AN EXPERIMENTAL STUDY OF STRATIFIED THERMAL ENERGY STORAGE UNDER VARIABLE INLET TEMPERATURE CONDITIONS

By

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NOMENCLATURE

English Letters

A	area, ft^2
C_p	specific heat at constant pressure, BTU/lbm.°F
D	baffle diameter, ft
d	perforation diameter, ft
$F_R U_L$	the slope of collector efficiency versus $(T_i - T_a)/G_T$ curve, $W/m^2.K$
$F_R(\tau\alpha)$	the y-intercept of collector efficiency versus $(T_i - T_a)/G_T$ curve
G_T	total incident solar radiation, W/m^2
H	total height of the tank, ft
h	enthalpy, BTU/lbm
L	baffle length, ft
$\dot{m}$	mass flow rate, lbm/sec
p	pitch (distance between adjacent centers), in.
Q	volumetric flow rate, GPM
$\dot{Q}$	heat loss rate, BTU/hr
Re	Reynolds number, $\rho Vd/\alpha\mu$
r	flow rate correction factor
T	temperature, °F
t	time, sec
t	baffle thickness (in Appendix "A"), in.
V	average velocity, ft/sec

V	volume (in Appendix "D"), ft^3

Greek Letters

α	porosity
Δ	designates a difference when used as a prefix
η	collector efficiency
μ	absolute viscosity, lbm/ft.sec
ρ	density, lbm/ft^3
Σ	summation sign

Subscripts

1,2,3	designated points
a	ambient
b	blocked
C	columns (in Appendix "A")
c	cross sectional (in Appendix "E")
h	hole (perforation)
i	designates a slab number (in Appendix "D")
i	instantaneous (in Appendix "E")
max	maximum
min	minimum
R	rows
t	total
u	useful

Abbreviations

EXP	the exponential function

GPM	gallons per minutes
SST	single stratified tank
STS	stratified thermal storage
TC	thermocouple
TTS	thermocline thermal storage

CHAPTER I

INTRODUCTION

Prior to 1974, the total energy consumption has been increased at a rate of 4 to 5 % annually within the United States as well as the world. Approximately 31 % of this energy is used for the generation of electricity. The consumption rate doubles every ten years; therefore, the generating capacity must also double every ten years (Krenz, 1984). In order to meet this highly increasing consumption of energy, energy conservation and load management should be utilized more effectively. Thermal energy storage is believed to have a great contribution in the future towards cutting down the energy demand, reducing the cost of producing energy, and increasing the use of solar energy systems. This chapter is devoted to the description of the motivation of the present work. The objectives and method of approach are also described herein.

1.1 Purpose

Thermal energy storage tanks, which maintain liquids at different temperatures separated (the warm liquid on top of the cold liquid) in a single tank, have been used for energy conservation and load management applications for quite some time. Upon using thermal energy storage tanks, it is desirable, under certain circumstances, to store liquids of unlike temperatures in a single tank. One might think of using a two tank system as a solution to the above mentioned problem; but that would require double the volume of material for a given amount of storage, hence double the cost and space required.

Most of the thermal energy storage systems utilize water as the working fluid. It is also the working fluid in many energy systems. The reason lies behind the desirable characteristics that water has. Some of these characteristics are: nontoxic, very high specific heat, inexpensive, and abundant.

An example of a thermal energy storage system that utilizes water as the working fluid is a single stratified tank (SST). In this type of system, the hot water is stored on top of the cold water without a membrane that separates the two liquids. A number of studies has been done on this type of tank (Abdoly and Rapp, 1982; Cole and Bellinger, 1982; Davis and Bartera, 1975; Ghajar et al., 1987; Khun et al., 1980; Lavan and Thompson, 1977; Loehrke et al., 1979; Sliwinski et al., 1978; Wildin and Truman, 1985; and Zurigat et al., 1988). Almost all of these studies that were done, or are being done, concentrated on how to charge or discharge the tank with hot or chilled water with a minimum amount of mixing between the hot and the cold liquid, because it is well known that mixing is associated with a loss in the thermodynamic availability; or in other words, energy is being lost. The mechanisms that limit the approach to high performance and cause losses in the thermodynamic availability are (see Fig. 1.1): (1) heat loss to the ambient surroundings, (2) heat conduction along the wall and the associated buoyancy-driven motions in the fluid body, (3) thermal diffusion from the hot portion of the fluid to the cold portion, and (4) mixing during charge or discharge cycle. There are two distinct cases experienced with the SST: the thermocline thermal storage (TTS) and the stratified thermal storage (STS). In the TTS, the inlet temperature of the fluid is constant or varies slightly, a case commonly encountered in chilled water storage. In the STS, the inlet temperature varies, a case that is common among solar collector-energy storage systems. In the latter system, which is the focus of this study, the water is heated through the solar collector and then stored in the thermal storage tank along with the warm water that has already been stored in the tank.

Before going any further in describing the stratified thermal storage systems, a definition of stratification ought to be stated at this point. The term " stratification ", as used throughout this study, is defined as a measure of the difference between the maximum and minimum storage tank temperatures at a given time (Fanney and Klein, 1988). The stratified thermal storage is a promising device for storing low-to-medium temperature thermal energy for space cooling

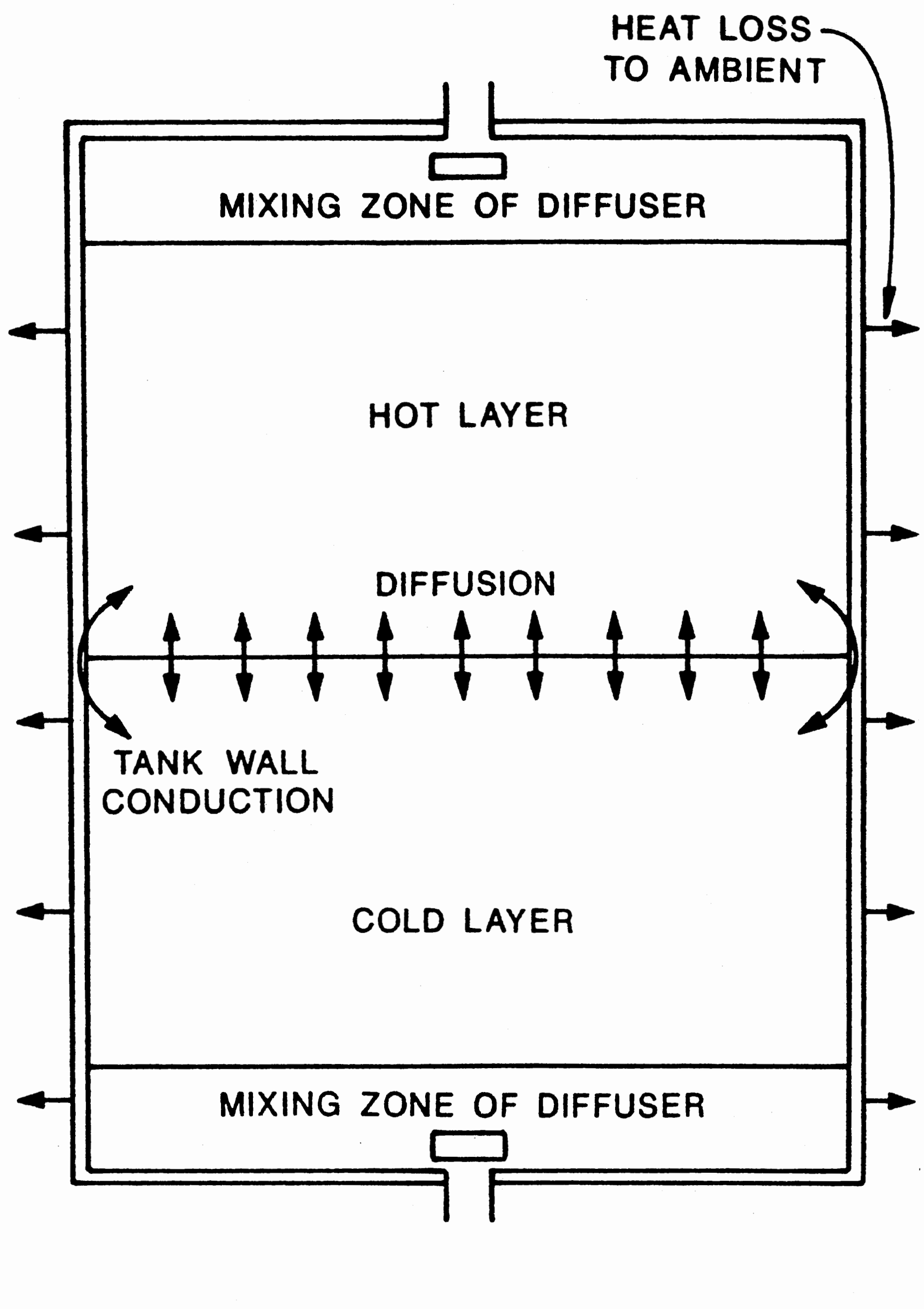


Figure 1.1 Heat Loss Mechanisms.

and residential applications. Increased efficiencies of solar systems can be achieved with well designed thermal storage systems. Usually, problems are encountered when thermal storage is used along with solar collectors; those problems mainly consist of mixing and stratification disturbances; hence, causing the thermal energy storage efficiency to drop. The cause of these problems is the fluctuation in the hot water temperature that flows through the solar collector and then stored inside the storage tank for later usage. The fluctuation is often caused by the passing clouds that would block the sun rays. A typical incident solar radiation curve for two different locations in the U.S.A. are shown in Fig. 1.2. Since these fluctuations are difficult to reproduce on an experimental setup, a step change in the temperature would be a good representation of the fluctuating temperatures to use in the laboratory.

The present study focuses on the investigation of stratified thermal storage (STS) tank performance under wide range of flow parameters (flow rates and inlet temperature profiles) and different inlet configurations. Different inlet configurations have been designed to enhance thermal stratification in storage tanks (Wildin and Truman, 1985; Cole and Bellinger, 1982; Zurigat et al., 1988; and Khun et al., 1980), see Figures 1.3 and 1.4. Inlet designs which utilize hydrostatic and hydrodynamic effects to guide the incoming flow to its proper level of stratification with a minimum amount of mixing is the purpose of this study. The

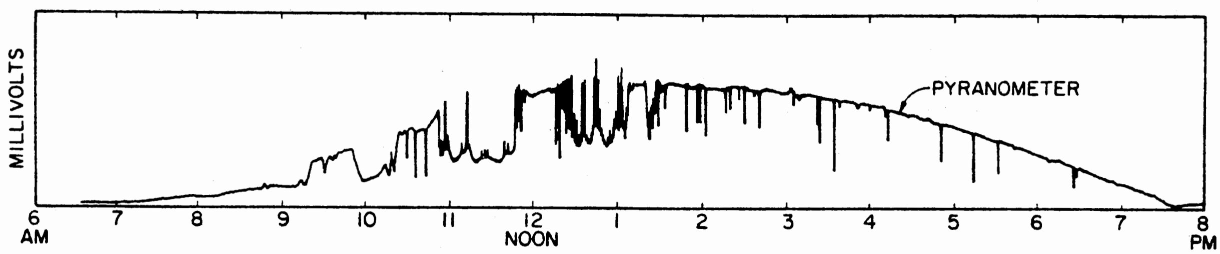


Figure 1.2-a Incident Solar Radiation Curve on a Site in Muskogee, Oklahoma; April 28, 1977. (Adopted from The Use of Solar Energy in the Heating of Asphalt in Storage Tanks; Interim Report; Parker et al., 1977)

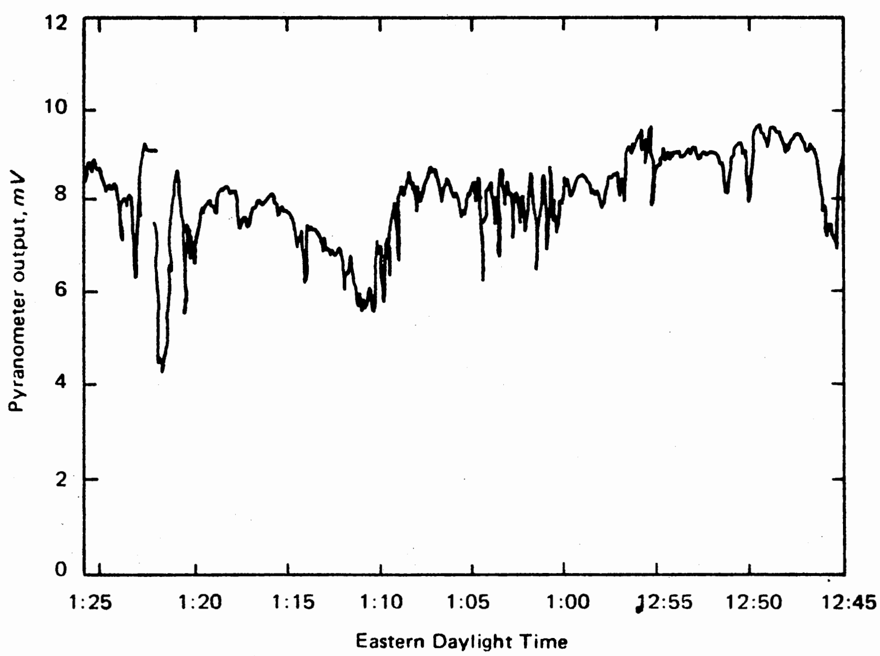


Figure 1.2-b Incident Solar Radiation Curve on a Site in Gaithersburg, Maryland; March 11, 1974. (Adopted from Solar Heating and Cooling: Engineering, Practical Design, and Economics; Kreider and Kreith, 1976)

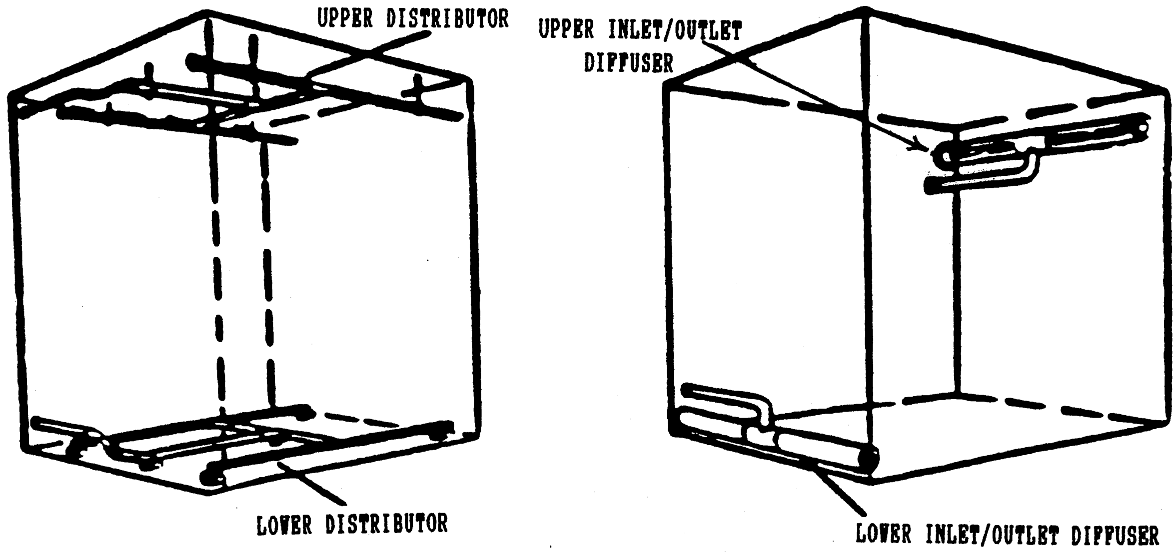


Figure 1.3-a Stratified Thermal Storage Tank Inlet Diffusers. (Wildin and Truman, 1985)

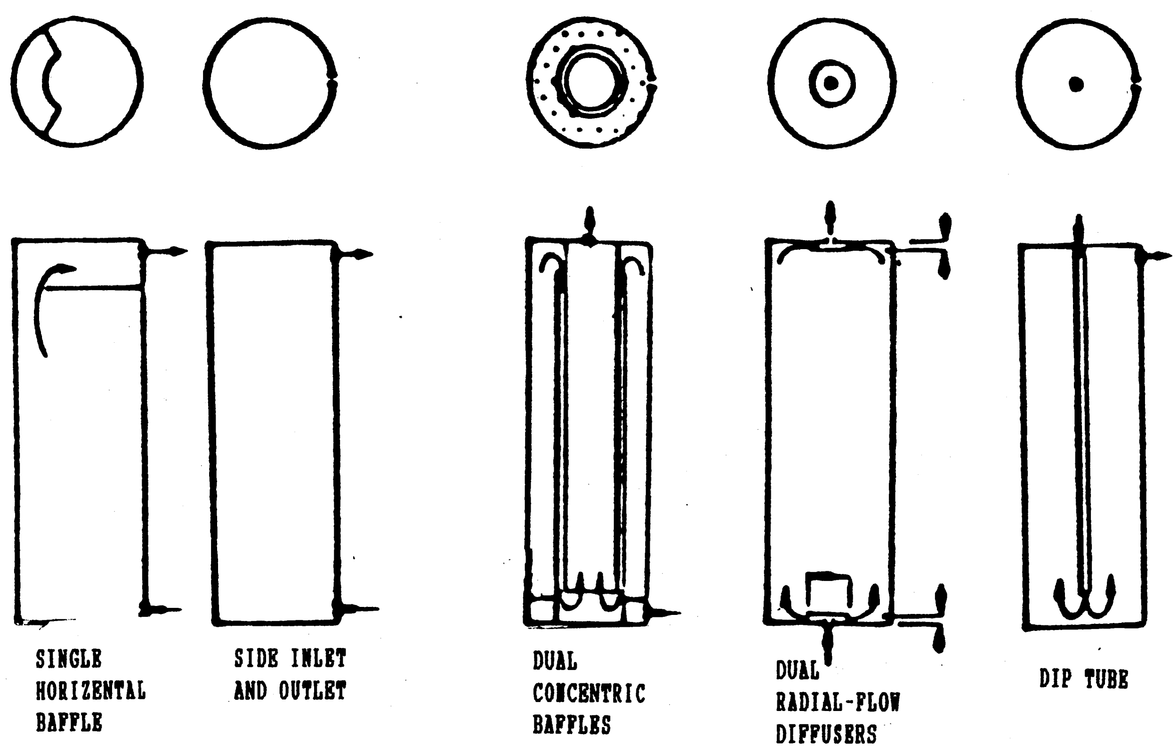


Figure 1.3-b Stratified Thermal Storage Tank Inlet Diffusers. (Cole and Bellinger, 1982)

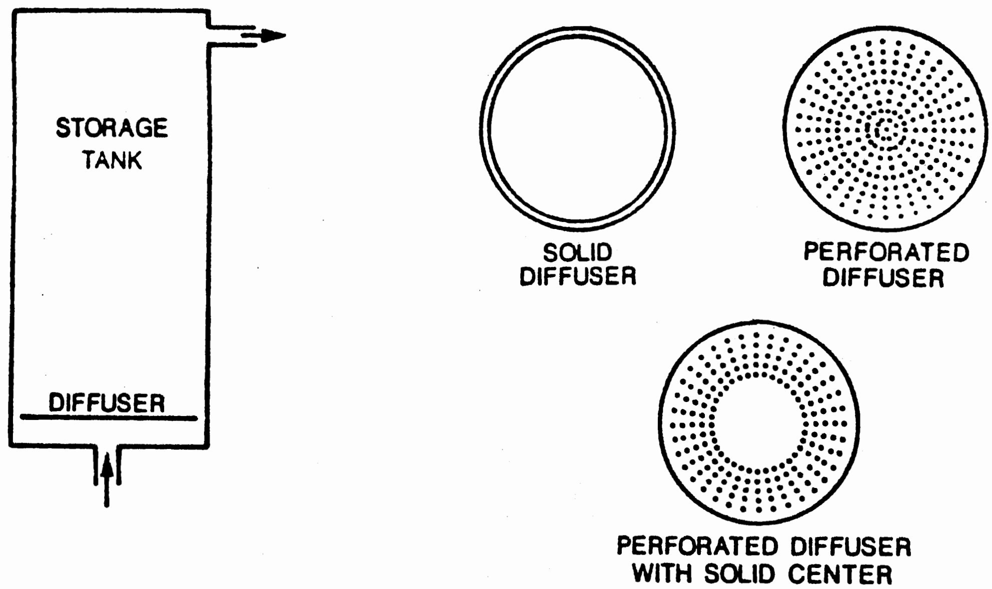


Figure 1.4-a Stratified Thermal Storage Tank Inlet Diffusers. (Zurigat et al., 1988)

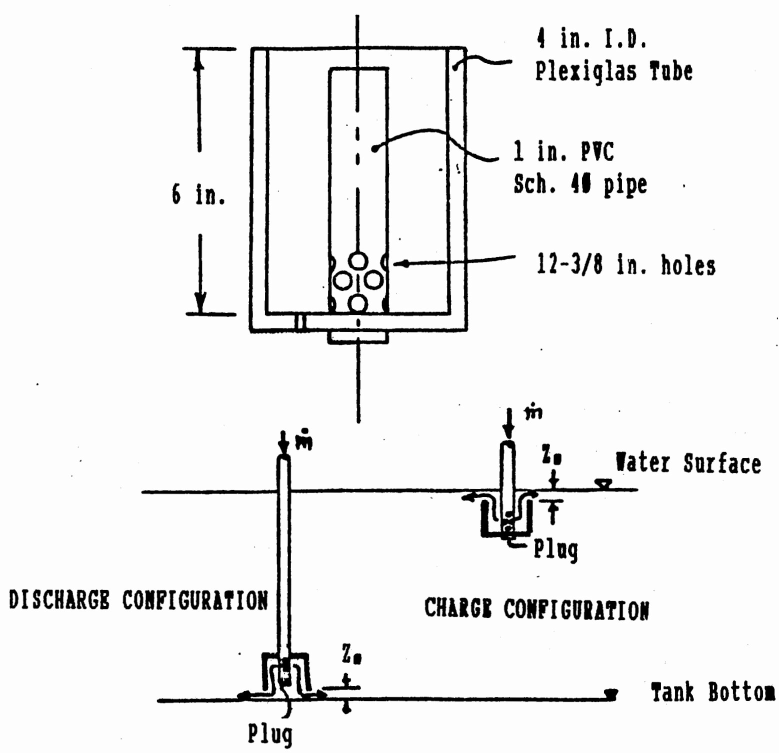


Figure 1.4-b Stratified Thermal Storage Tank Inlet Diffusers. (Khun et al., 1980)

inlet designs that were investigated in this study are described in Section 3.1.

1.2 Objectives and Method of Approach

The problem of mixing and stratification disturbances under variable inlet temperature conditions, has been the critical issue in thermal storage systems. This study's primary goal is to keep both the mixing and stratification disturbances as minimum as possible. The specific objectives of this study are:

1. Design a complete experimental setup that would incorporate different types of inlet configurations.
2. Experimentally investigate the performance of a stratified thermal storage tank with a specific inlet design under wide range of flow conditions (flow rates and inlet temperature profiles).
3. Assess the feasibility of stratification enhancement designs.
4. Improve the overall efficiency of the solar collector-thermal energy storage systems.
5. Develop a data base for verification of a two- or three-dimensional analytical model.

The method of approach included the following steps:

1. Reviewing the literature on the STS, as well as the TTS, in order to gain a better understanding of what the main features of the experimental setup design should be (see Chapter 2).

2. Building an experimental setup that will fulfill the above mentioned objectives (see Chapter 3).
3. Developing the appropriate computer codes that will help in designing the experimental setup as well as the codes for analyzing and reducing the data. The computer codes are listed in Appendixes A through E, and in Rao et al., 1988.
4. Evaluating the performance of a solar collector - thermal energy storage system for a specific inlet design operating under a wide range of flow rates and inlet temperature profiles, so an optimum design would be obtained (see Chapter 4).
5. Finally, stating the conclusions and recommendations about the findings of this study. These discussions are presented in Chapter 5.

CHAPTER II

LITERATURE REVIEW

The single stratified tank has been investigated by many researchers, both analytically and experimentally. Most of these investigations were conducted on the TTS and very little was done in relation to the STS. The results of the studies on the effects that are of concern to the STS systems are presented next.

Experiments done by Wildin and Truman (1985) suggested that a value of Richardson number greater than or equal to unity is sufficient for maintaining good stratification. While Cole and Bellinger (1981) recommended a value of Richardson number greater than about 0.25 - 0.48 in order to maintain a high degree of thermal stratification in water. Experiments conducted at the U. S. Army Construction Engineering Research Laboratory, Champaign, Illinois (Sliwinski et al., 1978), discussed the effect of increased energy input rate due to stratification. It was observed that stratification would occur in the storage tank for a minimum value of Richardson number of 0.244, and at values less than 0.002 the tank is completely mixed. It was also observed that small increases in Richardson number result in large increases in the degree of stratification, and at large values of the inverse of Peclet number (Reynolds number times Prandtl number) the degree of stratification becomes independent of changes of Richardson number. It was suggested that designers should place horizontal inlets as near the top surface and outlets as near the bottom surface, of the tank as possible in order to avoid having any stagnant regions above and below the inlet and outlet.

Miller (1977) investigated the effect of thermally conducting side walls on an initially stratified fluid in a cylindrical tank. Experiments were carried out on two different kinds of tank material: one aluminium and the other glass. It was found that the degradation of the thermocline is ten times faster in aluminium tanks than that in glass tanks. Sherman et al. (1978) showed results that agreed with those of Miller (1977). Sherman et al. experimentally analyzed five sets of data for a fiberglass thermal storage tank which was initially stratified. The five sets of data included no liner, and copper, aluminium, steel, and stainless steel liners. It was found that vertical conduction down the walls of the tank does indeed reduce thermal stratification to a considerable extent. On the other hand, it was concluded that convection inside the thermally stratified storage tank is of a minor significance.

Lavan and Thompson (1977) studied the effect of height-to-diameter ratio (aspect ratio). Stratification was found to increase with increasing height-to-diameter ratio. A ratio of four was recommended by Cole and Bellinger (1982) to provide best stratification without excessive thermal losses. A ratio of ten was recommended by Abdoly and Rapp (1982). However, this value would result in a high surface area-to-volume ratio and subsequently increase the heat loss and insulation cost.

The effect of internal baffling was studied by Davis and Bartera (1975). The study aimed at enhancing thermal stratification in storage tanks. The baffles used consist of two square baffle plates placed on opposite sides of the tank with the center of each plate aligned with the inlet of the tank and spaced two inches from the wall. The water entering the tank would be impinged on the center of the plate in order to prevent turbulence and reduce mixing. The experiments were not technically comprehensive and no conclusive results or recommendations were provided. Cole and Bellinger (1982) showed that dip tubes and vertical baffling (see Fig. 2.1) degrade stratification; on the other hand, simple diffusers, such as the dual radial-flow diffusers, provide the best stratification. Experimental investigations conducted at the National Bureau of Standards (Fanney and Klein, 1988) to evaluate the thermal performance of solar domestic hot water systems, concluded that systems that employ stratification enhancing return tubes, as opposed to standard return tubes (see Fig. 2.2), would improve the thermal performance of the solar system only slightly through the use of reduced flow rates.

The effect of system flow rates on thermal

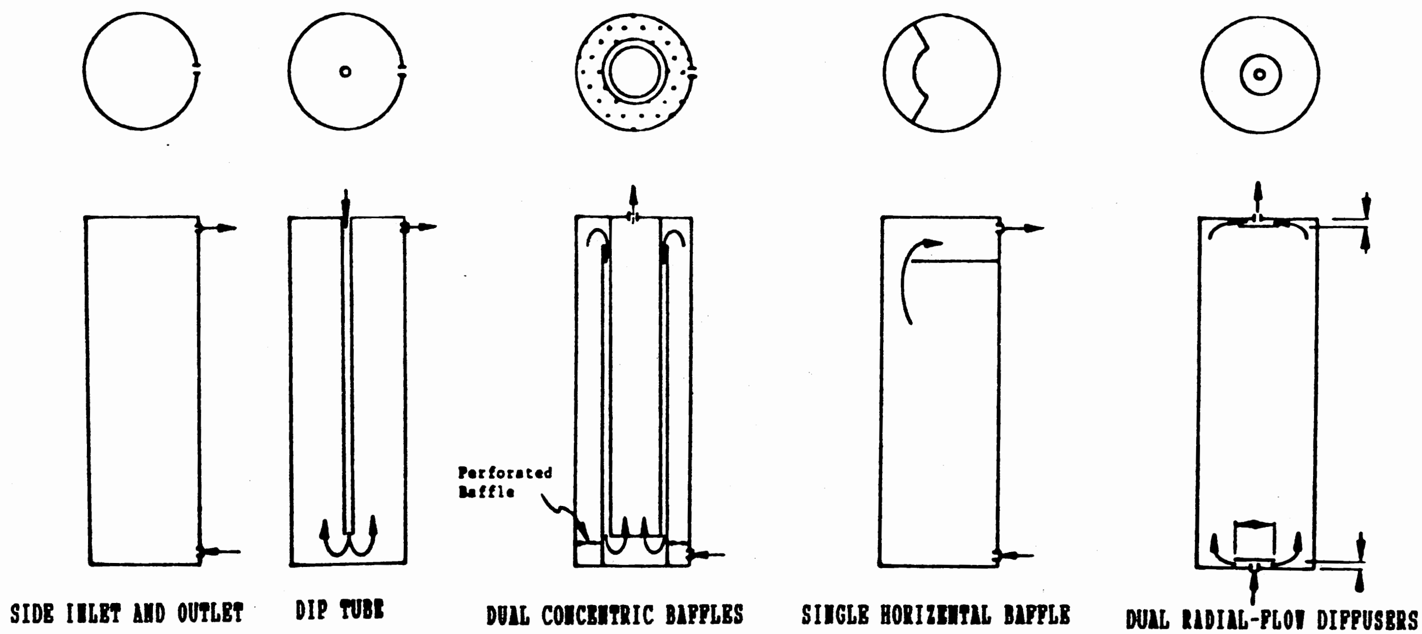


Figure 2.1 Stratified Thermal Storage Tank Inlet Diffusers.
(Cole and Bellinger, 1982)

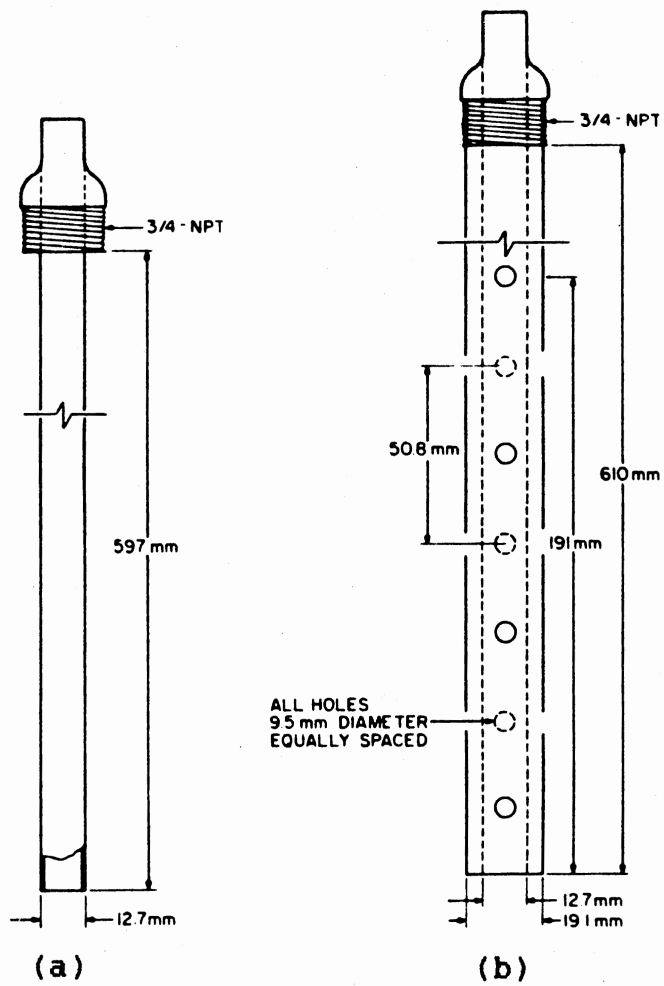


Figure 2.2 (a) Standard Return Tube, (b) Stratification Enhancement Return Tube.

stratification was studied by Wuestling et al. (1985). It was found that systems operating at reduced flow rates (on the order of twenty percent less than those of conventional flow rates) would result in a higher degree of thermal stratification which in turn reduces the inlet temperature to the solar collector causing the collector efficiency to increase. However, reducing the flow rate of the fluid through the solar collector results in lower values of heat removal factor, and consequently, lower the efficiency of the collector, but the reduction in the inlet temperature to the collector often outweighs the reduction in the heat removal factor. Cole and Bellinger (1982) confirmed this result and recommended an inlet velocity as minimum as possible. Fanney and Klein's (1988) experiments revealed that the performance of a typical single tank solar domestic hot water system can be significantly improved (better stratification and reduction in mixing) if reduced flow rates were to be used in a storage tank with a standard return tube. It was also found that the reduced flow rate depends on a number of factors. These factors include array size of the collector, storage tank capacity, and the load imposed on the system. It was recommended that the optimum flow rate should be approached cautiously; otherwise imbalances may occur if the collector array flow rate was reduced under a certain level. Lavan and Thompson (1977) showed that thermal stratification can still be maintained at high flow rates, but stratification would be improved with decreasing flow rates.

From the foregoing discussion, several conclusions were drawn concerning the determination of the main features of the experimental setup. For example: the material that the test tank was made of is steel, which has less vertical conduction compared to other materials like copper and aluminium, and has a lower cost than Plexiglas; a reasonable value of four for aspect ratio was chosen; a reasonable range of flow rate between 1.89 l/min (Ø.5 GPM) and 7.57 l/min (2.Ø GPM) which would give a maximum velocity of Ø.44 m/sec (1.45 ft/sec) in a 1.91 cm (Ø.75 in.) diameter pipe; and finally, internal baffling was adopted since it is believed that internal baffling will enhance stratification. The design of the different baffles and diffusers used are described in the next chapter along with the complete experimental setup.

CHAPTER III

DESCRIPTION OF THE EXPERIMENTAL SETUP AND PROCEDURES

Experiments with variable inlet water temperature were conducted to test innovative inlet distributor designs for solar energy storage applications. In addition to establishing the need for such inlet designs, a comparative study was done between a commonly used inlet diffuser and a distributor manifold with two types of baffles. In this chapter the experimental setup used along with the experimental and data reduction procedures are described.

