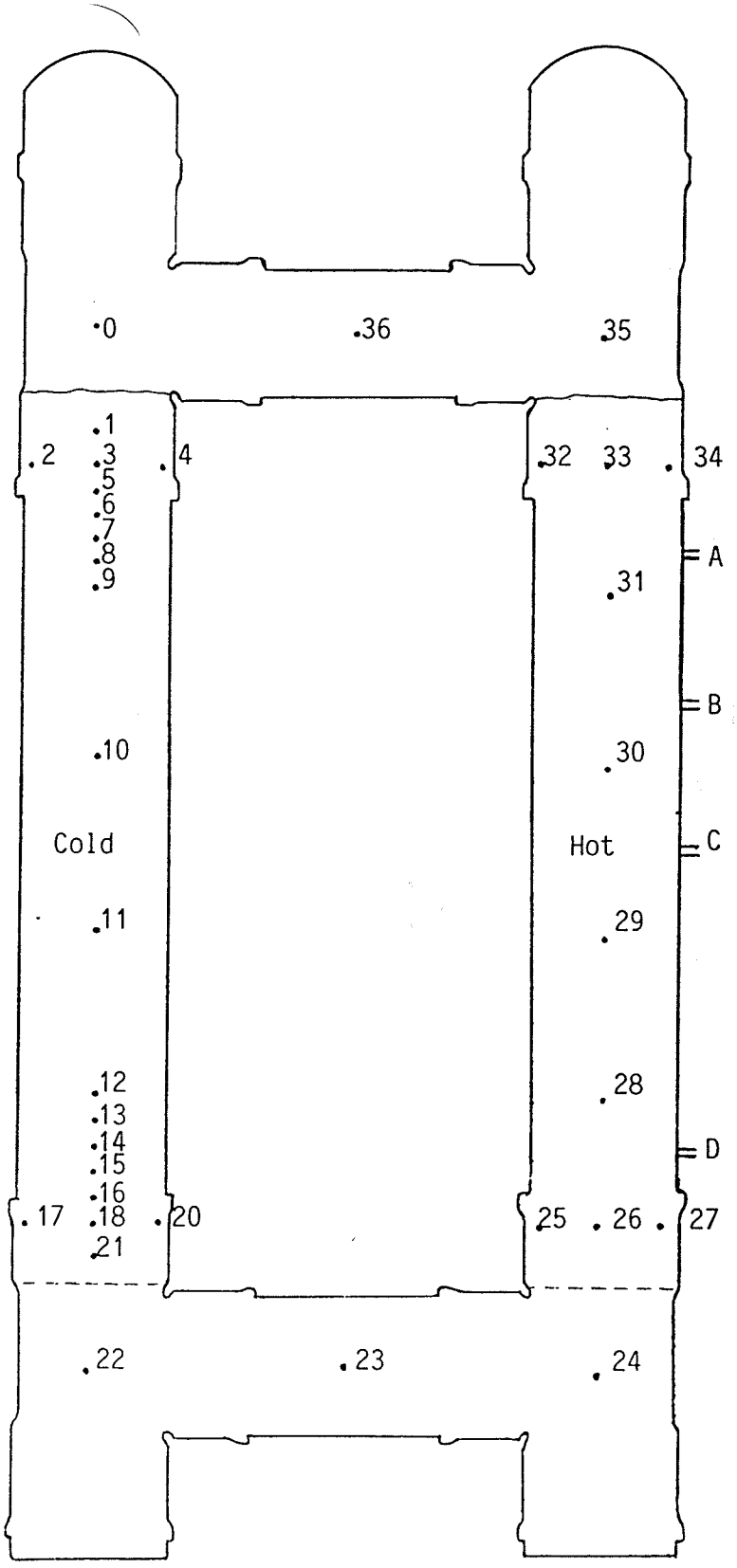

FIGURE 6: Locations of thermocouples and air sampling ports.

using the following equation (Mohsenin 1970):

$$\epsilon = \left(1-\frac{\rho_b}{\rho_k}\right)(100\%) \qquad (3.1)$$

where:

ϵ = porosity,

ρ_b = bulk density (kg/m^3),

ρ_k = kernel density (kg/m^3).

The porosities were required for the calculation of grain permeabilities. Each time the columns were filled with grain, the mass of the grain was determined by weighing the grain prior to filling on a Mettler PC16 electronic balance which measured to a precision of 0.1 g. The procedure for procuring the different grain permeabilities was as follows. Given the volume of each column, the mass of grain required to obtain a desired porosity in each column was calculated. The grain was weighed and loaded into each column. When a high porosity was required, each column was filled about half-way by pouring the grain through a pipe with a 90° elbow at the end. The elbow reduced the grain velocity before it fell into the column. This procedure lowered the grain density in the bottom half of the column, resulting in a more uniform density over the height of the column. The upper half of the column was filled by pouring the grain directly into the column. When a lower porosity was required, the grain was poured directly into the column while forcing a steel rod in and out of the placed grain for the purpose of packing the grain. The porosity of the grain in each column was an average porosity for the column.

Air sampling ports in the free-convection apparatus were used

for the injection of carbon dioxide into the column and for the withdrawal of intergranular air samples performed in the measurement of airflow. The ports were plastic tubes, 10 mm in diameter and 100 mm in length, inserted into the wall of the polyvinyl chloride pipe, flush with the inside wall. The external ends of the tubes were covered with a rubber septum through which hypodermic needles were inserted 100 mm into the grain column during injection and sampling; the sample size was 3 mL. The ports were located 150, 650, 900 and 1150 mm above the perforated floor in the hot column. For each injection, 60 mL of pure carbon dioxide was injected from a syringe through a 3 mm ID hypodermic needle into the center of the grain column through Port C (Figure 6). The intergranular air samples were withdrawn through a 0.5 mm ID needle using a 5 mL syringe; 3 mL air samples were taken from the center of the column through port A. The air samples were kept cold from the time they were taken until the time they were analyzed. Samples were analyzed using a Perkin-Elmer Sigma 3B gas chromatograph with a thermal conductivity detector. The detector temperature was 150°C, the oven temperature was 65°C and the carrier gas was helium. Carbon dioxide was separated from the other gases by a 1.8 m column packed with Porapak N (50/80 mesk). A 1 mL gas volume was fixed as the injection volume. The percentage of carbon dioxide in the air sample was calculated using an HP 3380 A integrator.

3.2 Procedure For Measuring Airflow Rates

The procedure followed for measuring the airflow resulting from free-convection heat transfer in the free-convection apparatus was as follows. After the columns had been filled, temperature differences between the columns were imposed by adjusting the thermostatic controls

in the circulators and starting the fluid circulation. The caps were placed at the top of each column thereby sealing the apparatus. The data acquisition system was then programmed to record temperatures at all points in the apparatus every 2 h for the duration of the test. The equipment was then allowed to stabilize for 24 h before airflow measurements were made. Initially, a trial airflow measurement was made: the carbon dioxide was injected at time zero and the air samples were withdrawn every 5 min, 20 samples in total. These samples were analyzed to determine approximately what the traverse time was for that temperature difference and grain permeability. On the basis of this result, the time intervals between future samples were determined so that the peak carbon dioxide concentration was sampled. The injection-sampling procedure was repeated three times for each temperature difference and grain permeability. The time interval between the last sampling and the next carbon dioxide injection was at least 30 min. Interference from earlier injections was immediately recognized since the ambient level of carbon dioxide was higher; where interference was observed, the injection was repeated at a later time. By taking 20 samples of air per injection, the volume added to the columns was equal to the volume of air removed. The volume of air in one column was approximately 19750 mL, about one quarter of the entire air volume in the apparatus. Thus, the addition of 60 mL of carbon dioxide was insignificant. The time interval between the withdrawal of air samples was designed such that the first and last samples would contain only ambient levels of carbon dioxide and that the increase and decrease of carbon dioxide levels as the carbon dioxide passed the sampling point would be clearly recognized (Figure 7).

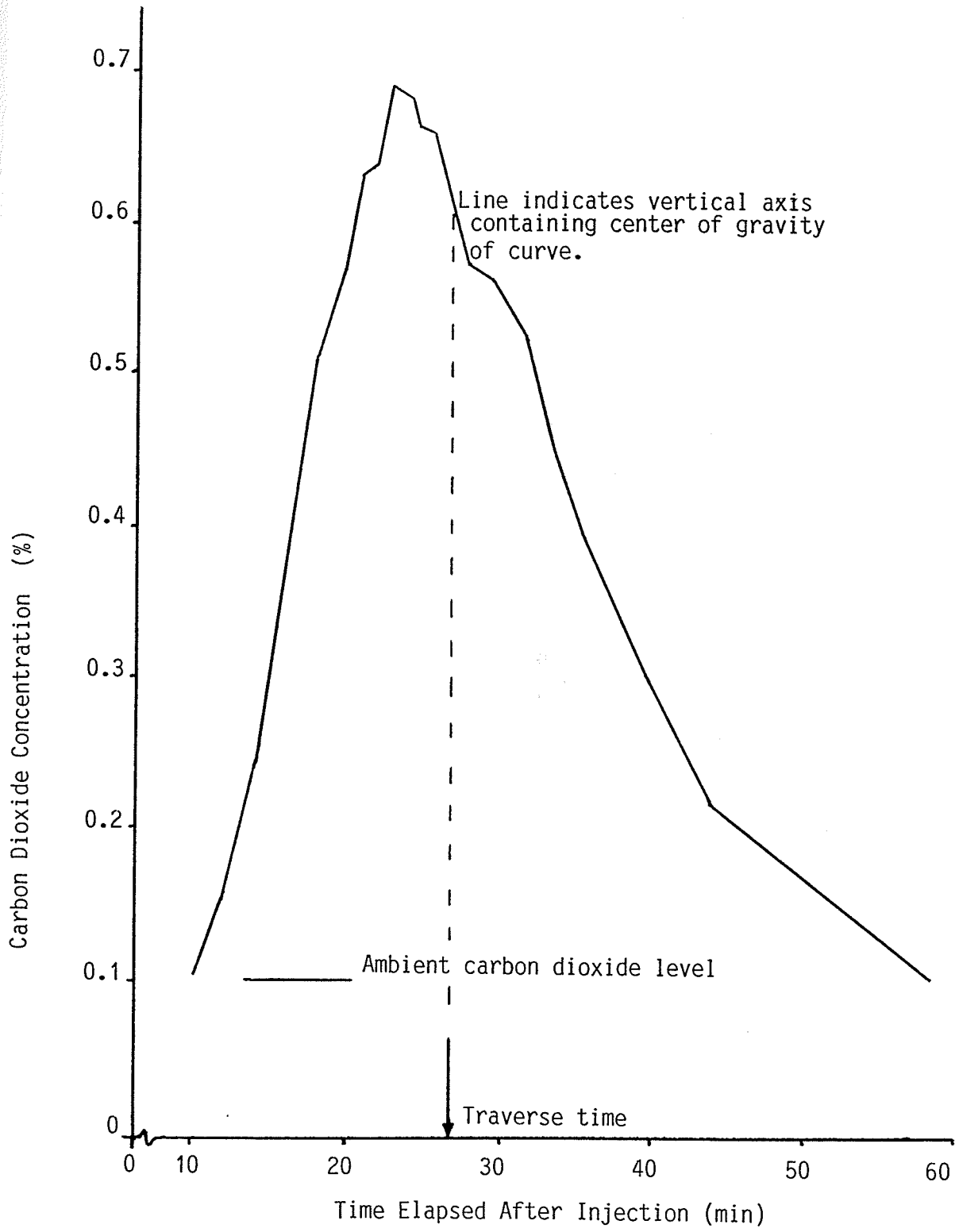

FIGURE 7: Movement of tracer gas past sampling point caused by convective airflow.

