

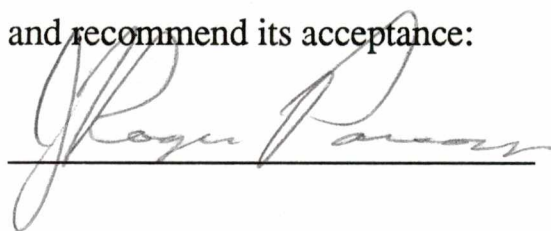
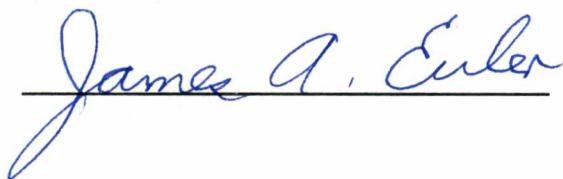
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Date July 26, 1988

**A STUDY OF THE
TRANSIENT EFFECTS
OF THERMOACOUSTIC
CONVECTION HEAT
TRANSFER IN AIR**

**A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville**

**Jeffrey A. Catt
August 1988**

To My New Wife
Julieann

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My deepest gratitude goes to my wife Julieann for her love and encouragement, and to our Lord, whom we serve, Christ Jesus.

ABSTRACT

An experimental study of Thermoacoustic Convection (TAC) heat transfer in air is presented. The experimental apparatus consisted of an insulated rectangular box with a foil heating element attached to the upper endplate. The heating element was connected to a DC power source. The endplate opposite the heating element could be removed to facilitate experimentation in open, as well as enclosed, containers. Thermocouples were placed along the length of the container to measure the transient air temperature. The enclosed apparatus could be evacuated to experimentally measure the effect of radiation absorption by the thermocouples.

- The presence of air around the thermocouple was found to have a cooling effect on it. It was proposed that the magnitude of this cooling effect be evaluated as a means of determining if a forced convective cooling process was taking place. Once this was found to be the case, the Nusselt number for each thermocouple bead in air was determined for specific points in time. These values were presented as an indication of the relative magnitudes of air movement within the container. The results were examined for insight into the transient and spatial variation of Nusselt number (and, therefore, air movement) within the container. Results were presented for both enclosed and open container geometries to observe any affect of cavity configuration on TAC.

The results confirm the existence of TAC. Notable spatial and transient variations of the air movement indicative of TAC were observed. In addition, significant differences were found between experimentation in open and enclosed container geometries.

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LIST OF SYMBOLS USED

a_0	speed of sound
a	accommodation coefficient
A	surface area
$A_{\text{box end}}$	internal surface area of box endplate
A_{foil}	surface area of foil heater surface
A_{tc}	surface area of thermocouple bead
B	ratio of half the length of the side of a square to the distance between the center of the sphere and the center of the square surface
C	thermocouple bead specific heat
C_{Chromel}	specific heat of Chromel-P
C_{Alumel}	specific heat of Alumel
c_p	constant pressure specific heat
d_{tc}	diameter of thermocouple bead
E_0	heat conducted per unit surface area
$F_{\text{foil-tc}}$	view factor from foil heater surface to thermocouple bead
$F_{\text{tc-foil}}$	view factor from thermocouple bead to foil heater surface
$F_{\text{tc-box end}}$	view factor from thermocouple bead to internal box endplate
$F_{\text{sphere-square}}$	view factor from sphere to square centered above sphere

h	overall convective heat transfer coefficient of the thermocouple
k_{air}	thermal conductivity of air
L	length
m_{tc}	mass of the thermocouple bead
Nu	Nusselt number
p_0	initial pressure
p_1	pressure behind a travelling shock wave
P	pressure
P_g	pressure of saturated steam
P_v	partial pressure of water vapor in air
q	rate of heat transfer
$q_{\text{COND,air}}$	rate of heat transferred by conduction from thermocouple to air
$q_{\text{COND,wire}}$	rate of heat transferred by conduction from thermocouple through thermocouple wires
$q_{\text{CONV,air}}$	rate of heat transferred by convection from thermocouple to air
q_{RAD}	rate of heat transferred by radiation exchange
t	time
T	temperature
$T_{\text{box end}}$	temperature of the box endplate
T_i	initial temperature
T_{foil}	temperature of the foil heater surface

T_{tc}	temperature of the thermocouple bead
T_0	temperature of the surface
T_{∞}	initial or core temperature of the medium
w_0	rate of heat release per unit area

Greek Symbols

α_{air}	radiative absorptivity of air
δp	perturbation of pressure
ΔE_{tc}	change in internal energy of the thermocouple bead
ϵ_{air}	radiative emissivity of air
ϵ_{foil}	emissivity of the foil heater surface
ϵ_{tc}	emissivity of the thermocouple bead
Φ	relative humidity
γ	ratio of specific heats
λ	molecular mean free path
Λ_0	free molecular conductivity
$\rho_{Chromel}$	density of Chromel-P
ρ_{Alumel}	density of Alumel
σ	Stefan-Boltzmann constant
τ	radiative transmittance of air

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Research in the area of thermoacoustic convection (TAC) heat transfer is recognized to be of great importance for a number of reasons. Probably the most significant of these is the possibility that in weightless environments TAC may become one of the principle means by which heat is transferred through a fluid. For this reason alone a fundamental understanding of the TAC process is crucially important and of great interest in a variety of applications.

One important application is in the field of space manufacturing processes. Microgravity conditions can provide uniformity and purity of materials that cannot be produced in a gravity environment, where density differences and buoyancy effects can compromise a manufacturing process. It is also noted that most manufacturing processes involve the transfer of heat to and through fluids. In this environment TAC may become a significant contributor, if not the dominant mode of heat transfer.

TAC becomes more significant as the rate of heat flux is increased and, for this reason, has been reported to have reached

significant levels even in gravity environments. For example, in cryogenic flow lines where large temperature differences lead to large heat fluxes, thermoacoustic oscillations have been cited as the primary factor in the rise in the upstream energy of a cryogen when it experiences a downstream thermal energy input.¹ Cryogenic systems are also known to be susceptible to instabilities resulting from the formation of thermoacoustic oscillations. These oscillations are responsible for the difficulty in the transport of cryogens and the shortening of the operating life of low temperature systems.¹ It has also been proposed that superconducting power lines (possibly to be cooled by supercritical helium) are also prime candidates for these instabilities.²

- The TAC process may be described as follows. It should be obvious that the thermal and mechanical responses of a fluid are inherently linked. When a fluid is subjected to the rapid addition of heat, either at a boundary or generated from within the fluid itself (e.g., chemical reactions), the medium reacts with a decrease in the density of that portion of fluid in closest proximity of the boundary. A decrease in density indicates an expansion in the control volume occupied by that portion of fluid. This volumetric change results in the propagation of a pressure wave through the bulk fluid in much the same manner as a moving piston propagates pressure waves to its environment. As in the case of the moving piston, the pressure waves are of acoustic origin and move away from the expanding portion of

fluid subjected to the temperature increase. These moving pressure waves induce fluid motion and provide a convective mode to the transfer of heat. This added convective mode allows for a greater amount of heat to be transferred through (or into) the medium than would occur if the TAC process was not present. In short, TAC is the transfer of heat through a medium as the result of thermally induced pressure wave propagation (see Figure 1.1).

While a large number of analytical investigations of the TAC heat transfer process have been completed, very little has been done in the area of experimental research. The only recent experimental research undertaken in the area of TAC heat transfer has been performed by Parang and Salah-Eddine.^{3,4,5} Their experimental and analytical research will be expanded upon in the following section. The present study is a continuation and development of that investigation.

1.2 LITERATURE REVIEW

Sondhauss and Rijke Oscillations:

The first account of sound waves being generated by the addition of heat to a fluid was recorded in 1850 by Sondhauss.⁶ While observing glassblowers he noted that it was not uncommon for the glass bulb and the blowing tube to “sing” when the bulb was heated.

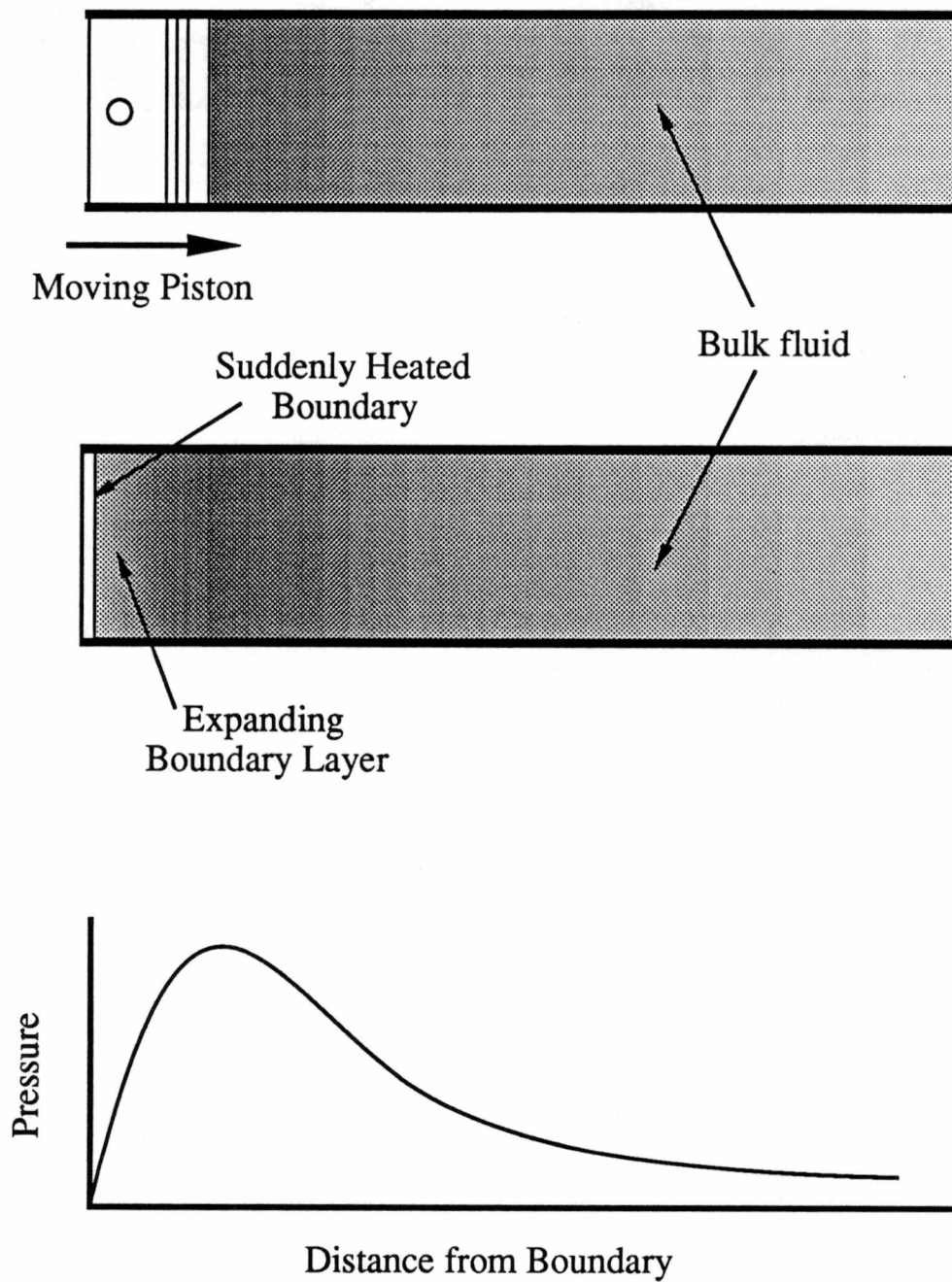


Figure 1.1 Thermoacoustic Convection and the Moving Piston

Sondhauss found that the tone was produced by the vibration of the air within the tube and was characteristic of the geometry of the tube cavity. The "Sondhauss Tube" is shown in Figure 1.2. Sondhauss noted that the tone grew more intense as the rate of heat transferred to the tube was increased. Sondhauss also showed that the tone was not the result of any tube vibration but solely due to the acoustical vibration of the air within the tube.

Soon after Sondhauss published his findings, Rijke discovered that a tone could also be produced if a wire screen was positioned in the lower half of a vertically positioned open-ended tube and the wire screen heated.⁷ He noted that the tone would cease if either end of the tube were closed, indicating that the movement of air through the tube was necessary for production of the tone. The "Rijke Tube" is shown in Figure 1.3. Rijke also noted that the tone was most intense when the heater was positioned one-fourth of the tube's length from the lower end. He published his findings in 1859 along with an explanation that the tone was produced by the successive expansion and contraction of the air flowing through the tube and encountering first the heated wire screen and then the cooler walls of the tube.

Rayleigh, in 1878, published the criterion for the sustained production of these acoustic vibrations: "If heat be given to the air at the moment of greatest condensation or taken from it at the moment of greatest rarefaction, the vibration is encouraged."⁸ This criterion is believed to be the explanation of how thermoacoustic oscillations are

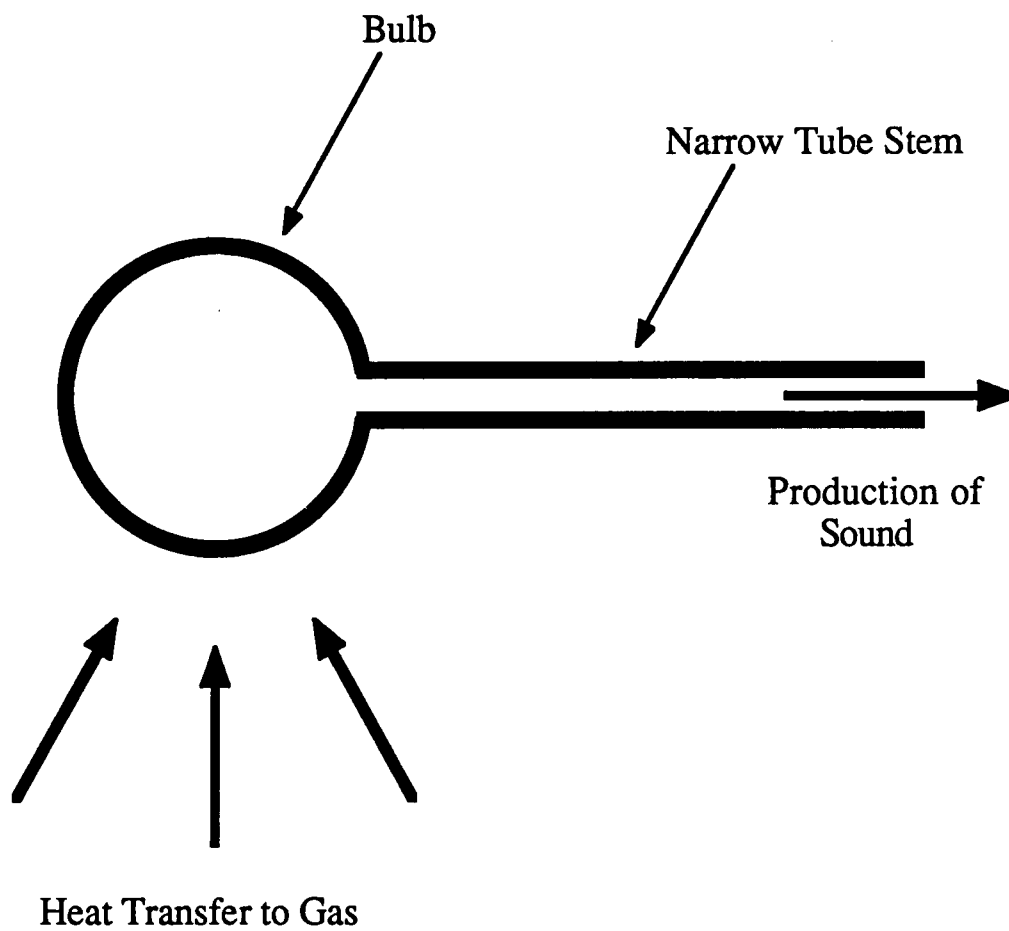


Figure 1.2 Sound Production from the Sondhauss Tube

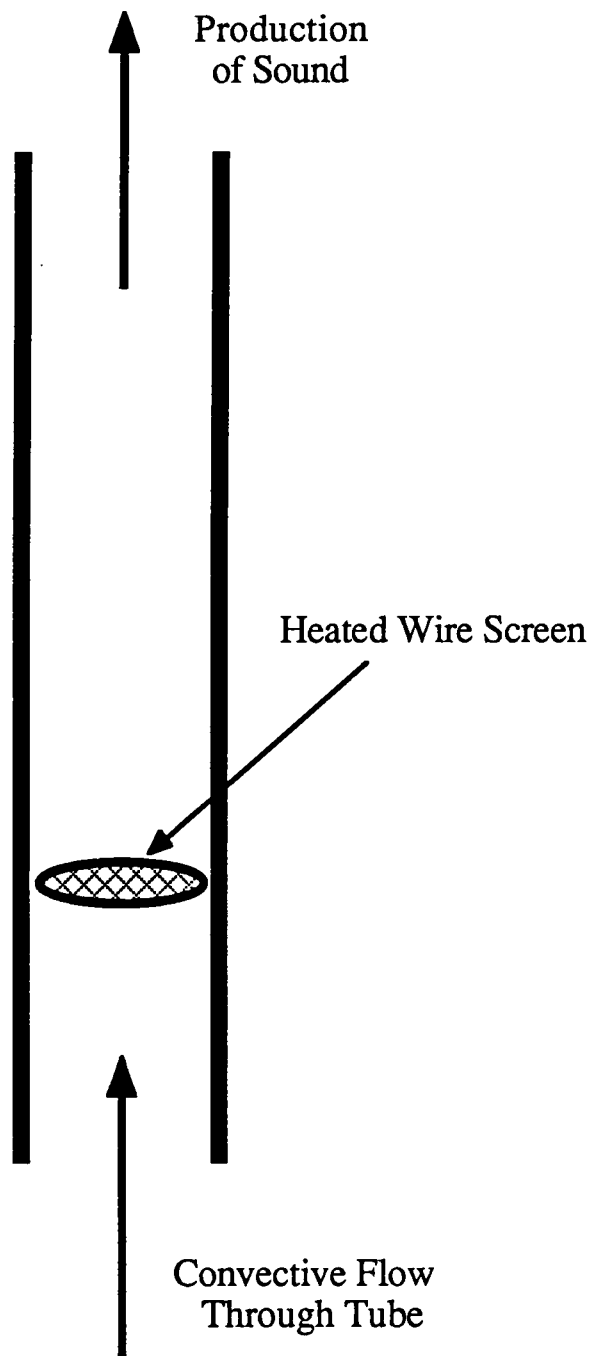


Figure 1.3 Sound Production from the Rijke Tube

sustained, but gives no indication of how the oscillations are begun. These observations, along with those of Sondhauss and Rijke, mark the initial insights into the effect that the transfer of heat has on generating pressure waves.

Recent Contributions:

In an analytical study of TAC, Chu compared the pressure field as established in a fluid driven by a piston with that established by the rapid heating of a fluid in a narrow zone.⁹ His analogy, or “reduction theorem”, can best be described in the form of the following equation.

$$\partial^2[\delta p/(\gamma p_0)] / \partial t^2 - a_0^2 \nabla^2[\delta p_0/(\gamma p_0)] = \partial[q/(c_p T_0)] / \partial t$$

The terms δp , p_0 , a_0 , q , γ , c_p are pressure perturbation, initial pressure, speed of sound, rate of heat transfer to the fluid, ratio of specific heats and constant pressure specific heat, respectively. In the above equation the effect of heating appears as a nonhomogeneous term providing the required energy to drive the pressure waves and produce fluid motion. The above equation is valid for a moderate rate of heat release defined as $qL/(c_p T_0 a_0) \ll 1$ where L denotes the characteristic length in the problem. Chu was able to derive the following solution to the modified wave equation

$$\delta p/p_0 = (\gamma - 1)w_0/(2a_0 p_0)$$

where w_0 is the rate of heat release per unit area. He also noted that if the rate of heat release is high the linearized theory is no longer valid. For this case he presented an exact solution for an idealized problem. It is found that for higher rates of heat release, shock waves, rather than infinitesimal pressure waves, are produced. The shock strength in air can be shown to be

$$p_1/p_0 = 0.325(w_0/(a_0 p_0))^{2/3}$$

A numerical investigation of a one-dimensional TAC model was performed by Larkin.¹⁰ His model consists of a fluid (helium) enclosed by two infinite parallel plates and evaluated assuming a zero-gravity environment. One of the endplates is subjected to a step change in temperature raising it to twice its initial temperature (273°K to 546°K). The numerical results for the transient pressure, temperature, velocity and density profiles within the fluid were then presented. He found that even in the absence of any buoyancy effects, there was evidence to indicate that fluid motion can be established as a result of thermal gradients within the fluid. He noted that the velocity of the fluid expressed an acoustic oscillatory tendency. It was also found that the transient temperature profile indicated a much greater magnitude of heat being transferred to the fluid than could be accounted for by conduction. He credited this increased rate of heat

flow to the convective mode that the acoustic oscillations give to the fluid. The transfer of heat through a medium was therefore established to be the result of the convective nature of the acoustic pressure waves, i.e., the thermally driven acoustic convection or thermoacoustic convection heat transfer process.