3.1 Experimental Setup

The experimental setup used consists of an insulated water heater tank, a tap water settling tank, an insulated test tank, a catch tank, circulation and metering system, temperature sensor arrays, a data acquisition system, and a distributor manifold. The components of the experimental setup were connected through 1.91 cm (0.75 in.) CPVC pipes. A schematic of the setup is shown in Fig. 3.1.

The water heater tank, an insulated cubic steel tank [0.762 m (30 in.) sides, with a capacity of 0.3786 m^3 (100 gallons) wrapped with 5.08 cm (2 in.) 0.27 k-factor

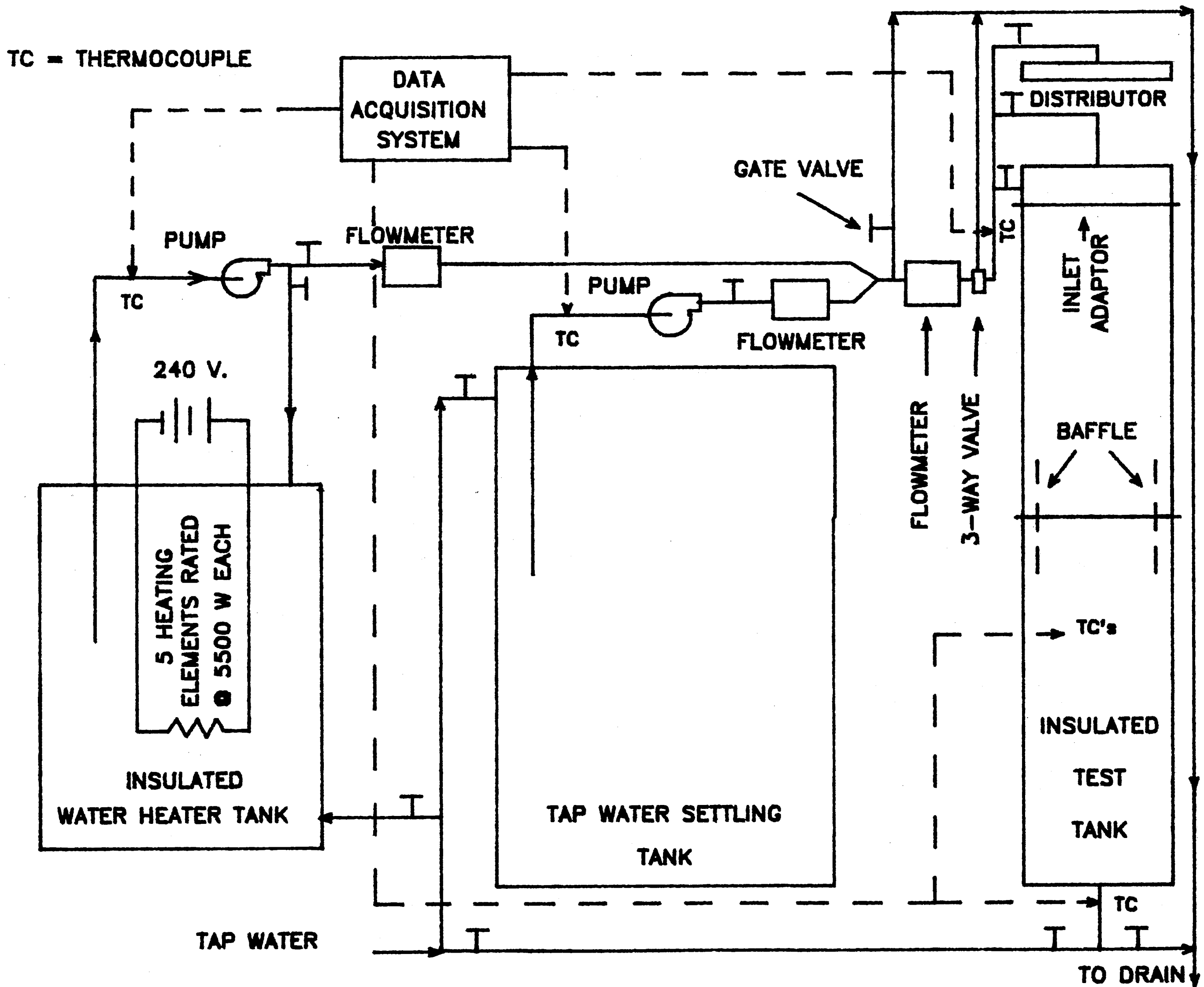


Figure 3.1 Schematic of the Experimental Setup.

fiberglass insulation], is capable of providing hot water at any desired temperature up to 93 °C (200 °F). The rating of the heating elements was calculated based on the need to raise the temperature of the tank water volume 49 °C (120 °F) above its initial temperature in approximately one hour. It was found that for those requirements five electric heating elements, rated at 5500 watts each, would suffice. The five electric heating elements were installed in the four sides of the tank as shown in Fig. 3.2.

The tap water settling tank, a 0.757 m^3 (200 gallons) cylindrical plastic tank, was used to store tap water overnight in order to have the water at an approximately uniform room temperature. The stored water was used to remove heat from the hot water that was coming from the water heater. The rate at which heat was removed was varied by varying the tap water flow rate.

The test tank, an insulated, cylindrical, commercial steel tank with vertical axis [0.254 cm (0.1 in.) thick wall, 0.406 m (16 in.) diameter, 1.576 m (62.06 in.) high wrapped with 7.62 cm (3 in.) 0.27 k-factor fiberglass insulation], consists of three parts: the bottom part [0.82 m (32.31 in.) high], the top part [0.66 m (26 in.) high], and the inlet adaptor [0.1 m (3.75 in.) high]. The bottom part connects to the top part by a pair of flanges, another pair of flanges connects the top part to the inlet adaptor. A schematic of the test tank is shown in Fig. 3.3. The inlet adaptor has two types of inlets, a top inlet

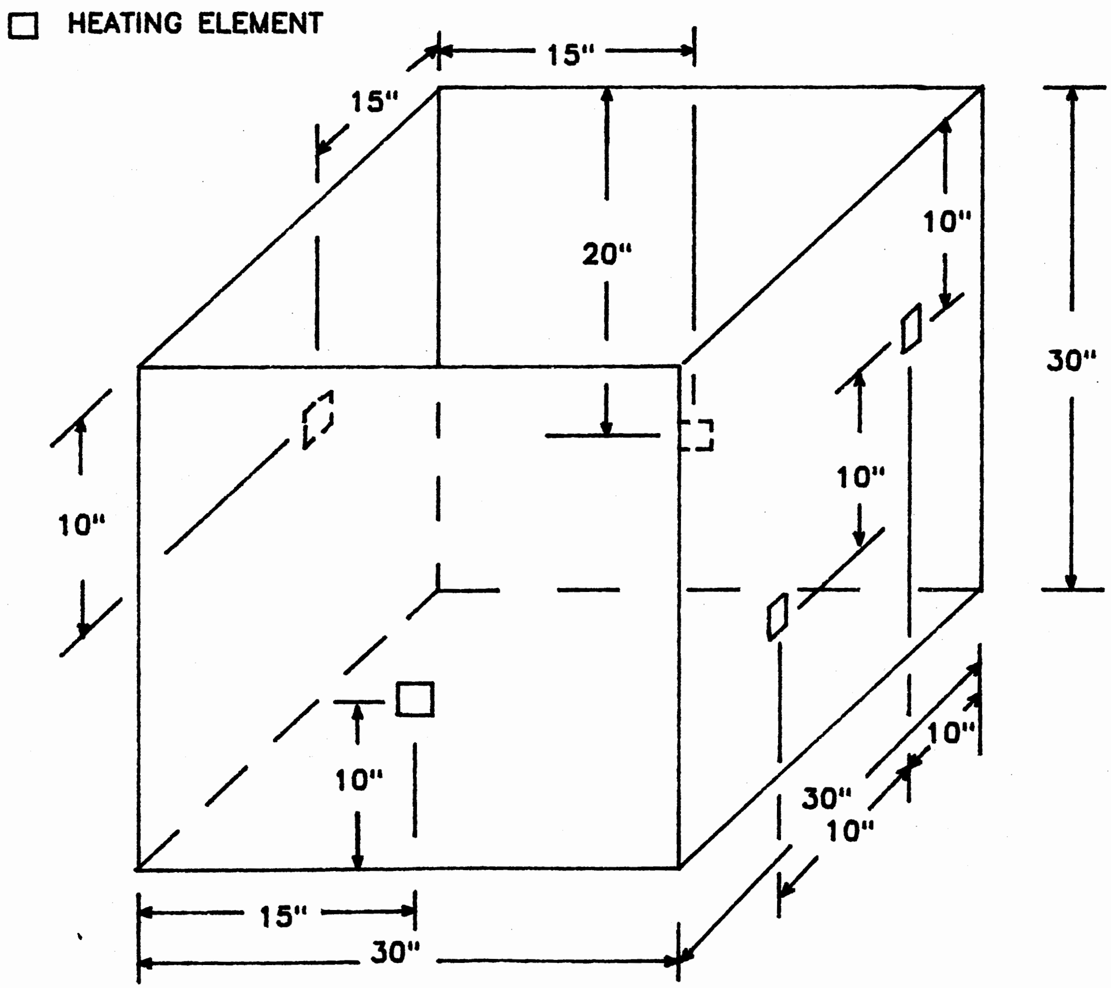


Figure 3.2 Schematic of the Water Heater Tank.

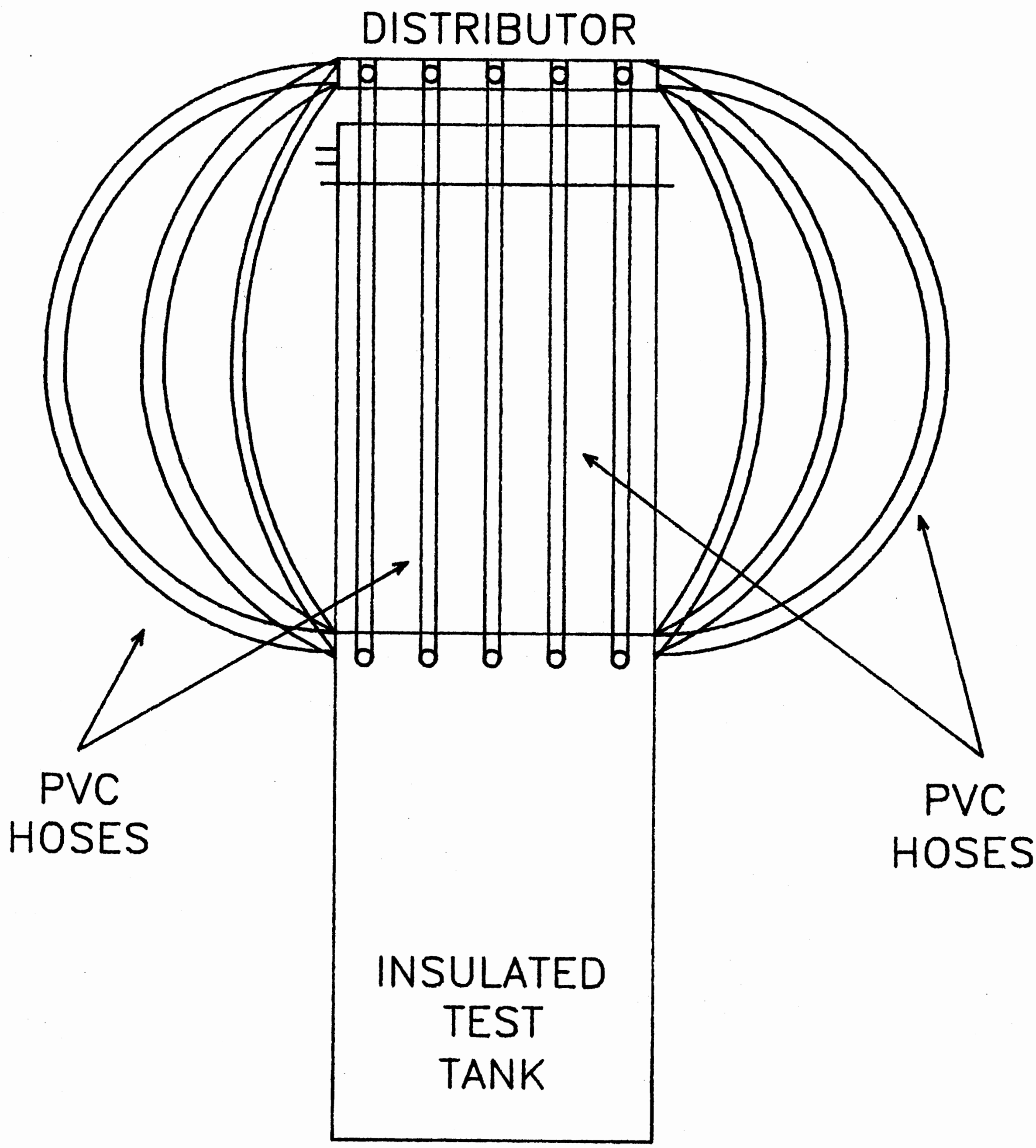


Figure 3.3 Schematic of the Test Tank with the First Distributor Used.

and a side inlet. The test tank is also equipped with a distributor manifold, which will be discussed later in this section. Both the inlet adaptor and the distributor manifold permit the investigation of three types of inlets.

Different kinds of turbulence and mixing reducers were designed and built to test the thermal energy storage tank. The top inlet was tested using a solid inlet diffuser. The diffuser is a 1.27 cm (Ø.5 in.) thick, 35.56 cm (14 in.) diameter Plexiglas disc. The distributor manifold was tested using two types of baffles: a solid short baffle and a long perforated baflle with a solid center (see Fig. 3.4). The first was a Ø.254 cm (Ø.1 in.) thick wall, 15.24 cm (6 in.) high, 34.93 cm (13.75 in.) diameter solid steel baffle. The second was a Ø.159 cm (1/16 in.) thick wall, 35.56 cm (14 in.) diameter, 1.47 m (58 in.) high black iron baffle that had 15.24 cm (6 in.) unperforated solid approximately around mid-height, and the rest of the baffle height was perforated to permit leakage. The perforation arrays consist of Ø.79 cm (Ø.31 in.) holes arranged in a square pitch layout with 62 columns and 16 rows per foot of baffle length (see Appendix A for a complete description of the hole sizing and density).

The catch tank, a combination of two plastic scaled tanks that can hold up to Ø.341 m^3 (9Ø gallons), was used to collect the water that was forced out of the test tank during the experimental runs.

The circulation and metering system of the experimental

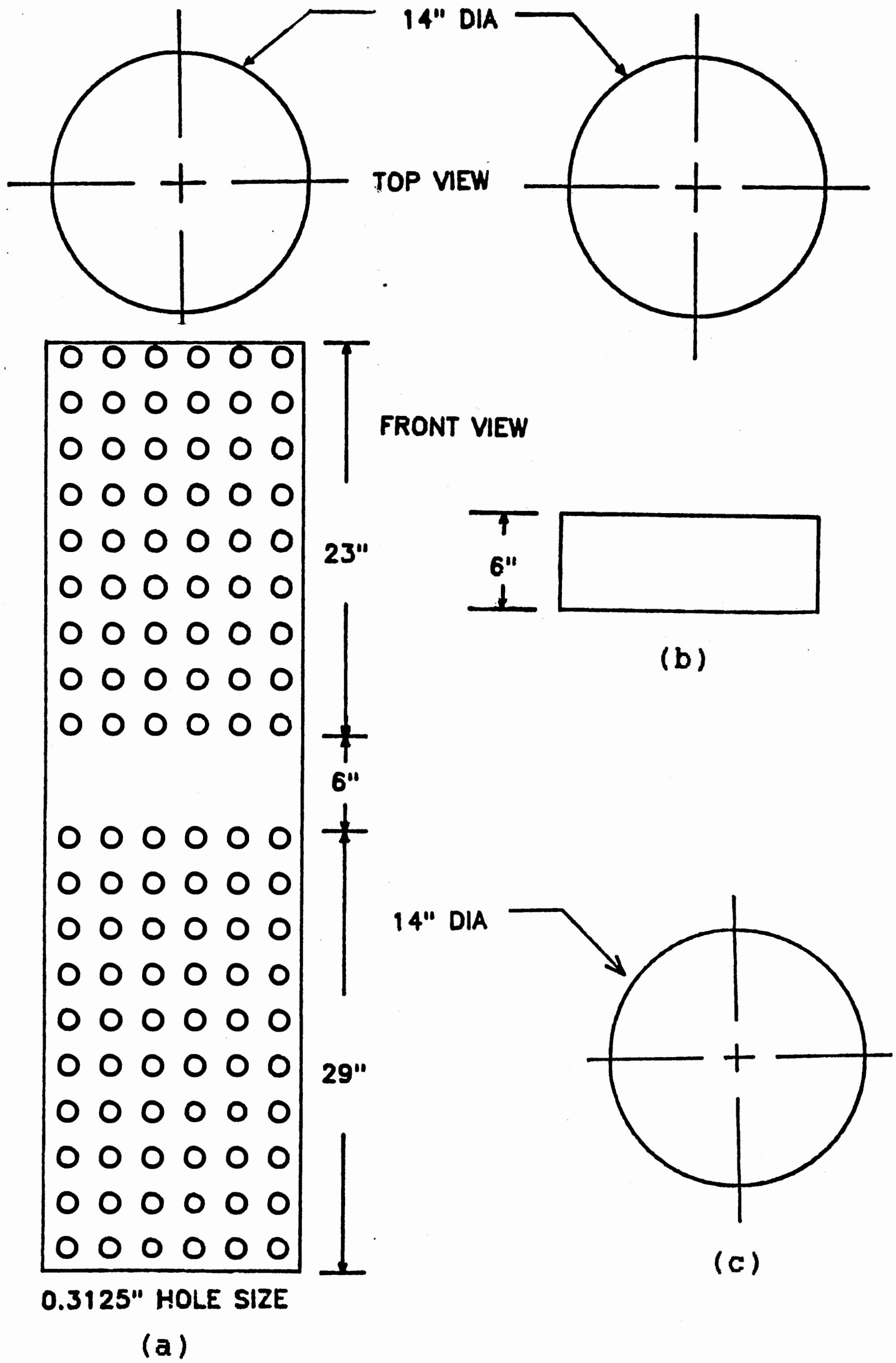


Figure 3.4 (a) Perforated Baffle, (b) Solid Baffle, and (c) Solid Inlet Diffuser.

setup consists of two pumps and four flowmeters. One pump, rated at Ø.5 HP, was used to pump hot water, while the other, rated at Ø.75 HP, was used to pump tap water. One of the flowmeters was used for hot water, the second for tap water, and the other two were used to monitor the flow rate of the water flowing into the test tank (one for high flow rates, 2 - 7 GPM, and the other for low flow rates, Ø.1 - 2 GPM). Although the flow rate was monitored, the average flow rate was considered in order to account for the fluctuations of the flowmeter. The average flow rate was obtained by dividing the total water volume in the catch tank by the total time of the experiment read by a stop watch. The accuracy of this averaging process ranged between 1 to 1Ø % of the flowmeter reading.

The temperature sensor arrays consist of 36 T-type thermocouples mounted in 9 levels with four thermocouples at each level. At each level, one thermocouple extends 2Ø.32 cm (8 in.), to the center of the tank, the second thermocouple extends 1Ø.16 cm (4 in.), the third thermocouple extends 5.Ø8 cm (2 in.), and the last thermocouple extends 1.27 cm (Ø.5 in.), half the distance between the baffle wall and the test tank wall. The accuracy of the thermocouples, according to the manufacturer, is ± Ø.Ø5 ^{o}C (or Ø.4 % of the thermocouple reading). The first thermocouple level is located 13.65 cm (5.375 in.) from the top of the tank, the rest of the levels are about 15.24 cm (6 in.) apart down the test tank as shown in Fig. 3.5. Four additional thermo-

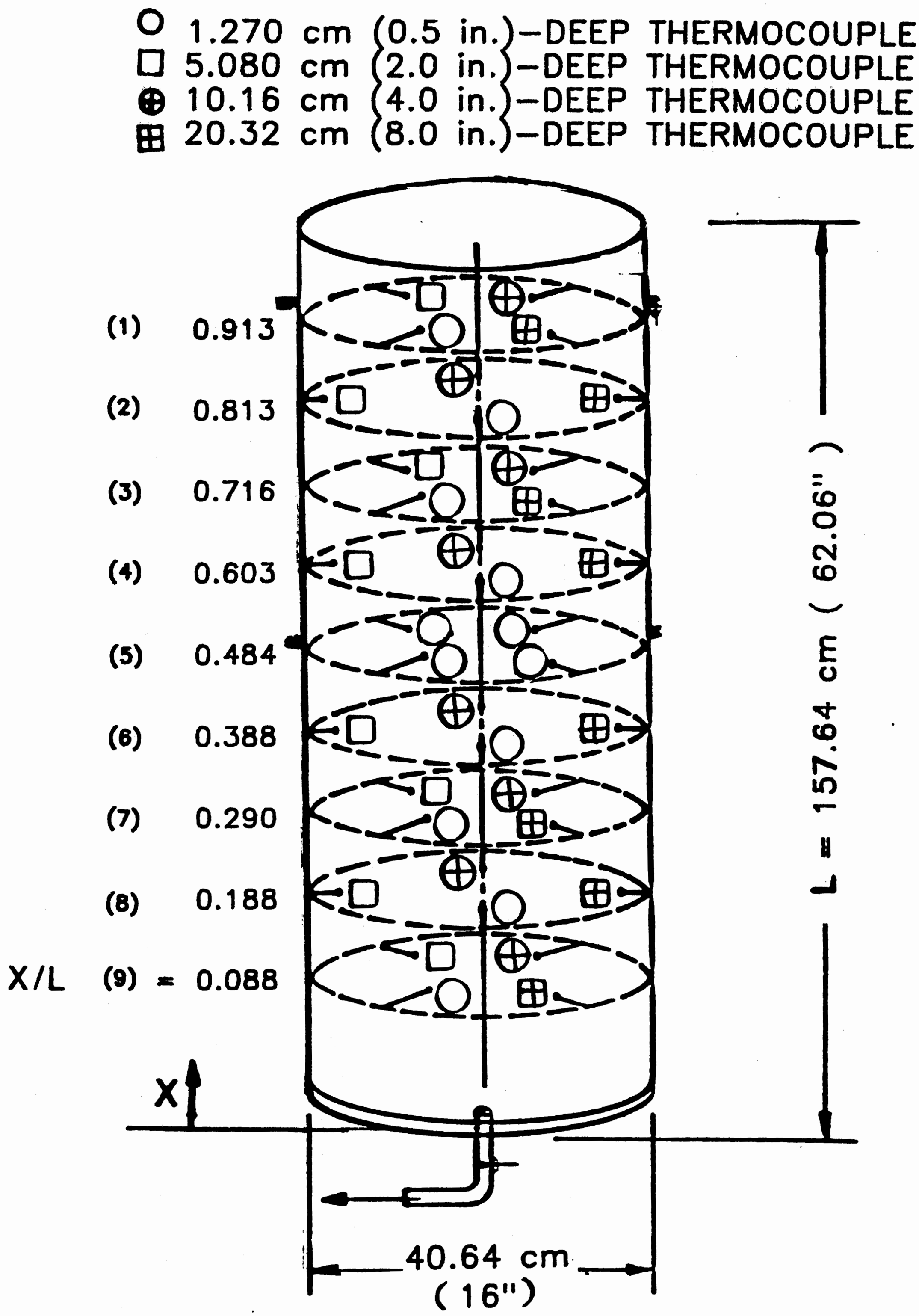


Figure 3.5 Thermocouple Locations Inside the Test Tank.

couples were used to measure the inlet, outlet, hot and tap water temperatures.

The data acquisition system was a Monitor Labs (model ML-9302) 40-channel data logger interfaced with a TI professional computer. Data were collected 20, 30, 45, and 75 seconds - depending on the flow rate. Calibration of the thermocouples showed that the accuracy of temperature measurements was within ± 0.27 °C (± 0.5 °F).

A distributor manifold, located on top of the test tank, distributes the incoming flow into 32 inlets, located around the circumference of the test tank at approximately mid-height. The distributor is a steel disc [0.406 m (16 in.) diameter, 3.81 cm (1.5 in.) high], has thirty-two 1/2 x 1/2 in. brass hose barbs welded around the disc circumference. The 32 barbs on the disc were connected to the 32 inlets on the test tank by 1.219 m (4 ft.) long, 1.27 cm (0.5 in.) diameter PVC flexible hoses.

Two different types of experimental runs were conducted with the different inlets to the test tank. One type of experiments utilized the different inlets with constant inlet temperature profiles; while the other type utilized the different inlets with variable inlet temperature profiles; but with more emphasis on the variable inlet temperature profiles. Initial runs, that used the side inlet and constant inlet temperature, showed that there is some fluctuation in the fifth level temperature profile (see Fig. 3.6 - the numbers on the curves indicate the level

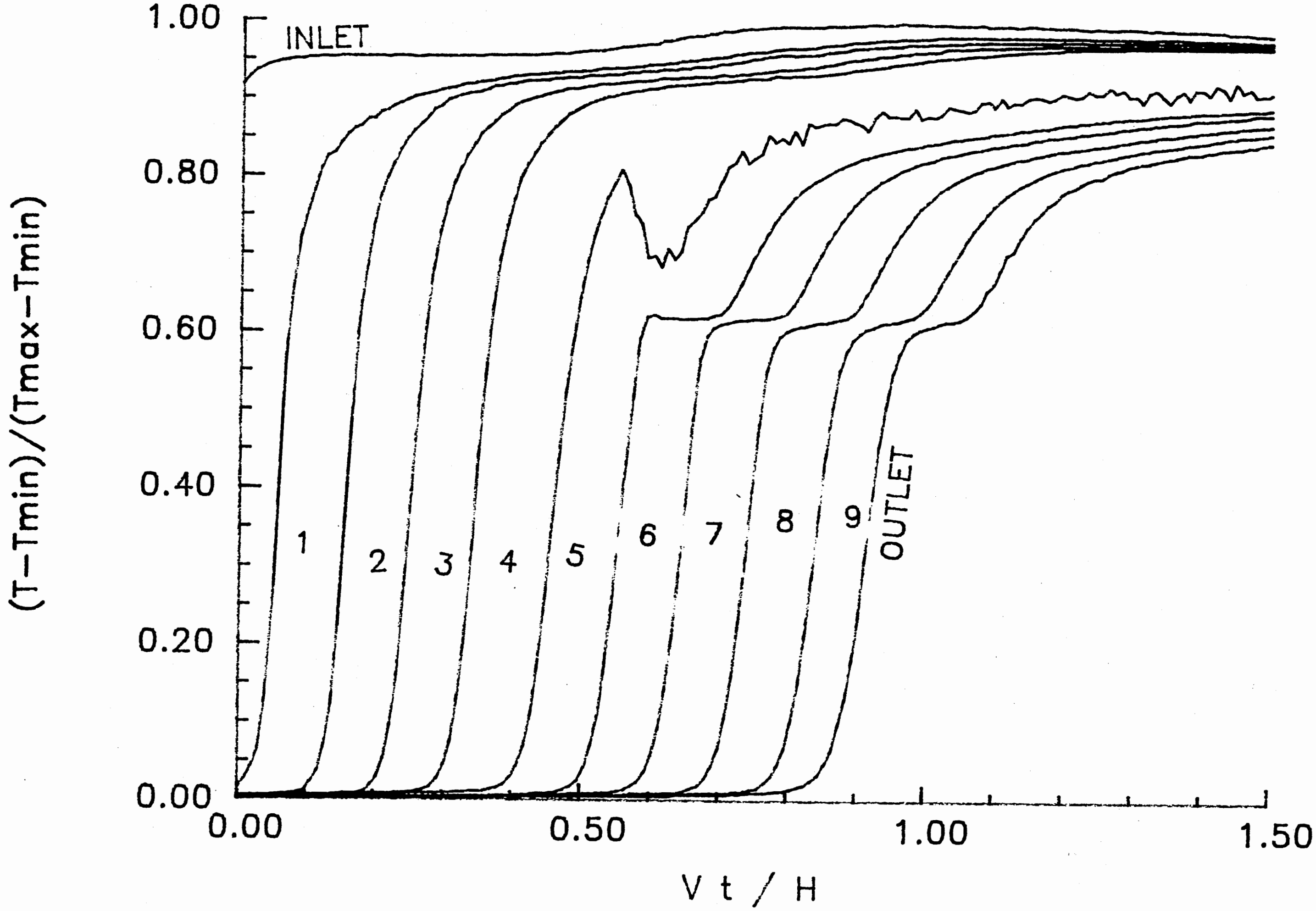


Figure 3.6 Transient Temperature Profiles with Fluctuation Due to Thermosiphoning.

number, see Nomenclature for abscissa and ordinate definitions). The fluctuation was due to the thermosiphoning effect, where the inlets at mid-height are. This effect caused the hot water to rise in the PVC hoses, as soon as it reached the fifth level, replacing the cold water that was initially in the hoses and causing the fluctuation in the temperature profile at that level.

Experiments that used the distributor manifold with variable inlet temperature revealed another disadvantage associated with this distributor. In this case, the temperature of the water flowing into the disc was not the same as that coming into the test tank through the PVC hoses. This difference in temperature was detected by temporarily installing a thermocouple in an arbitrarily chosen PVC inlet hose. That temperature smearing was due to the large volume of water inside the disc compared to the volume of water that was coming in.

To overcome the problems of thermosiphoning and inlet temperature smearing, another distributor manifold was constructed. The new distributor was made out of 1.27 cm (0.5 in.) CPVC pipes that divides the incoming flow pipe into two pipes by means of a tee fitting, then each of the two pipes divides the flow into another two pipes and so on until 32 pipes are obtained which in turn connect to the 32 inlets at tank mid-height. At the end of each of the 32 CPVC pipes a gate valve was installed (see Fig. 3.7). The valves were fully closed during the side and top inlet runs

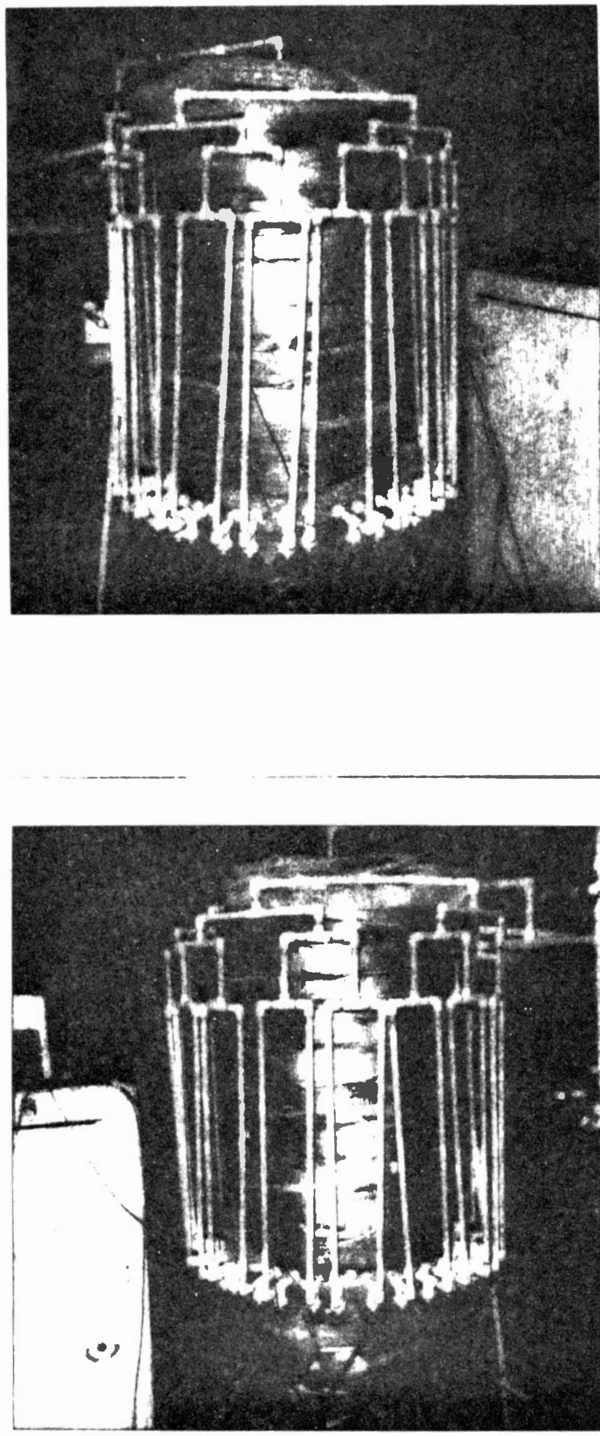


Figure 3.7 A Photograph of the Second Distributor Used.

in order to avoid thermosiphoning, but were fully open when the mid-height inlet was in use. It should be noted here that the small cross sectional area of the CPVC pipes had eliminated the temperature smearing.

