COMPUTER AIDED DESIGN FOR SOIL-AIR HEAT EXCHANGERS

by

Quanmin Lei

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ABSTRACT

Increasing demands for optimal design of buried pipe ventilation air tempering systems necessitate computer aided studies of the systems. This research work was aimed at developing design procedures. The comprehensive analysis and development of prediction equations presented here for various conditions in the system are intended to advance the understanding of soil-air heat exchanger design.

Using a finite element approach, a FORTRAN computer program was developed. The model approximately described the system phenomena of varying thermal conductivities in the soil, latent heat exchange in both soil and air, changing boundary values as well as soil moisture migration. Extensive investigations were done with the following key variables in the system: pipe diameter and pipe length, air velocity, soil properties, pipe thermal resistance, contact resistance, convective heat transfer coefficients, and undisturbed soil temperatures. The investigation included the effects of hourly, daily and seasonal air temperature variation and of continuous and intermittent operation. Dimensional analysis was first used in this study to extend the range of the simulated data for application. All of these efforts make this model unique and very advanced.

It was found that the air temperature differential between the inlet and the outlet could be 3 °C or more when water vapor condensation occurred in a pipe length of more than 20 m. The design curves presented

show that lower airflow rates can use shorter pipe lengths while higher airflow rates will require longer pipe lengths in order to obtain the same temperature differential. A smaller pipe diameter results in a higher temperature differential compared to a larger pipe diameter but may not result in higher energy. The low thermal conductivities of plastic pipes can reduce the temperature differential approximately 2 °C compared to other materials such as copper. Poor contact condition at the interface between the pipe wall and the soil may cause about 3 °C difference in outlet air temperatures in comparison to intimate contact. High density and high moisture content of soil improved thermal performance. Increasing the ratio of the heat transfer coefficient to the air velocity significantly increased the temperature differential. Air temperature differentials also increased linearly with the increase in undisturbed soil temperature. All of the simulated data varied exponentially in a plot of dimensionless groups.

Validated by comparison to another theoretical analysis, this model provided an average difference of 4 °C between the measured and the predicted outlet air temperatures for winter operation. It was concluded that the simulated curves or the approximate equations developed in the present investigation can be used in preliminary designs of soil-air heat exchangers.

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Chapter I

INTRODUCTION

1.1 POTENTIAL OF SOIL-AIR HEAT EXCHANGE

Harnessing nature through technology has become a common practice. In the face of rising concerns about energy supplies throughout the world, recent efforts to utilize natural resources have caused a widespread interest in using underground pipes as air inlets to supply air for thermal environmental modification. This method of preconditioning ventilation air with low energy consumption shows promise in livestock and plant growing structures.

An air tempering system using soil as a heat source or sink usually employs buried pipes in which air is circulated to achieve temperature and humidity control. Research conducted on soil temperatures has indicated that there exists a time lag between seasonal mean air temperature and seasonal mean soil temperature. Soil temperatures at depths of more than two meters remain relatively constant in spite of variation with location, type of soil, depth, time of year, etc.. For a very cold or hot season, existence of a great temperature difference or thermal potential between soil temperature and air temperature makes the above innovative idea possible. It is thus reasonable to expect that some cooling and dehumidification can be obtained without mechanical refrigeration when ambient air is forced through the buried pipe in summer. Winter ambient air temperatures can be increased by as much as 16 °C or more (Scott et al. 1965), depending mainly on the airflow rates, pipe lengths, and the ambient air temperatures. Although the soil microclimate in the vicinity of the buried pipes will undergo seasonal changes, a soil with a high heat capacity presents an excellent heat source or sink on a short-term or seasonal basis.

Livestock environmental research has shown that the "thermal stress" in farrowing houses due to seasonal and daily temperature variations significantly reduces production. To provide a desirable livestock environment, soil-air heat exchangers are capable of effectively reducing heating or cooling loads. The air tempering system could also provide an economical and less energy consuming means of environmental enhancement for greenhouses, human dwellings, and other buildings.

1.2 NEED FOR A COMPUTER SIMULATION MODEL

The use of a soil-heat source or sink is not "free". A mechanical system is required to force air through the pipe for the soil-air heat exchange. The major problem associated with using the thermal potential involves finding an efficient method of extracting or injecting heat. It is essential to select appropriate parameters such as air velocity, pipe diameter and pipe length to balance the energy required for air movement against the increased heat transfer rates at high rates of airflow over a specific range.

A large number of uncertainties regarding overall heat transfer characteristics both in the soil and in the air have greatly retarded application of the exchanger. Experiments can reveal these uncertainties. But various conditions and variables within the system are very expensive to include in a complete experiment and would require very long experiment duration. In the Canadian prairie climate little or no useful data are available. Existing theoretical models for buried pipe air tempering systems are very limited and of little use. To meet the needs of designers of soil-air heat exchangers research efforts are needed to collect reliable field data and to develop a comprehensive mathematical model for analysing the entire system.

1.3 OBJECTIVE OF STUDY

1. To develop a finite element model describing the system phenomena including varying material properties, latent heat exchange both in the soil and in the air, and changing boundary values as well as soil moisture movement near the pipe.
2. To study the system performance characteristics over a broad range of practical conditions and to develop information for design purposes.
3. To use Glenlea test conditions for comparison of field data to simulated data, emphasizing the development of design procedures.

Chapter II

REVIEW OF LITERATURE

2.1 HISTORICAL BACKGROUND

The earth on which we live has been intriguing researchers' imaginations for centuries. The concept of using deep soil to cool or warm ventilation air can be traced back to at least 900 A.D. (Bahadori 1978). It was only after the Second World War, however, that the concept gained the attention of numerous scientists. Recently, increasing concerns about the availability and cost of energy throughout the world have greatly expanded the interest in ventilation air tempering systems using the soil as a heat sink or source.

Over one thousand years ago Iranian architects began to use the underground to cool ventilation air in their buildings (Bahadori 1978). One of the common methods of tempering the indoor environment consisted of a wind tower and a soil-air heat exchanger. Bahadori described it in this way:

> "The wind tower is placed some 50 m from the building and is connected to it by a tunnel. When the trees, shrubs and grass in the ground over the tunnel are watered, water seeps through the soil and keeps the inside surfaces of the tunnel walls damp. Thus air from the tower is evaporatively cooled as it passes through the tunnel."

The outlet was in the basement of the building and from there the air was circulated to the upper floors. Other passive systems included a wind tower operating directly in conjunction with an underground stream. Since underground water is usually cold, compared to ambient air, the air at the outlet was so cool that food was often stored in the basement. The use of the soil as a heat source was also introduced in a Swiss patent by Zoelly in 1912. The technology is already widely used, mainly in Sweden, Germany, France and to a lesser extent in other European countries (Svec et al. 1983).

In the late 1940's and the early 1950's there were a considerable number of attempts in the U.S. and Europe to develop soil heat pumps to the commercial stage. However, these systems were associated with high initial costs and an insufficient ability to produce an optimum thermal environment. They soon lost out in competition with conventional air conditioning because of the availability of cheap energy at that time. Interest was mainly limited to research. In 1946 a survey was conducted on the use of soil, air and underground water as three basic resources for heat pumps by the Southern Research Institute, Birmingham (Kemler 1946).

From 1948 to 1950 the Philadelphia Electric Power Company did research with two residential soil heat pumps in the Philadelphia area in the U.S. (Kidder and Neher 1952; Harlow and Klapper 1952). A ground coil system has been operated in a house in Vancouver, B.C., Canada since 1948 (DBR Report PC5 1953). Hopper (1952) studied the performance of a soil heat pump installed in a five-room house at Port Credit, Ontario, Canada. Griffith (1952) reported heat extraction rates of 30 to 60 W/m for copper pipes buried at a depth of 2 m in "moist soil" in England. Smith (1951, 1956) has investigated factors useful in ground grid design for heat pumps for several years, based on an experimental installation at the University of Washington. Considerable research with soil heat pumps has been done in the St. Louis area (Whitlow 1953) and in Hopkinsville, Kentucky, U.S. (Baker 1953). Vestal and Fluker (1956) have completed an investigation of the use of soil at shallow depths as a heat source or sink for a heat pump. Fifty-seven tests of both continuous and intermittent operation were conducted in Texas, U.S..

In the 1960's more comprehensive research was done with emphasis on determining soil heat transfer coefficients, the effect of intermittent operation and exchanger efficiency. One of the few controlled studies was reported by Scott et al. (1965). The tests, conducted at Cornell University from March 1964 until December 1965, attempted to determine the capability and efficiency of soil-air heat exchangers and to develop a design criterion for such systems. Based on an installation of 15 m of 16 mm diameter copper tubing placed 1.2 m below ground level, Cropsey (1966) endeavored to correlate some experimental results with various theories on heat transfer to a saturated soil. But based on the cost of energy in the 1960's, the usefulness of the soil-air heat exchanger was still questionable from an economic point of view.

In recent years, demand for energy saving techniques has revived interest in soil-air heat exchangers as part of a solar supplemented passive system. The use of low cost plastic pipes instead of more expensive metal tubes improved the economic aspects. Rosenblad (1979) described an array of 19 vertical 10 m long, 90 mm diameter PVC pipes used as a soil heat exchanger. Acevedo (1979) reported the results of experiments conducted to use the soil for air conditioning in the high

Mojave desert. Design data for air flow in plastic corrugated drainage pipes were collected by Carson et al. (1980). At Purdue University, Eckhoff and Okos (1980) tested water, saturated soil, rock and phase change materials as three thermal storage media to determine their feasibility for agricultural application. Many other more elaborate soil-air systems with plastic pipes have been built in the past decade. One of these systems has been studied near Fort Atkinson, Wisconsin, U.S. from 1979 to 1981 (Cramer and Kammel 1980; Kammel and Cramer 1981). In southwestern British Columbia, a network of buried pipes under a greenhouse floor was used to store excess solar energy (Staley et al. 1983). More complete research with soil-air heat exchangers has been conducted in Illinois, U.S.. Several of these systems, mostly installed on swine facilities, have been in operation since 1978 (Goetsch et al. 1981; Goetsch and Muehling 1983).

A number of mathematical models have been developed for analysing buried pipe systems. The theoretical analyses use various methods from the classical theory for soil-pipe heat conduction developed by Ingersoll and Plass (1948, 1951) to a large assortment of computer programs using varying degrees of sophistication. These endeavors have definitely confirmed the potential for soil-air heat exchangers.

2.2 THEORETICAL DEVELOPMENT

Most of the existing models of heat conduction associated with buried pipes are founded on classical theory due principally to Jean Baptiste Joseph Fourier (1768-1830). One of the most authoritative works on the subject in the 1940's was that of Carslaw and Jaeger (1959).

Allen (1920), King (1947) and others initially studied heat transfer from pipes buried in soil. However, Ingersoll and Plass (1948, 1951) brought some order and set forth a relatively simple treatment of the problem. Their work suggested that a mathematical model should be established with simplifying assumptions because of the following difficulties:

1. Lack of knowledge of thermal conductivity and diffusivity of soil in a given location;
2. Moisture migration from the warmer to the colder regions;
3. Possible underground water movement;
4. Ice formation around the pipe;
5. Periodic temperature variation;
6. Possible boundary layer effects;
7. Lack of intimate contact of the exchanger with the soil.

There are also difficulties in determining soil temperatures at any given depth and convective heat transfer coefficients at the pipe wall due to possible condensation or evaporation of moisture inside the pipe.

Therefore, the solution to the most general equations for heat conduction in pipes buried in soil presents a great challenge. Assuming an infinitely permanent line heat source or sink (constant heat flow rate) in an infinite soil medium at a uniform initial temperature, Ingersoll et al. (1954) gave the temperature differential ΔT' (°C) between the initial soil temperature and the point under consideration at or near the pipe as:

$$\Delta T' = \frac{Q}{2\pi k} \int_{s}^{\infty} \frac{\exp(-\beta^2)}{\beta} \, d\beta = \frac{Q}{2\pi k} I(s) \qquad [2\text{-}1]$$

where,

Q = rate of heat flow per unit length of pipe, W/m
Pi = 3.14159
$s = r / [2(\alpha t)^{0.5}]$
k = soil thermal conductivity, W/(m°C)
r = distance from pipe center line (applicable to pipe surface), m
α = soil thermal diffusivity, m^2/s
t = time after start, s
β = variable of integration.

This equation is only valid for $\alpha t/r^2>20$. Carslaw and Jaeger (1959) gave a more general equation involving Bessel functions:

$$\Delta T' = \frac{Q}{k} G(x,p) \tag{2-2}$$

where,

$$G(x,p) = \frac{1}{Pi^2} \int_0^{\infty} (e^{-\beta^2 x} - 1) \frac{J_0(p\beta)Y_1(\beta)-Y_0(p\beta)J_1(\beta)}{[J_1^2(\beta)+Y_1^2(\beta)]} \frac{d\beta}{\beta^2}$$

$x = \alpha t/R^2$
Pi = 3.14159
R = pipe radius, m
$p = r/R$.

Scott (1962) has developed a steady-state model to approximate the mechanism of soil-air heat exchange. It is assumed that the pipe, buried at an isolated depth, is surrounded by two distinct soil cylinders. By equating the heat loss by the air with the heat gain by the soil, the outlet temperature can be expressed as:

$$To = Tus + \frac{(Ti - Tus)}{\exp\left(\frac{U\ L}{M'Ca}\right)} \tag{2-3}$$

where,

To = outlet air temperature, °C
Ti = inlet air temperature, °C
Tus = undisturbed soil temperature, °C
U = overall coefficient of heat transfer between air and soil, W/(m°C)

L = pipe length, m
M' = mass air flow rate, kg/s
Ca = specific heat of air, J/(kg°C).

A more simplified approach for calculating heat transfer as a function of pipe length, L (m), has been used by Kreider (1980). The heat, Q (W), transferred at a slow rate is given by

$$Q = 0.7\, L \frac{Ti - To}{\log\left(\dfrac{Tus - Ti}{Tus - To}\right)} \qquad [2\text{-}4]$$

Scott et al. (1984) have recently developed a periodic steady-state model in order to make better predictions for an actual operation. Using the conduction transfer function method, Kimball (1983) also predicted heat fluxes into various soils.

In addition, a number of mathematical models have been developed for the evaluation of heat losses from subsurface pipes carrying hot water. The method of images was used by Kendrick et al. (1973) to calculate the heat loss from a hot water pipe buried at a given depth below the surface in a homogeneous soil with a constant soil surface temperature.

However, no mathematical models cited will accurately describe the mechanism because of many factors affecting the exchanger performance. To meet the demands for the design of the soil-air heat exchanger it is required that a high level of mathematical model be developed and that the system variables be comprehensively studied.

2.3 EXPERIMENTAL INSTALLATION AND DATA COLLECTION

A fairly large number of experimental installations of soil-air heat exchangers have been examined since the 1950's. The pipe materials used in most experiments can be classified either as metal or as plastic.

2.3.1 Metal Conduit

Smith (1951) conducted one of the early experiments at the University of Washington. The exchanger, using F-12 gas as a working fluid, consisted of 45 m of U-shaped copper tubing, 13 mm and 19 mm in diameters, buried at depths from 1.22 m to 1.80 m. This work was an attempt to find reliable information on the coefficient of heat transfer, the time of continuous operation, the effect of moisture migration, the average number of hours of actual operation during heating or cooling seasons and annual heat absorption per square meter of soil area. Further tests of this type used Dichlorodifluoromethane as a working fluid with intermittent operation (1952-1953).

Freund and Whitlow (1959) studied several tubing coils in soil to gain experience in the characteristics, design and operation of heat pumps using a soil heat source. One of the studies used horizontal coils made from 488 m of 28.6 mm diameter copper tubes in four sections of 122 m each. The tubes were laid in trenches 1.2 m deep and 0.3 m wide. The refrigerant in all cases was F-12. One year's operation of nine heat pump installations produced valuable information.

Three separate U-shaped copper tubing coils of 12.7, 25.4 and 50.8 mm diameters, each of 49 m nominal length, buried 1.5 m below the soil surface were tested in Texas (Vestal et al. 1956). A dimensional analysis was used to obtain the correlation of test data. Cropsey (1966) conducted similar research using a building made for the experiment. The building had a calculated heat loss of 23.5 W with a 1.8 °C temperature difference between inside and outside. He used 15.2 m of 15.9 mm copper tubing placed 1.2 m below the surface in a 7.6 m long trench, 0.6 m wide, to heat the building.

A soil-air heat exchanger, consisting of 134 m of Armco HEL-COR pipe, 457 mm in diameter, buried at an average depth of 2.4 m in a silty clay soil, has been investigated on the Cornell Poultry Research Farm since 1964 (Scott et al. 1965). It was reported that the airflow rates of approximately 0.6129 kg/s, 1.1199 kg/s, and 1.3696 kg/s provided a favorable heat transfer effect on both continuous and intermittent operation.

2.3.2 Plastic Pipes

Research by Cramer and Kammel (1980, 1981) applied soil-air heat exchangers for cooling or heating a swine farrowing house. Four perforated plastic drainage pipes, 152 mm in diameter, each connected to 304 mm diameter PVC risers at a depth of 1.22 m below the soil surface were employed in the system. It was found that the system effectively leveled the diurnal temperature peaks and valleys.

The physiological benefits of using a buried pipe to temper ventilation air in swine operations have been examined by Weisbecker and Jacobson (1980). The system consisted of a network of buried corrugated plastic drain tiles. A rough economic analysis was done using the air temperature measurements from this underground air tempering system.

In central Illinois, several air tempering systems using nonperforated, corrugated plastic drainage pipe as heat exchangers have been monitored since 1981 (Goetsch et al. 1981, 1983). These installations have provided for refinement in construction, development of installation guidelines and determination of optimum pipe lengths. The soil-air heat exchangers have been used to heat or cool swine farrowing-nursery houses. Most soils involved were silty loam and silty clay soils. It was recommended that narrow trenches with rounded bottoms and hand blinding methods be used to ensure constant slope and minimal tile deflection and damage. It was also suggested that tile lines be 2.4 m to 3.0 m apart, if possible, so as to maximize soil heat storage. Data collected from these systems indicated that the use of soil-air heat exchangers for preconditioning livestock ventilation air holds a great deal of promise.

A laboratory experiment with PVC pipe was conducted by Svec et al. (1983). They attempted to evaluate heat transfer characteristics of soil-air heat exchangers. Dale and Turner (1979) also tested a solar energy collector with reflective wings which supplied several buried PVC pipes with energy for heating soil and groundwater.

There is no doubt that the above research has advanced the state of the art of soil-air heat exchangers. It should be noted that it is the drainage tile industry, with the introduction of corrugated plastic pipe, that has helped reduce the cost of the systems. However, many questions about the systems still remain unanswered.

2.4 FACTORS AFFECTING THE EXCHANGER PERFORMANCE

2.4.1 Soil Temperature

Undisturbed soil temperatures and initial soil temperatures near the pipes appreciablly affect the exchanger performance. Penrod and Steward (1966) measured soil temperatures to a depth of 3.4 m for ten successive years and showed conclusively that the annual variation in daily mean soil temperatures is harmonic. According to Kusuda and Achenbach (1965), the annual soil temperature cycle, Tus(y,t), for a soil with a given thermal diffusivity may be approximated by the simple harmonic function:

$$Tus(y,t) = Tm + A \exp(-y/D) \sin(wt-P_0-y/D) \qquad [2\text{-}5]$$

where,

- Tm = annual mean soil temperature, °C
- A = amplitude of the soil surface temperature cycle, °C
- y = depth, m
- D = $(2a/w)^{0.5}$ soil damping depth, m
- w = angular velocity of the surface temperature variation, rad/day
- P_0 = phase angle of the soil temperature cycle relative to a data point, rad
- a = soil thermal diffusivity, m^2/day.

Based on station measurements they listed the values of Tm, A and Po for various soil temperature stations in the U.S.. For a similar model, Smith et al. (1966) presented a method whereby one can accurately measure and interpret soil temperatures.

To investigate the feasibility of tempering ventilation air, Costello et al. (1984) have developed an interesting soil temperature model. Local average monthly shallow soil temperature data are fitted with the help of multiple linear regression to a sine-wave. The derived shallow soil temperature parameters allow estimation of temperatures at other depths for determining the potential energy available from the system.

2.4.2 Thermal Properties of Soils

There are substantial amounts of data scattered throughout the literature on thermal properties of soils of wide textual characteristics. Gravel, sand, sandy loam, silt loam, and clay, and even rocks and peats have been thermally described.

No solution of a buried pipe heat conduction problem can be undertaken without a considerable knowledge of the thermal properties of the soils involved. The most important property is thermal conductivity. Kersten (1948) did many experiments to determine this property. Nineteen different soils were monitored at various conditions of moisture content and density. It was found that the thermal conductivity differs according to whether the soil is frozen or not. At a constant moisture content, an increase in density results in an increase in conductivity. An increase in moisture content at a constant density also results in an increase in conductivity. Thermal conductivity, k, in W/(m°C), can be predicted for practical purposes as follows:

For silt and clay soils, unfrozen:

$$k = 0.1442\,[0.9\log(m.c.\%) - 0.2]\,A \qquad [2\text{-}6]$$

where,

$$A = 10^{0.0006243\,\gamma}$$

γ = soil density, kg/m^3.

For silt and clay soil, frozen:

$$k = 0.1442\,[0.01\,A + 0.025\,B(\text{m.c.\%})] \qquad [2\text{-}7]$$

where,

$$A = 10^{0.0013197\,\gamma}$$

$$B = 10^{0.0008740\,\gamma}.$$

The equations apply for soil moisture contents greater than 7 percent and the predicted results should be accurate within 25 percent.

DeVries (1963) has presented a survey of theoretical work which expresses the thermal conductivity as a function of the conductivities and volume fractions of soil constituents as analogous to expressing the electric conductivity of a granular material. An ideal soil cube presented by Parkerson (1951) has also been used to demonstrate and evaluate the interrelation and correlation of the thermal conductivity of soils. Field readings of thermal conductivity at several research stations in the Tennessee Valley area have been taken from 1949 to 1951 (Carter 1951). Carter believed that the thermal conductivity was sensitive to moisture change.

A laboratory study on thermal conductivity of soils for use in the design of soil-air heat exchangers has been pursued by Smith et al. (1950). Three methods that were used were Kersten's soil container, a buried sphere and a cylindrical soil container for transient testing. These have been adapted to approach actual soil conditions and to compare with the data from other workers. No general equations for mathematical determination were given because of insufficient experimental data. But several charts for estimating thermal conductivities of different soils under given conditions have been introduced.

Thermal diffusivity is another factor which influences the soil heat exchange process. It is expressed as the ratio of the thermal conductivity to the heat capacity per unit volume of soil. The volumetric heat capacity of soil (Cs) can be found by adding the heat capacities of the volume fractions of solid material, Xs, water (or ice), Xw, and air, Xa, in one cm^3, respectively (DeVries 1963). Thus, if Cs', Cw, and Ca denote the heat capacities of solid material, water (or ice), and air, respectively, one has

$$Cs = Xs\ Cs' + Xw\ Cw + Xa\ Ca \tag{2-8}$$

The specific heats of twelve different mineral soils and soil materials were measured by Kersten (1948). He found that the specific heat of most soil minerals varied linearly from 0.67 ± 0.04 J/(cm^3 °C) at -18 °C to 0.80 ± 0.04 J/(cm^3 °C) at 60 °C.

Carter (1951) measured both the specific heat and thermal diffusivity of various soil samples. It was reported that in most cases the variation in thermal diffusivity with moisture is small over the range of 10 to 25 percent soil moisture content.

2.4.3 Meteorological Variables

Meteorological variables, including hourly ambient air temperature and relative humidity ratio or moisture content of the air, noticeably influence exchanger performance. Geiger (1965) described the phenomenon of the climate near the ground which greatly affects the shallow soil temperatures. Local weather data must be consulted before sizing exchangers. Monthly Meteorological Summary, Monthly Radiation Summary, Environment Canada, Atmospheric Environment and The Climates of Canada for Agriculture are some of the good sources for determining these variables.

2.4.4 Airflow Rate

Airflow rate is one of the key parameters on which pipe outlet air temperature is dependent in a ventilation air tempering system using a soil heat source or sink. The air flow rate selected must meet the demands of the facilities to be conditioned and must also keep the coefficient of performance or heat energy ratio as high as possible. Mass air flow rates or air velocities are usually recommended in design procedures.

2.4.5 Pipe Type, Diameter and Length

While initial cost and ease of installation of a soil-air heat exchanger are important, the selection of the type of pipe depends primarily upon flow characteristics of air in the pipe, the pipe thermal properties, chemical resistance and mechanical endurance. In recent years, the choice has focussed mostly on plastic corrugated drainage pipes and PVC pipes in various configurations for economic reasons. Many researchers (Svec et al. 1983; Bose et al. 1979) have demonstrated that there is a significant drop in extraction rates due to poor thermal conductivity of the plastic pipe. However, it is believed that thermal conductivity of the pipe has little effect on pipe outlet air temperatures in spite of the great drop in extraction rate (Spengler and Stombaugh 1983).

Sizing pipe diameter and length for the exchanger is difficult and requires considerable knowledge of the system. Penrod (1954) illustrated the method of Ingersoll and Plass for determining pipe length. Using the same method, Smith (1951) calculated and plotted a family of curves for several types of soils showing the relation of the outside pipe diameter to its heat transfer factor, q, $W/(m^2\,^\circ C)$. His work indicates that long smaller diameter pipes are more effective per unit of area than short larger diameter pipes.

Vestal and Fluker (1956), on the basis of experimental investigations, derived a design equation for buried pipe heat pumps by means of dimensional analysis:

$$L = \frac{Q}{[a\,(Ta/Tr)^{m}\,(Sr)^{n}\,](Ta-Tr)I} \qquad [2\text{-}9]$$

where,

- L = pipe length, m
- n = a constant, 0.29
- m = n/(d+1)
- Q = total instantaneous rate of heat transfer, W
- d, a = empirical constants
- Ta = average fluid temperature in the pipe, °C
- Tr = average soil temperature at the pipe depth, °C
- Sr = initial or reference degree of soil saturation
- I = intermittency or continuousness factor based on dimensionless group variable plotting.

Based on theoretical analysis for economic optimization of buried pipe parameters, pipe lengths from 10 m to 120 m and pipe diameters from 100 mm to 380 mm have been estimated by Spengler and Stombaugh (1983). Installations using buried pipes as air tempering systems in Illinois indicate that as the pipe size increases the relative cost per unit length markedly rises. Pipe diameters from 76 mm to 610 mm and pipe lengths from 15.2 m to 152.4 m corresponding to airflow rates from 0.010 m^3/s to 0.74 m^3/s are suggested for a preliminary design of the system.

2.4.6 Heat Transfer by Convection

The convective heat transfer coefficient depends primarily on the flow conditions, which can be characterized by the Reynolds number, Re, and on the air temperature profiles resulting from the rate of heat flow through the pipe and the soil medium.

Spengler and Stombaugh (1983) have used the data describing friction factors for corrugated drainage pipes (Carson et al. 1980) to adjust the Nusselt number determined for fully developed, turbulent flow in smooth pipes. The Nusselt number for corrugated pipe, Nur, is calculated by:

$$Nur = 0.023\ Re^{0.8}\ Pr^{0.4} * COR \qquad [2\text{-}10]$$

where Pr is the Prandtl number, and the correction factor is:

$$COR = 1.7 + (6*10^{-6} Re)$$

if Reynolds number, $Re \leq 133{,}000$ (General Electric 1977).

Sibley and Raghavan (1984) have studied heat transfer coefficients for air flow in plastic corrugated drainage tubes. Their results indicate that the drainage tube heat transfer coefficients are similar in magnitude to those found in smooth pipes of the same nominal diameter. An empirical relationship relating Nusselt number to Reynolds number was derived for prediction purposes.

There is a possibility of condensation occurring when saturated air comes in contact with a pipe surface at a lower temperature. Chaddock

(1957) conducted an investigation of the average deterioration of the heat transfer coefficient inside horizontal tubes for several refrigerant vapors. Heat transfer data were also taken by Akers and Rosson (1960) for methanol and Freon-12 condensing inside a horizontal tube. Both experimental and analytical results presented by Chato (1962) for determination of condensation performance inside horizontal and inclined tubes have shown significant increases in overall heat transfer. Moreover, Soliman (1971,1982) has undertaken extensive studies, both analytically and experimentally, on two-phase flow patterns with condensation inside horizontal tubes. Five data sets corresponding to different combinations of tube diameter and test fluid including steam were obtained in the investigation (Soliman 1983).

Unfortunately, none of these data or developed equations would be valid for air and water mixtures simply because of different fluid conditions. Little attention has been given to the analysis of heat transfer rates with condensation in a soil-air heat exchanger, even though it is recommended that the system be installed with a tile slope of at least 0.25 percent because of possible water drips in the line (Goetsh and Muehling 1983).

2.4.7 The Influence of Soil Moisture Movement

A diffusion of moisture from warmer to cooler regions in moist soils has been noted to change the thermal conductivity (Ingersoll et al. 1954). Whatever the mechanics of the process, the effect is that the soil immediately surrounding a cold pipe soon becomes saturated with moisture and that the soil surrounding a hot pipe soon loses its moisture content as the flow of heat progresses (Parkerson 1951). Experimental data taken at several depths (Smith 1956; Scott et al. 1965) indicate monthly changes in moisture content in the soil surrounding the pipe. DeVries (1963) has theoretically demonstrated the procedures for calculating soil thermal conductivity when the influence of moisture migration on heat transfer in soil must be accounted for. Jumikis (1962) collected experimental data for a particular soil showing how soil moisture moves in a thermal gradient. A soil moisture distribution function under a one-dimensional temperature gradient was put forward by Sutor (1966) as the basis of his experiments and the summary of other investigators' work (Smith 1943; Gurr et al. 1952; Rolling et al. 1954).

Yeh (1976) illustrated that soil moisture movement in a thermal gradient is minimal in very dry soils or fully saturated soils, and is a maximum at 75 percent saturation. Therefore, since the soil around a cold pipe rapidly becomes saturated, saturated soil characteristics may be employed in the design of a soil-air heat exchanger. For a hot pipe, dry-soil characteristics may be used until experience justifies a partial adoption of saturated soil characteristics (Parkerson 1951).

2.4.8 Contact Resistance

Many present designs of soil-air heat exchangers have ignored the effect of contact resistance between the pipe wall and the soil. Analogous to thermal resistance of the pipe, lack of intimate contact at the pipe-soil interface gives rise to a marked temperature change in the soil temperature profile. But the outlet air temperatures are believed to be not dramatically affected. There is an argument that because of high thermal resistance, heat exchange with the soil will be significantly diminished, especially under cyclic thermal loading (Svec et al. 1983).

Smith (1956) also studied the contact resistance for buried pipes coupled with a heat pump. By temperature gradient plotting based on experimental results and a steady-state equation, he illustrated an apparent thermal conductivity for soil that would take into account both inside and outside heat transfer coefficients. Using data obtained under controlled laboratory conditions, Svec et al. (1983) did a similar analysis and arrived at values for contact resistances per unit length ranging from 0.12 m°C/W to 0.45 m°C/W for clay and sandy clay soil. The results of the above studies have indicated clearly that quality is much poorer for hot pipes than for cold pipes.

2.4.9 Effect of Ice Formation

When freezing of moist soil around the exchanger pipe takes place, the heat flow from the cylindrical surface which bounds the regions of frozen and unfrozen soils includes the release of latent heat (Jumikis 1977). The freezing will improve the performance of winter operation but will retard the cooling of the pipe somewhat (Ingersoll 1954). For moisture content increases about 6 to 12 percent the conductivity of frozen soils becomes progressively greater than that of the unfrozen soils (Kersten 1948).

2.4.10 Other Factors

Other factors which enter into consideration in a more rigorous analysis of the heat exchanger include underground water movement, effects of vertical pipe parts, the fluid boundary-layer effect, and the exchanger behaviour in intermittent and continuous operation.

For a horizontal pipe buried about 2 m below the surface, underground water movement rarely is a factor because of insignificant flow. For vertical pipes and greater depths, however, there may be slow movement of water varying from negligibly small values to several feet per day (Ingersoll 1954).

The effects of the vertical pipes at the inlet and outlet locations probably dramatically influence the exchanger performance, especially when the pipes are buried at relatively great depths. So far there has been little or no information published about the effects. Oliver and Braud (1981) and Braud et al. (1983) have studied a soil-water heat exchanger with vertical pipes.

The effect of fluid velocity on heat transfer through the fluid boundary-layer has been demonstrated by Nievergeld et al. (1980).

2.5 COMPUTER SIMULATION

The use of a computer as an aid in the design of soil-air heat exchangers has become fashionable. At the present not many useful computer models are available for the exchanger design. Most existing models for analysis of the entire system, including buildings, soil heat storage with heat exchangers or with solar collectors, have been developed by applying the techniques of finite difference or finite element.

In the summer of 1980 at the University of Manitoba, a preliminary finite difference program was developed to determine a practical pipe length and the effective heat source or sink radius (Britton 1982). Spengler and Stombaugh (1983) established an informative model of soil-air heat exchangers using 2-dimensional finite differences to permit the economic optimization of buried-pipe parameters. Only thermal performance for winter ventilation of swine housing was simulated to obtain outlet air temperatures as a function of lateral length, pipe diameter and airflow rate.

Puri and Okos (1980) studied soil storage performance and related parameters including air and water as heat transfer fluids. A 3-dimensional finite difference unsteady state numerical model for determining the heat transfer performance of a saturated soil storage unit was also presented.

Kung et al. (1980) simulated simultaneous water and heat transfer in partly frozen soils. Using a 2-dimensional finite difference technique, Colliver et al. (1982) compared heating requirements for underground soil bermed houses. George (1979) studied heating and cooling of ventilation air for a passive solar house. In addition, a computer program was used to simulate the operation of buried warm water pipes beneath a greenhouse (Parker et al. 1981). Transient greenhouse energy flows and a rock bed energy storage system (Duncan et al. 1976) were also simulated.

More sophisticated computer models and comprehensive research can lead to the development of suitable guidelines for the design of a ventilation air tempering system. A number of finite element analyses for such systems have been used. Mohan (1973) has developed a finite element model analysing heat flow around buried pipes. Timmons and Bottcher (1981) have done a finite element thermal analysis to predict transient heating or cooling loads in livestock housing. Using triangular and quadrilateral linear, or quadratic, curved elements to handle boundary conditions and material types, Svec et al. (1983) have developed a steady-state program to compare their laboratory results for soil-air heat exchangers. Good agreement was reported.

A time dependent axisymmetric finite element formulation of a buried pipe system has been recently presented by Puri (1984). The model first involves the solution of simultaneous equations of heat transfer and moisture diffusion in the soil. But the effect of soil surface temperature was ignored and very limited conditions within the system were considered.

2.6 OTHER APPLICATIONS

The use of soil as a heat source or sink in agricultural engineering is related to many other applications. The following are some examples:

Since the temperature of deep coal mine ventilation air when it leaves the mine is generally near that of deep well water, there is a potential for the use of mine air in greenhouse environment control (Peterson and Walker 1975). Experiments show that this system can greatly cut down the energy required for environmental control of a greenhouse. But the air is nearly saturated with moisture.

A vertical soil-coupled heat exchanger using water in heat pumps is another attraction (Oliver and Braud 1981). Thermal conductance with a vertical steel casing and a PVC plastic inner return pipe was found to be 4.86 W/(m°C) for continuous operation (Braud et al. 1983).

The feasibility of soil warming with a buried pipe network from a power plant has been considered for agriculture and environmental control in animal shelters (Shapiro and Roller 1975; Alpert et al. 1976; Hirst 1973; Rykbost et al. 1976). The benefits from the system in maturity, growth rates, yield and frost protection were measured for potatoes (Allred et al. 1973). The effect of raising soil temperature on lettuce growth in a greenhouse was also examined and the potentially valuable energy resource was recognized (Roller and Elwell 1980).

2.7 ECONOMIC ANALYSIS

Once the feasibility of soil-air heat exchangers is worked out, economic considerations are essential to put the concept into practice. Over 20 years ago, the major reason for no wide public acceptance of the system was its high initial cost. Freund and Whitlow (1959) reported that for a typical soil coil system the copper tubing materials cost $860 (U.S.) out of a total installation cost of $2000 (U.S.), based on 1959 costs. According to Scott et al. (1965), besides the initial installation cost of $2271 (U.S.) the net benefit was roughly estimated to be $60.50 (U.S.) for the exchanger applied to a poultry enterprise.

This was only sufficient to cover the operational expenses plus $5 (U.S.).

Fortunately, as great research efforts have been made to gain insight into integrated systems, the introduction of plastic pipes is bringing practical acceptance of the idea. Walker and Buxton (1977) have analysed economically and practically the use of a soil-air heat exchanger to heat or cool greenhouses by investigating the deep-soil temperatures in the United States. But the conclusions were not very optimistic for most of the areas of the country.

An economic model for the exchanger has been developed by Spengler and Stombaugh (1983). It was concluded that although supplemental heat was still needed for a 20-sow farrowing house economic considerations of an optimal soil-air system led to several system designs providing substantial cost and energy savings. Goetsch and Muehling (1983) calculated total monthly and seasonal ventilation heating loads. In accordance with their field data, heat supplied by the soil-air heat exchanger seemed to eliminate or to effectively reduce the "thermal stress" for swine in a farrow-nursery housing unit.

Chapter III

MODELING OF THE EXCHANGER

3.1 GENERAL MATHEMATICAL REPRESENTATION

The mathematical description of a soil-air heat exchanger, similar to the one shown in Figure 1, falls into thermal field problems with 3-dimensional transient heat transfer by conduction, convection, and radiation. In addition, consideration of soil moisture diffusion results in a general formulation for simultaneous heat transfer and moisture movement as proposed by Philip and DeVries (1957) and validated by Puri (1984). This formulation can be used to approximate the mechanism of the soil pipe systems. If the vapor-liquid interface is assumed to be temperature dependent only, and only constant total pressure and homogeneous soil media are considered, then heat transfer in the soil is governed by the law of energy conservation:

$$Cs\frac{\delta T}{\delta t} = \frac{\delta^2 Q}{\delta x^2} + \frac{\delta^2 Q}{\delta y^2} + \frac{\delta^2 Q}{\delta z^2} \quad \text{and} \quad Q = (k\ T) - hg(Dv\ \gamma'\ \emptyset) \qquad [3\text{-}1]$$

Moisture diffusion in the soil can be described by the conservation of mass equation:

$$\frac{\delta \emptyset}{\delta t} = \frac{\delta^2 G}{\delta x^2} + \frac{\delta^2 G}{\delta y^2} + \frac{\delta^2 G}{\delta z^2} + \frac{\delta K}{\delta z'} \quad \text{and} \quad G = (Dt\ T) + (Di\ \emptyset) \qquad [3\text{-}2]$$

where,

δ = differential operand
Cs = volumetric thermal capacity of soil, J/(m^3 °C)
T = soil temperature, °C
t = time, s

k = soil thermal conductivity, W/(m °C)
hg = moisture heat of vaporization, J/kg
Dv = isothermal diffusivity of moisture in vapor form, m^2/s
γ' = density of moisture, kg/m^3
$\emptyset$ = volumetric moisture content
m^3 of moisture/m^3 of moist soil
Dt = thermal moisture diffusivity, $m^2/(s°C)$
Di = isothermal moisture diffusivity, m^2/s
K = hydraulic conductivity, m/s
z' = coordinate axis in the direction of gravity, m.

It is a considerable challenge to find an exact solution to equations [3-1] and [3-2]. The difficulties are usually reduced by deleting the moisture diffusion equation by assuming very low rates of soil moisture movement under thermal gradients. Thus, the general governing equation for the heat conduction of a buried pipe in a cylindrical coordinate system, including possible heat generation, q (W/m^3), can be expressed as follows:

$$Cs\frac{\delta T}{\delta t} = \frac{\delta^2(kT)}{\delta r^2} + \frac{1}{r}\frac{\delta(kT)}{\delta r} + \frac{1}{r^2}\frac{\delta^2(kT)}{\delta \emptyset^2} + \frac{\delta^2(kT)}{\delta z^2} + q \qquad [3\text{-}3]$$

where,
$r = (x^2 + y^2)^{0.5}$, m
$\emptyset$ = angular coordinate of radius r, rad.

When the pipe is buried to a relatively great depth, the effect of soil surface temperature variation becomes negligibly small. The 3-dimensional problem can then be simplified by dropping out the third term on the right side of equation [3-3]. If $q = 0$, the equation reduces to:

$$Cs\frac{\delta T}{\delta t} = \frac{\delta^2(kT)}{\delta r^2} + \frac{1}{r}\frac{\delta(kT)}{\delta r} + \frac{\delta^2(kT)}{\delta z^2} \qquad [3\text{-}4]$$

This axisymmetric formulation, associated with the simplified boundary conditions shown in Figure 2, has been developed and used by Puri (1984) in simulating heat conduction around a horizontal pipe under very limited conditions.

Research by Deaton and Frost (1964) on natural-gas pipe lines has indicated that the temperature gradient in the radial direction is at least 10^5 greater than the gradient in the longitudinal direction. Therefore, neglect of heat transfer in the pipe line direction should not cause significant error. The interpolation of air temperatures along the pipe from knowing the soil temperature profile at a chosen cross section leads to close predictions of system performance. Since symmetry in soil pipe systems often exists, reasonable boundary conditions can be easily obtained. Figure 3 illustrates a rectangular region in which heat transfer in soil can be described by the equation:

$$Cs\frac{\partial T}{\partial t} = \frac{\partial^2(kT)}{\partial x^2} + \frac{\partial^2(kT)}{\partial y^2} \qquad [3\text{-}5]$$

Some boundary conditions associated with this equation are shown in Figure 3 (b). The initial condition, $T(x,y,0)$, can be found by using a one-dimensional model for undisturbed soil temperature (Sec. 3.4). As long as the temperature profiles of the soil have been evaluated, for instance, with 2-dimensional finite element techniques, an energy balance equation can be used for determining the air temperatures along the pipe (Sec. 3.3.3). Since this work is focused mainly on the investigation of a large number of variables and the development of practical data for design purposes, the model was based on the following differential equation:

$$C_s\frac{\partial T}{\partial t} = \frac{\partial^2 (kT)}{\partial r^2} + \frac{1}{r}\frac{\partial (kT)}{\partial r} \qquad [3\text{-}6]$$

The solution region for this equation with unit pipe length is illustrated in Figure 4.