Another major numerical investigation of a one-dimensional TAC heat transfer process was performed by Spradley, Burgeois, Fan and Grodzka.¹¹ Their models consisted of a compressible newtonian fluid (helium) which could either be enclosed by two infinite parallel plates (or two infinite concentric cylinders). The first model using the two infinite plates was basically the same model employed by Larkin. It was evaluated assuming a zero-gravity environment and subjecting one of the plates to a step change in temperature to twice its initial temperature (273°K to 546°K). As in Larkin's study, Spradley, et al. found that in the absence of any buoyancy effects, fluid motion can be established as a result of fluid compressibility and thermal gradients within the fluid. All their results were in good agreement with those of Larkin with one important exception. The maximum velocity amplitudes calculated by Spradley, et al. were one order of magnitude lower than those of Larkin. This discrepancy was attributed by Spradley, et al. to the different numerical techniques used in each study. In their work the following conclusions were reached:

- a) the thermally induced wave motion is acoustical.
- b) TAC can greatly enhance the rate of heat transfer.

- c) the mean pressure rise in a confined fluid is more rapid due to thermoacoustic effects.
- d) pressure convection effects on the conservation of energy can strongly influence the transient fluid behavior.
- e) the magnitude of the effects of thermoacoustic convection is a strong function of the severity of the thermal boundary conditions.

An analytical study was performed by Kassoy in which he examined the basic equations governing the fluid characteristics of a perfect gas confined to a slot when the boundaries of the slot undergo a monotonically varying temperature disturbance of a relatively gentle nature.¹² Kassoy employed a perturbation method with the small parameter defined as the ratio of acoustic to conduction time. In his analysis he also found it useful to divide the gas into two portions. These were defined as the expanding boundary layers and the core fluid which responds to that expanding boundary layer. Kassoy concluded that the fully conductive transient heat transfer process was fundamentally affected by the induced fluid motion and that to accurately assess the problem would require a numerical solution of coupled nonlinear differential equations.

Subsequently, Clarke, Kassoy, and Riley performed another analytical analysis based on a perturbation method.¹³ This method allowed for one-dimensional unsteady solutions to the Navier-Stokes equations. Their model consisted of an inert compressible gas confined by two infinite parallel walls which were suddenly heated by

a specified addition of energy. The primary focus of this study was the mathematical description of the conditions required to promote the evolution of weak shock waves to full strength.

Using a similar model, Radhwan and Kassoy performed another perturbation study in which the energy addition at the boundaries was six orders of magnitude larger than the slot model original researched by Kassoy.¹⁴ The effect of the increased energy addition was essentially to promote a finite velocity at the boundary layer edge which acted like a time varying piston. This mechanical effect enabled the acoustic field to retain its linear character. An explicit expression for the piston analogy of boundary heat addition was derived.

The first experiments on the TAC phenomenon in microgravity conditions were performed by Salah-Eddine.⁴ His experimental apparatus consisted of an insulated cylinder and two endplates. The upper endplate was outfitted with a heater capable of reaching temperatures in excess of 1500°F in less than two seconds. Along the axis of the cylinder were mounted four thermocouples used to record the transient temperature profile of the enclosed air. The entire apparatus was designed to facilitate experimentation in both gravity and low-gravity environments. The low-gravity trials were performed by drop testing the entire apparatus in the Two-Seconds Zero-Gravity Drop Tower facilities of the NASA Lewis Research Center. The experimental results were compared with the results of a numerical model based on the model formulated by Spradley, et al. in

which conduction and radiation were assumed to be the only active models of heat transfer. It was found that the temperatures measured by the thermocouples were greater than those predicted by the numerical model. However, it should be noted that in this study the experimental data was corrected for radiation effects which were numerically computed. There is some indication that the numerical values computed concerning the contribution of radiation may be inaccurate. This point will be expanded upon and discussed in this study. His experimental data showed much smaller fluid temperatures than those predicted by the Spradley, et al. numerical model. He also found no significant difference between experimental results in gravity and low-gravity environments for the particular geometry and rates of heat addition used in his study.

1.3 RESEARCH OBJECTIVES

In spite of the time that has elapsed since the discovery of thermoacoustic oscillations in 1850, various fundamental questions relating to their origin and contribution to the heat transfer process remain to be investigated. As can be seen from the literature review, the analytical models currently proposed provide contradictory results and are unable to accurately predict the degree of heat transfer associated with the contribution of TAC. This is not surprising since

very little experimental work has been performed in this area and there remains a great need for experimental evidence of the TAC phenomenon and its effects on heat transfer in fluids. Without this evidence, verification of any proposed analytical model is impossible. It is the intent of this research to provide experimental information on TAC heat transfer and, therefore, help to achieve a better understanding of this important process. It is believed that increasing the availability of experimental data will help to provide a foundation for a comprehensive verification of the analytical modeling of TAC. With this in mind, the following research objectives are pursued in this study.

The primary purpose of this research is to examine the transient effects of TAC in a controlled environment. This study is not necessarily concerned with the mechanism that produces the oscillations, but rather the convective mode established by the imposed pressure field. This investigation consists of the study of the transient heating of a confined fluid (air) by the rapid increase in temperature of a single boundary surface. The examination of TAC is carried out by measurement and observation of the transient temperature variation within the fluid medium and, if possible, by directly recording the oscillatory nature of the pressure waves. Attempts are then made to draw basic conclusions about the importance of TAC heat transfer in the transport of heat through a fluid. To accomplish the previously

stated purposes, the following specific research objectives will be pursued in this study:

- a) design and construct an appropriate experimental apparatus to measure the transient temperatures of the fluid and a single heated boundary in a one-dimensional heat transfer process involving TAC.
- b) determine experimentally the heat transferred to the thermocouples due to the radiative effects of the heater surface.
- c) determine experimentally the heat transferred to an enclosed medium due to the combined effects of radiation, conduction and TAC.
- d) analytically make use of the radiative test data to account for the contribution of radiation to the heating of the thermocouple in the medium.
- e) determine analytically, from the experimental data, if there is a significant degree of forced convection heat transfer occurring throughout the medium (a result of bulk fluid movement as produced by TAC).
- f) determine analytically, from the experimental data, the transient Nusselt number of each of the thermocouple beads in the medium.
- g) examine the Nusselt number and draw appropriate conclusions about the relative magnitudes of heat transfer and air movement around the thermocouple bead.
- h) experimentally record any pressure oscillations within the medium.

i) determine experimentally the heat transferred to an open medium due to the combined effects of radiation, conduction, and TAC, and make appropriate comparisons with the enclosed medium experiments (an indication of the geometric effects of the cavity on TAC).

CHAPTER 2

THE EXPERIMENTAL INVESTIGATION

2.1 EXPERIMENTAL APPARATUS

The objectives pursued in the design of the test container were to effectively isolate the system from the environment, provide a single boundary capable of reaching high temperatures in a very short time, and simulate, as closely as possible, one-dimensional heat transfer and fluid flow characteristics in the internal fluid. An air tight container was designed to have a 6 x 6 x 12 inch internal volume once it was insulated. The container consisted of a 10 inch square duct, 12 inches long, with two endplates and was constructed out of 3/4 steel. Insulation was built up in layers along the sides of the duct to decrease the internal area to a 6 inch square and also to serve as side boundaries. The container was designed to have both endplates removable to provide easy access to the heater and instrumentation and also to facilitate secondary experimentation in which the endplate of the container opposite the heater was removed to allow for open air experimentation. When in place, the endplates made an effective seal with the box due to the use of 3/32 inch diameter viton O-rings and silicon sealant. Simulation of one-dimensional heat transfer and fluid

flow characteristics was accomplished by insuring that the sides of the container were well insulated and that the heating surface was flat, oriented perpendicularly to the insulated sides of the container, and extended completely to the side boundaries. The insulation used was Fiberfrax Duraboard LD. This material, made from ceramic fibers, was built up in 1/4 inch layers on the sides of the container to provide the necessary insulation. At the mean temperature that the insulation would be exposed to (approximately 400°C) the thermal conductivity of the material is 0.10 W/(m °C).

In order to eliminate any buoyancy effects, the upper end of the container was chosen as the surface upon which to mount the heater. Previous research by Salah-Eddine has concluded that the difference in buoyancy effects between gravity and weightless environments should not be significant for this orientation.¹⁵ The heater was designed to simulate, as closely as possible, a step change in surface temperature and is capable of reaching high temperatures (in excess of 1500°F) within two seconds. This was accomplished by connecting two 12 volt lead acid batteries (Taylor maintenance-free automotive batteries) to a pair of copper busbars which were separated by a thin piece of stainless steel foil (type 301). The batteries were connected in parallel by way of battery cables to help provide a more consistent supply of power and increase the number of test runs that could be performed before the batteries needed to be recharged. This helped to provide a greater degree of repeatability between successive runs. A Trumbull

scissor switch was installed in the system circuit to facilitate manual control of the heating process. A pair of copper busbars were used to attach the wiring of the system (primarily 10 gage wiring) to the foil in order to maintain a uniform current and therefore a uniform temperature across the foil at any instant of time. The busbars were attached in such a way that a 6 x 6 inch square of the foil was exposed to the internal cavity. The thin piece of foil provided a relatively high resistance as compared with the wiring of the system and therefore heated very rapidly. In an attempt to minimize the bubbling up of the foil due to thermal expansion, three ceramic tubes approximately 1/10 inch diameter were positioned across the foil at 1.5 inch intervals. A diagram of the heater circuit with the ceramic restrictors in place is shown in Figure 2.1.

To perform the radiative tests the apparatus had to be designed in such a way that a vacuum could be pulled on the container. Therefore a Duoseal Two-stage model 1400 vacuum pump was connected to the container and was found to be capable of reducing the pressure within the container to 70 microns of mercury.

2.2 INSTRUMENTATION

For the enclosed air tests the container was outfitted with seven thermocouples along its axis to record the transient temperature

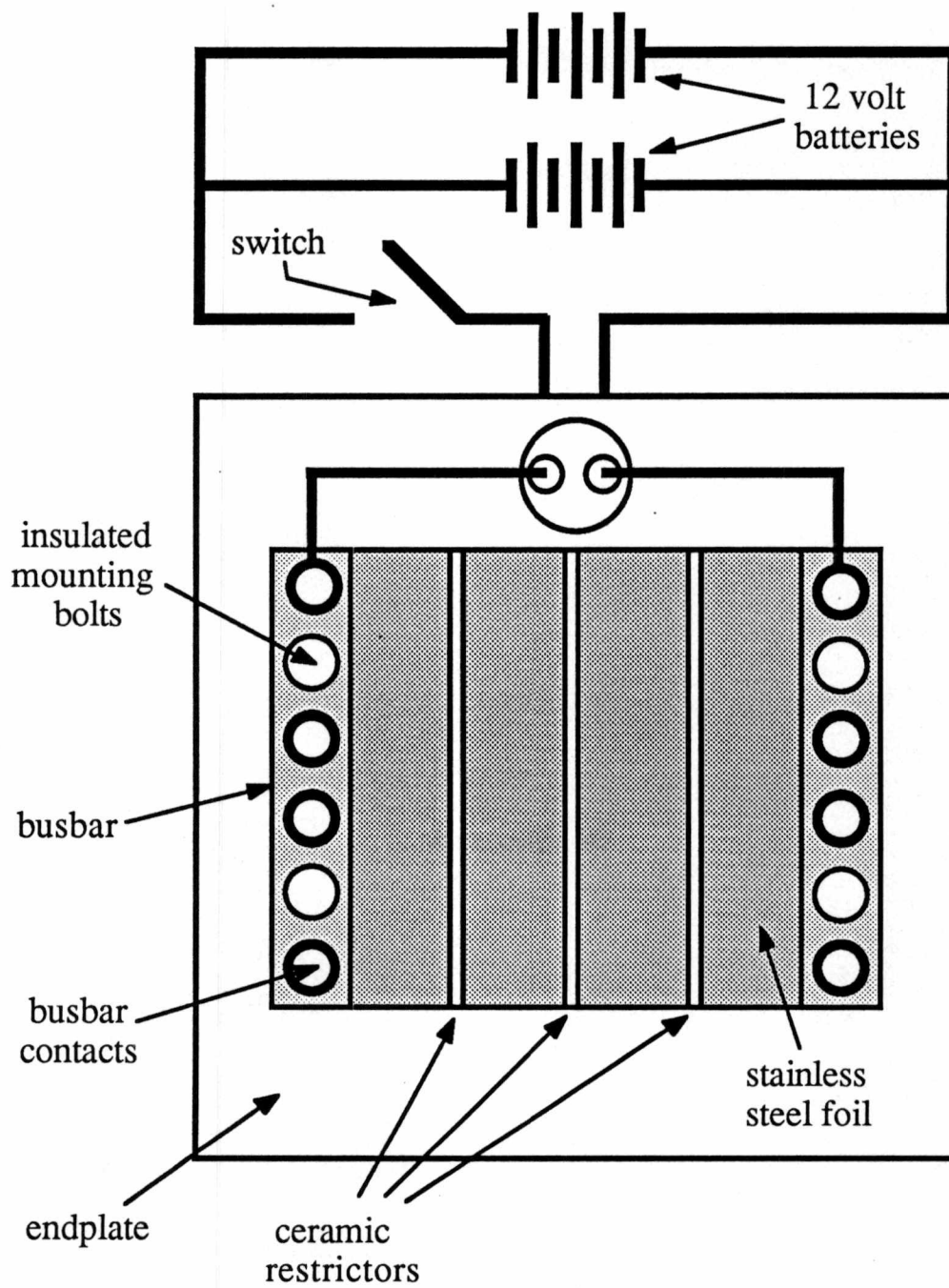


Figure 2.1 Schematic of Heater and Circuit

profile of the medium. Thermocouples were positioned at axial distances of 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, and 11.0 inches from the heater surface. For convenience, the number of thermocouples positioned along the axis of the container in the open air tests was decreased to three. These were positioned at axial distances of 0.5, 4.0, and 8.0 inches from the heater surface. Due to the transient nature of the variables measured, thermocouples with a very fast response time and capable of withstanding the high temperature environment were needed. Omega type K (chromel-alumel) thermocouples with a 0.003 inch bead on 0.001 inch wires were chosen to make these measurements. The time constant of these thermocouples is 0.05 seconds. The thermocouples were supported by a 1/4 inch diameter ceramic tube fixed to the lower endplate of the container. A ceramic tube was chosen since it provided a rigid support for the thermocouples and still minimized any axial heat transfer. Also, the thermocouple lead wires were insulated with a plastic coating and a fiberglass sheathing that not only served to protect the thermocouple lead wires from the high temperature environment but also to insulate them from the ceramic support rod.

In addition to these thermocouples, a thermocouple was attached to the heater surface to record its transient temperature. This was performed by spot welding separate 0.002 inch chromel and alumel thermocouple wires to the foil. Care was taken to ensure that the wires were welded as close together as possible and that they were oriented

on a line perpendicular to the direction of current flow. This was done in order to minimize the effects of any voltage drop between the two thermocouple wires on the temperature reading. All thermocouples were referenced to a thermocouple placed in a Kaye electronic ice bath.

The thermocouples were connected to a Hewlett Packard 3497A Data Acquisition/Control Unit. This Unit was placed in series with a HP 3456A Digital Voltmeter and a HP 9000 217 computer. A computer program was developed to read the voltage outputs from the thermocouples and the heater circuit current measuring device. The program was employed to:

- a) signal the onset of data acquisition in order that the heating process could be manually begun.
- b) accumulate as many voltage outputs as possible from the heater surface thermocouple, the seven axially mounted internal thermocouples, and the heater circuit current measuring device. The data acquisition program, when written to scan as many readings as possible without compromising accuracy, scanned the complete set of thermocouples approximately every 0.23 seconds. This works out to be, approximately, one reading every 0.03 seconds.
- c) assign an appropriate time value to each voltage measurement to indicate when the measurement was made (this was performed by making use of the Hewlett-Packard computer's internal clock).

d) after scanning the complete set of thermocouples 50 times (taking approximately 11 seconds) signal the end of data acquisition in order that the heating process could be terminated.

e) convert the voltages measured from the thermocouples to equivalent temperatures (this was performed using a ninth order polynomial curve fit equation given in Appendix E.1).¹⁵

f) convert the voltages measured from the current measuring device in the heater circuit to an equivalent current (a proportional conversion recommended on the device itself). This measurement was recorded as an indication of the state of the batteries. When inconsistent measurements were recorded concerning the current drop, the batteries were recharged.

g) send current, temperature, and time data to a data file and tabulated data to a hard copy.

The two programs that were used to accomplish these tasks are given in Appendices E.2 and E.3.

In addition to the temperature measurements an overall pressure measurement needed to be made in order to determine the extent to which conduction would play a role in the radiative tests. Therefore a NRC type 521 thermocouple vacuum gauge was placed in the vacuum line between the container and the pump. The gauge was connected to a NRC type 741 portable thermocouple gauge control which allowed visual reading of the system pressure in microns of mercury.

A sensitive pressure sensor was also placed in the container to record any thermoacoustic oscillations produced as a result of the sudden temperature rise of the surface. The sensor chosen for making these measurements was a Brüel-Kjær model 4145 microphone since the waves that were to be generated are of acoustic origin. The signal from the microphone was sent, first through a model 2619 pre-amplifier, then to a model 3347 Brüel-Kjær Real-Time 1/3 Octave Analyzer. The analyzer consisted of two pieces of equipment, these being a model 4710 Control and Display Unit and a model 3347 Frequency Analyzer. These were in turn connected with a model 2307 Brüel-Kjær Level Recorder which was used to print hard copies of the transient acoustic signal within the box at a specified frequency. A sound proof room was also available that was large enough to contain the entire apparatus and the power supply. A schematic diagram of the container's internal instrumentation is given in Figure 2.2. Though this diagram is used to illustrate both the thermocouple and microphone placement within the container, these devices were used independently of one another to perform their respective measurements. A diagram illustrating the relationship between the test container and the instruments used in acquiring the data is given in Figure 2.3.