3.2 Experimental Procedures

The procedures for data collection and reduction are described in the following steps:

3.2.1 Experimental Data Collection

1. The tap water settling tank is filled with water at least 24 hours before the experimental run is scheduled. It should be noted here that the capacity of the tank is enough to run two, or sometimes three, experiments.
2. The experimental flow rate and the inlet temperature profile are determined (an example of a variable inlet temperature profile is shown in Fig. 3.8). According to the inlet temperature profile, a temperature-time table is constructed (see Table I).
3. Both the water heater tank and the test tank are then filled with tap water. Then the heating elements are turned on as well as the circulation pump, so that the hot water will be at a uniform temperature before the start of the experiment.
4. The TI computer is then booted up with a system disk

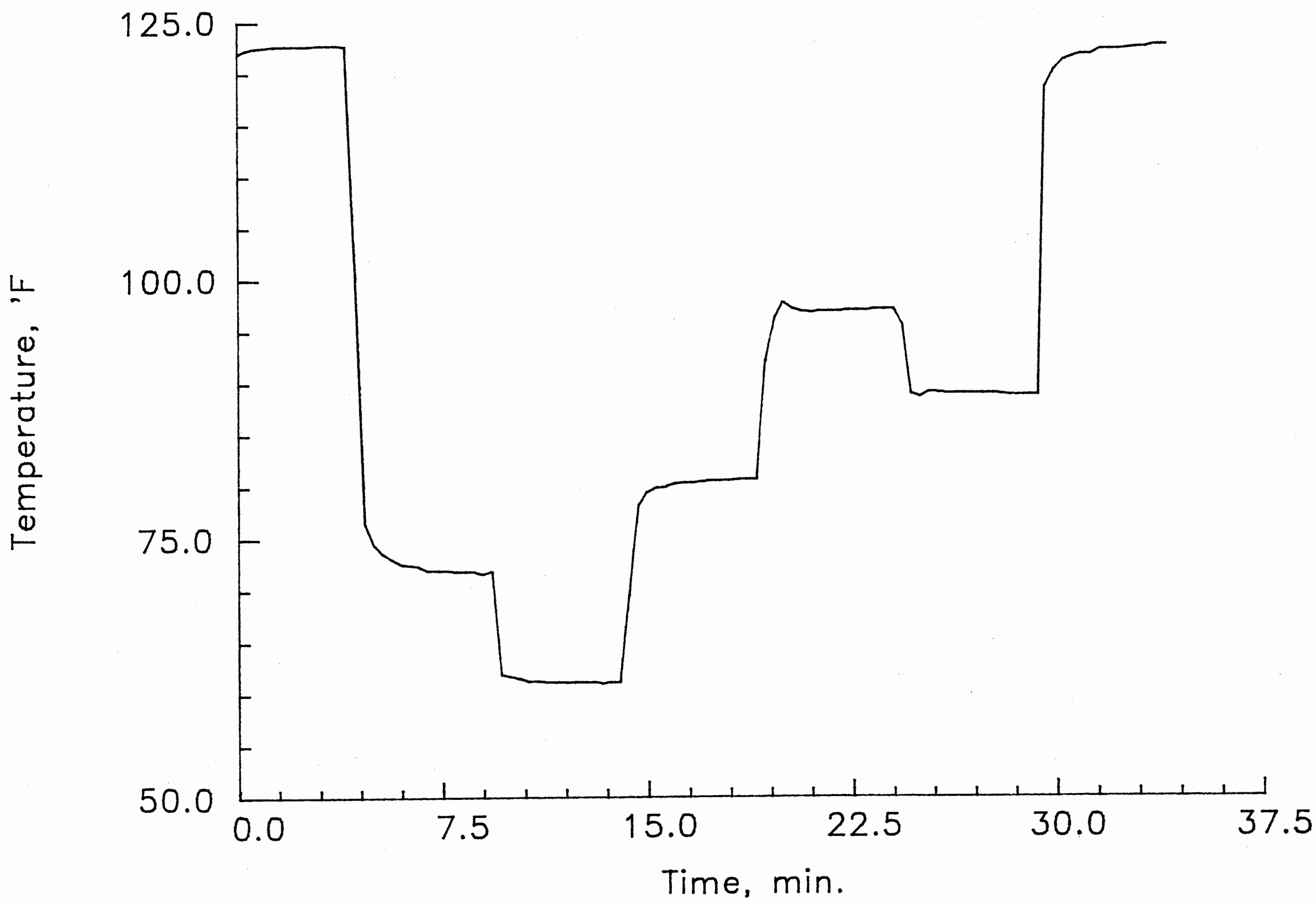


Figure 3.8 A Variable Inlet Temperature Profile.

TABLE I

EXAMPLE OF A TEMPERATURE-TIME TABLE
WHICH CORRESPONDS TO FIGURE 3.8

Time (min)	Temperature (°F)
1 - 5	120.0
5 - 10	70.0
10 - 15	60.0
15 - 20	80.0
20 - 25	97.0
25 - 30	90.0
30 - 35	120.0

that has a RAMDISK installed. This will allow the data logger to transfer the data to the RAMDISK which will be copied later to a floppy disk. The data logger is then turned on and set to the desired specifications.

5. The data transferring process starts by executing a batch file called LOG, the format of this command is:

   A>LOG B: filename.DAT

   the batch file, LOG, will then execute the communication software KERMIT so the RAMDISK will start receiving the transferred data; at the same time, the data will be printed on the screen (the process is terminated when the back slash key and the letter C are pressed at the same time. After doing so, the batch file will execute the copying command to copy the data from the RAMDISK to the floppy disk under the file name specified earlier).

6. While the data is being printed on the screen, the hot water temperature is monitored so when the required hot water temperature is reached the heating elements are turned off. Usually the required hot water temperature is the highest temperature on the inlet temperature profile.
7. When the required hot water temperature is reached, the valve on the circulation pipe is shut and the valve on the pipe that goes to the test tank is opened allowing the hot water to flow through the hot water flowmeter. The pump on the tap water settling tank is now turned on allowing the tap water to flow through the tap water flowmeter.
8. Based on the first entry on temperature-time table constructed in step # 2, the flow rates of the hot and tap water are determined by looking at the tables generated by the MIXING program (a complete description of the MIXING program along with a sample output can be found in Appendix B). While setting the flow rates, the 3-way valve should be in a position where all the water is flowing into the drain (see Fig. 3.1).
9. At this time, step # 5 should be repeated in order to start taking actual experimental readings but this time the return key should not be pressed after typing the command: A>LOG B: filename.DAT .

10. When both flow rates are set, the high or low flowmeter should be adjusted to the specified experiment flow rate, which is usually done by adjusting the gate valve on the drain pipe (see Fig. 3.1).
11. If all the flow rates are set and if the top or side inlet is used, the 3-way valve is now switched to the other position where all the water would flow into the test tank and at the same time the stop watch should be started and the return key is pressed on the computer keyboard. But if the distributor is being used, a time lag should be introduced between both switching the 3-way valve and starting the time on the stop watch and pressing the return key on the keyboard. The time lag (in minutes) is equal to the volume of the water inside the distributor, which is one gallon, divided by the volumetric flow rate in gallons per minute (GPM).
12. The tap water initially in the tank is now forced out and collected in the scaled catch tank. The collection of this water is done in order to find the average flow rate of the run since the flowmeter keeps fluctuating -sometimes due to the difference of the head on the pump and sometimes due to the operator when variable inlet temperature is used. The average flow rate is calculated by dividing the total volume in the catch tank by the total time of

the experiment read by the stop watch.

13. If variable inlet temperature is used, the flowmeters are adjusted during the run according to both the temperature-time table constructed in step # 2 and the MIXING program output. But if constant inlet temperature is to be used, nothing need to be done during the run except watching for fluctuations in the flowmeter reading when the pump head differs, so an adjustment can be done.
14. The end of the last entry on the temperature-time table plus the time lag introduced in the beginning of the run, if any, marks the end of the experiment. At this time the pumps are turned off, the timing is stopped, and the back slash along with the letter C are pressed on the keyboard to terminate the data collection process.

3.2.2 Experimental Data Reduction

The data collected using the above described procedures, can be reduced by the following steps:

1. The data is first reduced by executing the two softwares TVSTIME and SORT developed in Rao et al. (1988). The TVSTIME averages the four thermocouple readings in each level at each time step. The averaged temperatures are stored in nine data files as shown below:

AVEØ.DAT

AVE1.DAT

| |

AVE8.DAT.

AVEØ has the average temperatures of level 1 (TC 1, 11, 12, and 13); AVE1 has the temperatures of level 2 (TC 2, 14, 15, and 16); AVE2 has the temperatures of level 3 (TC 3, 17, 18, and 19), through AVE8 that has the temperatures of level 9 (TC 9, 35, 36, and 37). The SORT sorts out the data by writing the temperature of each thermocouple at each time step in a data file. The forty data files are:

CHAN_Ø.DAT

CHAN_1.DAT

| |

CHAN_39.DAT.

CHAN_Ø stores the inlet temperature; CHAN_1, 5, 9, 14, 18, 22 through 26, 3Ø, and 34 store the temperatures of the thermocouples that are extended Ø.5 inch; CHAN_4, 8, 11, 15, 19, 27, 31, and 35 store the temperatures of the thermocouples that are extended 2 inches; CHAN_3, 7, 12, 16, 2Ø, 28, 32, and 36 store the temperatures of the thermocouples that are extended 4 inches; CHAN_2, 6, 13, 17, 21, 29, 33, and 37 store the temperatures of the thermocouples that are extended 8 inches; CHAN_1Ø stores the outlet temperature; CHAN_38 stores the hot water temperature; and CHAN_39 stores the cold water temperature.

2. After the average and sort files are obtained, a program called LVL2DIM is executed to merge the temperatures of the inlet and the outlet (CHAN_Ø .DAT and CHAN_1Ø.DAT) into a data file called OUTPUT2.DAT (see Appendix C).
3. LVL2NDIM is then executed to obtain dimensionless temperatures for both inlet and outlet. The output of this program is stored in a data file called TDIME2.DAT (see Appendix C). This program will also print out on the screen the maximum and the minimum temperatures in the data file OUTPUT2.DAT, these temperatures will be used as an input in step # 5.
4. Another program called LVLDIM is executed, this program reads the average data files and merges them into one data file called OUTPUT.DAT (see Appendix C).
5. LVLNDIM is the last program executed to obtain the averaged temperatures in a dimensionless form. The execution of this program requires the maximum and minimum inlet and outlet temperatures found in step # 3 (see Appendix C).
6. The final step is to plot the data in a dimensionless form of $(T-T_{min})/(T_{max}-T_{min})$ versus Vt/H. A plotting routine called FPA (developed by

R.D. Delahoussaye, an instructor at the School of Mechanical and Aerospace Engineering, Oklahoma State University), was used to develop all of the plots throughout this thesis.

The results of the experimental runs that are collected and reduced using the foregoing procedures are presented and discussed in the next chapter.

CHAPTER IV

RESULTS AND DISCUSSION

Stratified thermal storage experiments (variable inlet temperature) were conducted for the charging mode of operation (the water fed into the thermal storage tank is at an equal or higher temperature than the initial temperature of the tank). The flow rates used ranged from 1.89 l/min (0.5 GPM) to 7.57 l/min (2.0 GPM) and different inlet temperature profiles were chosen randomly (see Tables II through V). The results from the outlined experiments followed by an interpretation of their significance to stratified thermal storage tanks are presented herein. This chapter is divided into the following sections: (1) static runs, (2) comparison of two different baffles, (3) parametric study, and (4) comparison of different inlet configurations.

4.1 Static Runs

The thermal storage test tank, described in Chapter III, was put under two static runs with no insulation around it. The two static runs were made to determine the heat loss from the thermal storage tank to the environment. In both runs, the test tank was filled with hot water at a temperature of about 65.6 ^{o}C (150 ^{o}F). In the first static run,

TABLE II

SUMMARY OF EXPERIMENTAL RUNS (SIDE INLET)

RUN NUMBER	FLOW RATE (GPM) MARKED	AVERAGE	INITIAL TEMP. ('F)	AMBIENT TEMP. ('F)	MAXIMUM TEMP. ('F)	MINIMUM TEMP. ('F)	INLET PROFILE
3	1.0	1.055	54.0	64.4	160.5	52.9	CONSTANT
4	1.0	1.001	53.0	65.3	105.5	52.8	VARIABLE
7	1.0	0.974	52.0	73.4	120.6	51.4	VARIABLE
8	0.5	0.446	54.0	73.4	119.9	53.2	VARIABLE
9	1.0	1.018	52.0	74.3	156.3	50.5	VARIABLE
10	1.0	1.011	52.0	74.3	161.8	50.5	CONSTANT
30	2.0	2.020	69.5	77.9	122.2	69.3	VARIABLE
31	1.0	1.013	69.0	77.9	123.8	68.5	VARIABLE
32	0.5	0.498	69.0	79.7	124.5	69.2	VARIABLE

TABLE III

SUMMARY OF EXPERIMENTAL RUNS (TOP INLET)

RUN NUMBER	FLOW RATE (GPM) MARKED	FLOW RATE (GPM) AVERAGE	INITIAL TEMP. ('F)	AMBIENT TEMP. ('F)	MAXIMUM TEMP. ('F)	MINIMUM TEMP. ('F)	INLET PROFILE
33	2.0	2.009	68.5	77.0	121.7	68.6	VARIABLE
34	1.0	0.973	69.0	80.6	120.9	68.9	VARIABLE
35	0.5	0.525	68.5	78.8	121.7	68.3	VARIABLE

TABLE IV

SUMMARY OF EXPERIMENTAL RUNS (SOLID BAFFLE)

RUN NUMBER	FLOW RATE (GPM)		INITIAL TEMP. ('F)	AMBIENT TEMP. ('F)	MAXIMUM TEMP. ('F)	MINIMUM TEMP. ('F)	INLET PROFILE
	MARKED	AVERAGE					
1	1.0	1.013	56.0	75.2	169.2	55.0	CONSTANT
2	1.0	0.998	53.0	69.8	147.1	52.8	VARIABLE
5	1.0	0.977	52.0	73.4	120.3	51.3	VARIABLE
6	0.5	0.525	52.0	73.4	120.1	51.2	VARIABLE
11	1.0	1.023	51.0	67.1	120.6	50.3	VARIABLE
12	1.5	1.475	48.0	72.5	106.1	47.9	VARIABLE
13	0.5	0.515	51.5	71.6	122.4	50.8	VARIABLE
14	2.0	2.044	53.5	77.0	122.8	52.9	VARIABLE
15	0.5	0.456	53.7	70.7	121.1	52.9	VARIABLE

TABLE V

SUMMARY OF EXPERIMENTAL RUNS (PERFORATED BAFFLE)

RUN NUMBER	FLOW RATE (GPM) MARKED	AVERAGE	INITIAL TEMP. ('F)	AMBIENT TEMP. ('F)	MAXIMUM TEMP. ('F)	MINIMUM TEMP. ('F)	INLET PROFILE
16	0.5	0.500	56.0	68.0	120.9	55.3	VARIABLE
17	1.0	0.993	56.0	68.9	121.1	55.9	VARIABLE
18	1.0	1.035	57.0	68.9	149.3	57.0	VARIABLE
19	2.0	2.046	57.0	68.9	126.9	55.7	VARIABLE
20	1.5	1.510	62.0	71.6	120.7	61.8	VARIABLE
21	1.0	1.035	67.0	75.2	123.1	65.2	VARIABLE
22	2.0	2.050	66.5	73.4	119.8	66.5	VARIABLE
23	0.5	0.521	66.5	78.8	121.6	66.5	VARIABLE
24	1.0	1.036	67.0	77.0	121.5	66.5	VARIABLE
25	2.0	2.084	68.0	76.1	121.3	67.6	VARIABLE
26	0.5	0.510	68.5	79.7	122.6	68.9	VARIABLE
27	2.0	2.008	69.0	78.8	120.2	68.7	VARIABLE
28	1.0	1.019	69.5	78.8	120.8	69.0	VARIABLE
29	0.5	0.502	67.0	77.9	121.3	67.3	VARIABLE

measurements were taken at 10 minute intervals for about 14 hours, while in the second static run, measurements were taken at 15 minute intervals for about 20 hours. Both runs took place inside a room of an ambient temperature of about 21.1 °C (70 °F). After the temperatures in the nine levels of the test tank (see Fig. 3.5) had been recorded, a computer code was written to determine the total amount of heat lost from each level and from the tank as a whole (see Appendix D). The results of the "HEATLOSS" program showed that the average heat loss rates from the test tank for the first and second static runs were 1640 and 1350 BTU/hr, respectively (see Section D.3). The reason that the heat loss rate is lower in the second case than that in the first is due to the total time of the run. Since the average heat loss rate is considered, one would expect to have a lower average heat loss rate over longer periods of time. In the first hour or two, the difference in temperatures between the water inside the tank and the ambient outside the tank is too big, so a higher heat loss rate is expected. However, as time passes by, a smaller difference is experienced and consequently smaller heat loss rate.

Plots of temperature versus the height of the tank for the two static runs are shown in Figures 4.1 and 4.2. It can be seen from the figures that the gap between each curve and the next keeps getting smaller and smaller as time progresses (from top to bottom), even though the time difference between each two consecutive curves is constant. Figures 4.1

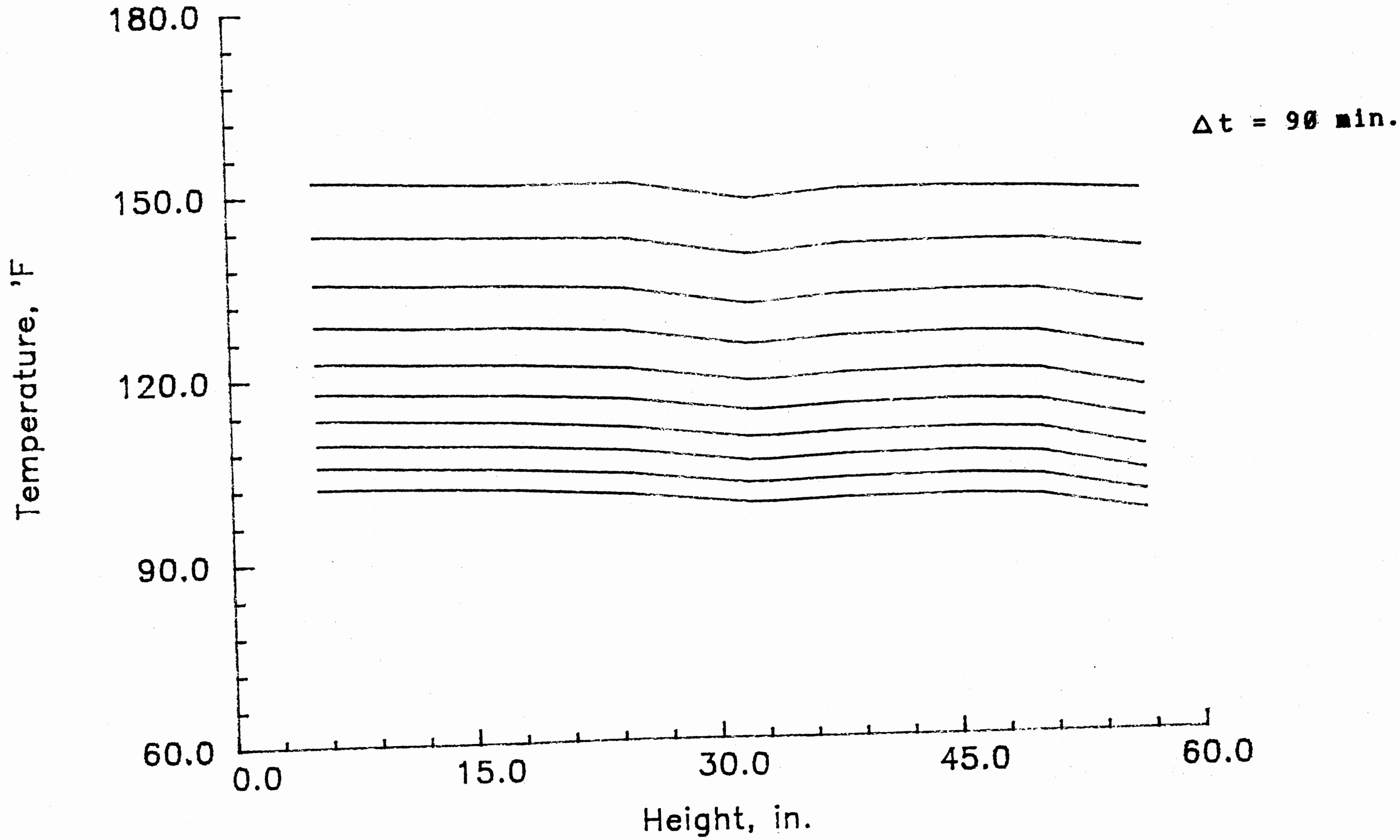


Figure 4.1 Static Run Temperature Profiles (Static Run # 1).

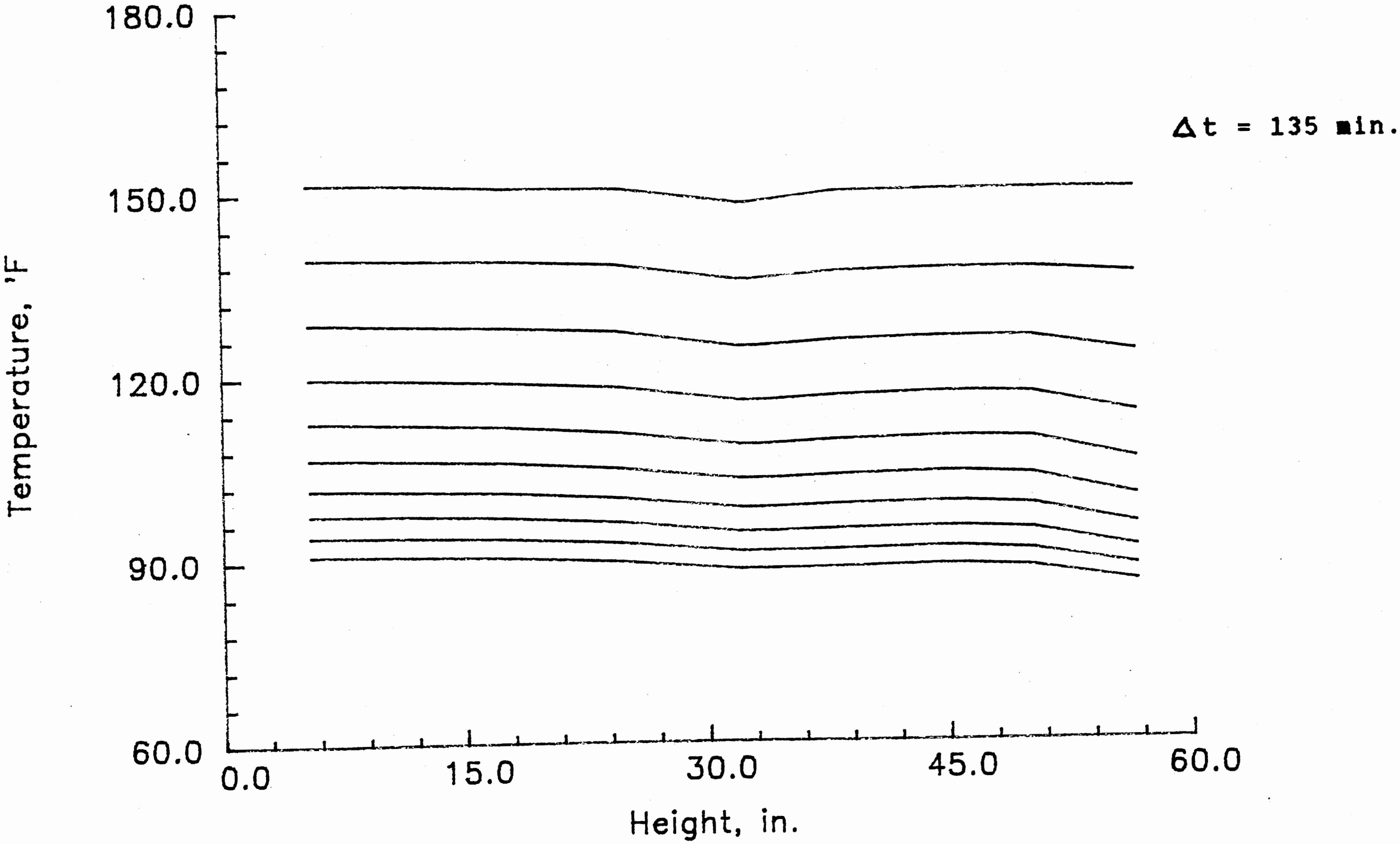


Figure 4.2 Static Run Temperature Profiles (Static Run # 2).

and 4.2 agree with what was stated earlier about the heat loss rate being lower over longer periods of time.

However, it is of interest to know how much heat is lost over the first few hours, specifically the first hour, since this is usually the actual run time of most of the experimental runs. The reason for this interest lies behind determining the critical thickness of the insulation that will minimize the heat loss to the ambient, and as a result minimize the loss in the thermodynamic availability.

The computer code "HEATLOSS" has an option of calculating the total amount of heat loss rate either over the whole period of run time or hour by hour. An hour by hour calculation was done (only over the first hour of the run) on both static runs. It was found that the total heat loss rates from the test tank for the first and second static runs were equal to 2460 and 2370 BTU/hr, respectively. The latter value being lower than the first value, also supports what was interpreted earlier about the heat loss rate being lower over longer periods of time.

The computed values of heat loss rate over the first hour were used to determine the critical thickness of the insulation. This was done by comparing the values obtained by the "HEATLOSS" program to those obtained by the program "INSUL" (developed by Zurigat and listed in Appendix A of Zurigat and Liche, 1987). The program "INSUL" figures the critical thickness of the insulation based on a minimum amount of heat loss to the ambient, which is usually a percentage chosen by the user (a value of 95% was used in this case). A thickness of 7.57 cm (3 in.) of Ø.27 k-factor fiberglass insulation was recommended.

After the insulation had been wrapped around the test tank, a duplicate experiment of static run # 2 was made to verify that the 7.57 cm (3 in.) insulation would suffice.

Figure 4.3 shows a plot of the temperatures of the nine levels inside the tank versus the height of the tank. Comparing Figure 4.3 to Figure 4.2, it can be noticed that the gap between each two successive curves had become much smaller, and a big difference in temperatures can not be noticed.

It can be concluded from the last static run that a 7.57 cm (3 in.) of Ø.27 k-factor fiberglass insulation is enough to reduce the heat loss to the ambient by an amount equal to 82% of the heat rate obtained in static run # 2.

4.2 Comparison of Two Different Baffles

Experimental runs were made on the two baffles, that were described in Chapter III (see Fig. 3.4), to determine which one of the baffles performs better under identical flow conditions (inlet temperature profile and flow rate).

Figures 4.4 and 4.5 show transient temperature profiles for a run conducted on the solid baffle and another on the perforated baffle design, respectively. Both runs had approximately the same inlet temperature profile and flow rate (≈ 1.5 GPM).

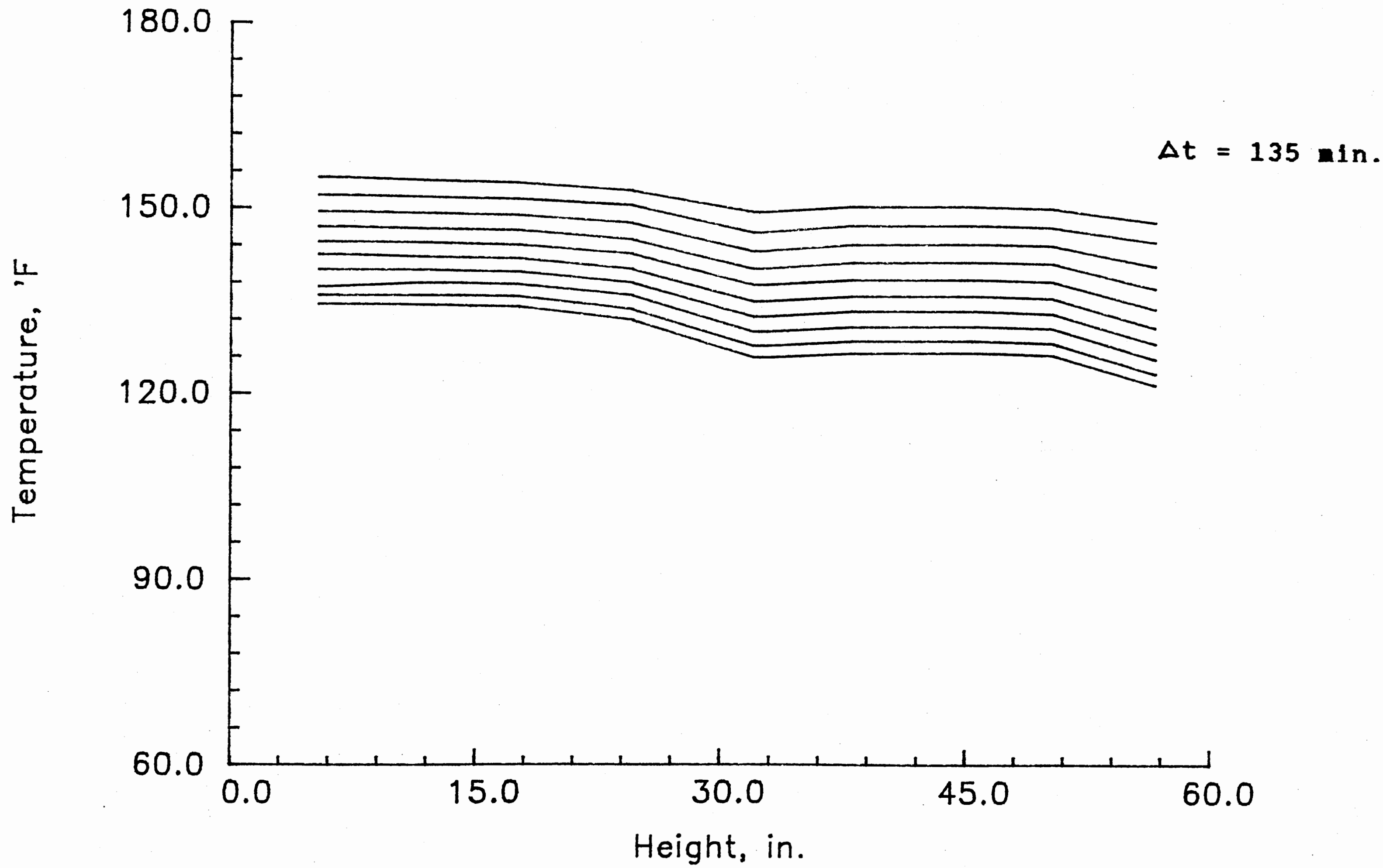


Figure 4.3 Static Run Temperature Profiles (Static Run # 3).

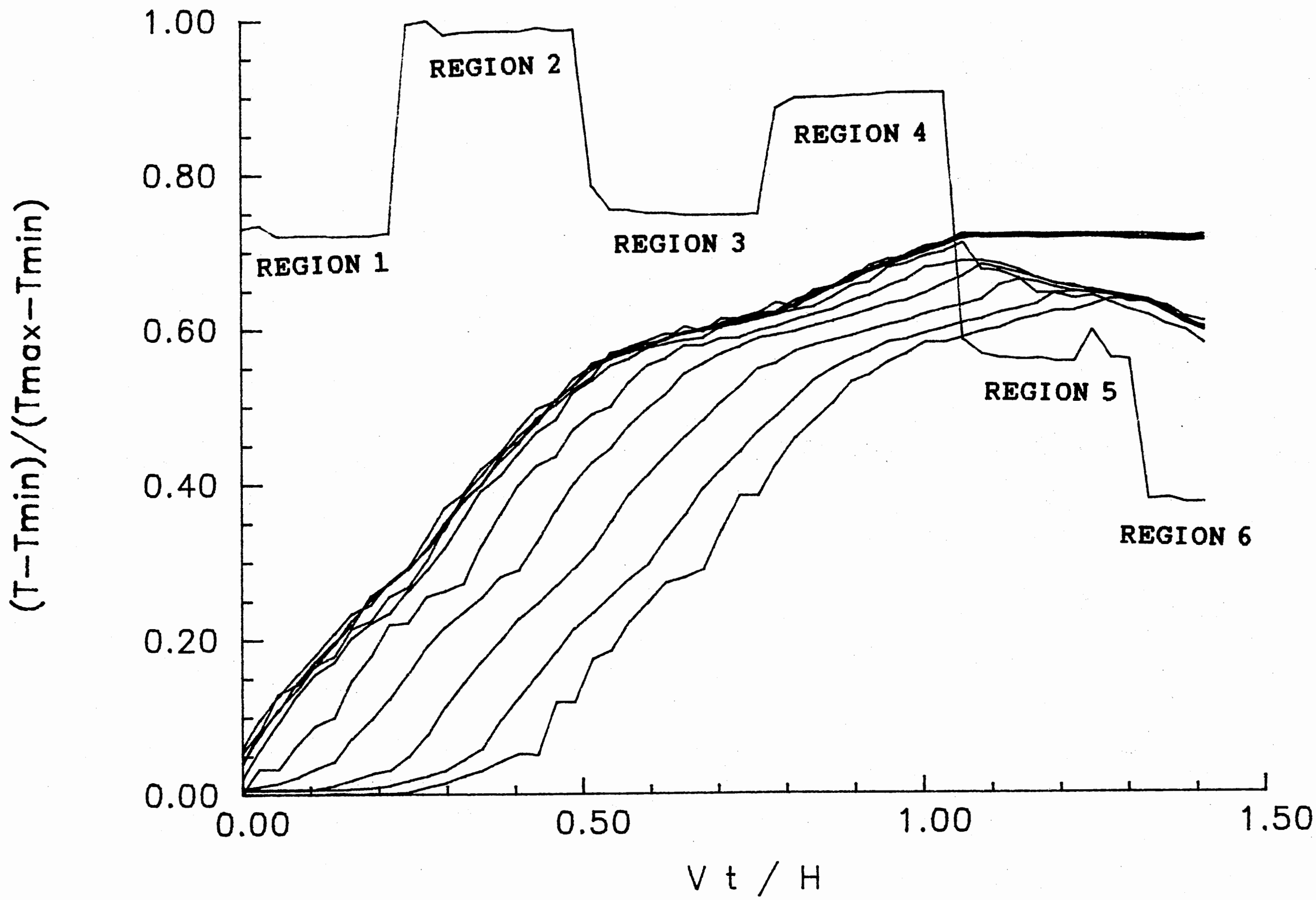


Figure 4.4 Transient Temperature Profile (Run # 12).