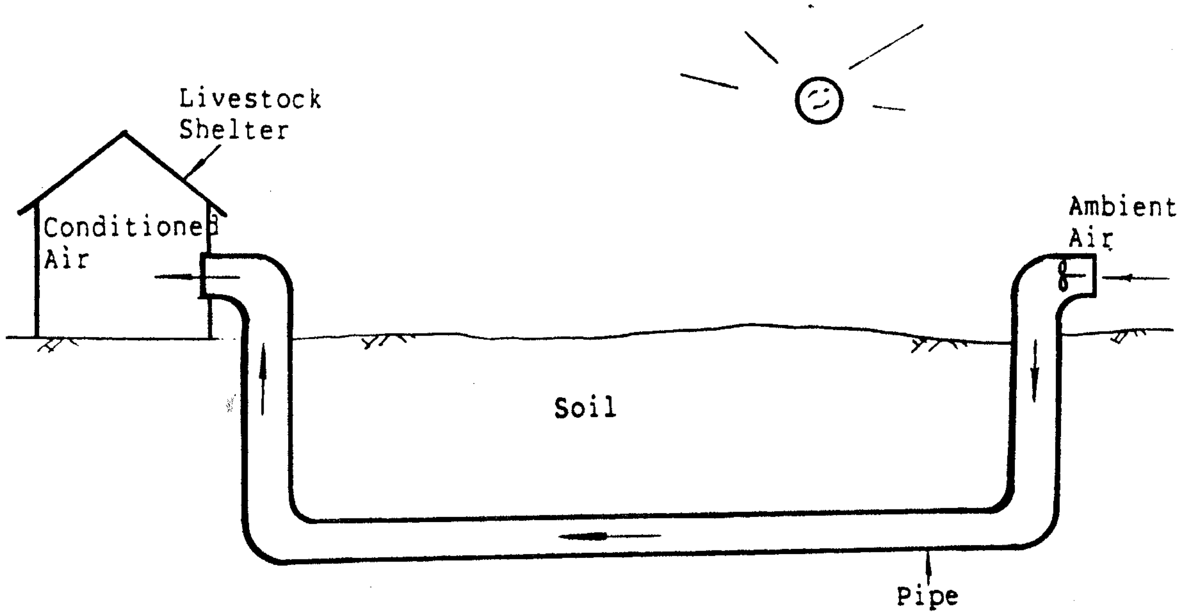

Figure 1: A Buried Pipe Ventilation Air Tempering System

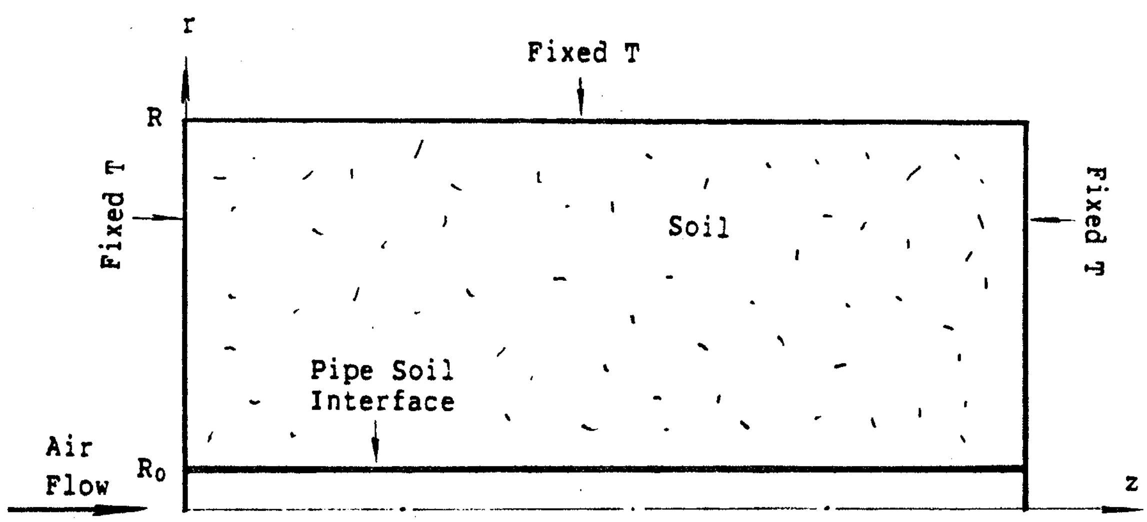

Figure 2: A Solution Region for Axisymmetric Formulation
(Source: Puri (1984))

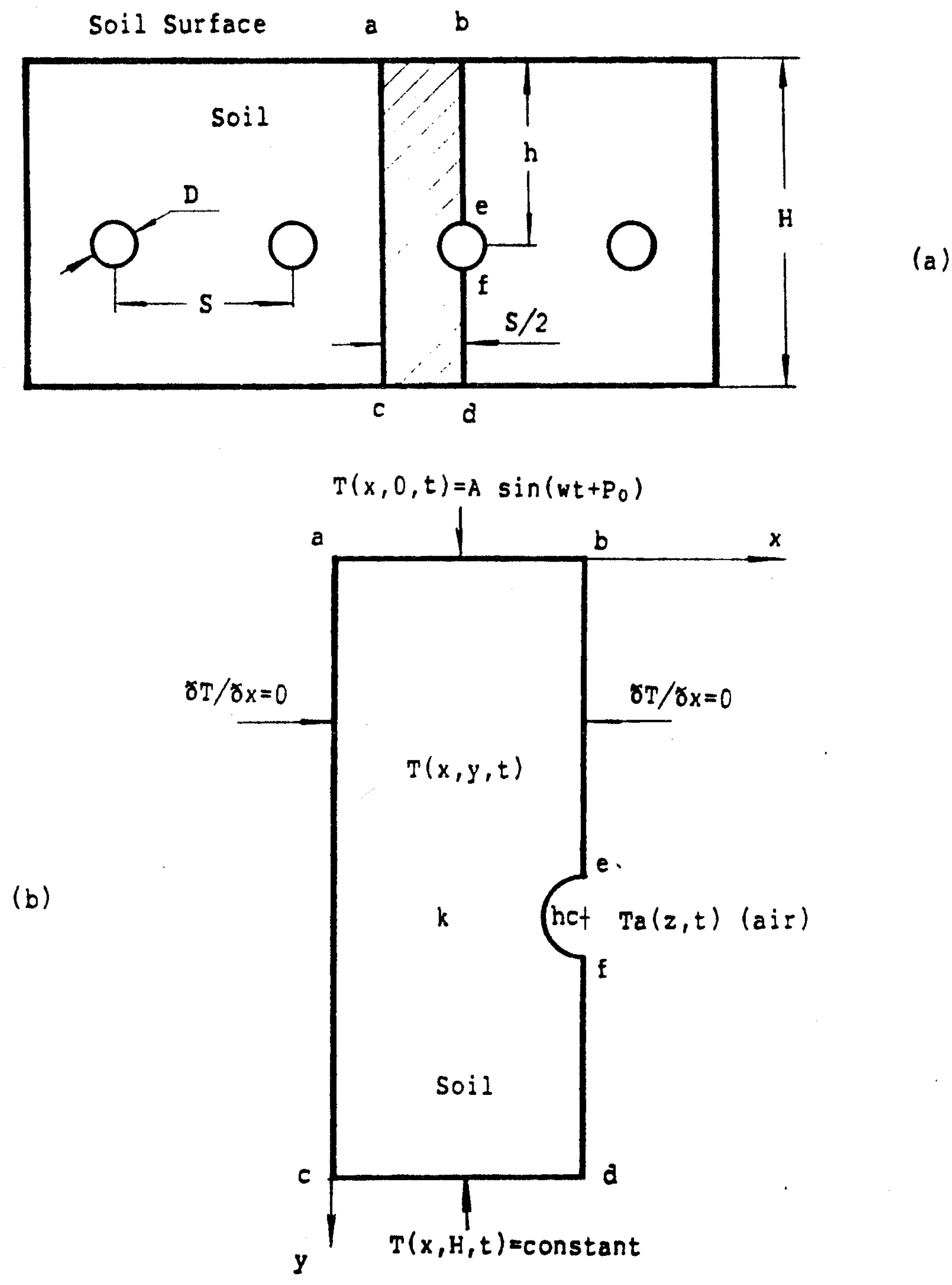

Figure 3: A Solution Region in Cartesian Coordinate System
(a) Cross Section of a Buried Pipe System
(b) A Rectangular Region and Possible Boundary Conditions for 2-Dimensional Finite Element Formulation

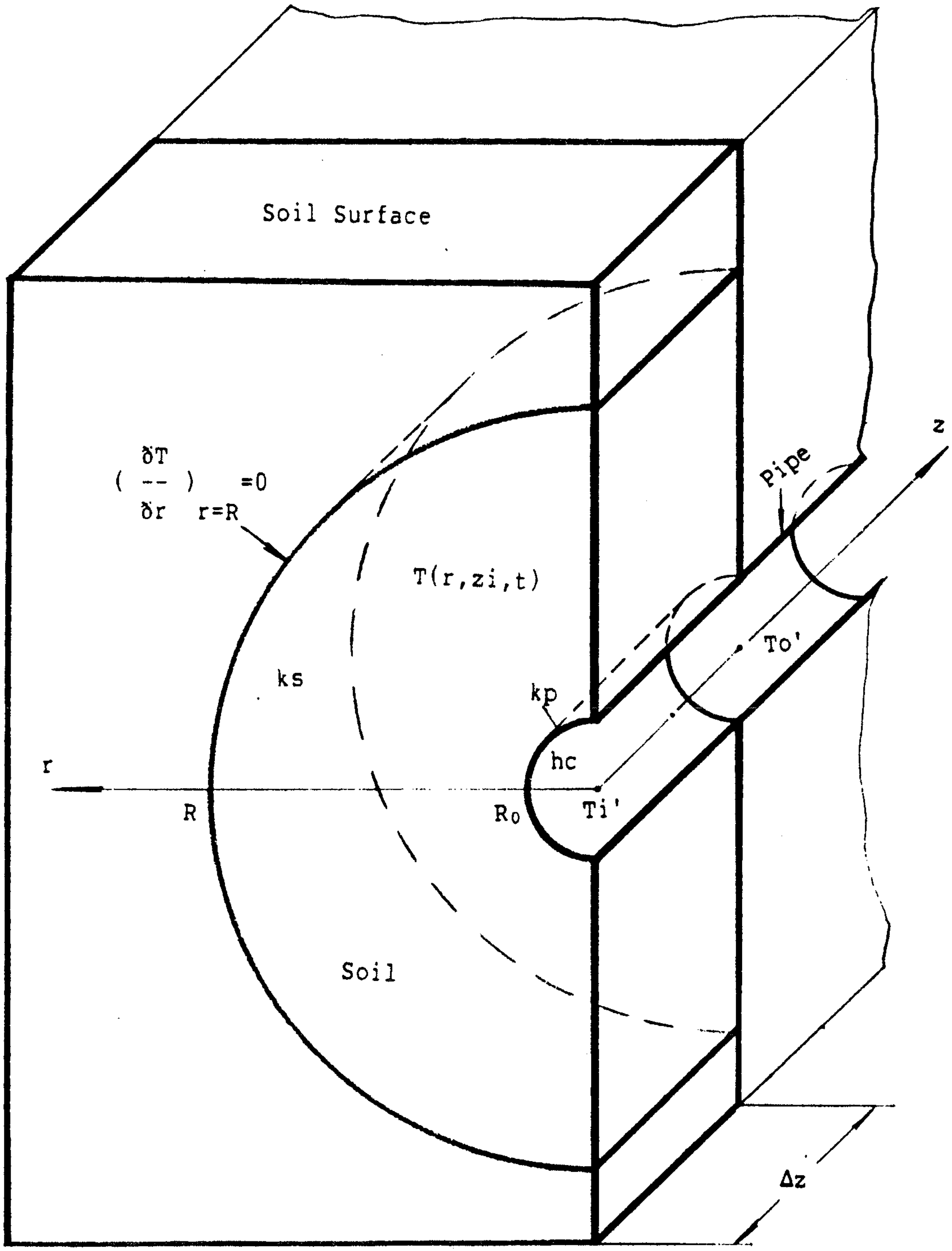

Figure 4: A Soil Cylinder of Differential Length in the System

3.2 ASSUMPTIONS

Actual situations are often very difficult to model. In any simulation, idealizations and assumptions are necessary to simplify the actual physical conditions. It is not possible to describe the phenomena completely accurately in the computer model because a number of uncertainties are embedded in the mathematical model. A variety of assumptions thus become necessary. In order to simplify the study of the exchanger performance the following assumptions were made:

1. The radial heat flow is much greater than the longitudinal heat flow (e.g., at least 100 times greater). This assumption is essentially true meaning that equation [3-6] does not significantly lose the accuracy level as evaluated by Puri (1984) using equation [3-4].
2. With the assumption of a homogenous and isotropic soil medium, the effect of soil surface temperature variation can be neglected. The accuracy of this idealization depends primarily upon whether the depth of the buried pipe is relatively large or not.
3. The rate of underground water movement is small enough to be ignored. The variation of soil moisture concentration around the pipe is considered to be only a linear function of the temperature gradients.
4. The outer surface of the soil cylinder, as idealized in Figure 4, is chosen so that the average soil temperature on that surface is assumed to remain constant.
5. The pipe has constant thermal properties and has uniform wall temperatures across the pipe.

6. The air moves at a constant flow rate through the pipe. Any kinetic and potential energy changes of the air mass as well as energy transfer by conduction in the axial direction are negligible.

3.3 NUMERICAL IMPLEMENTATION WITHIN SEGMENTED PIPE LENGTH

3.3.1 Boundary and Initial Conditions

An axisymmetric coordinate system as shown in Figure 4 was set up to facilitate the problem solution. The initial conditions associated with equation [3-6] are:

$$T(r,0) = Tus(h,t_0) \qquad [3\text{-}7\ a]$$

where,

$Tus(h,t_0)$ = temperature (°C) of undisturbed soil at the depth, h (m)

t_0 = the day of start.

Note that this condition is not described exactly because the actual soil temperature profiles vary with depth, soil properties, and meteorological changes. Experimental measurements indicate that there will be less variation in soil temperature when the pipe is buried deeper in the soil. The above assumed initial condition should not give rise to large errors in the simulation, especially with continuous operation.

The boundary conditions are:

at r = R and z = zi:

$$T(R,t) = Tus(h,t)$$

$$[3\text{-}7\ b]$$

at $r = R_0$ and z = zi:

$$k\frac{\delta T}{\delta r}(R_0,t) = hc[\ T(R_0,t) - Ta(zi,t)\ ]$$

$$= Ma'Ca\left[\frac{\partial Ta}{\partial t}(zi,t) + Va\frac{\partial Ta}{\partial z}(zi,t) \right]$$

[3-7 c]

with,

$Ta(0,t) = Ti$ = ambient air temperature, °C

[3-7 d]

where,

R_0 = inside radius of the pipe, m
R = arbitrarily large radial distance, m
zi = distance along the pipe from inlet, m
$Ta(zi,t)$ = air temperature at zi, °C
hc = heat transfer coefficient at pipe wall and at zi, $W/(m^2K)$
Ma' = mass of air flow per unit area of pipe, kg/m^2
Ca = specific heat of the air, J/(kg K)
Va = air velocity, m/s.

Equation [3-7 b] does not represent the exact conditions of the buried pipe. This has led to the development of a temperature model for undisturbed soil which can be used to modify these conditions (Sec. 3.4).

3.3.2 Finite Element Formulation

The finite element method is a highly versatile numerical technique for solving problems in engineering and physics. This method has the flexibility to deal with non-linear material behavior and changing boundary conditions as well as multi-phase materials with complicated geometries.

The essence of the method is the division of the continuous body into a finite number of discrete elements of specified shapes interconnected at their apexes or nodes. For the analysis of heat conduction in a solid, as shown in Figure 4, the domain is divided into elements and a temperature interpolation equation is defined over each:

$$Tm(r,t) = [\ N\ ]\ \{\ T\ \}e \qquad [3\text{-}8]$$

where,
$Tm(r,t)$ = temperature at any point within an element, °C
$[\ N\ ]$ = row matrix containing the interpolation or shape function
$\{\ T\ \}e$ = temperatures at nodal points, °C.

Temperature gradients are given by:

$$\{\ g\ \} = [\ B\ ]\ \{\ T\ \}e \qquad [3\text{-}9]$$

where,
$\{\ g\ \}$ = element temperature gradient, °C/m
$[\ B\ ]$ = matrix related to derivations of the shape functions, 1/m.

In order to ensure the continuity of the temperature across the nodal points for the neighboring elements and to provide the best approximation possible to the true temperature distribution, an adjustment is made by minimizing a functional related to the governing differential equation [3-6] and the associated boundary conditions. This functional of variation is derived from Segerlind (1976):

$$Ł = \iiint 1/2[\ k(\partial T/\partial r)^2 + 2\ Cs(\partial T/\partial t)T\ ]\ dV$$
$$+ \iint hc/2\ [T^2 - 2T\ Ta + Ta^2]\ dS$$
$$+ \iint q'\ T\ dS \qquad [3\text{-}10]$$

where,
$Ł$ = functional of variation, W°C
q' = heat flux, W/m^2
dV = 2*3.14159 r dr dz, m^3
dS = 2*3.14159 r dz, m^2.

The satisfaction of a few restricted conditions validates this equation. A differentiation with respect to nodal temperatures, T, in the equation and an approximation of the time derivative using a forward explicit finite difference scheme yield the following heat balance equation for the discretized solid:

$$\left(\frac{2}{\Delta t}[C] + [K]\right)\{T\}_1 = \left(\frac{2}{\Delta t}[C] - [K]\right)\{T\}_0 + 2\{F\}^*$$

[3-11 a]

where,

Δt = time interval, s

$\{T\}_1$ = nodal temperatures at time instant $t + \Delta t$, °C

$\{T\}_0$ = nodal temperatures at time instant t, °C

$\{F\}^* = (\{F\}_1 + \{F\}_0)/2$, mean thermal force matrix.

The conductivity matrix is given by:

$$[K] = \sum_{e=1}^{n} [K]_e$$

$$= \sum_{e=1}^{n} \left\{ \iiint [B]_e^T [D]_e [B]_e \, dV + \iint hc \, [N]_e^T [N]_e \, dS \right\}$$

[3-11 b]

The thermal force matrix is given by:

$$\{F\} = \sum_{e=1}^{n} (-\{f\}_e)$$

$$= \sum_{e=1}^{n} \left(-\iint q' [N]_e^T \, dS + \iint hc \, Ta [N]_e^T \, dS \right)$$

[3-11 c]

The heat capacitance matrix is given by:

$$[C] = \sum_{e=1}^{n} ([C]_e)$$

$$= \sum_{e=1}^{n} \left(\iiint Cs [N]_e^T [N]_e \, dV \right)$$

[3-11 d]

For an element containing a phase boundary, the volumetric heat can be approximated by determining the enthalpy gradient with respect to temperatures (Sec. 3.5).

3.3.3 Interpolating Air Temperature

If no mechanical work is done by the air fluid as it is circulated through the pipe, the thermal energy changes and flow work will become the dominant effects in the prediction of air temperatures (Incropera and DeWitt 1981). An idealized cylinder with a segmented pipe length of Δz (m) containing constant air flow (control volume), as illustrated in Figure 4, can be considered such that an energy balance is appropriately applied to determine the temperatures varying with axial position. Equation [3-7 c] clearly states that energy extracted or injected by heat conduction throughout the soil must equal the fluid thermal energy increases plus the net rate at which work is done in moving the fluid through the control volume. If constant temperature at the pipe wall is assumed and a central finite difference scheme is employed, equation [3-7 c] can be written as:

$$Ma'Ca\left[\frac{(T^*)_1 - (T^*)_0}{\Delta t} + Va\frac{(To')_1 - (Ti')_1}{\Delta z}\right] = hc[T(R_0,t) - (T^*)_0] \qquad [3\text{-}12]$$

where,

$(T^*)_1$, $(T^*)_0$ = bulk temperatures of the air at the instant time t and t-Δt, respectively, °C

$(Ti')_1$, $(To')_1$ = temperatures at inlet and outlet in the control volume at time t, °C

$T^* = (To' + Ti') / 2$

Let,

$$N = \frac{\Delta z}{\Delta t}\,\frac{1}{Va} \quad \text{(dimensionless)} \qquad [3\text{-}13]$$

and

$$J = \frac{hc\ \Delta z}{2Ma'\ Ca\ Va} \quad \text{(dimensionless)} \qquad [3\text{-}14]$$

Hence, this solution procedure yields the following equation for estimating the temperature of the outlet air:

$$(To')_1 = \frac{2J\ T(R_0,t) + (Ti')_1(1 - J - 0.5N) + N(T^*)_0}{(1 + J + 0.5N)} \qquad [3\text{-}15]$$

When the time interval Δt becomes very large N becomes negligibly small and equation [3-15] approaches the steady-state case or is dependent on the input air temperature only.

3.4 UNDISTURBED SOIL TEMPERATURE MODEL

The application of soil-air heat exchangers has necessitated a thorough understanding of soil response to actual installation conditions. An undisturbed soil temperature model attempts to modify the initial and boundary conditions of the problem in order to obtain a better approximation of the soil temperatures.

Soil temperature relates to climate, but the relationship is affected by soil depth, texture, soil water content, surface cover (vegetation, snow), landscape position, and man's manipulation. A harmonic function for simple one-dimensional transient heat conduction is given by equation [2-5]:

$$Tus(y,t) = Tm + A\ \exp(-y/D)\ \sin(wt - P_0 - y/D)$$

A proposal by Costello and Braud (1984) to use shallow soil temperature data for determining the parameters in this equation by using multiple linear regression has been validated for local temperature data (Environment Canada 1977-1983). The modified method has also provided an opportunity for an estimate of soil thermal diffusivity on condition that soil temperature data at more than one depths are available (Appendix A).

With the adding of an angular coordinate, ϕ, the initial and boundary conditions given in equation [3-7] approximate a real temperature distribution:

$$T(r,\phi,0) = Tus(y,t_0) \qquad [3\text{-}16]$$

$$T(R,\phi,t) = Tus(y,t) \qquad [3\text{-}17]$$

A better estimate is made by the integration on the outer perimeter, P (P=2*3.14*R), of the soil cylinder:

$$T(r,0) = \frac{\int Tus(y,t_0)\, dy}{\int dy} \qquad [3\text{-}18\ a]$$

$$T(R,t) = \frac{\int Tus(y,t)\, dy}{\int dy} \qquad [3\text{-}18\ b]$$

A subprogram called TOST (Appendix E, F) provides for the computation of these values by using Simpson's method for the determination of the integrals.

3.5 ICE FORMATION IN SOIL

This simulation takes into account the formation of ice lenses around the pipe in moist soil. Based on the assumptions made, the temperature distribution (T_1) for the frozen portion of the soil and the temperature distribution (T_2) for the unfrozen part can be described by the two partial differential equations:

$$Cs_1 \frac{\delta T_1}{\delta t} = \frac{\delta^2 (k_1 T_1)}{\delta r^2} + \frac{1}{r} \frac{\delta (k_1 T_1)}{\delta r} \qquad [3\text{-}19]$$

$$Cs_2 \frac{\delta T_2}{\delta t} = \frac{\delta^2 (k_2 T_2)}{\delta r^2} + \frac{1}{r} \frac{\delta (k_2 T_2)}{\delta r} \qquad [3\text{-}20]$$

where Cs_1, k_1 and Cs_2, k_2 are volumetric specific heats and thermal conductivities for frozen and unfrozen soil, respectively. At the freezing boundary, where $r = R'$, $T_1 = T_2 = 0^{\circ}C$, release of latent heat results and the heat balance is determined by:

$$-k_1 \left[\left(\frac{\delta T_1}{\delta r}\right)_{r=R'} A\ dt \right] = -\ k_2 \left[\left(\frac{\delta T_2}{\delta r}\right)_{r=R'} A\ dt \right] - Lw\ \gamma\ w\ A\ dR' \qquad [3\text{-}21]$$

where,

- A = area of freezing boundary, m^2
- Lw = latent heat of fusion of water (or ice) (334.88 kJ/kg)
- γ = density of dry soil, kg/m^3
- w = soil moisture content by dry weight, decimal.

There is a possibility that a number of frozen soil rings may be formed around the pipe, which complicates the problem. The difficulties, including those resulting from other physical conditions, promote the use of the finite element method. In the program, the solution region of the soil can be treated as composite cylinders which possess different thermal properties varying with temperature and moisture concentration. Before a computation is done for an element, its thermal conductivity will be automatically identified depending on whether the mean temperature of the element is below zero or not.

The latent heat involved in a phase change, from unfrozen soil to soil whose water is partially frozen, or vice versa, is mathematically represented by a Dirac function acting on the soil heat capacity. A very useful technique in the finite element method, proposed by Comini et al. (1974) and adopted by Hsu and Pizey (1981), states that the integral of heat capacity with respect to temperature is a smooth function of temperature even during the phase transformation. Hence the enthalpy of the material is defined as:

$$H(T) = \int_{T_0}^{T} (Cs)r(T)\, dT \qquad [3\text{-}22\ a]$$

and is introduced into the computation. Thus, for an element containing a frost boundary, the heat capacity (Cs)r can be evaluated by the following procedures: (i) Determine the nodal values of enthalpy $\{H(t)\}$ corresponding to the nodal temperatures $\{T(t)\}$ and interpolate the enthalpy in the element as follows:

$$H(r,t) = [\ N\ ]\ \{H(t)\} \qquad [3\text{-}22\ b]$$

(ii) Since by definition:

$$(Cs)r = dH\ /\ dT \qquad [3\text{-}22\ c]$$

the values can be approximated by determining the enthalpy gradient with respect to temperature as:

$$(Cs)r(T) = \frac{1}{3}\left(\frac{\partial\{H\}/\partial x}{\partial\{T\}/\partial x} + \frac{\partial\{H\}/\partial y}{\partial\{T\}/\partial y} + \frac{\partial\{H\}/\partial z}{\partial\{T\}/\partial z} \right) \qquad [3\text{-}22\ d]$$

or in this case

$$(Cs)r(T) = \frac{\delta\{H\}/\delta r}{\delta\{T\}/\delta r} \qquad [3\text{-}23]$$

Finally, (iii) the element heat capacity can be calculated from the following integral:

$$[\ C\ ]e = \iiint (Cs)r\ [\ N\ ]e^{T}\ [\ N\ ]e\ dV \qquad [3\text{-}24]$$

in which the volumetric heat of the soil, (Cs)r, is different from the Cs, in equation [3-11 d]. Appendix B gives more details for the evaluation of (Cs)r.

3.6 WATER VAPOR CONDENSATION INSIDE PIPE

In an effort to simulate the significant physical conditions existing in the buried pipe systems, heat transfer by convection inside the pipe must be considered.

No matter what the details of the transfer mechanism are, the problem reduces to estimating practical values of convective heat transfer coefficients. An existing phenomenon, which causes a great increase in the convective heat transfer coefficient, is condensation of water vapor from the system air. Water vapor can be added to the air by evaporation of water from wet surfaces of the pipe. These processes of dehumidification and humidification have been graphically illustrated on psychrometric charts. Since water rarely remains inside the pipe as heating proceeds, especially in a pipe with a definite slope, significant humidification rarely occurs.

In the case of no condensation, the Nusselt number for turbulent flow in long smooth conduits can be evaluated by the following equation (Kreith 1973):

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.33} \qquad [3\text{-}25]$$

where,

Nu = Nusselt number defined as hc D / ka
D = pipe diameter, m
ka = thermal conductivity of air, W/(m K)
Re = Reynolds number defined as Va D' / u
D' = hydraulic diameter (here, D' = D), m
u = absolute viscosity, (N s)/m^2
Pr = Prandtl number defined as Ca u / ka.

This equation is valid for Re > 6000 and Pr > 0.7. All properties are required to be evaluated at a temperature approximately halfway between the pipe wall and the bulk mean temperature in view of variations in the physical properties with temperature change.

Empirical equations for evaluating heat transfer coefficients involving condensation along a horizontal tube are few. Correlation expressions of Nusselt number proposed by Akers (1960) and Chato (1962), and two-phase pattern flow data presented by Rahman (1983) as well as results of comprehensive studies of Soliman (1982, 1983) are not valid for the case considered. Personal correspondence with Soliman has led to the adoption of the principles of simultaneous heat and mass transfer between water wetted surfaces and air (ASHRAE Fundamentals Handbook 1981) for estimating this coefficient in the program.

In brief, when the mean air temperature reaches the dew-point temperature, the air/water vapor mixture will be dehumidified and water or wetted surfaces will appear inside the pipe. If low mass transfer rates are present the Lewis relation which states that the ratio of the heat transfer coefficient to the mass transfer coefficient is equal to the specific heat per unit volume at constant pressure of the mixture offers a method for approximating the heat transfer coefficient. Assuming that there is a direct contact between water and air, that there are identical areas of the heat and mass transfer, and constant humid specific heat, the heat transfer coefficient due to the air condensation inside the pipe has been derived from the analogy of the heat-mass transfer, and written as follows:

$$hc' = \frac{D\, Þ'\, Va\, Ca}{4\, \Delta z} \ln\left(\frac{Hi - Hin}{Hi - Hout}\right) \qquad [3\text{-}26]$$

where,

hc' = heat transfer coefficient due to condensation, $W/(m^2\,^\circ C)$
Þ' = air density at local temperature, kg/m^3
Δz = control volume length, m
Hi = enthalpy at the temperature of interface (pipe wall), J/kg
Hin = enthalpy at air bulk temperature of inlet, J/kg
Hout = enthalpy at air bulk temperature of outlet, J/kg.

The details for the derivation of equation [3-26] have been given in Appendix C. Evaluation of the enthalpy corresponding to the temperatures considered was done with reference to ASAE (American Society of Agricultural Engineers) Data (ASAE D271.2).

3.7 SOIL MOISTURE MIGRATION

The exact rates of the movement of soil moisture under temperature gradients can be quantitatively evaluated by solving, simultaneously, heat and moisture diffusion equations such as equations [3-1] and [3-2]. In this work it is only required to determine the influence of moisture movement on daily and seasonal temperature fluctuations. This study was limited to the evaluation of local thermal conductivity of the soil owing to the changing moisture contents. The local values are then used in computation for each element.

Many experimental investigations (Smith 1943; Gurr 1952; Rollong 1954) have demonstrated that the profile of one-dimensional soil moisture distribution in non-isothermic conditions has a similarity to the curve described by the mathematical function:

$$w - w_0 = - \alpha \, (r - b)^3 \qquad [3\text{-}27]$$

If w, w_0 stand for current and initial moisture contents, respectively, at the radius of r, it then becomes a question of what the values of the constant b and the coefficient α should be for a given soil pattern and thermal gradient. Sutor's 1966 study suggested conclusively that the coefficient α was a function of four variables: initial moisture content (w_0), temperature gradient (dT/dr), mean temperature (Tm), and soil specific weight (γ). He has also presented the related pertinent mathematical expressions.

In this preliminary consideration, the coefficient, α, is assumed to be a function of temperature gradient only and can be approximated mathematically, as follows:

$$\alpha = c \, (dT/dr) - d$$

[3-28]

where the constants c and d can be evaluated from Sutor's experimental data. Accordingly, if the moisture migration under the temperature gradient quickly reaches steady-state conditions and if uniform initial moisture distribution is assumed, equation [3-27] becomes:

$$w = w_0 - (c(dT/dr) - d) (r - R)^3$$

$$R_0 \leq r \leq R \leq 2.0 \text{ m} \qquad [3\text{-}29]$$

where,

dT/dr = average temperature gradient, °C/m, defined as:

$$\sum_{i=1}^{n} \frac{T(r)_{i+1} - T(r)_i}{(r)_{i+1} - (r)_i}$$

Hence, the local thermal conductivity (k) corresponding to the local moisture content can be recalculated. If 1.10 is chosen for c and 8.7 for d, a subprogram will recalculate k only when dT/dr is greater than 8.0 °C/m, otherwise soil moisture migration can be ignored.

3.8 UNITS AND DEFINITIONS

SI units have been used throughout this thesis. This has brought about some slight differences in the formulations which have been extracted from literature containing Imperial units or US customary units.

The Standards of ASAE (American Society of Agricultural Engineers) have been adhered to as consistently as possible. Because a computer format has been used for the thesis printing, some symbols used in the thesis may be different from published standards.

In order to predict the system thermal performance and to provide design data, the following definitions are introduced.

- The Exchanger Effectiveness (E), expressed in percent, is defined as the ratio of the inlet/outlet air temperature difference to the maximum possible system temperature difference:

$$E = \frac{Ti - To}{Ti - Tus} * 100 \tag{3-30}$$

- The Exchanger Heat Capacity (Cap), W, is expressed as the product of the system temperature differential ΔT or the absolute value of Ti - To (°C), mass rate of air flow Ma (kg/s), and the specific heat of air at constant pressure Ca (J/(kg°C)). That is:

$$Cap = \Delta T \ Ma \ Ca \tag{3-31}$$

- Heat Energy Ratio (HER) or Coefficient of Performance (COP) is defined as the ratio of the heat delivered to a building divided by the energy expended in operating the machinery (i.e., an electric fan), namely:

$$HER = \frac{\text{heat delivered}}{\text{energy expended}} \tag{3-32}$$

Chapter IV

DATA DEVELOPMENT FOR DESIGN PURPOSES

4.1 DESIGN CRITERIA

A satisfactory design for a soil-air heat exchanger must be one in which the designer can utilize the available resources to produce maximum economic results. For this purpose, Heat Energy Ratio (HER), defined by equation [3-32], provides a direct judgement of system performance should energy expended be exactly known.

Other useful criteria for the design, presented in section 3.8, are the temperature differential (ΔT), the heat capacity (Cap), and the effectiveness (E). The first criterion is only a relative value of temperature increase or decrease between inlet and outlet. The second is like an authorized judge who not only adjudicates the level of energy available from the system but displays the effects of the thermal performance and the fluid condition as well. The last criterion states the thermal efficiency of the system. This term is of importance when considering soil temperature recovery.

A large number of variables affecting the system thermal performance made the analysis difficult. It was thus necessary to classify these variables under the following heads: geometric factors, dynamic factors, system thermal conductivity factors, and performance factors. Because all of the system thermal expressions are complex functions of several variables, the author believes that an investigation of single variables will produce a close analytical approximation of the effects on the system. Factor grouping analysis or dimensional analysis may be more valuable from a practical point of view. To facilitate the simulation, some system variables and constants are listed in Table 1 and 2.

The goal of design data development in this chapter was to try to provide the designer with reliable design information. Because of the existence of many operating conditions it is impossible to investigate all of the situations. It is hoped that the graphs or the approximate equations presented in this chapter will prove useful in the design of real systems.

TABLE 1

System Variables

Variable	Symbol	Unit	Range	Comment
Diameter	D	m	0.100 --- 0.500	
Length	L	m	10 --- 120	
Velocity	Va	m/s	1 --- 6	For test: 0.5 --- 23
Soil types			Sand, silt, silty clay, clay	
Soil conductivity	ks	W/(m°C)	Calculated from Kersten's	Empirical equations
Soil m.c. by d.w.	w_0		Dry to saturated	
Soil density (dry)	γ	kg/m^3	900 --- 1500	From Jumikis (1977)
Convective coefficient	hc	$W/(m^2 °C)$	Calculated	Non-condensing and condensing
Pipe conductivity	kp	W/(m°C)	0.134 (PVC)	45.87(steel) 387.7(copper)
Contact resistance	CR	$m^2 °C/W$	0.004541 (heating) 0.005258 (cooling)	0.05 --- 0.00005, test only
Pipe depth	Y	m	1 --- 6	Mostly, Y=3
Ambient air temperature	Ti	°C	Weather data	Including dew point temperature
Undisturbed soil temperature	Tus	°C	Estimated from a model	sec. 3.4

TABLE 2

System Constants

Quantity	Symbol	Unit	Value	Comment
Specific heat of air	Cp	J/(kg˚C)	1004.64	Kreith (1973)
Mass heat capacity of soil solid	Cs'	J/(kg˚C)	837.2	Jumikis (1977) at 0 ˚C
Mass heat capacity of water	Cw	J/(kg˚C)	4186.0	Jumikis (1977) at 0 ˚C
Mass heat capacity of ice	Ci	J/(kg˚C)	2093.0	Jumikis (1977) at 0 ˚C
Volumetric heat of PVC pipe	Cpp	J/(m^3˚C)	1,512,820.4	Ogorkiewicz (1970)

4.2 GEOMETRIC FACTORS: DIAMETER AND LENGTH

The proper selection of pipe diameter requires a thorough understanding of the effect of this variable on fluid conditions and system thermal response. For silty clay soil with bulk density, 1800 kg/m^3, and moisture content 30% (dry basis), nine computer runs were done for pipe diameters ranging from 0.1 m to 0.5 m. A transformed linear regression model

$$\ln(E) = -B*D + \ln(A)$$

was developed for the data fitted by SAS (Statistical Analysis System). Figure 5 overlays E and Cap versus the pipe diameters for the conditions given. The data were best described with a confidence level of 0.05 and a R-squared value of 0.97 by using the constants: ln(A) = 4.6773 with standard deviation (STD) $S_1 = 0.05$; and B = 2.9873 with STD $S_2 = 0.10$. The function for E, expressed in percent, can then be written as:

$$E = 107.45 \exp(-2.99\, D) \qquad [4\text{-}1\ a]$$

By applying uncertainty analysis techniques, the uncertainty or the possible error of E was estimated by:

$$\Delta E = \left[\sum_{i=1}^{n} \left(\frac{\delta E}{\delta xi} \Delta xi \right)^2 \right]^{0.5}$$

For this model,

$$\Delta E = E \left[(S_1)^2 + (D\, S_2)^2 \right]^{0.5} \qquad [4\text{-}1\ b]$$

At D = 0.500 m, ΔE = 1.7% but the average value was approximately 2.5%. Hence, the total error of E was about 7.5% (3*2.5%). This same method was applied throughout this chapter for estimating errors in other variables.

An undisturbed soil temperature of 5.8 °C was estimated for the average pipe depth of 3.0 m with operation time in January. When the ambient air temperature was -20 °C, mean air velocity 3.0 m/s, and air density 1.29 kg/m^3 at 0 °C average temperature, the exchanger heat capacity, Cap in kW, can be approximated by the equation below:

$$Cap = 84.65\, D^2 \exp(-2.99\, D) \pm 0.5 \qquad [4\text{-}2]$$

Another geometric factor is pipe length. Since pipe length affects installation area as well as initial investment, knowing the system thermal response to pipe length should indicate optimum economic design. For the same soil conditions and operating conditions as above, data from 40 computer runs were processed in SAS programs for pipe lengths varying from 10 m to 120 m with pipe diameters from 0.150 m to 0.350 m. Figure 6 provides a family of curves of ΔT or E versus pipe lengths for each diameter concerned. The average standard deviation of the variables for each curve is below 0.4. With a confidence level of 0.05 and an average R-squared value of 0.98, the family of curves for the heating process was described mathematically as follows:

$$\Delta T = 25.8[\ 1 - \exp(-0.141(0.8 - D)^3 * L)\ ] \quad \pm 1.2 \qquad [4\text{-}3]$$

Where ΔT = temperature differential, °C; D = pipe diameter, m; and L = pipe total length, m. In the cooling process, data collected from the outputs showed very similar curve shapes to those for heating under the same thermal potential.

For all of these computer simulations, a soil cylinder radius of 1 m was chosen to ensure the assumed boundary condition. Since initial runs with 0.5, 1.0, 1.5 hour time steps indicated no significant differences in the final results, a 2 hour time interval was used to reduce the computer execution time. All data were selected from computer outputs of 12 hour simulations which approached steady-state. Twenty elements in the radial direction, including the elements containing pipe thermal resistance and contact resistance, were used for predicting soil temperature profiles at each differential length of the soil cylinder. With soil moisture migration in the heating case, a high soil moisture content near the cool pipe required that a low value of contact resistance be used. Other system constants listed in Table 2 were used in the program.

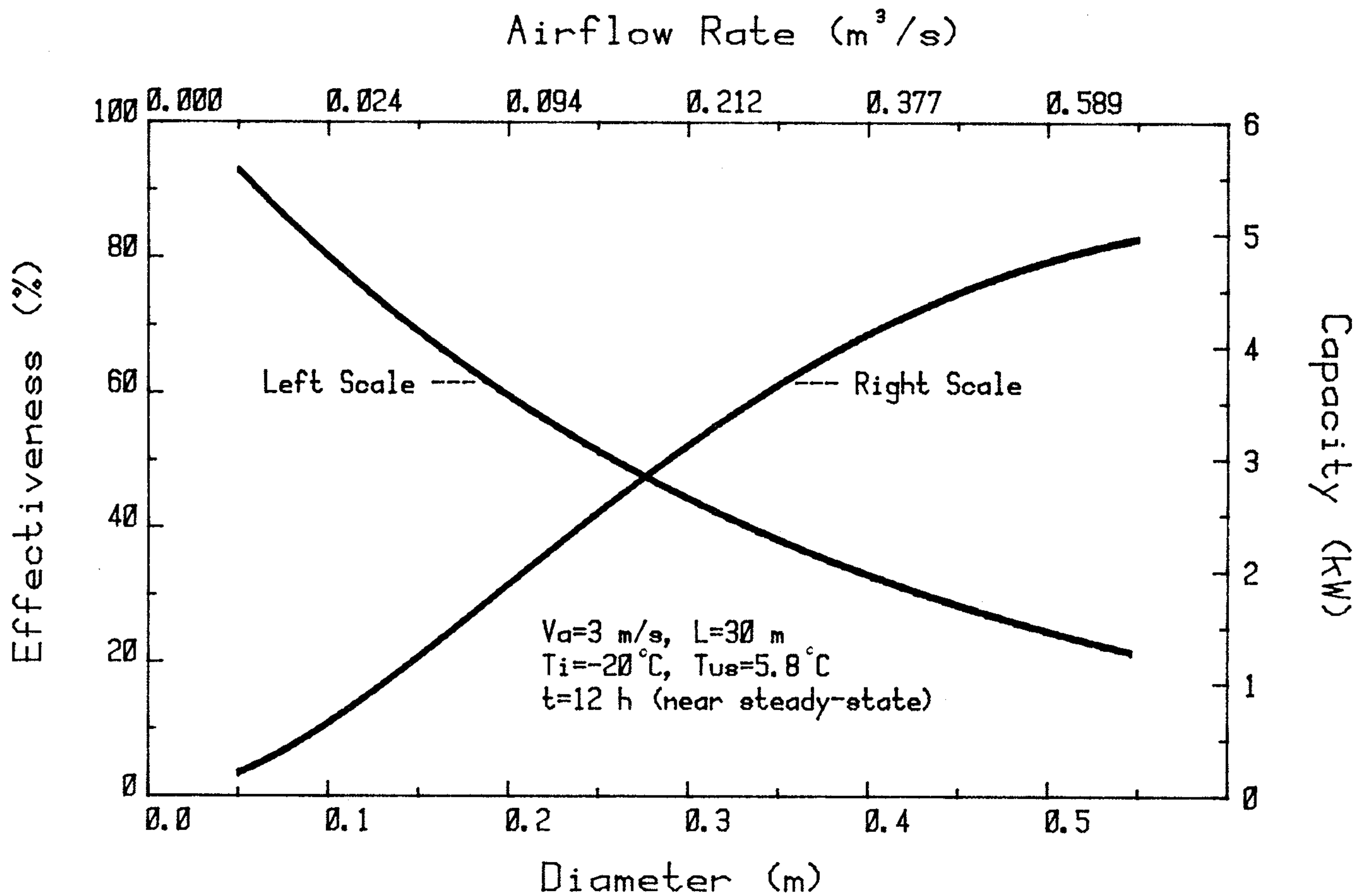

FIG. 5: SYSTEM THERMAL RESPONSE TO PIPE DIAMETERS

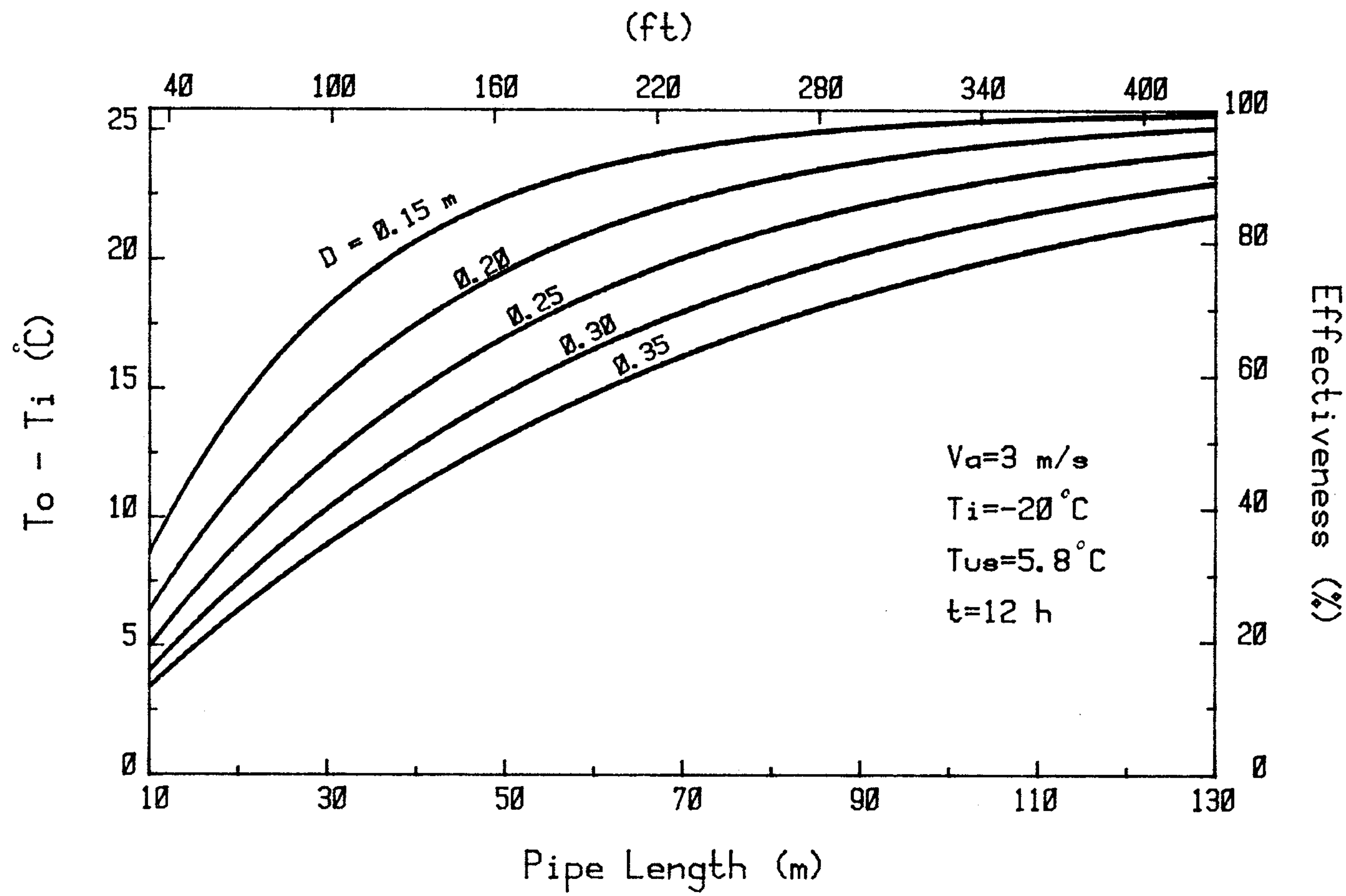

FIG. 6: THERMAL EFFECT OF LENGTH AND DIAMETER

4.3 DYNAMIC FACTORS: AIRFLOW RATE

Airflow rates play an important role in the system thermal performance. In order to exchange sufficient energy to meet the needs of the facility and to keep the expended energy as low as possible, the designer must know the thermal tendency of the entire system in order to maximize the overall heat transfer coefficient.