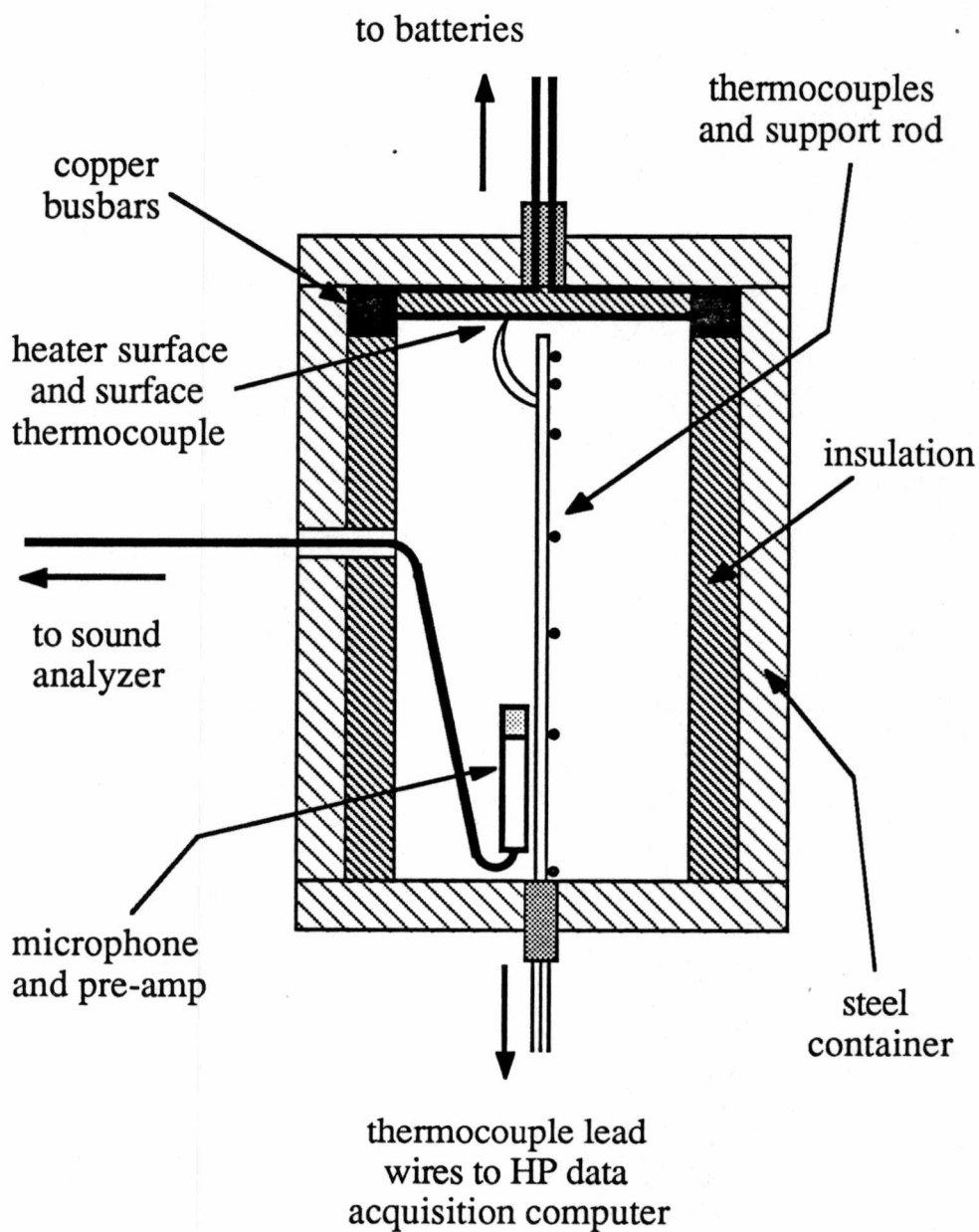


Figure 2.2 Internal Instrumentation of the TAC Test Apparatus

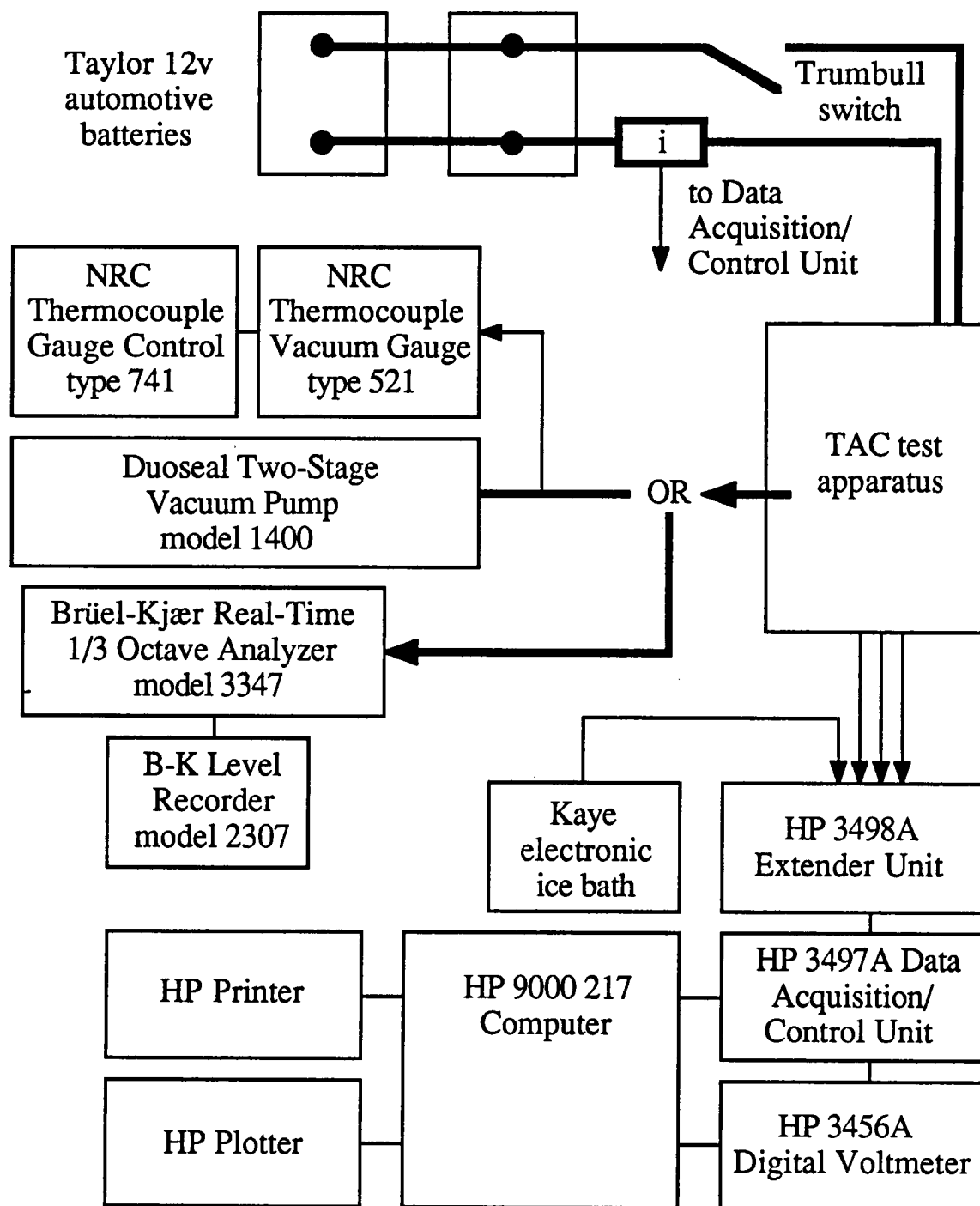


Figure 2.3 Schematic of Container and Data Acquisition Instruments

2.3 EXPERIMENTAL PROCEDURE

The experimental analysis consisted of matching sets of data obtained in two different fashions. First, a number of experiments, hereafter referred to as the "vacuum" or "radiative" tests, were run with the test box evacuated. After activation of the heater, the temperature rise of the thermocouples was recorded. This temperature rise was attributed to the radiative absorption of the thermocouples. A second series of experiments, referred to as the "enclosed air" tests, were then performed with the box enclosing air initially at atmospheric pressure as the working medium. After activation of the heater, the temperature rise of the thermocouples was again recorded. Each trial of the radiative set was paired with a trial of the enclosed air set by matching the heater's transient temperature profiles. This allowed for some compensation of the radiative absorption of the thermocouples in the enclosed air set of experiments. This is an important consideration in light of the fact that the previous experimental work performed by Salah-Eddine relied solely on an analytical determination of the radiative effect of the heater on the thermocouples and was found to have largely underestimated the effect.¹⁵ The experimental data was then analyzed to determine if forced convection heat transfer played a significant role in the air tests. A transient range of Nusselt number was then calculated for each of the thermocouples as an indication of the relative magnitudes of fluid

movement within the container. This analysis was analytical in nature and is, therefore, presented in the following chapter. Acoustic pressure traces were also recorded as another means of presenting data concerning TAC.

Another series of experiments, referred to as the "open air" tests, were performed in the same manner as the enclosed air tests but with the end wall of the container removed. This was done by removing the lower endplate and elevating the container to a position of 18 inches above the table surface. These tests were performed for the purpose of comparison with the enclosed air tests.

Specifically, the experimental procedure followed this routine. An experimental test run began with the recording of the internal pressure of the test box. This measurement was only critical during the vacuum test cases since the degree to which conduction was significant was dependent upon the mass of air within the box. Next, the computer data acquisition program was started. This program was designed to measure the reference (ice bath) temperature and then produce a tone signaling the onset of data acquisition. At this tone the heater circuit was closed initiating the heating process. This was performed by manually closing a switch. The computer then gathered data from the thermocouples, the heater surface, and the current measuring device for approximately 11 seconds. At the end of the data acquisition process the computer produced another tone. At this tone the switch was opened, terminating the heating process. The gathered

data was then stored in data files and used to produce graphical representations of the output. The plots were then compared for repeatability and analyzed.

The Vacuum Tests

Preliminary tests showed that, all other variables being the same, the vacuum tests were characterized by a higher transient foil temperature profile than the air tests. This is due to the fact that the cooling effects of the air are not present in the vacuum tests and a higher transient foil temperature results. In order to best match the two differing transient foil temperature profiles, the heater temperature for the radiative case had to be lowered. This introduced no great difficulty since the foil temperature could be effectively lowered by increasing the external electrical resistance in the system. This was done by simply replacing a portion of the system wiring with a greater length of lower gauge wire. After using a number of different wire lengths, a transient foil temperature template was generated that could be used for matching with the air tests (see Figure 2.4). All the tests were found to be highly repeatable.

Five vacuum tests were made at an initial system pressure of 70 microns of mercury or less. Of course, during the heating process the internal pressure of the test box rose, but it is reasonable to assume that the density of the air within the box remained constant.

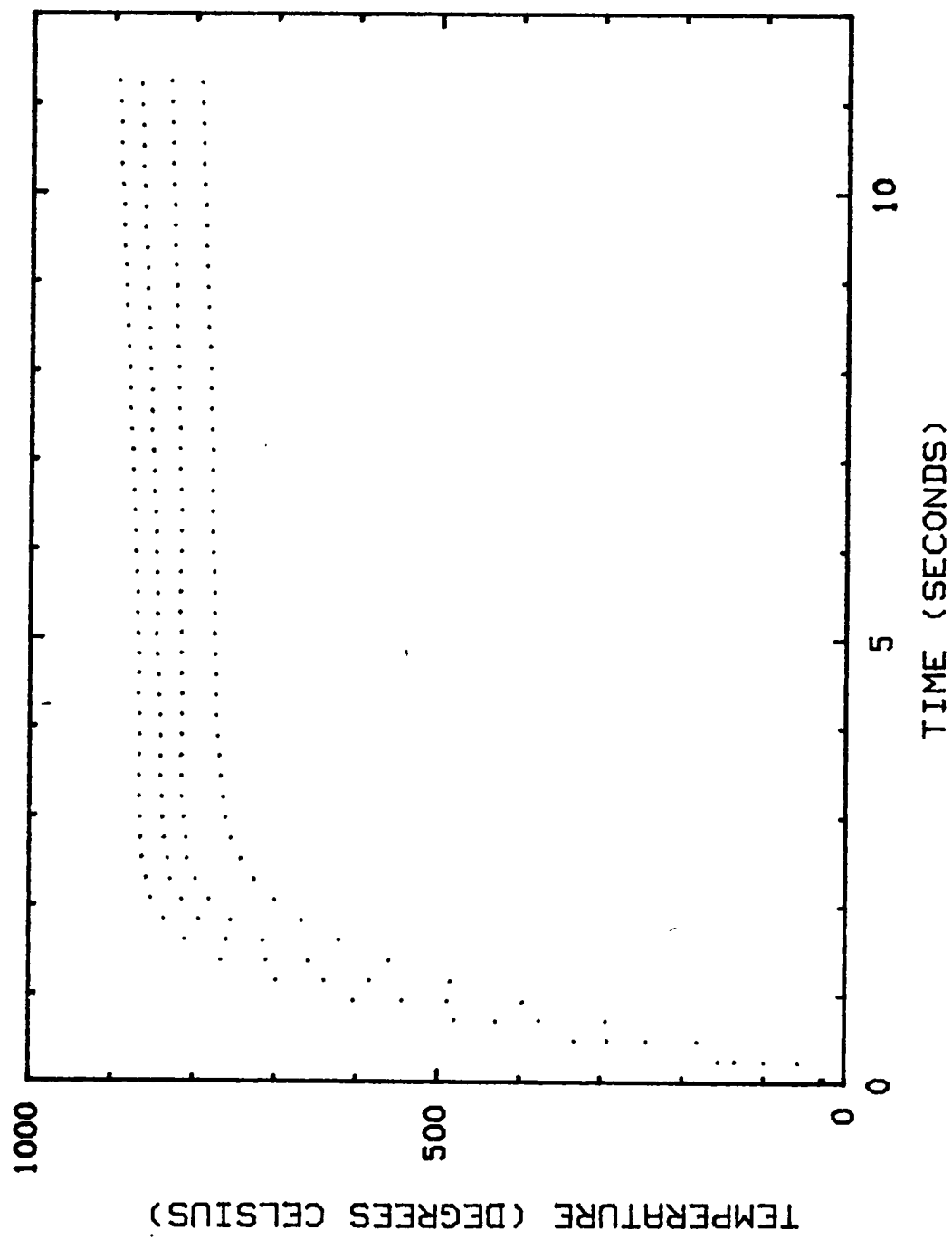


Figure 2.4 Vacuum Test Heater Temperature Template

A typical vacuum (radiative) plot of the transient surface and thermocouple temperatures is shown in Figure 2.5. The complete set of original data is presented in Appendix F.1. Each point plotted in these figures represents a single measured temperature. The upper most curve is the data recorded for the transient surface temperature of the heated boundary. The sharp rise and subsequent leveling of the surface temperature is typical of the surface heating element. The lower curves are the transient temperature records of the thermocouples in the air medium. The temperature of the thermocouples, after a slight lag, also increases but does not necessarily level out to the degree that the surface temperature does. Thermocouples at greater distances from the heater surface record smaller rates of temperature increase.

The Enclosed Air Tests

The air tests were performed with the test box enclosed and an internal air pressure of one atmosphere. After producing a plot of an enclosed air test, the transient foil temperature profile was then compared graphically with the template described in the preceding paragraph. Once a suitable radiative match was found, comparison of the two cases could be made. As stated earlier, the reason that more battery power needs to be supplied to the heater in the air cases to achieve the same surface temperatures as the vacuum cases is the

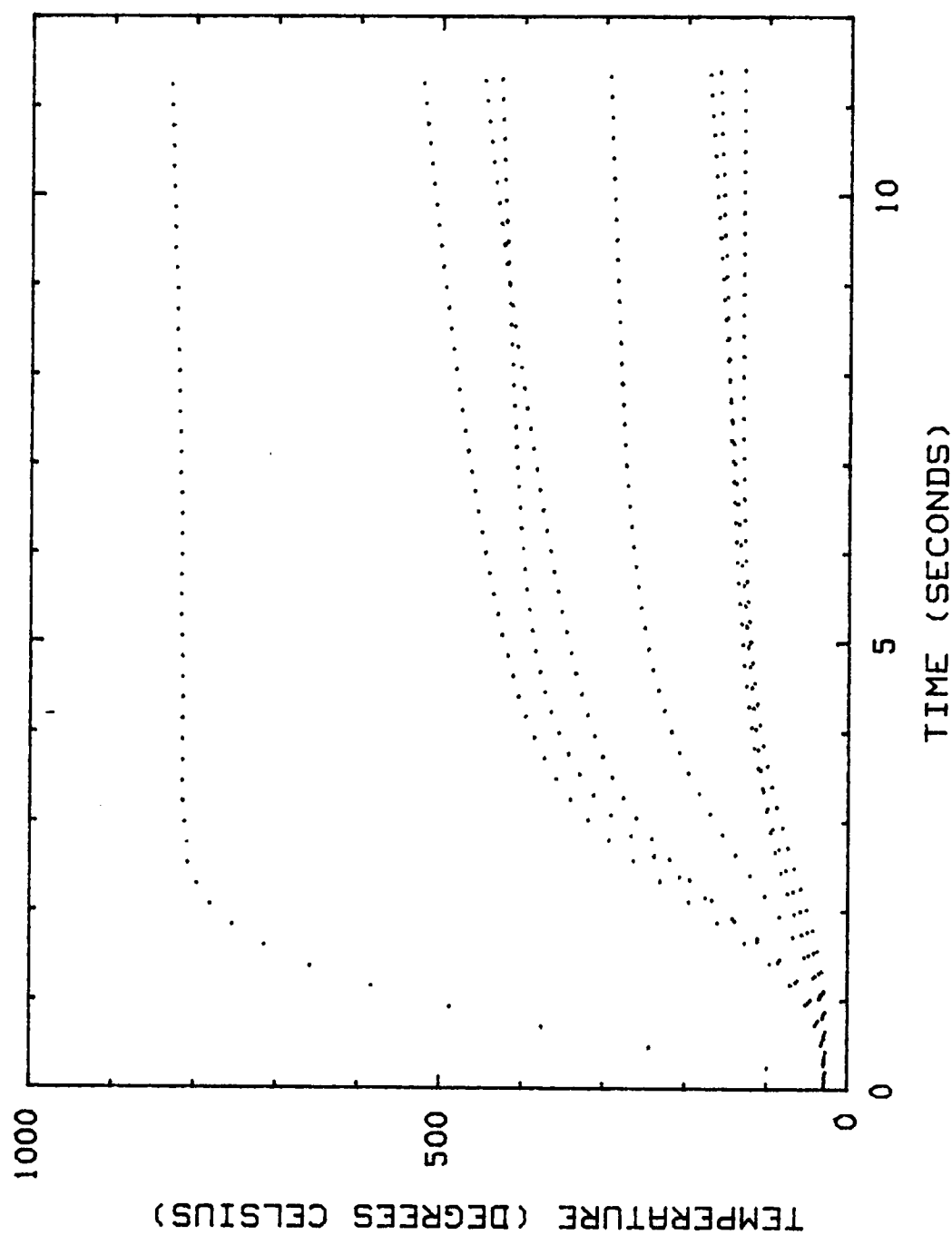


Figure 2.5 Typical Vacuum Test Data

removal of heat by the enclosed air. This point will be returned to later.

Three original test runs are presented in Appendix F.2. The thermocouple temperatures found for a given transient surface temperature profile are found to be highly repeatable. The transient surface and thermocouple temperatures for a typical enclosed air test is given in Figure 2.6. As before, the sharp rise and subsequent leveling of the surface temperature along with the increase in thermocouple temperature after a slight delay are observed. In this figure the raw data is presented with no differentiation being made between the contributions of different modes of heat transfer.

The Open Air Tests

The open air tests were performed in much the same manner as the enclosed air tests. Three open air tests were performed and were, again, found to be highly repeatable. Again, the matching process was undertaken in an attempt to account for the effects of radiation. The transient surface temperature and thermocouple temperatures for the open air tests are presented in Figure 2.7. The original data is given in Appendix F.3. Note the similarity between the open and enclosed air plots.