The traverse time of the carbon dioxide through the grain column was determined from the analysis of the air samples for each injection. The method used to determine the traverse time was adapted from the salt-velocity method used for the measurement of discharge, developed by C. M. Allen (Hooper 1960). A plot of carbon dioxide concentration against sample time was constructed (Figure 7). The area below the curve is determined by integration and the vertical line dividing the area below the curve into equal areas is the line that contains the center of gravity of the curve, assuming that the area below the curve had a uniform density. The traverse time is the time between injection and the passage of the center of gravity of the curve. A computer program was developed to compute the traverse time for each data set containing carbon dioxide concentrations and sampling times. The minimum and maximum time between the center of gravity was calculated as the last ambient carbon dioxide level measured before the peak arrived and the first ambient carbon dioxide level measured after the peak had passed, respectively. The ambient level of carbon dioxide in the apparatus was 0.1%.

Tests were conducted to measure the convective airflow through wheat at a porosity of 47% for temperature differences of 10, 20, 30, 40 and 45°C and at a porosity of 44% for temperature differences of 20 and 40°C. Tests were also conducted for rapeseed at a porosity of 44% for temperature differences of 20 and 40°C. For each condition, the airflow was measured three times.

3.3 Resistance-Measurement Apparatus

For the airflows resulting from free-convection heat transfer in

the free-convection apparatus to be predicted from measured temperatures it was necessary to measure the resistance of the grains to low airflow. There is no information reported in the ASAE Yearbook of Standards for airflows below 0.00025 $(m^3/s)/m^2$, the relationship between the airflow and pressure gradient is only an extrapolation of that for higher airflows (ASAE 1983). Thus, for both grains used, it was necessary to measure the resistance of the grain to airflows in the range anticipated for free-convection.

The apparatus used was designed to conform as well as possible to the apparatus described by ISO Standard 4174 (International Standards Organization 1980). The apparatus (Figure 8) consisted of an airtight wooden plenum chamber having dimensions 750 mm by 750 mm by 500 mm in height and a 203 mm ID cardboard tube, 2400 mm in height. The tube was attached to the plenum chamber and the joint was sealed with silicone sealant to be airtight. A perforated floor, similar to that used in the free-convection apparatus separated the column from the plenum chamber. The column was equipped with air sampling ports located at 200, 700, 1200 and 2200 mm above the perforated floor. These ports were similar to those described in the free-convection apparatus. A small pump was used to supply air. The air was pumped through a chamber to dampen out pulsations from the pump. The airflow rate was measured using a Gilmont R433 variable-area flowmeter. A Dwyer pressure gauge measured the pressure difference between Port A and D in the column and was zeroed under conditions of no flow. The air temperature inside and outside of the apparatus was measured with Type T thermocouples, the relative humidity of the air was measured with a psychrometer.

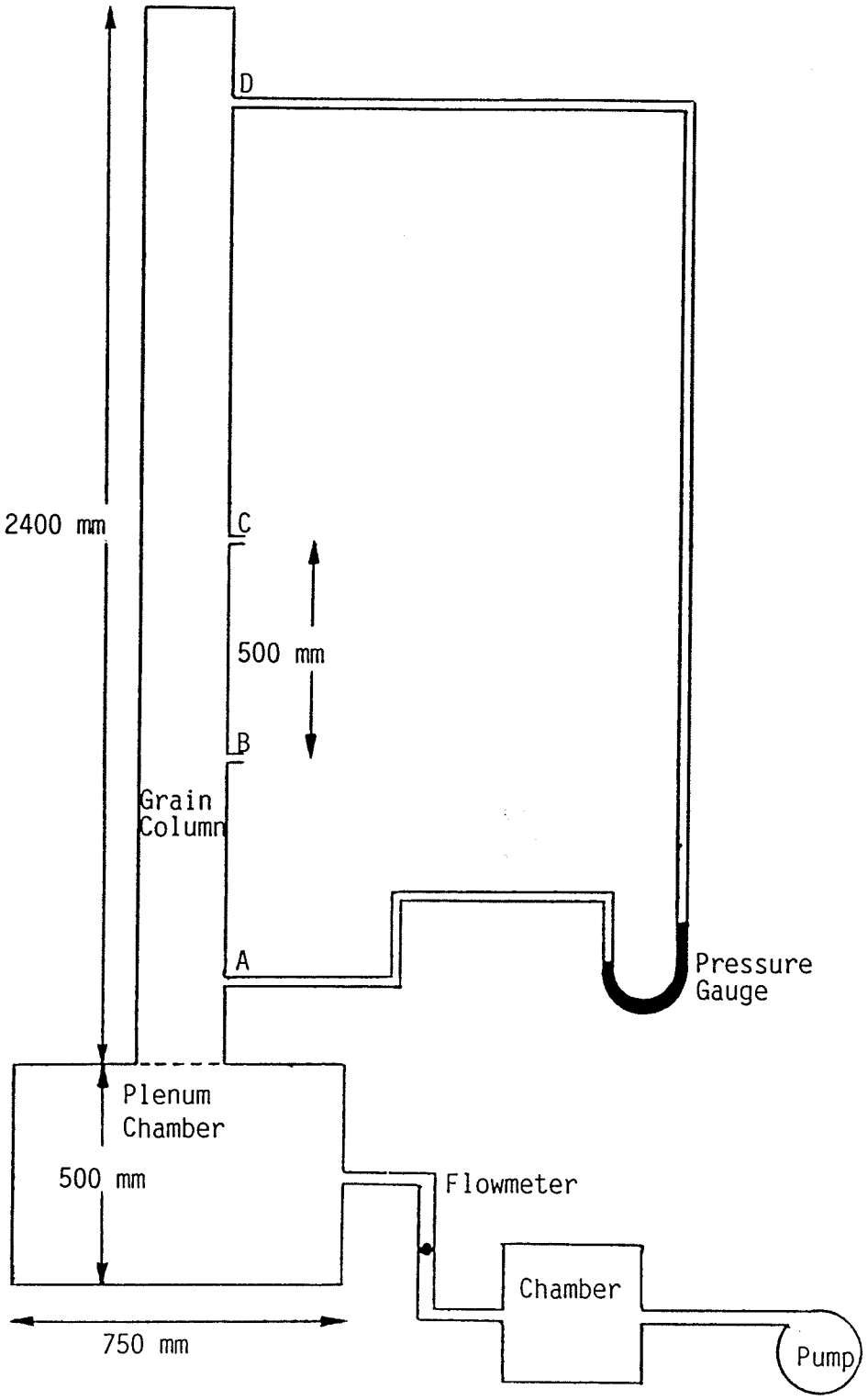

FIGURE 8: Resistance-measurement apparatus.

3.4 Procedure For Measuring The Resistance Of Grain To Airflow

The following procedure was used for each grain tested: the kernel density of a randomly selected sample of seed was determined using the same procedure as described previously. The mass of grain required to obtain a desired porosity was calculated using the known volume of the column and was weighed out with an electronic balance. The column was then filled in a manner similar to that described before. The pump was started and the airflow rate adjusted, the pump was allowed to run for 15 min before measurements were made. The grain temperature and the temperature, relative humidity and barometric pressure of the air were measured at the start of the test. Resistance measurements were then made for the grain at airflows ranging from 0.0001366 to 0.0009615 $(m^3/s)/m^2$. Resistance measurements were made for the wheat at 47 and 44% porosities and for rapeseed at 44% porosity. Although the column height in the resistance measurement apparatus was greater than that in the free-convection apparatus, both columns had the same average porosity when filled by the manner described.

3.5 Calibration Of Variable-Area Flowmeter

A calibration was performed on the Gilmont variable-area flowmeter. Although a calibration curve was supplied with the flowmeter for standard temperature and pressure conditions, this calibration was performed under the conditions of the laboratory so that the effects of pressure and temperature would be accounted for. A constant-head tank was used to provide an air supply at a constant pressure (Figure 9). The rate of water flow to the graduated container was regulated by adjusting Valve B. Valve A was then adjusted so that a small amount of water continually trickled out through the overflow at Port D, thereby main-