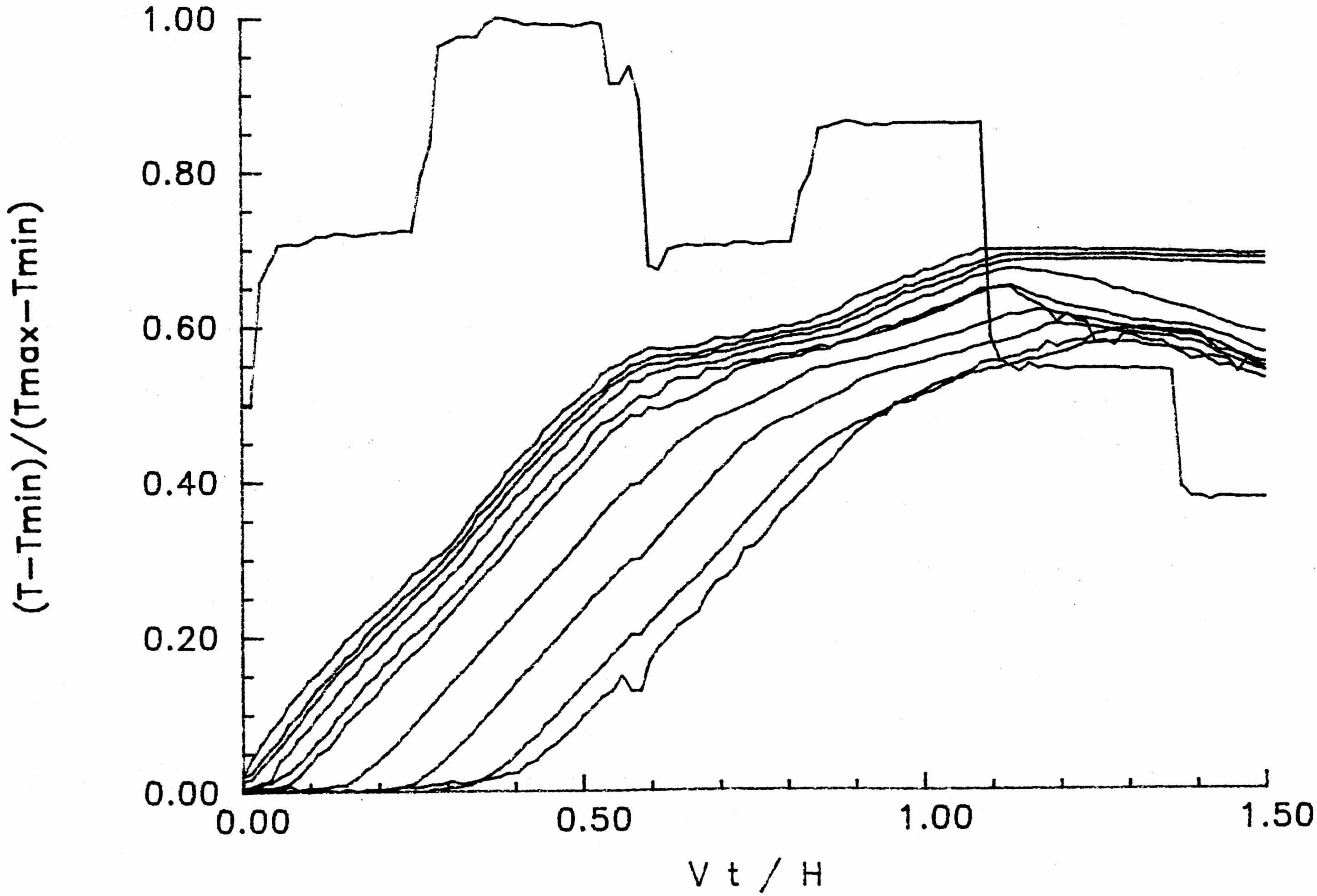


Figure 4.5 Transient Temperature Profile (Run # 2Ø).

Before discussing these figures in detail, it would be helpful to explain what the curves on these figures represent. On each transient temperature profile shown in this study, eleven curves are plotted; the first curve, which has the step changes, represents the inlet temperature profile; the last curve represents the outlet temperature profile, and the nine curves between the inlet and the outlet profiles represent the nine thermocouple levels inside the test tank (see Fig. 3.5). In these figures, the ordinate is a dimensionless temperature that is defined in terms of the maximum and the minimum temperatures for a particular experimental run which can be found in Tables II through V. The abscissa is a dimensionless time defined in terms of the velocity, V, which can be solved for from the average flow rate also given in Tables II through V for a particular experimental run, and the total height of the tank, H.

From Figures 4.4 and 4.5, it can be noticed that in the first two regions (the first two step changes in the inlet temperature profile), where the inlet temperature is much higher than the initial temperature inside the tank, a sharp increase in the fluid temperature had occurred. The increase in the fluid temperature had occurred rather rapidly in the first five thermocouple levels compared to that in the last four thermocouple levels. This observation can be explained if natural buoyancy and momentum phenomena are considered.

When the fluid enters the tank, the momentum carried with the fluid gets diffused, in both directions (upwards and downwards), as soon as the fluid hits the baffle; if the entering fluid is at a higher temperature than that of the existing fluid inside the tank, natural buoyancy will force the fluid to travel upwards; on the other hand, if the entering fluid is at a lower temperature than that of the existing fluid inside the tank, natural buoyancy tends to drive the fluid downwards.

In the figures considered (4.4 and 4.5), the inlet temperature was higher, in the first two regions, than the existing water temperature, so both natural buoyancy and part of the momentum forces had driven some of the fluid upwards, while only the part of the momentum force that was carried with the fluid that went downwards, had forced the rest of the fluid to travel downwards. The fluid that had travelled downwards, as soon as it finds a way to travel to a higher temperature level, where it belongs, it will take it. The only way after travelling downwards is the end of the solid baffle -or the beginning of the perforations in the perforated baffle design (see Fig. 3.4). Travelling that way, the fluid is going to pass through some levels of unlike temperature causing mixing and / or circulation zones in all the levels it passes through. Mixing and circulation zones are not favored in storage tanks, because, as explained earlier, loss in the thermodynamic availability is more likely to occur.

In the third region, less temperature difference between the inlet and the existing water temperature is found. This caused a less steep slope in the temperature curves. It can be noticed here that the temperatures are still increasing because the inlet temperature is still at a higher temperature than that inside the tank.

In the fourth region, the temperature difference is back up again, which causes the slope in the temperature curves to steepen.

In the fifth and sixth regions, the situation is reversed, the inlet temperature has dropped below the temperatures of all the nine levels; now both natural buoyancy and part of the momentum are acting downwards, while only the part of the momentum that was carried with the fluid that went upwards, is acting in the upward direction. Since the flow rate was not high enough (≈ 1.5 GPM), only the fourth level was cooled off (see the fifth and sixth regions of Figure 4.5), and the rest of the levels in the top half of the tank (levels 1, 2, and 3) kept on having the same temperatures. It can be also noticed that the bottom half of the tank had cooled off considerably.

So far the effect of the different baffle designs used has not been discussed. A closer look at the first five levels of Figures 4.4 and 4.5 will show the effect. Figure 4.4 shows that the first five levels are nearly at the same temperature, at least in the first four regions; and the levels cannot be distinguished from one another. On the contrary, by looking at Figure 4.5, it can be seen that the first five levels can be distinguished from one another, which means that the levels differ in temperature. The temperature difference between the different levels, which was defined earlier in Chapter I as stratification, was increased when the perforated baffle was used. The perforations in the baffle restrained some of the fluid going upwards from mixing with the fluid of unlike temperature, and permitted mixing to occur only in the regions between the inside wall of the tank and the outside wall of the perforated baffle.

Figures 4.6 and 4.7 are another example that show the same occurrences. The figures show the transient temperature profiles for two runs made under approximately identical flow rate (≈ 1.0 GPM) and inlet temperature profile; the first (see Fig. 4.6) utilized the solid baffle, while the second (see Fig. 4.7) utilized the perforated baffle. One observation worth mentioning in here, besides the observations mentioned about the previous set of figures, is that the temperatures in both Figures 4.6 and 4.7, were not as high as the temperatures in the previous two runs. This is due to the inlet temperature profile which provided a higher energy input to the storage tank in the first case (Figures 4.4 and 4.5) than that in the second case (Figures 4.6 and 4.7).

Two other runs were compared, but this time a higher flow rate was used (≈ 2.0 GPM). Figures 4.8 and 4.9 basically reveal the same observations that were seen earlier in the previous two sets. One more observation needs to be

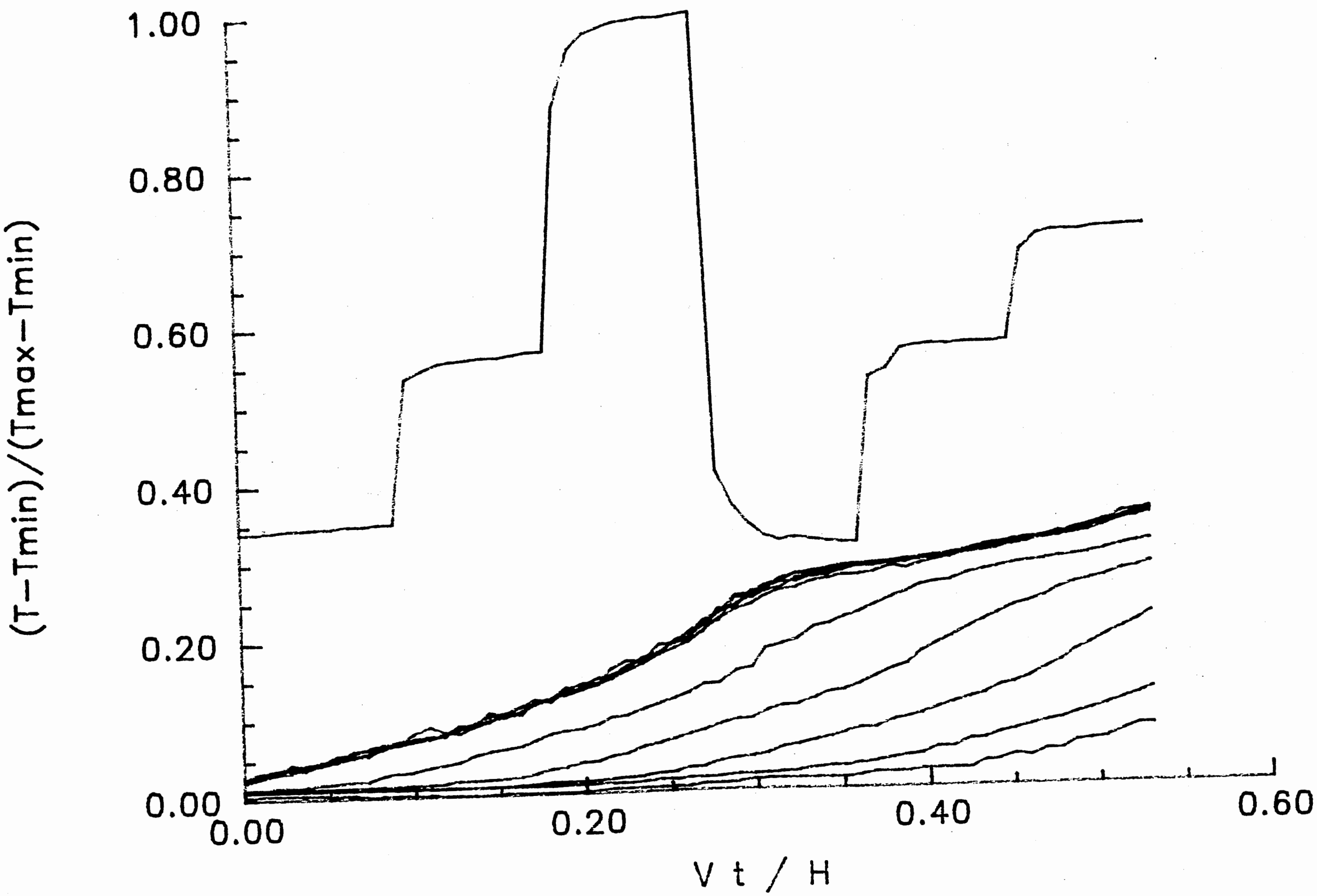


Figure 4.6 Transient Temperature Profile (Run # 5).

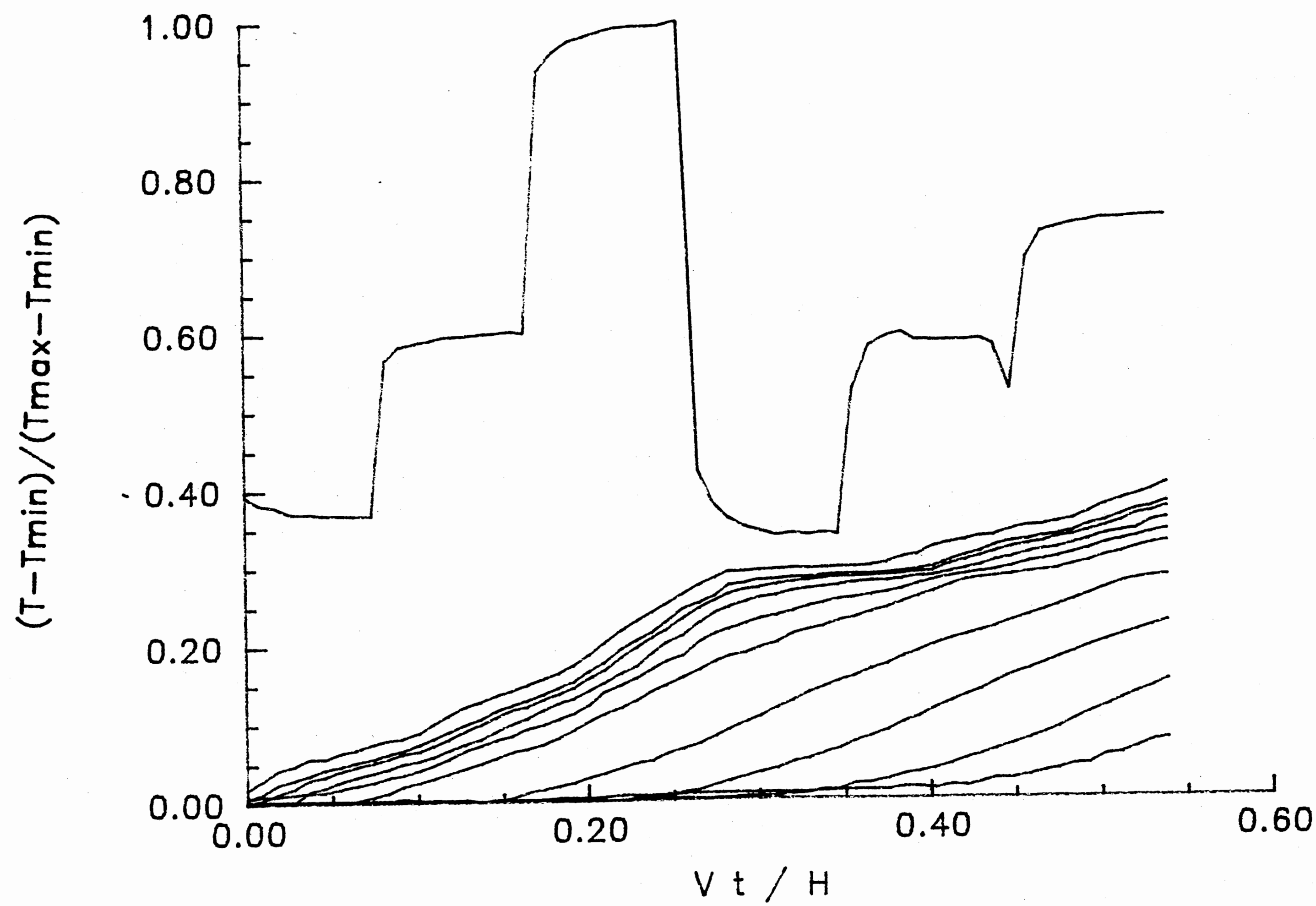


Figure 4.7 Transient Temperature Profile (Run # 17).

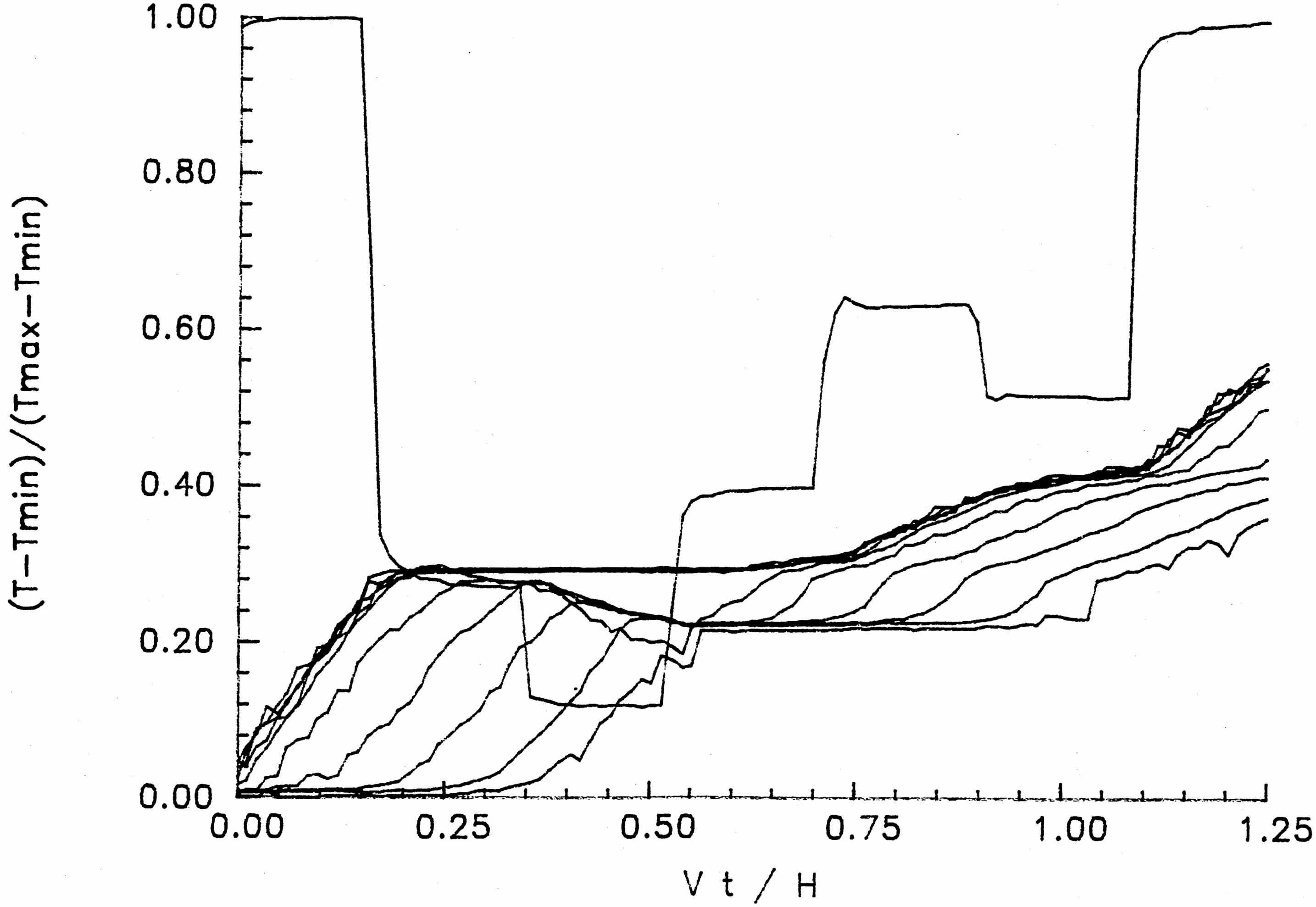


Figure 4.8 Transient Temperature Profile (Run # 14).

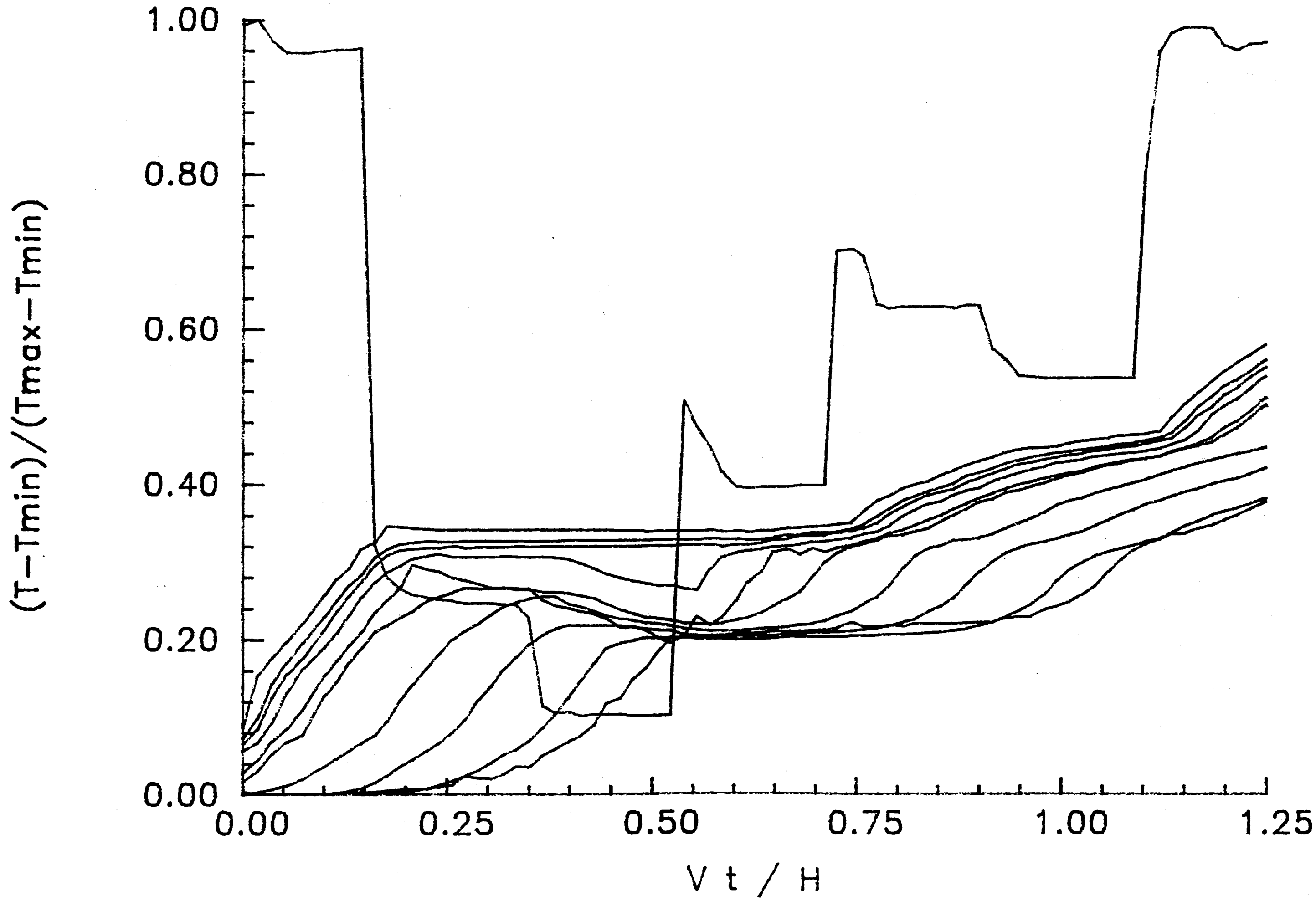


Figure 4.9 Transient Temperature Profile (Run # 19).

added here. Even though the flow rate was doubled, the momentum of the flow was not enough to let the fluid reach higher than level four and cool it off. This observation can be seen clearly by looking at regions two and three of the inlet temperature profile in Figure 4.9.

It can be concluded from the past discussion (see Figures 4.4 through 4.9) that the perforated baffle design had not improved stratification appreciably. The reason that the perforated baffle did not perform as it was expected is mainly due to mixing plus two other contributions: the first is the material that the baffle was made off; the second is the wall thickness of the baffle. First, the material was black iron, which has a higher conductivity compared to that of water. So the walls of the perforated baffle would transfer the heat by vertical (axial) conduction from the hot water layers to the cold layers faster than the water would. Second, the thickness of the wall of the perforated baffle was too small. This would help in increasing the radial conduction through the walls of the baffle, and consequently transfer the heat from the water that is entraped in the annulus to the water levels inside the test tank. Thus, heat transfer, either by radial or vertical conduction, works against the purpose of thermal storage.

4.3 Parametric Study

A total of nine experimental runs (see Figures 4.10 through 4.18) were made for the purpose of parametric study.

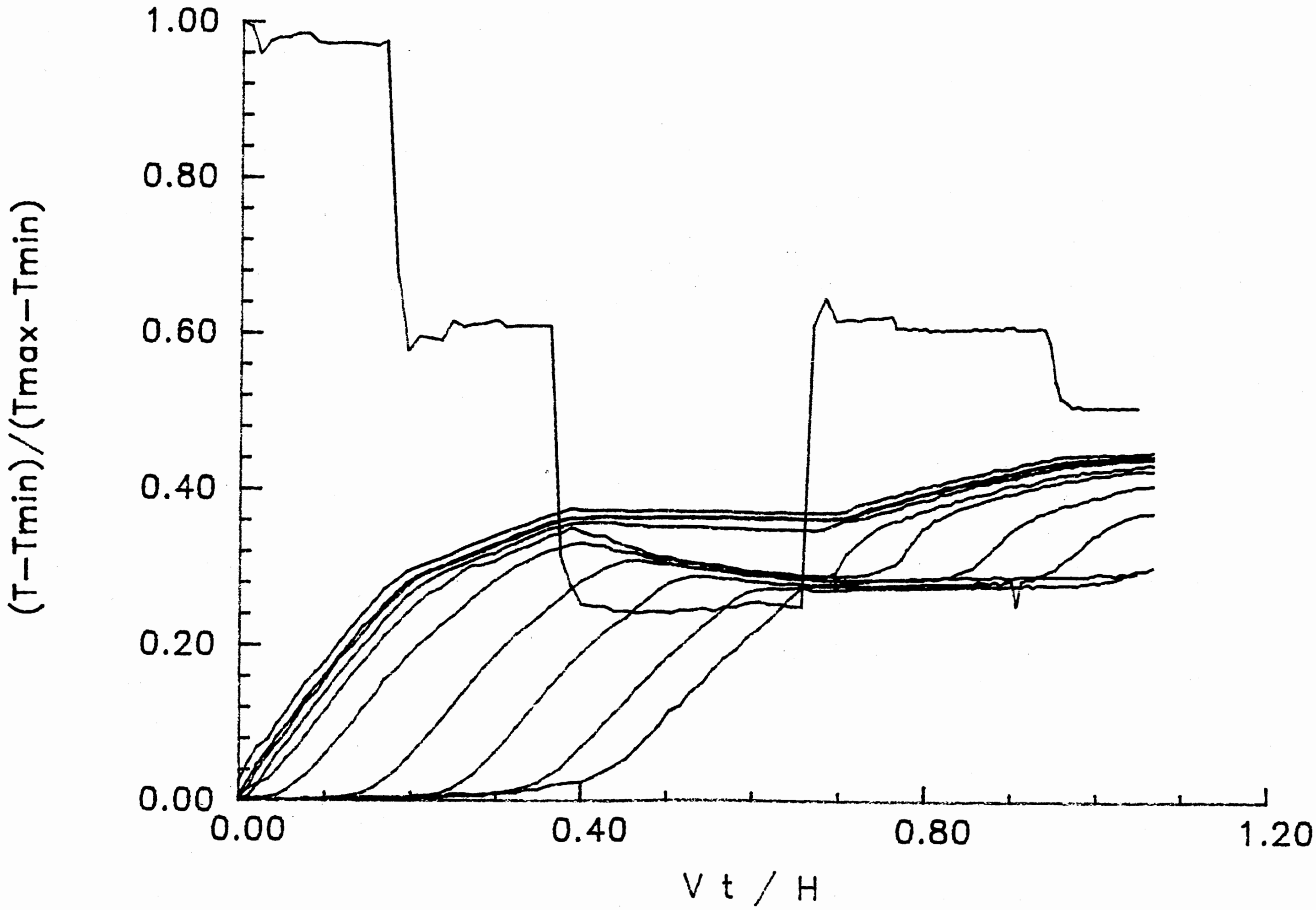


Figure 4.1Ø Transient Temperature Profile (Run # 23).

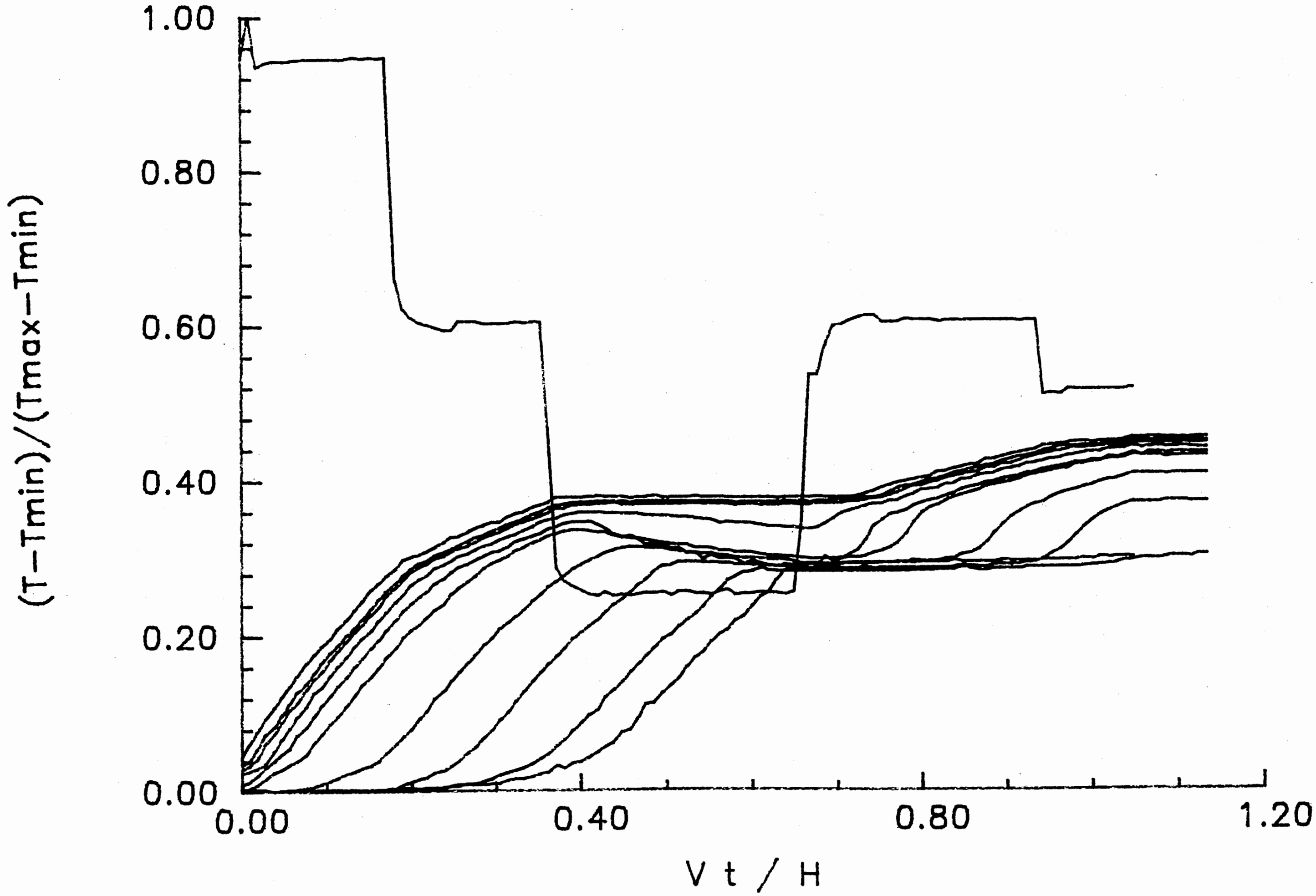


Figure 4.11 Transient Temperature Profile (Run # 21).

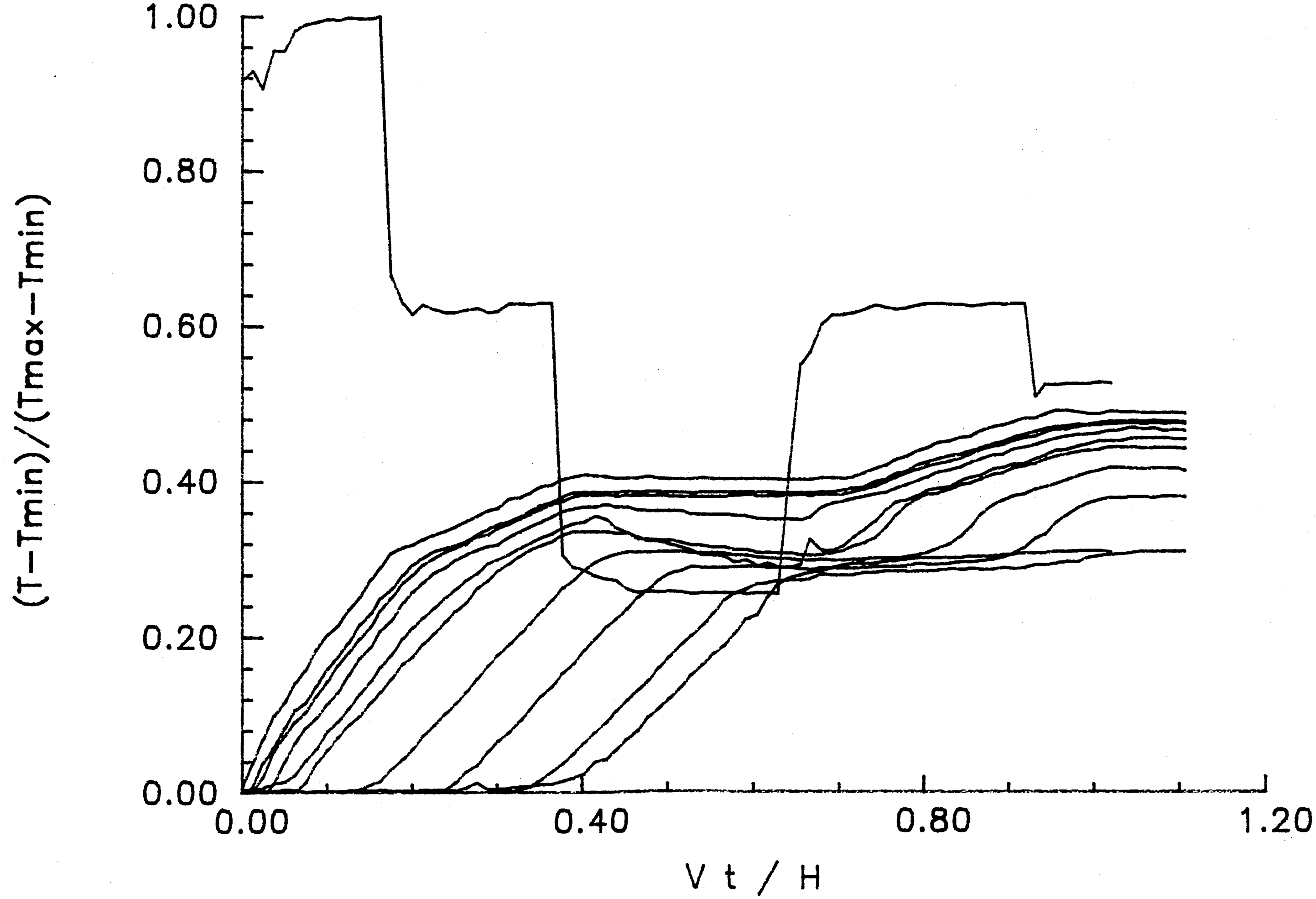


Figure 4.12 Transient Temperature Profile (Run # 22).