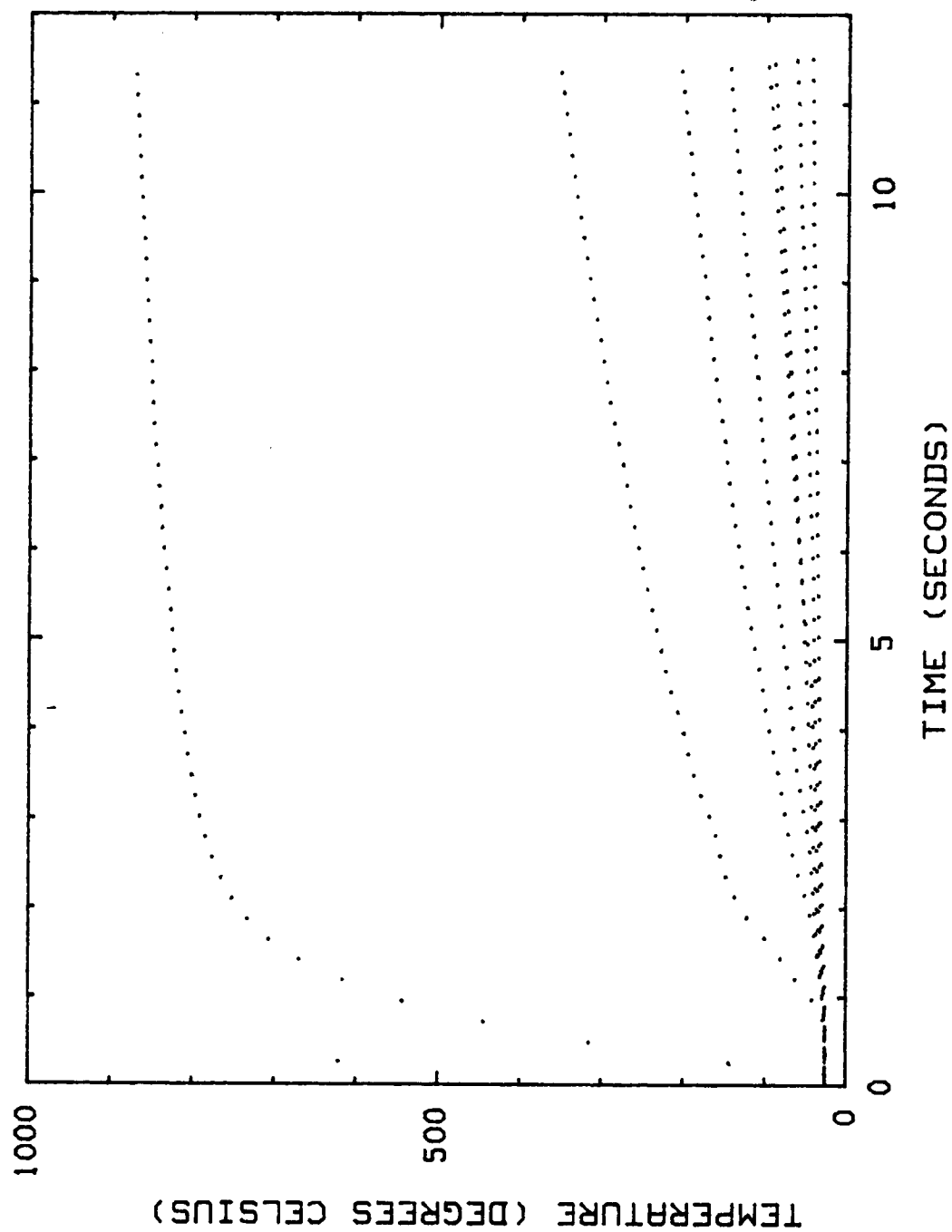


Figure 2.6 Typical Enclosed Air Test Data

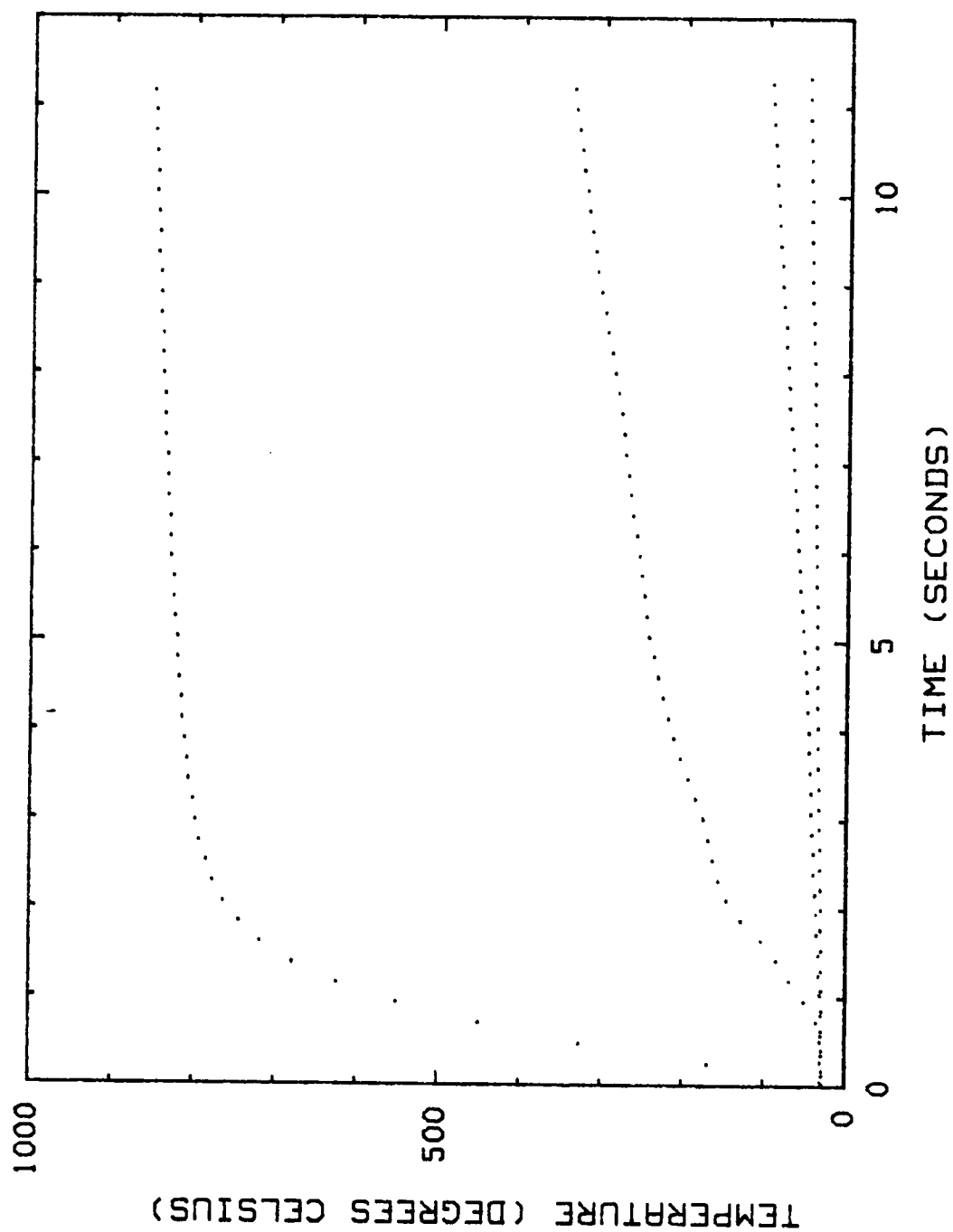


Figure 2.7 Typical Open Air Test Data

Comparison of the Air and Vacuum Tests

A significant observation can be made when the results for the vacuum (radiative) case are compared with either the enclosed air or open air tests. This is the fact that, for each of the thermocouples along the length of the box, the temperature plots show a lower transient temperature profile for the air tests than for the radiative tests. These results would, at first, seem contrary to the hypothesis that if TAC were present heat would better be transferred into the medium. It seems that one should certainly expect that this mode of heat transfer would have an additive effect on the radiative mode of heat transfer and, therefore, result in higher transient temperature profiles. The primary reason behind observing a lower temperature in the air cases is revealed in the nature of the thermocouple temperature measurement process. Since the only significant difference between the vacuum and air tests is the presence of air around the thermocouples, then the mere presence of the air must be responsible for the lower temperatures recorded. When a heat transfer analysis of the temperature measurement process and the role of TAC are discussed, these results are found to be justified and necessary for the existence of TAC. These concepts are further pursued in the following chapter in which the analytical investigation is presented.

CHAPTER 3

THE ANALYTICAL INVESTIGATION

3.1 CONCEPTS AND THEORY

In this chapter a transient heat transfer analysis on an individual thermocouple is performed and equations describing this process are derived. It will be shown that such an analysis is necessary to gain an understanding of the heat transfer processes involved. It will be shown that a thermocouple bead, no matter how small, is capable of absorbing more incident radiation emitted by the heater than the air surrounding it. This is due to the simple fact that the absorptivity of the opaque thermocouple is at least one order of magnitude greater than that of the transparent air. This results in a thermocouple temperature that is increased over that of the air surrounding it. Since the thermocouple bead is at an elevated temperature, a threefold cooling process takes place. First, it is cooled by means of radiation exchange with the cooler walls of the box (note that radiation exchange with the heater is the sole means by which the thermocouple bead is heated). Second, the thermocouple bead is cooled by conduction by way of the small thermocouple wires that connect the bead of the thermocouple to the lead wires. Third, it is cooled by heat transfer to the air surrounding

it. From the raw data it can be seen that in the vacuum tests the thermocouple is not cooled as efficiently in this third manner and, therefore, a higher bead temperature results. This third means of cooling is to be examined as the key to determining if TAC is present in the medium. This line of reasoning is based on the assumption that TAC causes a movement of the core fluid. This convective element increases the heat transfer from the higher temperature thermocouple bead to the fluid. Although the TAC heat transfer process also serves to increase the temperature of the air over that which would be expected if conduction alone was present, the thermocouple bead is still cooled by the fluid since its temperature always remains above that of the surrounding air due to its higher radiation absorption. Figure 3.1 qualitatively depicts the transient temperature profiles of the heater surface, thermocouple bead, surrounding air, and air as the sole result of conduction and radiation (i.e., without the contribution of TAC) as they are expected to vary relative to one another.

Specifically, the analytical investigation consists of determining, from the experimental data, if the thermocouple is being cooled by a forced convective process. If it is found that significant forced convection heat transfer is present then, it is argued, TAC (being the only physical phenomenon responsible for the bulk movement of air) will have been observed. Once this has been established, the value of the Nusselt number for the thermocouple bead in air will be calculated

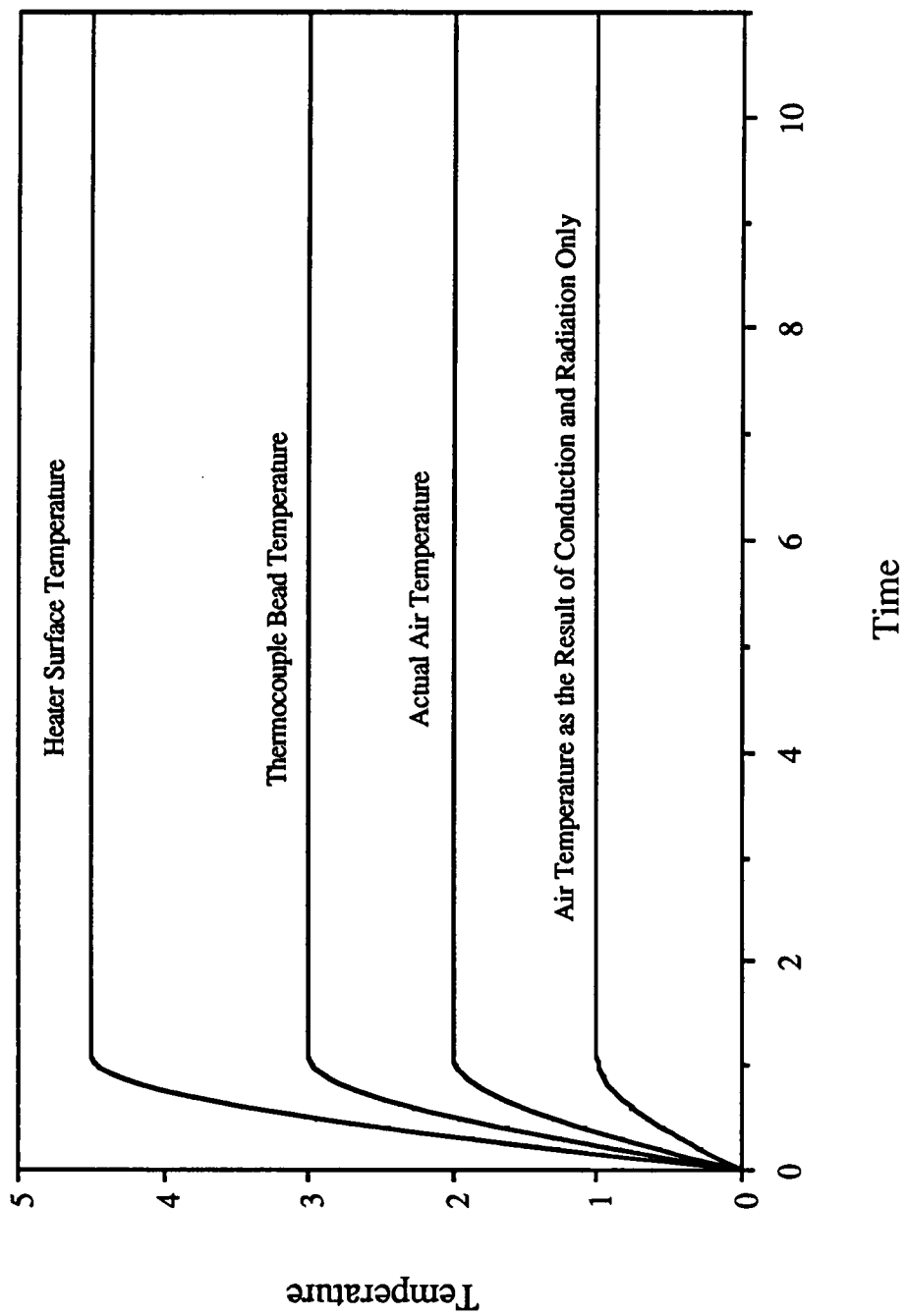


Figure 3.1 Proposed TAC Temperature Hierarchy

and examined as a relative indicator of how this air movement varies along the container.

3.2 ANALYTICAL PROCEDURE

The motivation for the analytical analysis was, in part, to find an appropriate way to present the experimental data. The information obtained from this analysis will serve, primarily, to indicate the existence of TAC and, secondarily, to portray some characteristics of the TAC phenomenon. The existence of TAC will be established by performing an energy balance on the thermocouple bead for both the air and vacuum test cases. Experimental results for the total amount of heat transferred from the thermocouple to the air will be compared with calculated values estimating the effect of conduction and free convection to the air. If it is found that the magnitude of heat transferred to the air cannot be accounted for by conduction and free convection to the air, a forced convection heat transfer process must have taken place. Since thermoacoustic convection is the only means by which a bulk movement of the air could be established, this will be presented as evidence of the presence of this phenomenon. It is emphasized at this point that the analysis in this chapter is only designed to indicate if forced convection *exists*, not to give an accurate quantitative assessment of its magnitude. Some of the assumptions made may seem extreme and unjustified but they are made to provide a

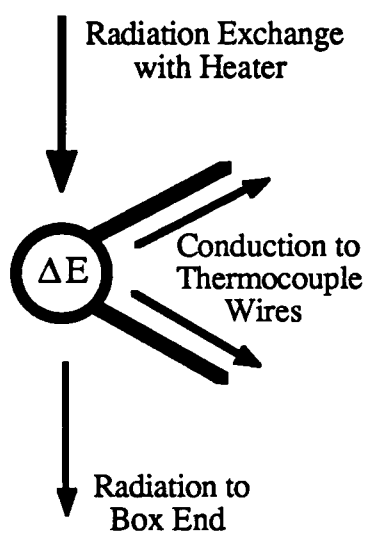
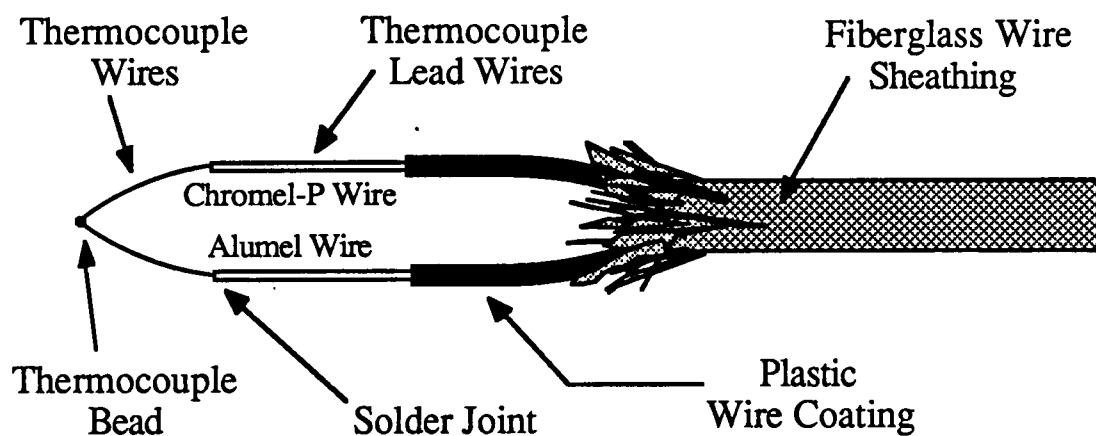
“worst case” analysis. If, in spite of these extreme assumptions, forced convection is found to be significant, the calculated values will be conservative and underestimated. It is believed that the relative magnitudes of the values found will serve as an indication of how the air movement within the container varies with time and with distance from the heater surface. In accomplishing these objectives, the following analysis was undertaken.

The thermocouple bead was chosen as the control volume to be examined. A diagram of the actual thermocouple configuration is given in Figure 3.2, along with diagrams comparing the modes of heat transfer to and from a thermocouple bead for both the vacuum and air tests. Performing an energy balance on the thermocouple bead for the air case gives

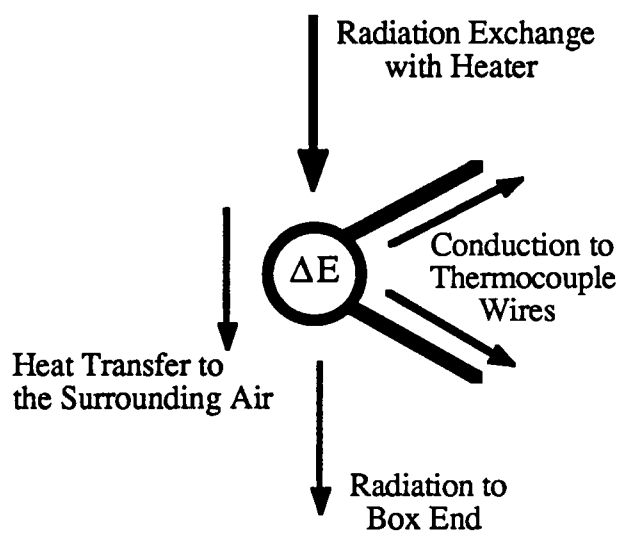
$$q_{\text{RAD}}|_{\text{AIR}} - q_{\text{COND,wire}}|_{\text{AIR}} - q_{\text{CONV,air}}|_{\text{AIR}} = \Delta E_{\text{tc}}|_{\text{AIR}}.$$

This equation incorporates a convective term to express the heat transferred to the surrounding air and is valid whether conduction, free convection, or forced convection is the actual mode of heat transfer. The preceding equation can be expanded to

$$\begin{aligned} & \sigma \epsilon_{\text{foil}} A_{\text{foil}} F_{\text{foil-tc}} (T_{\text{foil}}^4 - T_{\text{tc}}|_{\text{AIR}}^4) \\ & - \sigma \epsilon_{\text{tc}} A_{\text{tc}} F_{\text{tc-box end}} (T_{\text{tc}}|_{\text{AIR}}^4 - T_{\text{box end}}^4) \\ & - q_{\text{COND,wire}}|_{\text{AIR}} - q_{\text{CONV,air}}|_{\text{AIR}} = m_{\text{tc}} C (dT/dt)|_{\text{AIR}} \end{aligned} \quad (1)$$



VACUUM CASE



AIR CASE

Figure 3.2 The Amplified Thermocouple

In writing Equation (1) the following assumptions are made:

- a) convection rather than conduction is the active mode of heat transfer to the surrounding air. The convective term includes any heat transferred by conduction and approaches a finite lower limit as convection becomes less significant. This lower limit is the heat transferred by conduction.
- b) the radiative absorption of the air is negligible. This assumption is valid since the emissivity (and the absorptivity) of air, even at 100% relative humidity, remains less than 0.045 over the longest dimension of the test container.¹⁶ In the absence of scattering effects, this results in a transmittance of over 95% of the air between the heater surface and the thermocouple mounted 11 inches away (see Appendix C.1).
- c) the foil and thermocouple exhibit diffuse gray body radiative characteristics.

The complete set of view factors can then be evaluated by making a common substitution to simplify Equation (1).

$$A_{\text{foil}}F_{\text{foil-tc}} = A_{\text{tc}}F_{\text{tc-foil}} \quad (2)$$

This substitution allows all the view factors in Equation (1) to be readily evaluated with the use of a single configuration factor equation. The view factor from a sphere to a square with the sphere centered above the square can be expressed as

$$F_{\text{sphere-square}} = \sin^{-1} [B^2 / (1 + B^2)] / \pi$$

where B is the ratio of half the length of a side of the square to the distance between the center of the sphere and the center of the square surface.¹⁷ This equation was used to derive the view factors for each thermocouple which are presented in Table 3.1.