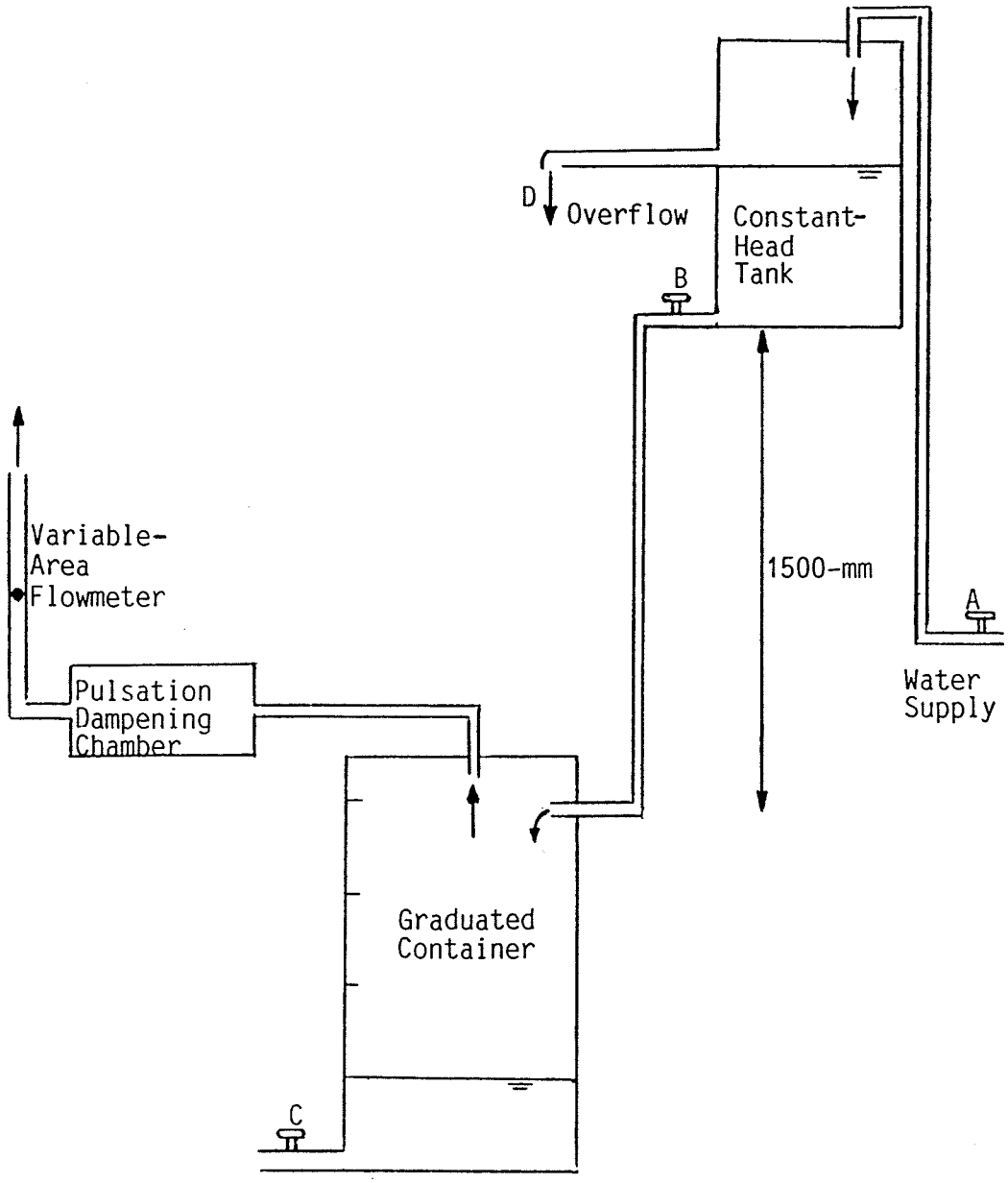

FIGURE 9: Constant-head apparatus used for calibrating variable-area flowmeter.

taining a constant height of water in the tank. When the flow rate was set, the time required to fill a 2000 mL volume, ±10 mL, was measured with a stopwatch that was readable to 0.25 s. The percentage error was approximately 0.25%. The flowmeter was calibrated for airflows ranging from 0.0001366 to 0.0009615 $(m^3/s)/m^2$.

3.6 Calibration Of Pressure Gauge

The Dwyer pressure guage, a U-tube manometer type, was calibrated against a T.E.M. Engineering micromanometer, the most accurate instrument that was available for comparison. The calibration was performed using the resistance-measurement apparatus. The two pressure gauges were connected in parallel and zeroed under conditions of no flow. Using the same procedure as for the resistance measurements, the Dwyer gauge was calibrated for airflows in the range 0.0004418 to 0.1769800 $(m^3/s)/m^2$.

3.7 Calibration Of Tracer Gas

The purpose of this calibration was to determine the relationship between the traverse time of carbon dioxide through grain and the airflow rate through the grain. Without this calibration, consideration would have had to be given to the effects of carbon dioxide diffusion, sorption of carbon dioxide by the grain and the injection of carbon dioxide and removal of air samples. All of these factors affect the measurement of the free-convection airflow, but by performing this calibration, the effects of these factors were taken into account. The resistance-measurement apparatus (Figure 8) was used for the calibration.

The procedure used for calibrating the tracer gas was as follows.

The column was filled to the desired porosity, the pump was started and the airflow rate was adjusted to obtain the desired flow rate. The flow was permitted to stabilize for 15 min before the carbon dioxide was injected into the center of the grain column through Port B (Figure 8) and air samples were withdrawn from the center of the grain column through Port C. The tracer gas was calibrated for airflows ranging from 0.0001366 to 0.0003636 $(m^3/s)/m^2$ for wheat at 47 and 44% porosities.

4. MATHEMATICAL MODEL

4.1 Problems Involved In Modelling Free-Convection Heat Transfer

The mechanism of free-convection heat transfer is very complex. This becomes apparent when a simple case of convective flow is examined. Consider a layer of fluid heated from below; in response to the heating, the bottom layer of the fluid expands and thereby becomes less dense than the layer above it. The warmer and lighter bottom layer is buoyed upward as the cooler layer above it tends to sink. The driving force behind the convective flow is the buoyancy of the heated layer (Kreith and Black 1980). The magnitude of this force is determined by the temperature difference between the top and bottom layers of the fluid. The mechanism becomes complex as the temperature distribution becomes altered by the convective flow itself, which transfers heat from the bottom layer to the top. Thus, the force that drives the flow is modified by the flow. Thus, even the simplest system undergoing vigorous convective motion can not yet be given an exact mathematical description (Velarde and Normand 1980).

4.2 Procedure For Prediction Of Airflow Rates

The airflow rate through the free-convection apparatus was predicted using the following procedure. The driving force behind the air movement was assumed to be the difference in the gravitational force on equal volumes of air of differing densities. The free-convection apparatus was divided into elements (Figure 10); the density of the air in each element was calculated from the measured temperature; where an element contained more than one thermocouple, the average temperature was used. The pressure at the base of each column was calculated by

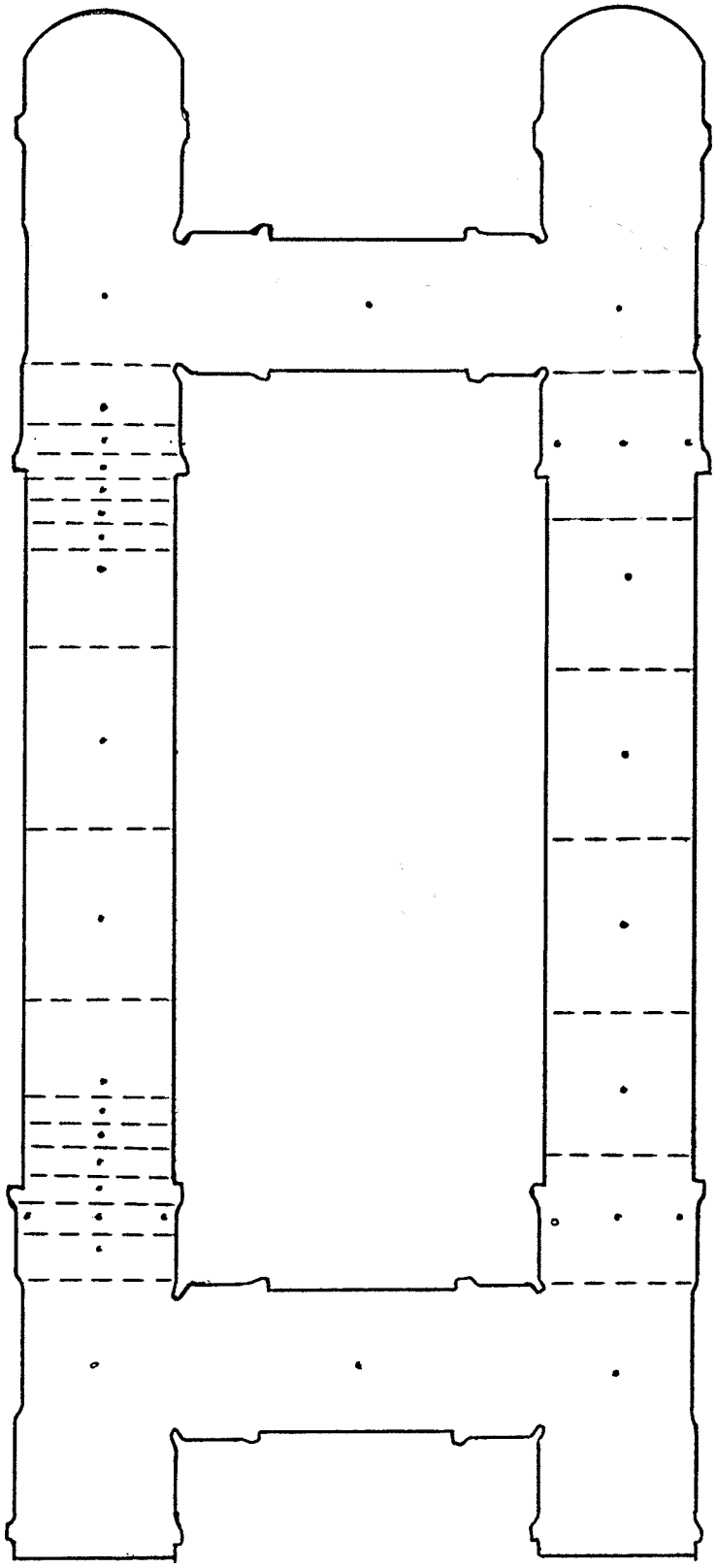

FIGURE 10: Free-convection apparatus divided into elements for the purpose of calculating airflows.

summing the forces of gravity on the air masses in each element, and the airflow rate was determined from the measured pressure gradient-airflow relationships.

A computer program was developed to calculate the pressure difference between the columns of the free-convection apparatus, the procedure used was as follows:

1. For each test, temperatures were recorded on magnetic tape by the data acquisition system. These temperatures that were measured at the time of an airflow measurement were read off the tape and placed in an array.

2. The moisture content of the grain was put into the program.

3. The volume of air in each element was calculated on the basis of grain porosity.

4. The grain moisture content was converted into percentage dry basis from percentage wet basis by using the following equation (ASAE 1983):

$$\%M_d = \frac{100\ (\%M_w)}{100 - \%M_w} \qquad (4.1)$$

where:

$\%M_d$ = grain moisture content, percent dry basis,

$\%M_w$ = grain moisture content, precent wet basis.

5. The relative humidity of the intergranular air was determined for the air in each element from the Chung equation (ASAE 1983):

$$RH = e^{[(-529,43/(T + 50.998))e^{(-17.609\ Md)}]} \qquad (4.2)$$

where:

RH = relative humidity (%),

T = air temperature (°C).

6. The measured temperatures and calculated relative humidity values were used to determine the air density in each element from the mathematical model of the psychrometric chart (Brooker 1967).

7. The pressure resulting from each element was calculated from:

$$P = \rho g h \tag{4.3}$$

where:

P = pressure (Pa),

ρ = air density (kg/m^3),

g = gravitational constant (m/s^2),

h = element height (m).