For comparable results the same soil features and system conditions, as mentioned in the above section, were used in this section. Only the heating process is illustrated because cooling cases show similar shapes in the related curves. Figure 7 supplies information on the thermal effects of airflow rates and pipe diameters. Sixteen pairs of output data for airflow rates from 0.010 m^3/s to 0.410 m^3/s, and pipe diameters of 0.150 m and 0.250 m were studied. With a confidence level of 0.05, the following mathematical expressions were best fitted to the data:

$$\Delta T = 20.7 \exp(-3.0*M) \quad \pm 1.5 \qquad (L=30\ m,\ D=0.150\ m) \tag{4-4 a}$$

$$\Delta T = 20.4 \exp(-3.1*M) \quad \pm 1.3 \qquad (L=30\ m,\ D=0.250\ m) \tag{4-4 b}$$

where M is the volume rate of airflow over the range of 0.010 m^3/s to 0.410 m^3/s. For air density 1.29 kg/m^3 at 0 °C mean temperature, the heat capacity (kW) can be approximated by:

$$Cap = 1.296\ M\ [\ 20.7\exp(-3.0*M) + 20.4\exp(-3.1*M)\ ]\ /\ 2 \quad \pm 0.5 \tag{4-5}$$

Figure 8 illustrates the temperature differential ΔT versus airflow rates and pipe lengths. The effects of airflow rates and pipe lengths on heat capacities were plotted in Figure 9. Under the conditions given, ΔT, for 0.250 m diameter, can be estimated by using the following expressions:

$$\Delta T = 16.51 \exp(-3.2*M) \quad \pm 1.6 \qquad (L=20\ m) \qquad [4\text{-}6\ a]$$

$$\Delta T = 23.0 \exp(-2.4*M) \quad \pm 1.4 \qquad (L=40\ m) \qquad [4\text{-}6\ b]$$

Similarly, estimated heat capacities can be written as follows:

$$Cap = 21.4\ M \exp(-3.2*M) \quad \pm 0.6 \qquad (L=20\ m) \qquad [4\text{-}7\ a]$$

$$Cap = 26.4\ M \exp(-3.1*M) \quad \pm 0.3 \qquad (L=30\ m) \qquad [4\text{-}7\ b]$$

$$Cap = 29.8\ M \exp(-2.4*M) \quad \pm 0.4 \qquad (L=40\ m) \qquad [4\text{-}7\ c]$$

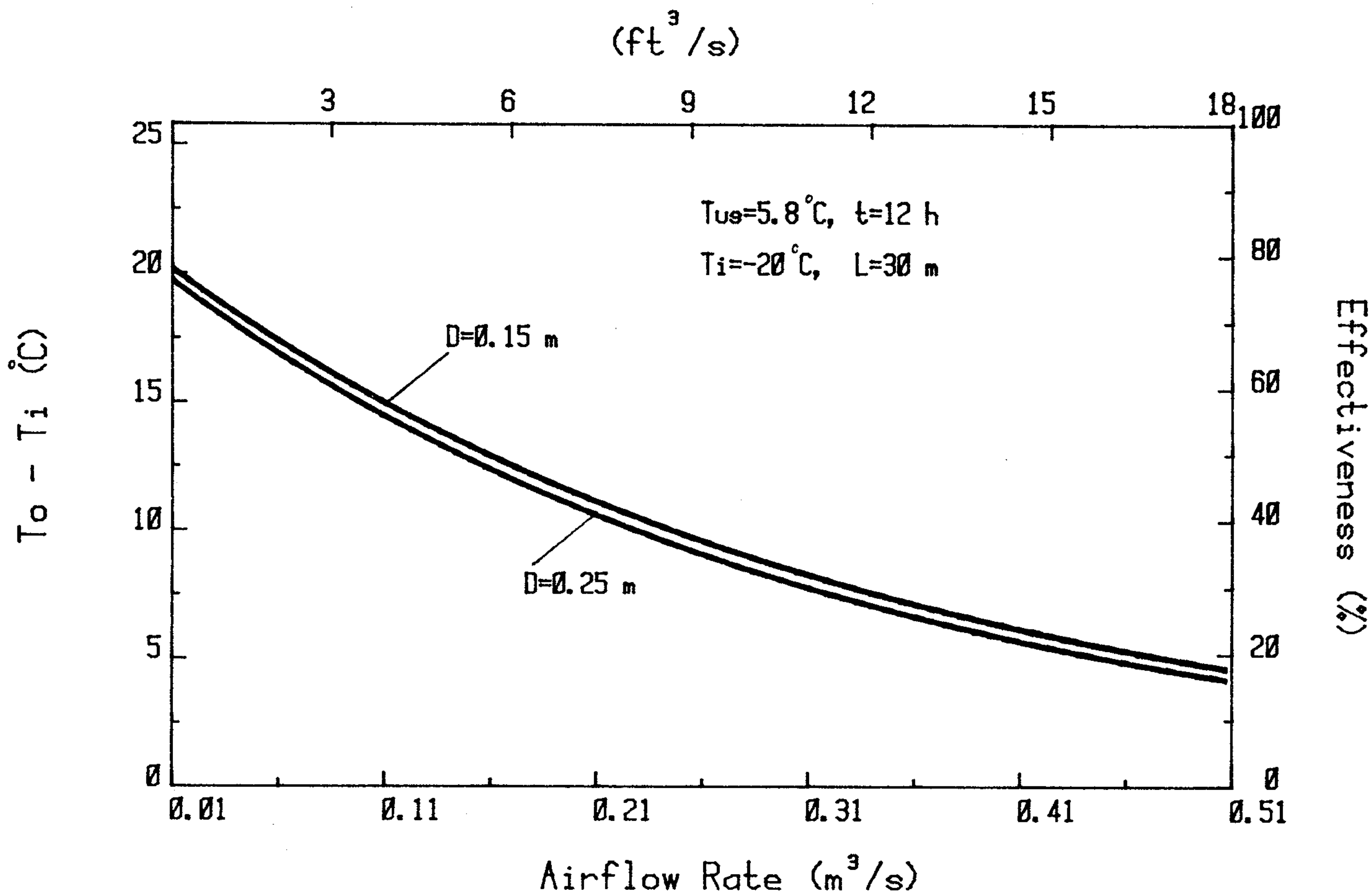

FIG. 7: THERMAL EFFECT OF AIRFLOW RATES

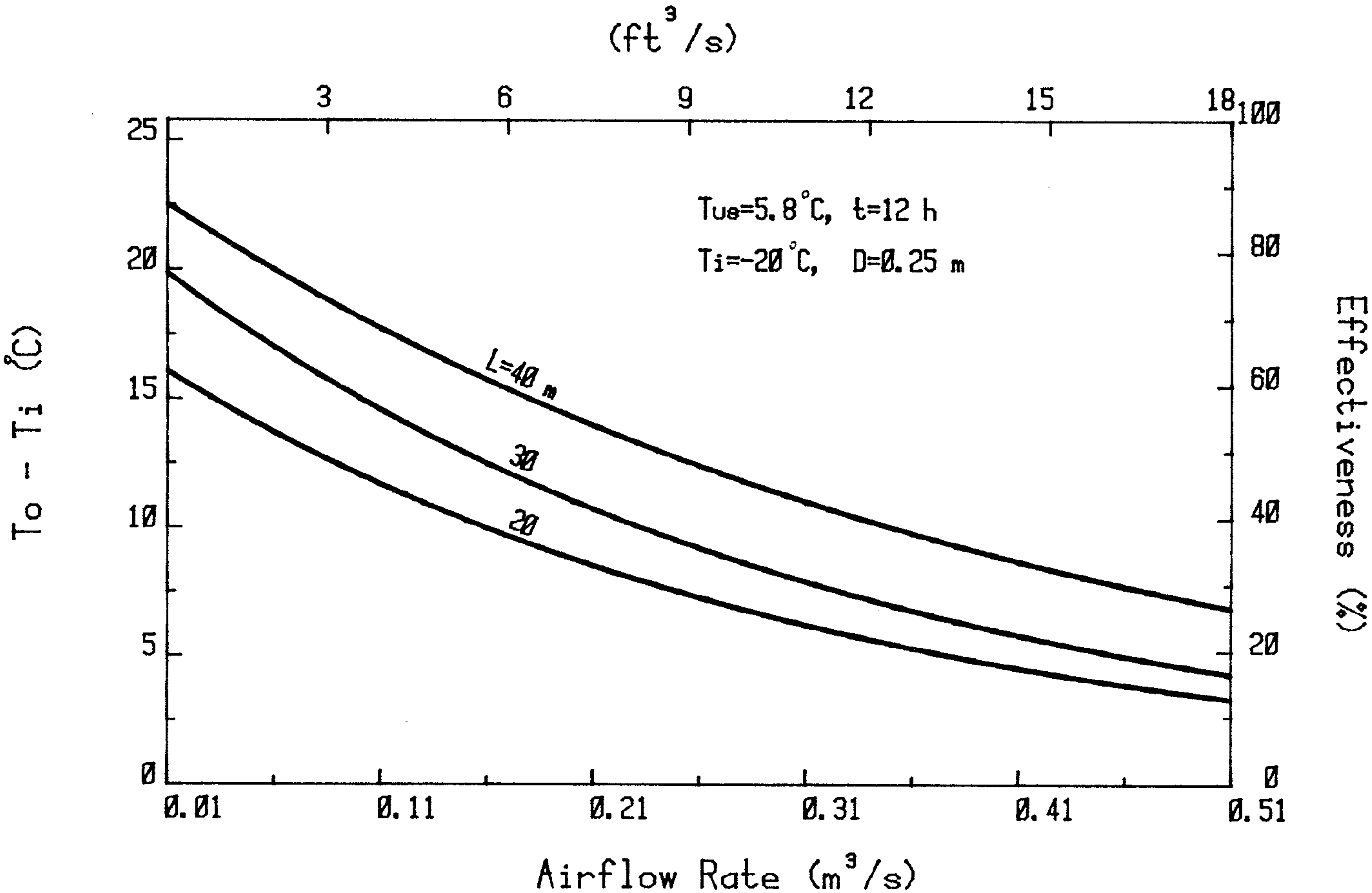

FIG. 8: THERMAL EFFECT OF AIRFLOW RATES AND PIPE LENGTHS

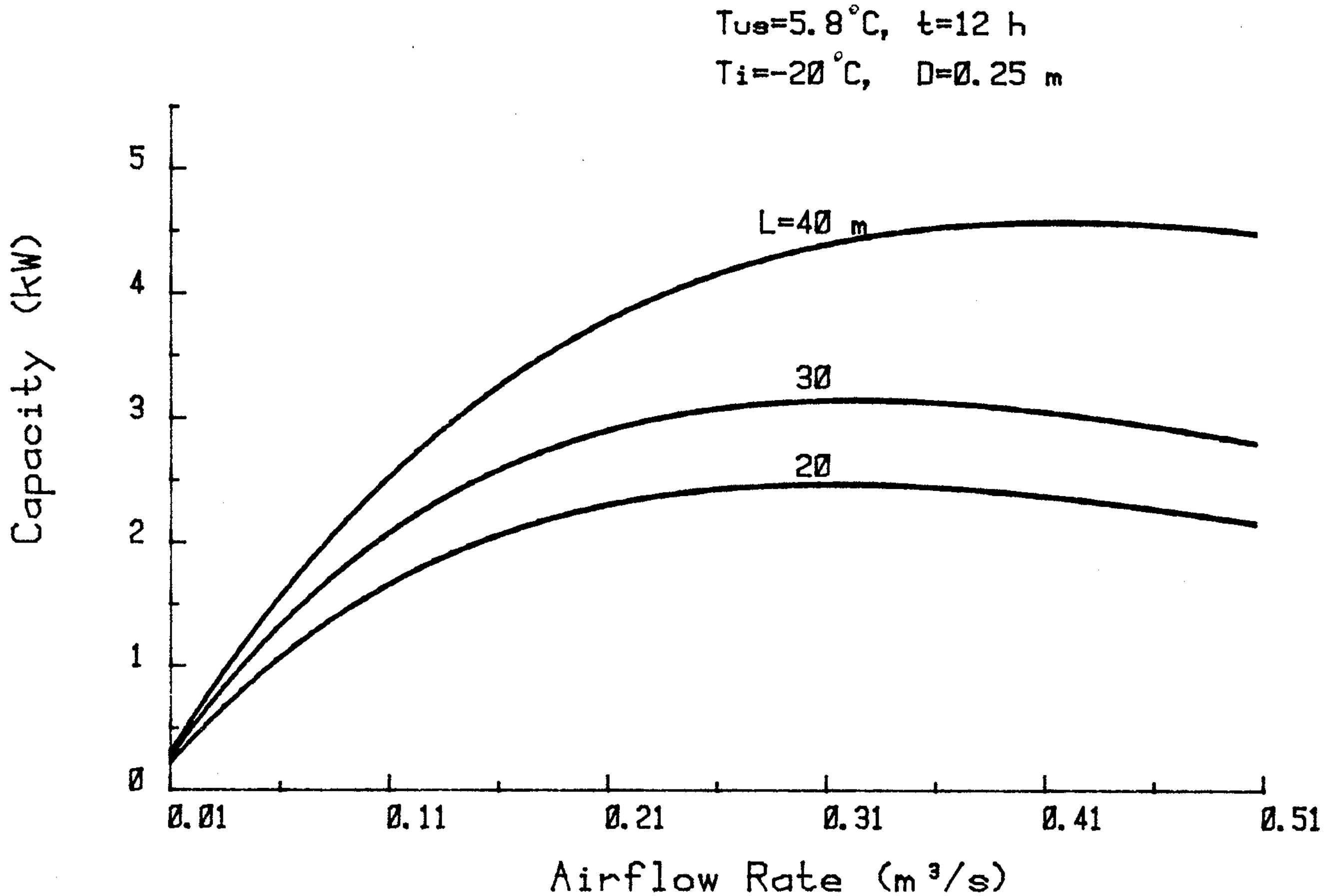

FIG. 9: HEAT CAPACITY VS. AIRFLOW RATES AND PIPE LENGTHS

4.4 SYSTEM THERMAL CONDUCTIVITY FACTORS

4.4.1 Soil Types and Properties

Soil types tested in the simulation were sand, silt, silty clay, and clay. Some properties for each soil texture are listed in Table 3. Literature suggests that it should be reasonable to use soil characteristics at high moisture content for a cool pipe and at low moisture content for a hot pipe. Before the thermal calculations for each soil element, the soil thermal conductivity is evaluated from Kersten's expressions in a subprogram, on the basis of soil texture, initial and instantaneous moisture content, current soil temperature, and dry soil density. Figures 10 and 11 represent air temperature distributions along the pipe for four types of soils in both heating and cooling cases.

For heating

$$Ta = -25.8 \exp(-A*z) + 5.8 \quad \pm 0.3 \tag{4-8}$$

where z is the distance from the inlet in m, and the values of A given by regression analysis are 0.039, 0.040, 0.041, and 0.044 for silty clay, silt, clay, and sand, respectively.

For cooling

$$Ta = 30.0 \exp(-A*z) \quad \pm 0.8 \tag{4-9}$$

where the values of A are 0.029, 0.030, 0.034, and 0.040 for silty clay, silt, clay and sand, respectively.

Twenty-one runs with densities, γ, for dry silty clay varying from 900 to 1500 kg/m^3 with three levels of soil saturation (25%, 60%, 95%)

at a variety of moisture contents were studied to provide further information on the effects of soil properties. The data points at each saturation level illustrated in Figure 12 show good linearity with soil density. They can be written mathematically as follows:

$$\Delta T = 0.00194\ \gamma + 9.159 \quad \pm 0.25 \qquad (S = 95\%) \qquad [4\text{-}10\ a]$$

$$\Delta T = 0.00195\ \gamma + 8.895 \quad \pm 0.20 \qquad (S = 60\%) \qquad [4\text{-}10\ b]$$

$$\Delta T = 0.00185\ \gamma + 8.098 \quad \pm 0.20 \qquad (S = 25\%) \qquad [4\text{-}10\ c]$$

4.4.2 Thermal Conductivity of Pipe

Plastic pipes with a low thermal conductivity have a noticeable temperature difference between a circulating fluid and the surrounding soil. How this influences the overall temperature differential, however, still remains questionable. The model containing a pipe resistance element allows the mechanism to be studied.

Three materials with high, medium, and low values of thermal conductivities were tested under the same thermal conditions as in the last section. At 0 °C mean temperature thermal conductivities of 387.74 W/(m°C) and volumetric heat of 37,401 kJ/(m^3°C) for pure copper, 45.87 W/(m°C) and 3,613 kJ/(m^3°C) for mild steel (1% C) (Kreith 1973), and 0.134 W/(m°C) and 1,513 kJ/(m^3°C) for PVC pipe (Svec 1983; Ogorkiewicz 1970) were used as input data. Air temperature distributions along the pipe for the three materials are graphically shown in Figure 13. The transformed linear regression equation gives:

TABLE 3

Some Properties of Soils for Data Input

Quantity	Sand	Silt	Silty clay	Clay
Specific gravity, G	2.65	2.68	2.70	2.75
Quality	wet	wet	wet	wet and dense
		--- Heating ---		
Bulk density* kg/m^3	1950	1800	1700	1900
Degree of saturation, S%	95	95	95	95
Moisture content, w_0	0.25	0.37	0.47	0.31
Dry density kg/m^3	1560	1314	1156	1450
Saturated m.c.	0.264	0.390	0.495	0.326
		--- Cooling ---		
Bulk density* kg/m^3	1700	1600	1600	1800
Degree of saturation, S%	30	30	30	30
Moisture content, w_0	0.077	0.093	0.094	0.072
Dry density kg/m^3	1578	1464	1463	1682
Saturated m.c.	0.256	0.310	0.313	0.231

* --- From Jumikis (1977)

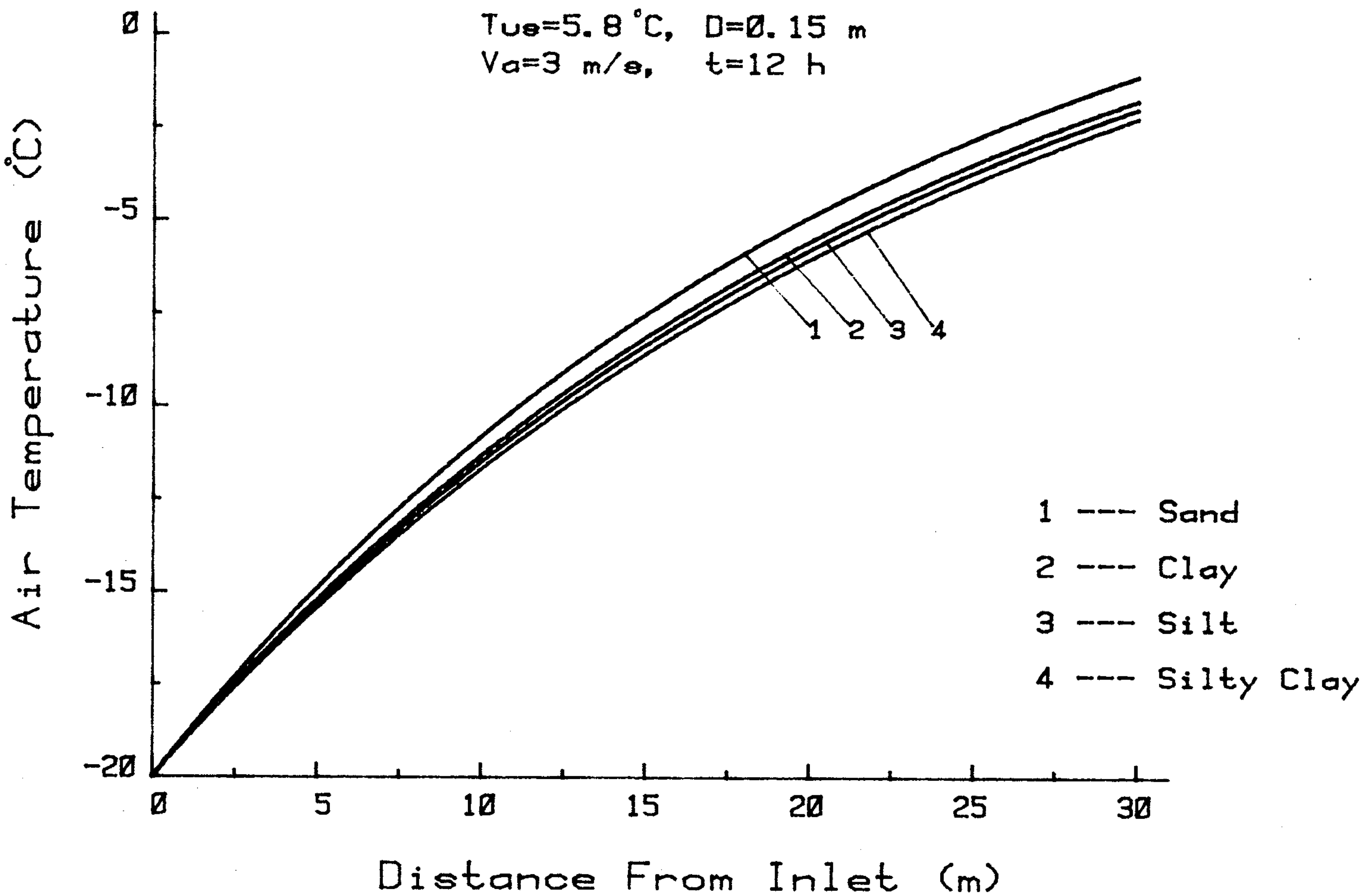

FIG. 1Ø: HEATING CURVES VS. SOIL TYPES

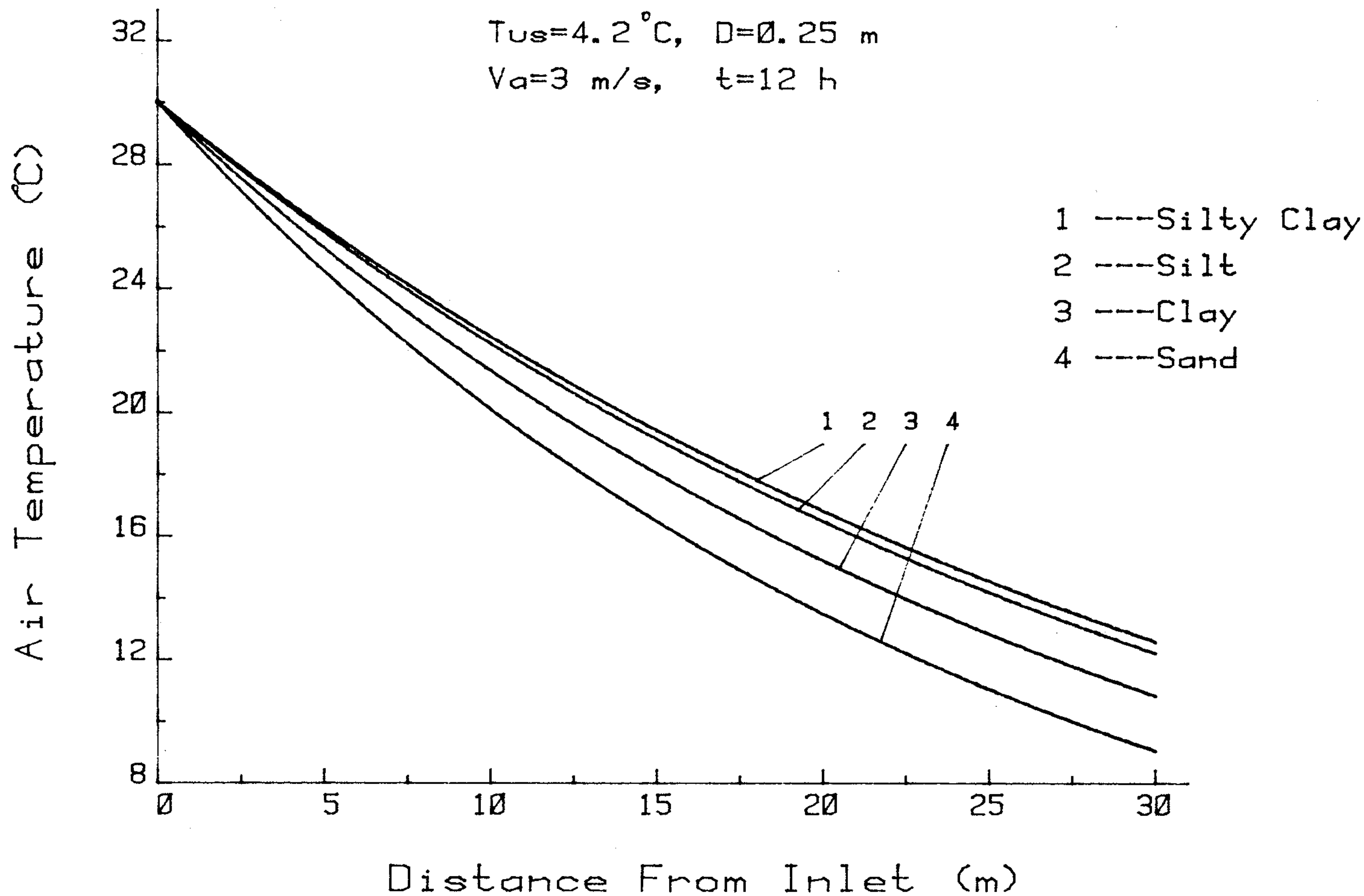

FIG. 11: COOLING CURVES VS. SOIL TYPES

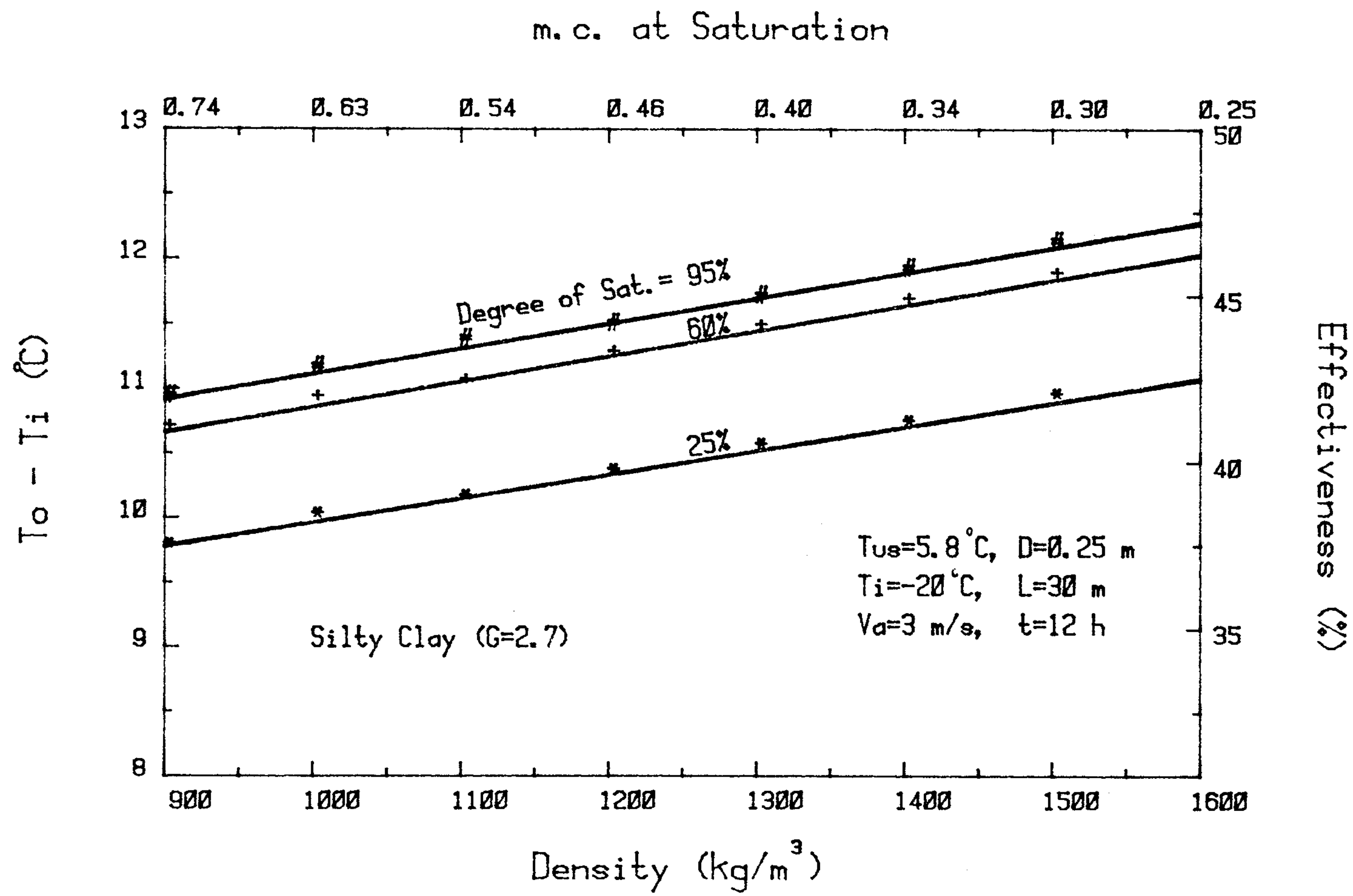

FIG. 12: THERMAL EFFECT OF SOIL DENSITY AND MOISTURE

$$Ta = -25.8 \exp(-A*z) + 5.8 \quad \pm 0.1 \qquad [4-11]$$

where the values of A are 0.049, 0.047, and 0.040 for copper, steel, and PVC, respectively. Other conditions are given in the Figure.

The soil temperature profile at z = 6 m from the inlet is illustrated in Figure 14. The temperature drop through the pipe is magnified for clarity. The data can be approximated by the equations:

$$T(r,t) = A*r - B \qquad (t = 12\text{ h},\ 0.075\text{ m} \le r \le 0.078\text{ m}) \qquad [4-12\text{ a}]$$

$$T(r,t) = F*r - G \qquad (t = 12\text{ h},\ 0.078\text{ m} \le r \le 0.080\text{ m}) \qquad [4-12\text{ b}]$$

$$T(r,t) = -P \exp(\ -Q(r-0.08)\ ) + 5.8 \quad \pm 0.1 \qquad (t = 12\text{ h},\ r \ge 0.080\text{ m}) \qquad [4-12\text{ c}]$$

where, A = 0.40, 3.30, and 1003.73; B = 1.92, 3.09, and 80.19; F = 329.20, 338.50, and 302.40; G = 27.57, 29.24, and 25.49; P = 7.03, 7.10, and 7.96; Q = 15.0, 14.0, and 13 .0 for copper, steel and PVC, respectively. Obviously, the values of A are temperature gradients for the pipe materials. The temperature drop due to the contact resistance is given in equation [4-12 b].

4.4.3 Convective Heat Transfer Coefficients

One of the key variables in the exchanger operation is the convective heat transfer coefficient. Unfortunately, the coefficient is not independent of other variables in the system. It is closely related to dynamic, geometric, and other variables such as air velocity, pipe diameter, and air temperature as well as pipe surface roughness.

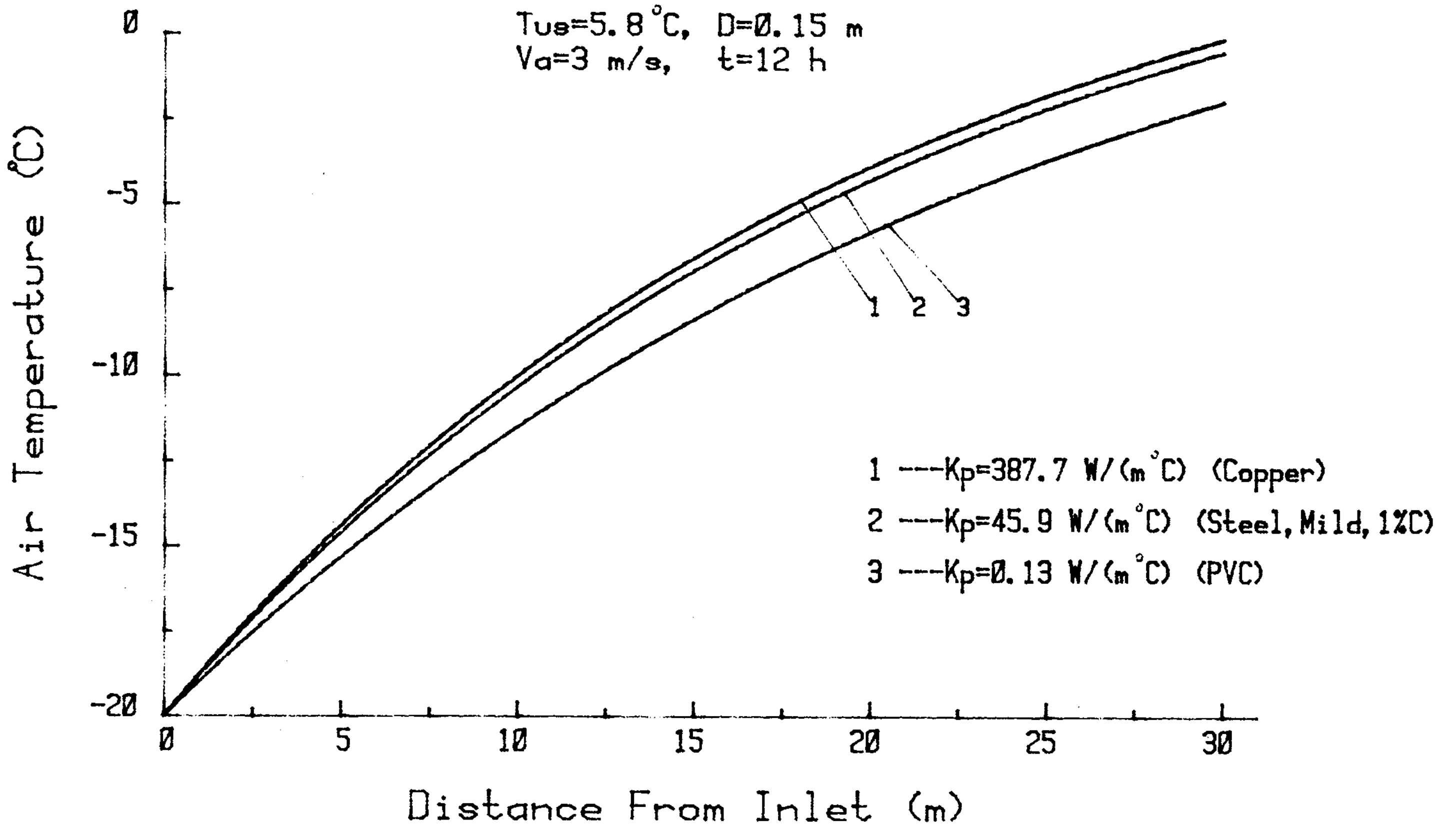

FIG. 13: AIR TEMPERATURE DISTRIBUTION VS. PIPE CONDUCTIVITIES

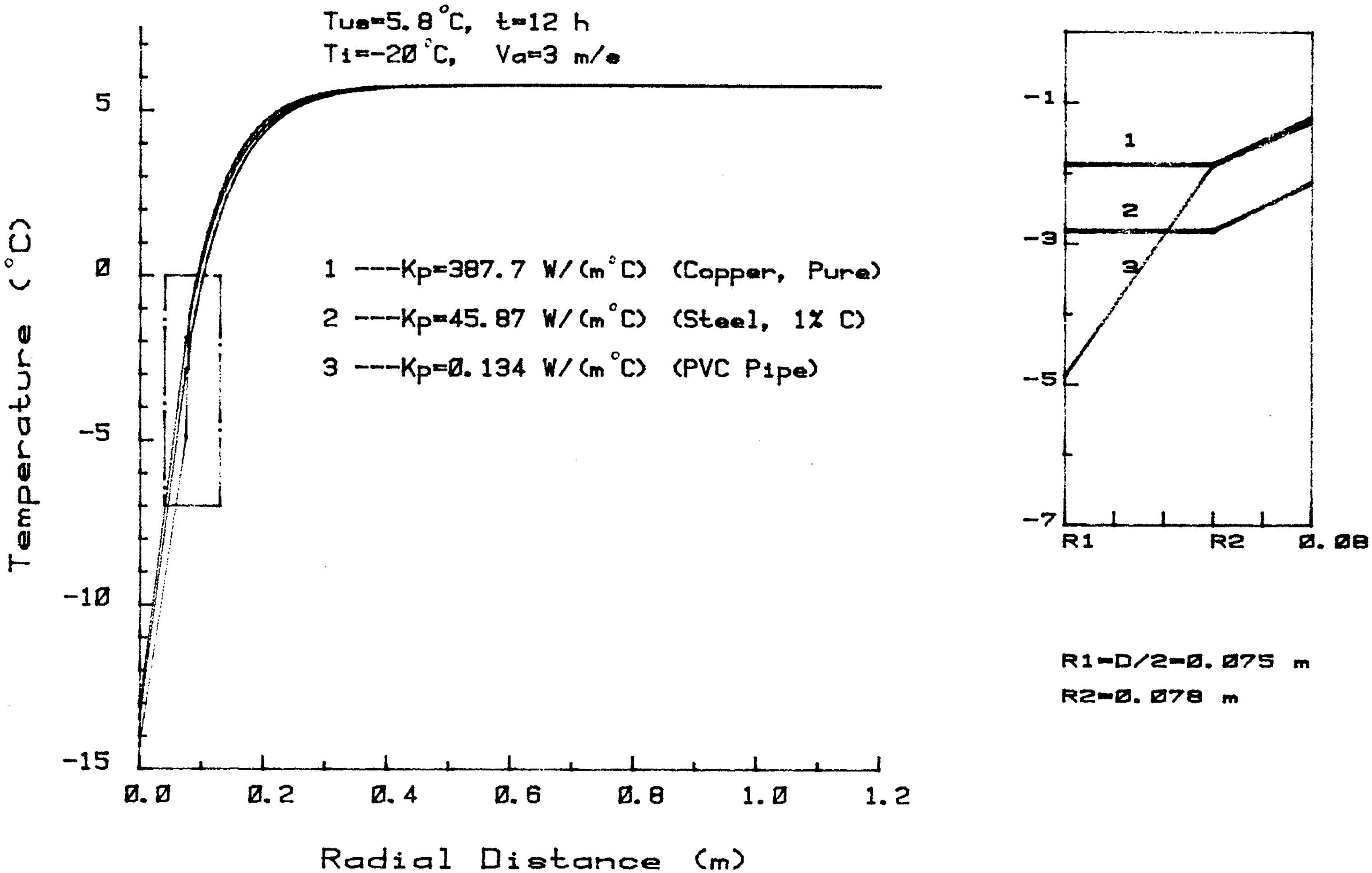

FIG. 14: SOIL TEMPERATURE PROFILE AT Z=6 m

For convenient comparisons of condensation, air cooling operation in the summer was simulated for the previous soil conditions. Four sets of data were calculated. The simulation was run with combinations of pipe diameters of 0.150 m and 0.250 m and with the relative humidity of the ambient air at 20% (non-condensing) and 80% (condensing). The heat transfer coefficients were changed by increasing the air velocity (1 to 6 m/s). The program automatically checks psychrometric charts to determine which process is occurring. Since the heat transfer coefficients were recalculated when the difference of current and previous air temperatures along the pipe exceeds a given value, average numbers were used in plotting Figures 15 and 16. To illustrate the increase in hc, the abscissas are the ratio of the coefficient hc to the air velocity Va.

For non-condensing cooling:

$$\Delta T = 5.3\ hc/Va - 5.83 \quad \pm 3.5$$

$$(D = 0.150\ m,\ hc/Va = 3.8 \text{ to } 5.6\ J/(m^3\,^\circ C)) \qquad [4\text{-}13\ a]$$

$$\Delta T = 6.26\ hc/Va - 12.68 \quad \pm 2.5$$

$$(D = 0.250\ m,\ hc/Va = 3.4 \text{ to } 5.0\ J/(m^3\,^\circ C)) \qquad [4\text{-}13\ b]$$

For cooling with condensation along the entire pipe length:

$$\Delta T = 1.090\ hc/Va + 5.33 \quad \pm 3.0$$

$$(D = 0.150\ m,\ hc/Va = 11 \text{ to } 19\ J/(m^3\,^\circ C)) \qquad [4\text{-}13\ c]$$

$$\Delta T = 1.028\ hc/Va - 0.85 \quad \pm 2.5$$

$$(D = 0.250\ m,\ hc/Va = 13 \text{ to } 24\ J/(m^3\,^\circ C)) \qquad [4\text{-}13\ d]$$

With ambient air temperature of 30 °C and a dew point temperature of 26 °C (R.H. = 80%) the air was cooled with condensation. Air temperature distribution along the pipe for simultaneous mass and heat transfer is illustrated in Figure 17. A non-condensing curve for the same conditions but with dew point temperature of 5 °C (R.H. = 20%) is presented for comparison. Regression analysis yielded the following mathematical expression:

$$Ta = 25.8 \exp(-A*z) + 4.2 \quad \pm 0.5 \qquad [4-14]$$

where A is 0.075 for non-condensing and 0.120 for condensing operation.

4.4.4 Contact Resistance

Like the thermal resistance of the pipe, the contact resistance results in a significant temperature difference at the interface between the pipe wall and the soil. To estimate the temperature differential, the same soil conditions and thermal potential as discussed in section 4.2 were used for input data. The heating curves illustrated in Figure 18 use two values of contact resistances, 0.05 and 0.00005 $m^2 °C/W$, one of which is very high while the other is very low in comparison to practical values. The derived expression is:

$$Ta = -25.8 \exp(-A*z) + 5.8 \quad \pm 0.3 \qquad [4-15]$$

where A = 0.03 at CR = 0.05 $m^2 °C/W$; A = 0.041 at CR = 0.00005 $m^2 °C/W$. The soil temperature profiles were similar to those of Figure 14.