Making the substitution in Equation (2) and solving for the heat transferred by convection to the surrounding air, Equation (1) becomes

$$\begin{aligned} q_{\text{CONV,air}}|_{\text{AIR}} = & \sigma \epsilon_{\text{foil}} A_{\text{tc}} F_{\text{tc-foil}} (T_{\text{foil}}^4 - T_{\text{tc}}|_{\text{AIR}}^4) \\ & - \sigma \epsilon_{\text{tc}} A_{\text{tc}} F_{\text{tc-box end}} (T_{\text{tc}}|_{\text{AIR}}^4 - T_{\text{box end}}^4) \\ & - q_{\text{COND,wire}}|_{\text{AIR}} - m_{\text{tc}} C (dT/dt)|_{\text{AIR}} \end{aligned} \quad (3)$$

In examining this equation it can be seen that all of the terms in it can be computed from the experimental data except for the terms expressing heat loss by convection to the surrounding air and conduction through the thermocouple wires. This equation is to be solved for the convective term, therefore, the term representing the heat conducted away from the bead by the thermocouple wires needs to be determined. The wire conduction term is a function of the temperature gradient along the thermocouple wire. Since it would be difficult, if not impossible, to try to measure this value along each

Table 3.1 View Factors Calculated for Each Thermocouple

Thermocouple #	Distance from Foil	$F_{tc-foil}$	$F_{tc-box\ end}$
1	1/2" (1.27 cm)	0.4258	0.0240
2	1" (2.54 cm)	0.3564	0.0263
3	2" (5.08 cm)	0.2434	0.0319
4	4" (10.16 cm)	0.1172	0.0496
5	6" (15.24 cm)	0.0641	0.0853
6	8" (20.32 cm)	0.0393	0.1667
7	11" (27.58 cm)	0.0221	0.4813

*the length of one half the side of the exposed foil is equal to that of the box end and is 3 inches.

thermocouple wire, it must be determined in an alternative fashion. This quantity can be evaluated by applying the following analysis.

Performing an energy balance on the thermocouple bead in the vacuum case gives

$$q_{\text{RAD}}|_{\text{VAC}} - q_{\text{COND,wire}}|_{\text{VAC}} = \Delta E_{\text{tc}}|_{\text{VAC}}$$

After appropriate substitution of the Stefan-Boltzmann law this equation can be expanded to

$$\begin{aligned} & \sigma \epsilon_{\text{foil}} A_{\text{foil}} F_{\text{foil-tc}} (T_{\text{foil}}^4 - T_{\text{tc}}|_{\text{VAC}}^4) \\ & - \sigma \epsilon_{\text{tc}} A_{\text{tc}} F_{\text{tc-box end}} (T_{\text{tc}}|_{\text{VAC}}^4 - T_{\text{box end}}^4) \\ & - q_{\text{COND,wire}}|_{\text{VAC}} = m_{\text{tc}} C (dT/dt)|_{\text{VAC}}. \end{aligned} \quad (4)$$

In writing the Equation (4) the following assumptions are made:

- a) it is assumed that the pressure in the container was low enough that conduction to the air can be considered negligible.
- b) similarly, it is assumed that convection to the surrounding air is negligible.
- c) the foil and thermocouple exhibit diffuse gray body radiative characteristics.

These assumptions are not made without some means of verification. For this experiment, the initial pressure within the container was lowered to 70 microns of mercury. Even at this

considerably low pressure the mean free path of the molecules was calculated to be 0.07 cm or 0.03 inches. This would seem to indicate that a fully molecular flow regime was not encountered. If it is assumed that the conduction heat loss from the thermocouple bead to the surrounding air was molecular in nature, calculations indicating the contribution of conduction to the low pressure air are given in Appendix C.2.

With the air at atmospheric pressure, using a transient analysis to calculate heat conduction gives a value almost three orders of magnitude lower than the comparative steady state value (see Appendix C.3). Details on the equation used to calculate the transient conduction to the air are given later in this chapter. This information is presented to exhibit to the reader the vast difference between transient experimentation and experimentation in the steady state. It is likely that transient considerations have a similar effect on conduction to low pressure air.

It must be emphasized at this point that these values are merely presented to give the reader a feel for the relative magnitudes of conduction to the surrounding air. They are not used at any point in the analysis, and are therefore left to the appendices for closer examination by the interested reader. Any contribution of conduction to the air in the vacuum case will be shown to be accounted for when the final equations are combined, and, in fact, will give a more

conservative estimate of the heat transfer to the air in the atmospheric tests.

Solving Equation (4) for the wire conduction term and making the substitution described by Equation (2) gives

$$\begin{aligned} q_{\text{COND,wire}}|_{\text{VAC}} = & \sigma \epsilon_{\text{foil}} A_{\text{tc}} F_{\text{tc-foil}} (T_{\text{foil}}^4 - T_{\text{tc}}|_{\text{VAC}}^4) \\ & - \sigma \epsilon_{\text{tc}} A_{\text{tc}} F_{\text{tc-box end}} (T_{\text{tc}}|_{\text{VAC}}^4 - T_{\text{box end}}^4) \\ & - m_{\text{tc}} C (dT/dt)|_{\text{VAC}} \end{aligned} \quad (5)$$

Given temperature data at a specific point in time, this equation can be solved for the wire conduction term in the vacuum test case.

A relation between the wire conduction term for the vacuum case and the wire conduction term of the air case will now be established. Basically, this term is assumed to be approximately the same as the wire conduction term in the vacuum case given equal thermocouple temperatures. In the strictest sense, this assumes that in both cases the temperature gradients along the thermocouple wires are equal, i.e., the thermocouple bead and wires have the same time-temperature history for both cases. It is evident from Figures 2.5 and 2.6 (pp. 32, 34) that the thermocouple temperature for the vacuum and air cases are not the same at any particular point in time. However, if the transient heater surface temperature could be modeled as a step change in temperature the contribution of radiation in Equations (3) and (5) would be equal (generally they are not, but an examination of

the raw data curves indicates that this is not an unreasonable approximation). Also, preliminary calculations have shown the energy storage term to play only a small role in the analysis due to the very small mass of the thermocouple bead (this is also a necessary condition for the thermocouple to have a very short response time); therefore, it will be assumed negligible. Applying this rough analysis indicates that the single wire conduction term in the vacuum case plays the role of the wire conduction term *and* the air convective term in the air case. Therefore, the *smaller* wire conduction term in the air case is being approximated by the *larger* wire conduction term found from the vacuum case. This, indeed, provides a lower limit to the heat transfer by convection in the air case. As mentioned earlier, another point to consider is the case in which heat transfer to the low pressure air in the vacuum case is more significant than anticipated by the previous assumptions. This is the "worst case" scenario and would give even larger values of the vacuum case wire conduction term since it would now include the contributions of conduction and, possibly, convection to the low pressure air surrounding the thermocouple in the vacuum case. This would ultimately result in a further decreased value of the heat transfer to the air in Equation (3). Therefore, the values found using this analysis give a lower limit (conservative estimate) for the heat transferred from the thermocouple bead to the air.

Equation (5) can now be used to establish a table of values for the wire conduction term as a function of thermocouple bead temperature. These tables may then be used in predicting the contribution of wire conduction to the cooling of the thermocouple bead in the air tests. The known dimensions, constants, and properties used in Equation (5) are tabulated in Table 3.2. The thermocouple bead properties were averaged from known properties of the two alloys used in producing the bead.¹⁸ The bead diameter was given by the manufacturer and verified by independent measurement. The needed view factors are the same as those presented in Table 3.1. A plot showing how conduction through the thermocouple wires varies with temperature for each thermocouple is given in Figure 3.3. The complete set of tables (one for each thermocouple) is given in Appendix A. These tables were used to interpolate the wire conduction term needed in Equation (3).

Equation (3) can now be solved for the heat transferred to the surrounding air by convection for any particular thermocouple and at any instant in time. This is performed by interpolating the values of the foil and thermocouple bead temperatures from the raw data for a particular point in time and substitution in Equation (3) of the appropriate values from Tables 3.1 and 3.2. Given the thermocouple bead temperature, the wire conduction term can be interpolated from the tables given in Appendix A. Again, it should be kept in mind that the convection heat transfer term and resulting Nusselt numbers

Table 3.2 Dimensions, Constants, and Properties Used in the
Evaluation of Equations (3), (5), and (6)*

Description	Symbol	Value
Thermocouple bead diameter ¹⁹	d_{tc}	$7.62 \times 10^{-5} \text{ m}$
Thermocouple bead surface area	A_{tc}	$1.82 \times 10^{-8} \text{ m}^2$
Thermocouple bead mass	m_{tc}	$2.01 \times 10^{-9} \text{ kg}$
Thermocouple bead specific heat	C	486 J/kg K
Thermal conductivity (air)	k_{air}	0.0272 W/m K
Thermal diffusivity (air)	α	$2.216 \times 10^{-5} \text{ m}^2/\text{s}$
Stefan-Boltzmann Constant	σ	$5.73 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$
Heater surface emissivity	ϵ_{foil}	1.0
Thermocouple bead emissivity	ϵ_{tc}	1.0

*values of T_{∞} , $T_{tc}|_{AIR}$, $T_{tc}|_{VAC}$, $dT/dt|_{AIR}$ and $dT/dt|_{VAC}$ change with the data and are, therefore, presented in Appendix B along with the Nusselt number results.

For more information on the values presented in this table see Appendix C.4.

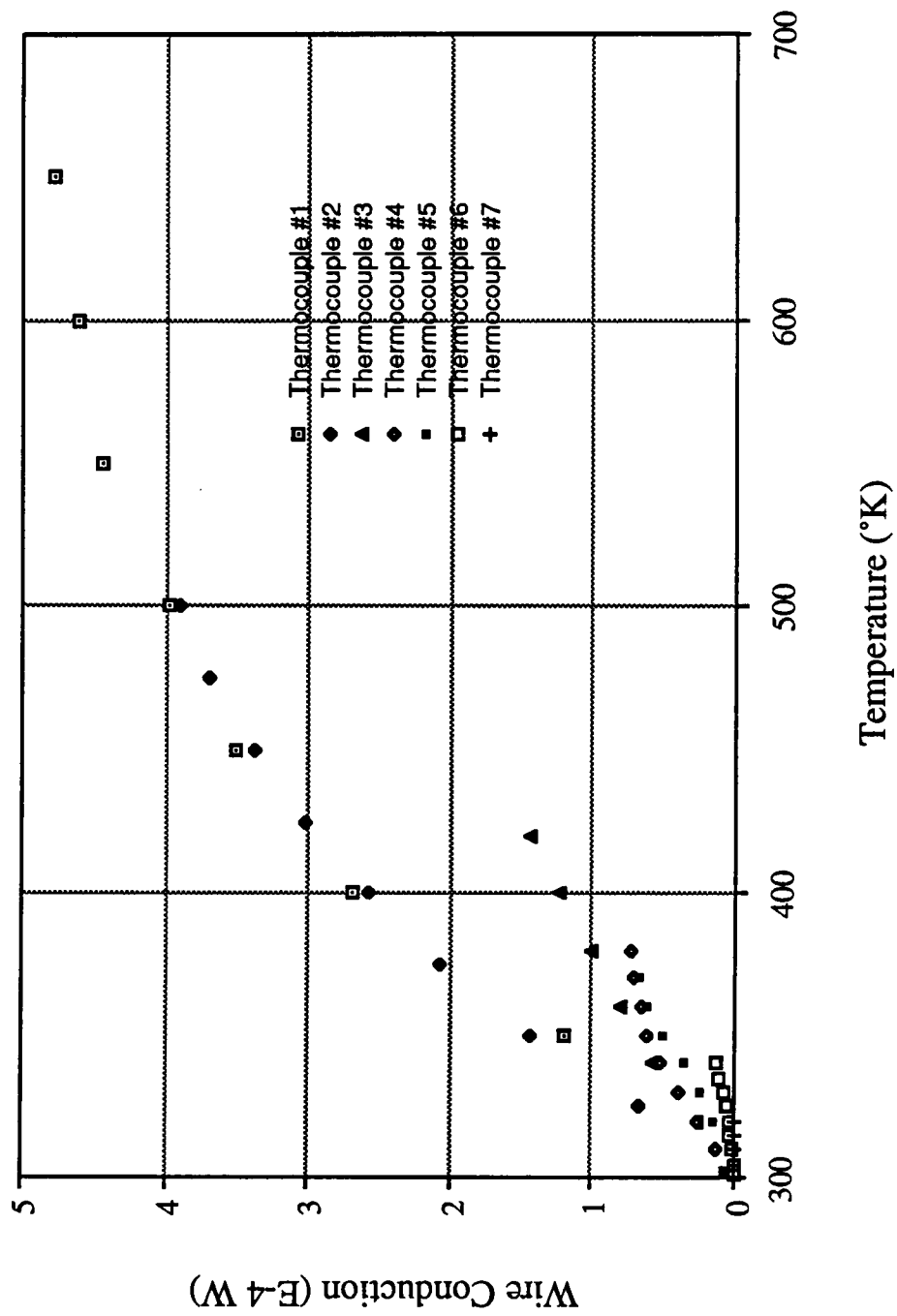


Figure 3.3 Relative Magnitudes of Wire Conduction

derived in this manner represent a lower limit and, in all probability, the actual values are somewhat higher than those presented.

Using Newton's Law of Cooling

$$q_{\text{CONV,air}} = hA_{\text{tc}}(T_{\text{tc}} - T_{\infty})$$

and knowing the heat transfer to the air, an overall average convective heat transfer coefficient can be calculated for each thermocouple at each point in time. The Nusselt number for the thermocouple bead in air is calculated by employing the following definition of the Nusselt number.

$$Nu = h d_{\text{tc}} / k_{\text{air}} \quad (6)$$

A transient lower limit to the Nusselt number is therefore derived for each thermocouple used in the experiment.

With the heat loss to the air predicted from the previous analysis, comparisons between it and the contributions of conduction and free convection to the air can be made. It is expected that the heat conducted to the surrounding air will be found to be a very small value. The following analysis describes a one-dimensional transient heat transfer model used to approximate the heat transferred through the air by conduction from the high temperature thermocouple bead.²⁰ This model assumes the fluid to behave as a semi-infinite slab, exposed

to a sudden temperature increase at its boundary. The boundary temperature increase is modelled as a step change in temperature and all fluid properties are assumed to remain constant. Under these conditions the surface heat flux is expressed by the following equation.

$$q_{\text{COND,air}} = k_{\text{air}} A (T_o - T_i) / (\pi \alpha t)^{1/2}$$

Making the appropriate substitution of the quantities found in the data, this equation becomes

$$q_{\text{COND,air}} = k_{\text{air}} A_{\text{tc}} (T_{\text{tc}} - T_{\infty}) / (\pi \alpha t)^{1/2}$$

where t will be represented as the time elapsed from the beginning of the test until the thermocouple reaches T_{tc} . The conduction heat flux to the air can be solved for in this equation by substitution of the values found in Appendix B. A typical comparison between values of heat loss to the air based on this transient conduction model are compared with those calculated for the experiment in Appendix C.5. It is also realized that a value for the minimum overall convective heat transfer coefficient can be found directly from this analysis by equating the conduction term to the equation describing convection heat transfer to the air.

$$h A_{\text{tc}} (T_{\text{tc}} - T_{\infty}) = k_{\text{air}} A_{\text{tc}} (T_{\text{tc}} - T_{\infty}) / (\pi \alpha t)^{1/2}$$

This equation can then be simplified to

$$h = k_{\text{air}} / (\pi \alpha t)^{1/2}$$

and solved for h to indicate the conduction limit of convection. Knowing h , an equivalent conduction limit Nusselt number can be found as a function of time only. The results of these calculations are also presented in Appendix C.5.

In estimating the contribution of free convection to the cooling of the thermocouple bead an exact method of analysis was not available. A rough comparison can be made using the transient experimental data found for conduction and free convection cooling of a heated horizontal wire in air.²¹ This research was performed by Parsons and Mulligan and concerned the stability of the initiation of the free convection process. Though their data was gathered under vastly different circumstances than the current experiment, it may be useful in performing an order of magnitude comparison. Listed below are a few of the conditions under which this data was gathered as compared with the current research:

- a) platinum wires of 3.0×10^{-5} m and 1.27×10^{-4} m diameter (compared with chromel-alumel thermocouple bead of 7.62×10^{-5} m)
- b) electrically heated (compared with heating by radiation)
- c) essentially constant heat flux (compared with variable heat flux)

d) total heating time—initiation of heating to one minute (compared with initiation of heating to 11 seconds)

These differences may be significant. Due to the lack of availability of more appropriate experimental data, the results of this study are used. Since Parsons and Mulligan's results are presented in nondimensional form (as Nusselt number versus Fourier number) the time scale in these results must be dimensionalized to allow for comparison with the results of this study. No other modification to their results are necessary. Comparisons between these differing modes of heat transfer are made at the end of this chapter.

Finally, it has been found that an upper limit to the experimental Nusselt numbers calculated from this analysis can be found. The upper limit may be established by simply assuming that the conduction heat loss through the thermocouple wires is negligible. Employing this approximation reduces Equation (3) to

$$\begin{aligned} q_{\text{CONV,air}}|_{\text{AIR}} = & \sigma \epsilon_{\text{foil}} A_{\text{tc}} F_{\text{tc-foil}} (T_{\text{foil}}^4 - T_{\text{tc}}|_{\text{AIR}}^4) \\ & - \sigma \epsilon_{\text{tc}} A_{\text{tc}} F_{\text{tc-box end}} (T_{\text{tc}}|_{\text{AIR}}^4 - T_{\text{box end}}^4) \\ & - m_{\text{tc}} C (dT/dt)|_{\text{AIR}} \end{aligned} \quad (7)$$

This approximate analysis may be preferable since no reference needs to be made to the vacuum tests and no further approximations need to be made to the air tests. Again, the overall convection heat transfer

coefficient and Nusselt number can be easily calculated and a transient upper limit established.

The tabulated results of these calculations for the enclosed air and open air tests are given in Appendix B.1 and B.2. With upper and lower limit transient Nusselt numbers known, a range of values of Nusselt number is established for each thermocouple at each instant in time. The tabulated results can be reduced to graphical form and are the subject of Chapter 4 along with the appropriate comparisons of conduction and free convection to the air.