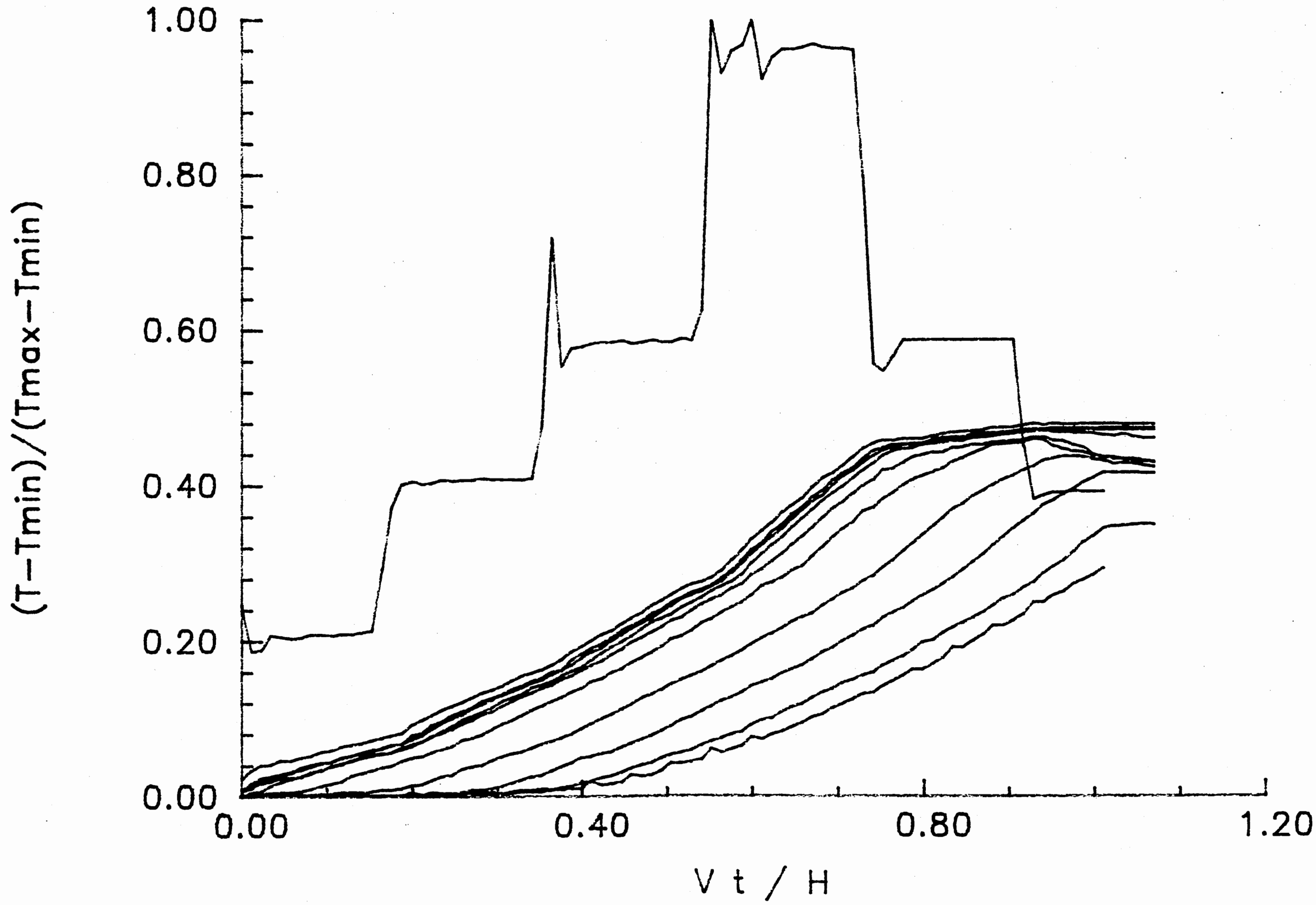


Figure 4.13 Transient Temperature Profile (Run # 26).

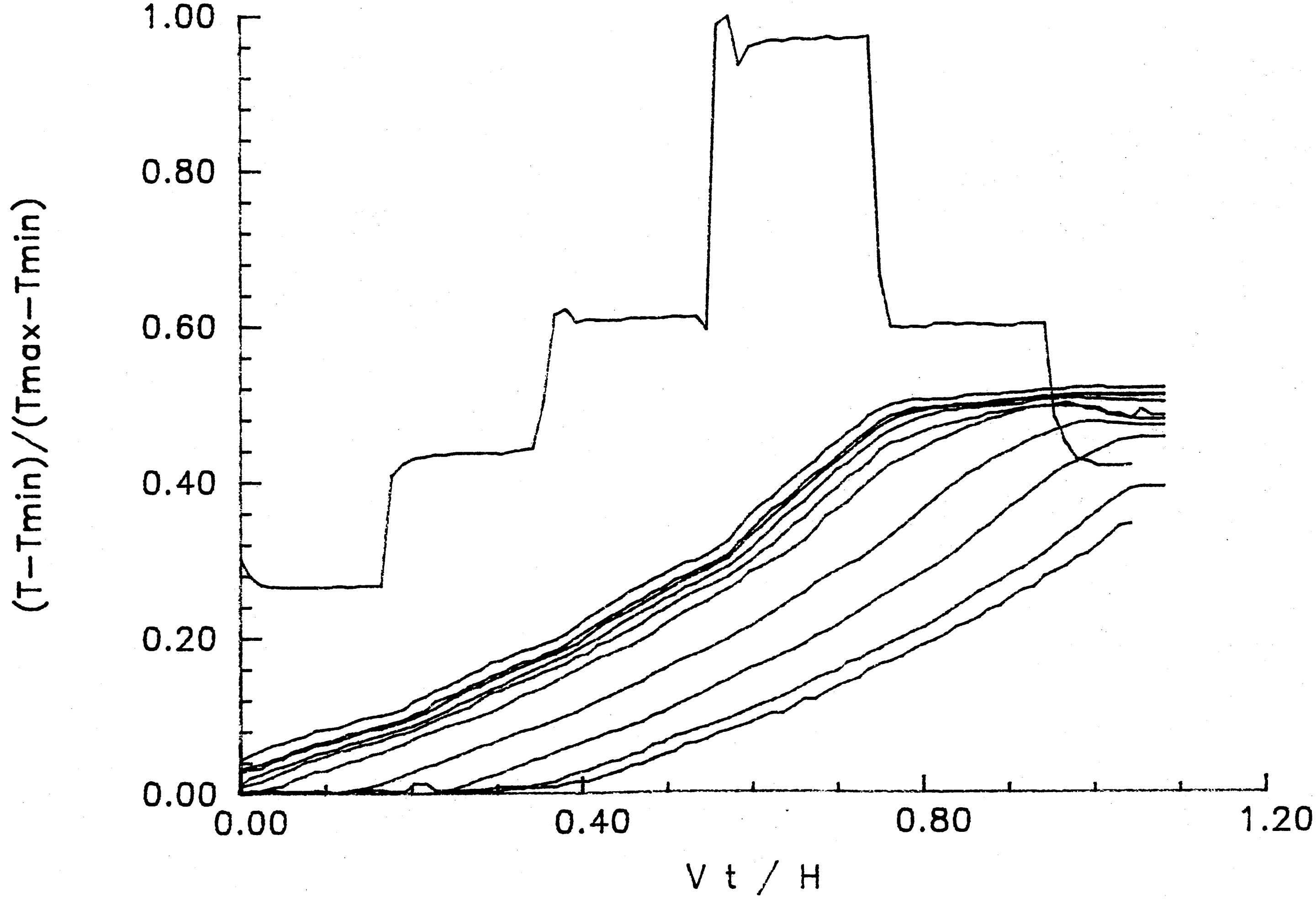


Figure 4.14 Transient Temperature Profile (Run # 24).

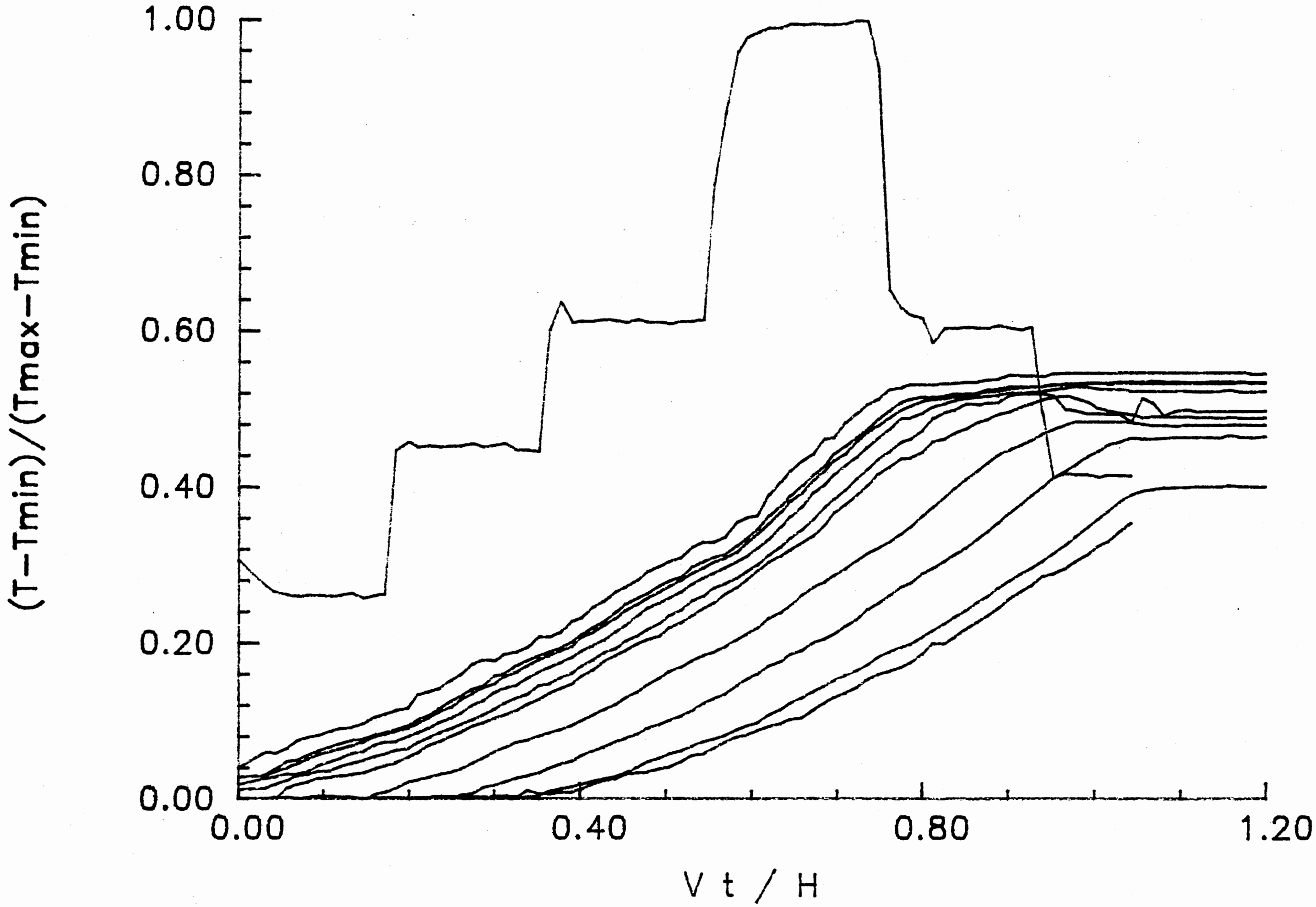


Figure 4.15 Transient Temperature Profile (Run # 25).

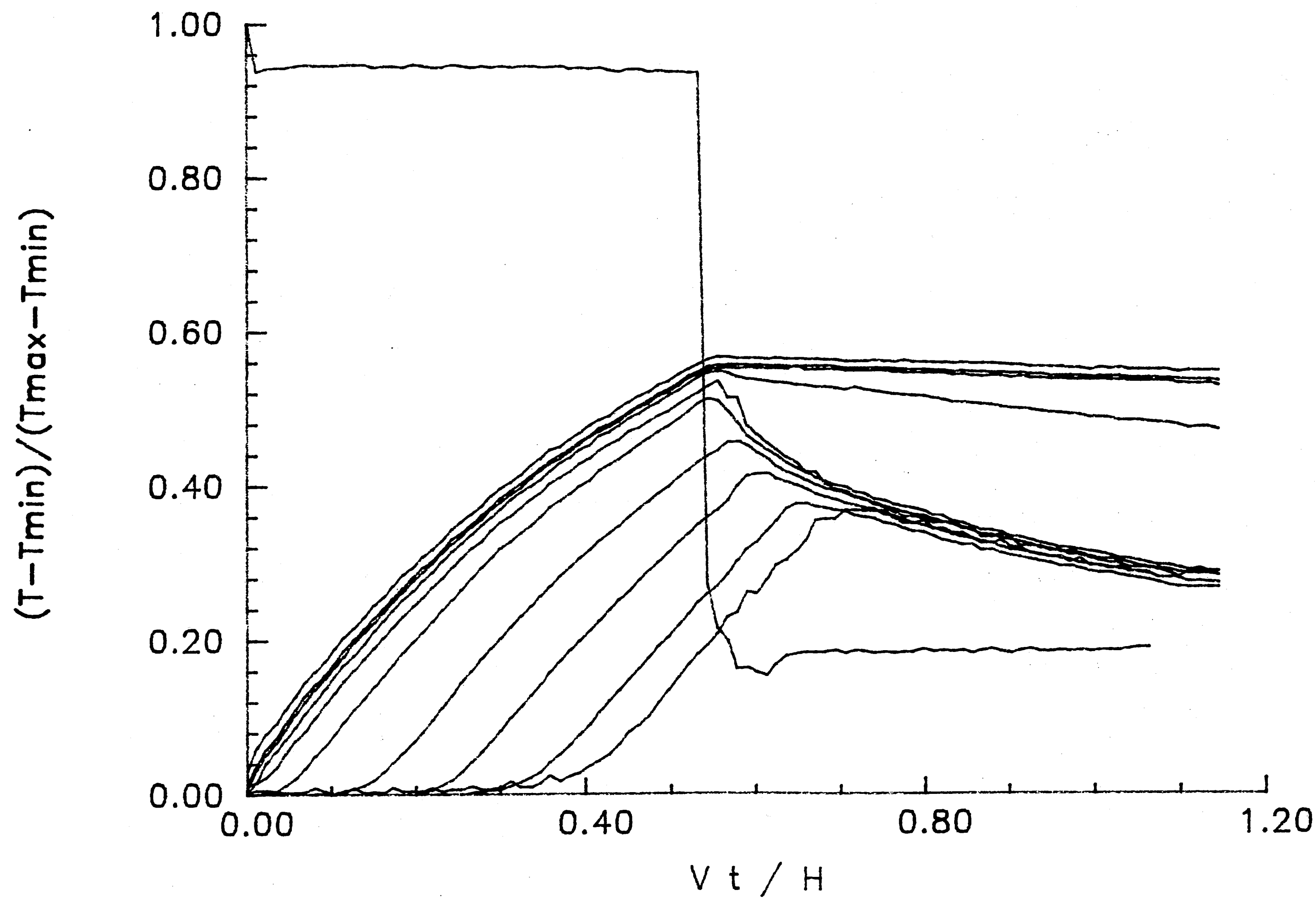


Figure 4.16 Transient Temperature Profile (Run # 29).

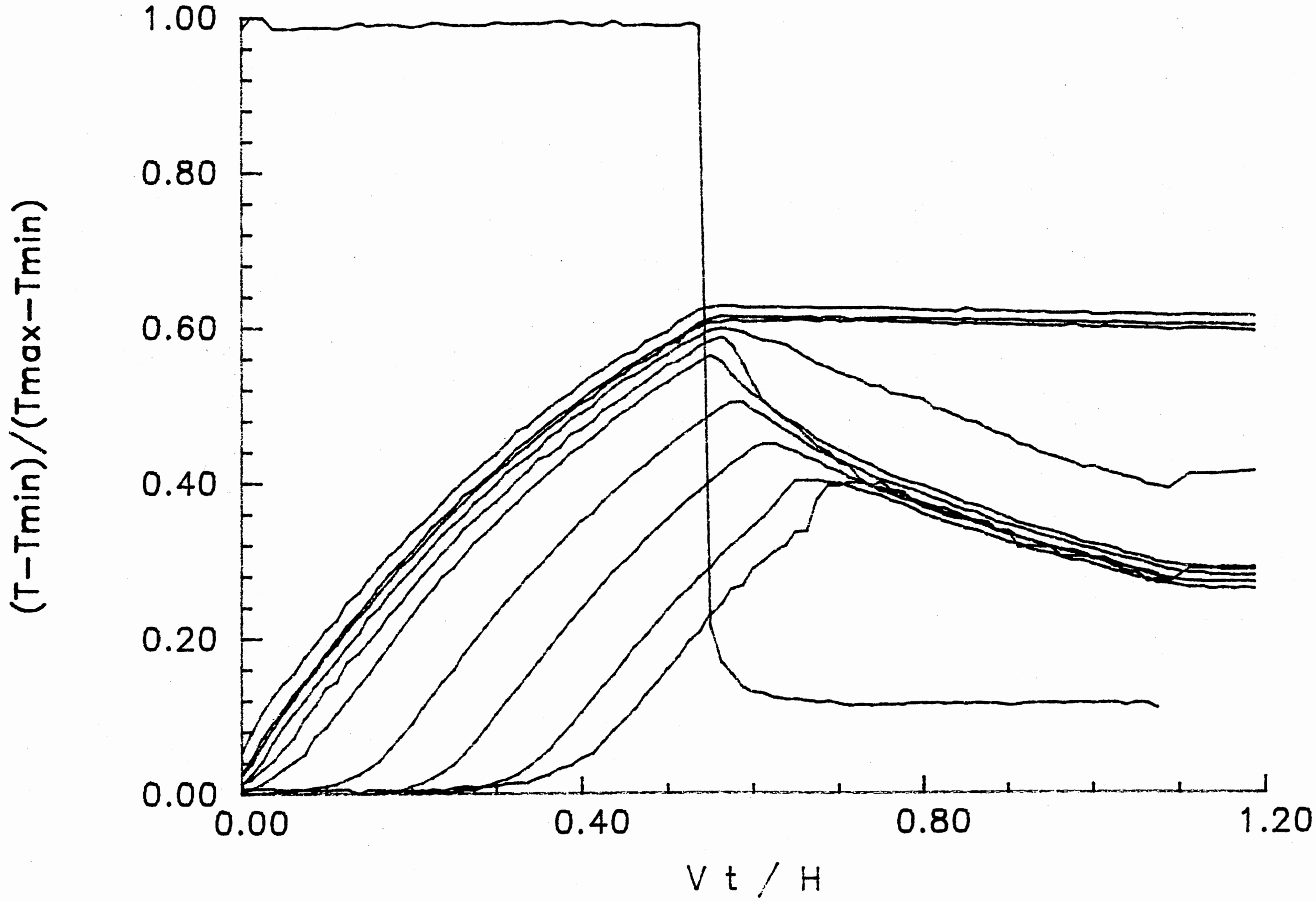


Figure 4.17 Transient Temperature Profile (Run # 28).

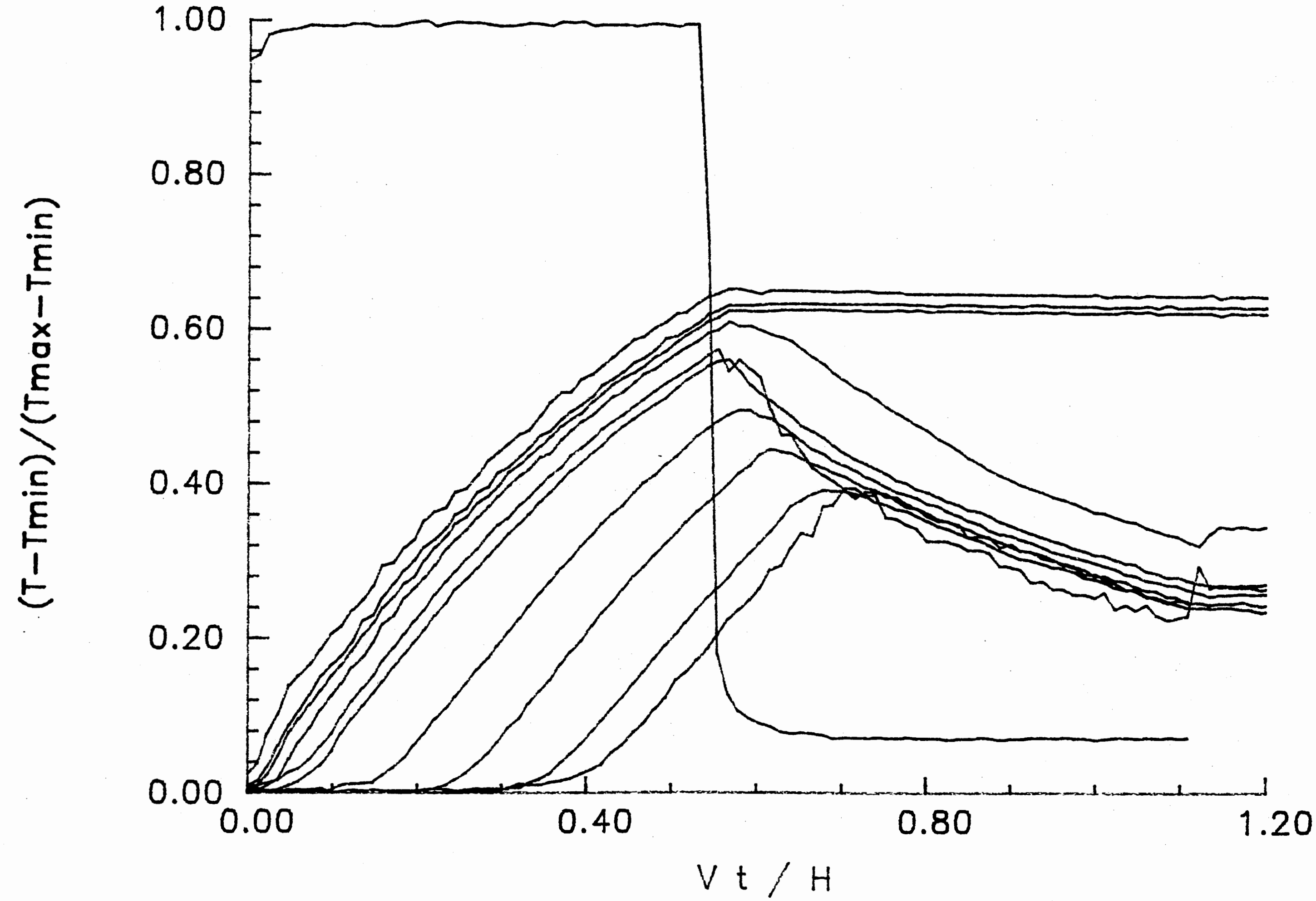


Figure 4.18 Transient Temperature Profile (Run # 27).

All of the experimental runs were conducted on the perforated baffle with variable inlet temperature profile.

In order to perform a parametric study on a thermal energy storage system, the energy input provided to the storage tank has to be the same in all of the experimental runs compared. The way this was done, was to increase (decrease) the time of each step change in the inlet temperature profile by an amount equal to the inverse of the ratio by which the flow rate was decreased (increased); for example, if for a certain step change in the inlet temperature profile the temperature was equal to 100 °F for a period of 5 minutes at a flow rate of 1.0 GPM, the period would be increased to 10 minutes at a reduced flow rate of 0.5 GPM, or vice versa.

A new feature was added to the present sets of experimental runs which was a short term static run. The static run was done right after the pump was switched off, and would usually last for approximately five minutes. The purpose of this static run was to show whether or not the fluid temperatures inside the test tank were affected by internal convective motions while the storage tank was not in use. Results, presented in Figures 4.10 through 4.18, indicate that no such motions as internal convective motions were present when the pump was switched off, which indicates the existence of stable stratification inside the test tank.

In this parametric study, the following three parameters were studied: first, the effect of different flow rates on stratification; second, the effect of different inlet temperature profiles on stratification; and third, the effects of flow rate and stratification on the solar collector efficiency, η_i.

4.3.1 Effect of Flow Rate on Stratification

The effect of flow rate on stratification was determined by choosing three different inlet temperature profiles, and for each inlet temperature profile, three flow rates of 0.5, 1.0, and 2.0 GPM were tested.

Figures 4.10, 4.11, and 4.12 show the transient temperature profiles for the three experimental runs tested with flow rates of 0.5, 1.0, and 2.0 GPM, respectively, and approximately the same inlet temperature profile. It can be noticed from the figures that as the flow rate increases, the temperature difference between each two successive levels also increases. The reason that this higher temperature difference occurs is that the fluid flowing at a higher flow rate (velocity), is going to reach its appropriate level of stratification faster than the fluid flowing at a lower flow rate.

Flowing at a higher flow rate in the annulus has a big advantage which is, the fluid that is entering at a high flow rate, i.e., 2.0 GPM, would not lose too much energy in travelling inside the annulus before it reaches its appropriate level of stratification; while the fluid entering at a low flow rate, i.e., 0.5 GPM, would experience more heat loss due to mixing because it would take it longer to reach its appropriate level of stratification.

The same behavior can be detected by looking at another set of runs which had a different inlet temperature profile. Figures 4.13, 4.14, and 4.15 show the transient temperature profiles for the three experimental runs with flow rates of 0.5, 1.0, and 2.0 GPM, respectively.

Finally, the last set of experimental runs are shown in Figures 4.16, 4.17, and 4.18 for flow rates of 0.5, 1.0, and 2.0 GPM, respectively. In these figures yet another inlet temperature profile had been used. The same observations in the previous two sets were also seen in here. One additional observation was seen in the last set of figures which is at a high flow rate ($\approx$ 2.0 GPM), the entering fluid in the second region of Figure 4.18, had cooled down the temperatures of the fourth level to lower temperatures as compared to those at the lower flow rate (see Figures 4.16 and 4.17). The reason for this behavior is the high flow rate that the entering fluid had.

4.3.2 Effect of Inlet Temperature on Stratification

Now let us find out how would the variations in the inlet temperature profile affect the stratification inside the test tank.

Looking at Figures 4.10, 4.13, and 4.16, in which all had a flow rate of about 0.5 GPM, it can be observed that when the inlet temperature is much higher than the temperatures at all of the nine levels (see the first two regions of Fig. 4.10, the fourth region of Fig 4.13, and the first region of Fig. 4.16), a sharp increase in fluid temperature was experienced. But when the differences in temperature between the entering fluid and the existing fluid were small (see the second and the fifth region of Fig. 4.10, and the first and the fifth region of Fig. 4.13), less sharp increase were obtained - an observation which was also made in the figures (Figures 4.4 through 4.9) which compared the two baffles in the previous section.

One other observation can be also noticed here. Whenever the entering temperature is at a higher temperature than the existing fluid temperature inside the tank, the temperatures of the first five levels, top half of the tank, were closer to one another; on the other hand, whenever the entering temperature is at a lower temperature than the existing fluid temperature inside the tank, the temperatures of the last five levels of the tank, bottom half of the tank, were closer to one another and the top half of the tank did not experience major changes in temperature. This effect can be clearly seen in the third region of Fig. 4.10 and in the second region of Fig. 4.16.

It is interesting to notice by looking at Figures 4.10, 4.13, and 4.16, that when the inlet temperature had gone below the existing fluid temperature inside the tank (see the third region of Fig. 4.10, the sixth region of Fig. 4.13, and the second region of Fig. 4.16), only the temperature at the fourth level of Fig. 4.16 was cooled down as compared to the temperatures at the same level in the regions mentioned in Figures 4.10 and 4.13, even though the flow rate was approximately the same in all three cases. The reason for this occurrence is that the difference in temperatures between the inlet temperature and the existing fluid temperature (in the regions mentioned), was higher in Fig. 4.16 as compared to those in Figures 4.10 and 4.13 so less energy input was provided.

4.3.3 Effects of Flow Rate and Stratification on Solar Collector Efficiency

Usually, thermal energy storage tanks are used in conjunction with solar collector systems. In order to assess such a system, the effects of flow rate and stratification on solar collector efficiency should be investigated. To perform such a study, a flat plate solar collector model developed by Zurigat (1988b) and coded by the author (see Appendix E), was used with the aid of the previous nine experimental runs (see Figures 4.10 through 4.18). The computer code has the capability of calculating the efficiency of a solar collector in two ways. The first is due to stratification and flow rate combined. The second is due to stratification only. The latter was done by inputing the storage tank outlet temperature as the collector inlet temperature using the same flow rate for all the experimental runs compared; while for the former, the actual average flow rates were used.

Figure 4.19 shows the combined efficiency curves for the first set of experimental runs compared in this section (see Figures 4.10, 4.11, and 4.12). The figure shows that for the high flow rate case (≈ 2.0 GPM), the efficiency of the collector was the highest at all times, followed by the medium flow rate (≈ 1.0 GPM), and then the lowest efficiency was for the low flow rate (≈ 0.5 GPM).

The reason that the efficiency of the collector is increased as the flow rate is increased is that the temperature rise through the collector is decreased, causing the average temperature in the collector to drop, and consequently the heat losses to the ambient are decreased. As the heat losses decrease, an increase in the actual useful energy gain would occur resulting in a higher collector efficiency (Duffie and Beckman, 1980).

Figures 4.20 and 4.21 show the combined efficiency curves for the second set (see Figures 4.13, 4.14, and 4.15) and the third set (see Figures 4.16, 4.17, and 4.18) of experiments, respectively. The figures show the same trend seen earlier.

In order to show the effect of stratification alone isolated from the effect of the flow rate, Figures 4.22, 4.23, and 4.24 are presented for the three sets of experiments conducted for the present parametric study. The figures show that the efficiency of the collector due to stratification was approximately equal at all of the

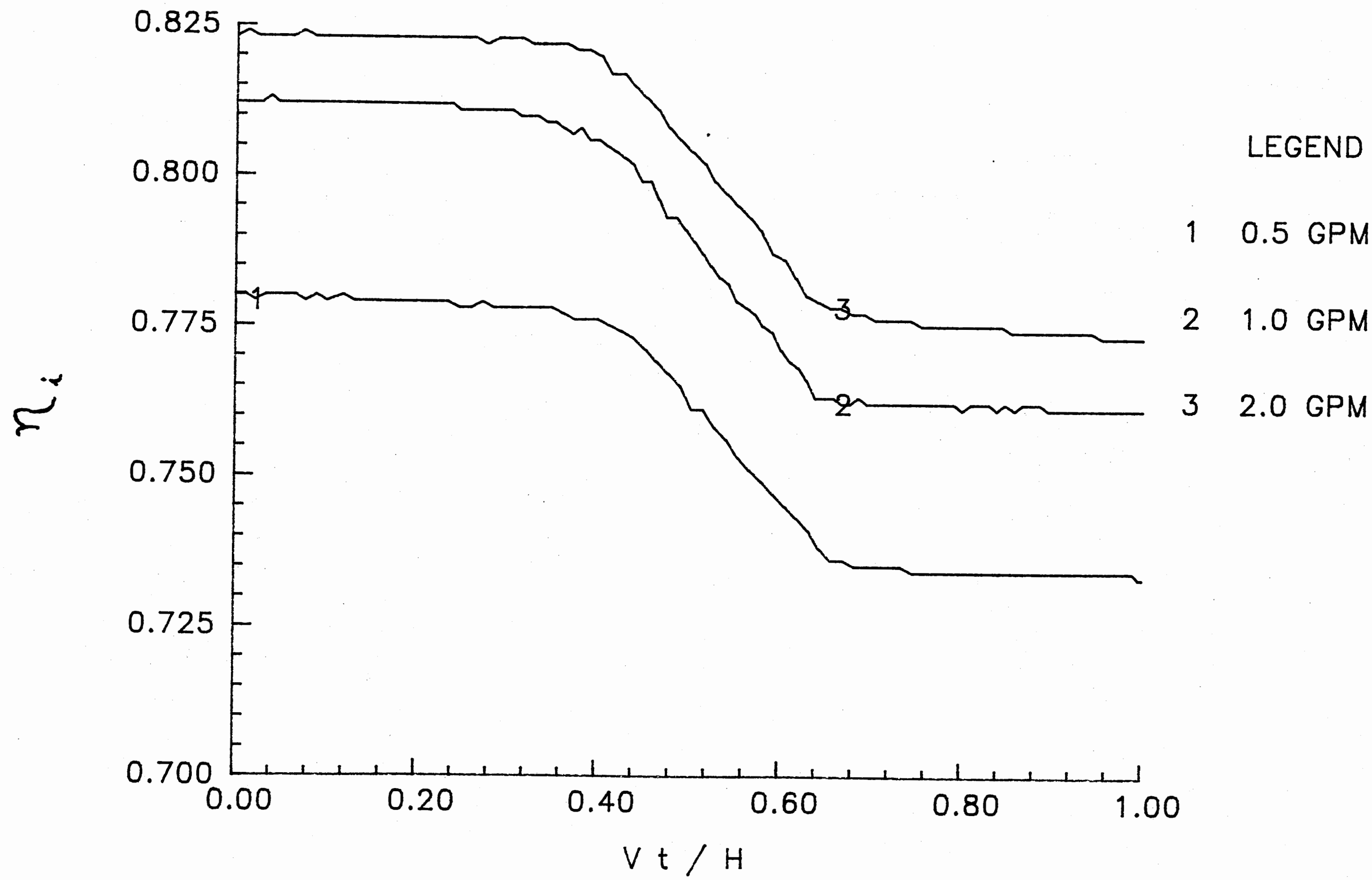


Figure 4.19 Combined Efficiency Curves (Runs # 21, 22, 23).