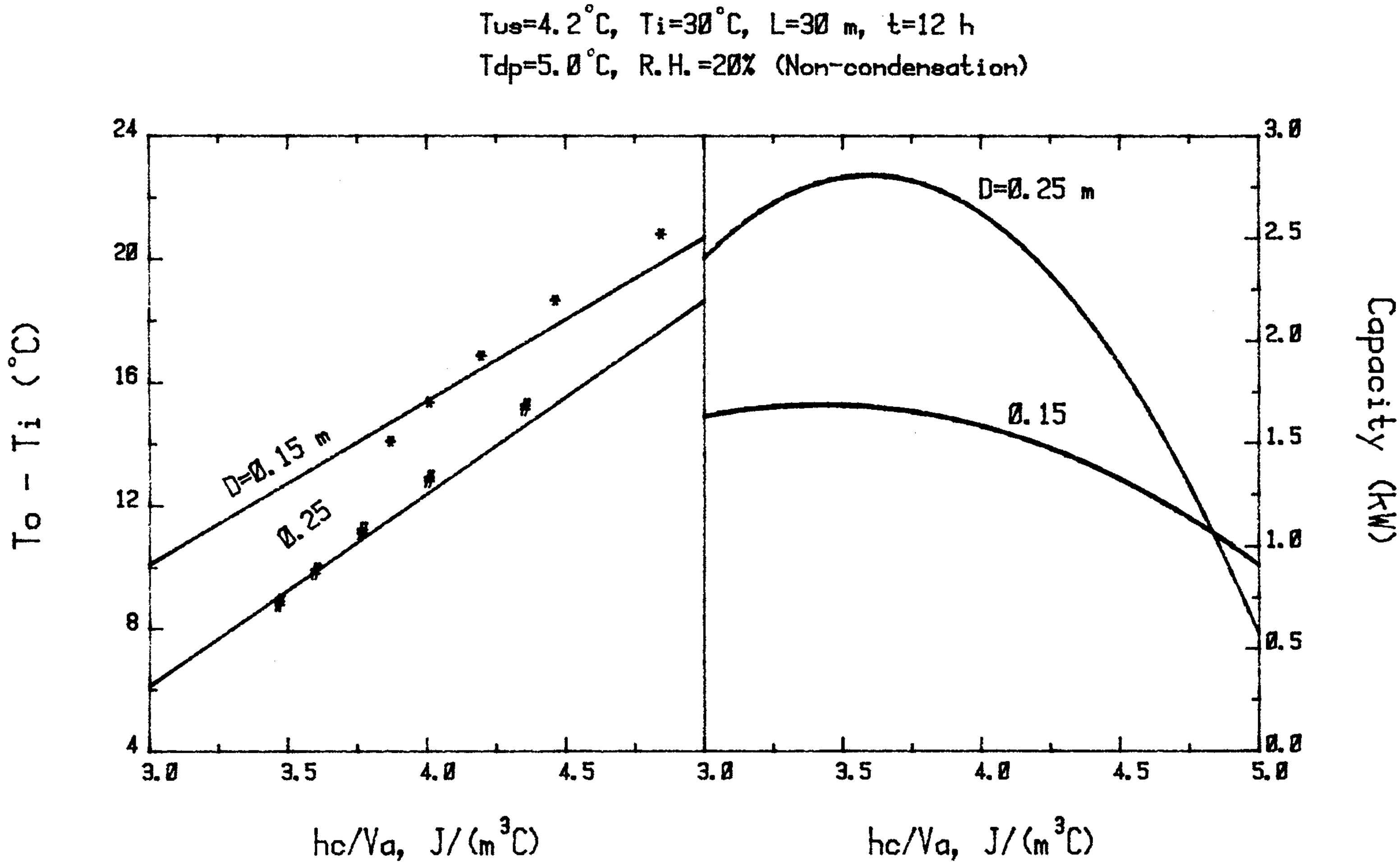

FIG. 15: THERMAL EFFECT OF HEAT TRANSFER COEFFICIENTS

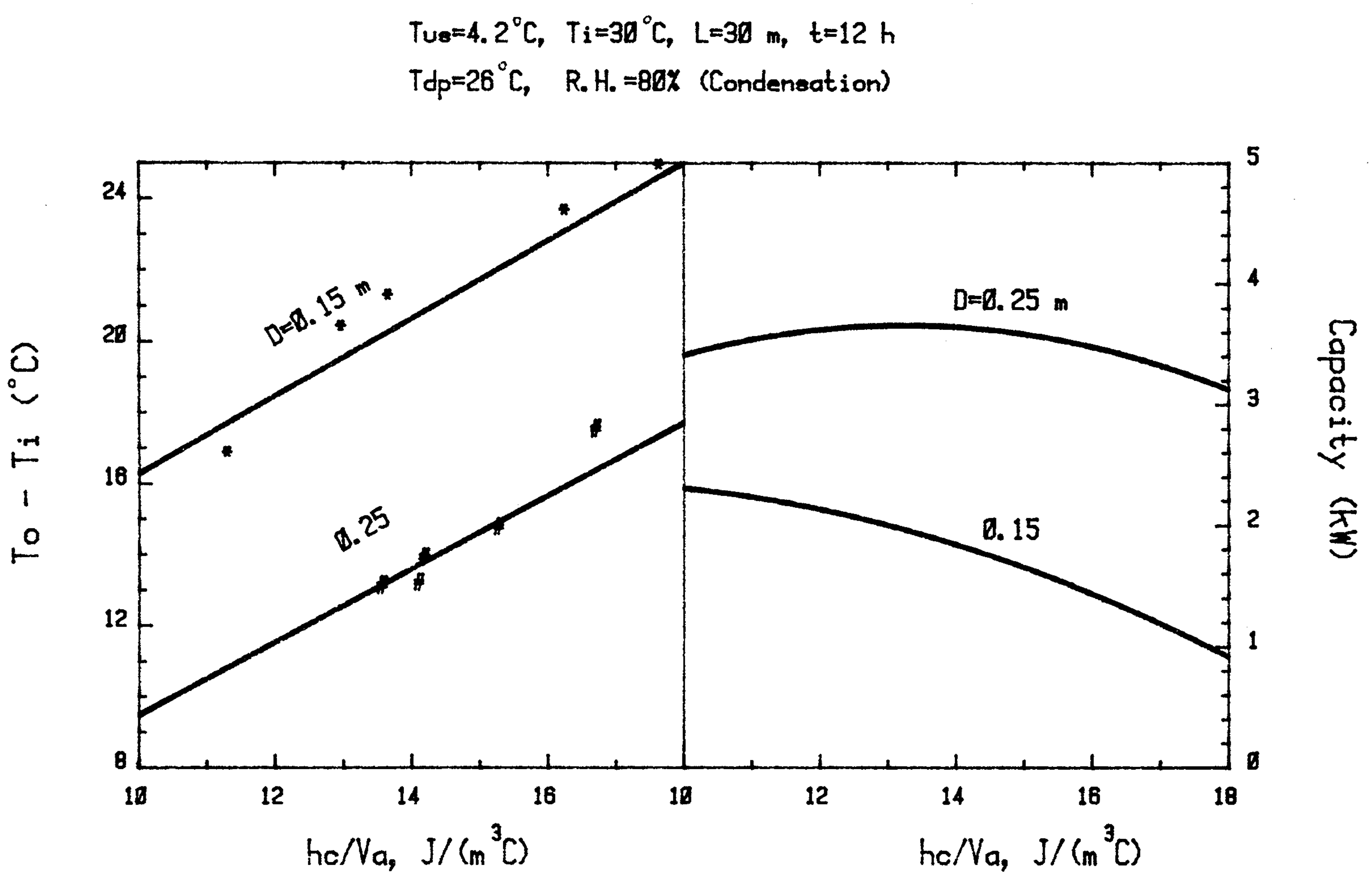

FIG. 16: THERMAL EFFECT OF hc WITH CONDENSATION

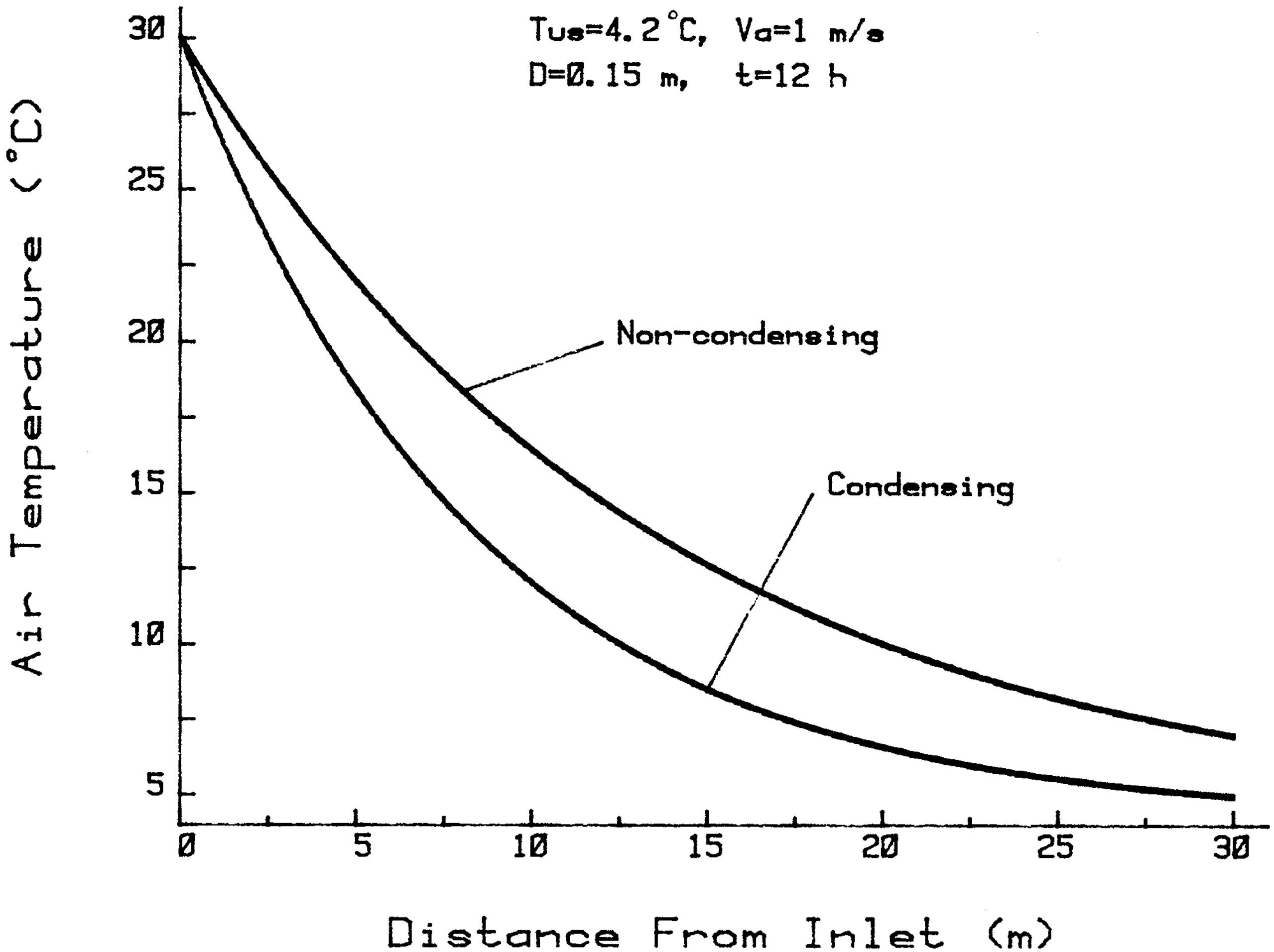

FIG. 17: COOLING WITH AND WITHOUT CONDENSATION

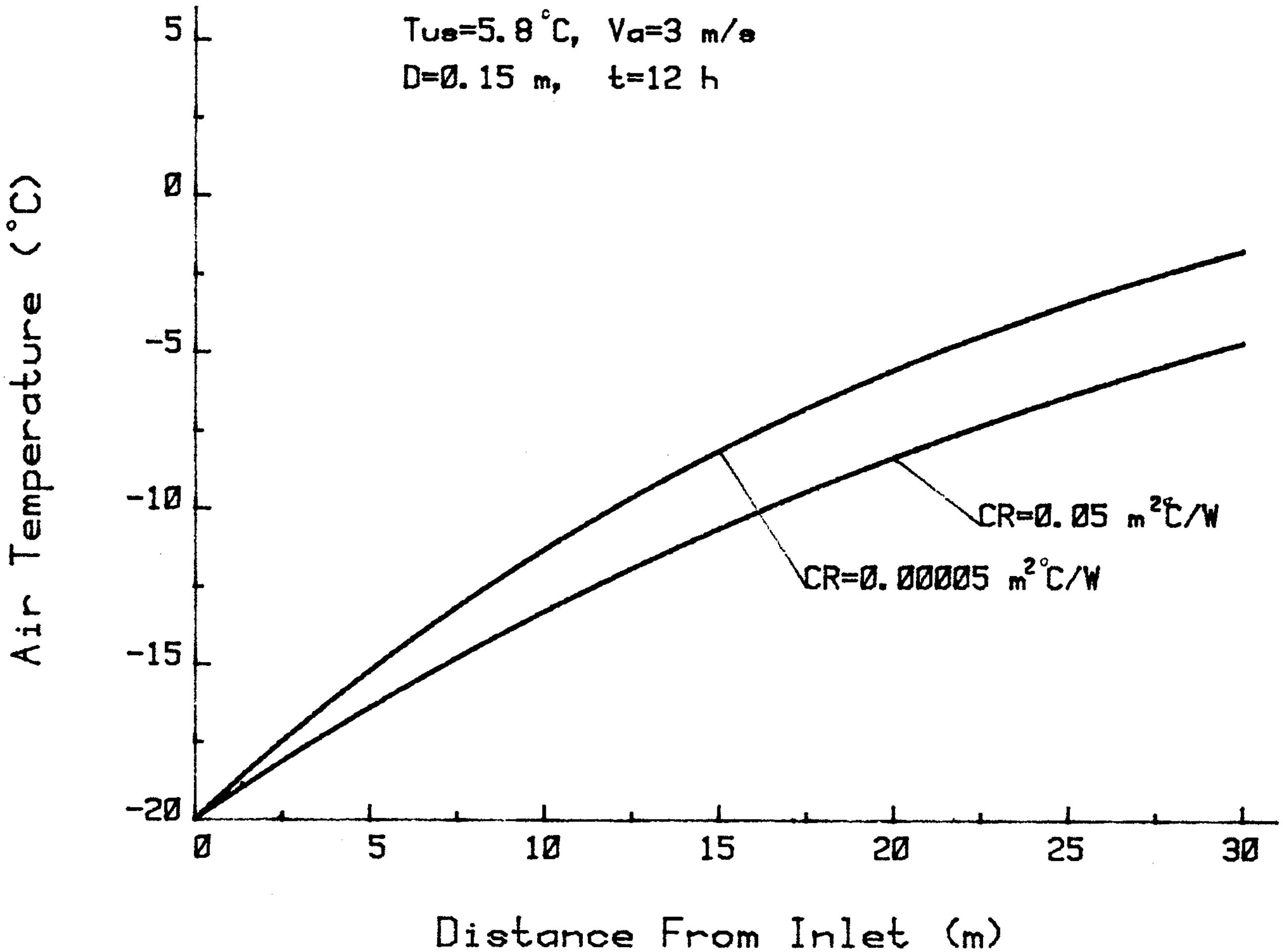

FIG. 18: THERMAL EFFECT OF CONTACT RESISTANCE

4.5 PERFORMANCE FACTORS

4.5.1 Air Temperature Variation

Average hourly and average monthly temperature variations in the ambient air occur periodically. While the system thermal potential varies mainly with the input air temperature, overall heat transfer with continued operation will fluctuate considerably. An analogy can be made to a mechanical system with damped vibrations influenced by an external exciting force. To create an exact analogy to a mechanical vibration system would require a considerable amount of knowledge on the thermal conditions of the soil and the fluid.

The results of simulation over two days in January for an air tempering system are shown in Figure 19. Silty clay with a bulk density of 1800 kg/m^3 and a moisture content of 30% (dry basis) was assumed in the simulation. Air temperatures from the weather records of 1970 in Winnipeg were used for the input data.

4.5.2 Undisturbed Soil Temperature

This variable is classified as a performance factor because the designer can select an appropriate depth or an existing soil temperature to design for a required use. On the other hand, the seasonal mean soil temperature varies harmonically but the amount of the variation decreases as the depth increases. The system temperature differential and heat capacity depend primarily upon this soil thermal potential.

Pipes buried at depths from 1 m to 6 m for silty clay were studied. Six computer runs were completed for a heating simulation. With a confidence level of 0.05, the data were analyzed. The results varied linearly with undisturbed soil temperature, Tus. Figure 20 presents the results graphically and the other operating conditions are also given in the Figure. The relation of ΔT with Tus can be estimated by:

$$\Delta T = 0.56\ Tus + 15.23 \quad \pm 1.2 \qquad \text{(January)} \tag{4-16}$$

The effectiveness, by definition, is:

$$E = \frac{0.56\ Tus + 15.23}{Tus + 20.0} * 100 \quad \pm 1.2 \tag{4-17}$$

4.5.3 Continuous and Intermittent Operation

The thermal efficiency of the exchanger for continuous operation depends largely on the effective volume of soil available to the system. In simulating continuous operation it may be necessary to increase the soil volume considered in order to secure zero heat flux at the outside surface of the soil cylinder. The program developed has the flexibility to recalculate the undisturbed soil temperatures and reset the solution domain, if necessary.

The seasonal behavior of the exchanger was demonstrated in Figure 21. The undisturbed soil temperatures at 3 m deep at Glenlea were estimated using the model in section 3.4. Mean monthly ambient air temperatures for Winnipeg (Environment Canada 1977-1983) were used for predicting the tempered air temperatures. This simulation was completed using the following conditions: 1800 kg/m^3 for bulk density of silty clay soil, 30% for initial moisture content of soil, 1.0 m to 1.5 m for the outside ra-

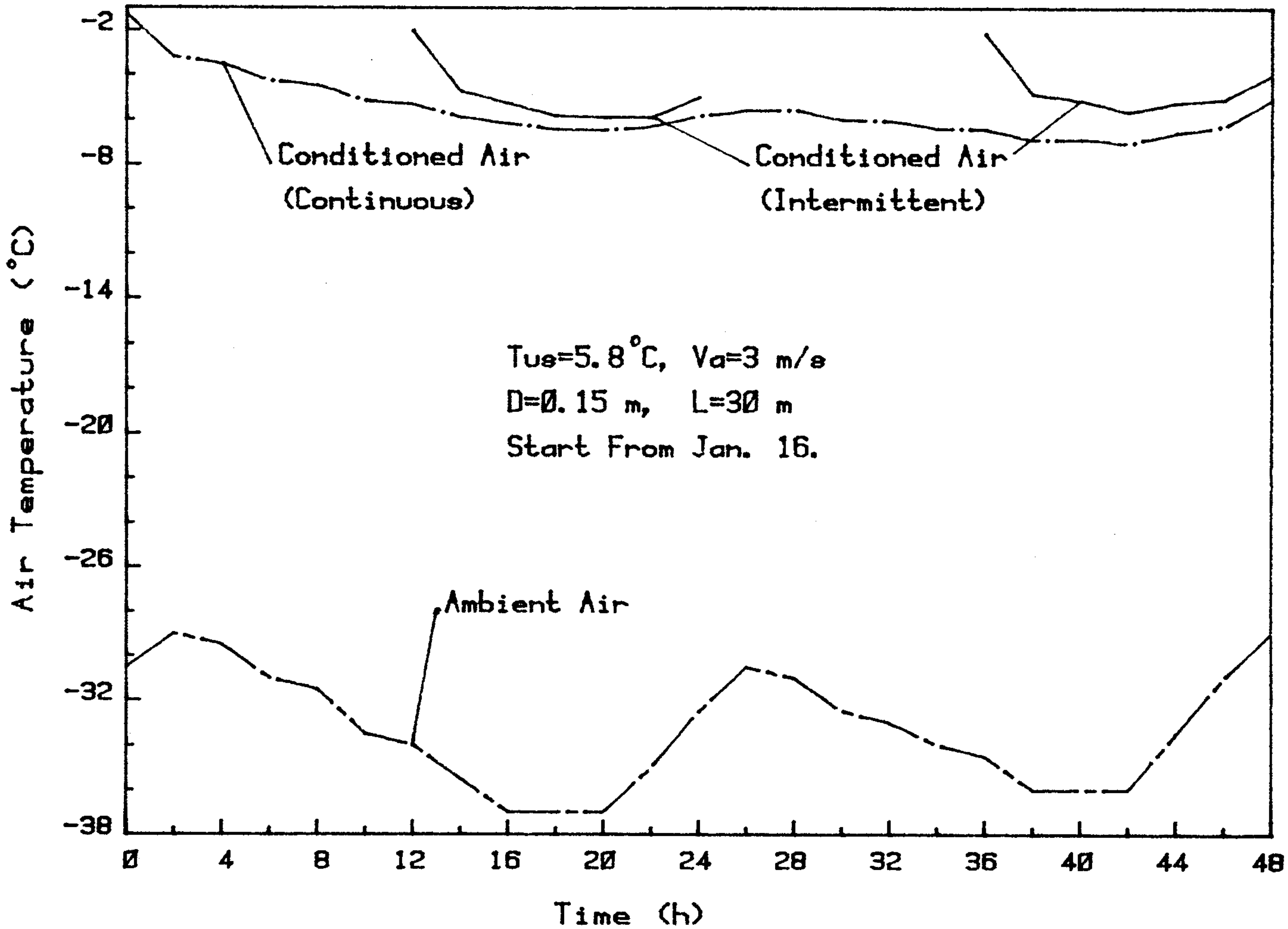

FIG. 19: COMPARISON OF CONTINUOUS AND INTERMITTENT OPERATION

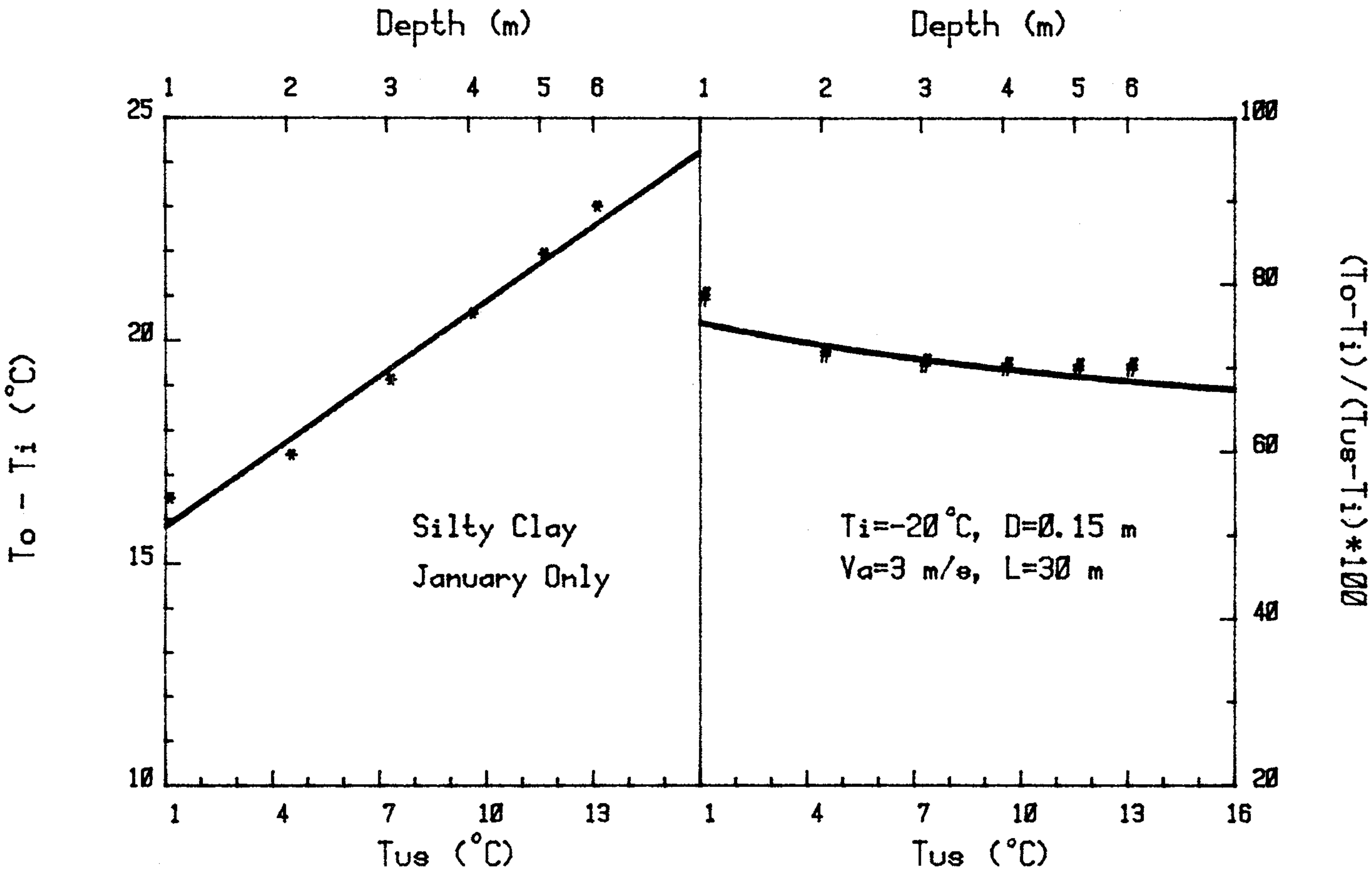

FIG. 20: THERMAL EFFECT OF UNDISTURBED SOIL TEMPERATURES

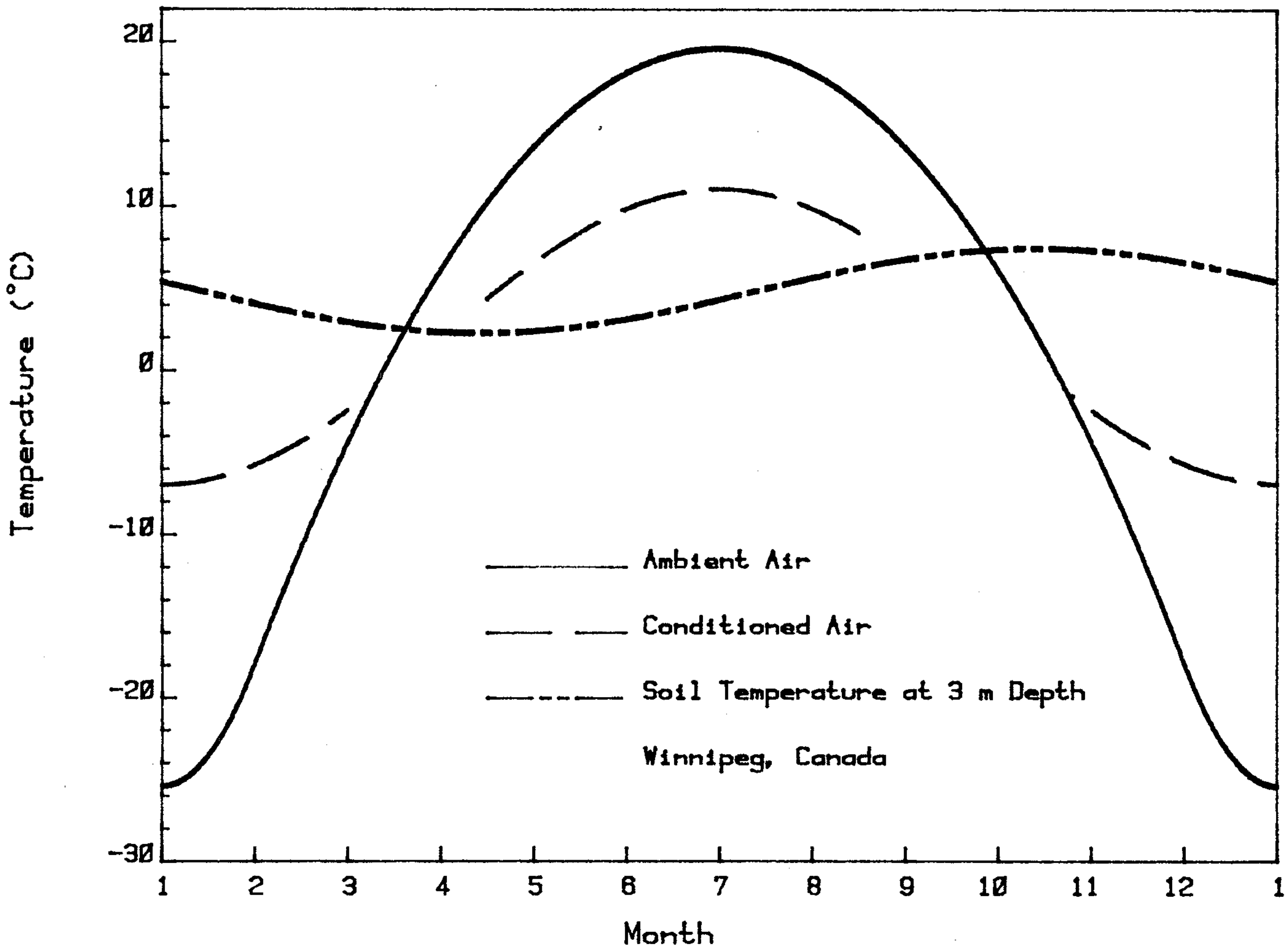

FIG. 21: SEASONAL BEHAVIOR OF SOIL-AIR HEAT EXCHANGERS

dius of the soil cylinder or solution region, 0.150 m for the pipe diameter, 30 m for the pipe length, 3 m/s for the air velocity and 120 hours for the time interval of the simulation.

Theoretically, intermittent operation allows time for soil temperature recovery. This gives an opportunity to use the system efficiently. However, intermittent operation complicates the simulation because of difficulties in estimating the exact recovery of soil temperature and soil moisture. Assuming the complete recovery of temperature and moisture in 12 h is only an approximation. Based on the conditions mentioned in section 4.5.1 and with the same input air temperatures, the conditioned air temperatures for intermittent operation are illustrated in Figure 19.

4.6 FACTOR GROUPING INVESTIGATION

4.6.1 Dimensionless Analysis

The soil-air heat exchange is characterized by many variables which complicate interpretation of research results. Dimensional analysis offers a method of combining several variables into dimensionless groups. These groups containing the physical quantities pertinent to the problem facilitate the interpretation and extend the range of application of experimental or simulated data.

The fundamental nature of dimensional analysis is to group variables into nondimensional groups to obtain the relation describing a physical phenomenon. To apply dimensional analysis exactly it is necessary to known in advance all of the variables that influence the phenomenon.

The proper selection of these variables is the key to the success of the method. The pertinent variables are expressed in terms of primary dimensions such as length L, time ø, temperature T, and mass M. According to the Buckingham Pi Theorem (Driest 1940; Kreith 1973), the required number of independent dimensionless groups is equal to the total number of the physical quantities, n, in the problem minus the number of primary dimensions, m, required to express the dimensions of the n physical quantities. For an adequate description of the temperature differential between the inlet and the outlet of a soil-air heat exchanger, it is reasonable to expect that the physical quantities listed in Table 4 are pertinent to the problem. There are seven physical quantities (n=7) and four primary dimensions (m=4). Therefore, three dimensionless groups are expected to correlate the data.

The reason why the thermal conductivity of soil and the convective heat transfer coefficient do not appear in the list of Table 4 is that they are temperature-dependent and calculated on the basis of input data such as bulk density and initial moisture content of soil, air velocity and pipe diameter. The quantity for soil water, Sw, is the product of bulk density and moisture content of soil. The last variable Rt in Table 4 is used to take into account the total thermal resistance of the pipe and the contact interface between the pipe and the surrounding soil. It is defined by the following equation

$$Rt = \frac{R \ln(R_1/R_0)}{kp} + \frac{R\ CR}{R_2} \qquad [4\text{-}18]$$

where R_0, R_1 = inside and outside radii of pipe, respectively, m
R_2 = radius distance at the contact interface, m
R = arbitrarily large radius of the soil cylinder, m
kp = thermal conductivity of the pipe, $W/(m\,^\circ C)$
CR = contact resistance, $m^2\,^\circ C/W$.

TABLE 4

Key Variables of the Exchanger for Dimensional Analysis

Variable	Symbol	Dimensions
Temperature differential (absolute value of To - Ti)	ΔT	[T]
Pipe diameter	D	[L]
Distance from inlet	Z	[L]
Air velocity	Va	[L/ø]
Quantity of soil water (product of bulk density and m.c. of soil)	Sw	$[M/L^3]$
System thermal potential (absolute value of Ti - Tus)	Ps	[T]
Total thermal resistance of the pipe and contact interface ([4-18])	Rt	$[T\phi^3/M]$

To find the dimensionless groups G_1, G_2, and G_3, the use of the Buckingham Pi Theorem yields a solution of the form

$$F(G_1, G_2, G_3) = 0 \qquad [4\text{-}19]$$

This can also be written as a product of the variables each raised to an unknown power:

$$G = \Delta T^a\ D^b\ Z^c\ Va^d\ Sw^e\ Ps^f\ Rt^g . \qquad [4\text{-}20]$$

Substituting with the variable dimensions gives:

$$G = [T]^a\ [L]^b\ [L]^c\ [L/\phi]^d\ [M/L^3]^e\ [T]^f\ [T\phi^3/M]^g \qquad [4\text{-}21]$$

For G to be dimensionless, the exponents for each primary dimension must separately add up to zero. This gives the set of the equations:

$$b + c + d - 3e = 0 \qquad \text{for } L$$

$$a + f + g = 0 \qquad \text{for } T$$

$$-d + 3g = 0 \qquad \text{for } \phi$$

$$e - g = 0 \qquad \text{for } M$$

Any set of values of a, b, c, d, and e that simultaneously satisfies these equations will make G dimensionless. The only restriction on the choice of the exponents is that each of the selected exponents be independent of the others. With a=1 and g=b=0 the solution of the equations leads to f=-1 and e=d=c=0. Thus the first dimensionless group is

$$G_1 = \frac{\Delta T}{Ps}$$

This is recognized as the heat exchanger effectiveness.

Similarly, with a=c=0 and d=-3, a=g=0 and c=1, the second and the third dimensionless groups are:

$$G_2 = \frac{Ps}{Va^3\ Sw\ Rt} \qquad \text{and} \qquad G_3 = \frac{Z}{D}$$

G_2 is now redefined as Le and G_3 redefined as Qu. Although the system temperature differential was defined as a function of six variables, with the aid of dimensional analysis, the seven original variables have been combined into three dimensionless groups. Equation [4-19] gives the functional relationship as:

$$\frac{\Delta T}{Ps} = f(Qu, Le) \qquad \text{or} \qquad E = 100\ f(Qu,Le) \tag{4-22}$$

4.6.2 Dimensionless Curves for Design

The simulation data obtained from previous sections of this Chapter can now be correlated in terms of three variables in Equation [4-22]. Heating data for 140 points were plotted in Figure 22 for intermittent operation. All of the data were obtained from computer outputs with the simulation time greater than six hours so that the heat exchanger was close to steady-state conditions. For plotting convenience the product of Qu and Le raised to the 1/3 power was used as the abscissa. It is interesting to note that all of the data points fall in an exponential envelope. A transformed linear regression model (R-squared = 0.95) gives the correlation equation for heating ventilation air under the conditions given as follows:

$$E = 100 \left[1 - \exp(-A*Qu*Le^{0.333}) \right] \quad (A = 0.032) \tag{4-23 a}$$

The outlet air temperature can be approximately predicted as:

$$To = Tus + (Ti - Tus) \exp(-A*Qu*Le^{0.333}) \quad (A = 0.032) \tag{4-23 b}$$

The heat capacity of the exchanger can be estimated as:

$$Cap = \pm(Ti - Tus)\ Ma\ Cp \left[1 - \exp(-A*Qu*Le^{0.333}) \right] \tag{4-23 c}$$

where A = 0.032; Ma = mass rate of air, kg/s; Cp = specific heat of air at constant pressure, J/(kg°C). The positive sign should be used in the cooling case and the negative sign should be used in the heating case.

Similarly, 83 pairs of data for cooling ventilation air were correlated for various thermal conditions as illustrated in Figure 23. The value of A is 0.0416.

Figure 24 demonstrates simulation for 3 days of continuous operation in the winter with the thermal conditions as presented in section 4.5.1. The A values of equations [4-23] are 0.034, 0.0315, and 0.0301 for the first, second, and third day, respectively.

4.7 PUMPING POWER AND HEAT ENERGY RATIO

If only air with constant and uniform velocity along the horizontal pipe is considered, the pumping power, Q (W), can be expressed in terms of the volume rate of the air, M (m^3/s), and the pressure drop between the inlet and the outlet, ΔP (N/m^2). This gives:

$$Q = M\,\Delta P \qquad \text{where} \qquad \Delta P = f\,(L/D)\,(þ' Va^2/2) \tag{4-24}$$

The drag-friction coefficient f has been estimated by (Kreith, 1973)

$$f = 0.184\,Re^{-0.2} \qquad \text{(Smooth tube; } Re > 10{,}000) \tag{4-25}$$

By definition, the heat energy ratio (HER) can be evaluated by the expression, β*Cap/Q, if the overall efficiency of the mechanical system, β, is included. This offers a method of optimal selection for the system variables. For example, by using equation [4-2] the heat energy ratio can be written as follows:

$$HER = 84650\,D^2 \exp(-2.99\,D)\,(\beta/Q) \tag{4-26}$$

Based on the conditions described in section 4.2, the HER can be approximately treated as a function of the pipe diameter only. Then maximizing the above equation gives an appropriate diameter for the design. The author suggests that this optimization of the system, including an economic analysis, be accomplished during the development of design procedures in the future.

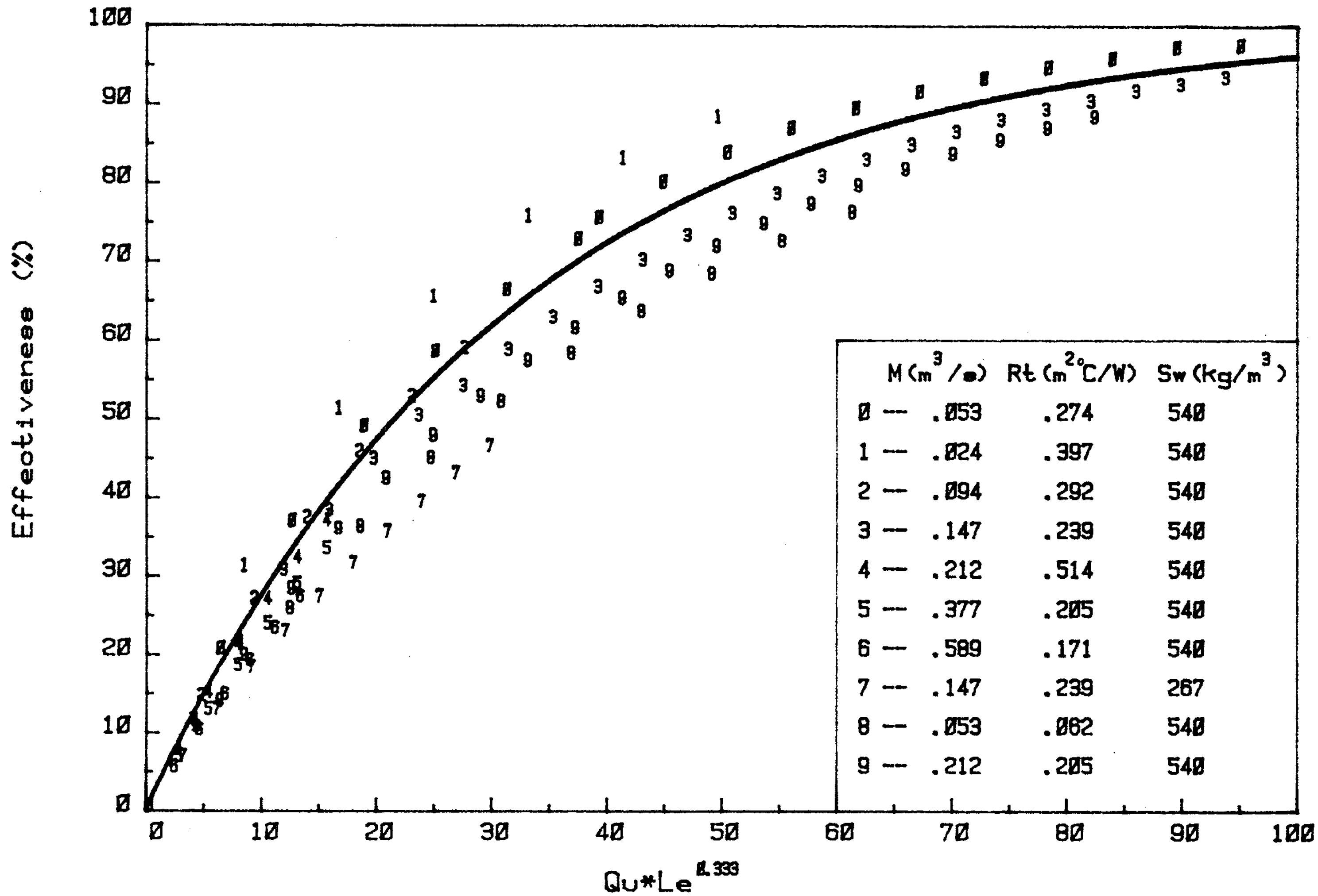

FIG. 22: DIMENSIONLESS DATA CORRELATION FOR HEATING CASE

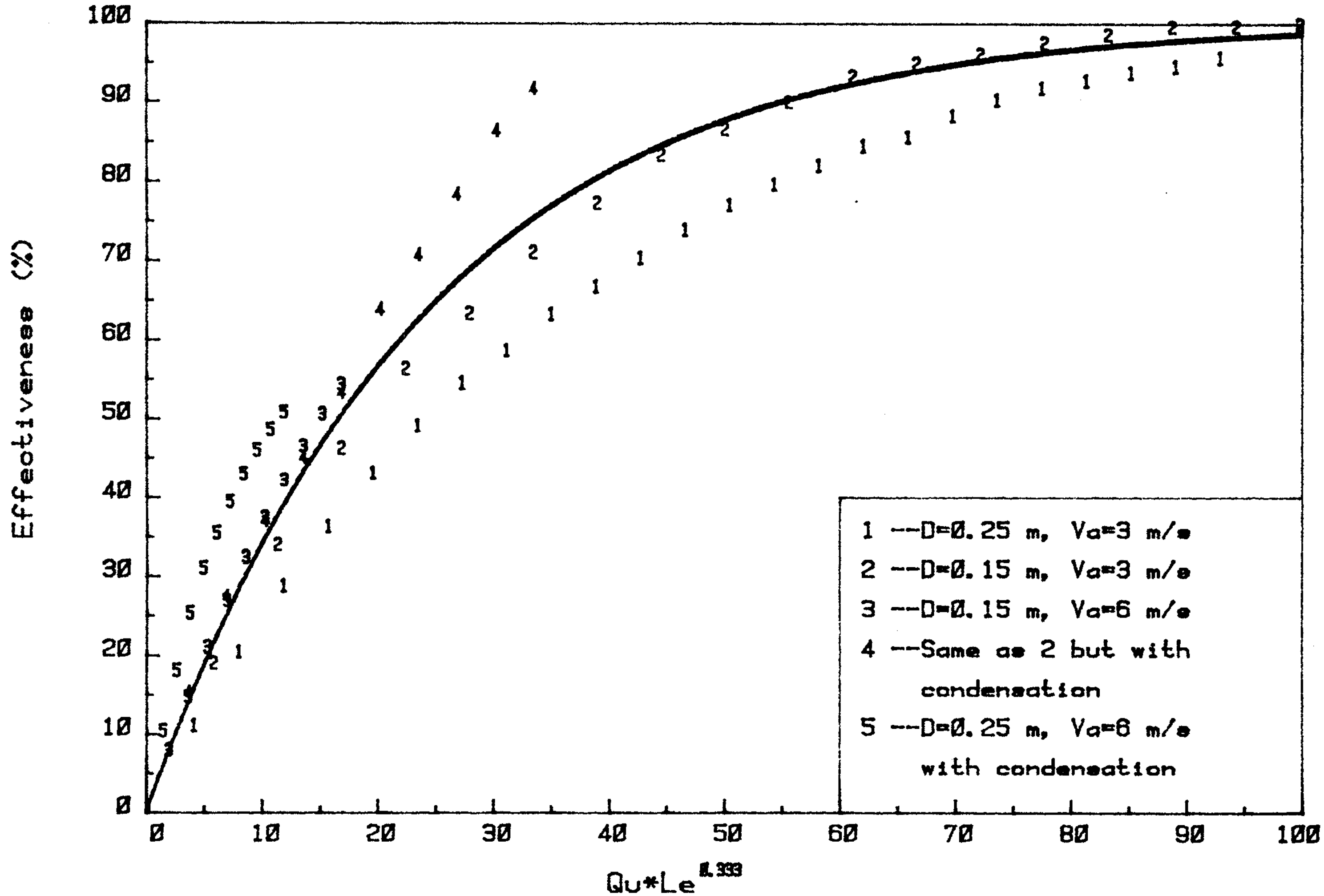

FIG. 23: DIMENSIONLESS DATA CORRELATION FOR COOLING CASE

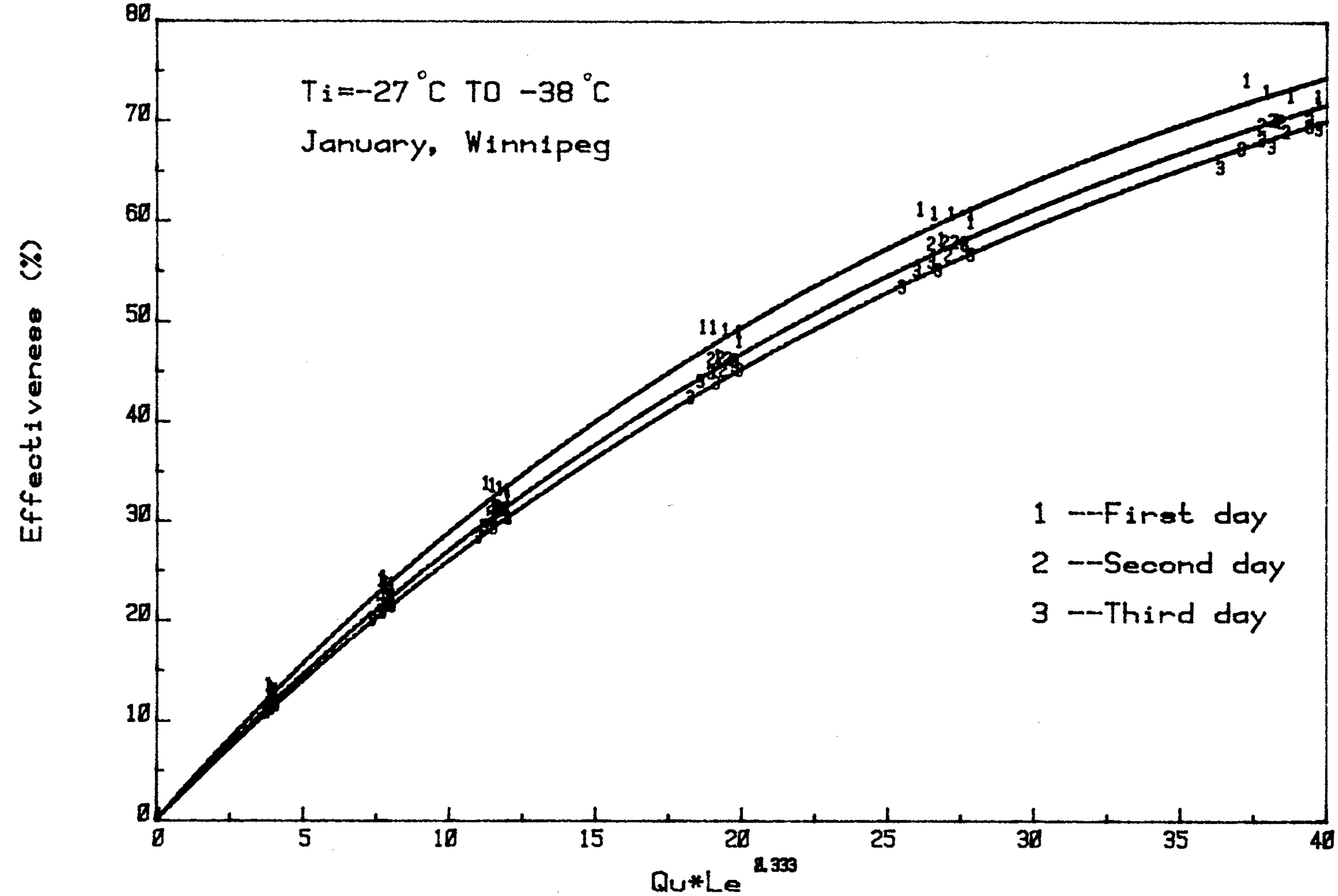

FIG. 24: DIMENSIONLESS CURVE FOR CONTINUOUS WINTER OPERATION

4.8 SOIL MOISTURE AND AIR QUALITY

The modeling of the soil moisture transfer in section 3.7 and the information presented in this section are aimed at presenting the quantitative effect of the moisture transfer on the thermal conductivities of soils as well as on the soil temperature profiles. Although the mechanism of the moisture transfer in non-isothermic conditions is complicated, based on the approximate model it is possible to demonstrate the dependence of this effect on initial moisture, moisture at saturation, mean temperature, magnitude of the temperature gradient and mechanical soil composition. To illustrate the above, Figure 25 and 26 show the moisture curves in a radial direction from the pipe surface and in a horizontal direction from the inlet and near the pipe surface, respectively. The soil texture under investigation was silty clay. The tendency for moisture movement under the temperature gradients for heating and cooling is illustrated.

Furthermore, the program is capable of emulating psychrometric charts. Information on air quality involving relative humidity, moisture content per kilogram of dry air and mean dry bulb temperature can be obtained. Table 5 was extracted from the general output of the computer program for a simulation cooling with condensation. The water rate in g/s removed from the air mixture is also approximated. This information could be used in selecting a pump to remove water from the pipes.

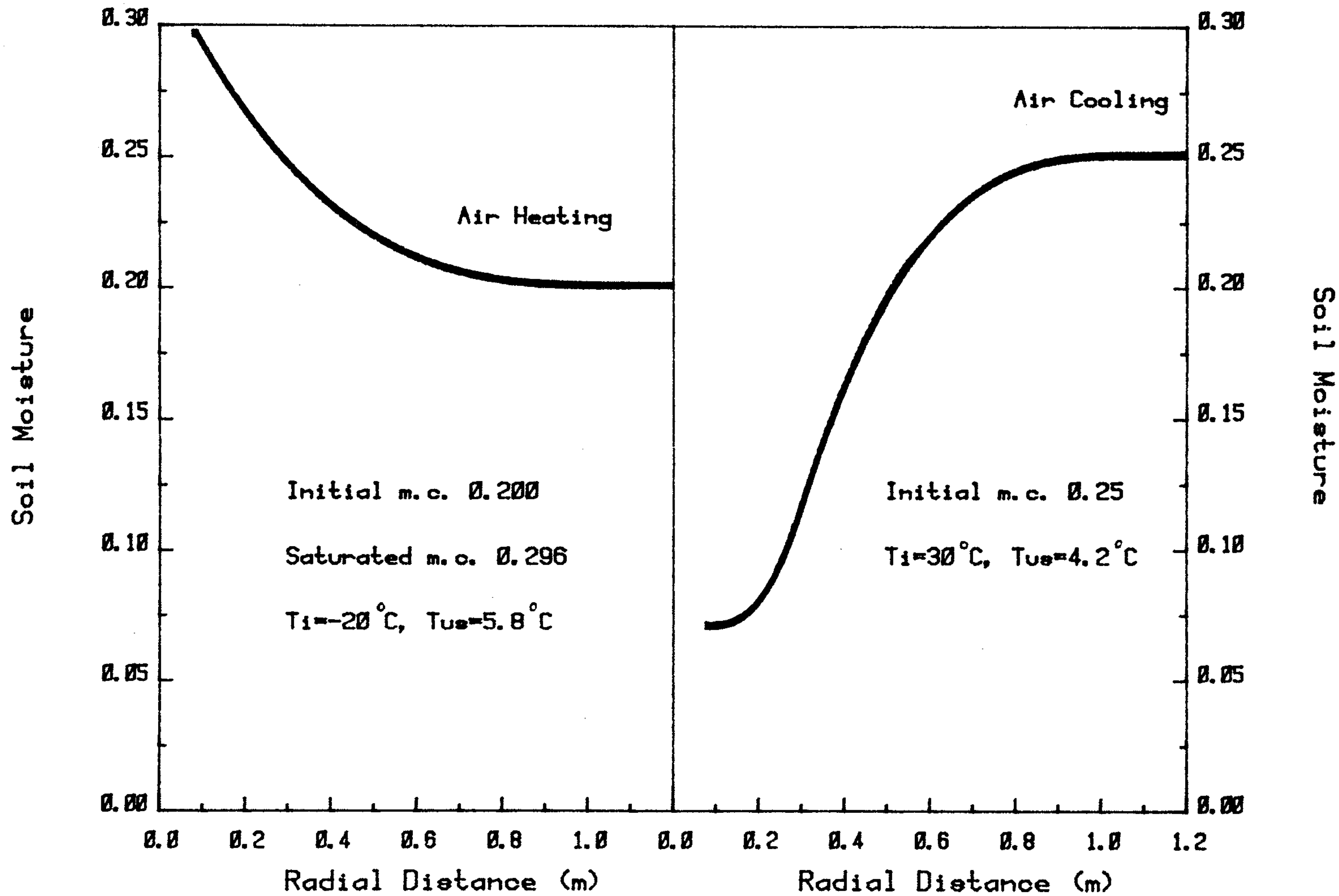

FIG. 25: MOISTURE CONTENT OF SOIL IN RADIAL DIRECTION AT Z=5 m

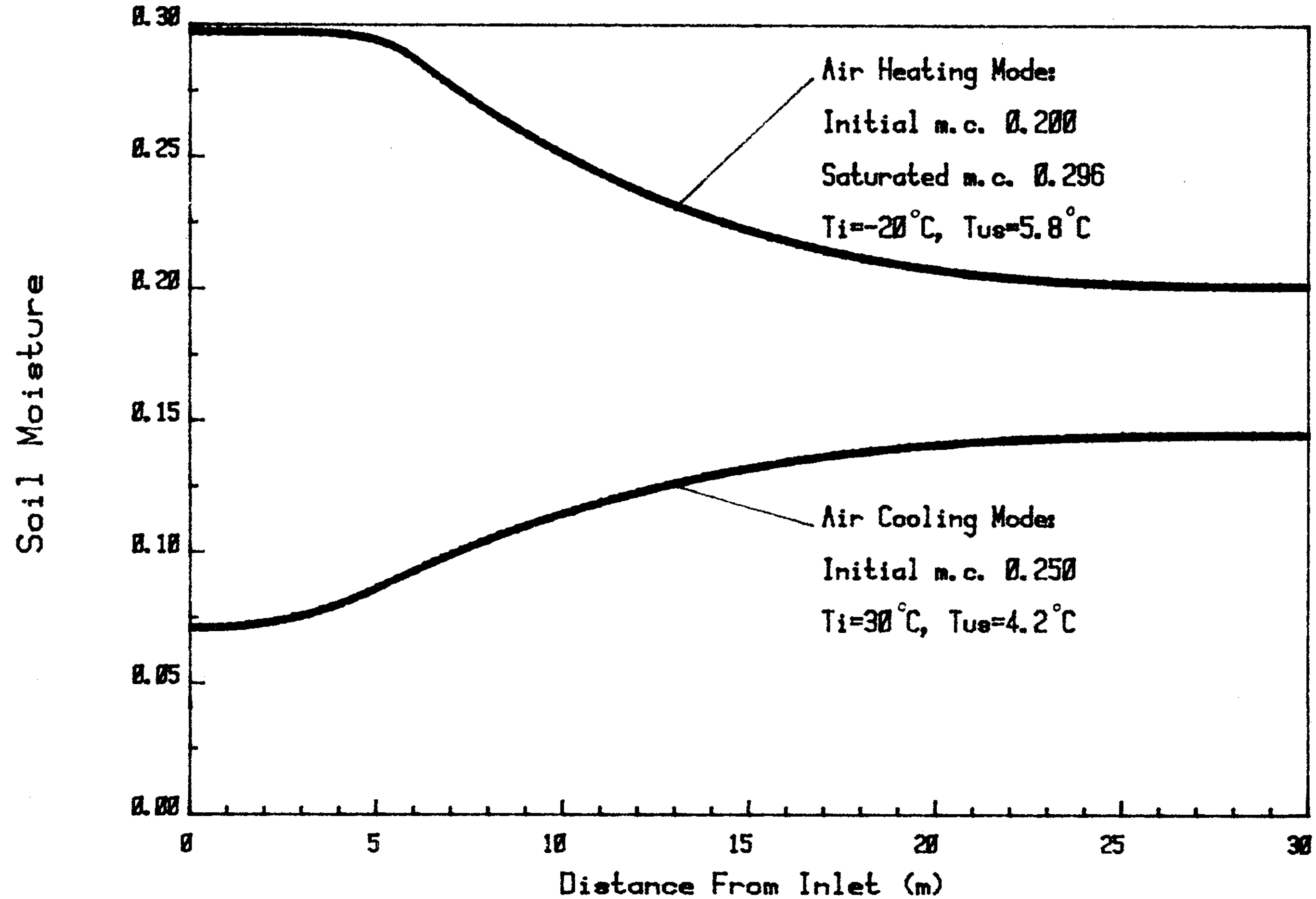

FIG. 26: MOISTURE CONTENT OF SOIL NEAR THE PIPE

TABLE 5

General Output of a Simulation for the Exchanger

Quantity	Hour 24	48	72	96	120
Ti (˚C)	27.417	19.917	16.000	20.083	22.583
To (˚C)	13.344	12.188	11.214	12.154	12.858
Ti - To (˚C)	14.073	7.729	4.786	7.929	9.725
E (%)	72.480	64.857	59.827	45.124	56.201
Cap (kW)	0.902	0.503	0.314	0.516	0.629
input air m.c. (kg/kg dry air)	0.0118	0.0089	0.0094	0.0068	0.0073
output air m.c. (kg/kg dry air)	0.0085	0.0084	0.0079	0.0063	0.0067
R.H.(in) (%)	51.667	61.250	83.167	46.750	42.833
R.H.(out) (%)	88.933	94.943	95.791	71.940	72.265
Water rate (g/s)	0.2072	0.0307	0.0966	0.0317	0.0400

Conditions: Va = 3 m/s D = 0.150 m L = 30 m Tus = 8.0 ˚C;
Silty clay soil with 0.25 initial moisture content;
Weather record 1970, Winnipeg, Canada.