The magnitudes of these differing modes of heat transfer to the air are illustrated in the form of Nusselt number versus time in Figure 3.4. The conduction curve represented in this figure represents the curve derived from the previous analytical determination of the conduction limit Nusselt number. The free convection curve represents experimental results found by Parsons for the transient cooling of a horizontal wire by conduction and free convection. In order to complete the comparison, the Nusselt numbers calculated for heat loss to the air found for thermocouple #2 are presented as typical experimental results. Note that both upper and lower limit Nusselt numbers are presented. It is clear from this figure that the analytically determined conduction limit Nusselt number falls well below the results of the current study, but also well below the results found by Parsons. Therefore, Parsons' results are used as the reference for the free convection limit in order to make a qualitative comparison with

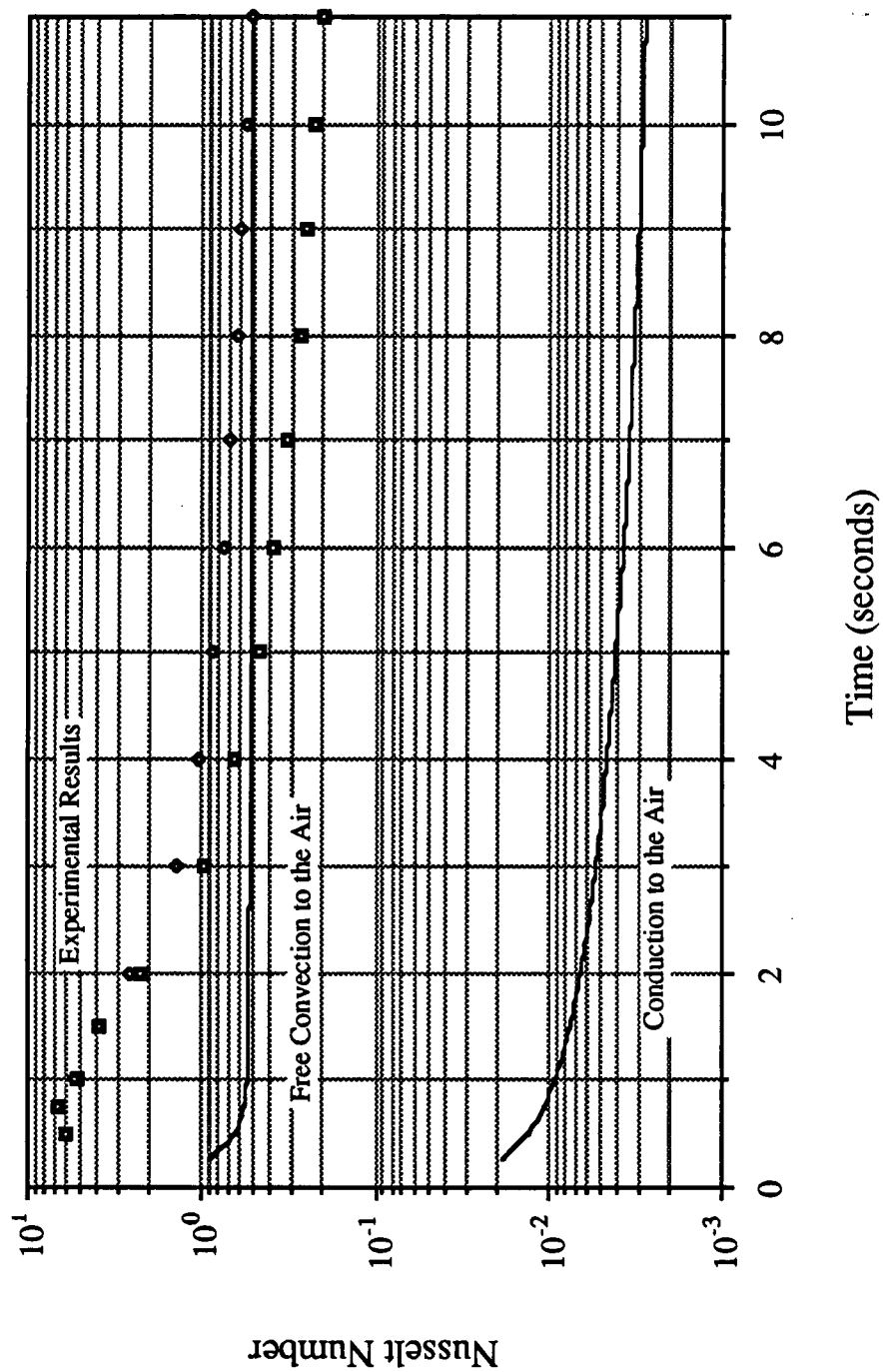


Figure 3.4 Modes of Heat Transfer to the Air—Thermocouple #2

the results found in Chapter 4. It is stressed that this comparison can only be made qualitatively since the control variables in the two experiments are not similar. Nevertheless, the differences between the magnitudes of these results seem to indicate the occurrence of significant forced convection in the current experiments. Since thermoacoustic convection is the only mechanism that can be responsible for this convective air movement, the presence of TAC in air is confirmed by the experimental data and the results of the previous analysis.

CHAPTER 4

PRESENTATION OF RESULTS

4.1 OVERVIEW OF THE PRESENTATION

The Nusselt number is an appropriate quantity to study since results are sought concerning the significance of the forced convective cooling process on a solid body (the thermocouple bead). The Nusselt numbers that are calculated based on the analysis of Chapter 3 will serve as an indication of the contribution of TAC heat transfer as evidenced by the bulk movement of air. Recall that the analysis in Chapter 3 consisted of the derivation of equations which give the upper and lower limiting values of the experimental Nusselt number for a specific thermocouple at a specific time. In addition, conduction and free convection Nusselt numbers were found. The complete listing of the actual Nusselt numbers and heat transfer coefficients derived for the enclosed air and the open air tests are presented in tabulated form in Appendices B.1 and B.2, respectively. The bulk of the results presented in the following two sections will be in graphical form with references being made to the appendices when needed.

The Nusselt number range is graphically represented as a set of points representing the minimum and maximum values calculated in

Chapter 3. Since measurements were made both transiently and spatially, two different presentations of the same data are employed to describe the results. In each of the following sections, the first series of figures show the variation with time of the Nusselt number for each thermocouple. The results are plotted as Nusselt number versus time elapsed since initiation of the test. In order to simplify this presentation, each figure represents the results of a single thermocouple and comparisons are made between thermocouples when appropriate. In addition to these results, Parsons' experimental results are plotted as a single curve representing the limit of free convection. This is provided to give the reader a feel for the magnitudes of the differing modes of heat transfer. The second series of figures present the spatial variation of Nusselt number at various points in time. These results are plotted as Nusselt number versus distance from the heater surface at a specific point in time.

4.2 ENCLOSED AIR RESULTS

Figures 4.1 through 4.7 present the variation of Nusselt number with time for each thermocouple. These figures primarily serve to illustrate the local variation of Nusselt number (and, therefore, the relative magnitude of convective air movement) with time at a particular location in the container. Apparent in these figures is the