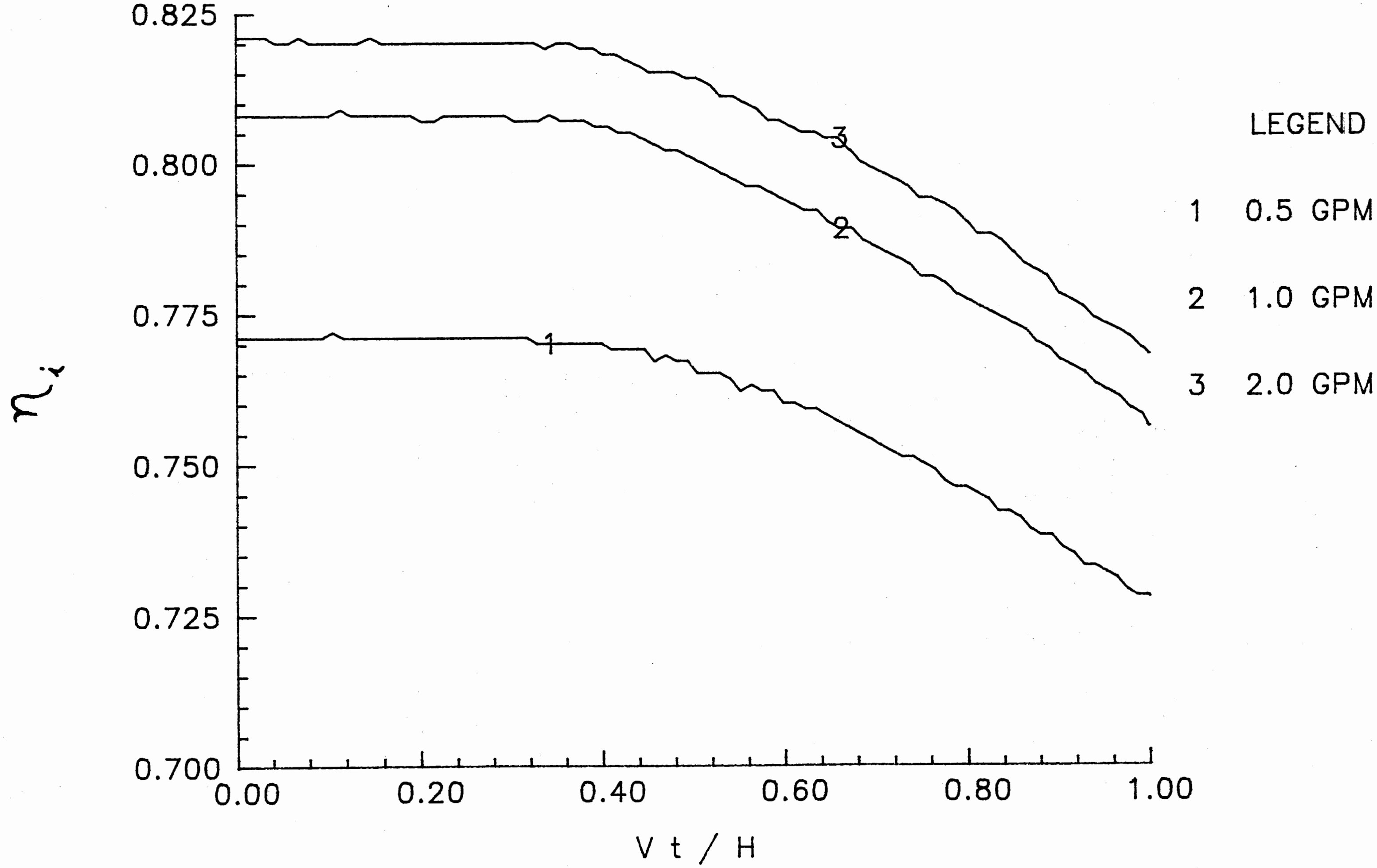


Figure 4.20 Combined Efficiency Curves (Runs # 24, 25, 26).

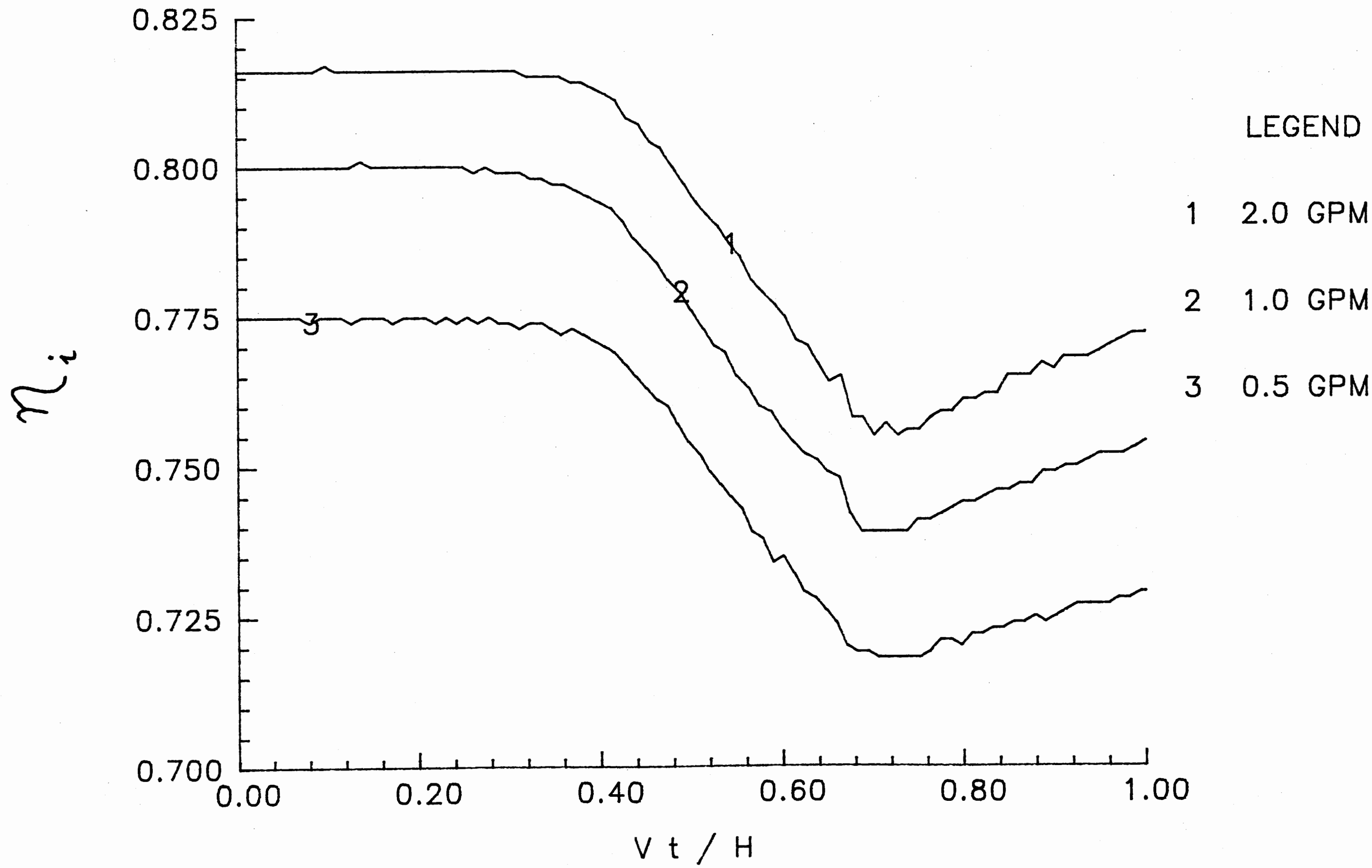


Figure 4.21 Combined Efficiency Curves (Runs # 27, 28, 29).

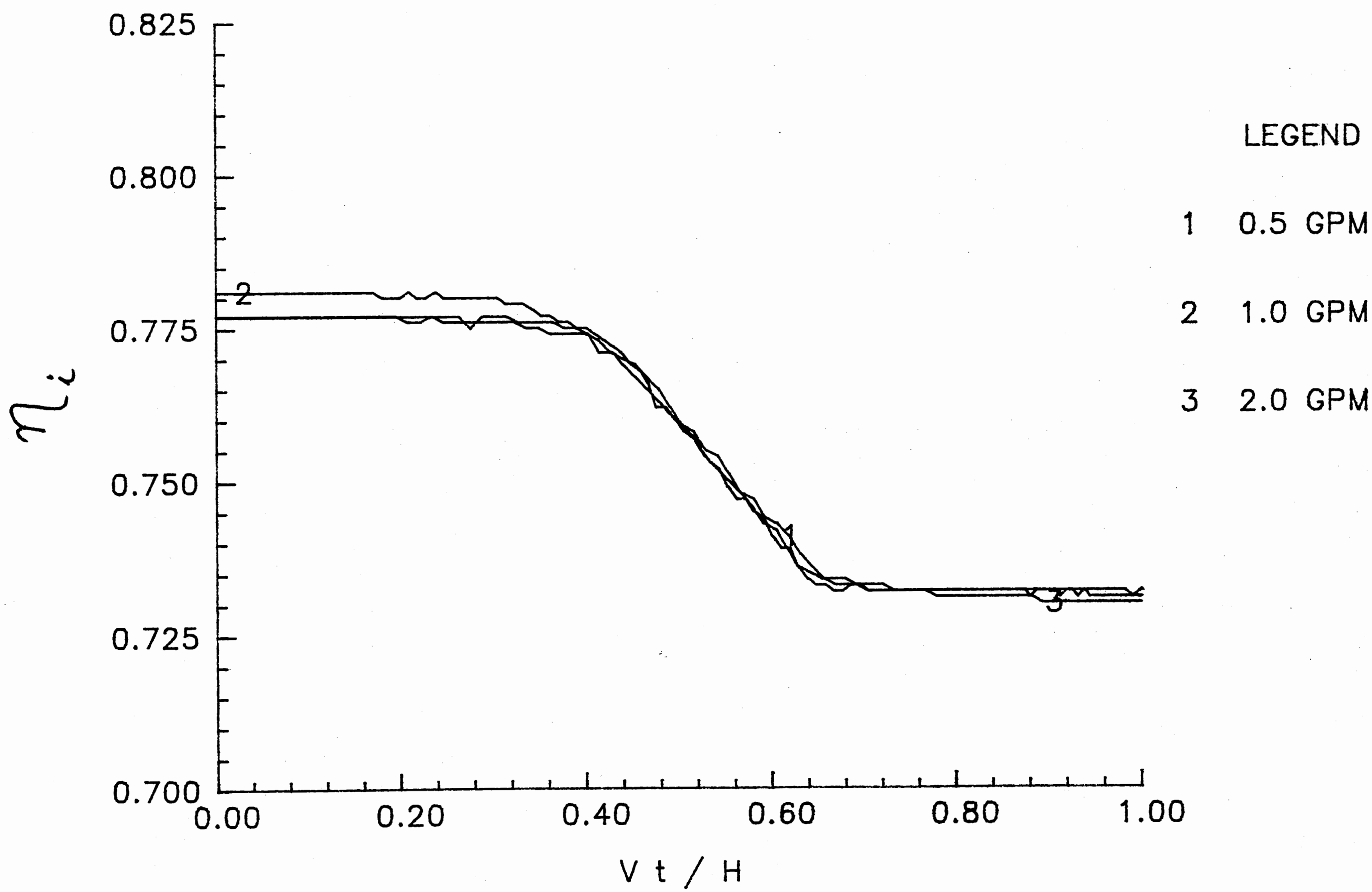


Figure 4.22 Collector Efficiency Curves due to Stratification (Runs # 21, 22, 23)

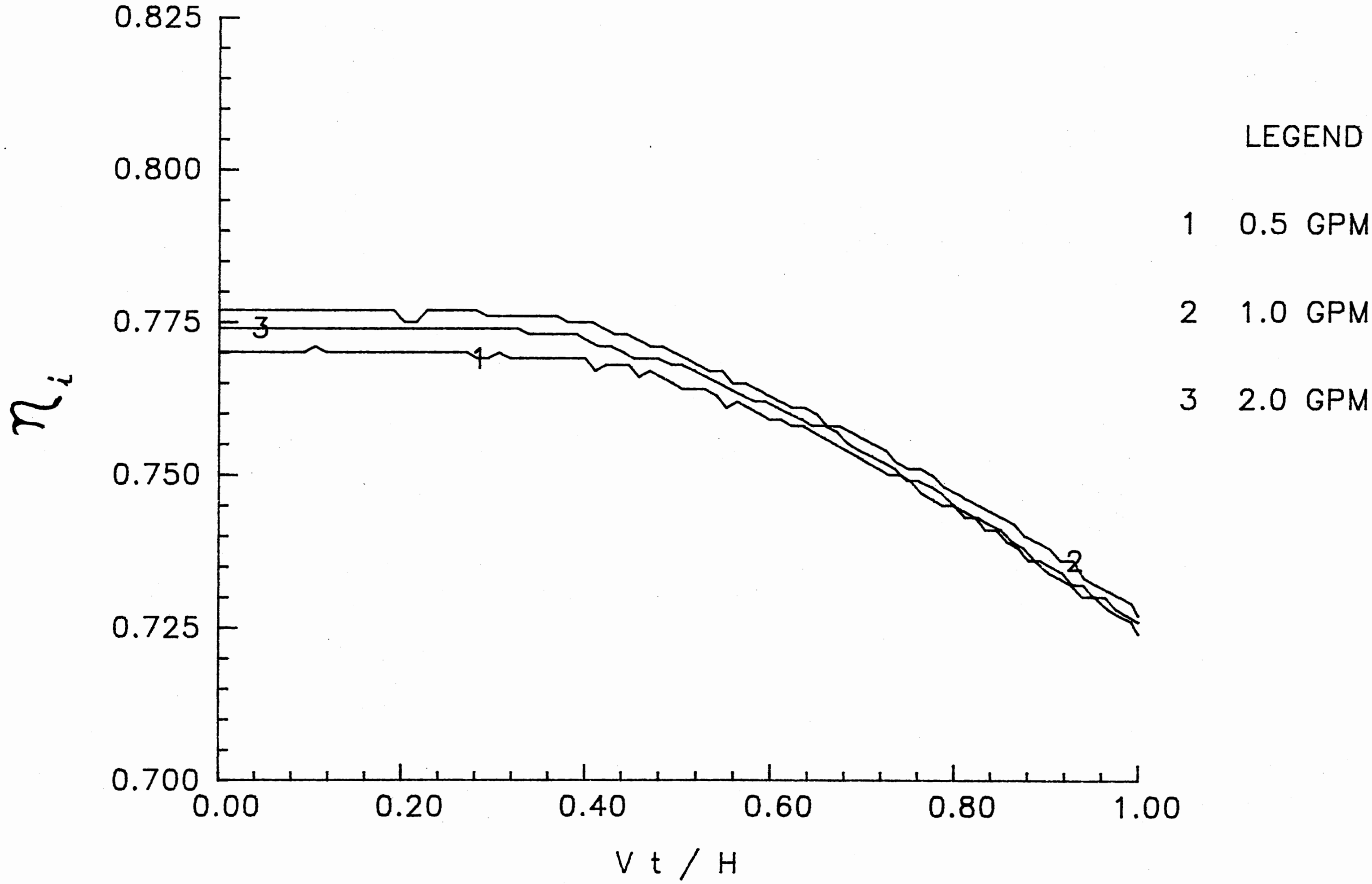


Figure 4.23 Collector Efficiency Curves due to Stratification (Runs # 24, 25, 26)

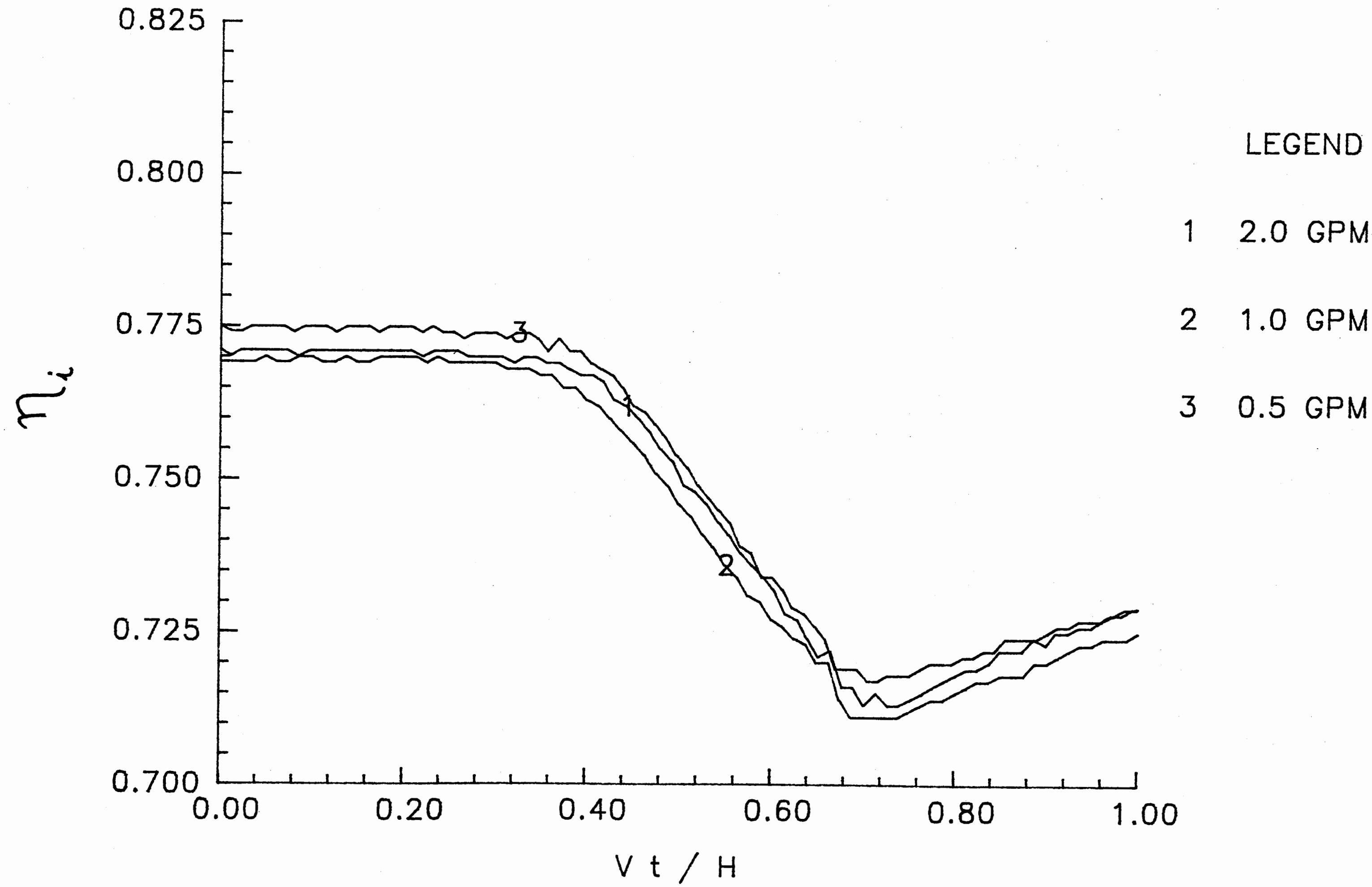


Figure 4.24 Collector Efficiency Curves due to Stratification (Runs # 27, 28, 29)

different flow rates tested.

From the foregoing discussion, it can be concluded that for this type of inlet (the mid-height inlet with perforated baffle), not only stratification was improved when higher flow rates were used (on the order of 2.0 GPM), but also the efficiency of the collector was increased by an appreciable amount. It was also concluded that the change in the inlet temperature profile works well, as far as stratification is concerned, when it includes large increases or decreases (fluctuations), because the large differences would create regions of considerable difference in temperatures within the storage tank (see the second region of Fig. 4.17). Since controlling the incident solar radiation is almost impossible, nothing can be done to improve stratification inside hot water storage tanks through inlet temperature profiles.

4.4 Comparison of Different Inlet Configurations

Nine more experimental runs were conducted so that a comparison between the mid-height inlet and the conventional inlets used (see Section 3.1) could be done.

The comparison was performed by using two different methods. The first method consisted of choosing one of the inlet temperature profiles used in conjunction with the mid-height inlet runs with perforated baffle, and using it to perform a side and top inlet experimental run at flow rates of 0.5, 1.0, and 2.0 GPM. The second method consisted of initially having the top half of the storage tank full of hot water, and the bottom half full of cold water. After creating this initial stratification inside the tank, cold water would be pumped in for about an hour at a rate of 1.0 GPM - so approximately one tank volume would be replaced. The process was repeated for the three different types of inlets (side, top, and mid-height inlets). This particular case is usually encountered when the hot water thermal storage is used during the early morning hours, when the sun's rays has just started hitting the solar collector plate.

Using the first method of comparison, the inlet temperature profile that was used in the first set of runs presented in Section 4.3, was chosen in here as well (see Figures 4.10, 4.11, or 4.12). Figures 4.10, 4.25, and 4.26 show the transient temperature profiles for the three different experimental runs that had a flow rate of 0.5 GPM, and utilized the mid-height, side, and top inlet, respectively. By looking at figures 4.25 and 4.26, it can be seen that in the first region, where the inlet temperature is the highest, the temperatures of the first level had reached almost as high as the inlet temperature, which is the best that can be obtained out of a thermal storage, because the performance of a solar system can be improved if the energy is stored at or near the temperature at which it was collected (Duffie and Beckman, 1980).

However, in the second and third regions of Figures 4.25

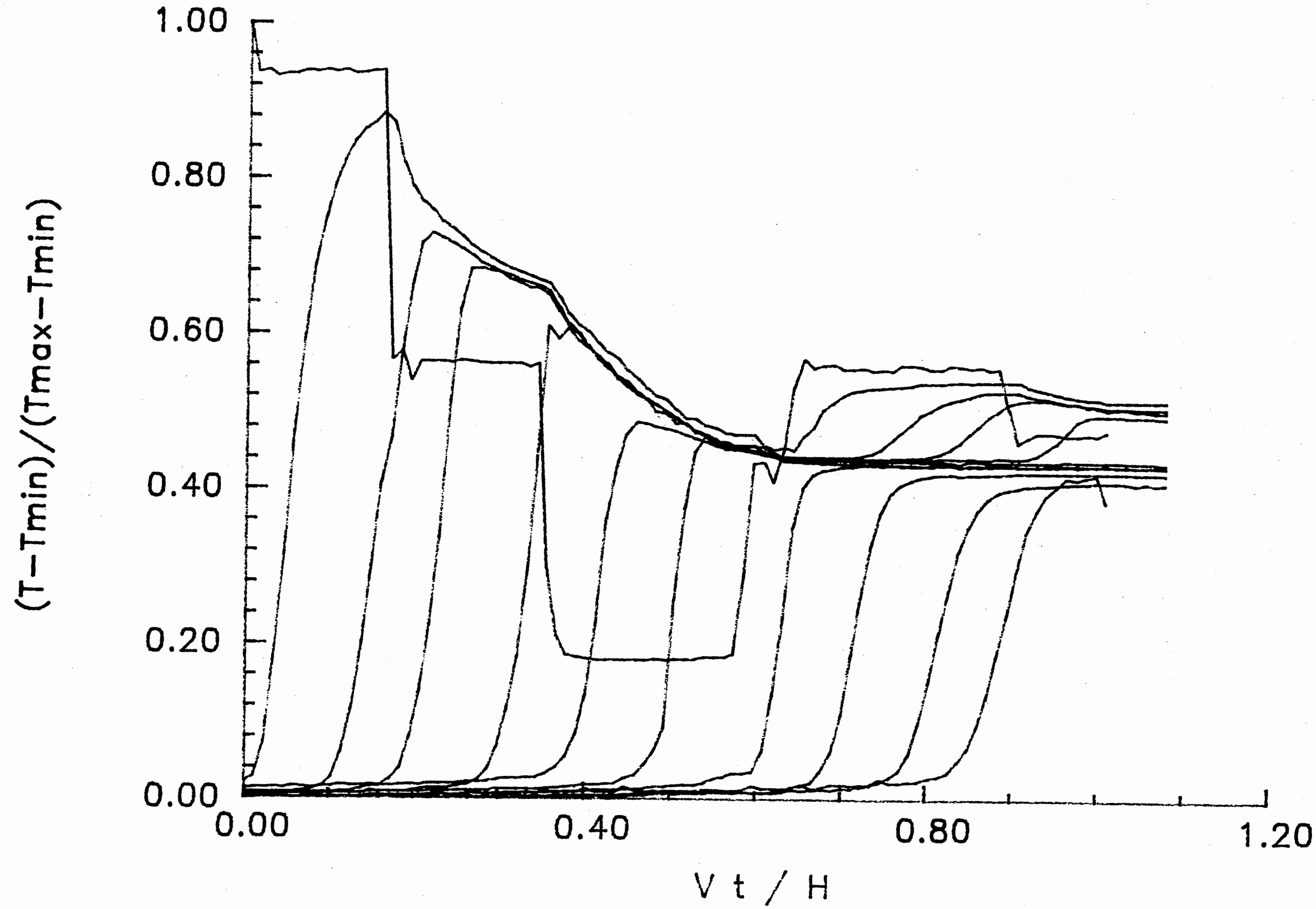


Figure 4.25 Transient Temperature Profile (Run # 32)

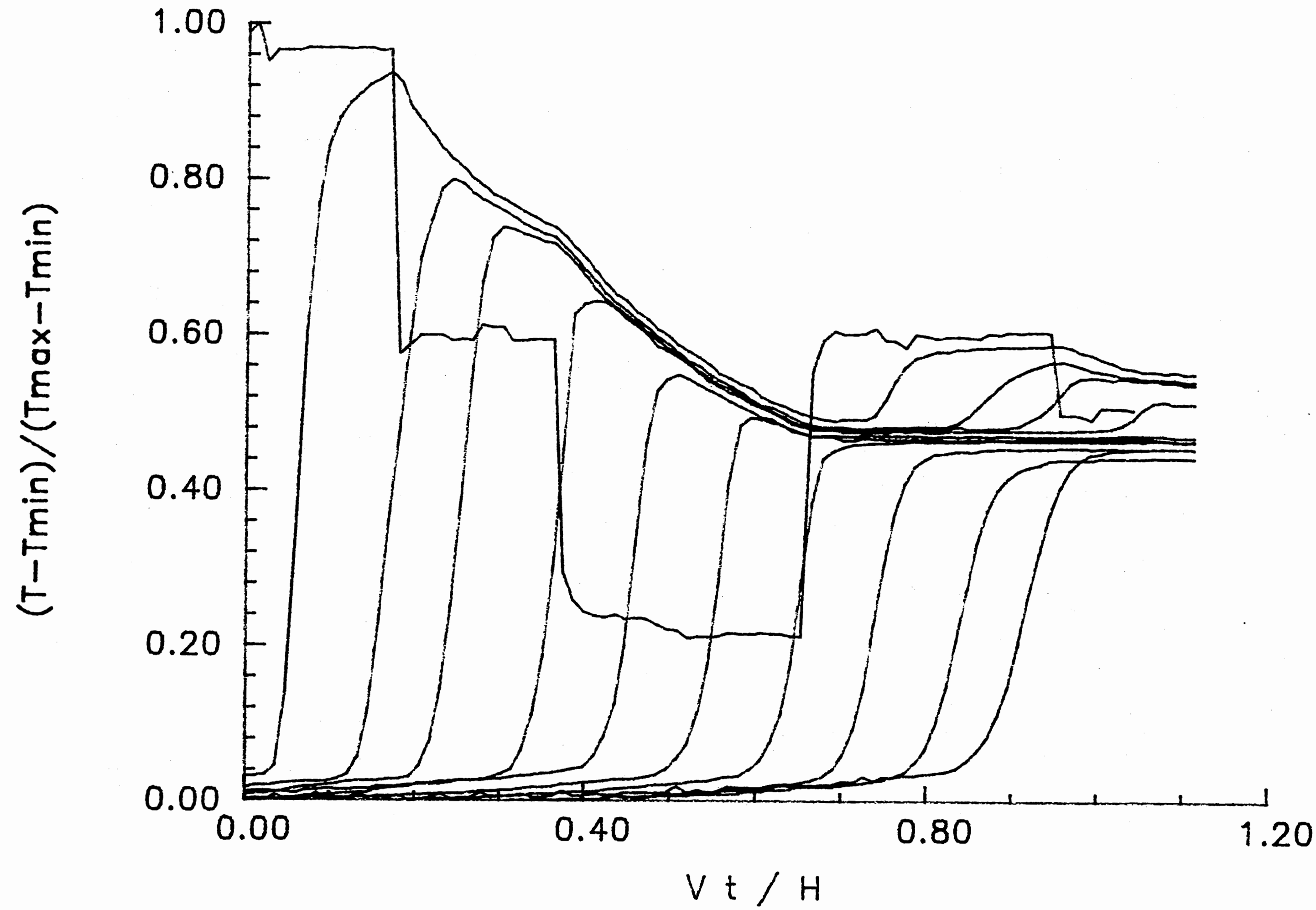


Figure 4.26 Transient Temperature Profile (Run # 35)

and 4.26, the inlet temperature had dropped down causing loss in the thermodynamic availability due to mixing and consequently a drop in the temperature at the first five levels had occurred.

In the fourth region, the inlet temperature had gone back up again causing the temperatures in the first four levels to go up as well.

Comparing the activities that had occurred in the storage tank using the side and top inlets to that using the mid-height inlet (see Fig. 4.10), it can be seen that the temperatures inside the storage tank never reached as high as the inlet temperature, which indicates mixing inside the tank. However, when the inlet temperature had dropped down in the second and third regions, the upper half of the tank kept on having approximately the same temperature, and the bottom half at another temperature, which indicates that stratification is present.

One might say that the side and top inlets also had two regions at different temperatures inside the test tank when the inlet temperature had dropped down (see the second and third regions of Figures 4.25 and 4.26). The previous statement is true to a certain degree, but it can be proven false if the period of time, for which the inlet temperature had dropped, is extended. If the extension were to be done, the temperatures of all levels will reach a temperature equal to that of the inlet (if the side or top inlet were used). But if the mid-height inlet were used, the top half of the tank will maintain its temperature that it had before the drop in the inlet temperature had occurred, and the bottom half will start having a new temperature close to that of the inlet (see Fig. 4.16). This point will be seen clearly when the second method of comparison is discussed.

The same activities and observations were detected when higher flow rates were tested, i.e., 1.0 and 2.0 GPM.

The results obtained upon using the second method of comparison, are shown in Figures 4.27, 4.28, and 4.29 which show the temperature versus tank height profiles at different time steps for three experimental runs that utilized the side, top, and mid-height inlet, respectively.

Figures 4.27 and 4.28 show that the initial stratification inside the test tank was disturbed after 6.67 minutes had elapsed, or after one eighth of the tank water volume had been displaced, and the tank was fully mixed after 33.3 minutes had elapsed, or after sixty percent of the tank hot water volume had been displaced. On the other hand, Figure 4.29 shows that the storage tank had approximately maintained its initial stratification the whole hour long.