Chapter V

APPLICATION OF THE SIMULATION

5.1 COMPARISON WITH ANOTHER THEORETICAL MODEL

Puri (1984) developed an axisymmetric finite element model with simultaneous heat and moisture transfer formulation for a soil-pipe system (Sec. 3.1). The narrow range of variables in that model limits the usefulness. Nevertheless, it is worthwhile to use the results for comparison to this study.

Time dependent curves of heating and cooling processes are illustrated in Figures 27 and 28, respectively. The heating and cooling modes and other thermal conditions described by Puri (1984) were used as input to calculate the data for these graphs. In the heating case, even though the output air temperatures for the first 6 hours are about 5 °C lower than Puri's results, the results for the next 6 hours show only about 1 °C difference. In the cooling case, the outlet air temperatures at each time interval are about 1 °C different except in the first 2 hours. The air temperature gradients, near the end of the pipe, presented by Puri (1984) are close to zero but non-zero values in this study give an indication that increasing the pipe length over 12 m would give an increase in the system temperature differential.

5.2 APPLICATION TO A TEST SITE

5.2.1 Experimental Installation

To study the performance characteristics of a soil-air heat exchanger for tempering ventilation air, a test site at the University of Manitoba's Glenlea Research Station was established during the summer and fall of 1984. Operation began on December 19, 1984. Monitoring of the system is scheduled to continue until three full years of performance data are available. All of the field data will be studied to improve and verify the theoretical model. Based on this expanded data base, better design procedures will be recommended.

The test facility is composed of four, 30 m long, polyvinylchloride (PVC) pipes buried about 3 m below the surface. The pipe diameters are 0.150 m and 0.250 m and the air velocities are 1, 3 and 6 m/s to allow for analysis of various operating conditions. The buried pipes are each separated horizontally by a distance of 5 m to assure isolation. Each pipe line was installed, in a parallel pattern, with hand backfilling near the pipe surfaces. The average line slope is 2 percent. After the completion of mechanical backfilling, a header was built up to connect the four pipes. The soil at Glenlea is silty clay and undisturbed soil temperatures are monitored to depths ranging from 0.5 m to 4.0 m. Air temperature is monitored at the inlet, the outlet and at 10 m intervals along the pipe length. The temperature of the soil around the pipes is also monitored. At each soil temperature monitoring point, thermocouples were placed in the soil along radial lines up to 1 m away from the pipe.

5.2.2 Simulating Winter Operation

Heating data available at this time from the air tempering system allow for verification of the model for winter operation. Table 6 lists the numbered pipes and the corresponding conditions for the system. Since actual data describing the soil conditions are still being collected, it is reasonable to treat the soil as silty clay with bulk density of 1800 kg/m^3 and average moisture content of 30% by dry weight.

Weather data for ambient air temperature were used as input with a time step of 3 hours. Each pipe operation was simulated from January 29 to February 3, 1985. The solution region was a hollow soil cylinder having 1 m radius and 30 m length. The operation of pipe #2 began on January 29, 1985. The profile of soil temperature in the simulation was uniformly initialized to 10 °C. The operation of pipe #1, #3, and #4 started on December 19, 1984. The soil temperature profile on January 29, simulated from start day or measured at the test site, can be used as the initial conditions for these three pipes. In the simulation the measured data were used as input soil temperatures.

5.2.3 Comparison

Generally, no mathematical analysis can be evaluated unless reliable field data from a similar test facility are available. It is fortunate indeed that this finite element model can be compared to actual conditions. The computer results can be compared directly with experimental results. Comparison of the results will give conclusive model evaluation.

TABLE 6

Conditions for Winter Operation of a Test Site in Winnipeg

Quantity	Unit	Pipe** #1	#2	#3	#4
Pipe diameter, D	m	0.250	0.150	0.250	0.150
Air velocity, Va	m/s	1.080	6.000	3.000	3.000
Mass rate of air, M	m^3/s	0.053	0.106	0.147	0.053
Undisturbed soil temperature*, Tus	°C	8.000	10.000	6.100	7.500
Date started		Dec. 19, 1984	Jan. 29, 1985	Dec. 19, 1984	Dec. 19, 1984

** Buried about 3 m below ground level.
* averaged from January 29 to February 3, 1985; 1 m away from the pipe surfaces.

Figure 29 illustrates the performance of pipe #2 for the first six days. All predicted outlet air temperatures, at 3 hour intervals, show good correlation to the measured data except in the first half day. The predicted outlet air temperature averages about 2.5 °C higher than the actual measured outlet air temperature. It was observed at the test site that a temperature increase of 2.5 °C was achieved in vertical parts of the pipe. Near the inlet there was an increase of about 3 °C while near the outlet the air temperature was reduced by about 0.5 °C. The simulation model does not account for vertical parts of the pipe. This means that the average outlet air temperature difference between actual measurement and predicted is about 5.0 °C. Nonhomogenous soil conditions could easily account for this difference.

Mean values of data for every 6 hours of operation of pipe #3 are plotted in Figure 30. The predicted air temperatures and the measured air temperatures at the outlet are surprisingly similar. This could be expected since the use of actual soil temperature data for initial soil temperature profiles in the simulation could have accounted for nonhomogenous soil conditions. If the temperature difference attributed to the vertical parts of the pipe is considered, then the difference between the measured and the predicted outlet air temperatures is of the order of 3 °C.

Pipe #1 and pipe #4 have the same mass flow rate of air. Theoretical considerations in section 5.3 indicate that two pipes with the same airflow rate should have almost the same temperature differentials. The experimental data as illustrated in Figure 31 support the theory.

The soil temperatures around pipe #2 at the end of 6 days of operation are graphed in Figure 32 for comparative purposes. The measured values in the Figure are averaged over each concentric circumference of the soil cylinder because the model predicts radial temperature gradients only within each pieced length along the pipe. However, Figure 32 still shows good results compared to actual temperatures. It should be noted that soil temperature profiles along the pipe at each radial distance approximate an exponential relationship. The measured temperatures also indicate that the soil may not be homogenous nor isotropic.

Table 7 is a copy of the computer output at 24:00 on February 3, 1985 for the simulation of pipe #4. Node zero indicates air temperatures along the pipe. Nodes 1 and 2 give the temperatures at the inside and the outside pipe surfaces. The contact interface between the pipe and the surrounding soil is between nodes 2 and 3 or in element 2.

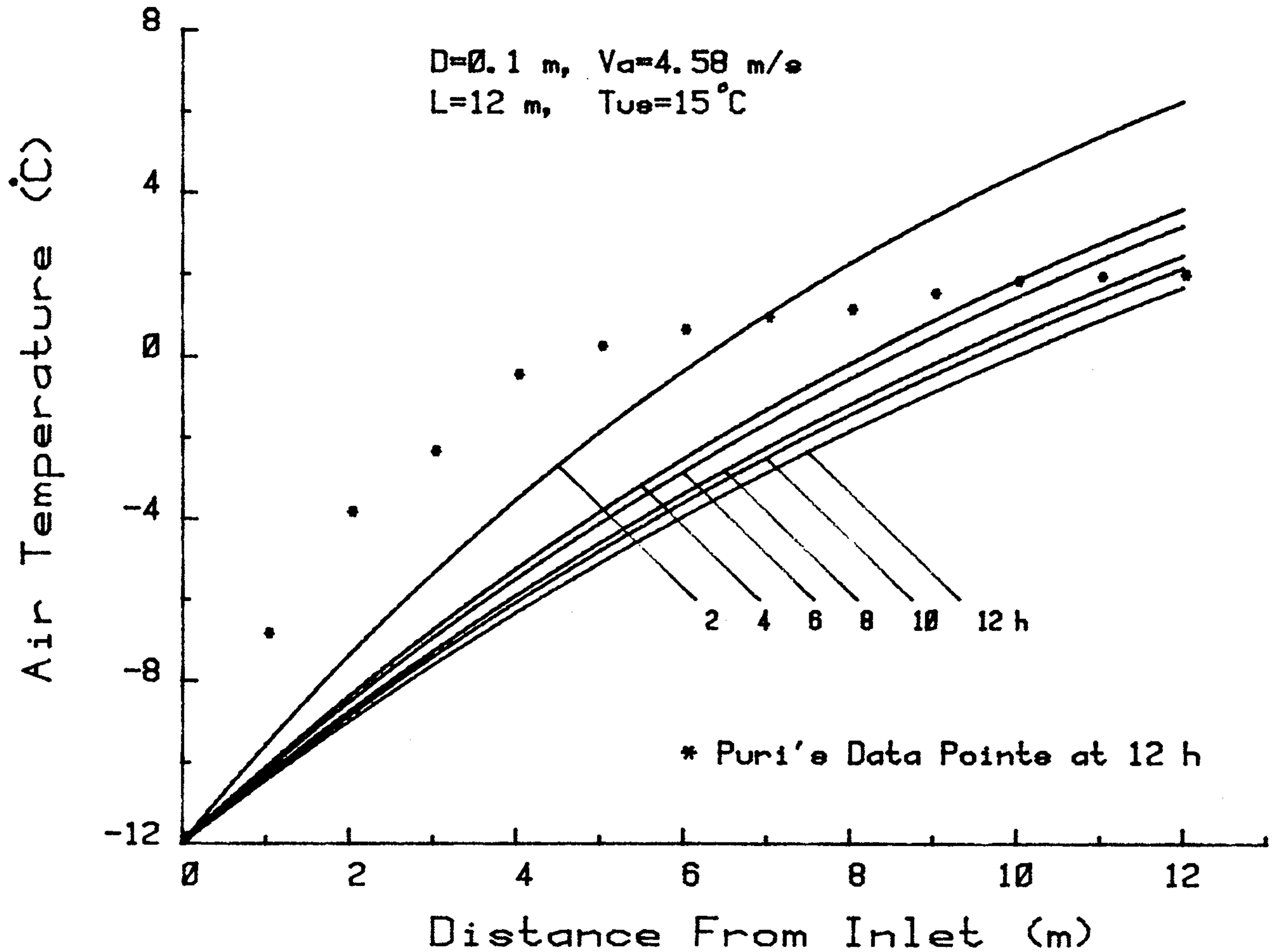

FIG. 27: HEATING PROCESS VS. TIME

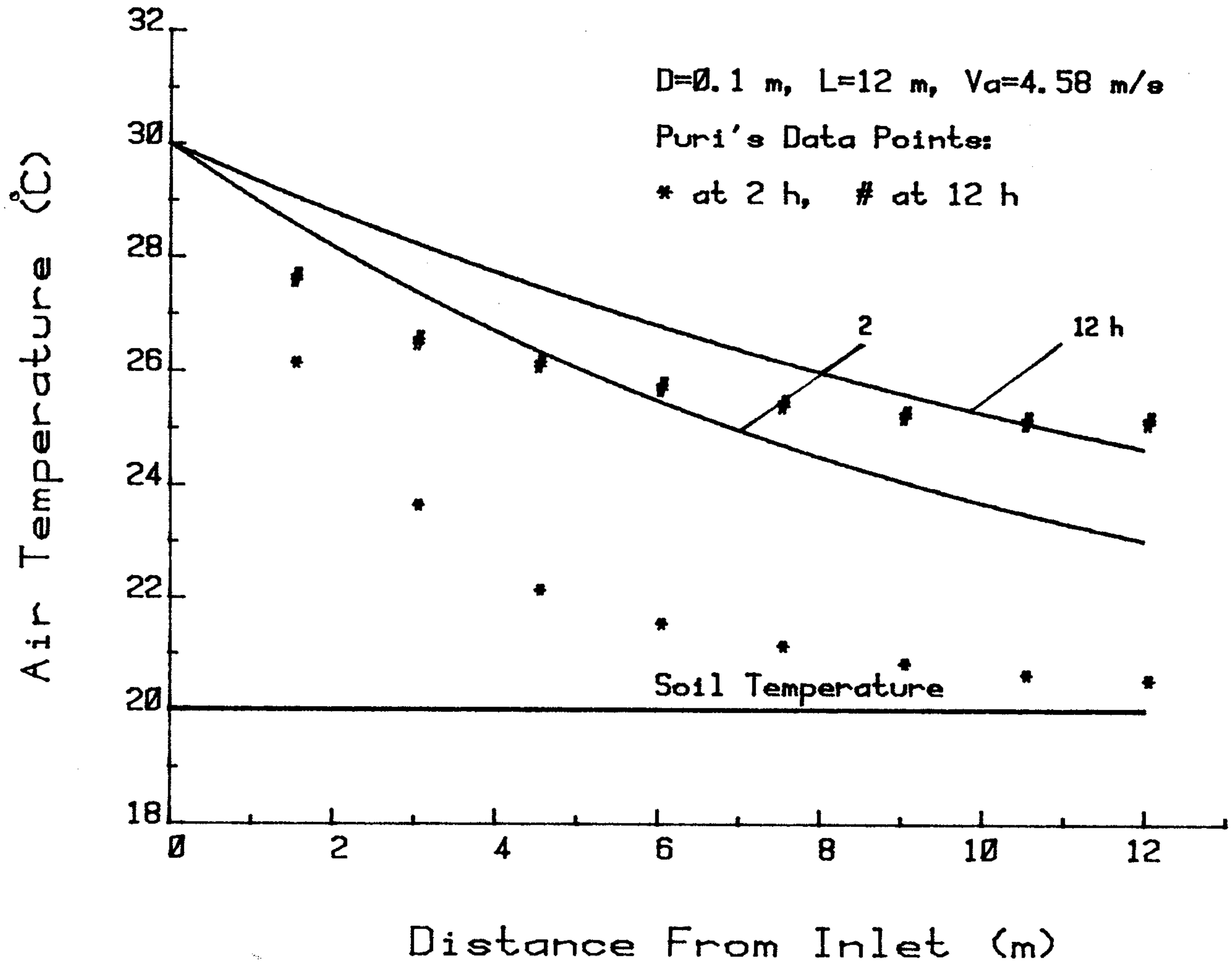

FIG. 28: COOLING PROCESS VS. TIME

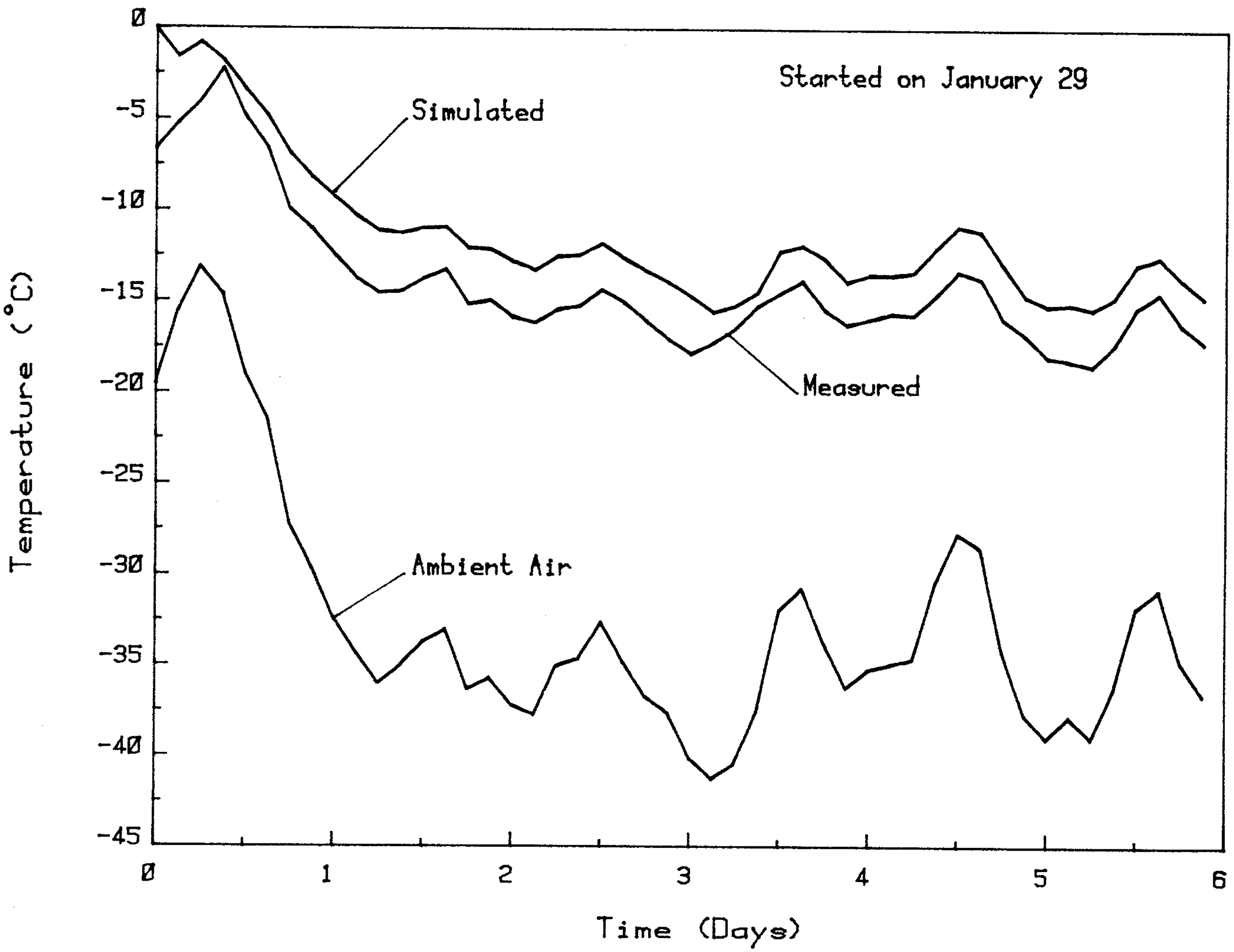

FIG. 29: OUTLET AIR TEMPERATURES FOR PIPE #2

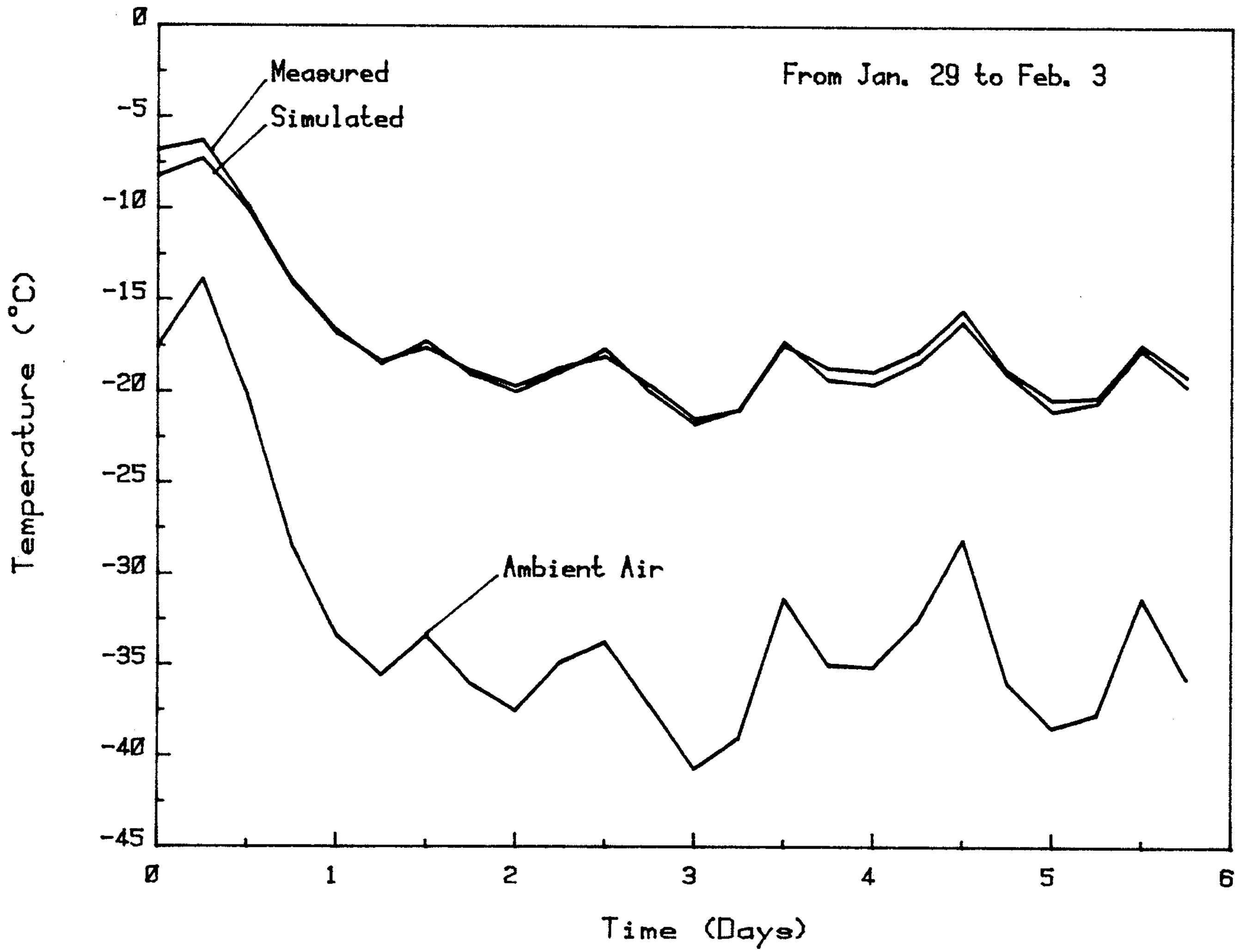

FIG. 30: OUTLET AIR TEMPERATURES FOR PIPE #3

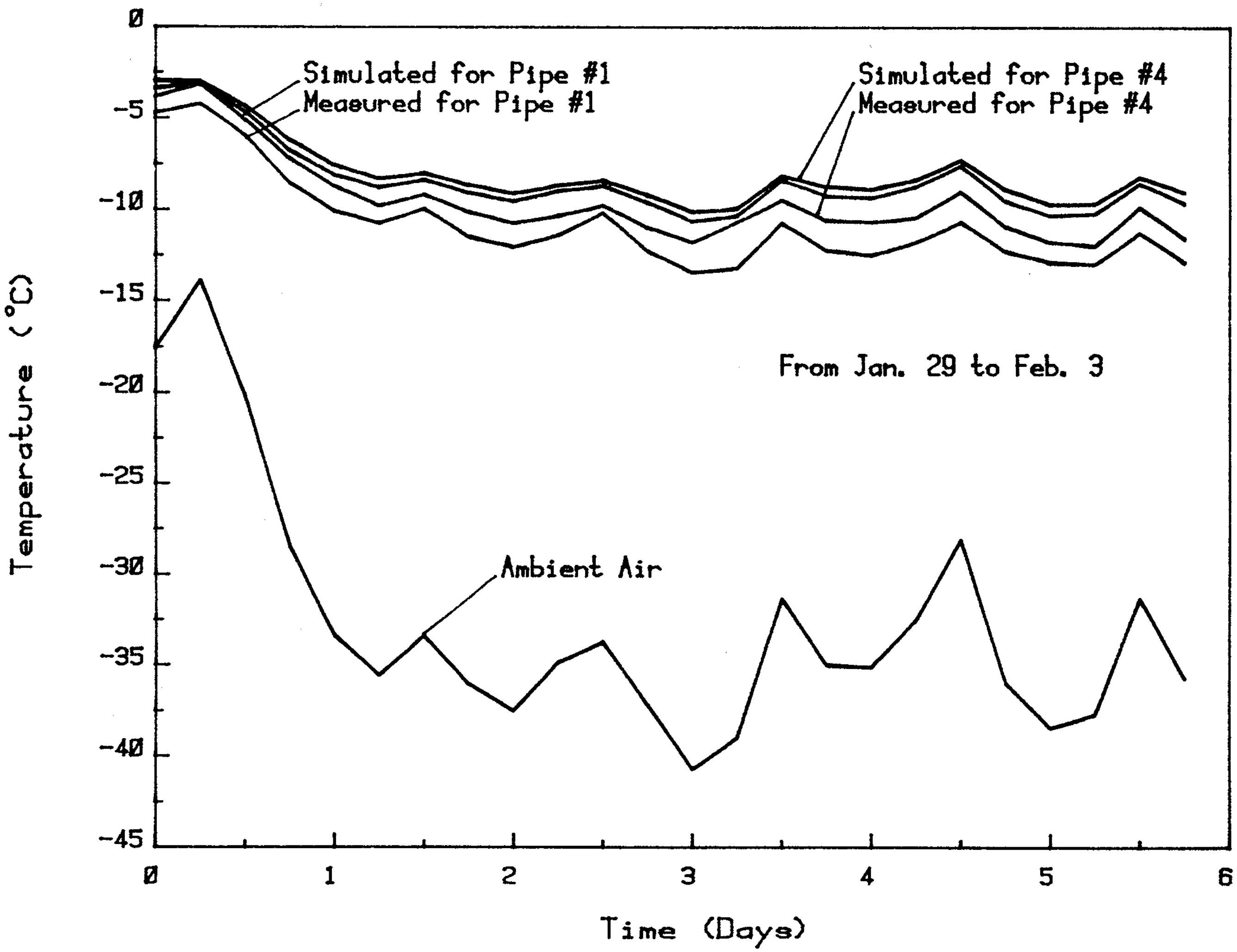

FIG. 31: OUTLET AIR TEMPERATURES FOR PIPE #1 AND #4

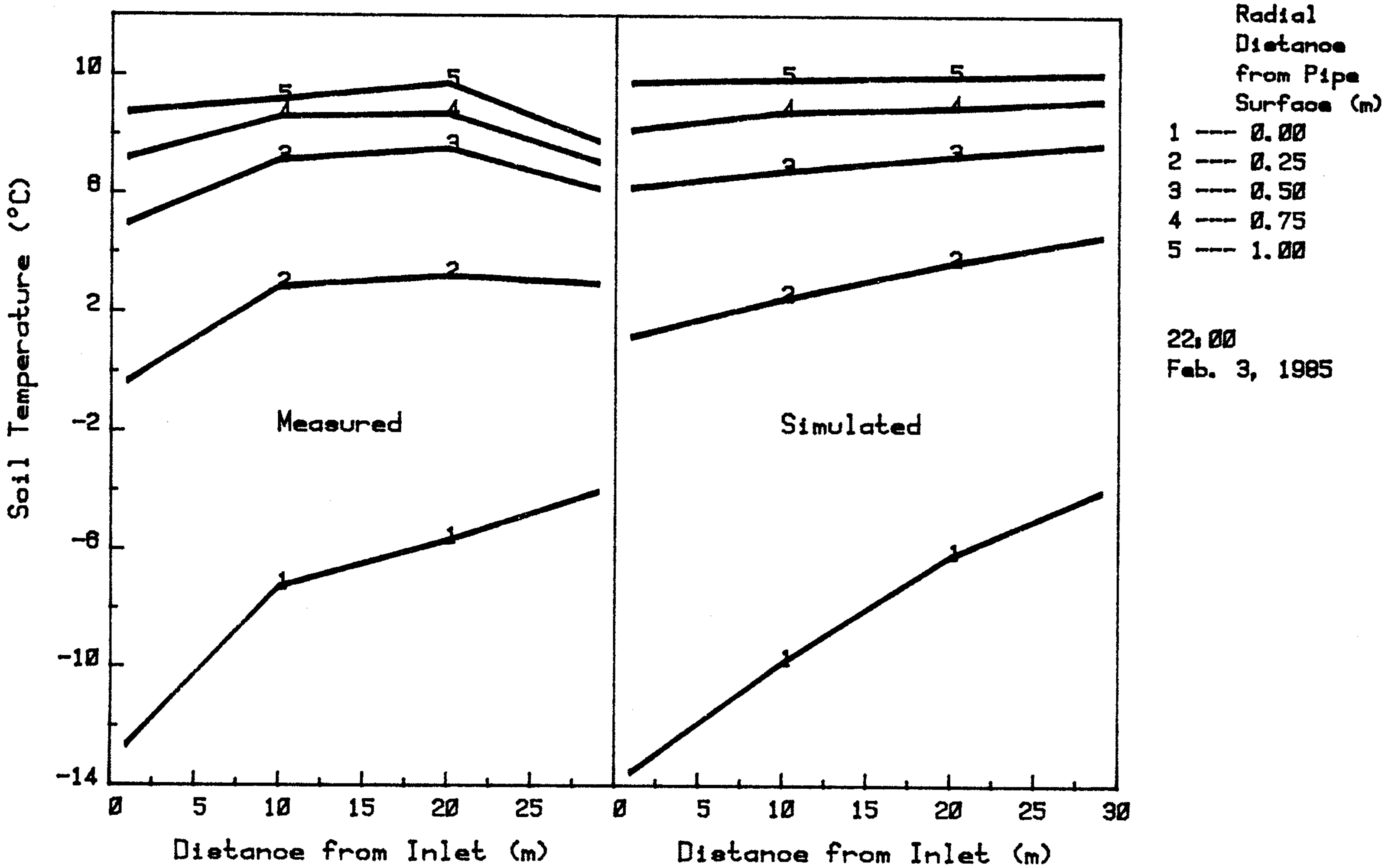

FIG. 32: SOIL TEMPERATURE PROFILES OF PIPE #2 AFTER 6 DAYS

TABLE 7

Soil Temperature Output of Pipe #4

SOIL TEMPERATURES AND AIR TEMPERATURES AT EACH LOCATION AND AT EACH TIME INTERVAL

(TEMPERATURE IN C)
START WITH 141.00 HOURS FROM THE BEGINNING

----- 3.000 HOURS LATER ----

PIPE LENGTH IN METER ---->

NODE NO.	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00
0	-36.7000	-35.4785	-34.3263	-33.2201	-32.1885	-31.1314	-30.1151	-29.1252	-28.1655	-27.2148	-26.2758	-25.3558	-24.4512	-23.5752
1	-21.8341	-21.7030	-21.3949	-20.8610	-20.4710	-19.6430	-18.8215	-18.1889	-17.5863	-16.7055	-15.9361	-15.2635	-14.4975	-13.9702
2	-15.5108	-14.9187	-14.2270	-13.2714	-12.7153	-11.7773	-11.1982	-10.6644	-10.3296	-9.7854	-9.0824	-8.6173	-8.1664	-7.7570
3	-14.4428	-13.8406	-13.1028	-12.1033	-11.5248	-10.5836	-10.0390	-9.5237	-9.2451	-8.7505	-8.0619	-7.6329	-7.2298	-6.8468
4	-10.2944	-9.8824	-9.2403	-8.3126	-7.8384	-6.9621	-6.5508	-6.1648	-6.0549	-5.6759	-5.0671	-4.7444	-4.4731	-4.1881
5	-7.5909	-7.2713	-6.7111	-5.8201	-5.4478	-4.6091	-4.2845	-3.9886	-3.9859	-3.6856	-3.1190	-2.8742	-2.6702	-2.4753
6	-5.6606	-5.4117	-4.9052	-4.0413	-3.7377	-2.9188	-2.6778	-2.4378	-2.5076	-2.2621	-1.7284	-1.5298	-1.3902	-1.2223
7	-4.1432	-3.9479	-3.4881	-2.6423	-2.4031	-1.8102	-1.3987	-1.1232	-1.3529	-1.1498	-0.6392	-0.4821	-0.3813	-0.2600
8	-2.8888	-2.7372	-2.3205	-1.4835	-1.3082	-0.5299	-0.3674	-0.1570	0.0746	0.2343	0.6899	0.8043	0.8671	0.9492
9	-1.8130	-1.6988	-1.3244	-0.5123	0.0942	0.8034	0.9207	1.0291	1.0704	1.2052	1.5975	1.6890	1.7381	1.8021
10	-0.8713	-0.7897	0.0130	0.7565	1.0833	1.6981	1.7921	1.8652	1.8249	2.0387	2.3763	2.4518	2.4820	2.5447
11	0.4051	0.4553	1.0140	1.6580	1.9449	2.4759	2.5543	2.6100	2.6777	2.7757	3.0667	3.1286	3.1819	3.2051
12	1.3819	1.4203	1.9051	2.4646	2.7208	3.1784	3.2435	3.2878	3.3572	3.4402	3.6882	3.7381	3.7647	3.7991
13	2.2707	2.3046	2.7233	3.2022	3.4259	3.8148	3.8673	3.9039	3.9686	4.0386	4.2481	4.2884	4.3101	4.3382
14	3.0897	3.1169	3.4720	3.8758	4.0890	4.3856	4.4388	4.4718	4.5291	4.5879	4.7627	4.7950	4.8128	4.8354
15	3.8506	3.8726	4.1679	4.5018	4.6648	4.9337	4.9684	4.9981	5.0464	5.0947	5.2376	5.2629	5.2773	5.2953
16	4.5591	4.5762	4.8150	5.0837	5.2175	5.4330	5.4606	5.4865	5.5257	5.5644	5.6783	5.6978	5.7091	5.7232
17	5.2214	5.2342	5.4197	5.6276	5.7328	5.8990	5.9201	5.9416	5.9720	6.0018	6.0893	6.1038	6.1123	6.1230
18	5.8425	5.8516	5.9867	6.1377	6.2151	6.3356	6.3508	6.3673	6.3894	6.4110	6.4741	6.4843	6.4905	6.4981
19	6.4268	6.4325	6.5201	6.6178	6.6683	6.7461	6.7559	6.7670	6.7812	6.7952	6.8358	6.8423	6.8462	6.8511
20	6.9781	6.9808	7.0235	7.0709	7.0956	7.1334	7.1381	7.1426	7.1506	7.1573	7.1770	7.1801	7.1820	7.1844
21	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000

PIPE LENGTH IN METER ---->

NODE NO.	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00
0	-22.7226	-21.9066	-21.1042	-20.3036	-19.5188	-18.7688	-18.0171	-17.2965	-16.5910	-15.9006	-15.2417	-14.6160	-13.9950	-13.3925
1	-13.4060	-12.9679	-12.3422	-11.5887	-10.9559	-10.6113	-9.8844	-9.5036	-8.9334	-8.4272	-8.1281	-7.8766	-7.2863	-6.8990
2	-7.3729	-7.2416	-6.7696	-6.0612	-5.6704	-5.5830	-4.9014	-4.5830	-4.2351	-3.9359	-3.8483	-3.7082	-3.2040	-2.9419
3	-6.4936	-6.3633	-5.9542	-5.2537	-4.8975	-4.8700	-4.1644	-3.8277	-3.5794	-3.2887	-3.2376	-3.1297	-2.6154	-2.3756
4	-3.9217	-3.9785	-3.6484	-2.9816	-2.7402	-2.7998	-2.1228	-1.8532	-1.6988	-1.2830	-1.5157	-1.5020	-1.0081	-0.8305
5	-2.2206	-2.4107	-2.1318	-1.4750	-1.2762	-1.4307	-0.7537	-0.5387	-0.4420	-0.1393	0.1521	0.1097	0.5534	0.6792
6	-1.1373	-1.2854	-1.0413	-0.3978	-0.2500	0.0537	0.6747	0.8400	0.8835	1.0848	1.2266	1.1769	1.5566	1.6581
7	-0.0884	0.0810	0.2823	0.8694	0.9763	1.0830	1.6147	1.7480	1.7888	1.9440	2.0813	2.0305	2.3594	2.4409
8	1.0180	1.0875	1.2393	1.7445	1.8319	1.9286	2.3911	2.5033	2.5323	2.6605	2.7885	2.7388	3.0214	3.0883
9	1.8481	1.9075	2.0532	2.4904	2.5648	2.6518	3.0527	3.1455	3.1664	3.2734	3.3921	3.3433	3.5871	3.6426
10	2.5754	2.6394	2.7632	3.1402	3.2034	3.2827	3.6279	3.7049	3.7217	3.8134	3.9194	3.8732	4.0827	4.1277
11	3.2299	3.2895	3.3957	3.7185	3.7724	3.8430	4.1391	4.2024	4.2139	4.2942	4.3863	4.3437	4.5228	4.5601
12	3.8206	3.8730	3.9621	4.2368	4.2828	4.3455	4.5976	4.6486	4.6593	4.7304	4.8090	4.7708	4.9228	4.9534
13	4.3588	4.4032	4.4787	4.7104	4.7499	4.8050	5.0174	5.0596	5.0673	5.1298	5.1955	5.1617	5.2894	5.3144
14	4.8544	4.8911	4.9540	5.1465	5.1800	5.2273	5.4037	5.4377	5.4439	5.4981	5.5522	5.5230	5.6288	5.6490
15	5.3122	5.3420	5.3934	5.5507	5.5787	5.6183	5.7623	5.7892	5.7942	5.8402	5.8839	5.8593	5.9454	5.9614
16	5.7377	5.7612	5.8022	5.9274	5.9503	5.9825	6.0970	6.1179	6.1218	6.1587	6.1941	6.1740	6.2423	6.2548
17	6.1348	6.1527	6.1842	6.2802	6.2982	6.3232	6.4110	6.4266	6.4296	6.4594	6.4856	6.4698	6.5221	6.5315
18	6.5070	6.5197	6.5425	6.6118	6.6250	6.6433	6.7065	6.7176	6.7197	6.7417	6.7605	6.7489	6.7864	6.7931
19	6.8570	6.8651	6.8798	6.9244	6.9330	6.9449	6.9855	6.9926	6.9939	7.0083	7.0203	7.0128	7.0369	7.0411
20	7.1873	7.1912	7.1983	7.2199	7.2241	7.2299	7.2496	7.2530	7.2536	7.2607	7.2664	7.2628	7.2744	7.2765
21	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000	7.5000

PIPE LENGTH IN METER ---->

NODE NO.	28.00	29.00	30.00
0	-12.8035	-12.2327	-11.6875
1	-6.4703	-6.1080	-5.8211
2	-2.6719	-2.4340	-2.2436
3	-2.1315	-1.9156	-1.7465
4	-0.6366	-0.4781	-0.3670
5	0.8231	0.9352	1.0012
6	1.7740	1.8640	1.9148
7	2.5349	2.6076	2.6464
8	3.1646	3.2243	3.2545
9	3.7057	3.7546	3.7779
10	4.1787	4.2190	4.2389
11	4.6022	4.6357	4.6497
12	4.9877	5.0152	5.0260
13	5.3421	5.3647	5.3730
14	5.6712	5.6896	5.6958
15	5.9790	5.9937	5.9983
16	6.2684	6.2798	6.2833
17	6.5416	6.5503	6.5527
18	6.8003	6.8065	6.8081
19	7.0456	7.0496	7.0506
20	7.2787	7.2806	7.2810
21	7.5000	7.5000	7.5000

Chapter VI

DISCUSSION

The intent of this discussion is to gain insight into soil-air heat exchangers. The goals of the interpretations are to develop or to improve design procedures for the systems.

First of all, it is necessary to examine some of the assumptions made in the model. A study of preliminary field data from Glenlea, Manitoba, has indicated that the ratio of radial heat flow to longitudinal heat flow is much greater than 100. Although the ratio near the inlet may be as low as 70, as illustrated in Figure 32, the simulated results compared with field data and with Puri's curves (Puri 1984) have shown that the neglect of axial heat flow in the soil cylinder is an acceptable approximation. The average soil temperature in each concentric circumference of the soil cylinder varies with the depth of the buried pipe, the distance from inlet, the soil texture and the meteorological conditions. The field data have also indicated that ignoring the temperature variation on the soil cylinder perimeter is acceptable when the pipe depth is 3.0 m or more.

Effect of Pipe Size --- The geometric factors of the pipe involve pipe diameter and pipe length. Changes in pipe diameter affect the Reynolds number and therefore affect the fluid conditions. In spite of increased convective heat transfer coefficients as the pipe diameter is increased, the temperature differential or effectiveness will decrease if other variables are held constant (Fig. 5). This fact can be shown by the following mathematical analysis.

Differentiating equation [3-15] with respect to the dimensionless variable J gives:

$$\frac{\delta (To')_1}{\delta J} = \frac{2}{(1+J)^2} [\ T(R_0,t) - (Ti')_1\ ] \qquad (N \to 0)$$

where $\frac{\delta (To')_1}{\delta J} > 0$ for heating,

$\frac{\delta (To')_1}{\delta J} < 0$ for cooling.

Inspection of the equation clearly indicates that the outlet temperature $(To')_1$ decreases for heating but increases for cooling as the variable J decreases. The definition of variable J in equation [3-14] makes J inversely proportional to diameter. It is readily concluded that the absolute value of the temperature differential is an inverse function of the pipe diameter (Eq. [4-1]).

The heat capacity (Cap) is a direct function of the pipe diameter (Fig. 5 and Eq. [4-2]). A simple explanation for this fact is that more mass of air is introduced for the exchange of energy per unit time as the pipe diameter increases. A similar mathematical proof, as above, could be given by using the definition of the capacity.

Since a longer pipe would allow for a larger volume of soil to be used, the increase in pipe length results in an increase in the temperature differential and heat capacity. But this energy gain would be the result of higher initial cost and more energy expended in moving air and may not be significant when the air temperature gradients near the outlet are relatively small. A smaller pipe diameter requires shorter length and a larger pipe diameter needs longer length in order to obtain the same temperature differential. Figure 6 or equation [4-3] could be used in determining pipe size in a preliminary design.

Effect of Airflow Rate --- Both theoretical and experimental data have indicated that the temperature differential depends basically on the combined effect of pipe diameter and air velocity (Eq. [4-4]). There is a slight reduction in outlet air temperature for larger pipe diameter at the same volume of air per unit time (Fig. 7). Temperature differential appreciably drops as the airflow rate increases. The higher airflow rate means that there is less time for the air to effectively exchange energy with the soil heat sink or source resulting in smaller temperature differentials. In analytical terms, the decrease in variable J in equation [3-14] with an increase in airflow rate results in a reduction of the temperature differential.

Longer pipe lengths will increase temperature differentials and heat capacity (Fig. 8 and Eq. [4-6]). Significant energy transfer can be achieved by using high airflow rates up to 0.210 m^3/s for a pipe length equal to or less than 30 m, and up to 0.310 m^3/s for a pipe length greater than 30 m (Fig. 9 and Eq. [4-7]). When a very high airflow rate is used in the system, the absolute energy transfer is low because of the resulting low temperature differential. The design curves and approximate equations presented here give useful information about the effect of airflow rate on the design and operation of a ventilation air tempering system.

Effect of Thermal Conductivity Factors --- In the simulations, among four types of soils, sand provides the highest temperature differential (Fig. 10 and 11). Sand usually contains solid quartz particles with its high thermal conductivity and is therefore a good heat sink or source. Clay is superior to silt and silty clay because clay often holds large amounts of water. This tends to give a ks value dependent largely upon the moisture content. But the overall effects of these four soil textures on the temperature differential make little significant difference.

The temperature differential varies linearly with the density of dry soil (Eq. [4-10]). Figure 12 shows that dry soil has less temperature differential than wet soil because of air voids between the soil grains.

The effect of thermal conductivity for the pipe is very evident. A plastic pipe usually has a very low value of thermal conductivity. But the small pipe thickness results in less significant difference related to pipe thermal resistance compared to overall thermal resistances of the whole system. In Figure 13 about a 2 °C temperature difference results from using a PVC pipe instead of using a copper or steel tube. In other words, a model for a buried pipe system will predict about a 2 °C error in the outlet air temperature by omitting the low thermal conductivity of the pipe. A temperature drop of 4 °C through the PVC pipe is shown in Figure 14.