8. The pressure change resulting from each element was summed per column to give P_1 and P_2, the pressure increases over isothermal conditions in columns 1 and 2 respectively. The pressure difference was found by:

$$\Delta P = P_1 - P_2. \tag{4.4}$$

5. RESULTS

5.1 Calibration Of Variable-Area Flowmeter

The variable-area flowmeter was calibrated using the constant-head apparatus (Figure 9) for airflows ranging from 0.0001366 to 0.0009615 $(m^3/s)/m^2$ in a 203 mm diameter pipe. This range in airflow corresponded to the scale reading on the flowmeter ranging from 5 to 28 divisions. Thus, the readability of the folwmeter was 0.000018 $(m^3/s)/m^2$. As mentioned in Section 3.5, the percentage error in the calibration was approximately 0.25%. A linear regression was performed on the data using SAS (Statistical Analysis Systems) GLM procedure (Anon. 1982). The resulting equation (R^2= 0.9939) is as follows:

$$Y = 0.0000462 + 0.0000123(Z) \qquad (5.1)$$

where:

Y = airflow rate $((m^3/s)/m^2)$,

Z = flowmeter reading.

The data from the calibration are presented in Appendix B.

5.2 Comparison Of Pressure Gauge

The U-tube pressure gauge used in the measurement of the resistance of grain to airflow was calibrated against a micromanometer. Using the resistance-measurement apparatus (Figure 8), the pressure readings from the two instruments were compared for airflows ranging from 0.0004418 to 0.176980 $(m^3/s)/m^2$. The results are presented in Table 1; both instruments registered similar pressure readings for each airflow and, therefore, both instruments were considered to be equally accurate. The resolution of the U-tube manometer was 0.098 Pa while the resolution of the micromanometer was 0.980 Pa. Thus, the U-tube

TABLE 1: Comparison of U-tube pressure gauge against micromanometer.

Airflow Rate ($(m^3/s)/m^2$)	Pressure Reading (Pa)	
	U-tube pressure guage	micromanometer
0.0004418	0.29	0.5
0.0008837	0.49	0.5
0.0017642	0.98	1.0
0.0026479	1.67	1.5
0.0044121	2.75	2.9
0.0061764	4.12	3.9
0.0088243	5.78	5.9
0.0441217	27.16	27.4
0.0794067	49.02	49.4
0.1147227	69.99	70.5
0.1500077	95.39	95.9
0.1764869	113.32	108.1

manometer was more useful in measuring small pressure changes than the micromanometer.

5.3 Calibration Of Tracer Gas

A calibration of the carbon dioxide tracer gas was performed using wheat having porosities of 47 and 44%. The range of airflows for which the calibration was performed was from 0.0001366 to 0.0003636 $(m^3/s)/m^2$. The computer program used to calculate the traverse time of the tracer gas calculated the traverse time to the nearest 30 s time interval. This approximation was done in recognition of the limitations of the tracer gas technique as a velocity-measurement method; it was observed that the precision of this technique was ±60 s at the higher airflow rates and ±180 s at the lower airflow rates. Although there were no dramatic differences in traverse time through the grain having different porosities at equal airflows, the equations relating airflow to traverse time were different. The equation for wheat having 47% porosity (R^2= 0.9800) was:

$$Y = 5200\ e^{-4370(Z)} \tag{5.2}$$

while the equation for wheat having 44% porosity (R^2= 0.9888) was:

$$Y = 5200\ e^{-4360(Z)} \tag{5.3}$$

where:

Y = traverse time (s),

Z = airflow rate $((m^3/s)/m^2)$.

However, the difference between the two equations is small. The results of the calibration are presented in Table 2.

5.4 Measured Resistance Of Grain To Airflow

The resistance of wheat having 44 and 47% porosities and rapeseed

TABLE 2: Calibration of tracer gas, for wheat having porosities of 47 and 44%.

Airflow Rate $((m^3/s)/m^2)$	Traverse Time For Carbon Dioxide Through 0.5 m Of Wheat (s)	
	47%	44%
0.0003636	1110	1050
0.0003174	1350	1350
0.0002722	1650	1650
0.0002270	1770	1830
0.0001818	2250	2190
0.0001366	2970	3060

having a porosity of 44%, to airflow was measured. The results are presented in Table 3. The airflow rate was measured to an accuracy of ±0.000002 $(m^3/s)/m^2$ and the resistance of the grain to airflow was measured to an accuracy of ±0.01 Pa. A non-linear regression was performed on the data using the SAS NLIN procedure (Anon. 1982). The equation for wheat having a porosity of 47% (R^2= 0.9996) was:

$$\nabla P = 48653\ (Q)^{1.4004} \tag{5.4}$$

the equation for wheat having a porosity of 44% (R^2= 0.9998) was:

$$\nabla P = 227500\ (Q)^{1.554} \tag{5.5}$$

and the equation for rapeseed having a porosity of 44% (R^2= 0.9995) was:

$$\nabla P = 11880\ (Q)^{1.093} \tag{5.6}$$

where:

∇P = pressure gradient (Pa/m grain depth),

Q = airflow rate $((m^3/s)/m^2)$.

The measured results were plotted (Figure 11) along with the relationship presented by ASAE (1983) for the resistance of wheat to airflows below 0.02 $(m^3/s)/m^2$.

5.5 Free-Convection Experiment

The airflow rate resulting from free-convection heat transfer in the free-convection apparatus was measured in the following experiments: A total of nine experiments were conducted, five experiments involved measuring the airflow through wheat having 47% porosity, two experiments for wheat having 44% porosity and two experiments for rapeseed having 44% porosity. In the wheat having 47% porosity, the airflow was measured for imposed temperature differences of 10, 20, 30, 40 and 45°C (experiments A to E, Table 4). In the wheat having 44% porosity, the

TABLE 3: Resistance of grain to airflow.

Grain	Porosity (%)	Airflow Rate ($(m^3/s)/m^2$)	Pressure Gradient (Pa/m)
Wheat	47	0.000221	0.29
		0.000311	0.56
		0.000407	0.84
		0.000489	1.21
		0.000594	1.52
		0.000685	1.83
		0.000781	2.17
		0.000865	2.49
		0.000962	2.87
Wheat	44	0.000137	0.25
		0.000182	0.34
		0.000227	0.49
		0.000272	0.64
		0.000317	0.83
		0.000363	1.03
Rapeseed	44	0.000137	0.83
		0.000182	0.93
		0.000227	1.23
		0.000272	1.42
		0.000317	1.72
		0.000363	2.16

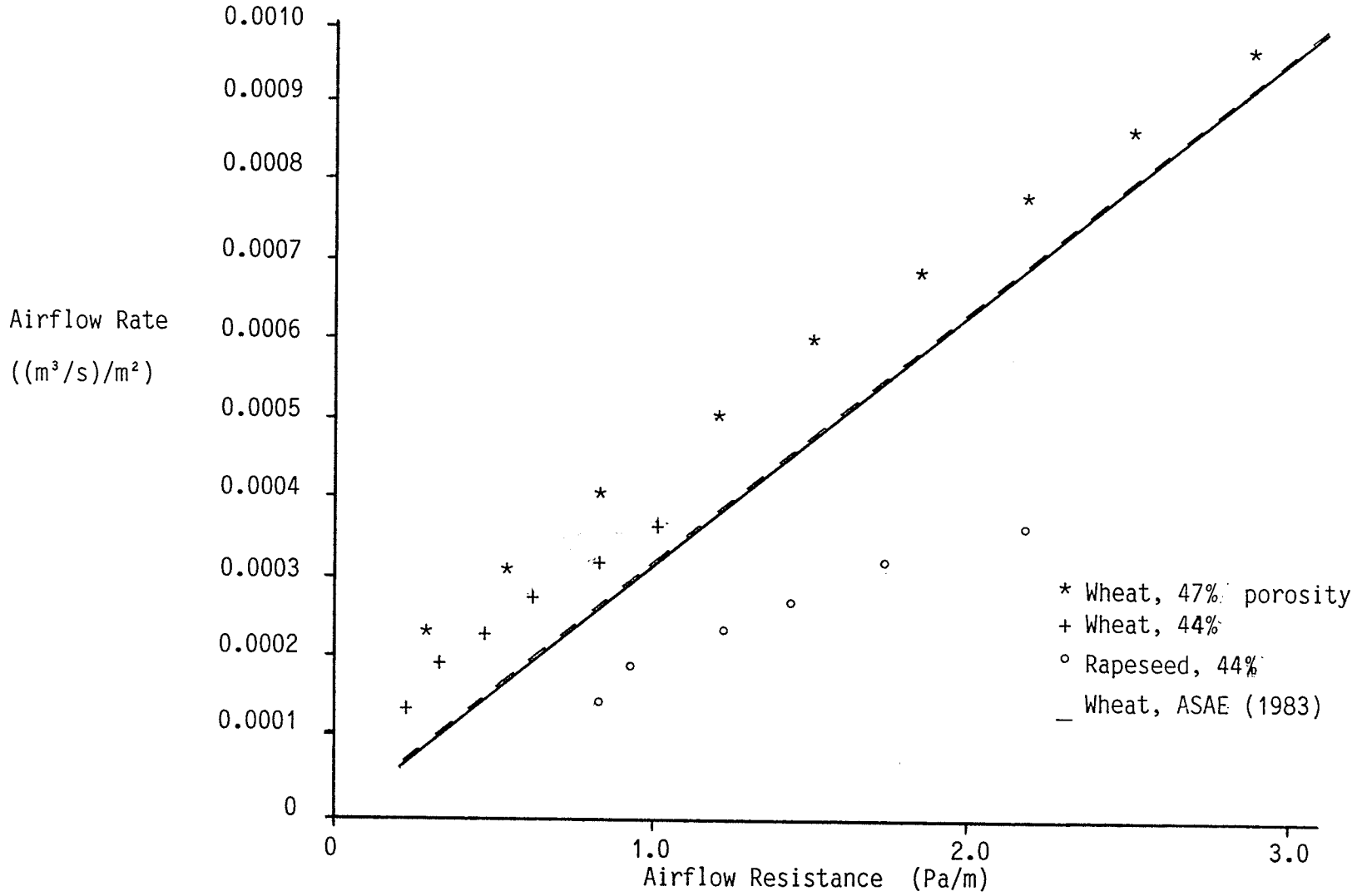

FIGURE 11: Resistance of grain to airflow: measured data and relationship presented by ASAE (1983) for wheat.

TABLE 4: Measured convective airflow rate in the free-convection apparatus.