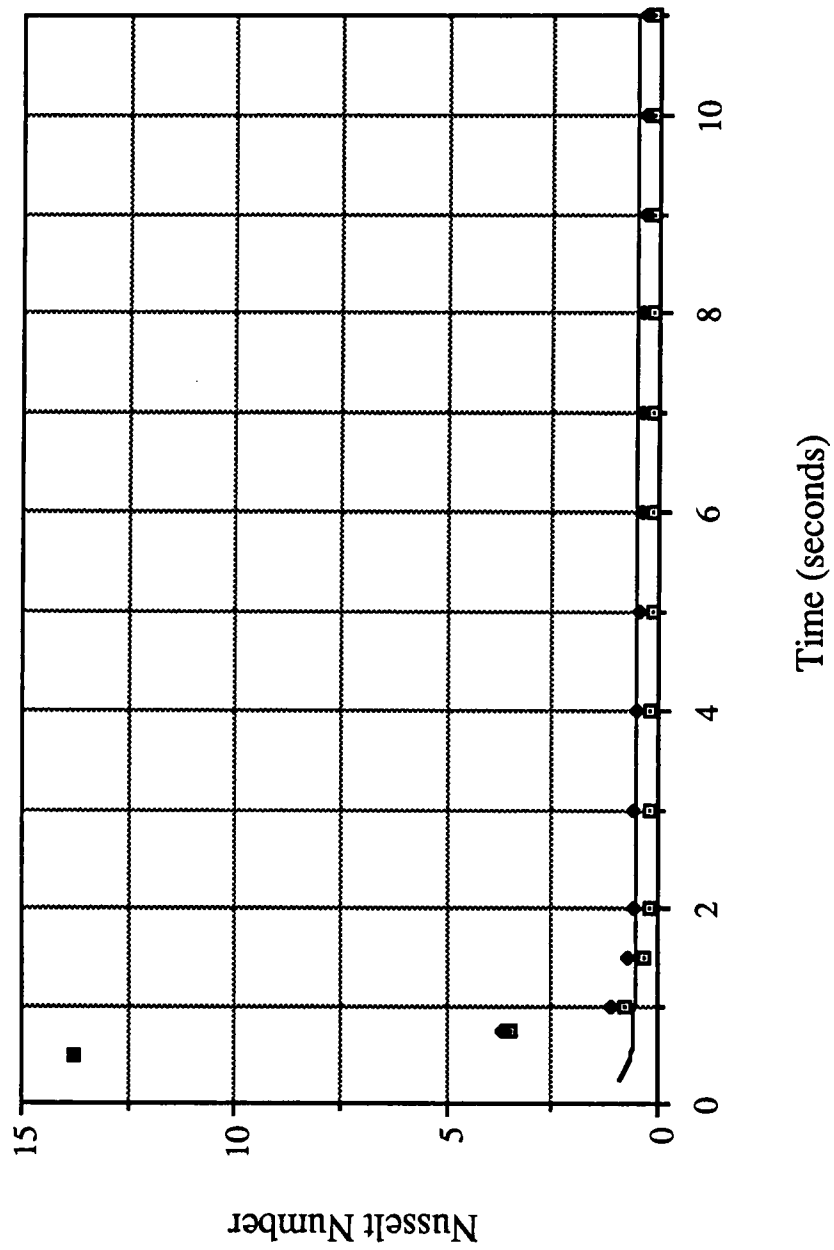


Figure 4.1 Variation of Nu with Time—Thermocouple #1

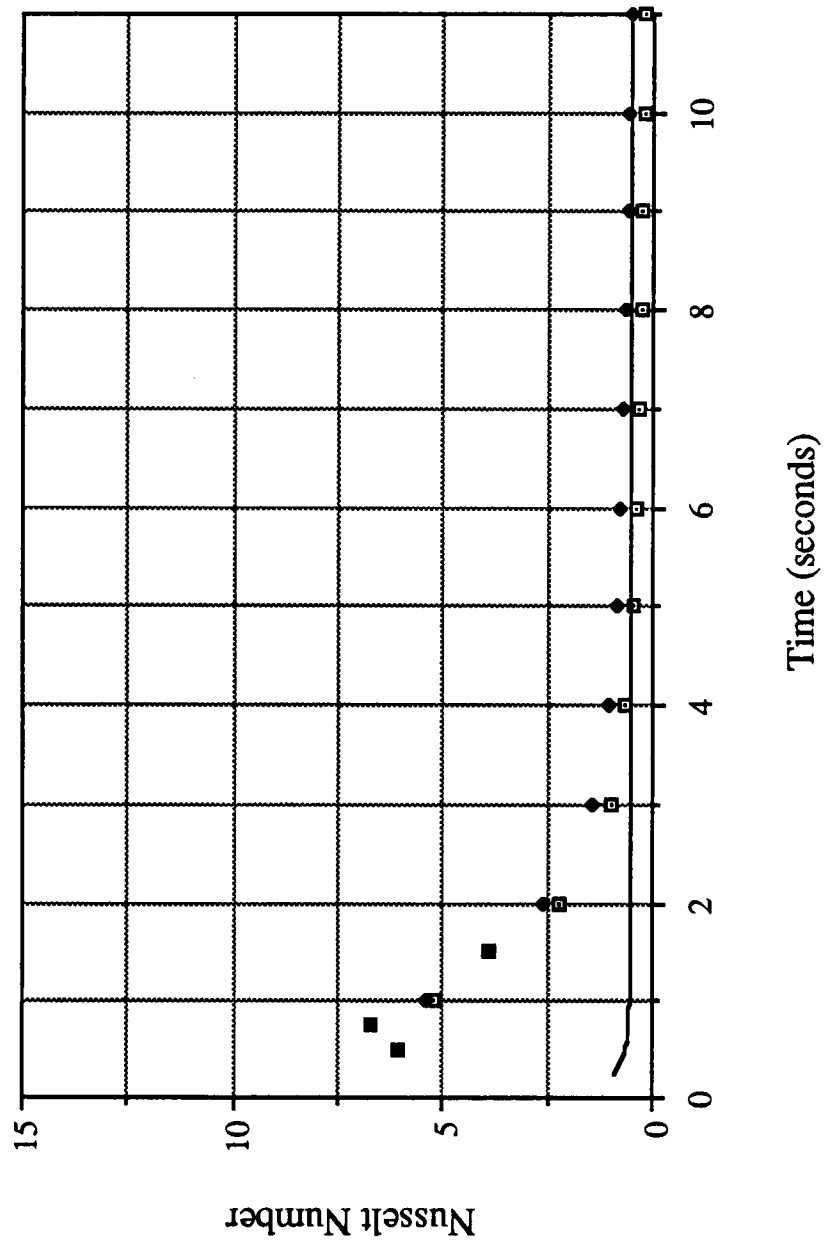


Figure 4.2 Variation of Nu with Time—Thermocouple #2

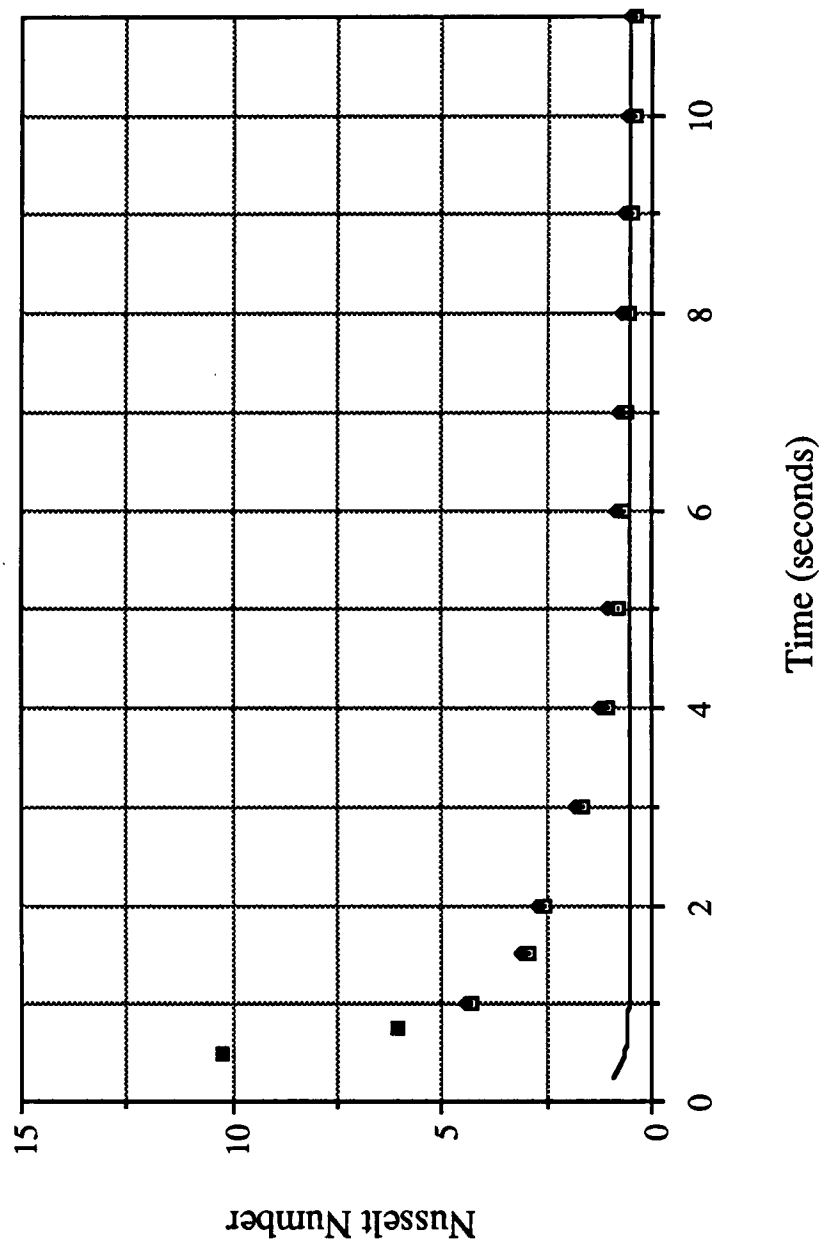


Figure 4.3 Variation of Nu with Time—Thermocouple #3

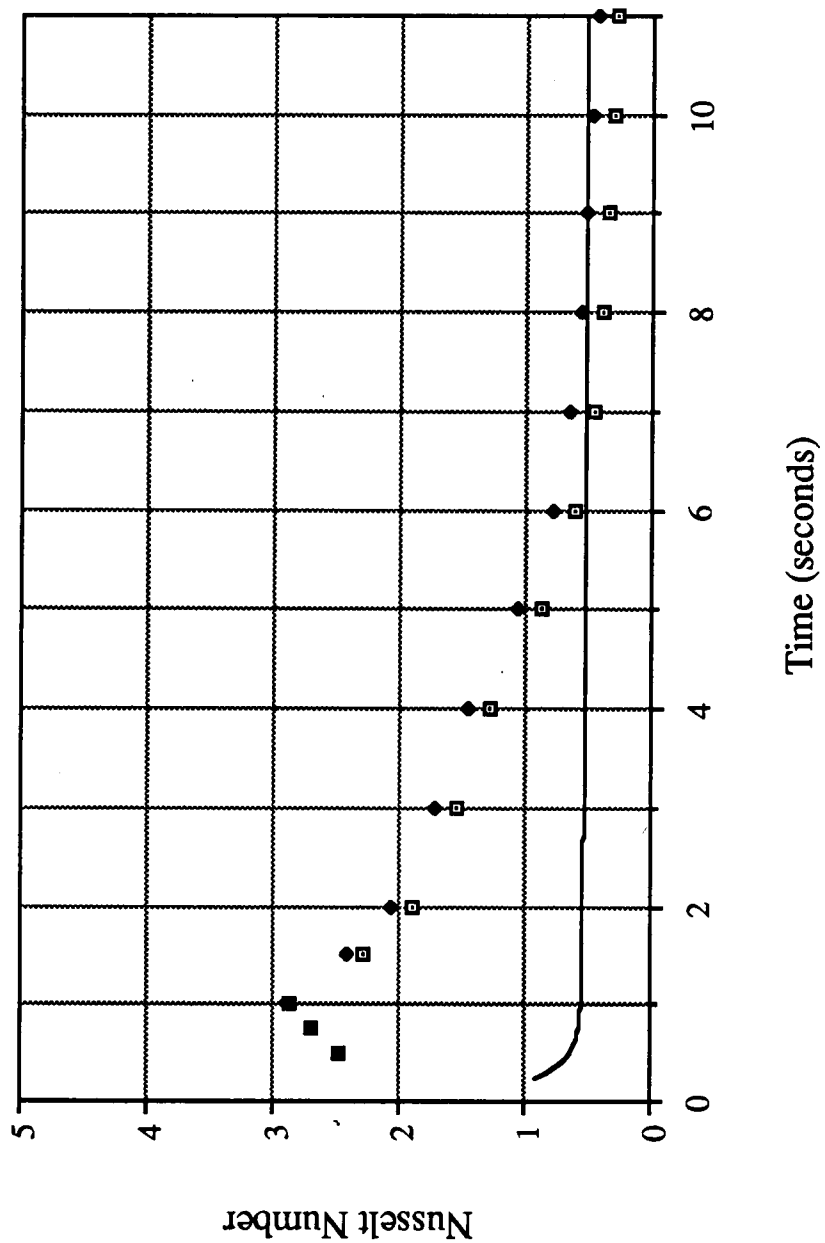


Figure 4.4 Variation of Nu with Time—Thermocouple #4

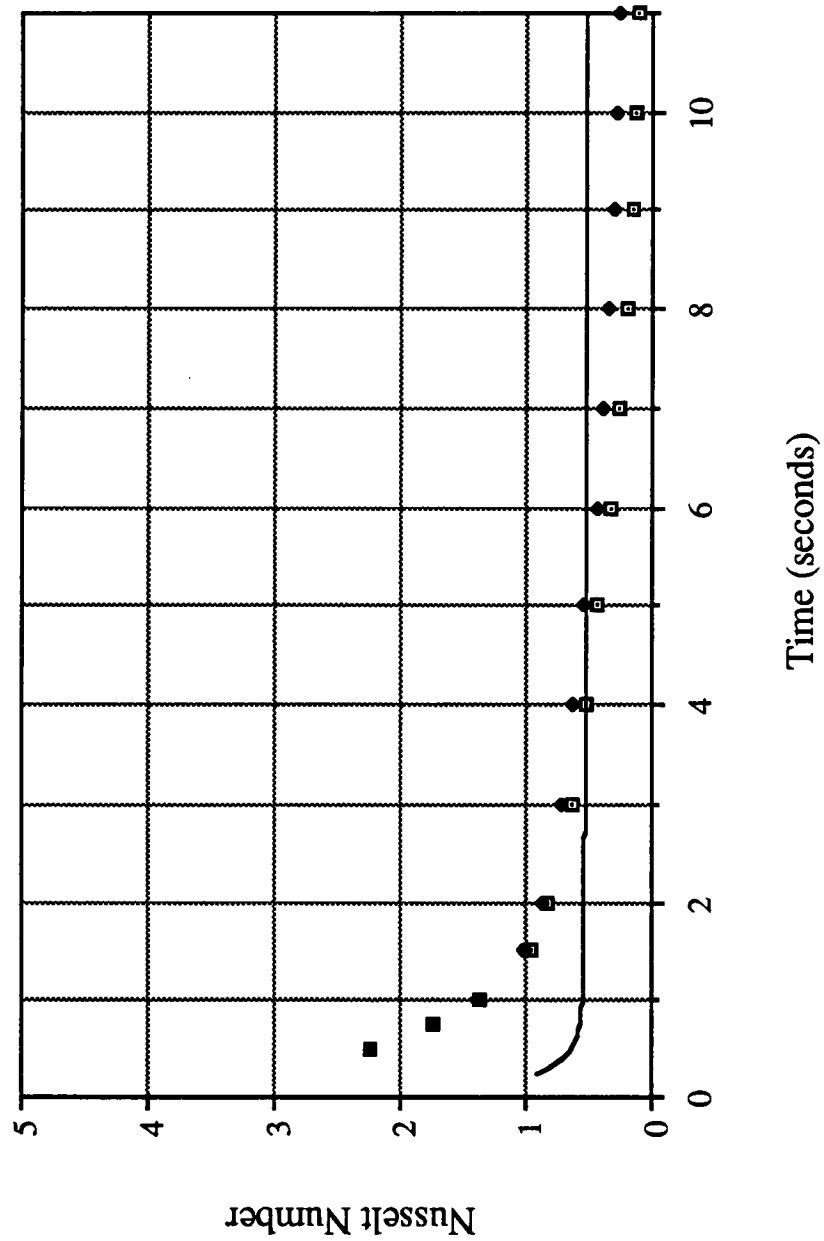


Figure 4.5 Variation of Nu with Time—Thermocouple #5

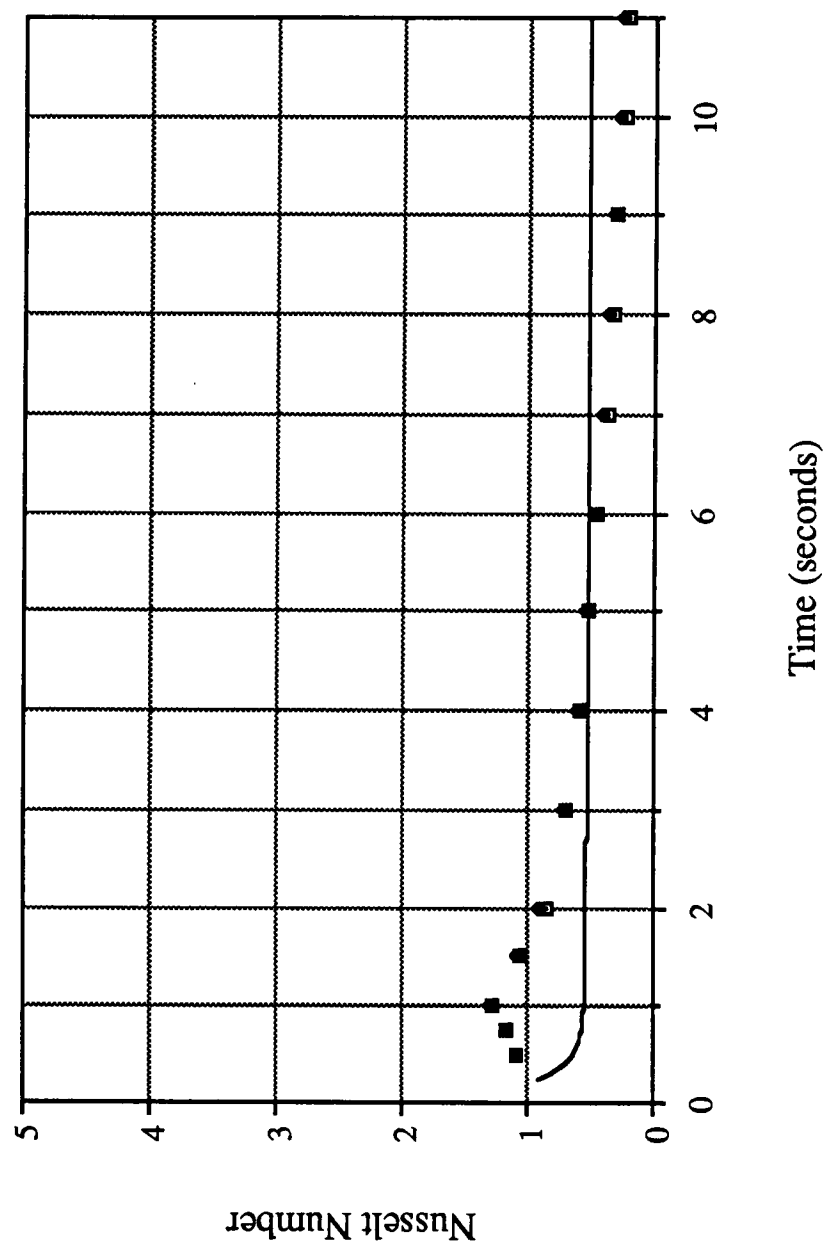


Figure 4.6 Variation of Nu with Time—Thermocouple #6

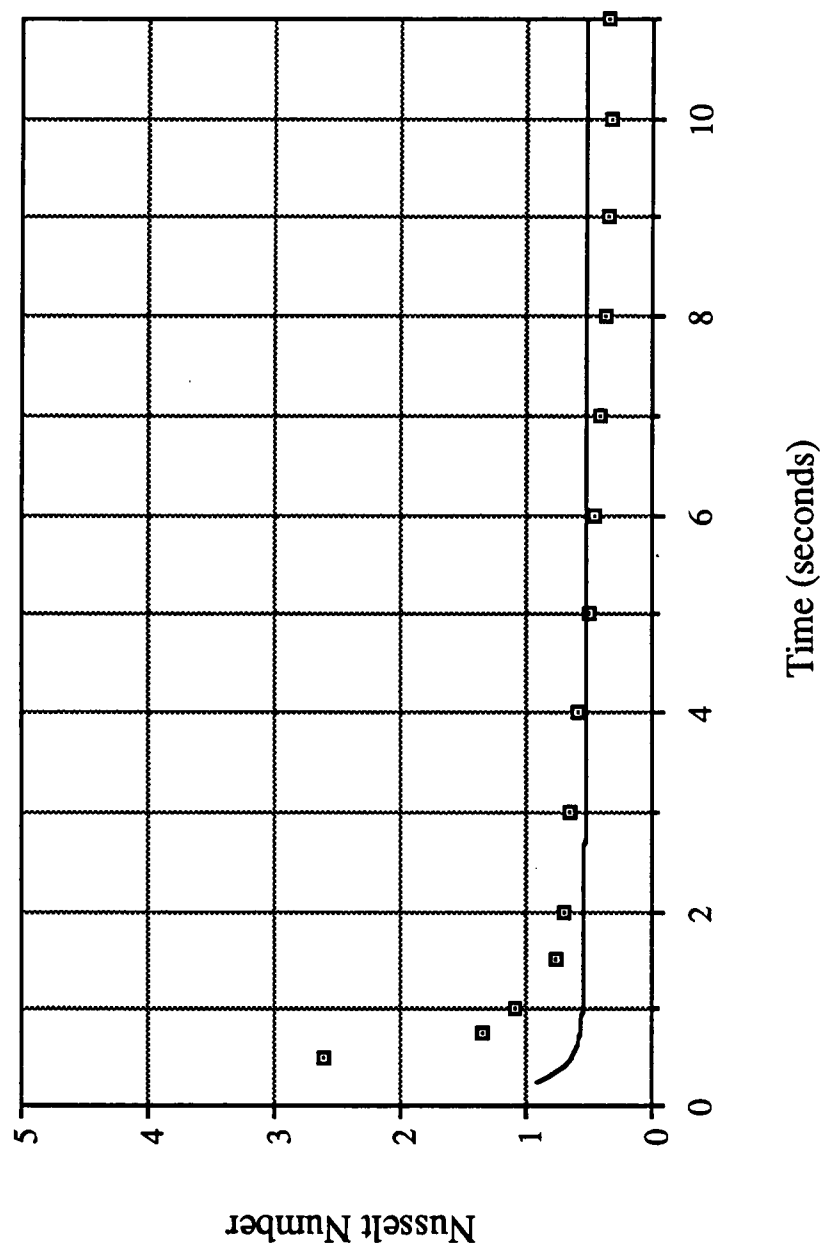


Figure 4.7 Variation of Nu with Time—Thermocouple #7

decay of the bulk air movement with time. Special attention should also be given to the lower most curve representing the contribution of transient conduction and free convection. Though only a very general comparison can be made between these sets of results, a significant difference is observed. This difference is due to the presence of forced convection heat transfer as can only be established by thermoacoustic convection.

In Figure 4.1 the computed values of Nusselt number for the thermocouple closest to the heater surface are presented. This thermocouple is referred to as thermocouple #1 and is positioned 0.5 inches from the heater surface. Larger values of Nusselt number found at the initiation of the test are followed by lower values which occur over most of the measurement period. It is observed that the range of Nusselt numbers decreases asymptotically with time. Since the Nusselt number is used as an indication of air movement, this figure shows a degree of air movement which decreases rather quickly with time. This trend is characteristic of the results.

Figure 4.2 presents a similar trend of results which were found for the thermocouple positioned 1 inch from the heater surface, referred to as thermocouple #2. Again the Nusselt number range was found to decrease quickly with time. The difference between the results of this study and the free convection curve indicate, at least initially, significant convective air movement. The increasing range of the Nusselt number with time, is due to the increasing contribution

of the wire conductive term. This is to be expected and is observed as characteristic of the results for large times.

Figure 4.3 presents the results for the third thermocouple from the heater surface. This thermocouple was referred to as #3 and was positioned 2 inches from the heater surface. The difference between the results and the free convection curve again indicate significant convective air movement at the location of this thermocouple.

Figure 4.4 presents the results found for the fourth thermocouple from the heater surface. This thermocouple was referred to as #4 and was positioned 4 inches from the heater surface. Also make a note of the ordinate scale change first made in this figure. The trend of the transient results for this location is the same as the trends discussed earlier with lower values of Nusselt number.

Figures 4.5, 4.6, and 4.7 present the results found for the thermocouples positioned 6, 8, and 11 inches from the heater surface, respectively. These thermocouples were referred to, in order, as thermocouples #5, #6, and #7, with thermocouple #7 being the thermocouple mounted next to the wall opposite the heater. The trends observed in all of these figures are the same as indicated previously with decreased values of Nusselt number.

Figures 4.8 through 4.21 present the enclosed air results as Nusselt number for all of the thermocouples at a specified point in time. These figures better illustrate the overall variation of Nusselt number (or air movement) along the length of the container. Two