The effect of convective heat transfer coefficients on the temperature differential can be estimated from the foregoing mathematical analysis with equations [3-14] and [3-15]. An increase in variable J with the increase in the ratio hc/Va leads to a high temperature differential (Fig. 15). To obtain a high coefficient, hc, air can be moved along the pipe at a high speed. But high air velocity may not result in a large ratio of hc/Va because of the nonlinear relationship. There is a ratio of hc/Va at which the maximum heat capacity can be achieved if other variables are held constant. This is because increasing the air velocity will reduce the temperature differential while decreasing the air velocity will reduce the volume of air per unit time. Plastic corrugated drainage tubes are preferable to smooth pipes because of the resulting higher heat transfer coefficients.

Heat transfer due to water vapor condensation inside the pipe increases the heat transfer coefficients so significantly that the temperature differential and the heat capacity are much higher than when there is no condensation (Fig. 16 and Fig. 17). The possibility of water vapor condensation inside the pipe depends mainly on the ambient air temperature, the relative humidity ratio, the pipe size, and the fluid conditions. Saturated air (about R.H.=100%) at the inlet has the potential of promoting high system efficiency in a cooling process when saturated air at the outlet is acceptable.

The effect of contact resistance between the pipe wall and the surrounding soil is similar to the effect of pipe thermal resistance. The outlet air temperature difference due to very high and very low values of contact resistance is about 3 °C (Fig. 18). Generally, in the heating case soil moisture movement due to thermal gradients improves the contact condition because of saturated soil conditions near the pipe. In the cooling case a poor contact may occur due to the dry soil around the pipe.

Effect of Performance Factors --- Outlet air temperature variations tend to follow the variations in ambient air temperature but the daily temperature peaks and valleys are leveled (Fig. 19). Higher air temperature differentials can be obtained with intermittent operation compared to continuous operation due to possible heat and moisture recovery in the soil. Intermittent operation may be an efficient way to utilize the system. A study of the seasonal behavior of a soil-air heat exchanger in Winnipeg has indicated that the system has low potential in late March and in early October (Fig. 21). The system has greater potential in the winter than in the summer in western Canadian prairie climatic conditions. The best cooling season is from early June to late August and the best heating season is from late November to late February.

The effect of undisturbed soil temperature on the system is obvious. The air temperature differential obtainable correlates linearly with the changes of undisturbed soil temperature and system thermal potential, Ti-Tus (Fig. 20 and Eq [4-16]). The existence of the linearity affords an easy way to extend the range of the presented design data to other different thermal potentials. The high correlation factors insure that the data will be valid for different potentials. It is interesting to note that the exchanger effectiveness may not increase as the potential increases. It was also noted that there exists no linear relationship between the air temperature differential and the depth of the buried pipe.

Dimensionless Curves --- Another method to extend the range of application for the data is to plot the data in dimensionless form. It was found that three dimensionless groups, E, Qu and Le (Sec. 4.6.1), were necessary to describe the phenomena of the system. Many sets of data plotted in dimensionless form for E, and $Qu*Le^{0.333}$ for both heating and cooling produced, in general, an exponential relationship (Fig. 22 and Fig. 23). Data points for cooling were slightly higher than those for heating, especially the data points for cooling with condensation. Equations [4-23] a, b, and c can be used to estimate the exchanger effectiveness, outlet air temperature, and heat capacity, respectively, over the given ranges for intermittent operation. For long term continuous operation, the curves are lower because of low recovery of soil temperatures and soil moisture contents. Figure 24 indicates that the daily air temperature variation has little or no effect on the dimensionless curves. The dimensionless curves or equations are thus valid for continuous operation but their application may provide only a rough estimate of conditions.

Effect of Soil Moisture Movement --- Based on an approximate model developed in Section 3.7, the curves for soil moisture movement (Fig. 25 and Fig. 26) indicate that the soil near the inlet and around the pipe soon becomes saturated for heating but becomes very dry for cooling. Apparently, soil containing a large percentage of water in the heating case possesses higher values of thermal conductivities compared to the cooling case in which the soil is very dry.

Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

A finite element model describing a buried pipe with internal airflow and radial heat flow in a soil-air heat exchanger has been developed. The model has been validated by comparison to another theoretical analysis and by a test facility at the University of Manitoba. Since no useful computer program was currently available, the mathematical modeling and expanded computer data processing in this analysis make this study unique and advanced. Results from this study, either simulated curves or approximate equations, can be used in the preliminary design of the systems.

From the numerical results and other system characteristics, the following conclusions can be drawn.

1. For a buried pipe system, 3 m deep or more, the simplified model has advantages in describing the most important phenomena presented in the system. Ice formation, water vapor condensation, and soil moisture migration were all accounted for. The inclusion of a large number of variables that influence the exchanger performance made it possible to simulate the behavior of these variables in the system.
2. The mass flow rate of air significantly affects the system performance in terms of air temperature differential and heat capacity. Lower airflow rates can use a shorter pipe while higher

airflow rates will require a longer pipe in order to obtain the same temperature differential. At the same air velocity, a smaller pipe diameter results in a higher temperature differential and higher effectiveness compared to a larger pipe diameter but may not produce a higher heat capacity. Therefore, sizing of the pipe diameter and length may be a compromise decision in a design.

3. Sand containing solid quartz particles is superior to clay, silt and silty clay for the system. High density and high moisture content of the soil improve the thermal performance.

4. The low thermal conductivities of plastic pipes can reduce the temperature differential approximately 2 °C compared to other materials such as copper. In winter, soil moisture movement produces a higher thermal conductivity of the soil than in summer. Moisture movement also smooths the contact between the pipe wall and the surrounding soil in winter but degrades the contact in summer. Very poor contact conditions may cause about 3 °C difference in outlet air temperatures.

5. Increasing the ratio of the convective heat transfer coefficient to the air velocity significantly increases the air temperature differential. But a higher heat transfer coefficient obtained by moving air along the pipe at higher speeds may not increase the total amount of energy available from the system.

6. Simultaneous heat and mass transfer calculations are an approach to estimate the resulting high heat transfer coefficients. The air temperature differential may increase 3 °C or more if the water vapor condensation occurs over a pipe length of more than 20 m.

7. Outlet air temperatures tend to follow ambient air temperature changes but the peaks and valleys are effectively leveled. Higher air temperature differentials can be achieved by intermittent operation as compared to continuous operation. Air temperature differentials also increase linearly with the increase in undisturbed soil temperature or system thermal potential, Ti-Tus.
8. Three dimensionless groups were developed in this study and are valid for extending the range of application of the simulation data. The system effectiveness is related exponentially to the product of Qu and Le raised to the one-third power.

For modifying the model or for developing a higher level finite element program to improve the prediction of the ventilation air tempering, the author presents the following recommendations for the future work.

1. Use a rectangular solution region for the cross section of the pipe, as described in Section 3.1. This would give more reasonable boundary conditions to handle temperature variation at the soil surface.
2. Include the vertical parts of the pipe in the analysis.
3. Study more rigorously the convective heat transfer coefficient as affected by water vapor condensation inside the pipe. The possible benefits of cooling by condensation (e.g., by spraying water at the inlet) in summer operation should be investigated.
4. Study the heat energy ratio to economically optimize the system.

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Appendix A

ESTIMATION OF UNDISTURBED SOIL TEMPERATURES

A.1 TRANSFORMATION OF THE EQUATION

A numerical technique which has gained widespread interest is used in the application of curve-fitting. The development of computer technology has allowed for even more complicated non-linear expressions to be transformed into linear forms suitable for fitting to various sets of data. For example, Eq [2-5] can be rewritten by using trigonometric formulas:

$$Tus(y,t) = Tm + \{ A \exp(-y/D) \cos(P_0 + y/D) \} \sin(wt) + \{ A \exp(-y/D) \sin(P_0 + y/D) \} \cos(wt) \quad [A-1]$$

Let, $B_0 = Tm$ [A-2]

$B_1 = A \exp(-y/D) \cos(P_0 + y/D)$ [A-3]

$B_2 = A \exp(-y/D) \sin(P_0 + y/D)$ [A-4]

$X_1 = \sin(wt)$ [A-5]

$X_2 = \cos(wt)$ [A-6]

Then, the transformed linear model is:

$$T(y,t) = B_0 + B_1X_1 + B_2X_2 \quad [A-7]$$

With this model, the parameters B_0, B_1, and B_2 can be estimated by means of multiple linear regression performed on the average monthly or average daily soil temperature data. The original parameters Tm, A, and P_0 can be found by inverting the transform as follows:

$$Tm = B_0 \qquad [A\text{-}8]$$

$$A = \exp(y/D)\ (B_1{}^2 + B_2{}^2)^{0.5} \qquad [A\text{-}9]$$

$$P_0 = \tan^{-1}(-B_2/B_1) - y/D \qquad [A\text{-}10]$$

However, with any one set of soil temperature data at depth y (m), these parameters will still remain unknown unless an estimate of the thermal diffusivity at the damping depth D is made. Inaccurate estimates of the diffusivity often cause large errors. To reduce the effects of thermal diffusivity on the other parameters, Costello et al. (1984) proposed that shallow soil temperature data ($y/D << 1$) be used.

A.2 SHALLOW SOIL TEMPERATURE DATA

For silty clay soil, thermal diffusivity a varies over the range 0.0008 to 0.003 m^2/h (Ingersoll, 1954) so that the damping depth is:

$$D = [\ 2\ a/w\ ]^{0.5} = 1.49 \text{ to } 2.89 \text{ m}$$

For shallow soil temperature data, commonly measured at 5 cm or 10 cm, the ratio of y/D becomes very small and can be ignored in Eqs [A-2] and [A-3]. The equations reduce to:

$$B_1 = A \cos P_0 \qquad [A\text{-}11]$$

$$B_2 = A \sin P_0 \qquad [A\text{-}12]$$

The inverse transforms are still the same but the thermal diffusivity a has little effect (no effect if y is zero) on the determination of A and P_0.

A.3 ESTIMATING THERMAL DIFFUSIVITY

By assuming that this soil property is independent of depth and temperature, adding Eqs [A-3] and [A-4] and applying the trigonometric transform technique, the following expression results:

$$0.707[\ (B_1 + B_2)/A\ ]\ \exp(y/D) = \sin(3.14/4 - P_0 - y/D) \qquad [A-13]$$

It should be noted that, no matter at which soil depth the temperature data are used in the model, the parameters A and P_0 are constant. This is so because the parameters refer to the soil pattern considered. If two sets of soil temperature data, e.g., at depth y and at shallow depth y*, are used in a multiple linear regression program such as the General Linear Model (GLM) in the SAS (Statistical Analysis System) library, the soil thermal diffusivity can be estimated by the following equation:

$$\frac{0.707(B_1+B_2)}{(B_1^{*2}+B_2^{*2})^{0.5}}\exp\left(\frac{y-y^*}{D}\right) = \sin\left\{\frac{3.14}{4} - \tan^{-1}\left(\frac{-B_2^*}{B_1^*}\right) - \frac{y-y^*}{D}\right\} \qquad [A-14]$$

where B_1, B_2, B_1^*, and B_2^* are parameters obtained from GLM outputs, based on soil temperature data at depth y, and at shallow depth y* (5 cm or 10 cm), respectively. The solution for the soil damping depth D can be found at the intersection of the two curves which are described by the right-hand and left-hand functions in this equation. A calculator or a short computer program can be also used for solving this transcendental equation for D. The soil thermal diffusivity α is thus given by:

$$\alpha = \frac{D^2 w}{2} \qquad [A-15]$$

A.4 APPLICATION TO LOCAL DATA

Once the soil thermal diffusivity is evaluated either by field measurements or by the method described above, the model can be modified by using a large amount of soil temperature data. With T(yi,t) as the expression of the undisturbed soil temperature whose parameters are evaluated from soil temperature data at depth yi, a better estimate can be obtained by applying statistical theory:

$$T(y,t) = \{ \sum_{i=1}^{n} T(yi,t) \} / n \qquad [A-16]$$

Daily soil temperature data for 1982 and 1983 (Environment Canada, 1977-1983) at a 10 cm depth at Glenlea Research Station, Winnipeg, were used for the GLM to evaluate the parameters defined. The monthly soil temperature data at 3 m depth from 1979 to 1983 were also used. All of the parameters estimated are shown in Table 8 and the estimating equations in Table 9. A computer program was used to solve Eq [A-14] for the soil damping depth (D = 1.65 m). The soil diffusivity was estimated as 0.0234 m^2/day which is reasonable for the silt clay soil at Glenlea. Table 10 indicates that the expression containing the parameters evaluated from the multiple linear regression gives results that agree well.

TABLE 8

Soil Temperature Parameters

Depth m	B_0 °C	B_1 °C	B_2 °C	Tm °C	A °C	P_0 rad
0.1	3.9503	-6.1447	-10.4152	3.9503	12.8483	2.0432
3	5.5767	-2.2882	2.1003	5.5767	19.1348	2.0660

D = 1.65 m
Data source: Glenlea Research Station, Winnipeg. 1979-1983.

TABLE 9

Undisturbed Soil Temperature Estimating Equations

Data based at depth m	T(y,t) °C
0.1	$T(y,t)=3.9503+12.8483\exp(-y/D)\sin(wt-2.0432-y/D)$
3	$T(y,t)=5.5767+19.1348\exp(-y/D)\sin(wt-2.0660-y/D)$
modified	$T(y,t)=1/2\{3.9503+5.5767+\exp(-y/D)[12.8483\sin(wt-2.0432-y/D)+19.1348\sin(wt-2.0660-y/D)]\}$

D = 1.65 m
w = 2*3.14/365 for t in days or w = 2*3.14/12 for t in months
Data source: Glenlea Research Station, Winnipeg. 1970-1983.

TABLE 10

Comparing Estimated Soil Temperature With Measured Data

Month	Estimated* °C	Measured# °C	Difference °C
Jan	5.30	5.50	0.20
Feb	3.96	4.30	0.34
March	2.84	3.30	0.46
April	2.22	2.80	0.58
May	2.29	2.30	0.01
June	3.03	2.70	-0.33
July	4.22	4.10	-0.12
Aug	5.56	6.30	0.74
Sept	6.69	8.10	1.41
Oct	7.30	8.60	1.30
Nov	7.23	8.20	0.97
Dec	6.50	7.10	0.60

* Calculated by:

$$T(y,t) = 1/2 \{3.9503+5.5765+\exp(-y/D)[12.8483\sin(wt-2.0432-y/D) + 19.1348\sin(wt-2.0660-y/D)]\}$$

where y = 3.0 m and D = 1.65 m.

Data source: Glenlea Research Station, Winnipeg. 1983.

Appendix B

EVALUATING SOIL VOLUMETRIC HEAT DUE TO ICE FORMATION

If Xs, Xw, and Xa denote the volumetric fractions of solid material, water (or ice) and air, respectively, then the heat capacity per unit of volume is:

$$Cs = Xs\ Cs' + Xw\ Cw + Xa\ Ca$$

The third term on the right-hand side can usually be neglected. The value of Cw is 4,186 J/(kg°C) for water and the value of Cw is 2093 J/(kg°C) for ice at 0°C (Jumikis, 1977). Many references state that the mass heat capacity of soil solids varies with parent materials and temperature. In this program an average value of 837.2 J/(kg°C) was used for the soil solids.

Thus, for unfrozen soil:

$$Cs = \gamma\ Cs' + \gamma\ w\ Cw \qquad [B-1]$$

For frozen soil:

$$Cs = \gamma\ Cs' + \gamma\ w\ Ci\ I + \gamma\ w\ (1-I)\ Cw \qquad [B-2]$$

where,

- I = proportion of ice defined as: $1 - w'/w$
- w' = unfrozen water portion relative to total water content, w,
- Ci = mass heat capacity of ice, J/(kg°C).

At the frost boundary,

$$(Cs)r(T) = \frac{\delta\{H\}/\delta r}{\delta\{T\}/\delta r}$$

Here, the enthalpies, in J/kg, of water and ice can be found from a psychrometric table:

$$H(T) = 4186\ T \qquad (0 \le T \le 2\ ^{\circ}C) \qquad [B-3]$$

$$H(T) = 2093\ T - 333{,}499 \qquad (-7 \le T \le 0\ ^{\circ}C) \qquad [B-4]$$

The enthalpies of a moist soil element containing the phase change boundary are given by:

$$H(T)s = \gamma Cs'\ T + 4186\gamma w\ T \qquad (0 \le T \le 2\ ^{\circ}C) \qquad [B-5]$$

$$H(T)s = \gamma Cs'\ T + 2093\gamma wI\ T - 333{,}499\gamma wI + 4186w(1-I)\gamma\ T \qquad (-7 \le T \le 0\ ^{\circ}C) \qquad [B-6]$$

If Ni and Nj denote the shape functions, the enthalpy and the temperature for any point within the element are:

$$H(r,t) = Ni\ H(Ti) + Nj\ H(Tj) \qquad [B-7]$$

$$T(r,t) = Ni\ Ti + Nj\ Tj \qquad [B-8]$$

So that

$$(Cs)r(T) = \frac{\dfrac{\delta Ni}{\delta r} H(Ti) + \dfrac{\delta Nj}{\delta r} H(Tj)}{\dfrac{\delta Ni}{\delta r} Ti + \dfrac{\delta Nj}{\delta r} Tj} \qquad [B-9]$$

Appendix C

ANALOGY OF THE HEAT AND MASS TRANSFER FOR THE COEFFICIENT HC

A simplified method commonly used for solving problems involving simultaneous heat and mass transfer was developed from the Lewis relation and gives satisfactory results for most air conditioning processes. It is fortunate that the Lewis relation holds for this case concerning air and water vapor at low mass transfer rates. The expression relating the ratio of the heat transfer coefficient to the mass transfer coefficient first entered into Lewis' (1922) study. Specifically for air and water vapor, the expression is:

$$\frac{hc'}{hm} = \rho' \, Ca \qquad \text{or} \qquad \frac{hc'}{Km\,Cpm} = 1 \qquad [C\text{-}1]$$

where,

- hc' = heat transfer coefficient due to condensation, $W/(m^2\,^\circ C)$
- hm = mass transfer coefficient defined as: $hm = Km/\rho'm$, m/s
- Km = mass transfer coefficient, $kg/(s\ m^2)$
- $\rho'm$ = mean density of dry air, kg/m^3
- Ca = specific heat at constant pressure, $J/(kg\ ^\circ C)$
- Cpm = specific heat of the humid airstream by definition: $Cpm = (1+Wa)Ca$, $J/(kg\ ^\circ C)$
- Wa = humidity ratio, kg of water vapor per kg of dry air.

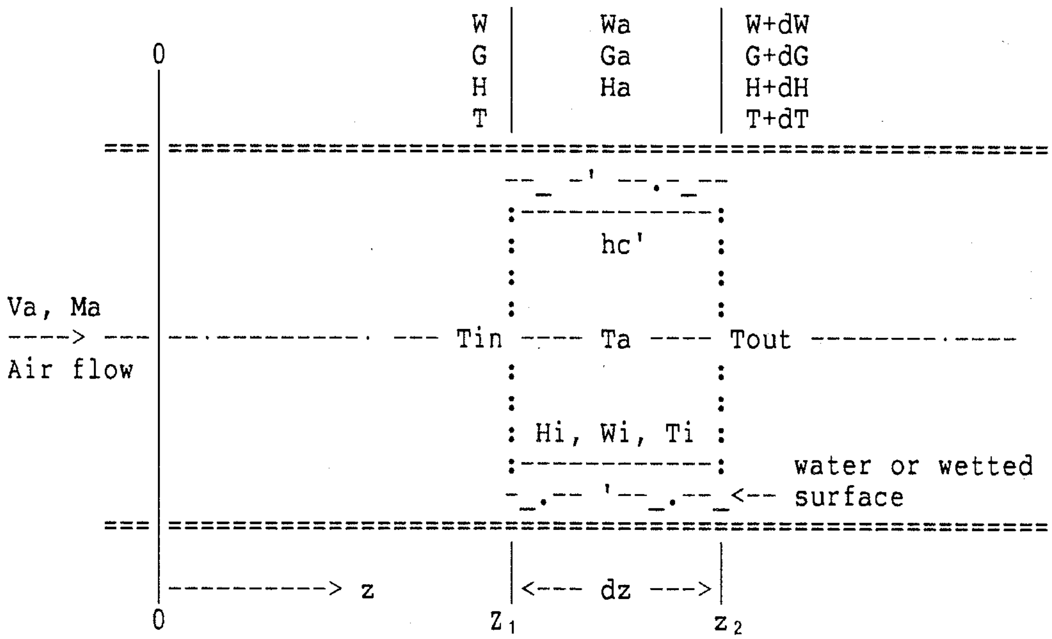

Figure 33: Heat and Mass Transfer Between Water-wetted Surfaces and Air

Since water is condensing, mass velocity per unit cross-sectional area for air, G (kg/(s m^2)), changes by an amount, dG, in a differential length as shown in Figure 33. Similar changes occur in temperature T, humidity ratio W, enthalpy H, and also in other properties. It has been shown that the total heat transfer q" (W/m^2) from the air and water mixture to the interface is (ASHRAE Fundamentals Handbook, 1981):

$$q'' = hc'(Ti - Ta) + Km(Wi - Wa)Hg' \qquad [C-2]$$

Assuming the Lewis relation to be valid gives:

$$q'' = Km\{ Cpm(Ti - Ta) + (Wi - Wa)Hg' \} \qquad [C-3]$$

where,

Hg' = enthalpy of vaporization, J/kg,
i, a = subscripts involving air-water interface quantity and property of the main fluid stream, respectively.

If the small changes in the latent heat of vaporization of water with temperature change are neglected, the total heat transfer can also be written:

$$q'' = Km(Hi - Ha) \tag{C-4}$$

Thus, whereas the driving potential for heat transfer is temperature difference and the driving potential for mass transfer is mass concentration or partial pressure, the driving potential for the simultaneous transfer of heat and mass in an air water-vapor mixture is, to a close approximation, enthalpy. In this case, if the areas of heat and mass transfer are identical, total energy transfer for the air can be approximated by the equation:

$$Ga\ dHa = Am\{ hc'(Hi - Ha) + Km(Wi - Wa)Hg' \}\ dz$$

Using the Lewis relation gives:

$$Ga\ dHa = hc'\{ Cpm(Hi - Ha) + (Wi - Wa)Hg' \}(Am/Cpm)\ dz \tag{C-5}$$

where, Ga is air mass flow rate per unit of cross-sectional area, in $kg/(s\ m^2)$ and Am is defined as the heat or mass transfer surface per m^3 of the control volume. It follows that:

$$Am\ dz = \left(\frac{3.14\ D\ dz}{(3.14\ D^2/4)\ dz} \right) dz = \frac{4\ dz}{D} \tag{C-6}$$

Comparing Eqs [C-3] and [C-4] and substituting Eq [C-6] into [C-5] results in:

$$Ga\ dHa = hc'(Hi - Ha) \frac{4\ dz}{D\ Cpm}$$

or,

$$hc'\ dz = \frac{D\ Cpm\ Ga}{4} \frac{dHa}{(Hi - Ha)} \tag{C-7}$$

Integrating within the control volume yields:

$$hc' = \frac{D\ Ga\ Cpm}{4(\ z_2 - z_1\ )} \ln\left(\frac{Hi - Hin}{Hi - Hout} \right) \qquad [C\text{-}8]$$

where, Hi, Hin, and Hout are the enthalpies at the temperatures of the interface, the inlet, and the outlet, respectively. Note that:

$$z_2 - z_1 = \Delta z$$

$$Ga = \rho'\ Va$$

$$Cpm = (\ 1 + Wa\ )Ca = Ca \qquad (\ Wa << 1\ )$$

Thus,

$$hc' = \frac{D\ Ca\ \rho'\ Va}{4\ \Delta z} \ln\left(\frac{Hi - Hin}{Hi - Hout} \right) \qquad [C\text{-}9]$$

Again, the Lewis relation offers an alternative method to simplify Eq [C-9]. Since

$$\frac{dHa}{dTa} = \frac{Ha - Hi}{Ta - Ti}$$

Eq [C-7] can be written as:

$$hc'\ dz = \frac{D\ Cpm\ Ga}{4} \frac{dTa}{(\ Ti - Ta\ )} \qquad [C\text{-}10]$$

Similarly, by integration, the heat transfer coefficient due to condensation inside the pipe can be estimated by the derived equation:

$$hc' = \frac{D\ Ca\ \rho'\ Va}{4\ \Delta z} \ln\left(\frac{Ti - Tin}{Ti - Tout} \right) \qquad [C\text{-}11]$$

It is essential to realize that since the interface temperature and outlet temperature are usually unknown the evaluation of these temperatures can be made only through trial and error. Fortunately, the use of high speed computers makes these determinations relatively easy.

Appendix D

FLOW CHART OF THE FEPSHE

The following flow charts describe the general flow during the execution of the Finite Element Program of the Soil-air Heat Exchanger (FEPSHE). The program options and control parameters are described in Appendix E.

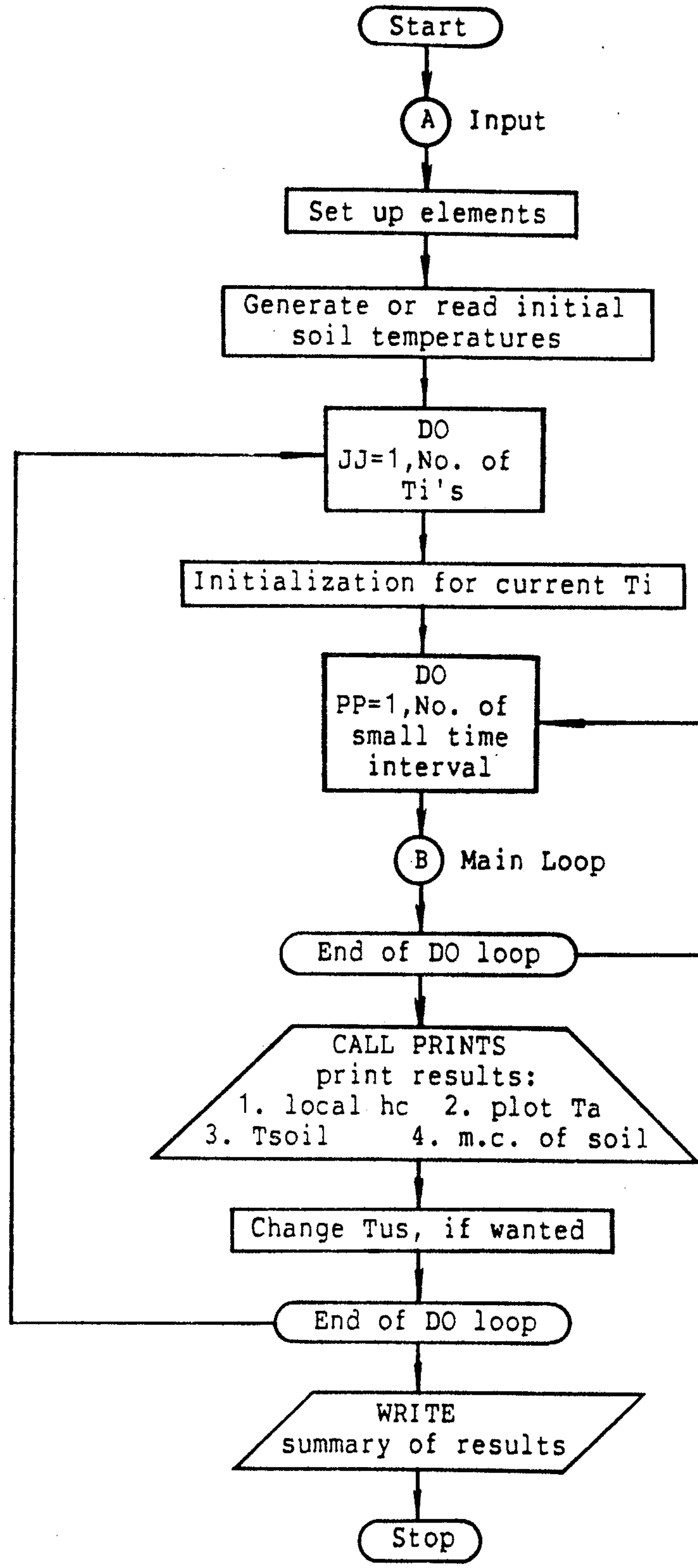

Figure 34: General Flow Diagram for the FEPSHE

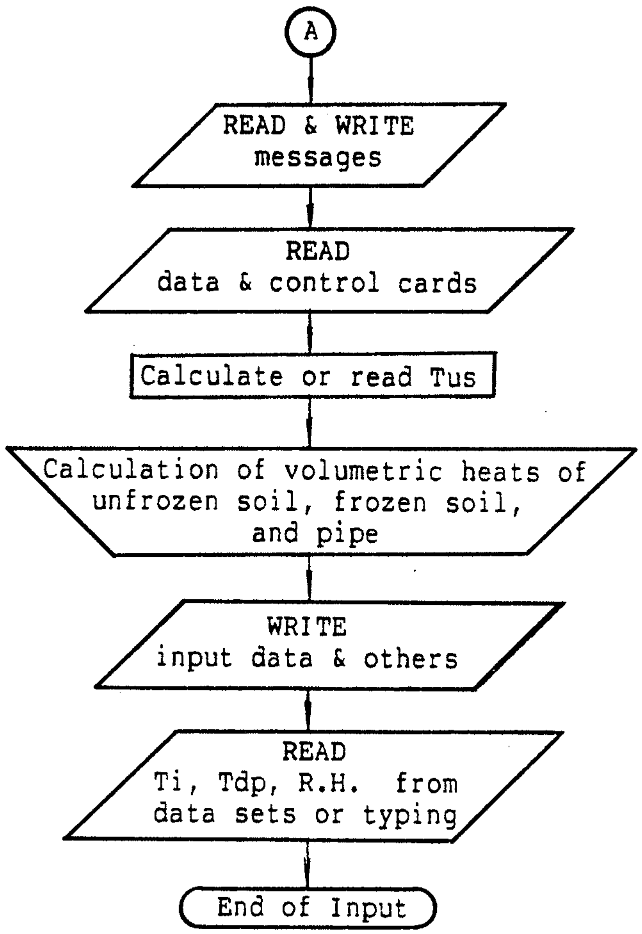

Figure 35: Flow Chart of Input for the FEPSHE

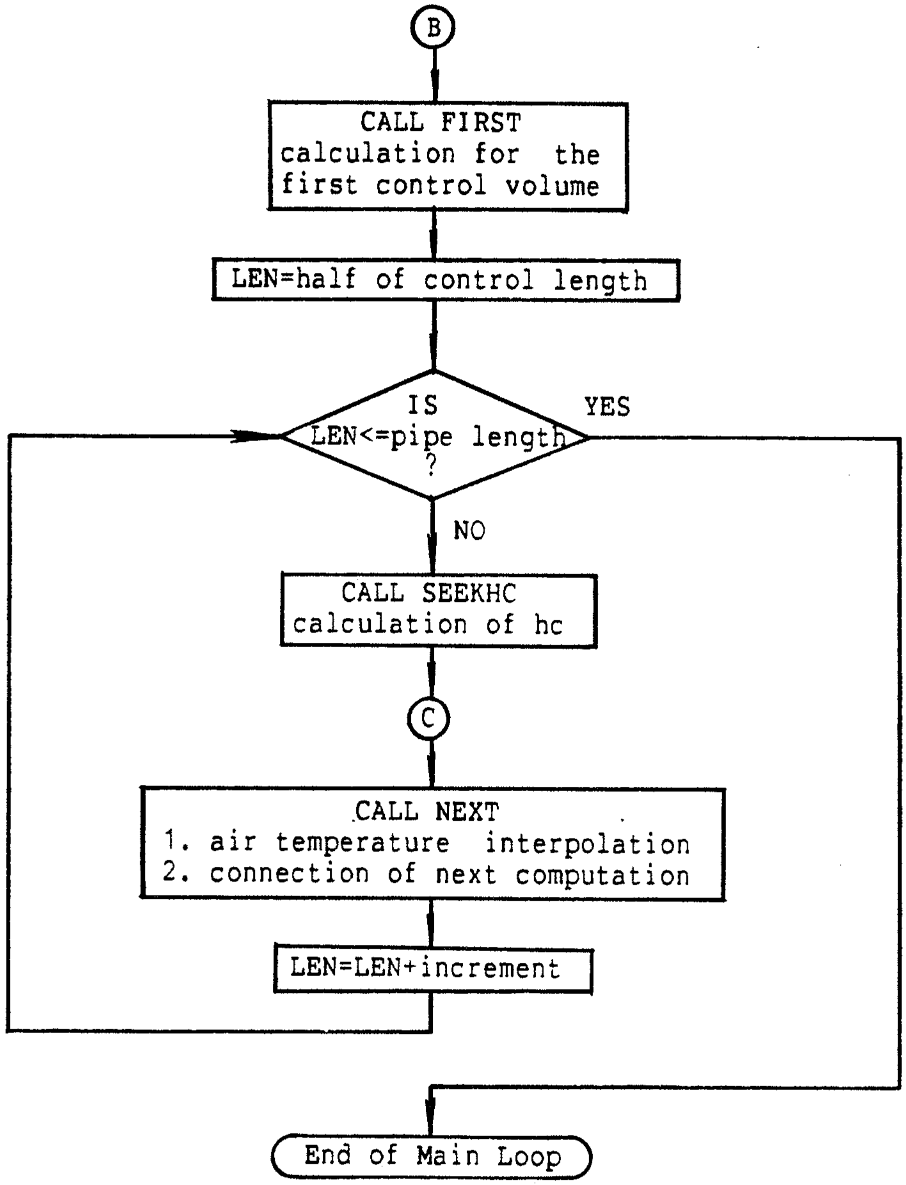

Figure 36: Flow Chart of Main Loop in the FEPSHE

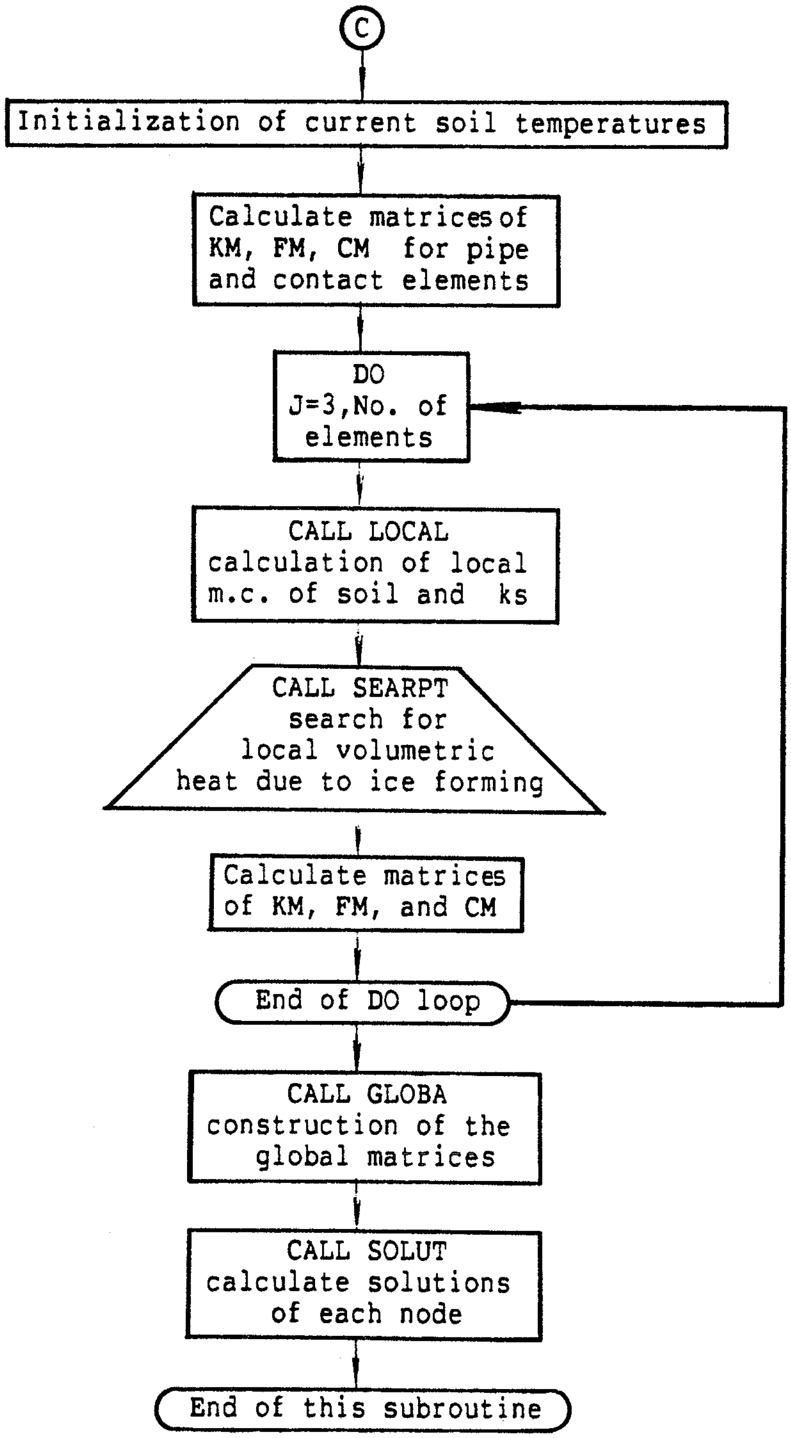

Figure 37: Flow Chart of Finite Element Subroutine in the FEPSHE

Appendix E

DESCRIPTION OF THE FEPSHE

The foregoing flow charts of the FEPSHE indicate how the program has been constructed. The program is characterized by the incorporation of variable thermal conductivities for soil, variable convective heat transfer coefficients and latent heat exchange in both soil and air as well as changing boundary conditions. To facilitate the data input for various conditions, the control of variables during execution, and the display of results and other analysis, the program has a number of control parameters and options. Detailed descriptions are as follows:

OPTIONS --- Character variable CONTRL*80(10) contains six strings of characters each up to 80 letters to supply options for input and output. They are:

CONTRL(1)='Print hc'

CONTRL(2)='Plot air temperatures'

CONTRL(3)='Read inlet air temperatures from a data set'

CONTRL(4)='Generate initial soil temperature profiles'

CONTRL(5)='One inlet air temperature'

CONTRL(6)='Generate elements'

Input of the exact character strings, including spaces, will instruct the computer to do as the strings indicate. Any different strings for CONTRL(3) will allow users to input ambient air temperatures and for CONTRL(5) to input multiple entries. Different strings for CONTRL(4) will require setting up a data set which contains the initial soil temperature profiles (e.g., from previous simulation) with a consistent format. If the finite elements are not self-generated, each nodal coordinate can be read from input. For the option of soil types, character variable TEX accepts 'Sand', 'Silt', 'Silty clay', and 'Clay'. Different character strings will stop the execution.

It is possible and sometimes necessary to have a different time increment between inlet air temperatures. The program permits different time increments to be stored in an array called TIME. In a winter simulation input values for dew point temperatures and relative humidity ratios would be only dummy values if the air quality is not of concern.

CONTROL PARAMETERS --- Integer variable TT, initialized in the first declaration statement, is a time division for each time increment between inlet air temperatures, so that a small time interval is available. This allows daily or weekly ambient air temperatures to be used as input. Variable TSOIL must be a dummy variable (assigned as -99) when the real function FOST is used for evaluating undisturbed soil temperatures. In the function FOST, modification of the boundary conditions by an integral is an alternative (Sec. 3.4). Variable DFCH contains "Days For Changing" undisturbed soil temperatures while a continuous simulation is being conducted. The moisture content of soil at saturation, MCOSA, is, in part, a control parameter which confines the values of the moisture contents within a reasonable range. There also exist many alternative decisions in the program without control parameters, for example, IF(0 .LT. 1) GOTO or THEN DO, in order to reduce input lines and facilitate the use and modification of the program.

REQUIREMENTS OF INPUT DATA --- Four or five parts of the input data are required before the program is submitted (reference the program list).

1. Messages. This part serves as a reminder of the user. Any notices in any format are acceptable. But to terminate, a new line must contain a character string "A STOP CARD".
2. Control Character Strings. Five lines must be given for character variable CONTRL(I) (I=1,2,...5) (see OPTIONS).
3. System Constants. Three lines subject to the READ statements in the program are required. The first line must contain the values of inside pipe diameter, inside pipe radius, outside pipe radius, outside soil radius, pipe length, and control length for each control volume. All of these dimensions must be in meters. The second line must have the values of pipe thermal conductivity (W/(m°C)), air velocity (m/s), specific heat of air (J/(kg°C)), time interval (h) (could be dummy only), contact resistance (m^2°C/W), depth of the buried pipe (m), undisturbed soil temperature (°C) (if the temperature model for undisturbed soil included in the program is used, type -99 here), and the days for changing the undisturbed soil temperatures (day). In the third line, the values of bulk density of soil (kg/m^3), initial soil moisture content (decimal), total days for the simulation (day), and the start date (hour, day, month, year; e.g., 1, 1, 1, 85) must be given.
4. Input Air Temperatures. This part must be deleted if CONTRL(3) has a string of "Read inlet air temperatures from a data set".

For the input, the first line must be "One inlet air temperature" or a different string. For only one input data the values of inlet air temperature (°C), dew point temperature (°C), relative humidity ratio (%), and start time (0.0) must be in the second line. For more than one data input, the second line is the total number of inlet air temperatures. The next inputs are inlet air temperatures (°C), dew point temperatures (°C), relative humidity ratios (%), and time increment between inlet air temperatures. The first values for each array must be typed on a new line.

5. Setting Up Elements. The first line in this part is a character string "Generate elements" or some other expressions. The following line is the total number of elements. For element generation no more lines are necessary, but for input of nodal coordinates the numbers must be typed in.