Experiment	Replicate	Temperature Difference (°C)	Traverse Time * (s)	Airflow Rate ((m³/s)/m²)
A	1	10	5820	0.000066
	2	10	5700	0.000069
	3	10	5940	0.000064
B1	1	20	2670	0.000153
	2	20	2610	0.000158
	3	20	2520	0.000166
B2	1	20	2430	0.000174
	2	20	2430	0.000174
	3	20	2370	0.000180
B3	1	20	2520	0.000166
	2	20	2520	0.000166
	3	20	2520	0.000166
C1	1	30	1770	0.000247
	2	30	1770	0.000247
	3	30	1770	0.000247
C2	1	30	1710	0.000255
	2	30	1710	0.000255
	3	30	1770	0.000247
D1	1	40	1350	0.000309
	2	40	1350	0.000309
	3	40	1410	0.000299
D2	1	40	1410	0.000299
	2	40	1410	0.000299
	3	40	1410	0.000299
E	1	45	1290	0.000319
	2	45	1230	0.000330
	3	45	1290	0.000319
F	1	20	2790	0.000143
	2	20	2730	0.000148
	3	20	2730	0.000148
G	1	40	1710	0.000255
	2	40	1650	0.000263
	3	40	1590	0.000272
H	1	20	4050	0.000057
	2	20	3930	0.000064
	3	20	3690	0.000079
J	1	40	2940	0.000130
	2	40	2820	0.000140
	3	40	2820	0.000140

Wheat 47%

Wheat 47%

Rope 49%

* Time for tracer gas to travel 0.5 m through apparatus.

airflow was measured for imposed temperature differences of 20 and 40°C (experiments F and G, Table 4). In the rapeseed having a porosity of 44%, the airflow was measured for imposed temperature differences of 20 and 40°C (experiments H and J, Table 4). In experiments B, C and D, the apparatus was filled three, two and two times, respectively (experiments B1, B2, B3, C1, C2, D1 and D2, Table 4). This was performed to determine whether the technique used to fill the apparatus had any effect on the airflow measurement. For each experiment, the airflow was measured three times, (three carbon dioxide injections) and each injection was described as a replicate. The airflow rate was determined from the measured traverse time and the calibration equations (5.2) and (5.3). The airflow rates presented in Table 4 are considered to be the measured airflow rates as opposed to predicted airflow rates.

For each measured airflow rate, a predicted airflow rate was determined using the method described in Section (4.2). The prediction of the airflow from a given set of conditions required calculation of the pressure difference between the two columns, then, using this pressure difference and equations (5.4), (5.5) or (5.6), the airflow rate through the grain within the apparatus was calculated. The predicted airflow rates and the calculated pressure difference for each experiment are presented in Appendix C. The measured airflow was plotted against the predicted airflow in Figure 12.

The airflow rates were also predicted using the relationship presented by ASAE (1983) for the resistance of wheat to low airflows instead of the resistances measured in this investigation. The airflows predicted from the two sets of resistance data are compared in Figure 13.

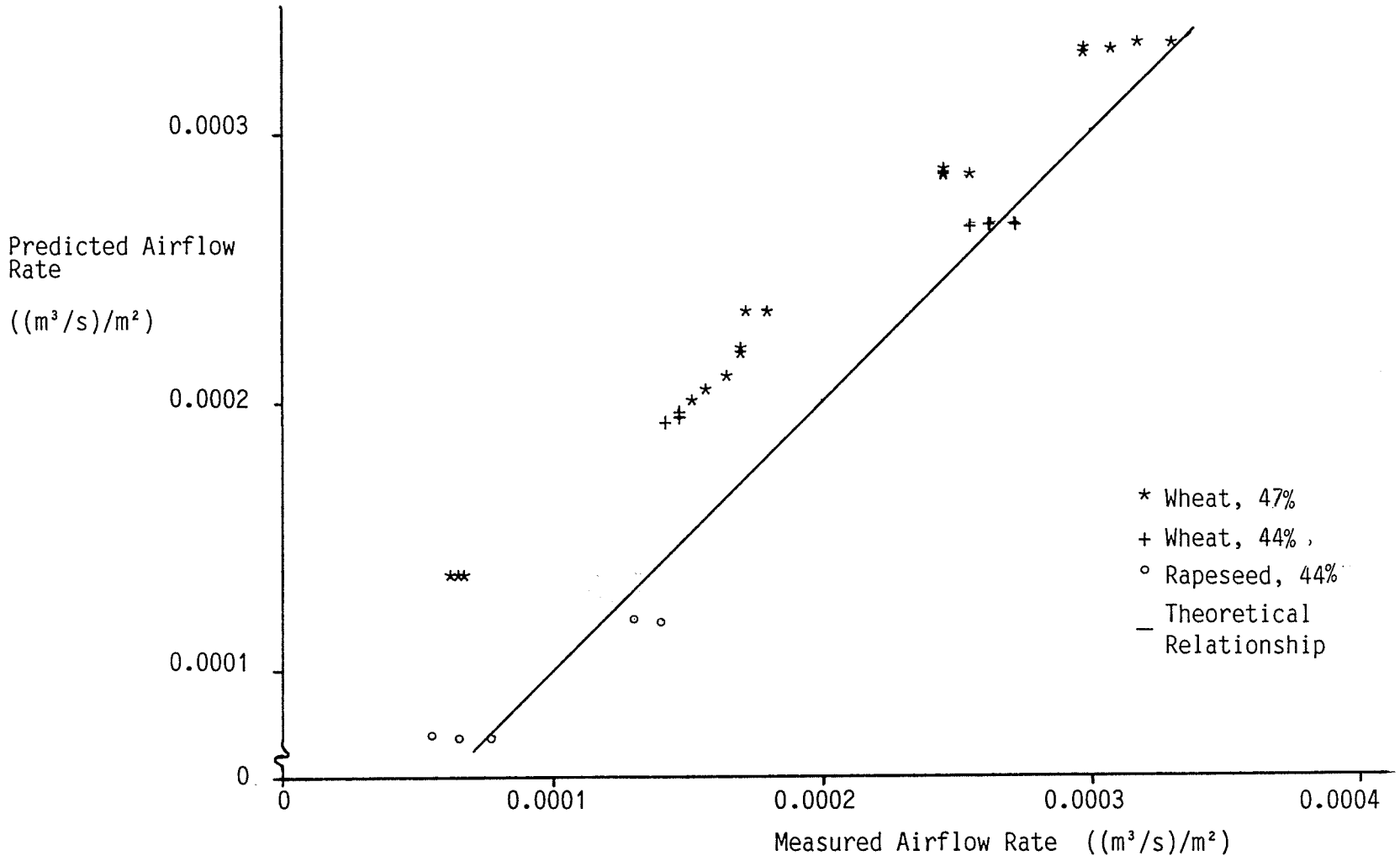

FIGURE 12: Comparison of measured and predicted airflow rates.

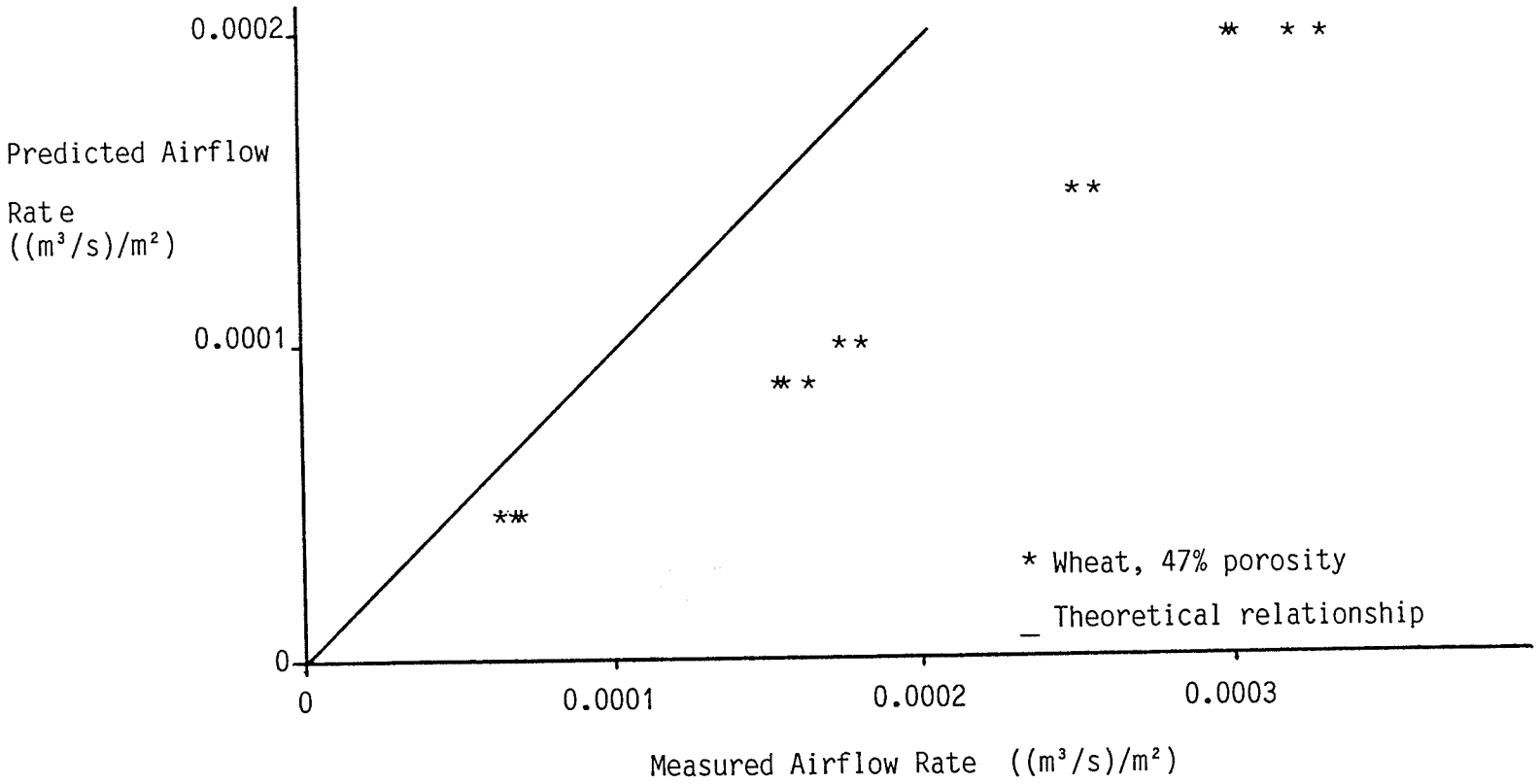

FIGURE 13: Comparison of measured and predicted airflow rates using resistances given by ASAE (1983).