Similar plots had been generated by Loehrke et al., 1979 (see Fig. 4.30). Their results for the conventional inlets, specifically the vertical jet, compare favorably to what have been obtained in the present study (see Figures 4.27 and 4.28). However, comparison of their results for the distribution manifolds (see Figure 4.30) with the results of the present study for the mid-height inlet (see

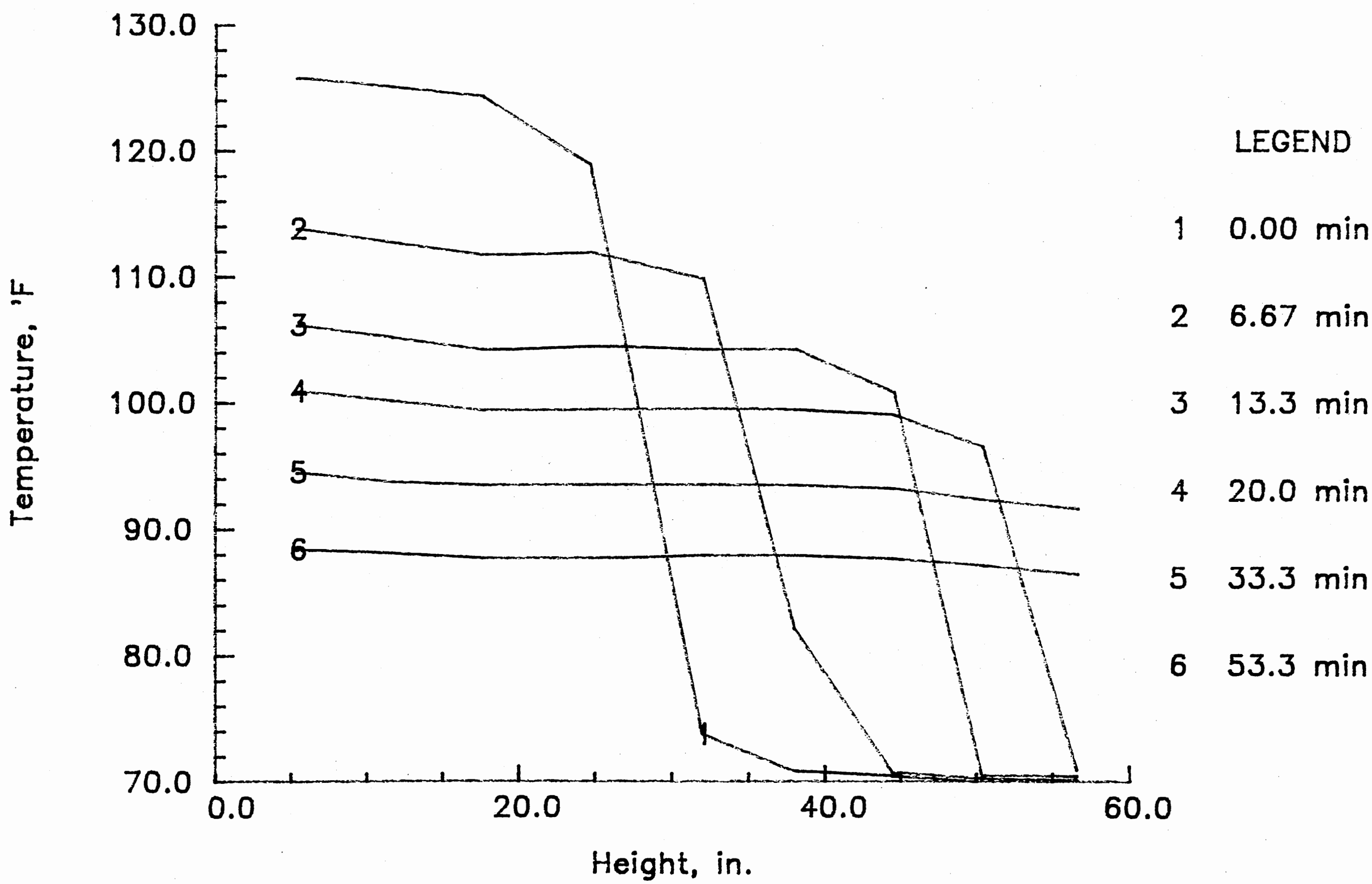


Figure 4.27 Transient Temperature Profile after an Initial Stratification was Established (Side Inlet)

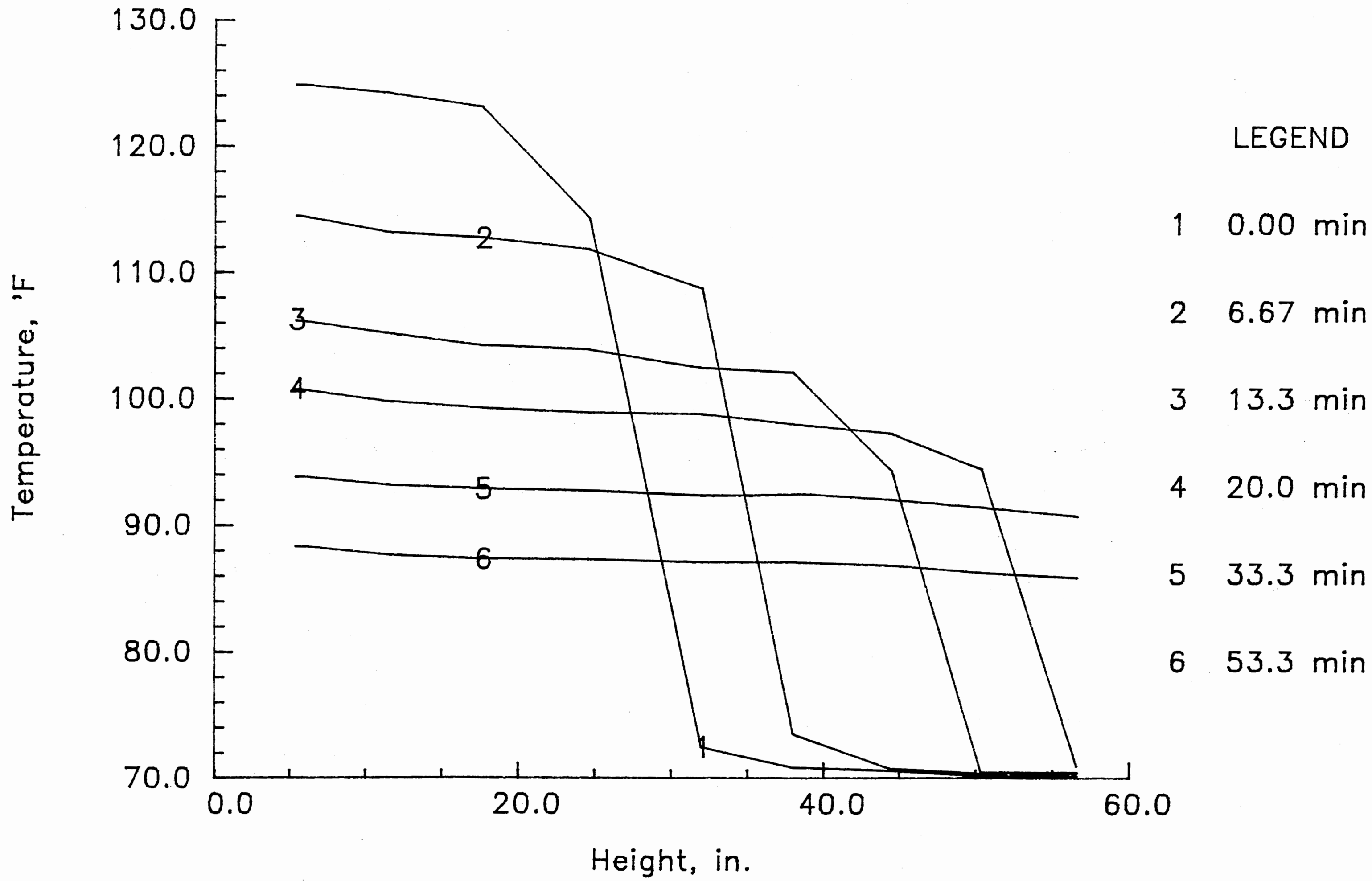


Figure 4.28 Transient Temperature Profile after an Initial Stratification was Established (Top Inlet)

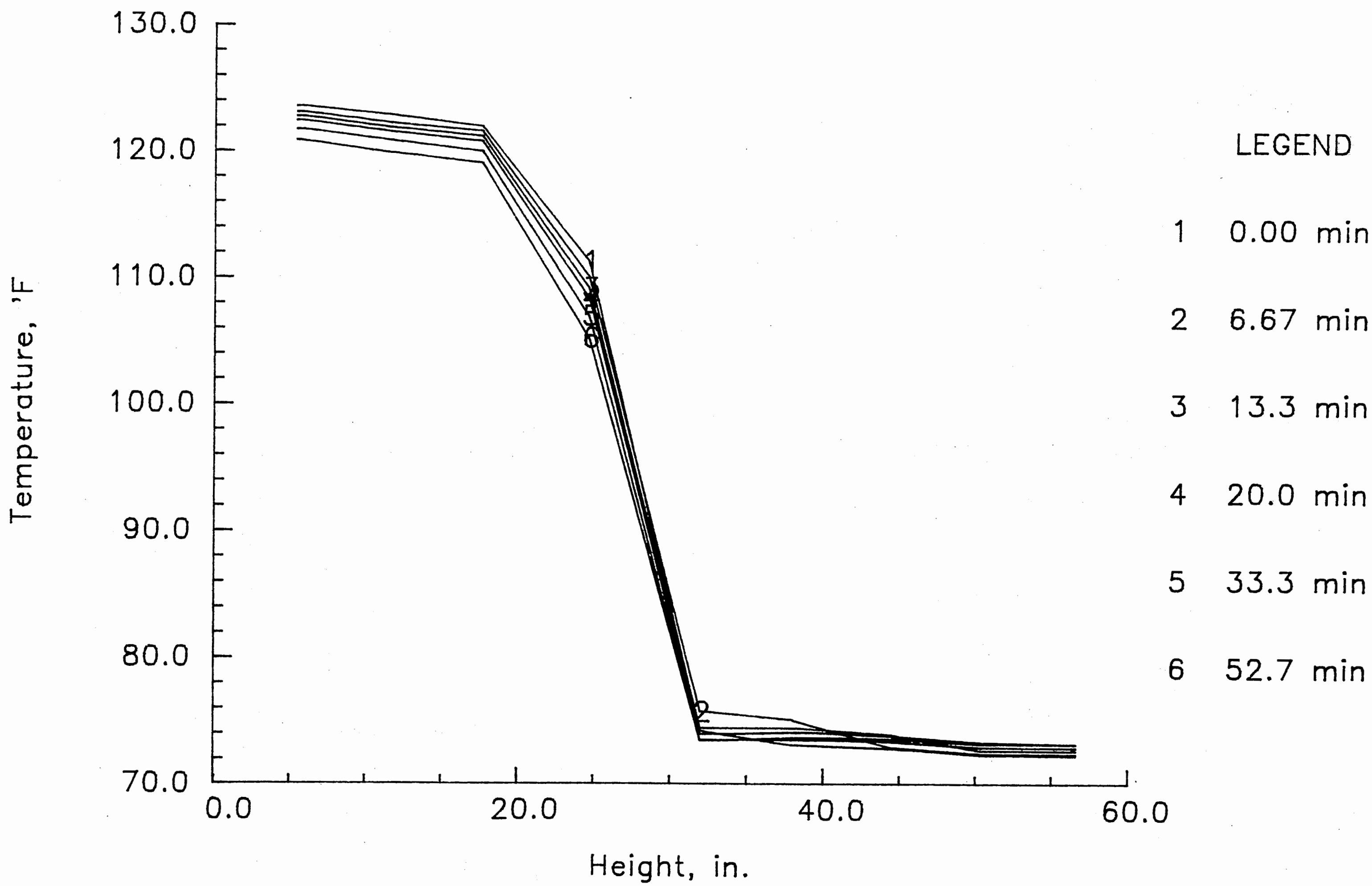
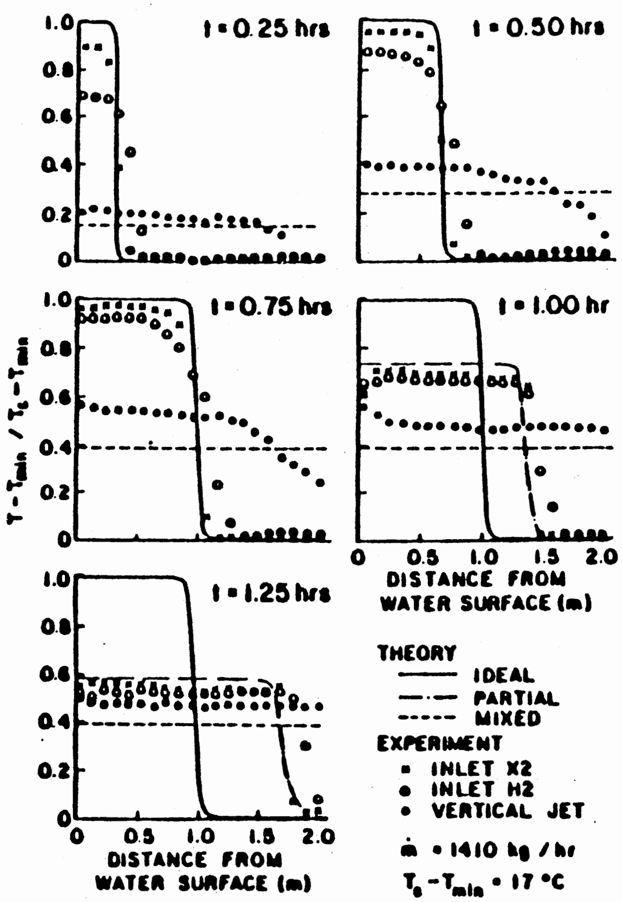
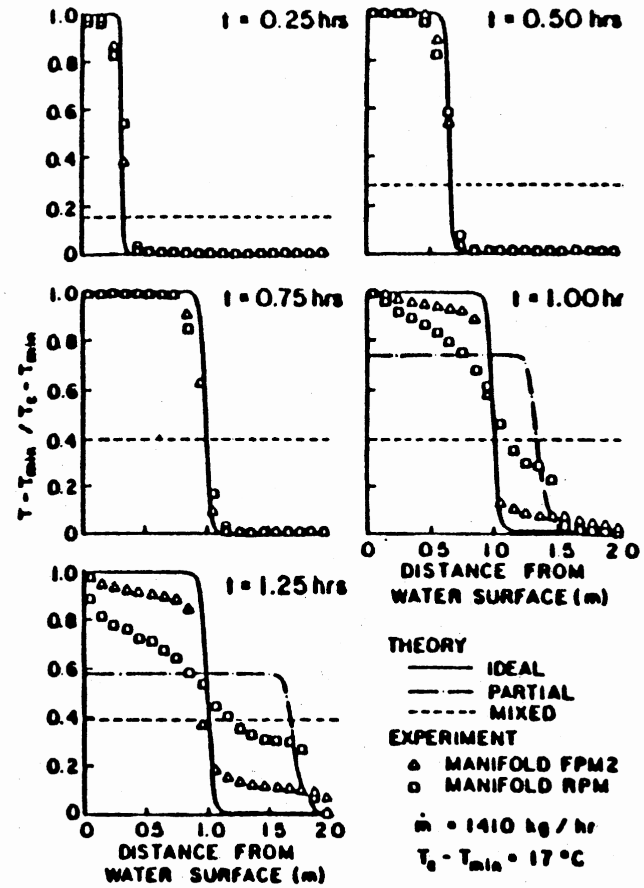


Figure 4.29 Transient Temperature Profile after an Initial Stratification was Established (Mid-Height Inlet)



conventional inlets.



distribution manifolds.

Figure 4.30 Tank Temperatures Profile During Charging and Recycle Experiments (Loehrke et al., 1979)

Figure 4.29), indicates that less mixing occurs with our inlet. For example, in Figure 4.29, the temperature, after approximately one hour had elapsed, had dropped by an amount equal to 3 or 4 % of the initial temperature, while in Figure 4.30, when the distributor manifold FPM2 (Flexible Porous Manifold) was used, the temperature, after approximately one hour had elapsed, had dropped by an amount equal to 10 - 12 % of the initial temperature, which indicates that better stratification and less mixing are associated with the type of inlet used in this study.

It has been shown from the past discussion, that the mid-height inlet with the perforated baffle works better than the conventional inlets (side and top inlets) with variable inlet temperature conditions. Even though, by using the mid-height inlet, the temperatures that are stored are not at or near the temperature at which they were collected (due to mixing), but it was shown that the tank can hold better stratification when the inlet temperature varies, which is something the conventional inlets cannot handle well.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary and Conclusions

Thermal storage is believed to have a great contribution in the future towards cutting down the energy demand, reducing the cost of producing energy, and increasing the use of solar energy systems. Thermal energy storage is already being used in load management applications, primarily it is used in shifting all or part of the energy demand to off-peak hours of the day.

The most common fluid used in thermal storage systems is water. Water has many desirable characteristics; for example: high specific heat, nontoxic, inexpensive, and abundant.

The single stratified tank (SST) is one of the devices used in thermal energy storage applications. Normally, there are two thermal cases encountered in the SST: the constant inlet temperature case and the variable inlet temperature case. The former case is usually encountered in the thermocline thermal storage, while the latter case is encountered in the stratified thermal storage.

Stratified thermal storage is a promising device for storing low-to-medium temperature thermal energy for residential and commercial heating and cooling applications.

The emphasis of this study was to experimentally investigate the performance of a stratified thermal energy storage system under wide range of flow conditions (flow rates and variable inlet temperature profiles). However, variable inlet temperature causes mixing and consequently loss in the thermodynamic availability. To solve this problem, different inlet designs which utilize hydrostatic and hydrodynamic effects to guide the incoming flow to its proper level of stratification with minimum amount of mixing were studied.

To accomplish the required task, a complete experimental setup was built. The investigation of the performance of a stratified thermal energy storage tank was done by conducting over 35 experiments covering a range of flow rates between 0.5 to 2.0 GPM and many different inlet temperature profiles for three types of inlet configurations: mid-height inlet with solid and perforated baffle, side inlet, and top inlet. The experiments were not used only to fulfill the objectives of this study, but also to generate a data base for a later verification of a two- or three-dimensional analytical model.

The general conclusions drawn from this study may be summarized as:

1. With the present experimental setup, one has the capability of conducting experiments under both constant and variable inlet temperature with three

types of inlets (conventional and mid-height), see Chapter III.

2. The experimental setup was initially used to determine the critical thickness of the insulation required to reduce the amount of heat loss to the ambient. This was done by comparing the heat loss from the static runs to the heat loss computed by the heat loss program. It was found that at the maximum conditions, a thickness of 3 inches would be sufficient to reduce the heat loss by an amount equal to 82% of that with no insulation (see Section 4.1).
3. To assess the feasibility of stratification enhancement designs, two types of baffles (solid and perforated) were tested in conjunction with the mid-height inlet. Stratification enhancement was detected when the perforated baffle was used. The enhancement was a direct result of the higher resistance in the perforated baffle as opposed to the solid baffle. However, the enhancement was hindered due to mixing in the fluid and conduction in the radial and vertical directions in the walls of the tank and the baffle (see Section 4.2).
4. While comparing the above mentioned baffles, it was found that the mixing that had occurred in the test tank was a result of the momentum carried with the incoming fluid. The momentum of the flow gets

diffused in both directions (upwards and downwards). The hot (cold) fluid that travelled downwards (upwards), is going to travel to its appropriate level of stratification through the center of the storage tank causing mixing and stratification disturbances (see Section 4.2).

5. The effect of flow rate on stratification was studied using the mid-height inlet. It was found that for the flow rates tested, the degree of stratification was increased with an increase in the flow rate(see Section 4.3.1).
6. The effect of inlet temperature profile was also studied using the mid-height inlet. It was found that large differences between the maximum and the minimum temperatures in the variable inlet temperature profile would create regions with considerable difference in temperatures (stratification) within the thermal energy storage tank (see Figures 4.16, 4.17, and 4.18).
7. In studying the effects of flow rate and stratification on solar collector efficiency, it was found that a higher efficiency is obtained with increased flow rate (see Figures 4.19, 4.20, and 4.21). On the other hand, effect of stratification alone was found to yield approximately equal efficiencies for all flow rates tested (see Figures 4.22, 4.23, and 4.24).

8. To confirm the existence of stable stratification, a short term static run was added to the parametric study runs. Results had shown that no motions such as internal convective motions are present in the already stratified test tank after the pump is switched off, which indicates stable stratification (see Figures 4.10 through 4.18).
9. Among the three types of inlets described in Chapter III, the mid-height inlet was found to perform much better than the conventional inlets under variable inlet temperature conditions. Results had shown that whenever the inlet temperature drops below the existing fluid temperature, the top half of the tank, which is already at a higher temperature, would not be mixed with the lower entering temperature (see Section 4.4).
10. Results obtained upon using the mid-height inlet were compared against similar results obtained by Loehrke et al. (1979). The comparison had shown that as far as minimizing mixing is concerned, the mid-height inlet used in this study performs better than the distributor manifold used in the study done by Loehrke et al. (1979), see Section 4.4.

5.2 Recommendations

Based on the observations made during this study, the following recommendations are made:

1. The tank and baffle material should have a conductivity equal or near that of water, or the fluid used in the storage, i.e., fiberglass. That would reduce radial and vertical conduction in the walls of both the tank and the baffle.
2. A computer model should be developed to simulate the storage tank used so the configurations can be varied (the size of the perforations, the spacing between the baffle wall and the tank wall, the height-to-diameter ratio, etc.), in order to come up with an optimum design with a minimum amount of mixing.
3. Flow visualization is strongly recommended in order to verify the movement of the fluid inside the test tank, since it was not easily detected using the thermocouples.

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APPENDIXES

APPENDIX A

BAFFLE HOLE SIZING AND DENSITY

According to Engineering Sciences Data Item No. 72010, " Pressure Losses Across Perforated Plates, Orifice plates and Cylindrical Tube Orifices in Ducts ", (1972), for thin plates: $0 < t/d < 0.4$ and $\alpha < 0.5$ the pressure loss is independent of Re as long as Re > 400, where Re is based on the velocity through the holes and the diameter of the hole.

Let

$$t/d = 0.2$$

where

t = baffle thickness

d = hole (perforation) diameter

For a 1/16 in. thick baffle

$$d = \frac{1/16 \text{ in.}}{0.2} = 0.3125 \text{ in.} \qquad \text{(A.1)}$$

Assuming the porosity, α, to be a minimum -so it can be increased later if a change in porosity is needed or proven to be a big factor in this study:

Let

$$\alpha = 0.15 \qquad \text{(A.2)}$$

The total baffle surface area:

$$A_t = \pi D L \tag{A.3}$$

where,

D = baffle diameter

L = baffle length

The area of a hole (perforation),

$$A_h = \pi d^2 / 4 \tag{A.4}$$

The blocked area,

$$A_b = (1 - \alpha) A_t \tag{A.5}$$

Also

$$A_b = \pi D L - N_R N_C A_h \tag{A.6}$$

where,

N_C = no. of columns = $\pi D / p$ (A.7)

N_R = no. of rows = L / p (A.8)

p = pitch (distance between two adjacent centers)

Substituting (A.5), (A.7), and (A.8) into (A.6)

$$(1 - \alpha) A_t = \pi D L (1 - (A_h / p^2)) \tag{A.9}$$

Substituting (A.3) and (A.4) into (A.9)

$$p = ((\pi d^2 / 4) / \alpha)^{1/2} \tag{A.10}$$

Substituting (A.1) and (A.2) into (A.10)

$$p = 0.715 \text{ in.} \tag{A.11}$$

Then from (A.7) and (A.11)

$$N_C = 62 \text{ Columns}$$

And from (A.8) and (A.11)

$$N_R = 16 \text{ Rows per foot.}$$

The number of columns and rows were used in constructing the perforated baffle used in this study.

APPENDIX B

THE " MIXING " PROGRAM

B.1 Description

This program was developed to generate tables of mixed temperature if hot and tap water are to be mixed at various combinations of flow rates.

The theory behind this program is based on a mass and energy balance on the control volume shown below in Fig. B.1.

Mass balance

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_1 \tag{B.1}$$

where

$\dot{m}$ = mass flow rate (lbm / sec)

Energy balance

$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_1 h_1 \tag{B.2}$$

where,

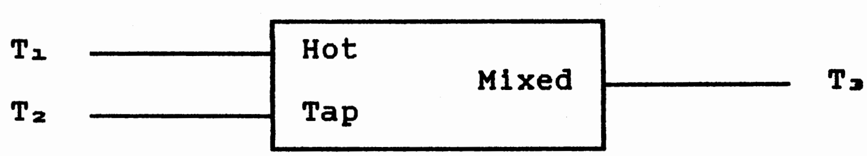

Figure B.1 Schematic of a Mixing Chamber h = enthalpy of the fluid (BTU / lbm)

Substituting (B.1) into (B.2)

$$(\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_2 h_2 + \dot{m}_1 h_1 \qquad (B.3)$$

Rearranging

$$\dot{m}_2 (h_2 - h_3) + \dot{m}_1 (h_1 - h_3) = 0 \qquad (B.4)$$

Knowing that the specific heat of water is constant over the temperature range used in the experiments (50 - 200°F), the enthalpy difference can be approximated as:

$$h_2 - h_3 = C_p (T_2 - T_3) \qquad (B.5)$$

and

$$h_1 - h_3 = C_p (T_1 - T_3) \qquad (B.6)$$

where

C_p = specific heat of water = 1.0 BTU / lbm °F

T = water temperature at the point indicated

Substituting (B.5) and (B.6) into (B.4) and solving for T_3,

$$T_3 = \frac{\dot{m}_2 T_2 + \dot{m}_1 T_1}{\dot{m}_1 + \dot{m}_2} \qquad (B.7)$$

Equation (B.7) was used in the MIXING program to find the mixed temperature at various flow rates. The flow rates ranged from 1 - 10 GPM on the tap water, and from 1.5 -9 GPM on the hot water (those flow rates were the limits on the flowmeters used). The hot water temperatures (T_1) used were 100, 120, 150, 180°F. The tap water temperature (T_2) ranged from 45 - 85°F.

To convert the volumetric flow rate to mass flow rate density is needed at that particular temperature. The relationship between mass and volumetric flow rate is:

$$\dot{m} = Q \rho$$

where

Q = volumetric flow rate

ρ = density of water.

Since the density is very much dependant on temperature, the following equation was used to evaluate the density at each specified temperature (Zografos et al., 1987):

$$\rho = (-3.0115\ E\text{-}6)\ T^3 + (9.6272\ E\text{-}4)\ T^2 - 0.11052\ T + 1022.4$$

where,

T = absolute temperature, K

ρ = density in kg/m^3 .

The computer code listing along with a sample output are shown in the following sections.

B.2 Listing

```
      OPEN(1,FILE='A:T3.DAT')
      OPEN(2,FILE='B:T3.DAT')

C---------------------------INPUTS---------------------------------

      WRITE(*,*)'DATA TO BE STORED ON A: OR B:( A = 1, B = 2 )'
      READ(*,*)CODE
      WRITE(*,*)'ENTER THE MINIMUM TAP WATER TEMP, (F)'
      READ(*,*)MIN
      WRITE(*,*)'ENTER THE MAXIMUM TAP WATER TEMP, (F)'
      READ(*,*)MAX
      I = MIN - 44
      N = MAX - 44
C--------------------------HEADINGS--------------------------------

      IF( CODE .EQ. 1) THEN
         WRITE(1,5)
      ELSE
         WRITE(2,5)
      ENDIF
 5    FORMAT(6X,'HOT GPM',2X,'HOT TEMP',2X,'TAP GPM',2X,'TAP TEMP',
     $2X,'MIX GPM',2X,'MIX TEMP')
C------------------------HOT WATER TEMP----------------------------

      WRITE(*,*)'ENTER THE HOT WATER TEMP'
      READ(*,*)T1
      RHO1 = DENS(T1)
C-------------------------TAP WATER TEMP---------------------------

       DO 1 J = I, N
          T2 = J + 44
          RHO2 = DENS(T2)
C-------------------------HOT WATER GPM----------------------------

        DO 1 K = 1, 16
             GPM1 = 1.0 + K * 0.5
C-------------------------TAP WATER GPM----------------------------

         DO 1 L = 1, 37
            GPM2 = 0.75 + L * 0.25

C--------------------MIXTURE TEMPERATURE CALCULATION---------------

            T3 = ( RHO2 * GPM2 * T2 + RHO1 * GPM1 * T1 ) / ( RHO1
     $              * GPM1 + RHO2 * GPM2 )
C----------------DENSITY AND FLOW RATE OF THE MIXTURE--------------

            RHO3 = DENS(T3)
            GPM3 = ( RHO2 * GPM2 + RHO1 * GPM1 ) / RHO3
```

```
C-----------------------TABULATED OUTPUT---------------------------

          IF( CODE .EQ. 1 ) THEN
             WRITE(1,10)GPM1, T1, GPM2, T2, GPM3, T3
          ELSE
             WRITE(2,10)GPM1, T1, GPM2, T2, GPM3, T3
          ENDIF
 10       FORMAT(1X,3(2X,F6.3,4X,F6.2))

C------------------------------------------------------------------

 1    CONTINUE

C------------------------------------------------------------------
      STOP
      END

C---------------------FUNCTION TO CALCULATE THE DENSITY ------------

      FUNCTION DENS(T)
      DENS = (-3.0115E-6 * T**3) + (9.6272E-4 * T**2) - (0.11052 * T)
     $  + 1022.4
      RETURN
      END

C------------------------------------------------------------------
```

B.3 Sample Output

HOT GPM	HOT TEMP	TAP GPM	TAP TEMP	MIX GPM	MIX TEMP
1.500	120.00	1.000	64.00	2.500	97.59
1.500	120.00	1.250	64.00	2.750	94.54
1.500	120.00	1.500	64.00	3.000	91.99
1.500	120.00	1.750	64.00	3.250	89.84
1.500	120.00	2.000	64.00	3.500	87.99
1.500	120.00	2.250	64.00	3.750	86.39
1.500	120.00	2.500	64.00	4.000	84.99
1.500	120.00	2.750	64.00	4.250	83.76
1.500	120.00	3.000	64.00	4.500	82.66
1.500	120.00	3.250	64.00	4.751	81.68
1.500	120.00	3.500	64.00	5.001	80.79
1.500	120.00	3.750	64.00	5.251	79.99
1.500	120.00	4.000	64.00	5.501	79.27
1.500	120.00	4.250	64.00	5.751	78.60
1.500	120.00	4.500	64.00	6.001	77.99
1.500	120.00	4.750	64.00	6.251	77.43
1.500	120.00	5.000	64.00	6.501	76.92
1.500	120.00	5.250	64.00	6.751	76.44
1.500	120.00	5.500	64.00	7.001	75.99
1.500	120.00	5.750	64.00	7.251	75.58
1.500	120.00	6.000	64.00	7.501	75.19
2.000	120.00	1.000	64.00	3.000	101.32
2.000	120.00	1.250	64.00	3.250	98.45
2.000	120.00	1.500	64.00	3.500	95.99
2.000	120.00	1.750	64.00	3.750	93.86
2.000	120.00	2.000	64.00	4.000	91.99
2.000	120.00	2.250	64.00	4.250	90.34
2.000	120.00	2.500	64.00	4.500	88.88
2.000	120.00	2.750	64.00	4.751	87.57
2.000	120.00	3.000	64.00	5.001	86.39
2.000	120.00	3.250	64.00	5.251	85.32
2.000	120.00	3.500	64.00	5.501	84.35
2.000	120.00	3.750	64.00	5.751	83.47
2.000	120.00	4.000	64.00	6.001	82.66
2.000	120.00	4.250	64.00	6.251	81.91
2.000	120.00	4.500	64.00	6.501	81.22
2.000	120.00	4.750	64.00	6.751	80.58
2.000	120.00	5.000	64.00	7.001	79.99
2.000	120.00	5.250	64.00	7.251	79.44
2.000	120.00	5.500	64.00	7.501	78.93
2.000	120.00	5.750	64.00	7.751	78.44

APPENDIX C

THE DATA REDUCTION PROGRAMS

C.1 LVL2DIM

```
C.............................................................C
C                                                             C
C   THIS PROGRAM READS THE TEMPERATURES FROM THE TWO CHANNEL FILES  C
C   - CHAN_0, CHAN_10 - THEN IT WRITES THE TEMPERATUES IN A FILE    C
C   CALLED 'OUTPUT2.DAT' IN A TWO DIMENSIONAL FORM.           C
C                                                             C
C                           BY                                C
C                 MOUTASEM ABU-HAMDAN ( 1988 )                C
C                                                             C
C     VARIBLES DESCRIPTION :                                  C
C                                                             C
C         NLEVEL = THE NUMBER OF THERMOCOUPLE LEVELS          C
C           IEND = THE MAXIMUM NUMBER OF DATA                 C
C           TIME = THE TIME INCREMENT AT WHICH THE DATA IS READ  C
C         TEXLVL = THE TEMP. IN THE CHANNELA FILES            C
C                                                             C
C.............................................................C
        DIMENSION TIME(300),TEXLVL(9,200)

C..........................DATA................................

        DATA NLEVEL / 2 /
        DATA IEND / 500 /
C......................DATA FILES...............................

        OPEN (16,FILE='A:OUTPUT2.DAT',STATUS='NEW')
        OPEN (17,FILE='A:CHAN_0.DAT',STATUS='OLD')
        OPEN (18,FILE='A:CHAN_10.DAT',STATUS='OLD')
C..................READING AND WRITING THE FILES.................

      DO 10 I = 1, NLEVEL

        GO TO ( 713, 714 ), I
713      DO 11 J = 1 , IEND
           READ(17,*,END=10)N, TEXLVL(I,J), TIME(J)
11       CONTINUE
        GO TO 10
```

```
714       DO 12 J = 1 , IEND
            READ(18,*,END=10)N, TEXLVL(I,J), TIME(J)
12        CONTINUE
10     CONTINUE
         IE = J - 1
        DO 715 I = 1 , IE
          WRITE(16,750)TIME(I),(TEXLVL(K,I),K=1,NLEVEL)
715     CONTINUE
750     FORMAT(10(1X,F6.2))
        STOP
        END
```

C.2 LVL2NDIM

```
C..............................................................C
C                                                              C
C    THIS PROGRAM READS THE OUTPUT DATA FILES THAT CONTAINS THE    C
C    INLET AND OUTLET TEMPERATURES DATA THAT WAS GENERATED BY THE  C
C    PROGRAM 'LVL2DIM.DAT' - THAT IS YOU HAVE TO RUN PROGRAM       C
C    'LVL2DIM' FIRST.                                          C
C                                                              C
C                            BY                                C
C                 MOUTASEM ABU-HAMDAN ( 1988 )                 C
C                                                              C
C       VARIABLES DESCRIPTION :                                C
C                                                              C
C              IEND = THE MAXIMUM NUMBER OF READINGS            C
C            NLEVEL = THE NUMBER OF LEVELS                      C
C            HEIGHT - HEIGHT OF THE TANK                        C
C               DIA = DIAMETER OF THE TANK                      C
C              TIME = THE TIME INCREMENTS AT WHICH DATA IS READ C
C            TEXLVL = THE TEMPERATURES IN THE 'OUTPUT.DAT' FILE C
C            TSTRLS = THE DIMENSIONLESS TEMPERATURE             C
C             TIMED = THE DIMENSIONLESS TIME                    C
C               TIM = DIMENSIONAL TIME                          C
C              AREA = CROSS SECTIONAL AREA OF THE TANK          C
C               GPM = THE VOLUMETRIC FLOW RATE IN GAL/MIN       C
C              QVOL = THE VOLUMETRIC FLOW RATE IN CUBIC FT/MIN  C
C              TMIN = THE MINIMUM TEMP. OCCURED DURING THE RUN  C
C              TMAX = THE MAXIMUM TEMP. OCCURED DURING THE RUN  C
C               VEL = THE VELOCITY OF THE FLOW                  C
C                                                              C
C..............................................................C

      DIMENSION TIME(300),TEXLVL(9,200),TSTRLS(9,200),TIMED(200)

C................................DATA...........................

      DATA IEND / 500 /
      DATA NLEVEL / 2 /
      DATA DIA, HEIGHT / 1.333, 62.4 /

C............................DATA FILES.........................

      OPEN(8,FILE='A:OUTPUT2.DAT',STATUS='OLD')
      OPEN(9,FILE='A:TDIME2.DAT',STATUS='NEW')

C..............................INPUTS...........................

      WRITE(*,*)
      WRITE(*,*)'ENTER FLOW RATE IN GPM'
      WRITE(*,*)
      READ(*,*)GPM
```

```
C.............................CONSTANTS............................

        PI = 3.1415927
        HEIGHT = HEIGHT / 12.
        QVOL = GPM / 7.48
        AREA = PI * DIA**2 / 4.0
        VEL = QVOL / AREA
        TIM = VEL / HEIGHT

C...................READING AND WRITING THE TEMPS...................

        DO 100 J = 1 , IEND
          READ(8,*,END=200)TIME(J), (TEXLVL(I,J), I = 1, NLEVEL)
100     CONTINUE
200     IE = J - 1

C...................FINDING THE MAX AND MIN TEMP...................

        TMIN = 1.E6
        TMAX = 0.0
        DO 300 J = 1 , IE
          DO 300 I = 1, NLEVEL
             TMAX = AMAX1 (TMAX, TEXLVL(I,J))
             TMIN = AMIN1 (TMIN, TEXLVL(I,J))
300     CONTINUE
        WRITE(*,*)
        WRITE(*,*)'  TMAX = ',TMAX
        WRITE(*,*)
        WRITE(*,*)'  TMIN = ',TMIN
        WRITE(*,*)

C.....................NON DIMENSIONLIZING TIME AND TEMP............

       DO 400 II = 1, IE
          TIMED(II) = TIM * TIME(II)
            DO 400 JJ = 1, NLEVEL
400            TSTRLS(JJ,II) = (TEXLVL(JJ,II) - TMIN) / (TMAX - TMIN)

C...............................PRINTING..........................

        DO 500 I = 1, IE
           WRITE(9,600) TIMED(I), (TSTRLS(K,I), K = 1, NLEVEL)
500     CONTINUE
600     FORMAT(10(1X,F6.3))

C...........................THE END..............................

        STOP
        END
```