Appendix F

PROGRAM LIST OF THE FEPSHE

```
C //LEI JOB '0227015,,,T=60,I=40,L=30,','LEI',NOTIFY=LEI,
C //  PASSWORD=
C //  EXEC WATFIV,SIZE=768K
C //SYSIN DD *
C $JOB  WATFIV   LEI,NOEXT,NOLIST
C =======================================================================
C * THIS IS A FINITE ELEMENT PROGRAM FOR SOIL-AIR HEAT EXCHANGERS      *
C *                   >>>>  FEPSHE  <<<<                                *
C *                                                                     *
C * WRITTEN BY QUANMIN LEI                     OCTOBER 4TH, 1984        *
C =======================================================================
C
      INTEGER I,NN,QQ,J,JJ,TT/1/,PP,Z,YES,PZ(10),YESPTR(100),N,DATE(4),
     *        POS/-1/,CC,YESPMC(100)
C
      REAL R1,R2,R3,DP,PL,KP,KS,VEL,CP,L,TSOIL,TINLET(100),TIME(100),
     *     MCOA(100,2),KFS,RD,MCOS,XP(150),TR(65,150),LEN,TIN,TDP,MASS,
     *     PI/3.14159/,RE,STIME,PTOUT(10,65),TOUT(65),PHC(10,65),BUW,
     *     PTF(10,65),CR,PC1,PC2,PCP,TF,PTR(10,65,151)
      REAL TBULK,HC,TOTIME,TOLET(100),EF(100),CAPTY(100),G,PSITY,
     *     TDPA(100),RH(100),OUTRH(100),PREOS,WRATE(100),FOST,DEPTH,
     *     RDAY,OLDT,MCOSA,FTOUT(65),DAYS,TVL,PMC(65,151),ANY,MYVAL,
     *     DFCH
C
      CHARACTER TITLE*80, STOP*80, CONTRL*80(10), TEX*80
C
C ==================== VARIABLE DICTIONARY ============================
C * --- INTEGER ---                                                     *
C * N      --- NO. OF POINTS CONSIDERED FOR AIR TEMP,N=PL/L*2+1         *
C * YES    --- INDICATION FOR THE CONDENSATION EQUATION USED            *
C * JJ     --- SUBSCRIPT FOR TIME AND INLET TEMPERATURE INTERVAL         *
C * QQ     --- NO. OF INLET TEMPERATURES                                *
C * I      --- SUBSCRIPT FOR LOCATION ALONG PIPE                         *
C * NN     --- NO. OF FINITE ELEMENT NODES,NN=NO. OF ELEMENTS+1          *
C * J      --- GENERAL SUBSCRIPT                                        *
C * PP     --- SUBSCRIPT FOR TIME INCREMENT                             *
C * TT     --- NO. OF TIME INCREMENTS                                   *
C * Z      --- NO. OF HC CALCULATED FROM A SUBROUTINE                   *
C * PZ     --- NO. OF HC WITHIN A GIVEN TIME (1-D)                      *
C * POS    --- POSITION WHERE CONDENSATION OCCURS                       *
C * YESPTR--- INDICATION FOR PRINT TEMPERATURES (1-D,0 OR 1)            *
C * DAYS   --- NO. OF DAYS OF OPERATION                                 *
C * DATE   --- ARRAY STORED DATE OF OPERATION (HR.,DAY,MON.,YEAR)       *
C * CC     --- FREE-USING SUBSCRIPT                                     *
C * YESPMC--- INDICATION FOR PRINT SOIL MOISTURE CONTENT                *
```

```
C *                                                                    *
C * --- REAL ---                                                       *
C * R1,R2,R3 --- INSIDE,OUTSIDE PIPE RADII AND OUTSIDE UNDISTURBED      *
C *                SOIL CYLINDER RADIUS,M.                             *
C * DP     --- DIAMETER OF THE PIPE, M.                                *
C * HC     --- HEAT TRANSFER COEFICIENT,W/M-M-C                        *
C * KP,KS  --- THERMAL CONDUCTIVITIES OF PIPE AND SOIL,W/M-C           *
C * VEL    --- AIR VELOCITY,M/S                                        *
C * TIN    --- INLET TEMPERATURE,C                                     *
C * TSOIL  --- SOIL TEMPERATURE,C                                      *
C * TOUT   --- ARRAY STORED AIR TEMPERATURE AT EACH POINT,C            *
C * FTOUT  --- ARRAY STORED PREVIOUS (FIRST) "TOUT",C                  *
C * TDP    --- DEW-POINT TEMP., C                                      *
C * TDPA   --- DEW-POINT TEMP. ARRAY (1-D),C                           *
C * MCOA   --- AIR M.C. AT INLET & OUTLET,KG/KG OF DRY AIR,(2-D)       *
C * RH     --- RELATIVE HUMIDITY(%) AT EACH INLET TEMP.(1-D)           *
C * OUTRH  --- RELATIVE HUMIDITY(%) AT EACH OULET TEMP.(1-D)           *
C * PREOS  --- SATURATION VAPOR PRESSURE AT T,PA (FUNCTION)            *
C * BUW    --- BULK UNIT WEIGHT OF SOIL,KG/CU-M                        *
C * G      --- SPESIFIC GRAVITY OF SOIL                                *
C * PSITY  --- SOIL POROSITY,DECIMAL                                   *
C * L      --- CONTROL LENGTH OF PIPE                                  *
C * PL     --- TOTAL LENGTH OF PIPE,M                                  *
C * CP     --- SPECIFIC HEAT OF AIR AT CONSTANT PRESSURE,J/KG-C        *
C * TF     --- FILM TEMPERATURE,C                                      *
C * LEN    --- PIPE LENGTH MEASURED FROM THE INLET,M                    *
C * TR     --- SOIL TEMP DISTRIBUTION AT EACH LOCATION (2-DIM.),C      *
C * KFS    --- THERMAL CONDUCTIVITY OF FROZEN SOIL,W/M-C               *
C * CR     --- CONTACT RESISTANCE BETWEEN THE PIPE AND SOIL,M-M-C/W    *
C * RD     --- UNIT WEIGHT OF DRY SOIL,KG/CU-M                         *
C * MCOS   --- MOISTURE CONTENT OF SOIL,DEC.                           *
C * MCOSA  --- MOISTURE CONTENT UPON FULL SATURATION,DEC.              *
C * TIME   --- ARRAY STORED EACH TIME INTERVAL,HR.                     *
C * TINLET--- INLET AIR TEMPERATURE (1-D),C                            *
C * XP     --- ARRAY STORED EACH NODAL COORDINATES,M                    *
C * MASS   --- MASS RATE OF AIR FLOW,KG/S                              *
C * STIME  --- SMALL TIME INTERVAL,STIME=TIME(JJ)/TT,HR.               *
C * PTOUT  --- PRINTED AIR TEMPERATURE (2-D),C                         *
C * PHC    --- PRINTED HEAT TRANSFER COEFFICIENTS (2-D),W/M-M-C        *
C * PTF    --- PRINTED FILM TEMPERATURES (2-D),C                       *
C * PTR    --- PRINTED TEMPERATURES OF BOTH AIR AND SOIL (3-D),C       *
C * PC1    --- VOLUMETRIC HEAT OF UNFROZEN SOIL,J/CU-M-C               *
C * PC2    --- VOLUMETRIC HEAT OF FROZEN SOIL,J/CU-M-C                 *
C * PCP    --- VOLUMETRIC HEAT OF THE PVC PIPE,J/CU-M-C                *
C * TBULK  --- BULK TEMPERAUTRE AT EACH LOCATION,C                     *
C * RE     --- REYNOLDS NUMBER                                         *
C * TOTIME--- TOTAL TIME ELAPSED FROM THE BEGINNING,HR.                *
C * TOLET  --- OUTLET AIR TEMPERATURES AT EACH TIME INTERVAL           *
C * EF     --- THE EXCHANGER EFFECTIVENESS AT EACH TIME INTERVAL (%)   *
C * CAPTY  --- THE EXCHANGER CAPACITY AT EACH TIME INTERVAL (J/S)      *
C * WRATE  --- WATER RATE DUE TO CONDENSATION (1-D),KG/S               *
C * FOST   --- FUNCTION OF SOIL TEMPERATURE,C                          *
C * DEPTH  --- DISTANCE OF PIPE CENTER FAR FROM SOIL SURFACE,M         *
C * RDAY   --- THE DAY OF OPERATION OR RUN-DAY,I.E. JAN 1ST IS 1       *
C * OLDT   --- A TIME KEEPER: OLD-TIME,HR.                             *
```

```
C * TVL    --- TIME INTERVAL, HR.                                        *
C * ANY    --- ANY TEMPORAY NUMBER                                       *
C * MYVAL --- MY VALUE OF UNDISTURBED SOIL TEMP, C                       *
C * DFCH   --- DAYS FOR CHANGING UNDISTURBED SOIL TEMP., DAY             *
C *                                                                      *
C * --- CHARACTER ---                                                    *
C * TITLE --- CHARACTER STORED INFORMATION FROM INPUT                    *
C * STOP   --- INPUT CONTROL CHARACTERS TO STOP INPUT LINES              *
C * CONTRL--- INPUT CONTROL CHARACTERS TO PLOT OR PRINT RESULTS          *
C * TEX    --- SOIL TEXTURES: SAND,SILT,SILTY CLAY, AND CLAY             *
C =======================================================================
C
C =======================================================================
C * INPUT AND OUTPUT TITLES OR NOTES; LAST LINE MUST BE 'A STOP CARD' *
C =======================================================================
      STOP='A STOP CARD'
      READ 10, TITLE
      PRINT 15
      WHILE ( TITLE .NE. STOP ) DO
         PRINT 20, TITLE
         READ 10, TITLE
      END WHILE
10    FORMAT (A80)
15    FORMAT ('1'//)
20    FORMAT (T2,A80/)
C =======================================================================
C * INPUT AND OUTPUT DATA                                                *
C * CONTROL CARDS:                                                       *
C *   CONTRL(1)='PRINT HC'                                               *
C *   CONTRL(2)='PLOT AIR TEMPERATURES'                                  *
C *   CONTRL(3)='READ INLET AIR TEMPERATURES FROM A DATA SET'            *
C *   CONTRL(4)='GENERATE INITIAL SOIL TEMPERATURE PROFILES'             *
C *   CONTRL(5)='ONE INLET AIR TEMPERATURE'                              *
C *   CONTRL(6)='GENERATE ELEMENTS'                                      *
C * INPUT OF EXACT CHARACTER STRINGS INCLUDING SPACES WILL INSTRUCT      *
C * THE COMPUTER TO DO AS THE STRINGS INDICATE                           *
C =======================================================================
      READ 22, CONTRL(1)
      READ 22, CONTRL(2)
      READ 22, CONTRL(3)
      READ 22, CONTRL(4)
      READ 22, TEX
      READ, DP, R1, R2, R3, PL,L
      READ, KP, VEL, CP, TVL, CR, DEPTH, TSOIL, DFCH
      READ, BUW, MCOS, DAYS,(DATE(I),I=1,4)
C
      CALL RUND(DATE,RDAY)
C ================
C * NOTES: IF YOU WANT TO USE "FOST" FUNCTION, INPUT TSOIL=-99
C ================
      MYVAL=TSOIL
      IF (MYVAL .LT. -50.0) TSOIL=FOST(RDAY,DEPTH,R3,MYVAL)
      CALL PROTY1(BUW,RD,KS,KFS,MCOS,PSITY,G,TEX,MCOSA)
C ================
C * CALCULATE VOLUMETRIC HEATS OF UNFROZEN SOIL AND FROZEN SOIL
```

```
C =================
      PC1=RD*(837.2+MCOS*4186.0)
      PC2=RD*(837.2+MCOS*2009.28*ABS(1-0.112/MCOS)+ABS(MCOS-0.112)*4186)
      PCP=1512820.4
C
      PRINT 30
      PRINT 40, DP, R1, R2, R3, PL, L, G, PC1
      PRINT 50, BUW, KP, KS, VEL, CP, TSOIL,PSITY,PC2
      PRINT 52, KFS, RD, MCOS, DAYS,MCOSA,TEX
      PRINT 53, (DATE(I),I=1,4)
      WRITE(12,25) VEL,KS,MCOS,TSOIL,DP,PL,DAYS,(DATE(I),I=1,4)
25    FORMAT(T23,6(F10.4,2X),F10.2,2X,2X,4(I2,1X)/)
C
      IF (CONTRL(3) .EQ. 'READ INLET AIR TEMPERATURES FROM A DATA SET')
     *     THEN DO
         CALL INLET(QQ,TINLET,TIME,TDPA,DAYS,DATE,RH,TVL)
      ELSE DO
         READ 22, CONTRL(5)
         IF (CONTRL(5) .EQ. 'ONE INLET AIR TEMPERATURE') THEN DO
            QQ=DAYS*24.0/TVL+0.5
            READ,TINLET(1),TDPA(1),RH(1),TIME(1)
            DO 68 I=2,QQ
               TINLET(I)=TINLET(1)
               TDPA(I)=TDPA(1)
               RH(I)=RH(1)
               TIME(I)=TVL
68          CONTINUE
            TIME(QQ+1)=TVL
         ELSE DO
            READ, QQ
            READ, (TINLET(I),I=1,QQ)
            J=QQ+1
            READ, (TIME(I),I=1,J)
            READ, (TDPA(I),I=1,QQ)
            READ, (RH(I),I=1,QQ)
         END IF
         CALL PLOT1(QQ,TIME,TINLET,TDPA,RH)
      END IF
C
      CALL SETUP(R1,R2,R3,XP,NN)
C =================
C * INITIALIZE TEMPERATURES OF AIR AND SOIL
C =================
      N=PL/L*2.0+1.5
      DO 69 I=1,N
         FTOUT(I)=TSOIL
69    CONTINUE
C
      IF (CONTRL(4) .EQ. 'GENERATE INITIAL SOIL TEMPERATURE PROFILES')
     *    THEN DO
         I=1
         LEN=(I-1)*L/2.0
         WHILE (LEN .LE. PL) DO
            PTR(1,I,1)=TINLET(1)
            DO 70 J=1,NN
```

```
            TR(I,J)=TSOIL
            PTR(1,I,J+1)=TR(I,J)
70        CONTINUE
          I=I+1
          LEN=(I-1)*L/2.0
        END WHILE
        N=I-1
      ELSE DO
        N=PL/L*2+1.5
        CALL RDTR(PTR,TR,N,NN,TINLET)
      END IF
      PRINT 72
      CALL PTPTR(PTR,1,N,NN,0.0,L,0.0,1,QQ)
C =================
C * MESSAGES FOR PRINT TEMP AND M. C. OF SOIL  (1-PRINT,0-NOT)
C =================
      DO 75 J=1,QQ
           YESPTR(J)=0
           IF (MOD(J,4) .EQ. 0) YESPTR(J)=1
           YESPMC(J)=0
75    CONTINUE
      YESPTR(QQ-1)=1
      YESPTR(QQ)=1
      YESPMC(QQ-1)=YESPMC(QQ)=1
C     IF (1 .GT. 0) GOTO 1000 (FOR TESTING INPUT)
C =====================================================================
C * THIS IS THE MAIN PROGRAM WHICH HAS THREE BIG LOOPS:              *
C * TEMPERATURE LOOP,TIME LOOP,AND LOCATION LOOP                     *
C =====================================================================
      TOTIME=OLDT=0.0
      DO 900 JJ=1,QQ
C
        CALL BEGIN(TINLET,TIME,JJ,TIN,TDP,TDPA,R1,VEL,MASS,MCOA,RH,HC,
     *             TSOIL)
C
        STIME=TIME(JJ+1)/TT*3600.0
C
        DO 800 PP=1,TT
C
          Z=0
          I=1
          TOUT(I)=TIN
          YES=0
C
          CALL FIRST(TOUT,TDP,Z,PP,I,PHC,PTF,XP,TR,KP,CR,KS,KFS,TSOIL,
     *                RD,MCOS,PC1,PC2,PCP,STIME,NN,VEL,R1,L,TF,PTOUT,
     *                PTR,YES,HC,POS,FTOUT,G,N,PMC)
C
          I=I+1
          TBULK=TOUT(I)
          LEN=(I-1)*L/2.0
C
          WHILE (LEN .LE. PL) DO
C
            CALL SEEKHC(TF,TDP,TOUT,YES,PTF,PHC,Z,HC,PP,I,TR,R1,VEL,
```

```
     *          L,XP,KP,CR,KS,KFS,TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,NN,POS,
     *          FTOUT,G,PMC)
C
                CALL FEM(XP,HC,I,TBULK,TR,KP,CR,KS,KFS,TSOIL,RD,MCOS,
     *                   PC1,PC2,PCP,STIME,NN,G,FTOUT,PMC)
C
                CALL NEXT(TOUT,R1,HC,L,CP,I,VEL,TR,PTOUT,PTR,NN,PP,STIME)
C
                I=I+1
                TBULK=TOUT(I)
                TF=(TOUT(I)+TR(I-1,1))*0.5
                LEN=(I-1)*L/2.0
C
             END WHILE
C
             DO 750 CC=1,I
                FTOUT(CC)=TOUT(CC)
750          CONTINUE
C
             N=I-1
C
             PZ(PP)=Z
C
800        CONTINUE
C
           CALL PRINTS(PHC,PTF,PZ,PTOUT,PTR,TT,YESPTR,CONTRL,JJ,
     *                 STIME,N,NN,L,TOTIME,QQ,POS,PMC,YESPMC)
           TOTIME=TOTIME+TIME(JJ+1)
           TOLET(JJ)=PTOUT(TT,N)
           ANY=ABS(TINLET(JJ)-TSOIL)
           IF (ANY .LT. 1) ANY=1.0
           EF(JJ)=ABS(TINLET(JJ)-TOLET(JJ))/ANY*100.0
           IF (ANY .LT. 1) EF(JJ)=1.0
           CAPTY(JJ)=(352.9/(273+(TINLET(JJ)+TOLET(JJ))*0.5))*VEL*3.14159*
     *(DP**2.0)/4.0*CP*ABS(TINLET(JJ)-TOLET(JJ))
C
         CALL HUMTY(POS,JJ,N,TT,RH,OUTRH,MCOA,PTOUT,WRATE,MASS)
         IF (TOTIME-OLDT .GE. DFCH*24.0) THEN DO
           OLDT=TOTIME
           RDAY=RDAY+10.0
           TSOIL=FOST(RDAY,DEPTH,R3,MYVAL)
         END IF
C
900      CONTINUE
C
         CALL WRITE1(DATE,VEL,KS,MCOS,TSOIL,DP,PL,DAYS,QQ,TINLET,TOLET,
     *               TIME,EF,CAPTY,MCOA,RH,OUTRH,WRATE)
C
         PRINT 60
C
1000     CONTINUE
C
22       FORMAT (A80)
30       FORMAT ('0'//T30,'THE TABLE OF INPUT DATA AND CALCULATED VALUES'/
     *                T30,'==============================================='//
```

```
     *          T2,'PIPE DIAM.',T16,'    R1 ',T29,'    R2  ',T42,'    R3  ',
     *          T55,'PIPE LENGTH',T72,'CONTROL LENGTH',T90,'SOIL SP.',
     *          'GRAVITY',T111,'VOL.HEAT OF UFS'/
     *          T2,'   (M)    ',T18,' (M)  ',T29,'  (M)  ',T42,'  (M)  ',
     *          T55,'   (M)     ',T72,'       (M)      ',T112,'(J/CU-M/C)'/)
40    FORMAT ('0',T3,F7.4,T16,F7.4,T29,F7.4,T42,F7.4,T58,F7.4,
     *          T77,F7.4,T95,F7.4,T113,F12.2///)
50    FORMAT ('0'/T2,'BUW OF SOIL', T16,'   KP ',T29,'   KS  ',T42,
     *          'AIR VEL.',T57,'SPE. HEAT ',T72,'SOIL TEMP.',T90,'SOIL ',
     *          'POROSITY',T111,'VOL.HEAT OF FS'/
     *          T2,'(KG/CU-M)',T16,'(W/M-C)',T29,'(W/M-C)',T42,
     *          '(M/S) ',T57,'(J/KG-C)',T72,'  (C) ',T112,'(J/CU-M/C)'
     *          //T5,F7.2,
     *          T16,F9.4,T29,F7.4,T42,F7.4,T57,F10.4,T72,F8.4,T94,F7.4,
     *          T113,F12.2//)
52    FORMAT ('0'//T2,' K OF F.S.',T16,'RD OF SOIL',T29,' MCOS ',T42,
     *           ' TIME ',T57,'M.C. SAT.',T72,'SOIL TEXTURE'/
     *          T2,'(W/M-C)',T16,'(KG/CU-M)',T29,'(DEC.)',T42,
     *          ' (DAY)',T57,'(DEC.)'///T2,F7.4,T16,F10.1,T29,F6.4,T41,
     *          F8.2,10X,F8.4,T73,A20//)
53    FORMAT('0'/T2,'START AT',1X,I2,':00',2X,3(I2,2X)//)
72    FORMAT ('0'//T2,'PRINT INITIAL SOIL AND AIR TEMPERATURE'//)
60    FORMAT('1'///)
      STOP
      END
C
C ======================================================================
C * FUNCTION "FOST" IS TO ESTIMATE SOIL TEMPERATURE FOR A GIVEN DAY    *
C ======================================================================
      REAL FUNCTION FOST(RDAY,DEPTH,R3,MYVAL)
      REAL RDAY,DEPTH,R3,T,Z,Y,W,D,H,A,B,SUM2,SUM4,AREA,H2,LAST,F,TM,
     *     A0,MYVAL
      INTEGER N/30/
C
      F(Y,Z,D,W,T,R3)=EXP(-Y/D)*(12.8483*SIN(W*T-118.6930*W-Y/D)
     *                          +19.1348*SIN(W*T-120.0182*W-Y/D))/
     *            ((1-((Z-Y)/R3)**2)**0.5)
      IF (MYVAL .GT. -50) THEN DO
         FOST=MYVAL
         IF (1 .GT. 0) GOTO 20
      END IF
      Z=DEPTH
      W=2.0*3.14159/365.0
      T=RDAY
      D=1.65
C SIMPSON'S INTEGRAL TECHNIQUE IS USED HERE FOR MODIFYING "TSOIL"
      IF (0 .GT. 1) THEN DO
         FOST=1.0/2.0*(3.9503+5.5767+EXP(-Z/D)*(12.8483*
     *   SIN(W*T-118.6930*W-Z/D)+19.1348*SIN(W*T-120.0182*W-Z/D)))
      ELSE DO
         TM=(3.9503+5.5767)/2.0
         A0=1/2.0
         A=Z-R3+0.1
         B=Z+R3-0.1
         H=(B-A)/N
```

```
         SUM2=SUM4=0.0
         Y=A+H
         H2=2.0*H
         LAST=B-3.0*H
         WHILE (Y .LE. LAST) DO
            SUM4=SUM4+F(Y,Z,D,W,T,R3)
            SUM2=SUM2+F(Y+H,Z,D,W,T,R3)
            Y=Y+H2
         END WHILE
         SUM4=4.0*(SUM4+F(B-H,Z,D,W,T,R3))
         SUM2=2.0*SUM2
         AREA=(F(A,Z,D,W,T,R3)+SUM4+SUM2+F(B,Z,D,W,T,R3))*H/3.0
         FOST=TM+A0*AREA/3.14159/R3
      END IF
20    CONTINUE
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "RUND" IS TO CALCULATE THE RUN-DAY IN A YEAR          *
C ====================================================================
      SUBROUTINE RUND(DATE,RDAY)
      INTEGER DATE(4),MONTH
      REAL RDAY
C
      MONTH=DATE(3)
      RDAY=(MONTH-1)*31+DATE(2)
      IF (MONTH .GE. 3) RDAY=RDAY-3
      IF (MONTH .GE. 5) RDAY=RDAY-1
      IF (MONTH .GE. 7) RDAY=RDAY-1
      IF (MONTH .GE. 10) RDAY=RDAY-1
      IF (MONTH .GE. 12) RDAY=RDAY-1
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "SETUP" IS TO INPUT OR GENERATE NODAL COORDINATES     *
C ====================================================================
      SUBROUTINE SETUP(R1,R2,R3,XP,NN)
      INTEGER NE, NN, J
      CHARACTER CONTRL*80(10)
      REAL R1, R2, R3, XP(150), D, DIS
C
      READ 10, CONTRL(6)
10    FORMAT (A80)
      READ, NE
      NN=NE+1
      IF ( CONTRL(6) .EQ. 'GENERATE ELEMENTS') GOTO 20
         READ, (XP(J),J=1,NN)
         PRINT 25
25    FORMAT ('1'//T2,'INPUT NODAL COORDINATES:'//T16,'NODAL NUMBER',
     *       10X,'NODAL VALUE(M.)'//)
          GOTO 40
20    CONTINUE
      D=(R3-R2)/(NE-2)
```

```
      XP(1)=R1
      XP(2)=R2
      XP(3)=R2+0.002
      DIS=XP(3)
      DO 30 J=4,NN
         DIS=DIS+D
         XP(J)=DIS
30    CONTINUE
      PRINT 35
35    FORMAT ('0'//T2,'GENERATED COORDINATES OF NODES:'//
     *         T16,'NODAL NUMBER',10X,'NODAL VALUE (M.)'//)
40    CONTINUE
      PRINT 50, (J,XP(J),J=1,NN)
50    FORMAT (T20,I3,15X,F9.5)
      RETURN
      END
C
C =====================================================================
C * SUBROUTINE "PLOT1" IS TO PLOT INLET AIR TEMPERATURES             *
C =====================================================================
      SUBROUTINE PLOT1(QQ,TIME,TINLET,TDPA,RH)
      INTEGER QQ, I, J, II, X, Y, CC
      REAL TIME(100), TINLET(100), TDPA(100), TT, RH(100)
      CHARACTER CARD(100)
C
      PRINT 10
      TT=0.0
      I=J=II=0
      X=5
      WHILE (II .LT. QQ) DO
         IF (I/X .EQ. J ) THEN DO
            II=II+1
            J=J+1
            TT=TT+TIME(J)
            Y=TINLET(J)+41.5
            IF (Y .LE. 0) Y=1
            DO 20 CC=1,85
               CARD(CC)=' '
20          CONTINUE
            CARD(41)='-'
            CARD(Y)='*'
            PRINT 70,TT,(CARD(CC),CC=1,82),TINLET(J),RH(J),TDPA(J)
         ELSE DO
            CARD(41)='|'
            CARD(Y)='*'
            PRINT 80,(CARD(CC),CC=1,82)
         END IF
         I=I+1
      END WHILE
      CARD(41)='|'
      DO 30 I=1,4
         PRINT 80,(CARD(CC),CC=1,82)
30    CONTINUE
      CARD(Y)=' '
      CARD(41)='-'
```

```
      TT=TT+TIME(J+1)
      PRINT 75,TT,(CARD(CC),CC=1,82)
      PRINT 90
10    FORMAT ('0'//T26,'INPUT AIR TEMPERATURE AND DEW POINT ',
     *        'TEMPERATURE VS. TIME '/T26,
     *                 '=========================================',
     *        '================'//T45,'TEMPERATURE  C'//
     *        T2,'TIME HR.',
     *        T12,'-40',T22,'-30',T32,'-20',T42,'-10',T52,'0',T62,'10',
     * T72,'20',T82,'30',T92,'40',T98,'INLET TEMP.C',T111,'R.H.%',T120,
     *        'D.P.TEMP. C'//T12,'|---------|---------|---------|',
     *         '---------|---------|---------|---------|---------|-->')
70    FORMAT (T2,F8.2,T12,82A1,T100,F7.2,T111,F5.1,T121,F7.2)
75    FORMAT (T2,F8.2,T12,82A1)
80    FORMAT (T12,82A1)
90    FORMAT (T52,'|'/T52,'|'/T52,'V'//)
      RETURN
      END
C
C =====================================================================
C * SUBROUTINE "BEGIN" IS TO INITIALIZE INLET AIR TEMP FOR MAIN LOOP  *
C =====================================================================
      SUBROUTINE BEGIN(TINLET,TIME,JJ,TIN,TDP,TDPA,R1,VEL,MASS,MCOA,RH,
     *                 HC,TSOIL)
      INTEGER JJ
      REAL TINLET(100),TIME(100),TDPA(100),TIN,TDP,R1,VEL,MASS,RE,
     *     MCOA(100,2),RH(100),PREOS,TEM,PS,PATM,HC,TSOIL
C
      PRINT 10, TINLET(JJ),TIME(JJ+1)
      TIN=TINLET(JJ)
      PRINT 15, TSOIL
      TDP=TDPA(JJ)
      PRINT 20, TDP
      TEM=TINLET(JJ)
      PS=RH(JJ)/100*PREOS(TEM)/1000
      PATM=101.32505
      MCOA(JJ,1)=0.6219*PS/(PATM-PS)
      PRINT 25,MCOA(JJ,1),RH(JJ),TEM
      MASS=(352.9/(273+TIN))*VEL*3.14159*R1**2
      PRINT 30, MASS
      CALL REYNS(VEL,R1,TIN,RE)
      PRINT 40, RE
      CALL HTCOEF(HC,TIN,VEL,R1)
10    FORMAT ('0'//T2,'THIS IS THE OUTPUT OF INLET AIR TEMPERATURE',1X,
     *        F9.4,' C AND TIME INTERVAL ',F8.2,' HOURS'/
     *             T2,'=========================================',1X,
     *              '============================================'//)
15    FORMAT('0'//T2,'UNDISTURBED SOIL TEMPERATURE IS ESTIMATED TO BE ',
     *       F8.4,' C.'/)
20    FORMAT ('0'//T2,'THE DEW-POINT TEMPERATURE IS ',F8.4,' C'//)
25    FORMAT ('0'//T2,'THE INLET HUMIDITY RATIO OF AIR MIXTURE IS ',
     *        F10.6,', BASED ON THE RELATIVE HUMIDITY ',F8.4,'% AND ',
     *        'TEMPERATURE ',F8.4,' C.'/)
30    FORMAT ('0'/T2,'THE MASS RATE OF AIR FLOW AT ENTRANCE IS ',F10.5,
     *        2X,'KG/S'/)
```

```
40    FORMAT ('0'//T2,'REYNOLDS NUMBER AT ENTRANCE OF THE PIPE IS ',
     *         F10.1//)
      RETURN
      END
C
C ======================================================================
C * FUNCTION "PREOS" IS TO CALCULATE SAT. VAPOR PRESS. (ASAED271.2)    *
C ======================================================================
      REAL FUNCTION PREOS(TEM)
      REAL TEM
      REAL*8 PS,R,A,B,C,D,E,F,G,T
C
      PS(R,A,B,C,D,E,F,G,T)=R*DEXP((A+B*T+C*T*T+D*T*T*T+E*T**4.0D0)
     */(F*T-G*T*T))
      R=22105649.25D00
      A=-27405.526D00
      B=97.5413D00
      C=-0.146244D00
      D=0.12558D-03
      E=-0.48502D-07
      F=4.34903D00
      G=0.39381D-02
      T=TEM+273.16
      PREOS=PS(R,A,B,C,D,E,F,G,T)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "REYNS" IS TO CALCULATE REYNOLDS UNMBER                 *
C ======================================================================
      SUBROUTINE REYNS(VEL,R1,TF,RE)
      REAL VEL,R1,TF,RE,CP,ADEN,KAIR,AVIS
C =================
C * ADEN  --- AIR DENSITY,KG/CU-M
C * KAIR  --- THERMAL CONDUCTIVITY OF AIR,W/M-C
C * AVIS  --- AIR VISCOSITY (*1000000),N-S/M-M
C =================
      CP=1004.64
      ADEN=(352.9/(273+TF))
      KAIR=0.0000638*TF+0.02422
      AVIS=0.0460714*TF+17.3369
      RE=(VEL*2*R1*ADEN/AVIS)*1000000
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "FIRST" IS TO CALCULATE 'HC' AND FIRST 'TBULK'          *
C ======================================================================
      SUBROUTINE FIRST(TOUT,TDP,Z,PP,I,PHC,PTF,XP,TR,KP,CR,KS,KFS,TSOIL,
     *                 RD,MCOS,PC1,PC2,PCP,STIME,NN,VEL,R1,L,TF,PTOUT,
     *                 PTR,YES,HC,POS,FTOUT,G,N,PMC)
      INTEGER Z,PP,I,NN,YES,SS,POS,COUNT,N,A,B,C
      REAL TOUT(65),TDP,PHC(10,65),PTF(10,65),XP(150),TR(65,150),CP,
     *     KP,CR,KS,KFS,TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,VEL,R1,L,TF,MT,
     *     PTOUT(10,65),PTR(10,65,151),MASS,TCOEF,PI/3.14159/,HC,CJ,RV,
```

```
     *     HC1,TBULK,FTOUT(65),G,PMC(65,151)
      REAL*8 INT,OUT,FACET,LT,DEN
C
      POS=-1
C INITIALIZE PMC
      C=NN+2
      DO 1 A=1,N
         DO 2 B=3,C
            PMC(A,B)=MCOS
2        CONTINUE
         PMC(A,1)=PMC(A,2)=PMC(A,3)=-1
1     CONTINUE
C
      HC1=HC
      COUNT=0
      TBULK=TOUT(I)
      CP=1004.64
      TF=(TOUT(I)+TR(1,1))*0.5
      IF (TF .LE. TDP .AND. TOUT(1) .GT. TSOIL) THEN DO
C
         POS=I
         Z=Z+1
         INT=TOUT(I)
         FACET=TR(1,1)
         OUT=INT*0.95
5     CONTINUE
         DEN=DABS(OUT-FACET)
         IF (DEN .LT. 1.0D-07) DEN=1.0D-07
         LT=DLOG(DABS(INT-FACET)/DEN)
         IF (LT .LE. 1.0D-01) LT=0.2D00
         MT=LT
         HC=(352.9/(273+TOUT(I)))*VEL*2*R1*CP/(4*L/2.0)*MT
         IF (HC .LT.HC1) HC=HC1*1.10
         IF (HC .GT. HC1*50) HC=HC1*25.0
C
         PHC(PP,Z)=HC
         PTF(PP,Z)=TF
         YES=1
         IF (0 .LT. 2) GO TO 8
C
      ELSE DO
C
         CALL HTCOEF(HC,TF,VEL,R1)
         Z=Z+1
         PHC(PP,Z)=HC
         PTF(PP,Z)=TF
C
      END IF
C
8     CONTINUE
      CALL FEM(XP,HC,I,TBULK,TR,KP,CR,KS,KFS,TSOIL,RD,MCOS,
     *          PC1,PC2,PCP,STIME,NN,G,FTOUT,PMC)
C
      RV=L/(2.0*STIME/1000.0*VEL)
      MASS=(352.9/(273+TF))*VEL*PI*R1**2
```

```
      TCOEF=2*PI*HC*R1*L/2.0
      CJ=TCOEF/(2*MASS*1004.64)
      TOUT(I+1)=((1-CJ-RV/2.0/1000.0)*TOUT(I)*1000.0+RV*TOUT(I)
     *+2*CJ*TR(1,1)*1000.0)/((1+CJ)*1000.0+RV/2.0)
      TBULK=(TOUT(I)+TOUT(I+1))*0.5
      TF=(TBULK+TR(1,1))*0.5
C
      IF (YES .EQ. 1) THEN DO
         IF (DABS(TOUT(I+1)-OUT) .GT. 0.2 .OR. DABS(FACET-TR(1,1))
     *.GT. 0.3) THEN DO
            OUT=TOUT(I+1)
            FACET=TR(1,1)
            COUNT=COUNT+1
            IF (COUNT .LE. 5) GO TO 5
         END IF
      END IF
C
      TF=(TOUT(I+1)+TR(1,1))*0.5
      PTOUT(PP,I)=TOUT(I)
      PTOUT(PP,I+1)=TOUT(I+1)
      PTR(PP,I,1)=TOUT(I)
      PTR(PP,I+1,1)=TOUT(I+1)
C
      DO 10 SS=1,NN
         PTR(PP,I,SS+1)=TR(I,SS)
10    CONTINUE
C
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "CONDES" IS TO CALCULATE LOCAL HC DUE TO CONDENSATION   *
C ======================================================================
      SUBROUTINE CONDES(HC,TF,TOUT,I,TR,R1,VEL,L,YES,XP,KP,CR,KS,KFS,
     *                  TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,NN,FTOUT,G,PMC)
      INTEGER I,NN,YES,COUNT
      REAL HC,TF,TOUT(65),TR(65,150),R1,VEL,L,XP(150),KP,KS,KFS,TSOIL,
     *     RD,MCOS,PC1,PC2,PCP,STIME,PV,CP,TBULK,RV,LMEANT,
     *     PI/3.14159/,MASS,CJ,TCOEF,FTOUT(65),G,PMC(65,151)
      REAL*8 INT,OUT,FACET,LT,DEN
C
      COUNT=0
      INT=TOUT(I-1)
      OUT=2D00*TOUT(I)-TOUT(I-1)
      FACET=TR(I-1,1)
      PV=352.9/(273+TOUT(I))
      CP=1004.64
C
10    CONTINUE
C
      TBULK=TOUT(I)
      DEN=DABS(OUT-FACET)
      IF (DEN .LT. 1D-07) DEN=1D-07
      LT=DLOG(DABS(INT-FACET)/DEN)
      IF (LT .LT. 1.0D-01) LT=0.4D00
```

```
      LMEANT=LT
      HC=PV*VEL*2*R1*CP/(4*L)*LMEANT
C
         CALL FEM(XP,HC,I,TBULK,TR,KP,CR,KS,KFS,TSOIL,RD,MCOS,
     *          PC1,PC2,PCP,STIME,NN,G,FTOUT,PMC)
      RV=L/(STIME/1000.0*VEL)
      MASS=(352.9/(273+TOUT(I)))*VEL*PI*R1**2
      TCOEF=2*PI*HC*R1*L
      CJ=TCOEF/(2*MASS*CP)
      TOUT(I+1)=(((1-CJ)*1000-RV/2)*TOUT(I-1)+RV*TOUT(I)+2*CJ*TR(I,1)
     **1000.0)/((1+CJ)*1000.0+RV/2.0)
      TOUT(I)=(TOUT(I-1)+TOUT(I+1))*0.5
C
      IF (DABS(TOUT(I+1)-OUT) .GT. 0.2 .OR. DABS(FACET-TR(I,1)) .GT.0.3)
     *THEN DO
         OUT=TOUT(I+1)
         FACET=TR(I,1)
         COUNT=COUNT+1
         IF (COUNT .LE. 3) GO TO 10
      END IF
      TF=(TOUT(I)+TR(I,1))*0.5
C
      RETURN
      END
C
C ===================================================================
C * SUBROUTINE "HTCOEF" IS TO CALCULATE HC WITH NON-CONDENSATION     *
C ===================================================================
      SUBROUTINE HTCOEF(HC,TFILM,VEL,R1)
      REAL HC,TFILM,VEL,R1,RE,CP,ADEN,KAIR,AVIS,ST
C
      CP=1004.64
      ADEN=(352.9/(273+TFILM))
      KAIR=0.0000638*TFILM+0.02422
      AVIS=0.0460714*TFILM+17.3369
      RE=(VEL*2*R1*ADEN/AVIS)*1000000
      ST=0.023*(RE**(-0.2))*(0.72**((-2)/3.0))
      HC=ST*CP*ADEN*VEL
      RETURN
      END
C
C ===================================================================
C * SUBROUTINE "FEM" USES THE FINITE ELEMENT METHOD TO DETERMINE SOIL *
C * TEMPERATURE PROFILES AT EACH LOCATION; LATENT HEAT, CHANGING KS,  *
C * AND SOIL MOISTURE MOVEMENT ARE TAKEN INTO ACCOUNT                 *
C ===================================================================
      SUBROUTINE FEM(XP,HC,I,TBULK,TR,KP,CR,KS,KFS,TSOIL,RD,MCOS,
     *               PC1,PC2,PCP,STIME,NN,G,FTOUT,PMC)
      INTEGER I, J, NN, NE, JJ, QK/0/
      REAL XP(150), HC, TBULK, TR(65,150), KP, CR, KS, KFS, TSOIL,
     *     RD, MCOS, PC1, PC2, PCP, STIME,  D, CRK, XP21, PMC(65,151),
     *     PROTPC, PROTK, DD, MTGRA, LOCKS, LOCKFS, LOCMC, G, FTOUT(65)
      REAL*8 STIME1,KM(150,4),FM(150,2),CM(150,4),T(150),AM(150,3),
     *       BM(150)
C ================== LOCAL VARIABLE DICTIONARY ======================
```

```
C * I        --- (I) SUBSCRIPT FOR THE PIPE LOCATION                          *
C * KM       --- (R,2-D) CONDUCTION OR K MATRIX,W/C                           *
C * FM       --- (R,2-D) FORCE MATRIX OR VECTOR ({F}1+{F}0) :,W               *
C * CM       --- (R,2-D) CAPACITANCE MATRIX,J/C                               *
C * CRK      --- (R) EQUIVALENT THERMAL CONDUCTIVITY DUE TO CONTACT           *
C *              RESISTANCE BETWEEN THE PIPE AND THE SOIL,W/M-C               *
C * PROTPC --- (R) VOLUMETRIC SPECIFIC HEAT IN EACH ELEMENT,                  *
C *              J/(CU-M)/C                                                   *
C * PROTK    --- (R) THERMAL CONDUCTIVITY OF EACH ELEMENT,W/M-C               *
C * T        --- (R,1-D) TEMPERATURE AT EACH NODE,C                           *
C * MTGRA    --- MEAN TEMP. GRADIENT, C/M                                     *
C * LOCKS    --- LOCAL KS, W/(C M)                                            *
C * LOCKFS --- LOCAL KFS, W/(C M)                                             *
C * LOCMC    --- LOCAL MCOS, DEC.                                             *
C * QK       --- (I) A VARIABLE TO CONTROL OUTSIDE BOUNDARY                   *
C *              CONDITION.IF QK=0,PUT T(NN)=TSOIL;IF QK IS NOT 0,            *
C *              THE BOUNDARY IS INSALUTED.                                   *
C ============================================================================
      STIME1=STIME
C =================
C * COPY INITIAL TEMPERATURE FROM TR-MATRIX TO T-MATRIX
C =================
      DO 5 J=1,NN
         T(J)=TR(I,J)
5     CONTINUE
      NE=NN-1
      CALL MDTDR(MTGRA,T,XP,NE)
C =================
C * CALCULATE K-MATRIX FOR THE FIRST TWO ELEMENTS
C =================
      XP21=XP(2)-XP(1)
      IF (XP21 .LT. 10.0E-6) XP21=10.0E-6
      D=(XP(2)+XP(1))/XP21
      KM(1,1)=KP*D
      KM(1,2)=(-1.0D0)*KM(1,1)
      KM(1,3)=KM(1,2)
      KM(1,4)=KM(1,1)
      KM(1,1)=KP*D+2.0D0*HC*XP(1)
C
      IF (CR .LT. 10.0E-7) CR=10.0E-7
      CRK=ALOG(XP(3)/XP(2))*XP(2)/CR
C
      D=(XP(3)+XP(2))/(XP(3)-XP(2))
      KM(2,1)=CRK*D
      KM(2,2)=(-1.0D0)*KM(2,1)
      KM(2,3)=KM(2,2)
      KM(2,4)=KM(2,1)
C =================
C * CALCULTAE FORCE MATRIX
C =================
      DO 10 J=1,NE
         FM(J,1)=0.0D0
         FM(J,2)=0.0D0
10    CONTINUE
      FM(1,1)=2.0D0*HC*(TBULK+FTOUT(I))*XP(1)
```

```
C =================
C * CALCULATE C-MATRIX FOR THE FIRST TWO ELEMENTS
C =================
      D=XP(2)-XP(1)
      IF (D .LT. 10.0E-6) D=10.0E-6
      CM(1,1)=PCP*(D**2.0D0)/6.0D0*(1.0D0+4.0D0*XP(1)/D)
      CM(1,2)=PCP*(D**2.0D0)/6.0D0*(1.0D0+2.0D0*XP(1)/D)
      CM(1,3)=CM(1,2)
      CM(1,4)=PCP*(D**2.0D0)/6.0D0*(3.0D0+4.0D0*XP(1)/D)
      IF ( T(2) .LE. 0.0D0) PROTPC=PC2
      IF ( T(2) .GT. 0.0D0) PROTPC=PC1
      D=XP(3)-XP(2)
      CM(2,1)=PROTPC*(D**2.0D0)/6.0D0*(1.0D0+4.0D0*XP(2)/D)
      CM(2,2)=PROTPC*(D**2.0D0)/6.0D0*(1.0D0+2.0D0*XP(2)/D)
      CM(2,3)=CM(2,2)
      CM(2,4)=PROTPC*(D**2.0D0)/6.0D0*(3.0D0+4.0D0*XP(2)/D)
C =================
C * CALCULATE EACH MATRIX FORM ELEMENT THREE
C =================
      DO 20 J=3,NE
         IF (0 .LT. 1) THEN DO
            CALL LOCAL(MTGRA,LOCKS,KS,LOCKFS,KFS,LOCMC,MCOS,XP,J,
     *                 NE,RD,G)
            PMC(I,J+1)=LOCMC
         ELSE DO
            LOCKS=KS
            LOCKFS=KFS
            LOCMC=MCOS
         END IF
C
         CALL SEARPT(T,J,PROTPC,PROTK,LOCKS,PC1,PC2,LOCKFS,RD,LOCMC)
C
      D=(XP(J+1)+XP(J))/(XP(J+1)-XP(J))
      KM(J,1)=PROTK*D
      KM(J,2)=(-1.0D0)*KM(J,1)
      KM(J,3)=KM(J,2)
      KM(J,4)=KM(J,1)
C
      D=XP(J)/(XP(J+1)-XP(J))
      DD=PROTPC*((XP(J+1)-XP(J))**2)/6.0D0
      CM(J,1)=DD*(1.0D0+4.0D0*D)
      CM(J,2)=DD*(1.0D0+2.0D0*D)
      CM(J,3)=CM(J,2)
      CM(J,4)=DD*(3.0D0+4.0D0*D)
C
20    CONTINUE
C
      CALL GLOBAL(NN,KM,FM,CM,STIME1,T,AM,BM)
C =================
C * REPLACE NODAL VALUES
C =================
      IF (QK .EQ. 0) THEN DO
         BM(NN)=TSOIL*AM(NN,3)
         AM(NN,2)=0.0D0
         BM(NN-1)=BM(NN-1)-AM(NN-1,3)*TSOIL
```

```
         AM(NN-1,3)=0.0D0
      END IF
      CALL SOLUT(AM,BM,NN,T)
C =================
C * COPY CURRENT TEMPERATURES FROM T-MATRIX TO TR-MATRIX
C =================
      DO 100 J=1,NN
         TR(I,J)=T(J)
100   CONTINUE
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "MDTDR" IS TO CALCULATE MEAN TEMP GRADIENT            *
C ====================================================================
      SUBROUTINE MDTDR(MTGRA,T,XP,NE)
      REAL*8 T(150)
      REAL   XP(150), SDTDR, MTGRA
      INTEGER J, NE
C
      SDTDR=0.0
      DO 10 J=2,NE
         SDTDR=SDTDR+(T(J+1)-T(J))/(XP(J+1)-XP(J))
10    CONTINUE
      MTGRA=SDTDR/(NE-1)
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "LOCAL" IS TO DETERMINE EFFECTS OF SOIL MOISTURE      *
C * MIGRATION ON KS OR KFS AND TO GIVE LOCAL VALUES                  *
C ====================================================================
      SUBROUTINE LOCAL(MTGRA,LOCKS,KS,LOCKFS,KFS,LOCMC,MCOS,XP,J,
     *                 NE,RD,G)
      REAL MTGRA,LOCKS,KS,LOCKFS,KFS,LOCMC,MCOS,XP(150),RD,G,R,A,B,
     *     HALFR
      INTEGER J,NE
C
      IF (ABS(MTGRA) .GE. 8.0) THEN DO
         R=(XP(J)+XP(J+1))/2.0
         HALFR=XP(NE+1)
         A=1.1*MTGRA-8.7
         B=R-HALFR
         LOCMC=(MCOS*100.0-A*B*B*B)/100.0
         CALL KSKFS(LOCKS,LOCKFS,LOCMC,RD,G)
      ELSE DO
         LOCKS=KS
         LOCKFS=KFS
         LOCMC=MCOS
      END IF
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "KSKFS" IS TO CALCULATE LOCAL VALUES OF KS AND KFS    *
```

```
C * KERSTEN'S EQUATIONS ARE USED                                          *
C ========================================================================
      SUBROUTINE KSKFS(LOCKS,LOCKFS,LOCMC,RD,G)
      REAL LOCKS,LOCKFS,LOCMC,RD,G,MCSAT
C
      MCSAT=1000.0/RD-1.0/G
      IF (LOCMC/MCSAT .GE. 1.0) LOCMC=MCSAT
      IF (G .GE. 2.679) THEN DO
         IF (LOCMC .LE. 0.07) LOCMC=0.072
            LOCKS=0.14425*(0.9*ALOG10(LOCMC*100)-0.2)*10**(0.0006243*RD)
            LOCKFS=0.14425*(0.01*10**(0.0013197*RD)
     *+0.025*10**(0.000874*RD)*LOCMC*100.0)
      ELSE DO
         IF (LOCMC .LE. 0.01) LOCMC=0.012
            LOCKS=0.14425*(0.7*ALOG10(LOCMC*100)+0.4)*10**(0.0006243*RD)
            LOCKFS=0.14425*(0.011*10**(0.001336*RD)
     *         +0.026*10**(0.0009114*RD)*LOCMC*100)
      END IF
      RETURN
      END
C
C ========================================================================
C * SUBROUTINE "SEARPT" IS TO SEARCH MATERIAL PROPERTIES FOR EACH          *
C * ELEMENT AND DETERMINE LATENT HEAT IN A PHASE CHANGE ELEMENT           *
C ========================================================================
      SUBROUTINE SEARPT(T,J,PROTPC,PROTK,LOCKS,PC1,PC2,LOCKFS,RD,LOCMC)