5.6 Comparison Of Mathematical Models

Many of the models presented in Chapter 3 were empirical relationships for airflow through corn and, since the permeability of corn is significantly different from wheat and rapeseed, it was not useful to apply those relationships to the data collected in this study. Therefore, the model by Gunasekaran et al. (1983) was found to be the only model suitable for comparison. In Table 5, measured airflows are compared to airflows predicted by the method described in Section (4.2) and to airflows predicted using equation (2.13):

$$Q = 0.0000381 \left(\Delta T \cdot H/h \right)^{0.87} \qquad (2.13)$$

where:

Q = airflow $((m^3/s)/m^2)$,

ΔT = temperature difference $(°C)$,

H = height of hot air column (m),

h = grain bed thickness (m).

TABLE 5: Comparison of measured airflows to airflows predicted by method described in Section (4.2), and to airflows predicted using equation (2.13).

Experiment	Replicate	Measured Airflow Rate $((m^3/s)/m^2)$	Predicted Airflow Rate (4.2) $((m^3/s)/m^2)$	Predicted Airflow Rate (2.13) $((m^3/s)/m^2)$
A	1	0.000066	0.000134	0.000282
	2	0.000069	0.000134	0.000282
	3	0.000064	0.000134	0.000282
B1	1	0.000153	0.000205	0.000516
	2	0.000158	0.000212	0.000516
	3	0.000166	0.000219	0.000516
B2	1	0.000174	0.000233	0.000516
	2	0.000174	0.000233	0.000516
	3	0.000180	0.000234	0.000516
B3	1	0.000166	0.000219	0.000516
	2	0.000166	0.000219	0.000516
	3	0.000166	0.000221	0.000516
C1	1	0.000247	0.000287	0.000735
	2	0.000247	0.000286	0.000735
	3	0.000247	0.000286	0.000735
C2	1	0.000255	0.000284	0.000735
	2	0.000255	0.000284	0.000735
	3	0.000247	0.000284	0.000735
D1	1	0.000309	0.000331	0.000943
	2	0.000309	0.000331	0.000943
	3	0.000299	0.000331	0.000943
D2	1	0.000299	0.000332	0.000943
	2	0.000299	0.000332	0.000943
	3	0.000299	0.000332	0.000943
E	1	0.000319	0.000334	0.001146
	2	0.000330	0.000334	0.001146
	3	0.000319	0.000334	0.001146
F	1	0.000143	0.000194	0.000516
	2	0.000148	0.000194	0.000516
	3	0.000148	0.000195	0.000516
G	1	0.000255	0.000266	0.000943
	2	0.000263	0.000266	0.000943
	3	0.000272	0.000266	0.000943
H	1	0.000057	0.000074	0.000516
	2	0.000064	0.000074	0.000516
	3	0.000079	0.000074	0.000516
J	1	0.000130	0.000118	0.000943
	2	0.000140	0.000118	0.000943
	3	0.000140	0.000118	0.000943

6. DISCUSSION

6.1 Interpretation Of Results

The objective of this project was to develop a simple method of predicting the airflow rate resulting from free-convection heat transfer in stored grain. The predicted airflow rates ranged from 0.000022 $(m^3/s)/m^2$ lower than measured airflow rates (0.000057 to 0.000140 $(m^3/s)/m^2$) for experiments performed with rapeseed to 0.000070 $(m^3/s)/m^2$ higher than measured airflow rates (0.000066 to 0.000330 $(m^3/s)/m^2$) for experiments performed with wheat. In an attempt to determine the source of the disagreement, the methods used to measure and predict the rate of convective airflow through the apparatus were closely examined.

One potential source of disagreement was in the calculation of traverse time, the traverse time was measured to an accuracy of ±30 s. However, any inaccuracy in the measurement of traverse time only accounted for an error of less than 10% in the measurement of the airflow. Other sources of error involved with the use of the tracer gas were taken into account by the calibration performed (Section 5.3). The only source of error in the calibration of the tracer gas, that is, the measurement of the airflow, was eliminated by the calibration of the variable-area flowmeter (Section 5.1). The percentage error in the calibration of the flowmeter was considered to be about 0.25% (Section 3.5). Thus, the error involved in the measurement of the airflow rate does not by itself account for the disagreement between measured and predicted values.

A second source of disagreement was in the method used to predict the airflow rate. Predictions were based on measured grain properties, measured temperatures and the measured resistance of the grain to air-

flow. Grain properties were determined according to ASAE Standard S352.1 (ASAE 1983), and temperatures were measured with an accuracy of ±1°C. Therefore, it was judged that the error introduced into the prediction of airflow resulting from errors involved in measuring grain properties and temperatures was not significant. The only remaining source of error was the measured resistance of the grains to airflow.

The instruments used to measure the resistance of grain to airflow were the variable-area flowmeter and the U-tube pressure gauge, both of which were calibrated. However, the variable-area flowmeter was calibrated for airflows ranging from 0.0004418 to 0.176980 $(m^3/s)/m^2$; predictions based on these calibrations were for airflows ranging from 0.000057 to 0.000330 $(m^3/s)/m^2$. Thus, airflow rates were predicted in a range below the range in which the instruments were calibrated. The disagreement between measured and predicted airflow rates was greatest at the lower airflow rates, while the difference between measured and predicted airflow rates was small at the higher airflow rates. Therefore, it was judged that errors involved in measuring very low pressures and airflow rates were responsible for a large part of the disagreement between measured and predicted airflow rates.

The data obtained in the measurement of the resistance of grain to airflow (Figure 11) was different from the results of other investigations. It was expected that the data could be closely approximated by a linear relationship between pressure gradient and airflow, with the line passing through the origin, such as the data presented by ASAE (1983). However, the data were best approximated by a non-linear relationship, equations (5.4), (5.5) and (5.6). This irregularity was a second indication of possible error in the measurement of low pres-

sures and airflow rates. A comparison was made between airflow rates predicted on the basis of measured resistances and resistances reported by ASAE (1983) (Figures 12 and 13). The airflow rates predicted using ASAE resistances were consistently lower than measured airflow rates and in general, less accurate than predictions based on measured resistances.

In general, the measured airflow rates for any given temperature difference were quite consistent (Table 5). The greatest disagreement between measured and predicted airflow rates was at low airflow rates where difficulties existed in accurately measuring the resistance of the grains to airflow. Therefore, the method used to predict airflow rates resulting from free-convection heat transfer in stored grain was judged to be satisfactory when accurate information regarding airflow rate-pressure gradient relationships were available.

6.2 Relation Of Results To Observations Of Other Researchers

It was difficult to compare the results of this investigation to the results of others since very little research has been conducted into actually measuring airflow rates resulting from free-convection in grain. The data obtained for free-convection through rough rice by Gunasekaran et al. (1983) were expressed in the following equation:

$$\log(Q) = \log(0.0008) + 0.87[\log(\nabla P)] \qquad (6.1)$$

while the data for wheat having 47% porosity in the present investigation can be expressed in a similar manner:

$$\log(Q) = \log(0.00046) + 0.68[\log(\nabla P)] \qquad (6.2)$$

where:

Q = airflow $((m^3/s)/m^2)$,

∇P = pressure gradient (Pa/m grain depth).

For a pressure gradient of 0.5 Pa/m, the airflow rate through rice was 0.00044 $(m^3/s)/m^2$, while the airflow rate through wheat was 0.00029 $(m^3/s)/m^2$. Thus, the airflow rate through the rice would be about 50% higher than the airflow through the wheat for the same pressure gradient in this particular example. Gunasekaran et al. (1983) measured airflows ranging from 0.0010 to 0.0122 $(m^3/s)/m^2$, while airflow measurements made in the present investigation were made in a much lower range, from 0.000057 to 0.000330 $(m^3/s)/m^2$. When equation (2.13), presented by Gunasekaran et al. (1983) for the prediction of free-convection airflow rates, was used to predict airflow rates from calculated pressure differences in the present investigation, the results were not accurate (Table 5). Equation (2.13) was used to predict airflows through wheat having 47% porosity; the predictions were between 260 and 330% higher than measured airflows. The method used in the present investigation provided predictions that ranged from 109% higher to 18% lower than measured airflows. The accuracy of equation (2.13) for predicting airflow rates through rough rice was not reported.

Berck (1975) measured convective airflow through wheat using a tracer gas and reported that airflow rates ranged from 0.000021 to 0.000760 $(m^3/s)/m^2$ for temperature differences that ranged from 12 to 25°C. However, no attempt was made to relate the airflow rate to the magnitude of the driving force and details concerning the methods used were not provided.

The model of natural convection used by Fraser et al. (1980) was very similar to the one developed in this investigation. Both relied on an empirical relationship between pressure gradient and airflow rate to determine the airflow rate through the grain resulting from natural

convection. In this investigation, airflows were measured in a laboratory apparatus where the factors affecting free-convection were controlled as carefully as possible. In spite of this, the difference between measured and predicted airflow rates was significant. As shown in Figures 12 and 13, the use of slightly different resistance data has a dramatic effect on the predicted airflow rates. Thus, errors in the natural convection model of Fraser et al. (1980) were probably a result of incorrect assumptions concerning the resistance of grain to airflow.

6.3 Generalizations Of Results

The results of this investigation provide more quantitative information concerning the airflow rate resulting from convective heat transfer in stored grain. This information provides a reference point for researchers modelling convective flow through grain. Secondly, this investigation provides a fairly simple method of predicting the airflow rate from basic grain properties, temperature differences and the resistance of grain to airflow. This method can not yet be used to accurately predict the airflow in bins since many factors which affect the airflow rate were not taken into consideration in the laboratory apparatus. These factors are:

1. airflow patterns within the bin,

2. variations in the resistance of grain to airflow within the grain bin.

3. effects of wind pressures on the air movement within the bin.

Even if the airflow rates resulting from convective heat transfer in stored grain could be predicted exactly, the effects of convection could not be accurately predicted unless the airflow patterns within the bin were known. Thus, to predict the rate of moisture migration in a bin

requires knowledge of the airflow patterns within the bin. Airflow patterns are affected by the presence of dockage and segregation in the bin. The rate at which air moves through grain depends on the magnitude of the driving force and the amount of resistance the grain presents to the flow. In a grain bin, the resistance to flow may be quite varied, depending on the method used to fill the bin, the amount of dockage mixed with the grain and the moisture content of the grain. Finally, wind pressures on the outside of a bin can easily disrupt convective air currents in the bin. Most bins are not airtight and are usually exposed to winds. Even a fairly light wind of 24 km/h causes a pressure of 27.5 Pa on the bin wall, a pressure considerably larger than the pressure resulting from a 45°C temperature difference within the bin, which creates a pressure difference of 0.5 Pa/m grain height. The effects of wind on the movement of air within a bin has been observed by researchers measuring carbon dioxide diffusion in grain bins (personal communication, D. Waterer). Thus, the accurate estimation of moisture migration resulting from convection depends on many factors.