C.3 LVLDIM

```
C...............................................................C
C                                                               C
C    THIS PROGRAM READS THE TEMPERATURES FROM THE AVERAGE FILES C
C    - AVE0, AVE1, AVE2, etc. - THEN IT WRITE THE TEMPERATURES  C
C    IN A FILE CALLED 'OUTPUT.DAT' IN A TWO DIMENSIONAL FORM.   C
C                                                               C
C                             BY                                C
C                    MR. YOUSEF H. ZURIGAT                      C
C                                                               C
C                         MODIFIED BY                           C
C                    MOUTASEM ABU-HAMDAN                        C
C                                                               C
C      VARIBLES DESCRIPTION :                                   C
C                                                               C
C           NLEVL = THE NUMBER OF THERMOCOUPLE LEVELS           C
C            IEND = THE MAXIMUM NUMBER OF DATA                  C
C            TIME = THE TIME INCREMENT AT WHICH THE DATA IS READ C
C          TEXLVL = THE TEMP. IN THE AVERAGE FILES              C
C                                                               C
C...............................................................C

        DIMENSION TIME(300),TEXLVL(9,200)

C.............................DATA................................

        DATA NLEVL / 9 /
        DATA IEND / 500 /
C.......................DATA FILES................................
        OPEN (8,FILE='A:AVE0.DAT',STATUS='OLD')
        OPEN (9,FILE='A:AVE1.DAT',STATUS='OLD')
        OPEN (10,FILE='A:AVE2.DAT',STATUS='OLD')
        OPEN (11,FILE='A:AVE3.DAT',STATUS='OLD')
        OPEN (12,FILE='A:AVE4.DAT',STATUS='OLD')
        OPEN (13,FILE='A:AVE5.DAT',STATUS='OLD')
        OPEN (14,FILE='A:AVE6.DAT',STATUS='OLD')
        OPEN (15,FILE='A:AVE7.DAT',STATUS='OLD')
        OPEN (16,FILE='A:AVE8.DAT',STATUS='OLD')
        OPEN (3,FILE='A:OUTPUT.DAT',STATUS='NEW')
        OPEN (17,FILE='A:CHAN_0.DAT',STATUS='OLD')
        OPEN (18,FILE='A:CHAN_10.DAT',STATUS='OLD')
C..................READING THE FILES..............................
        DO 10 I = 1, NLEVL

        GO TO (713, 714, 715, 716, 717, 718, 719, 720, 721), I

713      DO 11 J = 1 , IEND

        READ(8,*,END=10)TIME(J), TEXLVL(I,J)
11      CONTINUE
```

```
        GO TO 10
714     DO 12 J = 1 , IEND

        READ(9,*,END=10)TIME(J), TEXLVL(I,J)
12      CONTINUE
        GO TO 10
715     DO 13 J = 1 , IEND
        READ(10,*,END=10)TIME(J), TEXLVL(I,J)
13      CONTINUE
        GO TO 10
716     DO 14 J = 1 , IEND

        READ(11,*,END=10)TIME(J), TEXLVL(I,J)
14      CONTINUE
        GO TO 10
717     DO 15 J = 1 , IEND

        READ(12,*,END=10)TIME(J), TEXLVL(I,J)
15      CONTINUE
        GO TO 10
718     DO 16 J = 1 , IEND

        READ(13,*,END=10)TIME(J), TEXLVL(I,J)
16      CONTINUE
        GO TO 10
719     DO 17 J = 1 , IEND

        READ(14,*,END=10)TIME(J), TEXLVL(I,J)
17      CONTINUE
        GO TO 10
720     DO 18 J = 1 , IEND

        READ(15,*,END=10)TIME(J), TEXLVL(I,J)
18      CONTINUE
        GO TO 10
721     DO 19 J = 1 , IEND

        READ(16,*,END=10)TIME(J), TEXLVL(I,J)
19      CONTINUE

10      CONTINUE
        IE=J-1

C
        DO 798 I=1,IE
        WRITE(03,333)TIME(I),(TEXLVL(K,I),K=1,NLEVL)
798     CONTINUE
333     FORMAT(10(1X,F6.2))

          STOP
          END
```

C.4 LVLNDIM

```
C...........................................................C
C                                                           C
C    THIS PROGRAM READS THE OUTPUT DATA FILE THAT CONTAINS THE     C
C    9-LEVELS TEMPERATURE DATA THAT WAS GENERATED BY THE PROGRAM   C
C    'LVLDIM' - THAT IS YOU HAVE TO RUN PROGRAM 'LVLDIM' FIRST,     C
C    ALSO YOU HAVE TO RUN PROGRAM 'LVL2NDIM' BEFORE THIS PROGRAM   C
C    IN ORDER TO KNOW WHAT ARE THE MINIMUM AND MAXIMUM INLET TEMP. C
C                                                           C
C                          BY                               C
C                 MR. YOUSEF H. ZUIRGAT                     C
C                                                           C
C                      MODIFIED BY                          C
C               MOUTASEM ABU-HAMDAN ( 1988 )                C
C                                                           C
C       VARIABLES DESCRIPTION :                             C
C                                                           C
C              IEND = THE MAXIMUM NUMBER OF READINGS        C
C             NLEVL = THE NUMBER OF LEVELS                  C
C            HEIGHT - HEIGHT OF THE TANK                    C
C               DIA = DIAMETER OF THE TANK                  C
C              TIME = THE TIME INCREMENTS AT WHICH DATA IS READ    C
C            TEXLVL = THE TEMPERATURES IN THE 'OUTPUT.DAT' FILE    C
C            TSTRLS = THE DIMENSIONLESS TEMPERATURE         C
C             TIMED = THE DIMENSIONLESS TIME                C
C               TIM = DIMENSIONAL TIME                      C
C              AREA = CROSS SECTIONAL AREA OF THE TANK      C
C               GPM = THE VOLUMETRIC FLOW RATE IN GAL/MIN   C
C              QVOL = THE VOLUMETRIC FLOW RATE IN CUBIC FT/MIN     C
C              TMIN = THE MINIMUM TEMP. OCCURED DURING THE RUN     C
C              TMAX = THE MAXIMUM TEMP. OCCURED DURING THE RUN     C
C               VEL = THE VELOCITY OF THE FLOW              C
C                                                           C
C...........................................................C

        DIMENSION TIME(300),TEXLVL(9,200),TSTRLS(9,200),TIMED(200)
C..............................DATA.............................

        DATA IEND / 500 /
        DATA NLEVL / 9 /
        DATA DIA, HEIGHT / 1.333, 62.4 /
C..........................DATA FILES...........................

        OPEN(8,FILE='A:OUTPUT.DAT',STATUS='OLD')
        OPEN(9,FILE='A:TDIME.DAT',STATUS='NEW')
C............................INPUTS.............................

        WRITE(*,*)'ENTER FLOW RATE IN GPM'
        WRITE(*,*)
        READ(*,*)GPM
```

```
      WRITE(*,*)
      WRITE(*,*)'ENTER THE MAXIMUM INLET TEMPERATURE, 'F'
      WRITE(*,*)
      READ(*,*)TMAX
      WRITE(*,*)
      WRITE(*,*)'ENTER THE MINIMUM INLET TEMPERATURE, 'F'
      WRITE(*,*)
      READ(*,*)TMIN

C.............................CONSTANTS............................

      PI = 3.1415927
      HEIGHT = HEIGHT / 12.
      QVOL = GPM / 7.48
      AREA = PI * DIA**2 / 4.0
      VEL = QVOL / AREA
      TIM = VEL / HEIGHT

C.............READING THE TEMP. FRROM THE OUTPUT FILE...............

      DO 100 J = 1 , IEND
        READ(8,*,END=200)TIME(J), (TEXLVL(I,J), I = 1, NLEVL)
100   CONTINUE
200   IE = J - 1

C.....................NON DIMENSIONLIZING TIME AND TEMP............

     DO 400 II = 1, IE
        TIMED(II) = TIM * TIME(II)
          DO 400 JJ = 1, NLEVL
400          TSTRLS(JJ,II) = (TEXLVL(JJ,II) - TMIN) / (TMAX - TMIN)

C................................PRINTING..........................

      DO 500 I = 1, IE
         WRITE(9,600) TIMED(I), (TSTRLS(K,I), K = 1, NLEVL)
500   CONTINUE
600   FORMAT(10(1X,F6.3))

C............................THE END...............................

      STOP
      END
```

APPENDIX D

THE HEATLOSS PROGRAM

D.1 Description

The heat loss rate calculations were done using the sensible heat loss equation:

$$Q_i = m_i C_p (T_2 - T_1)_i \qquad (D.1)$$

where,

Q_i = sensible heat loss from slab i

m_i = mass of slab i

C_p = specific heat of water (assumed constant in the temperature region used)

$(T_2 - T_1)$ = difference in temperature in slab i between two successive time intervals

The mass of each slab can be replaced by

$$m_i = \rho V_i \qquad (D.2)$$

where,

ρ = density of water as a function of temperature

V_i = volume of slab i (see Fig. D.1)

Substituting (D.2) into (D.1) we get

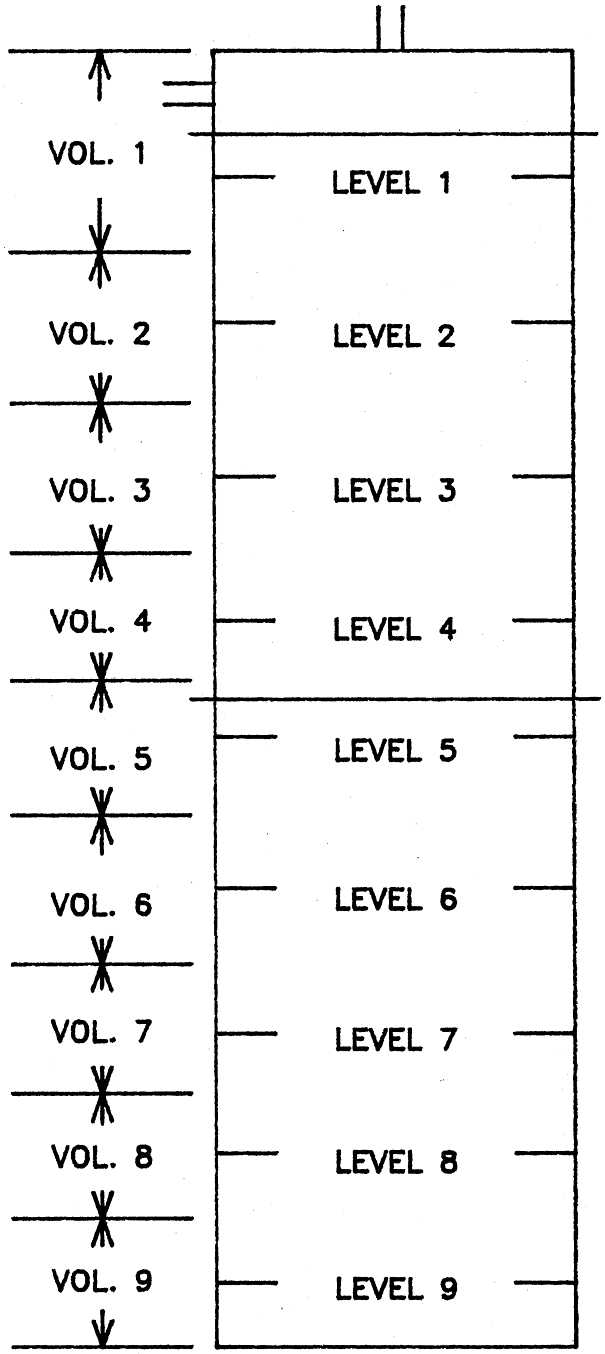

Figure D.1 Test Tank Slab Divisions

$$Q_i = \rho V_i C_p (T_2 - T_1)_i \quad (D.3)$$

Equation (D.3) was used in the program "HEATLOSS" to calculate the heat loss from each slab. The equation was averaged by integrating it over the total run time. The integration was done by taking the sum of the heat losses from each slab divided by the total time of the run, or in mathematical notation:

$$\dot{Q}_i = \Sigma Q_i / t \quad (D.4)$$

where,

$\dot{Q}_i$ = heat loss rate from slab i

t = total run time

Then the total heat loss rate of the test tank was calculated by taking the sum of all the heat loss rates of all the slabs. The hour by hour calculations were done using the same procedure stated above, but instead of integrating over the whole time of the run, the specified time was used. A listing of the program followed by an output are shown next.

D.2 Listing

```
C.............................................................C
C                                                             C
C                   HEATLOSS PROGRAM                          C
C                                                             C
C                 MOUTASEM G. ABU-HAMDAN                      C
C                       NOV. 1987                             C
C                                                             C
C        VARIABLES DESCRIPTION :                              C
C                                                             C
C              CONST = HEIGHT OF EACH LEVEL                   C
C                 CP = SPECIFIC HEAT OF THE WATER             C
C               DENS = FUNCTION TO CALCULATE THE DENSITY      C
C             DENSIT = DENSITY AT A GIVEN TEMP.               C
C                DIA = THE DIAMETER OF THE TANK               C
C               HOUR = A CHARACTER VARIABLE TO STORE THE ANSWER   C
C                      TO THE HOUR BY HOUR CALCULATIONS       C
C                 HR = THE PERIOD OF THE HOUR BY HOUR CALCULATIONS C
C             LENGTH = A COUNTER TO ADD THE HEIGHT OF THE LEVELS  C
C              LIMIT = A LIMIT ON THE TIME IN HEATLOSS HOUR BY    C
C                      HOUR CALCULATIONS                      C
C                 PI = CONSTANT EQUAL TO 3.1415927            C
C                  Q = THE HEAT LOST FROM A LEVEL             C
C               QTOT = THE HEAT LOST FROM THE TANK            C
C              TDENS = TEMP. THAT YOU NEED TO FIND THE DENSITY AT C
C               TEMP = TEMP. OF A LEVEL AT A GIVEN TIME       C
C              TEMP1 = DUMMY VARIABLE FOR THE VARIABLE TEMP.  C
C               TIME = A GIVEN TIME OF THE RUNNIMG TIME       C
C                VOL = VOLUME OF EACH LEVEL                   C
C                  X = THE DISTANCE FROM THE TOP OF THE TANK  C
C                                                             C
C.............................................................C
      CHARACTER HOUR*1
      DIMENSION X(11), VOL(9)
C.......................THERMOCOUPLE LOCATIONS IN INCHES..............

      DATA X / 0., 5.375, 11.625, 17.625, 24.625, 32., 38., 44.5,
     1         50.375, 56.625, 62.0625 /

C...................OPEN READ & OUTPUT FILES..........................

      OPEN(1,FILE='B:AVE0.DAT',STATUS='OLD')
      OPEN(2,FILE='B:AVE1.DAT',STATUS='OLD')
      OPEN(3,FILE='B:AVE2.DAT',STATUS='OLD')
      OPEN(4,FILE='B:AVE3.DAT',STATUS='OLD')
      OPEN(5,FILE='B:AVE4.DAT',STATUS='OLD')
      OPEN(6,FILE='B:AVE5.DAT',STATUS='OLD')
      OPEN(7,FILE='B:AVE6.DAT',STATUS='OLD')
      OPEN(8,FILE='B:AVE7.DAT',STATUS='OLD')
      OPEN(9,FILE='B:AVE8.DAT',STATUS='OLD')
      OPEN(10,FILE='B:HEATLOSS.DAT',STATUS='NEW')
```

```
C............................INPUTS................................

      WRITE(*,*)
      WRITE(*,*)'DO YOU NEED HOUR BY HOUR HEATLOSS CALCULATIONS? (Y/N)'
      WRITE(*,*)
      READ(*,*)HOUR
      IF ( HOUR .EQ. 'Y' ) THEN
       WRITE(*,*)
       WRITE(*,*)'OVER HOW MUCH TIME DO YOU NEED THE CALCULATIONS, (hr)'
       WRITE(*,*)
       READ(*,*)HR
       LIMIT = HR * 60.0
      END IF
C...........................CONSTANTS................................

      DIA = 1.333333
      CP = 1.
      PI = 3.1415927
C.......................INITIALIZATION...............................

      Q = 0.0
      QTOT = 0.0
      LENGTH = 0.0
C............LOOP TO CALCULATE THE VOLUME OF EACH SLAB...............

      DO 10 I = 1, 9
            CONST = X(I+1) - LENGTH + 0.5 * ( X(I+2) - X(I+1) )
            VOL(I) = CONST * PI * DIA**2 / 48.
            LENGTH = LENGTH + CONST
10    CONTINUE
C..................CALCULATING THE HEAT LOSS..........................

      DO 60 I = 1, 9
            ID = I
          DO 40 J = 1, 1000
C                ... READING THE TEMPERATURES ...

                 READ(ID,20,END=45)TIME,TEMP1
 20              FORMAT(F6.2,9X,F6.2)
                 IF ( HOUR .EQ. 'Y' .AND. TIME .GT. LIMIT ) GO TO 45
                 IF( J .EQ. 1 ) TEMP = TEMP1
                 TDENS = TEMP1
C           ... FIGURING OUT THE DENSITY ACCORDINGLY ...

                 DENSIT = DENS(TDENS)
                 Q = Q + VOL(I) * DENSIT * CP * ( TEMP1 - TEMP )
C           ... UPDATING THE OLD TEMPERATURE ...

                 TEMP = TEMP1
 40       CONTINUE
C          ... CONVERTING THE TIME TO HOURS ...

 45         TIME = TIME / 60.0
```

```
C          ... THE HEAT LOSS RATE ...

           Q = Q / TIME

C             ... PRINTING THE HEAT LOSS ...
           WRITE(10,50)I, Q
 50        FORMAT(1X,'THE TOTAL HEAT LOSS FROM LEVEL # ',I1,' =',F10.2,
     $2X,'BTU/H')
C          ... ADDING THE HEAT LOSS FROM EACH LEVEL TO THE ...
C               ... TOTAL HEAT LOSS FROM THE TANK ...
           QTOT = QTOT + Q

C          ... UPDATING THE HEAT LOSS FROM EACH LEVEL ...

           Q = 0.0
 60   CONTINUE

C.............PRINTING THE TOTAL HEAT LOSS FROM THE TANK.............

      WRITE(10,*)
      WRITE(10,70)QTOT
 70   FORMAT(1X,'THE TOTAL HEAT LOSS FROM THE TANK = ',F17.2,2X,'BTU/H')
      WRITE(10,80)TIME
 80   FORMAT(/,1X,'OVER A PERIOD OF TIME EQUAL TO ',F5.2,' hrs.')

C.........................FINISH....................................

      STOP
      END

C....................FUNCTION TO CALCULATE THE DENSITY...............C
C                                                                   C
C...................................................................C

      FUNCTION DENS(T)

C          ... CONVERTING THE TEMPERATURE TO KELVINS ...

      T = ( ( T - 32.0 ) * 5. / 9. ) + 273.15

C          ... CALCULATING THE DENSITY ...

      DENS = -3.0115E-06 * T**3 + 9.6272E-04 * T**2 - 0.11052 * T
     $  + 1022.4

C       ... CONVERTING THE DENSITY TO lbm / cubic foot ...

      DENS = DENS * .062428
      RETURN

C              ... THE END ...

      END
C...................................................................
```

D.3 Sample Output

THE TOTAL HEAT LOSS FROM LEVEL # 1 = -223.50 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 2 = -173.47 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 3 = -186.22 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 4 = -195.25 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 5 = -182.69 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 6 = -165.81 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 7 = -169.46 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 8 = -171.80 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 9 = -173.46 BTU/H

THE TOTAL HEAT LOSS FROM THE TANK = -1641.65 BTU/H

OVER A PERIOD OF TIME EQUAL TO 13.88 hrs.

THE TOTAL HEAT LOSS FROM LEVEL # 1 = -334.95 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 2 = -262.46 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 3 = -271.68 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 4 = -300.63 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 5 = -290.41 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 6 = -251.98 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 7 = -244.27 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 8 = -239.62 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 9 = -261.89 BTU/H

THE TOTAL HEAT LOSS FROM THE TANK = -2457.91 BTU/H

OVER A PERIOD OF TIME EQUAL TO 1.05 hrs.

THE TOTAL HEAT LOSS FROM LEVEL # 1 = -183.35 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 2 = -142.73 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 3 = -152.41 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 4 = -158.04 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 5 = -148.56 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 6 = -136.21 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 7 = -139.99 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 8 = -142.63 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 9 = -144.22 BTU/H

THE TOTAL HEAT LOSS FROM THE TANK = -1348.13 BTU/H

OVER A PERIOD OF TIME EQUAL TO 20.27 hrs.

THE TOTAL HEAT LOSS FROM LEVEL # 1 = -318.31 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 2 = -252.72 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 3 = -242.65 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 4 = -268.85 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 5 = -273.58 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 6 = -250.66 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 7 = -247.88 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 8 = -260.23 BTU/H
THE TOTAL HEAT LOSS FROM LEVEL # 9 = -257.07 BTU/H

THE TOTAL HEAT LOSS FROM THE TANK = -2371.97 BTU/H

OVER A PERIOD OF TIME EQUAL TO 1.03 hrs.

APPENDIX E

THE COMPUTER CODE "EFFCINT"

E.1 Description

The procedure outlined for calculation of the efficiency of a flat plate solar collector is based on that outlined in Duffie and Beckman, 1980. The procedure is to be carried out for an actual collector, thus a plot of η_i versus (T_i-T_a) / G_T is needed,

where,

η_i = Instantaneous efficiency

T_i = Inlet temperature to the solar collector

T_a = Ambient temperature

G_T = Total incident radiation flux.

Figure 5 presented by Fanney and Klein (1988), is to be used for these calculations (see Fig. E.1). This Figure is for a collector with a surface area of 4.2 m^2 and for flow rates of 0.02 and 0.0033 kg/s-m^2.
Assuming that the above mentioned collector is hooked to a supply tank with flow rates similar to those done in this study, then a flow rate correction factor need to be calculated in order to be able to use Figure E.1.

Let,

G_T = 870 W/m^2

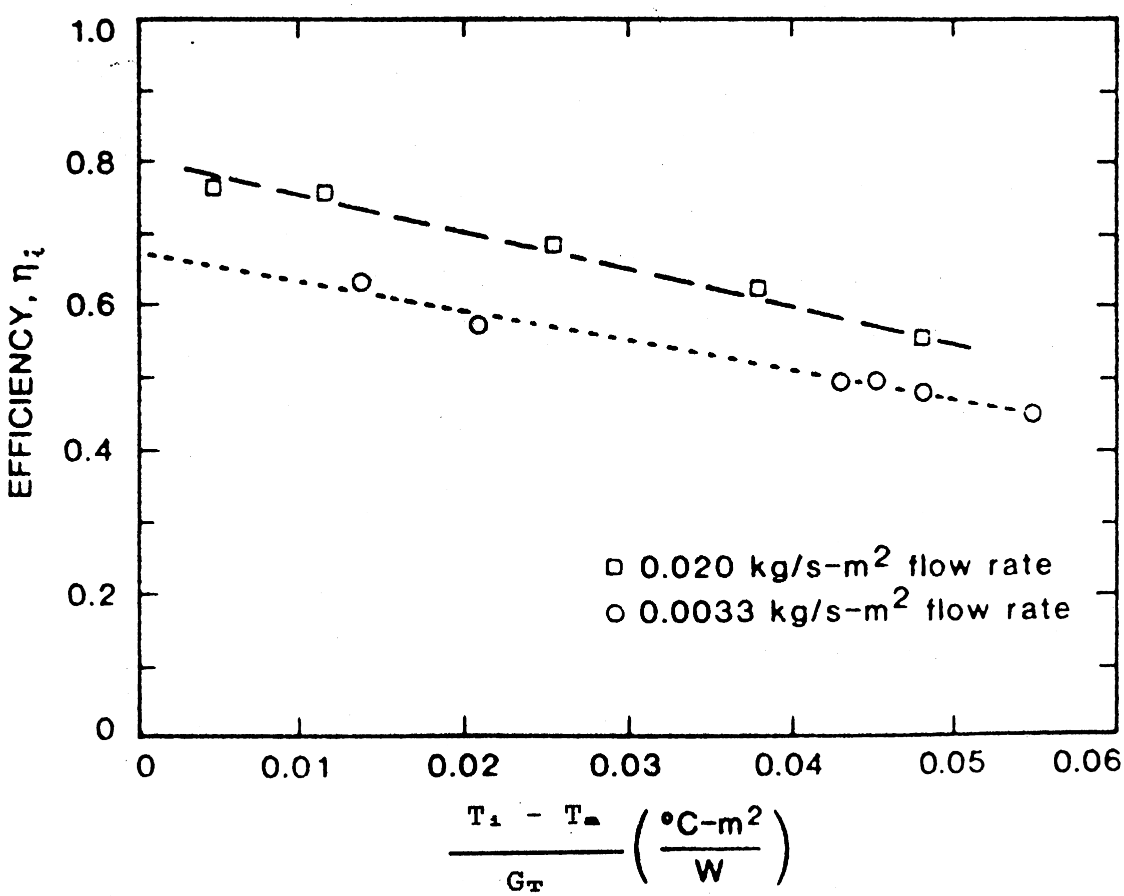

Figure E.1 Solar Collector Efficiency Curves. (Adopted from Fanney and Klein, 1988) and keep it constant throughout the simulation time.

Also let,

$$T_a = 25 \ ^oC$$

Then the useful gain of the collector is

$$Q_u = A_c \left[G_T F_R(\tau\alpha) - F_R U_L (T_i - T_a) \right] \quad (E.1)$$

and

$$\eta_i = \frac{Q_u}{A_c G_T} = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{G_T} \quad (E.2)$$

where,

$F_R(\tau\alpha)$ = is the y-intercept of Fig. E.1

A_c = surface area of the collector, 4.2 m^2

$F_R U_L$ = is the slope of Fig. E.1

Then the flow rate correction factor, r, is

$$r = \frac{(F_R U_L)_{use}}{(F_R U_L)_{test}} = \frac{[F_R(\tau\alpha)]_{use}}{[F_R(\tau\alpha)]_{test}} \quad (E.3)$$

also

$$r = \frac{\left\{ \frac{\dot{m} C_p}{A_c F' U_L} \left[1 - \exp\left(- \frac{A_c F' U_L}{\dot{m} C_p}\right) \right] \right\}_{use}}{\left\{ \frac{\dot{m} C_p}{A_c F' U_L} \left[1 - \exp\left(- \frac{A_c F' U_L}{\dot{m} C_p}\right) \right] \right\}_{test}} \quad (E.4)$$

where the subscript "use" refers to the values to be used from the experiments of this study, and the subscript "test" refers to the values from Fig. E.1; and

$$F'U_L = -\frac{\dot{m}\,C_p}{A_c}\ln\left(1 - \frac{F_R U_L A_c}{\dot{m}\,C_p}\right) \qquad (E.5)$$

where,

$\dot{m}$ = mass flow rate through the collector

C_p = specific heat of the water.

For water, $F'U_L$ can be the same in both the numerator and the denominator of Eq. (E.4).

The procedure to solve for the flow rate correction factor, r, is the following:

1. Solve for $F'U_L$ using Eq. (E.5) by substituting in the values given in Fig. E.1, which are,

   $F_R U_L$ = 4.1 W/m²-K

   $\dot{m}$ = 0.0033 kg/s-m²

2. Solve for the flow rate correction factor, r, using Eq. (E.4) and the value of $F'U_L$ obtained in step # 1.

3. Solve for $(F_R U_L)_{use}$ and $[F_R(\tau\alpha)]_{use}$ using Eq. (E.3), the value of r obtained in step # 2, and the values of $(F_R U_L)_{test}$ and $[F_R(\tau\alpha)]_{test}$ from Fig. E.1, which are,

   $F_R U_L$ = 4.1 W/m²-K

   $F_R(\tau\alpha)$ = 0.68

4. After the use values of $F_R U_L$ and $F_R(\tau\alpha)$ are found, Eq. (E.2) can be solved to find the collector efficiency, η_i.

The above procedure was coded in a computer code called

"EFFCINT" to generate the collector efficiency curves for the experimental runs. The computer code has the option of calculating the collector efficiency due to stratification alone or due to stratification and flow rate combined. The efficiency due to stratification alone was done by inputing the outlet temperature readings of the storage tank as the collector inlet temperature using the same flow rate for all the experimental runs; while for the combined case, actual average flow rates of the experimental runs were used.

The computer code listing is shown next along with the variables description.

E.2 Listing

```
C...............................................................C
C                                                               C
C                   SOLAR COLLECTOR EFFICINCY                   C
C                                                               C
C                      YOUSEF H. ZURIGAT                        C
C                                                               C
C                              &                                C
C                                                               C
C                    MOUTASEM G. ABU-HAMDAN                     C
C                                                               C
C                          MAY, 1988                            C
C                                                               C
C    VARIABLES DESCRIPTION :                                    C
C                                                               C
C                A = A PART OF THE CORRECTION FACTOR EQUATION   C
C            ACOLL = THE SOLAR COLLECTOR SURFACE AREA ( SI UNITS )  C
C                B = A PART OF THE CORRECTION FACTOR EQUATION   C
C                C = A PART OF THE CORRECTION FACTOR EQUATION   C
C            CPENG = SPECIFIC HEAT OF THE WATER ( ENGLISH UNITS )   C
C             CPSI = SPECIFIC HEAT OF THE WATER ( SI UNITS )    C
C           DENSIT = THE DENSITY OF WATER AT THE CORRESPONDING TEMP  C
C              ETA = THE SOLAR COLLECTOR-THERMAL STORAGE EFFICIENCY  C
C             FILE = FILE NAME WHERE THE DATA IS STORED         C
C            FPRUL = THE CONSTANT F PRIME TIMES UL              C
C            FRTAU = THE CONSTANT FR TIME TAU TIMES ALPHA       C
C             FRUL = THE CONSTANT FR TIME UL                    C
C              GPM = THE FLOW RATE                              C
C               GT = THE SOLAR IRRADIANCE                       C
C            INDEX = AN INDEX TO INDICATE WHICH EFF. TO CALCULATE   C
C                N = A COUNTER                                  C
C                R = CORRECTION FACTOR                          C
C             TAMB = THE AMBIENT TEMP                           C
C             TCIN = THE COLLECTOR INLET TEMP.                  C
C            TCINN = COLLECTOR NONDIMENSIONLESS TEMP IN TDIME2.DAT  C
C            TDENS = THE TEMPERATURE YOU WANT TO FIND THE DENSITY AT C
C              TIM = NO DIMENSIONLESS TIME IN FILE TDIME2.DAT   C
C             TIME = THE TIME OF EACH READING                   C
C              TIN = TANK DIMENSIONLESS INLET TEMP IN TDIME2.DAT    C
C                                                               C
C...............................................................C
      CHARACTER FILE*12
      OPEN(1,FILE='A:CHAN_10.DAT',STATUS='OLD')
      OPEN(2,FILE='A:TDIME2.DAT',STATUS='OLD')
C.........................INPUTS.................................
      WRITE(*,*)
 5    WRITE(*,*)'ENTER "1" FOR EFFCIENCY DUE STRATIFICATION ONLY'
      WRITE(*,*)'      "2" FOR EFF. DUE TO FLOW RATE AND STRATIFICATION'
      WRITE(*,*)
      READ(*,*)INDEX
```

```
      IF ( INDEX .GT. 2 .OR. INDEX .LT. 1 ) THEN
          WRITE(*,*)
          WRITE(*,*)'         ***  INPUT ERROR  ***'
          WRITE(*,*)
          GO TO 5
      END IF
      IF ( INDEX .NE. 1 ) THEN
         WRITE(*,*)
         WRITE(*,*)'WHAT IS THE FLOW RATE FOR THIS RUN, GPM'
         WRITE(*,*)
         READ(*,*)GPM
      ELSE
         GPM = 0.5
      END IF
      WRITE(*,*)
      WRITE(*,*)'ENTER A FILE NAME WHERE YOU WOULD LIKE THE DATA'
      WRITE(*,*)'TO BE STORED - the file name should not exceed 8'
      WRITE(*,*)'characters and 3 character extension.'
      WRITE(*,*)
      READ(*,*)FILE
      OPEN(3,FILE=FILE,STATUS='NEW')

C.............................CONSTANTS................................
      ACOLL = 4.2
      GT = 870.
      FPRUL = 4.864
      CPENG = 1.0
      CPSI = 4184
      TAMB = 25.

C....................CORRECTION FACTOR CALCULATIONS.................

      DO 20 I = 1, 500
         READ(2,*,END=30)TIM, TIN, TCINN
         READ(1,*)N, TCIN, TIME
         TDENS = TCIN
         DENSIT = DENS ( TDENS )
C..
C         A = GPM / 7.48 / 60. * DENSIT * 0.45359
C..
         A = GPM * DENSIT * 0.00101067
         B = 1 - EXP ( - ACOLL * FPRUL / A / CPSI )

         C = 1 - EXP ( - FPRUL / 0.0033 / CPSI )
C..
C         R = GPM / 7.48 / 60. * DENSIT * CPENG * 3600. * B * FPRUL
C     $       / 0.0033 / CPSI / C / ACOLL / 10.764 / FPRUL / 0.17623
C..
         R = GPM * DENSIT * CPENG * B / CPSI / C / ACOLL * 1281.39
         FRUL = R * 4.1
         FRTAU = R * 0.68
         TCIN = ( TCIN - 32.0 ) / 1.8
         ETA = FRTAU - ( FRUL * ( TCIN - TAMB ) / GT )
```

```
        WRITE(3,10)TIM, ETA
 10     FORMAT(1X,E9.3,5X,E10.3)
 20   CONTINUE
 30   CLOSE(3)
      STOP
      END

C.....................FUNCTION TO CALCULATE THE DENSITY...............C
C                                                                     C
C.....................................................................C

      FUNCTION DENS(T)

C          ... CONVERTING THE TEMPERATURE TO KELVINS ...

      T = ( ( T - 32.0 ) * 5. / 9. ) + 273.15

C          ... CALCULATING THE DENSITY ...

      DENS = -3.0115E-06 * T**3 + 9.6272E-04 * T**2 - 0.11052 * T
     $  + 1022.4

C       ... CONVERTING THE DENSITY TO lbm / cubic foot ...
      DENS = DENS * .062428
      RETURN

C               ... THE END ...

      END

C......................................................................
```

VITA

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Master of Science

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Professional Society: Freshman Honorary Society (Phi Eta Sigma); Mechanical Engineering Honorary Society (Pi Tau Sigma); National Engineering Honorary Society (Tau Beta Pi); American Society of Mechanical Engineers (ASME).