      INTEGER J
      REAL PROTPC, PROTK, LOCKS, PC1, PC2, LOCKFS, RD, LOCMC, HTF,
     *     HTUF, T0, T1
      REAL*8 T(150)
C =================== LOCAL VARIABLE DICTIONARY =======================
C * HTF   --- ENTHALPY OF THE ELEMENT IN FROZEN SOIL,J/CU-M/C             *
C * HTUF  --- ENTHALPY OF THE ELEMENT IN UNFROZEN SOIL,J/CU-M/C           *
C * J     --- THE FIRST NODAL SUBSRIPT IN AN ELEMENT                      *
C * T0    --- TEMPERATURE LESS THAN 0.0  C                                *
C * T1    --- TEMPERATURE GREATER THAN 0.0  C                             *
C ========================================================================
      IF (T(J) .GT. 0.0D0 .AND. T(J+1) .GE. 0.0D0) THEN DO
         PROTK=LOCKS
         PROTPC=PC1
      ELSE DO
         IF (T(J) .LT. 0.0D0 .AND. T(J+1) .LE. 0.0D0) THEN DO
            PROTK=LOCKFS
            PROTPC=PC2
         ELSE DO
            IF (T(J) .LE. 0.0D0) THEN DO
               T0=T(J)
               T1=T(J+1)
               PROTK=LOCKS
            ELSE DO
               T0=T(J+1)
               T1=T(J)
               PROTK=LOCKFS
            END IF
            HTF=RD*T0*(837.2+2093.0*LOCMC)-333498.62*RD*LOCMC
```

```
          HTUF=RD*T1*(837.2+4186.0*LOCMC)
          PROTPC=(ABS(HTF)+ABS(HTUF))/(ABS(T0)+ABS(T1))
        END IF
      END IF
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "GLOBAL" IS TO CONSTRUCT GLOBAL MATRICE                 *
C ======================================================================
      SUBROUTINE GLOBAL(NN,KM,FM,CM,STIME1,T,AM,BM)
      INTEGER NN, I, J, NE
      REAL*8 KM(150,4), FM(150,2), CM(150,4), STIME1,T(150), AM(150,3),
     *     BM(150), A(150,4), B(150,2), CK(150,4)
C ==================== LOCAL VARIABLE DICTIONARY =====================
C * A     --- (R,2-D) A-MATRIX=( [K]+2[C]/STIME ), W/C                 *
C * CK    --- (R,2-D) MATRIX OF ( 2[C]/STIME-[K] ), W/C                *
C * AM    --- (R,2-D) GLOBAL MATRIX OF [A] ,W/C                        *
C * B     --- (R,2-D) B-MATRIX=( [F]+[CK][T0] ),W                      *
C * BM    --- (R,1-D) GLOBAL MATRIX OF [B], W                          *
C ======================================================================
C
      NE=NN-1
      DO 10 I=1,NE
        DO 20 J=1,4
          A(I,J)=KM(I,J)+2.0D0*CM(I,J)/STIME1
          CK(I,J)=2.0D0*CM(I,J)/STIME1-KM(I,J)
20      CONTINUE
        B(I,1)=FM(I,1)+CK(I,1)*T(I)+CK(I,2)*T(I+1)
        B(I,2)=FM(I,2)+CK(I,3)*T(I)+CK(I,4)*T(I+1)
10    CONTINUE
C
      AM(1,1)=A(1,1)
      AM(1,2)=A(1,2)
      AM(1,3)=0.0D0
C
      DO 30 I=2,NE
        AM(I,1)=A(I-1,3)
        AM(I,2)=A(I-1,4)+A(I,1)
        AM(I,3)=A(I,2)
30    CONTINUE
C
      AM(NN,1)=0.0D0
      AM(NN,2)=A(NE,3)
      AM(NN,3)=A(NE,4)
C
      BM(1)=B(1,1)
      BM(NN)=B(NE,2)
      DO 40 I=2,NE
        BM(I)=B(I-1,2)+B(I,1)
40    CONTINUE
      RETURN
      END
C
C ======================================================================
```

```
C * SUBROUTINE "SOLUT" IS TO CALCULATE SOLUTIONS OF EACH NODE BY       *
C * GAUSSIAN ELIMINATION METHOD AND BY USING BACKWARD SUBSTITUTION     *
C * TECHNIQUES                                                          *
C ======================================================================
      SUBROUTINE SOLUT(AM,BM,NN,T)
      INTEGER NN,I,J,NE
      REAL*8 AM(150,3), BM(150), T(150)
C
      NE=NN-1
      AM(2,2)=AM(2,2)-AM(1,2)/AM(1,1)*AM(2,1)
      BM(2)=BM(2)-BM(1)/AM(1,1)*AM(2,1)
      AM(2,1)=0.0D0
C
      DO 10 I=3,NE
         AM(I,2)=AM(I,2)-AM(I-1,3)/AM(I-1,2)*AM(I,1)
         BM(I)=BM(I)-BM(I-1)/AM(I-1,2)*AM(I,1)
         AM(I,1)=0.0D0
10    CONTINUE
C
      AM(NN,3)=AM(NN,3)-AM(NN-1,3)/AM(NN-1,2)*AM(NN,2)
      BM(NN)=BM(NN)-BM(NN-1)/AM(NN-1,2)*AM(NN,2)
      AM(NN,2)=0.0D0
C =================
C * CALCULATE RESULTE BY USING BACHWARD TECHNIQUE
C =================
      T(NN)=BM(NN)/AM(NN,3)
      I=NN-1
      WHILE (I .GE. 2) DO
         T(I)=(BM(I)-AM(I,3)*T(I+1))/AM(I,2)
         I=I-1
      END WHILE
      T(1)=(BM(1)-AM(1,2)*T(2))/AM(1,1)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "SEEKHC" IS TO EVALUATE HEAT TRANSFER COEFFICIENT       *
C * OR TO DECIDE IF THE PREVIOUS HC IS USED                             *
C ======================================================================
      SUBROUTINE SEEKHC(TF,TDP,TOUT,YES,PTF,PHC,Z,HC,PP,I,TR,R1,VEL,
     *   L,XP,KP,CR,KS,KFS,TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,NN,POS,FTOUT,
     *   G,PMC)
      INTEGER YES,Z,PP,I,NN,POS
      REAL TF,TDP,TOUT(65),PTF(10,65),PHC(10,65),HC,TR(65,150),R1,VEL
      REAL L,XP(150),KP,CR,KS,KFS,TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,G,
     *     FTOUT(65),PMC(65,151)
C
      IF (TF .LE. TDP .AND. TOUT(1) .GT. TSOIL) THEN DO
         IF (YES .EQ. 0 .OR. ABS(PTF(PP,Z)-TF) .GT. 3.0) THEN DO
            IF (YES .EQ. 0) POS=I
            CALL CONDES(HC,TF,TOUT,I,TR,R1,VEL,L,YES,XP,KP,CR,KS,KFS,
     *                  TSOIL,RD,MCOS,PC1,PC2,PCP,STIME,NN,FTOUT,G,PMC)
            Z=Z+1
            YES=1
            IF (HC .LT. PHC(PP,Z-1)) HC=PHC(PP,Z-1)*1.05
```

```
            IF (HC .GT. PHC(PP,Z-1)*50.0) HC=PHC(PP,Z-1)*25.0
            PHC(PP,Z)=HC
            PTF(PP,Z)=TF
         END IF
      ELSE DO
         IF (ABS(PTF(PP,Z)-TF) .GT. 2.0) THEN DO
            CALL HTCOEF(HC,TF,VEL,R1)
            Z=Z+1
            PHC(PP,Z)=HC
            PTF(PP,Z)=TF
         END IF
      END IF
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "NEXT" IS TO CALCULATE NEXT AIR TEMPERATURE BY USING   *
C * ENERGY BALANCE METHOD AND TO STORE CURRENT SOIL TEMP FROFILES     *
C ======================================================================
      SUBROUTINE NEXT(TOUT,R1,HC,L,CP,I,VEL,TR,PTOUT,PTR,NN,PP,STIME)
      INTEGER I,NN,PP,SS
      REAL TOUT(65),R1,HC,L,CP,VEL,TR(65,150),PTOUT(10,65),MASS,CJ,
     *     PTR(10,65,151),PI/3.14159/,TCOEF,RV,STIME
C
      IF (TOUT(1) .GT. TR(1,NN)) THEN DO
         IF (TR(I,1) .GE. TR(I-1,1)) TR(I,1)=TR(I-1,1)*0.99
      END IF
C
      RV=L/(STIME/1000.0*VEL)
      MASS=(352.9/(273+TOUT(I)))*VEL*PI*R1**2
      TCOEF=2*PI*HC*R1*L
      CJ=TCOEF/(2*MASS*CP)
      TOUT(I+1)=(((1-CJ)*1000-RV/2)*TOUT(I-1)+RV*TOUT(I)+2*CJ*TR(I,1)
     **1000.0)/((1+CJ)*1000.0+RV/2.0)
      TOUT(I)=(TOUT(I+1)+TOUT(I-1))*0.5
      PTOUT(PP,I)=TOUT(I)
      PTR(PP,I,1)=TOUT(I)
      DO 10 SS=1,NN
         PTR(PP,I,SS+1)=TR(I,SS)
10    CONTINUE
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PRINTS" IS TO PRINT OUT ALL REQUESTED RESULTS         *
C ======================================================================
      SUBROUTINE PRINTS(PHC,PTF,PZ,PTOUT,PTR,TT,YESPTR,CONTRL,JJ,
     *                  STIME,N,NN,L,TOTIME,QQ,POS,PMC,YESPMC)
      INTEGER PZ(10),TT,YESPTR(100),JJ,N,NN,QQ,POS, I,J,YESPMC(100)
      REAL PHC(10,65),PTF(10,65),PTOUT(10,65),PTR(10,65,151),STIME,L,
     *     TOTIME,TPASS,PMC(65,151)
      CHARACTER CONTRL*80(10)
C
      IF (CONTRL(1) .EQ. 'PRINT HC')
     *   CALL PTHC(PHC,PTF,PZ,TT,STIME,TOTIME,POS,PTOUT)
```

```
      IF (CONTRL(2) .EQ. 'PLOT AIR TEMPERATURES')
     *   CALL PTAIR(PTOUT,TT,N,STIME,L,TOTIME)
         IF ('WRITE TA' .EQ. 'WRITE TA') THEN DO
            TPASS=TOTIME+STIME*TT/3600.0
            WRITE(11,100) TPASS, N, L
            WRITE(11,200) ((PTOUT(I,J),J=1,N),I=1,TT)
100         FORMAT('0',T10,'AIR TEMPERATURE ALONG THE PIPE'/T10,
     *             F10.2,'HOURS LATER FROM THE BEGINNING'/T10,'N=',I3,
     *             5X,'CONTROL LENGTH =',F8.2/)
200         FORMAT((T2,10(F8.4,2X)/))
         END IF
      IF (YESPTR(JJ) .NE. 0)
     *   CALL PTPTR(PTR,TT,N,NN,STIME,L,TOTIME,JJ,QQ)
      IF (YESPMC(JJ) .NE. 0)
     *   CALL PPMC(PMC,N,NN,STIME,L,TOTIME,JJ,QQ)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "HUMTY" IS TO CALCULATE HUMIDITY RATIO & R. H.          *
C ======================================================================
      SUBROUTINE HUMTY(POS,JJ,N,TT,RH,OUTRH,MCOA,PTOUT,WRATE,MASS)
      INTEGER POS,JJ,N,TT
      REAL RH(100),OUTRH(100),MCOA(100,2),PTOUT(10,65),TEM,PREOS,
     *     PS,PV,PATM,WRATE(100),MASS
C
      PATM=101.32505
      IF (POS .GT. 0) THEN DO
         TEM=PTOUT(TT,POS)
         PV=MCOA(JJ,1)*PATM/(MCOA(JJ,1)+0.6219)
         OUTRH(JJ)=PV/(PREOS(TEM)/1000)*100
         IF (OUTRH(JJ) .GT. 100.0) OUTRH(JJ)=100.0
         TEM=PTOUT(TT,N)
         PV=OUTRH(JJ)/100*PREOS(TEM)/1000
         MCOA(JJ,2)=0.6219*PV/(PATM-PV)
         WRATE(JJ)=MASS*(MCOA(JJ,1)-MCOA(JJ,2))
      ELSE DO
         MCOA(JJ,2)=MCOA(JJ,1)
         TEM=PTOUT(TT,N)
         PV=MCOA(JJ,1)*PATM/(MCOA(JJ,1)+0.6219)
         OUTRH(JJ)=PV/(PREOS(TEM)/1000)*100
         WRATE(JJ)=0.0
      END IF
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PTHC" IS TO PRITN OUT HC AND RELATED FILM TEMP.        *
C ======================================================================
      SUBROUTINE PTHC(PHC,PTF,PZ,TT,STIME,TOTIME,POS,PTOUT)
      INTEGER TT,PZ(10),J,Z,K,POS
      REAL PHC(10,65),PTF(10,65),STIME,TINVL,TOTIME,PTOUT(10,65)
C
      PRINT 10,TOTIME
C
```

```
      DO 20 J=1,TT
         Z=PZ(J)
         TINVL=J*STIME/3600
         PRINT 30,TINVL
         PRINT 40,(PHC(J,K),K=1,Z)
         PRINT 50,(PTF(J,K),K=1,Z)
20    CONTINUE
      IF (POS .GT. 0) THEN DO
         PRINT 60,POS,PTOUT(TT,POS)
      END IF
10    FORMAT('0'//T12,'HEAT TRANSFER COEFFICIENTS AND CORRESPONDING ',
     *       'FIML TEMPERATURES AT EACH TIME INTERVAL'/
     *            T12,'---------------------------------------------',
     *       '-----------------------------------------'//T36,
     *       '( HC IN W/M-M-C AND TF IN C )'//T26,'START WITH',F12.2,
     *       2X,'HOURS FROM THE BEGINNING'//)
30    FORMAT('0'//T2,'----',F9.4,' HOURS LATER ----'//)
40    FORMAT('0'/T2,'HC:',(T5,10(F10.4,2X)/)/)
50    FORMAT('0'/T2,'TF:',(T5,10(F10.4,2X)/)/)
60    FORMAT('0'//T2,'CONDENSATION BEGAN AT THE POSITION ',I3,' ALONG',
     *       ' THE PIPE AND AT BULK TEMPERATURE ',F7.4,'C'//T2,
     *       'THE HEAT TRANSFER COEFFICIENTS HAVE BEEN EVALUATED BY ',
     * 'THE PRINCIPLE OF '//T2,'SIMULTANEOUS HEAT AND MASS TRANSFER ',
     *       'BETWEEN WATER-WETTED SURFACE AND AIR'//)
      RETURN
      END
C
C ====================================================================
C * SUBROUTINE "PTAIR" IS TO PLOT THE AIR TEMPERATURE IN THE PIPE    *
C * AND/OR TO PRINT THE RESULTS                                      *
C ====================================================================
      SUBROUTINE PTAIR(PTOUT,TT,N,STIME,L,TOTIME)
      INTEGER N,TT,J,K,II,I,CC,X,Y,G/0/
      REAL PTOUT(10,65),STIME,TINVL(10),L,LEN,TOTIME
      CHARACTER CARD(130)
C
      PRINT 10, TOTIME
      IF (TT .LE. 3) THEN DO
         DO 20 J=1,TT
            TINVL(J)=STIME*J/3600.0
20       CONTINUE
         PRINT 30,(TINVL(J),J=1,TT)
         PRINT 32
      ELSE DO
         PRINT 35
      END IF
C
      I=J=II=0
      WHILE (II .LT. N) DO
         IF (I/3 .EQ. J) THEN DO
            II=II+1
            J=J+1
            DO 40 CC=1,130
               CARD(CC)=' '
40          CONTINUE
```

```
            CARD(41)='-'
            DO 60 CC=1,TT
               Y=PTOUT(CC,II)+41.5
               IF (Y .LE. 0) Y=1
               CARD(Y)='*'
60          CONTINUE
            LEN=(J-1)*L/2.0
            IF (TT .LE. 3) THEN DO
               PRINT 70,LEN,(CARD(CC),CC=1,120),(PTOUT(CC,II),CC=1,TT)
            ELSE DO
               PRINT 80,LEN,(CARD(CC),CC=1,120)
            END IF
         ELSE DO
            DO 90 CC=1,130
               CARD(CC)=' '
90          CONTINUE
            CARD(41)='|'
            PRINT 110,(CARD(CC),CC=1,120)
         END IF
         I=I+1
      END WHILE
C
      PRINT 120
      IF (TT .GT. 3 .OR. G .EQ. 1)
     *   CALL TABAIR(PTOUT,N,TT,STIME,L,TOTIME)
10    FORMAT('0'//T43,'AIR TEMPERATURES IN THE PIPE AT EACH TIME ',
     *       'INTERVAL'/T43,'-----------------------------------------',
     *       '---------'//T58,'( TEMPERATURE IN C )'//
     *       T43,'START WITH',F12.2,1X,'HOURS FROM THE BEGINNING'/
     *       T2,' PIPE')
30    FORMAT(T2,'LENGTH M.',
     *       T12,'-40',T22,'-30',T32,'-20',T42,'-10',T52,'0',T62,'10',
     *        T72,'20',T82,'30',T92,'40',T96,5(F5.2,'HR.',1X)//)
32    FORMAT(T12,'|---------|---------|---------|',
     *         '---------|---------|---------|---------|---------|->'
     *         ,T96,'---------------------------------'/)
35    FORMAT(T2,'LENGTH M.',
     *       T12,'-40',T22,'-30',T32,'-20',T42,'-10',T52,'0',T62,'10',
     *        T72,'20',T82,'30',T92,'40'/
     *          /T12,'|---------|---------|---------|',
     *         '---------|---------|---------|---------|---------|-->')
70    FORMAT(T2,F5.2,T12,120A1,T96,5(F8.4,1X))
80    FORMAT(T2,F5.2,T12,120A1)
110   FORMAT(T12,120A1)
120   FORMAT(T52,'|'/T52,'|'/T52,'V'//)
      RETURN
      END
C
C =====================================================================
C * SUBROUTINE "TABAIR" IS TO TABULATE THE AIR TEMPERATURE            *
C =====================================================================
      SUBROUTINE TABAIR(PTOUT,N,TT,STIME,L,TOTIME)
      INTEGER N,TT,CC,J
      REAL PTOUT(10,65),STIME,L,X,PT(10),TOTIME
C
```

```
      DO 10 CC=1,TT
         PT(CC)=STIME*CC/3600.0
10    CONTINUE
      PRINT 15,TOTIME,(PT(CC),CC=1,TT)
      DO 20 J=1,N
         X=(J-1)*L/2.0
         PRINT 30,X,(PTOUT(CC,J),CC=1,TT)
20    CONTINUE
15    FORMAT('0'//T5,'AIR TEMPERATURE AT EACH TIME INTERVAL'/
     *            T5,'-------------------------------------'//
     *            T6,'(AIR TEMP. IN C, PIPE LENGTH IN M.)'//
     *            T5,'START WITH',F12.2,1X,'HOURS FROM THE BEGINNING'//
     *       T2,'LENGTH',T12,10(F6.3,'HR.',3X)//)
30    FORMAT('0'/T2,F5.2,T12,10(F9.5,3X)/)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PTPTR" IS TO PRINT TEMPS OF AIR AND SOIL              *
C ======================================================================
      SUBROUTINE PTPTR(PTR,TT,N,NN,STIME,L,TOTIME,JJ,QQ)
      INTEGER TT,N,NN,I,J,K,F,CC,SS,JJ,QQ
      REAL PTR(10,65,151),STIME,L,X,LOC(15),TOTIME
C
      PRINT 10,TOTIME
      DO 20 I=1,TT
         X=STIME*I/3600.0
         PRINT 30,X
         F=1
         SS=1
         CC=0
         WHILE (CC .LT. N) DO
            IF (N-CC .GT. 14) THEN DO
               DO 40 J=1,14
                  LOC(J)=CC*L/2.0
                  CC=CC+1
40             CONTINUE
               PRINT 50,(LOC(J),J=1,14)
               PRINT 52
               K=0
               PRINT 60,K,(PTR(I,J,1),J=F,CC)
               IF (JJ .EQ. QQ) WRITE(12,60) K,(PTR(I,J,K+1),J=F,CC)
               DO 70 K=1,NN
                  PRINT 60,K,(PTR(I,J,K+1),J=F,CC)
                  IF (JJ .EQ. QQ) WRITE(12,60) K,(PTR(I,J,K+1),J=F,CC)
70             CONTINUE
               F=CC+1
               SS=F
            ELSE DO
               K=N-CC
               DO 80 J=1,K
                  LOC(J)=(SS-1)*L/2.0
                  SS=SS+1
80             CONTINUE
               CC=N+1
```

```
                PRINT 50,(LOC(J),J=1,K)
                PRINT 52
                J=0
                PRINT 60,J,(PTR(I,K,1),K=F,N)
                IF (JJ .EQ. QQ) WRITE(12,60) J,(PTR(I,K,1),K=F,N)
                DO 90 K=1,NN
                   PRINT 60,K,(PTR(I,J,K+1),J=F,N)
                   IF (JJ .EQ. QQ) WRITE(12,60) K,(PTR(I,J,K+1),J=F,N)
90              CONTINUE
             END IF
          END WHILE
20    CONTINUE
C
10    FORMAT('0'//T20,'SOIL TEMPERATURES AND AIR TEMPERATURES ',
     *        'AT EACH LOCATION AND AT EACH',
     *        ' TIME INTERVAL'/T20,'----------------------------------',
     *        '---------------------',
     *        '--------------------------'//T52,'(TEMPERATURE IN C)'/
     *        T38,'START WITH',F12.2,1X,'HOURS FROM THE BEGINNING'//)
30    FORMAT('0'/T48,'-----',F7.3,' HOURS LATER ----'//)
50    FORMAT('0'/T10,'PIPE LENGTH IN METER ---->'/T2,'NODE'/T2,'NO.',
     *        T5,14(4X,F5.2))
52    FORMAT(T2,'----',T7,'------------------------------------------',
     *        '-----------------------------------------------------',
     *        '---------------------------------'//)
60    FORMAT(T2,I3,T7,14(F8.4,1X))
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PMC" IS TO PRINT OUT SOIL MOISTURE CONTENT            *
C ======================================================================
      SUBROUTINE PPMC(PMC,N,NN,STIME,L,TOTIME,JJ,QQ)
      INTEGER N,NN,I,J,K,F,CC,SS,JJ,QQ
      REAL PMC(65,151),STIME,L,X,LOC(15),TOTIME
C
      PRINT 10,TOTIME
         X=STIME/3600.0
         PRINT 30,X
         F=1
         SS=1
         CC=0
         WHILE (CC .LT. N) DO
            IF (N-CC .GT. 14) THEN DO
               DO 40 J=1,14
                  LOC(J)=CC*L/2.0
                  CC=CC+1
40             CONTINUE
               PRINT 50,(LOC(J),J=1,14)
               PRINT 52
               K=0
               PRINT 60,K,(PMC(J,1),J=F,CC)
               DO 70 K=1,NN
                  PRINT 60,K,(PMC(J,K+1),J=F,CC)
70             CONTINUE
```

```
               F=CC+1
               SS=F
            ELSE DO
               K=N-CC
               DO 80 J=1,K
                  LOC(J)=(SS-1)*L/2.0
                  SS=SS+1
80             CONTINUE
               CC=N+1
               PRINT 50,(LOC(J),J=1,K)
               PRINT 52
               J=0
               PRINT 60,J,(PMC(K,1),K=F,N)
               DO 90 K=1,NN
                  PRINT 60,K,(PMC(J,K+1),J=F,N)
90             CONTINUE
            END IF
         END WHILE
C
10    FORMAT('0'//T20,'MOISTURE CONTENT OF SOIL ',
     *       'AT EACH LOCATION AND AT EACH',
     *       ' TIME INTERVAL'/T20,'----------------------------------',
     *       '---------------------',
     *       '--------------------------'//
     *       T38,'START WITH',F12.2,1X,'HOURS FROM THE BEGINNING'//)
30    FORMAT('0'/T48,'-----',F7.3,' HOURS LATER ----'//)
50    FORMAT('0'/T10,'PIPE LENGTH IN METER ---->'/T2,'NODE'/T2,'NO.',
     *       T5,14(4X,F5.2))
52    FORMAT(T2,'----',T7,'---------------------------------------',
     *       '-------------------------------------------------------',
     *       '---------------------------------'//)
60    FORMAT(T2,I3,T7,14(F8.4,1X))
      RETURN
      END
C
C =====================================================================
C * SUBROUTINE "INLET" IS TO GENERATE AND PLOT TEMPERATURES OF        *
C * INLET AIR AND AVERAGE TEMPERATURES OF INLET AIR WITHIN A TIME     *
C * INTERVAL BY USING A WEATHER DATA SET                              *
C =====================================================================
      SUBROUTINE INLET(QQ,TINLET,TIME,TDPA,DAYS,DATE,RH,TVL)
      INTEGER QQ,I,J,YES,DATE(4)
      REAL TINLET(100),TIME(100),TDPA(100),TAIR(100),TEM,A,B,W,T,TAV,
     *     T1,T2,TVL,RH(100),DAYS
C
      TEM(A,B,W,T)=A+B*SIN(W*T)
      TAV(A,B,W,T1,T2)=A+B/(T2-T1)/W*(COS(W*T1)-COS(W*T2))
      QQ=DAYS*24.0/TVL+0.5
      YES=1
      IF (YES .EQ. 1) THEN DO
         CALL WDATA(DATE,TVL,QQ,TAIR,TIME,TINLET,TDPA,DAYS,RH)
      ELSE DO
      A=0.0
      B=10.0
      W=3.14159/12.0
```

```
C
      T=TIME(1)=0.0
      DO 10 I=1,QQ
         TAIR(I)=TEM(A,B,W,T)
         T1=T
         T2=T1+TVL
         TINLET(I)=TAV(A,B,W,T1,T2)
         TIME(I+1)=TVL
         T=T+TVL
10    CONTINUE
C
      I=1
      WHILE (I .LE. QQ) DO
         TDPA(I)=TAIR(I)*0.8
         I=I+1
      END WHILE
      END IF
      IF (QQ .EQ. 0) QQ=1
      CALL PLOT2(QQ,TIME,TINLET,TDPA,TAIR,RH)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PLOT2" IS TO PLOT INLET AIR TEMPERATURES              *
C ======================================================================
      SUBROUTINE PLOT2(QQ,TIME,TINLET,TDPA,TAIR,RH)
      INTEGER QQ, I, J, II, X, Y, CC, Z
      REAL TIME(100), TINLET(100), TDPA(100), TT, TAIR(100), RH(100)
      CHARACTER CARD(100)
C
      PRINT 10
      TT=0.0
      I=J=II=0
      X=5
      WHILE (II .LT. QQ) DO
         IF (I/X .EQ. J ) THEN DO
            II=II+1
            J=J+1
            TT=TT+TIME(J)
            Y=TINLET(J)+41.5
            Z=TAIR(J)+41.5
            IF (Z .EQ. 0) Z=1
            IF (Y .EQ. 0) Y=1
            DO 20 CC=1,85
               CARD(CC)=' '
20          CONTINUE
            CARD(41)='-'
            CARD(Y)='*'
            CARD(Z)='#'
         PRINT 70,TT,(CARD(CC),CC=1,82),TINLET(J),TAIR(J),TDPA(J),RH(J)
         ELSE DO
            CARD(Z)=' '
            CARD(Y)='*'
            CARD(41)='|'
            PRINT 80,(CARD(CC),CC=1,82)
```

```
         END IF
         I=I+1
      END WHILE
      CARD(Z)=' '
      CARD(41)='|'
      DO 30 I=1,4
         PRINT 80,(CARD(CC),CC=1,82)
30    CONTINUE
      CARD(Y)=' '
      CARD(41)='-'
      TT=TT+TIME(J+1)
      PRINT 75,TT,(CARD(CC),CC=1,82)
      PRINT 90
10    FORMAT ('0'//T26,'INPUT DRY BULB,DEW-POINT TEMP. AND RELATIVE ',
     *        'HUMIDITY VS. TIME '/T26,
     *          '============================================',
     *        '================'//T45,'TEMPERATURE  C'//
     *        T2,'TIME HR.',
     *        T12,'-40',T22,'-30',T32,'-20',T42,'-10',T52,'0',T62,'10',
     *        T72,'20',T82,'30',T92,'40',T98,'INL.AVE.',
     *        T107,'INSTANT',T114,' D.P.TEMP.',T126,'R.H.'
     *        /T99,'TEMP. C',T108,'TEMP.C',T119,'C',T126,'%'/
     *        T12,'|---------|---------|---------|',
     *         '---------|---------|---------|---------|---------|-->',
     *         T101,'-*-',T109,'-#-')
70    FORMAT (T2,F8.2,T12,82A1,T98,F7.2,T106,F7.2,T114,F7.2,T125,F5.1)
75    FORMAT (T2,F8.2,T12,82A1)
80    FORMAT (T12,82A1)
90    FORMAT (T52,'|'/T52,'|'/T52,'V'//)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "RDTR" IS TO READ INITIAL SOIL TEMPERATURES            *
C ======================================================================
      SUBROUTINE RDTR(PTR,TR,N,NN,TINLET)
      INTEGER N,NN,I,J,K,F,CC,SS,PP,LAST
      REAL PTR(10,65,151),TR(65,150),TINLET(100)
C
      PP=NN+1
         F=1
         CC=N
         WHILE (CC .GE. 1) DO
            IF (CC .GE. 14) THEN DO
               LAST=F+13
               DO 10 SS=1,PP
                  READ(15,60) K,(PTR(1,J,SS),J=F,LAST)
10             CONTINUE
               F=LAST+1
               CC=CC-14
            ELSE DO
               DO 15 SS=1,PP
                  READ(15,60) K,(PTR(1,J,SS),J=F,N)
15             CONTINUE
               CC=-1
```

```
            END IF
         END WHILE
      DO 20 I=1,N
         PTR(1,I,1)=TINLET(1)
20    CONTINUE
      DO 30 I=1,N
         DO 40 J=1,NN
            TR(I,J)=PTR(1,I,J+1)
40       CONTINUE
30    CONTINUE
60    FORMAT (T2,I3,T7,14(F8.4,1X))
      RETURN
      END
C
C =====================================================================
C * SUBROUTINE "WDATA" IS TO READ ORIGNAL WEATHER DATA AND           *
C * GENERATE INLET AIR TEMPERATURES FOR A GIVEN TIME INTERVAL        *
C =====================================================================
      SUBROUTINE WDATA(DATE,TVL,QQ,TAIR,TIME,TINLET,TDPA,DAYS,RH)
      INTEGER QQ,NUM(100),I,J,K,LAST,PP,F,YES,DATE(4),D,AA,
     *        X(24),Y(24),Z(24)
      REAL WTD(2500),TVL,TAIR(100),HOUR,T1,T2,SUMT,TIME(100),TINLET(100)
     *,TDPA(100),SUMDP,WDP(2500),RH(100),WRH(2500),SUMRH,DAYS
C
      K=0
10    FORMAT(T9,I2)
11    FORMAT(T9,I2,T20,24(I3,1X))
      DO 20 J=1,585
         READ(10,10) F
20    CONTINUE
25    FORMAT(T20,24(I3,1X))
      D=1
      AA=DAYS+0.5
      WHILE (D .LE. DAYS) DO
         READ(10,11) F,(X(J),J=1,24)
         READ(10,25) (Y(J),J=1,24)
         READ(10,25) (Z(J),J=1,24)
         DO 40 I=1,24
            WTD(K+1)=X(I)
            WDP(K+1)=Y(I)
            WRH(K+1)=Z(I)
            K=K+1
40       CONTINUE
         NUM(D)=F
         D=D+1
      END WHILE
      PP=K/TVL+0.5
      IF (QQ .GT. PP) QQ=PP
      YES=1
      IF (YES .EQ. 1) CALL PWDATA(WTD,K,1.0,DATE,WDP,NUM,WRH)
      TIME(1)=0.0
      J=1
      DO 60 I=1,QQ
         TAIR(I)=WTD(J)
         K=0
```

```
         SUMT=SUMDP=SUMRH=0.0
         T1=T2=0.0
         WHILE ((T2-T1) .LT. TVL) DO
             SUMT=SUMT+WTD(J)
             SUMDP=SUMDP+WDP(J)
             SUMRH=SUMRH+WRH(J)
             T2=T2+1.0
             J=J+1
             K=K+1
          END WHILE
          TINLET(I)=SUMT/K
          TDPA(I)=SUMDP/K
          RH(I)=SUMRH/K
          TIME(I+1)=TVL
60    CONTINUE
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PWDATA" IS TO PRINT ORIGNAL WEATHER DATA              *
C ======================================================================
      SUBROUTINE PWDATA(WTD,K,HOUR,DATE,WDP,NUM,WRH)
      INTEGER NUM(100),I,J,Y,CC,DATE(4),K,D
      REAL HOUR,WTD(2500),TT,WDP(2500),WRH(2500)
      CHARACTER CARD(100)
C
      PRINT 10, (DATE(I),I=1,4)
      TT=0.0
      D=0
      DO 20 I=1,K
         DO 30 CC=1,85
            CARD(CC)=' '
30       CONTINUE
         CARD(41)='|'
         Y=WTD(I)+41.5
         IF (Y .LE. 0) Y=1
         CARD(Y)='*'
         IF (MOD(I-1,24) .EQ. 0) THEN DO
            TT=0.0
            D=D+1
            CARD(41)='-'
            PRINT 70,NUM(D),TT,(CARD(CC),CC=1,82),WTD(I),WRH(I),WDP(I)
         ELSE DO
            TT=TT+HOUR
            PRINT 80,TT,(CARD(CC),CC=1,82),WTD(I),WRH(I),WDP(I)
         END IF
20    CONTINUE
      PRINT 90
10    FORMAT ('0'//T26,'WEATHER DATA IN WINNIPEG STARTING WITH ',
     *         I2,':00',1X,3(I2,2X)/T26,
     *                  '========================================',
     *         '================'//T45,'TEMPERATURE  C'//
     *         T2,'DATE HR.',
     *         T12,'-40',T22,'-30',T32,'-20',T42,'-10',T52,'0',T62,'10',
     *  T72,'20',T82,'30',T92,'40',T99,'AIR TEMP.C',T112,'R.H.%',T120,
```

```
     *         ' D.P.TEMP.C'//T12,'|---------|---------|---------|',
     *         '---------|---------|---------|---------|---------|-->')
70    FORMAT(T2,I2,2X,F4.1,T12,82A1,T100,F7.2,T111,F6.1,T122,F7.2)
80    FORMAT(T2,4X,F4.1,T12,82A1,T100,F7.2,T111,F6.1,T122,F7.2)
90    FORMAT(T52,'|'/T52,'|'/T52,'V'//)
      RETURN
      END
C
C ========================================================================
C * SUBROUTINE "RESULT" IS TO CALCULATE EFFECTIVENESS AND CAPACITY      *
C ========================================================================
      SUBROUTINE RESULT(TOUT,TSOIL,N,TOTIME,TIME,QQ,VEL,DP,CP)
      INTEGER QQ,N,I,J
      REAL TOUT(65),TSOIL,TOTIME,TIME(100),VEL,DP,CP,ADEN,Q,E
      CHARACTER CARD(130)
C
      DO 10 I=1,80
         CARD(I)='T'
10    CONTINUE
      PRINT 20,(CARD(I),I=1,60)
      TOTIME=TOTIME-TIME(QQ+1)
      ADEN=352.9/(273+(TOUT(1)+TOUT(N))*0.5)
      Q=ADEN*VEL*3.14159*(DP**2)/4.0*CP*ABS(TOUT(1)-TOUT(N))
      E=ABS((TOUT(1)-TOUT(N))/(TOUT(1)-TSOIL))*100
      PRINT 30,TOTIME,TOUT(1),TOUT(N),Q,E,(CARD(I),I=1,60)
20    FORMAT('0'//T20,80A1)
30    FORMAT(T20,'I',T79,'I'/T20,'I',2X,F10.1,1X,'HOURS LATER FROM ',
     *       'THE BEGINNING',T79,'I'/
     *       T20,'I',T79,'I'/T20,'I',2X,'INLET AIR TEMPERATURE',
     *       '= ',F9.4,2X,'C',T79,'I'/T20,'I',T79,'I'/
     *       T20,'I',2X,'OUTLET AIR TEMPERATURE= ',
     *       F9.4,2X,'C',T79,'I'/T20,'I',T79,'I'/T20,'I',2X,'THE HEAT ',
     *       'EXCHANGER CAPACITY= ',F11.4,'J/S',T79,'I'/
     *       T20,'I',T79,'I'/T20,'I',2X,
     *       'THE EXCHANGER EFFECTIVENESS= ',F7.2,2X,'%',T79,'I'/T20,'I',
     *       T79,'I'/T20,80A1//)
      RETURN
      END
C
C ========================================================================
C * SUBROUTINE "WRITE1" IS TO WRITE EFFECTIVENESS AND CAPACITY          *
C * INTO A DATASET AND PRINT AND PLOT THE RESULTS                       *
C ========================================================================
      SUBROUTINE WRITE1(DATE,VEL,KS,MCOS,TSOIL,DP,PL,DAYS,QQ,TINLET,
     *                  TOLET,TIME,EF,CAPTY,MCOA,RH,OUTRH,WRATE)
      INTEGER DATE(4),QQ,I,J,YES
      REAL VEL,MCOS,TSOIL,DP,PL,TINLET(100),TOLET(100),TIME(100),
     *     EF(100),CAPTY(100),HOURS(100),DT,KS,SUMH,MCOA(100,2),RH(100),
     *     OUTRH(100),WRATE(100),DAYS
C
      PRINT 10
      PRINT 20,VEL,KS,MCOS,TSOIL,DP,PL,DAYS,(DATE(I),I=1,4)
      WRITE(13,20) VEL,KS,MCOS,TSOIL,DP,PL,DAYS,(DATE(I),I=1,4)
      PRINT 30
      SUMH=0.0
```

```
      DO 40 I=1,QQ
         SUMH=SUMH+TIME(I+1)
         HOURS(I)=SUMH
         DT=ABS(TINLET(I)-TOLET(I))
         PRINT 50,HOURS(I),TINLET(I),TOLET(I),DT,EF(I),CAPTY(I),
     *           MCOA(I,1),MCOA(I,2),RH(I),OUTRH(I),WRATE(I)*1000
         WRITE(13,50) HOURS(I),TINLET(I),TOLET(I),DT,EF(I),CAPTY(I),
     *            MCOA(I,1),MCOA(I,2),RH(I),OUTRH(I),WRATE(I)*1000
40    CONTINUE
      YES=1
      IF (YES .EQ. 1) CALL PLOTEC(QQ,EF,CAPTY,HOURS)
10    FORMAT('0'//T42,'GENERAL OUTPUTS OF THE HEAT EXCHANGER VS.  ',
     *       'TIME'/T42,'================================',
     * '================'///T10,'CONDITIONS:',T22,'   VEL. M/S',3X,
     * 'KS W/M-C',4X,'MCOS DEC.',5X,'TSOIL C',5X,'DIAM. M',5X,'P.L. M',
     * 8X,'DAYS',6X,'START DATE'/T10,'-----------'/)
20    FORMAT(T23,6(F10.4,2X),F10.2,6X,4(I2,1X)///)
30    FORMAT(T15,'HOURS       TI C       TO C   ',1X,
     * ' TI-TO C',6X,'E %',2X,'CAPACITY J/S',
     * 5X,'W1',9X,'W2',4X,'R.H.%(IN)',2X,'R.H.%(OUT)',2X,
     * 'WATER G/S'/T10,'----------',
     * '--------------------------------------------------------------',
     * '--------------------------------------------------'//)
50    FORMAT(T10,11(F10.4,1X))
      RETURN
      END
C
C =======================================================================
C * SUBROUTINE "PLOTEC" IS TO PLOT THE EFFECTIVENESS AND CAPACITY     *
C =======================================================================
      SUBROUTINE PLOTEC(QQ,EF,CAPTY,HOURS)
      INTEGER QQ,I,J,X,Y,CC,II
      REAL EF(100),CAPTY(100),HOURS(100),Z
      CHARACTER CARD(130)
C
      PRINT 10
      I=J=II=0
      WHILE (II .LT. QQ) DO
         IF (I/4 .EQ. J) THEN DO
            II=II+1
            J=J+1
            DO 20 CC=1,115
               CARD(CC)=' '
20          CONTINUE
            CARD(51)='-'
            Y=ABS(EF(II)/2-52)
            IF (Y .LE. 0) Y=1
            IF (Y .GE. 130) Y=130
            CARD(Y)='*'
            X=CAPTY(II)/100*4+51
            IF (X .GT. 100) X=100
            CARD(X)='@'
            Z=CAPTY(II)/1000.0
            PRINT 30,EF(II),(CARD(CC),CC=1,115),HOURS(II),Z
         ELSE DO
```

```
            DO 40 CC=1,115
               CARD(CC)=' '
40          CONTINUE
            CARD(51)='|'
            PRINT 50,(CARD(CC),CC=1,115)
         END IF
         I=I+1
      END WHILE
      PRINT 60
10    FORMAT('0'//T36,'THE EFFECTIVENESS AND CAPACITY OF THE HEAT ',
     * 'EXCAHGER VS. TIME'/T36,'==================================',
     * '========================='//T20,'EFFECTIVENESS %',T64,'HR.',
     * T97,'CAPACITY KJ/S'//T15,'100',T25,'80',T35,'60',T45,'40',T55,
     * '20',T65,'0',T75,'0.25',T85,'0.5',T95,'0.75',T105,'1.0',T115,
     * '1.25',T125,
     * '1.5'/T13,'<-|---------|---------|---------|---------|---------|'
     * ,'---------|---------|---------|---------|---------|----------|',
     * '--->')
30    FORMAT(T2,F6.2,T15,115A1,T59,F6.1,T121,F9.6)
50    FORMAT(T15,115A1)
60    FORMAT(T65,'|'/T65,'V'//)
      RETURN
      END
C
C ======================================================================
C * SUBROUTINE "PROTY1" IS TO CALCULATE THE VALUES OF KS, KFS, RD,     *
C * PSITY AND MCOSA. THE KS-EQUATIONS ARE FROM KERSTEN,MINNESOTA       *
C ======================================================================
      SUBROUTINE PROTY1(BUW,RD,KS,KFS,MCOS,PSITY,G,TEX,MCOSA)
      REAL BUW,RD,KS,KFS,MCOS,PSITY,G,MCOSA
      CHARACTER TEX*80
C
      RD=BUW/(1+MCOS)
      IF (TEX .EQ. 'SILTY CLAY') THEN DO
         G=2.70
      ELSE DO
         IF (TEX .EQ. 'SAND' ) THEN DO
            G=2.65
         ELSE DO
            IF (TEX .EQ. 'SILT') THEN DO
               G=2.68
            ELSE DO
               IF (TEX .EQ. 'CLAY') THEN DO
                  G=2.75
               ELSE DO
                  PRINT 10,TEX
                  STOP
               END IF
            END IF
         END IF
      END IF
10    FORMAT('0'/T2,'*** STRANGE TEXTURE OF THE SOIL ',A20/)
C
      PSITY=1-RD/(G*1000.0)
      MCOSA=1000.0/RD-1.0/G
```

```
      IF (MCOS/MCOSA .GE. 1.015) THEN DO
         PRINT 20,MCOSA,MCOS,BUW,RD,G
20       FORMAT('0'/T2,'MOISTURE CONTENT UPON FULL SATURATION',F7.4,
     *   ' IS LESS THAN MOISTURE CONTENT BY DRY WEIGHT',F7.4/
     *   T2,'THIS IS NOT REASONABLE BASED ON BUW=',F10.2,', RD=',F10.2,
     *   'AND G=',F7.4//)
         STOP
      END IF
C
      IF (G .GE. 2.679) THEN DO
         IF (MCOS .GT. 0.07) THEN DO
            KS=1.731/12.0*(0.9*ALOG10(MCOS*100)-0.2)*10**(0.0006243*RD)
            KFS=1.731/12.0*(0.01*10**(0.0013197*RD)
     *+0.025*10**(0.000874*RD)*MCOS*100.0)
         ELSE DO
            PRINT 30,MCOS,TEX
30    FORMAT('0'/T2,'MOSITURE CONTENT OF SOIL',F7.4,' IS LESS THAN ',
     *         '0.07, BASED ON SOIL TEXTURE OF ',A20/
     *       T2,'WHICH IS INVALID FOR USING KERSTEN EQUATIONS FOR ',
     *         'ESTIMATING SOIL THERMAL CONDUCTIVITIES'/)
            STOP
         END IF
      ELSE DO
         IF (MCOS .GT. 0.01) THEN DO
            KS=1.731/12.0*(0.7*ALOG10(MCOS*100)+0.4)*10**(0.0006243*RD)
            KFS=1.731/12.0*(0.011*10**(0.001336*RD)
     *         +0.026*10**(0.0009114*RD)*MCOS*100)
         ELSE DO
            PRINT 30,MCOS,TEX
            STOP
         END IF
      END IF
      RETURN
      END
C
$ENTRY
THIS IS A FINITE ELEMENT PROGRAM FOR THE SIMULATION OF AN EARTH-AIR
HEAT EXCHANGER .
FOLLOWING ASSUMPTIONS ARE MADE:
     --- NO HEAT CONDUCTION IN THE SOIL IN THE DIRECTION OF AIR FLOW.
     --- HEAT TRANSFER COEFFICIENT IS CONSTANT IN THE UNIT LENGTH BUT
         VARIES WITH THE TEMPERATURE OR THE PIPE LENGTH.
     --- CONTACT RESISTANCE BETWEEN THE PIPE AND THE SOIL IS CONSTANT.
     --- MOSITURE MOVEMENT IS THE FUNCTION OF THERMAL GRADIENT ONLY.

  =================== SIMULATION FOR GLENLEA TEST SITE ===============
  * OBJECTIVE:                                                        *
  *    --- ACCUMULATE DATA FOR GRAPHIES                               *
  * NOTES:                                                            *
  *    --- TIME: JANUARY 29 - FEBRUARY 3, 1985 ;   FOR PIPE #4        *
  *    --- SOIL CYLINDER THICKNESS IS 1.0 M;                          *
  *    --- TIME INTERVAL = 3 HOUR;                                    *
  *    --- D = 0.150 M                                                *
  *    --- NO. OF ELEMENTS IS 20                                      *
  *    --- LENGTH = 30 M.                                             *
```

```
*     --- VEL = 3.00 M/S                                                  *
*     --- CONTACT RESISTANCE = 0.004541 K-M-M/W                           *
*     --- PCP=1512820.4  J/CU-M-C  (PVC)                                  *
*     --- DEW POINT TEMP AND R.H. ARE DUMMY NUMBERS HERE                  *
====================================================================

A STOP CARD
PRINT HC
PLOT AIR TEMPERATURES
READ INLET AIR TEMPERATURES FROM A DATA SET NOT
GENERATE INITIAL SOIL TEMPERATURE PROFILES NOT
SILTY CLAY
0.150, 0.0750, 0.0780, 1.0780,  30.0,  2.0,
0.1340, 3.000,1004.64, 3.0, 0.004541, 3.0, -99.0, 20.0
1800, 0.30, 6.0, 0,  29,1, 85,
ONE INLET AIR TEMPERATURE NOT
48
-19.6, -15.6, -13.2, -14.7, -19.0, -21.5, -27.3, -29.7, -32.5, -34.4,
-36.1, -35.1, -33.8, -33.1, -36.4, -35.8, -37.3, -37.8, -35.1, -34.7,
-32.7, -34.9, -36.8, -37.7, -40.2, -41.3, -40.5, -37.6, -32.0, -30.8,
-33.8, -36.3, -35.3, -35.0, -34.7, -30.5, -27.8, -28.6, -34.3, -37.8,
-39.1, -37.9, -39.1, -36.4, -31.9, -30.9, -34.9, -36.7, -36.0,
0,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,3,
-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,
-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,
-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,-99,
99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,
99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,99,
99,99,99,99,99,99,99,99,99,99,99,
GENERATE ELEMENTS
20
C //GO.FT12F001 DD DSN=LEI.TEST,DISP=OLD
C //GO.FT10F001 DD DSN=LEI.WDATA70,DISP=SHR
C //GO.FT13F001 DD DSN=LEI.DUMMY,DISP=OLD
C //GO.FT15F001 DD DSN=LEI.P#4J28,DISP=SHR
C //GO.FT11F001 DD DSN=LEI.TDUMMY,DISP=OLD
```