6.4 Limitations Of The Research

The measurement and prediction of airflow rates caused by free-convection was performed under laboratory conditions where great care was taken to control the factors affecting convection. Even with the care taken to eliminate error, the predicted airflow rates were in some cases up to 0.000070 $(m^3/s)/m^2$ higher than measured airflows. These limitations must be considered before applying the results of this investigation to any situation.

7. CONCLUSIONS

The following conclusions were drawn on the basis of the results of this investigation.

1. A method of predicting the airflow rate through grain resulting from free-convection heat transfer based on measured temperatures and grain properties was developed.

2. This empirical method of prediction was verified by comparing predicted and measured airflow rates in a laboratory apparatus and the method of prediction was found to be capable of predicting the airflow only approximately.

3. The empirical relationship developed between pressure gradient and airflow was considered to be resposible for the introduction of a large part of the error into the method of prediction. The resistance of grains to low airflows requires more study.

4. The method of prediction is judged to be only an approximate method for predicting airflow rates in actual storage bins because this investigation was conducted under laboratory conditions where many of the factors that are present in actual storage were carefully controlled.

5. Accurate predictions of moisture migration in actual storage bins requires more research into the airflow patterns within the bin, the effect of wind pressures on air movement and the resistance of grains to low airflows.

8. RECOMMENDATIONS

On the basis of the results obtained in this investigation it is recommended that in future studies of moisture migration caused by free-convection heat transfer in stored grain effort be directed toward measuring the resistance of grain to low airflows and examining the effect of wind pressures and variations in airflow resistance in bins on the patterns of convective air movement in storage bins.

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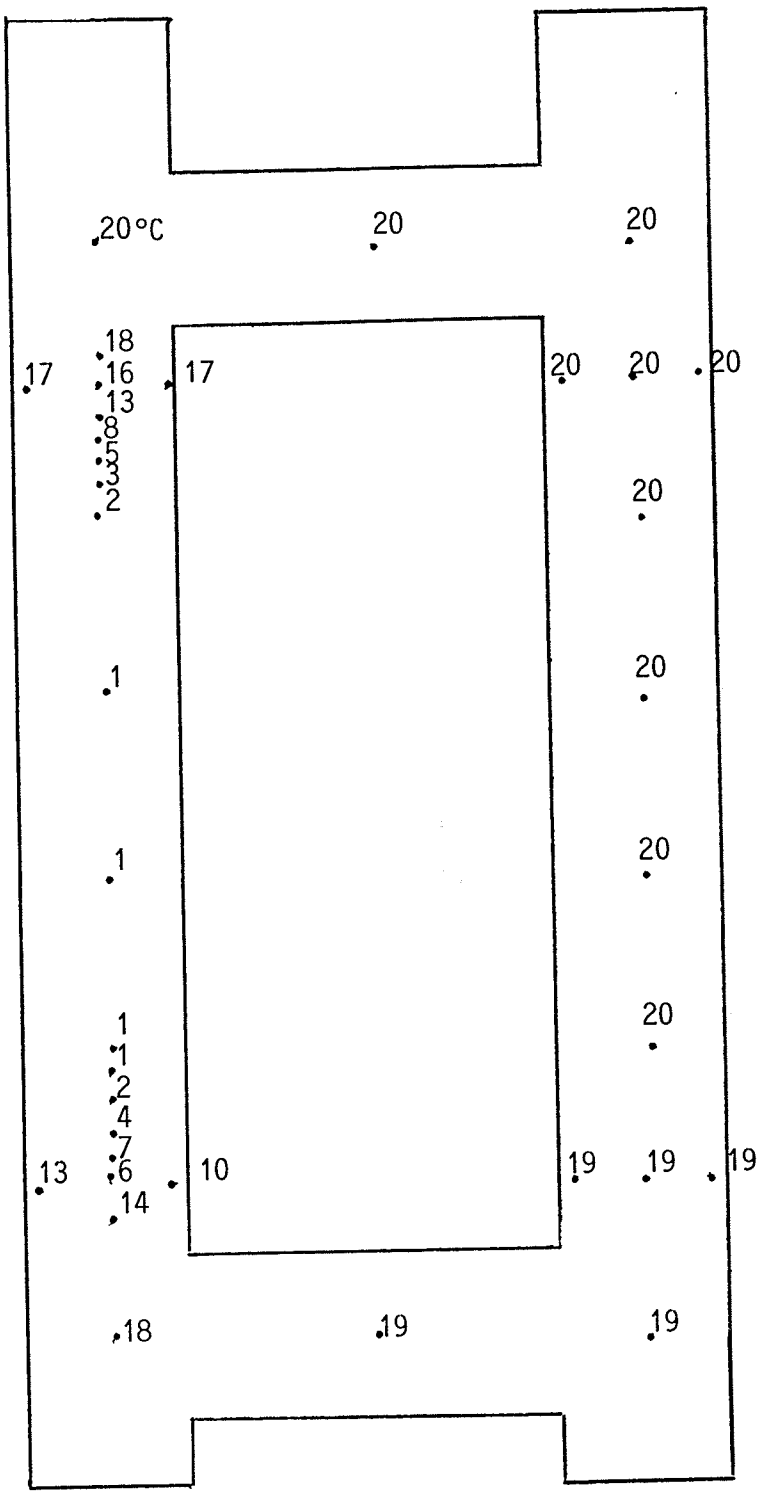
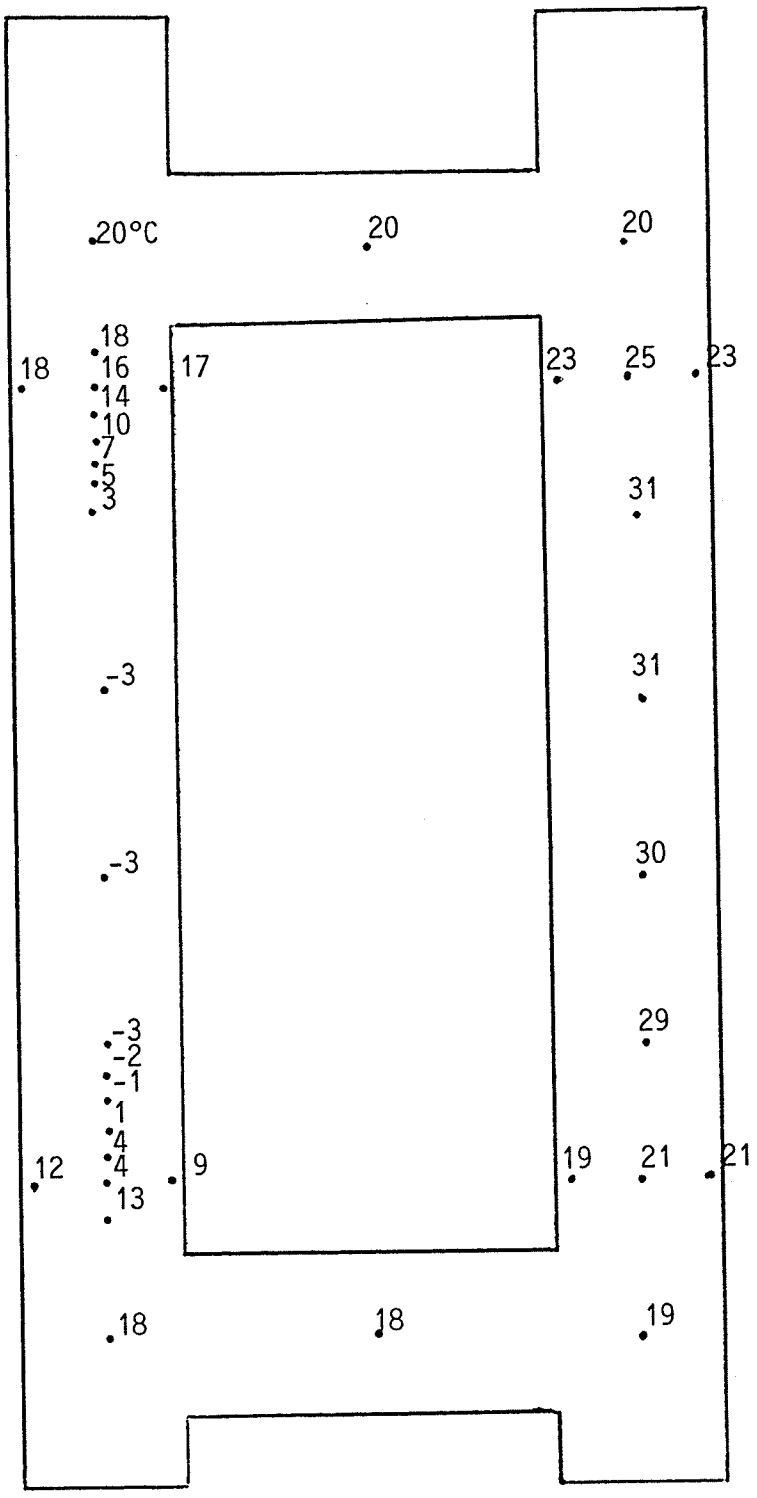
10. APPENDICES

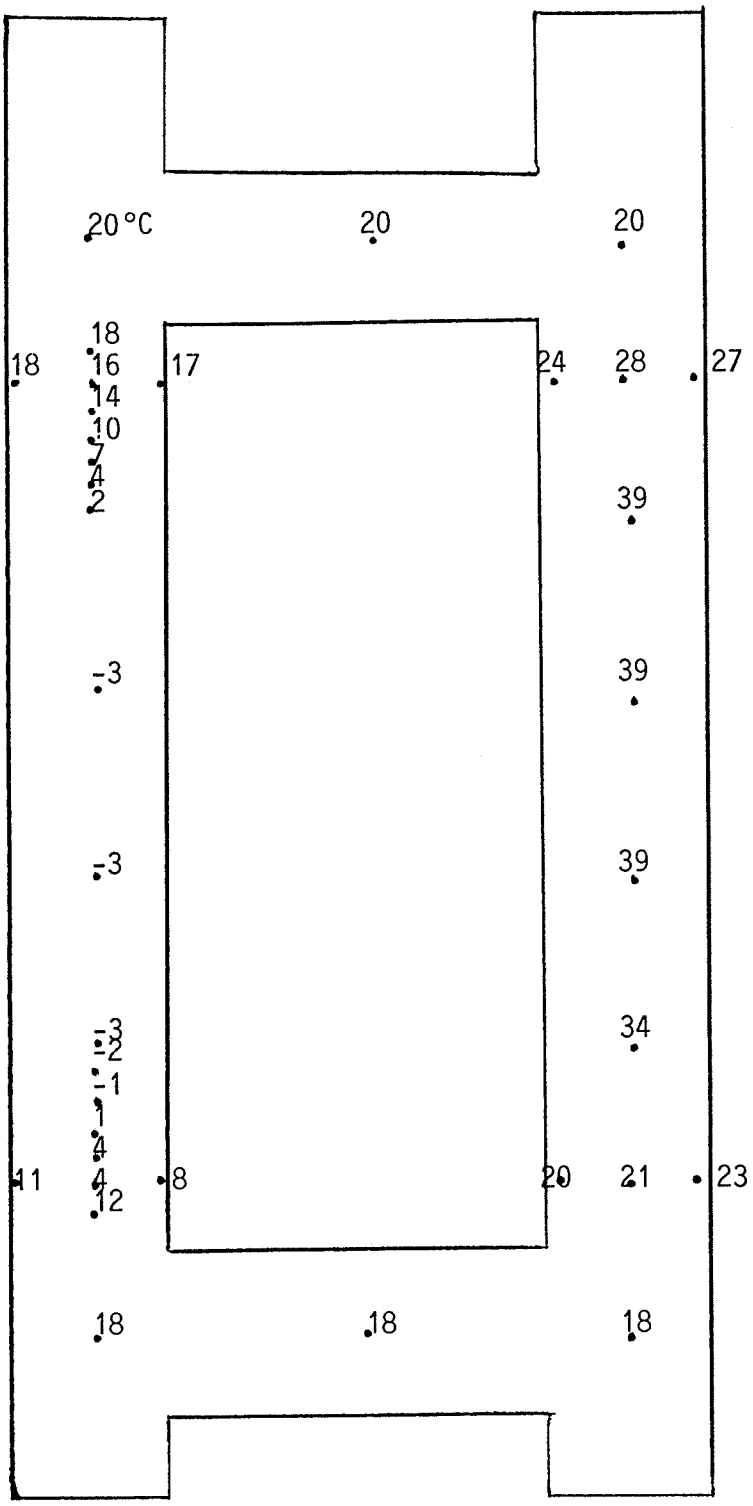
Appendix A: Typical temperature distributions in apparatus.



Experiment B1, replicate 1, temperature difference = 20°C



Experiment C1, replicate 1, temperature difference = 30°C.



Experiment D1, replicate 1, temperature difference = 40°C

Appendix B: Results of the calibration of the variable-area flowmeter.

Volume (mL)	Time (s)	Flowmeter Reading	Volume Flow Rate (mL/min)
3000	248.3	28.0	725
2000	188.3	24.5	636
2000	249.8	17.5	480
3000	661.7	8.5	272
2000	336.2	12.0	357
3000	624.4	9.0	288
3000	405.9	15.0	443
3000	355.0	20.0	507
3000	403.2	15.5	446
2000	218.6	21.5	549
2000	177.9	26.5	675
2000	205.8	23.0	583
2000	298.5	14.0	402
2000	388.5	10.5	309
2000	491.2	7.0	244
2000	556.8	5.0	215

Appendix C: Predicted airflow rates and calculated pressure differences.

Experiment	Replicate	Pressure Difference (Pa/m)	Airflow Rate ($(m^3/s)/m^2$)
A	1	0.183	0.000134
	2.	0.183	0.000134
	3	0.183	0.000134
B1	1	0.333	0.000205
	2	0.349	0.000212
	3	0.364	0.000219
B2	1	0.399	0.000233
	2	0.399	0.000233
	3	0.401	0.000234
B3	1	0.364	0.000219
	2	0.366	0.000219
	3	0.370	0.000221
C1	1	0.533	0.000287
	2	0.531	0.000286
	3	0.531	0.000286
C2	1	0.525	0.000284
	2	0.525	0.000284
	3	0.525	0.000284
D1	1	0.651	0.000331
	2	0.651	0.000331
	3	0.651	0.000331
D2	1	0.653	0.000332
	2	0.654	0.000332
	3	0.654	0.000332
E	1	0.659	0.000334
	2	0.659	0.000334
	3	0.659	0.000334
F	1	0.388	0.000194
	2	0.388	0.000194
	3	0.391	0.000195
G	1	0.632	0.000266
	2	0.632	0.000266
	3	0.632	0.000266
H	1	0.362	0.000074
	2	0.362	0.000074
	3	0.362	0.000074
J	1	0.607	0.000118
	2	0.607	0.000118
	3	0.607	0.000118

Appendix D: Computer programs-Intergration of the area below a curve.
Run on an HP 85 personal computer.

```
10 OPTION BASE !
20 DIM R(100),S(100),X(100),Y(100)
30 DISP "ENTER XMIN"
40 INPUT M1
50 DISP "ENTER XMAX"
60 INPUT M2
70 DISP "ENTER # OF DATA POINTS"
80 INPUT N
90 FOR I=1 TO N
100 DISP "ENTER X AND Y"
110 INPUT X(I),Y(I)
120 NEXT I
130 R(1)=x(1)
140 FOR I=2 TO M2-M!
150 R(I)=R(I-1)+1
160 NEXT I
170 R(I)=X(N)
180 Q=1
190 V=1
200 S(1)=Y(1)
210 FOR I=1 TO N-1
220 K=Y(I+1) Y(I)
230 L=X(I+1)-X(I)
240 Z=K/L
250 Q=Q+1
260 V=V+L
270 FOR C=Q TO V
280 S(C)=S(C-1)+Z
290 NEXT C
300 Q=C-1
310 NEXT I
320 FOR I=1 TO M2+1-M1
330 DISP R(I),S(I)
340 NEXT I
350 GCLEAR
360 PEN 1
370 SCALE 0,85,0,1
380 XAXIS 0,10
390 YAXIS 0,1
400 FOR I=1 TO N
410 PLOT R(I),S(I)
420 NEXT I
430 H=(R(N)-R(1))/N
440 P=0
450 FOR I=2 TO N-1
460 P=P+S(I)
470 NEXT I
480 A=H/2X(S(1)+2XP+S(N))
490 DISP "TOTAL AREA=",A
500 B=A/2
```

```
510 DISP "HALF OF TOTAL AREA=",B
520 T=INT(N/3)
530 N=T
540 DISP "T=",T
550 GOSUB 700
560 IF ABS(B-0)<=0.001 THEN 660
570 IF D>B THEN 620
580 N=N+1
590 DISP "N=",N
600 E=0
610 GOTO 550
620 N=N-1
630 E=D
640 GOSUB 700
650 IF E>0 THEN 680
660 DISP "CENTER LIES AT X=",N+M1-1
670 END
680 DISP "CENTER LIES BETWEEN X=",N+M1,"AND X=",N+M1+1
690 GOTO 670
700 P=0
710 D=0
720 FOR I=2 TO N-1
730 P=P+S(I)
740 NEXT I
750 D=H/2X(S(1)+2XP+S(N))
760 DISP D
770 RETURN
```

Calculation of Pressure Difference Between Columns in Free-Convection Apparatus.

```
 10 ASSIGN# 1 TO "Data"
 20 DIM X(120),Y(60),K(25)
 30 DISP "PROGRAM FOR PREDICTING THE PRESSURE DIFFERENCE BETWEEN COLD
    AND WARM AIR COLUMNS"
 40 DISP "ENTER THE SCAN NUMBER AT WHICH TO START ANALYSIS"
 60 INPUT S
 70 R=Sx2-1
 80 READ# 1,R , X(1)
 90 FOR I=2 TO 102
100 READ# 1 , R, X(1)
110 ON ERROR GOSUB 350
120 NEXT I
130 FOR I=5 TO 29
140 Y(I-4)=X(10)
150 NEXT I
190 FOR I=63 TO 87
200 Z(I-62)=X(I)
210 NEXT I
220 FOR I=92 TO 102
230 Z(-66)=X(I)
240 NEXT I
250 T1=X(4)
260 T2=X(62)
270 FOR I=1 TO 36
280 X(I)=(y(I)+Z(I))/2
290 NEXT I
300 DISP "AVG TEMPS BETWEEN";T1:"AND";T2;
310 FOR I=1 to 36
320 DISP X(I),I
330 NEXT I
340 GOTO 410
350 IF ERRN=33 THEN 380
360 DISP "ERROR" ERRN;"ON LINE";ERRL;
370 GOTTO 990
380 READ# 1; A$
390 I=I-1
400 RETURN
410 DISP "ENTER MOISTURE CONTENT OF GRAIN,%D.B"
420 INPUT M
430 FOR I=1 TO 36
440 Z(I)=1 . 8xX(I)+492
450 U=EXP(-(529.43/(Z(I)=50.998)))xEXP(-(17.609xM))
460 P=UxEXP(23.3924-11286.64897/Z(I)-.46057xLOG(Z(I)))
470 Q=.6219x(P/(14.696-P))
480 V=Qx85.78xZ(I)/(144xP)
490 Y(I)=1/Vx16
500 NEXT I
510 K(!)=.048
520 K(2)=.035
```

```
530 K(3)=.037
540 K(4)=.04
550 K(5)=.04
560 K(6)=.04
570 K(7)=.15
580 K(8)=.26
590 K(9)=.26
600 K(10)=.15
610 K(11)=.04
620 K(12)=.04
630 K(13)=.04
640 K(14)=.037
650 K(15)=.035
660 K(16)=.048
670 K(17)=.172
680 K(18)=.218
690 K(19)=.26
700 K(20)=.26
710 K(21)=.228
720 K(22)=.163
730 FOR I=1 TO 22
740 X(I)=K(I)x9 81
750 NEXT I
760 Z(1)=X(1)xY(2)
770 Z(2)=X(2)x(Y(3)+Y(4)=Y(3))/3
780 FOr I=3 TO 14
790 Z(I)=X(I)xY(I+3)
800 NEXT I
810 Z(15)=X(15)x(Y(18)+Y(19)+Y(20))/3
820 Z(16)=X(16)xY(21)
830 Z(17)=X(17x(Y(25)+Y(26)+Y(27))/3
840 Z(18)=X(18)xY(28)
850 Z(19)=X(19)xY(29)
860 Z(20)=X(20)xY(30)
870 Z(21)=X(21)xY(31)
880 Z(22)=X(22)x(Y(32)+Y(33)+Y(34))/3
890 S1=0
900 FOR I=1 TO 16
910 S1=S1+Z(I)
920 NEXT I
930 S2=0
940 FOR I=17 TO 22
950 S2=S2+Z(I)
960 NEXT I
970 F=S1-S2
980 DISP "THE PRESSURE DIFFERENCE IS";F: "PASCALS"
990 END
```