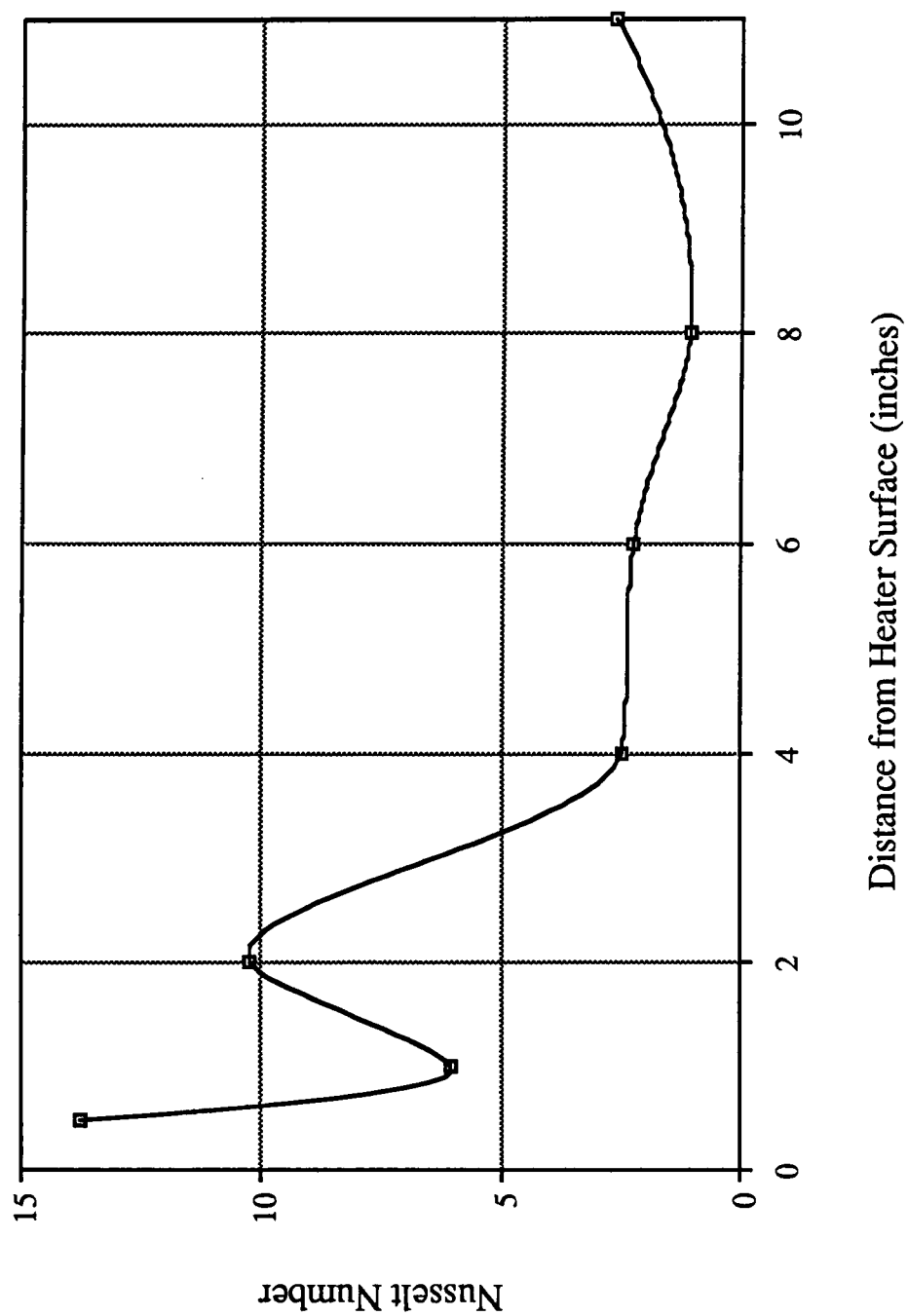


Figure 4.8 Spatial Variation of Nu —0.5 seconds

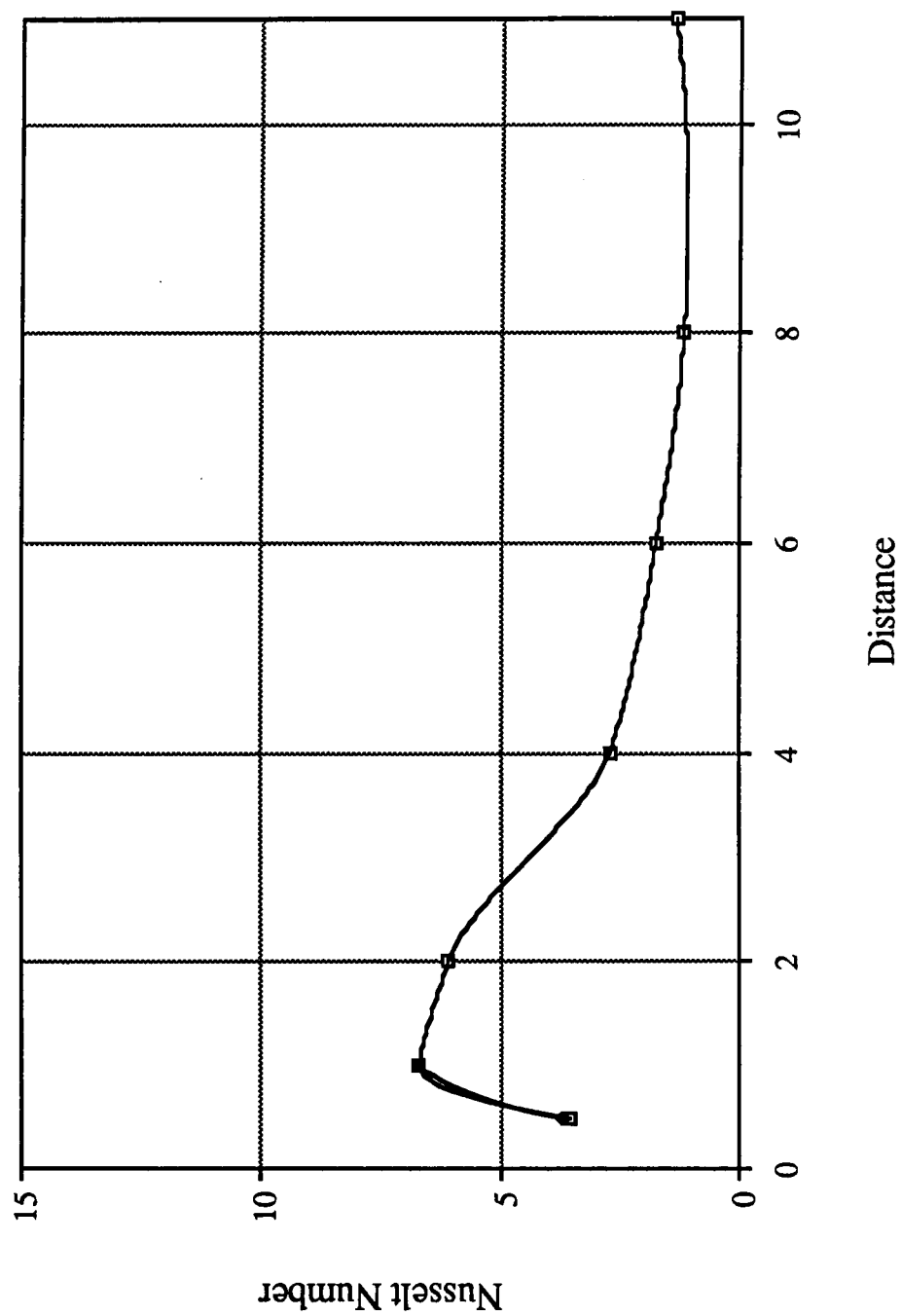


Figure 4.9 Spatial Variation of Nu —0.75 seconds

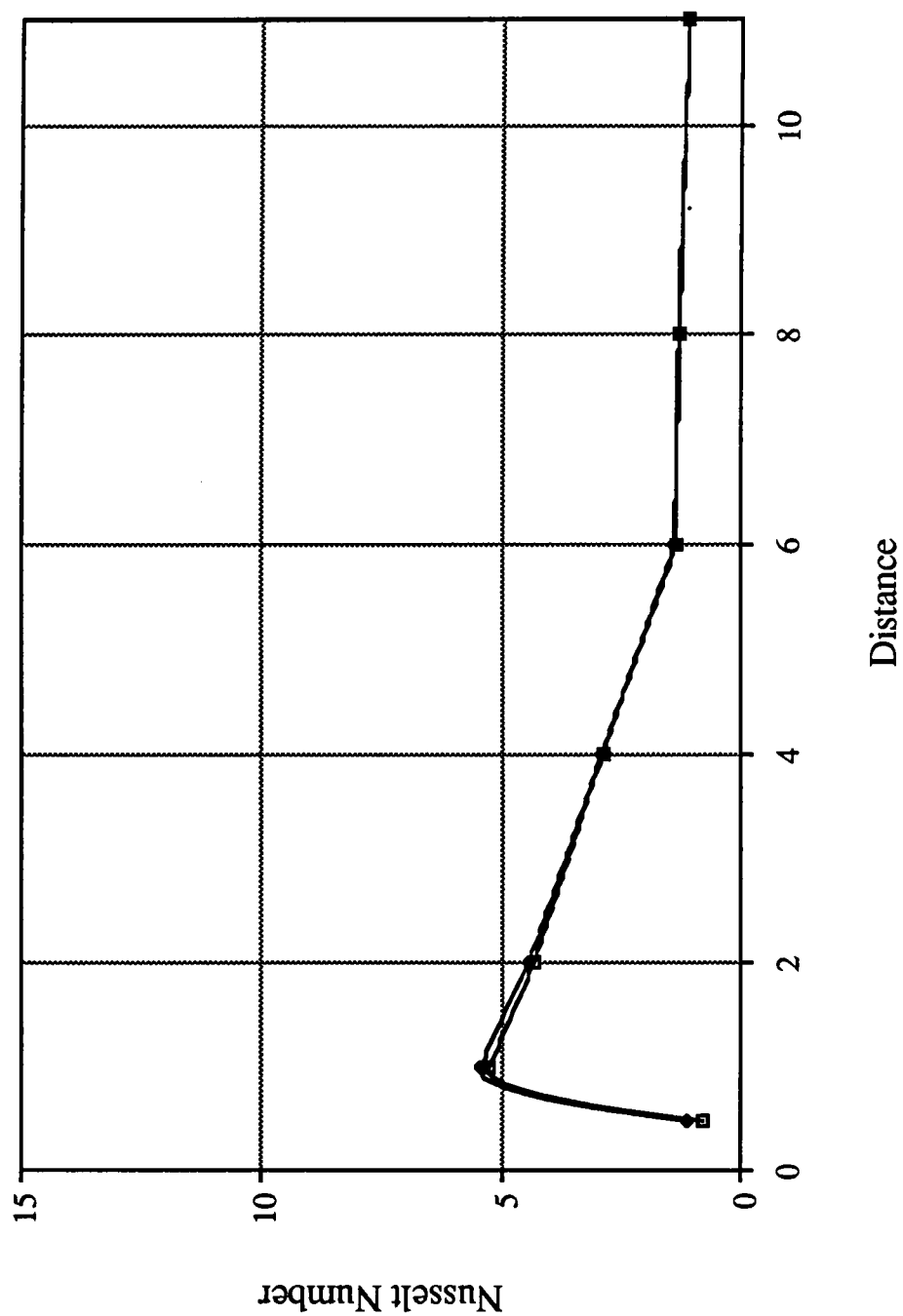


Figure 4.10 Spatial Variation of Nu—1.0 second

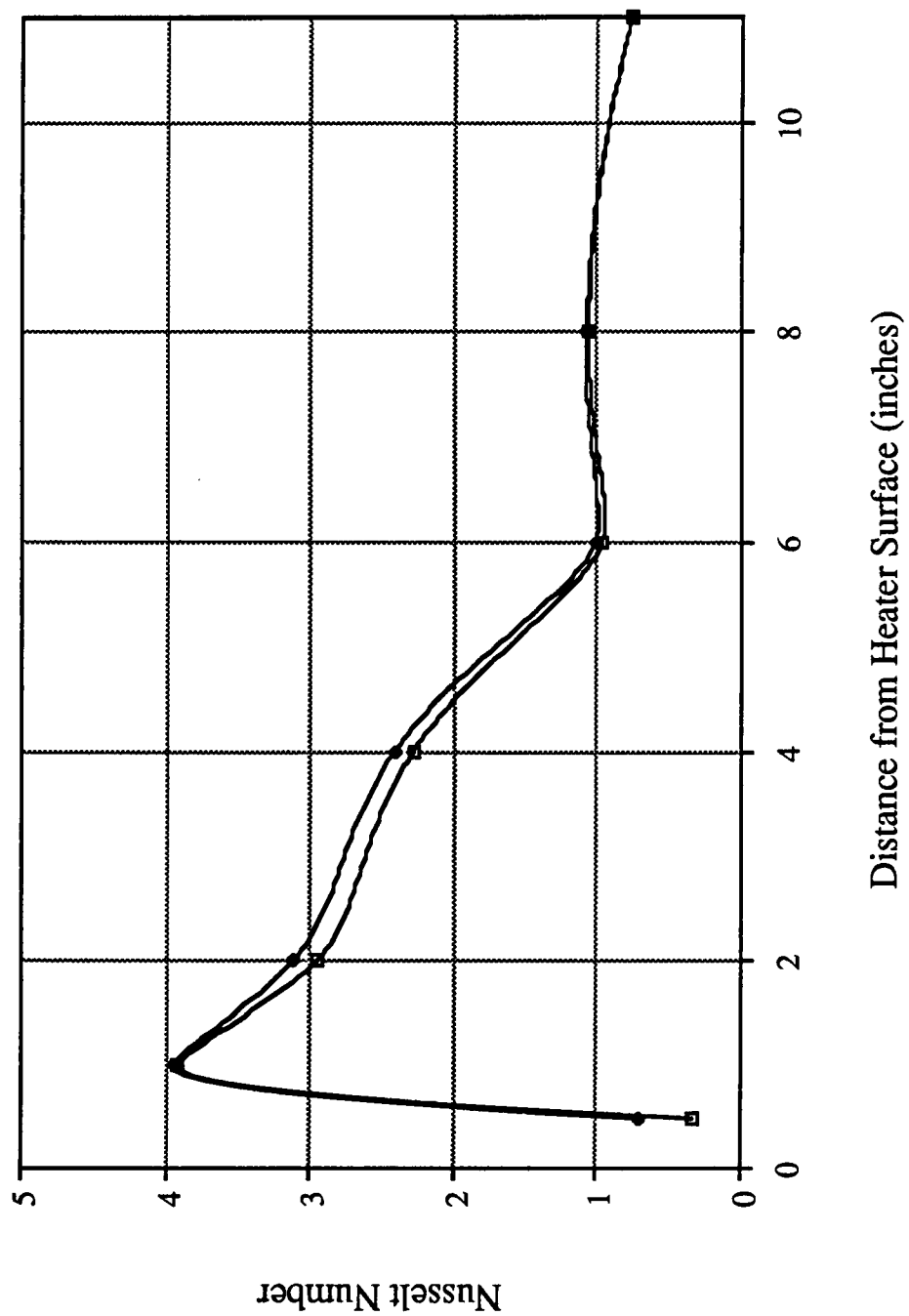


Figure 4.11 Spatial Variation of Nu—1.5 seconds

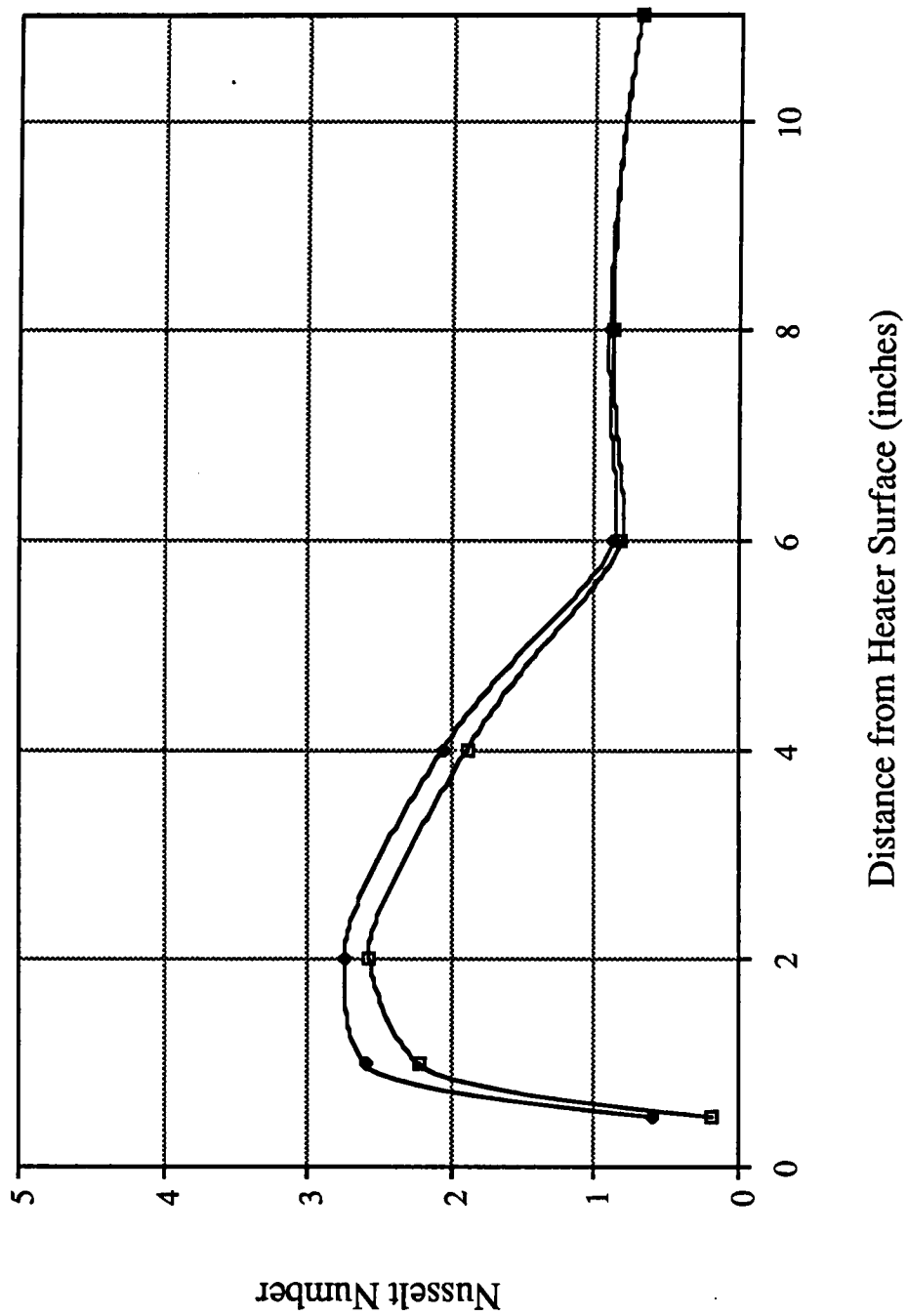


Figure 4.12 Spatial Variation of Nu—2.0 seconds

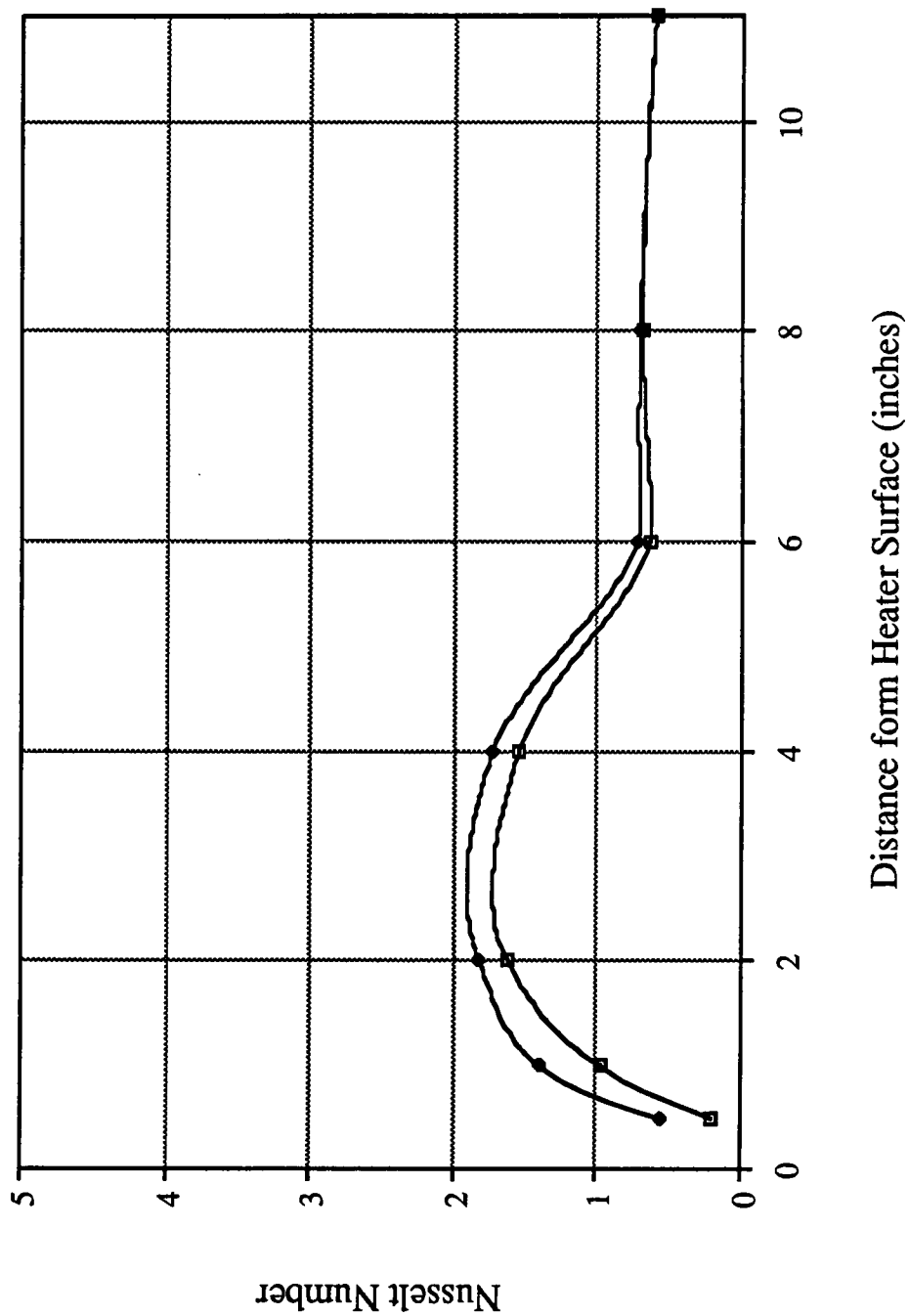


Figure 4.13 Spatial Variation of Nu —3.0 seconds

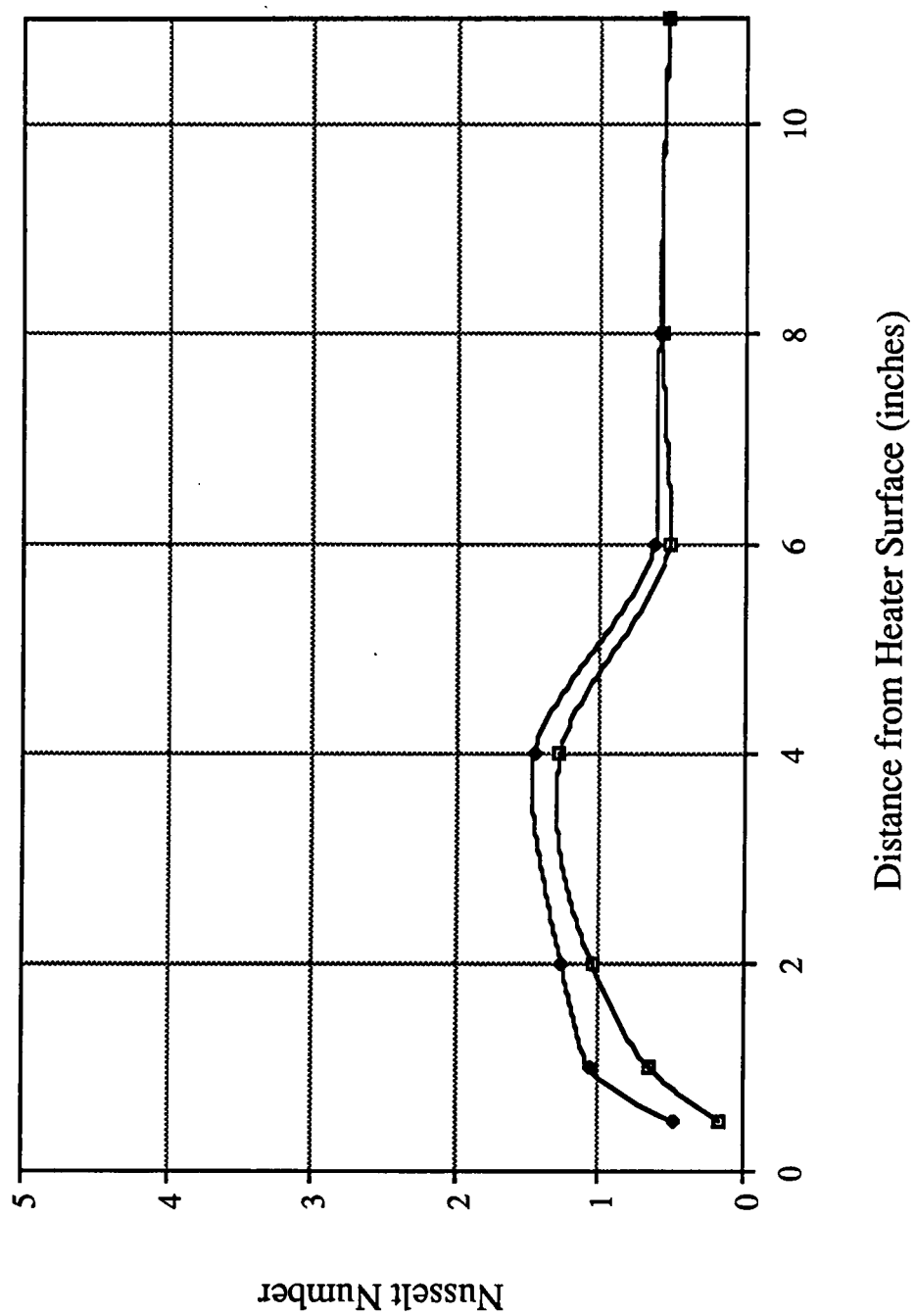


Figure 4.14 Spatial Variation of Nu —4.0 seconds

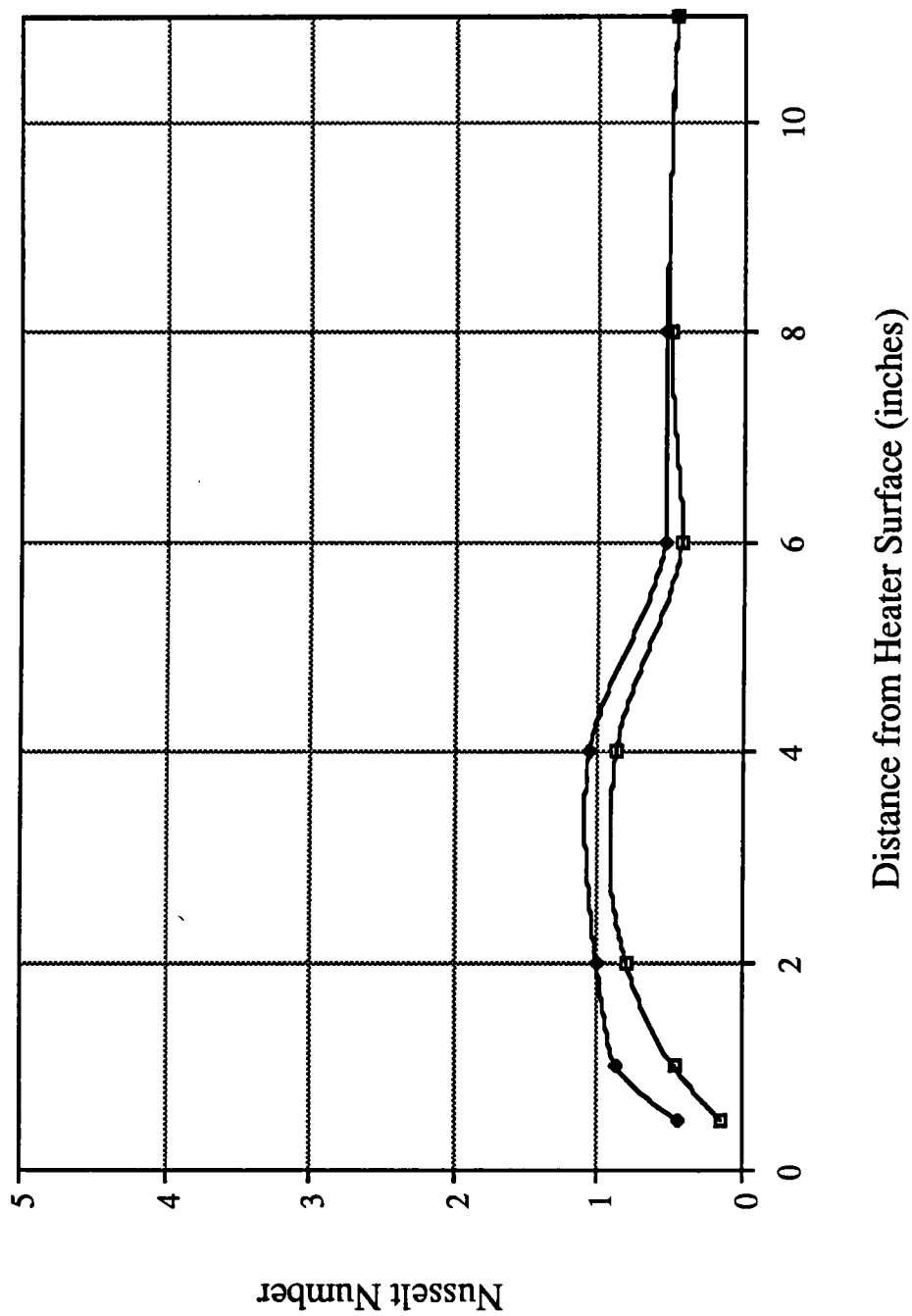


Figure 4.15 Spatial Variation of Nu—5.0 seconds

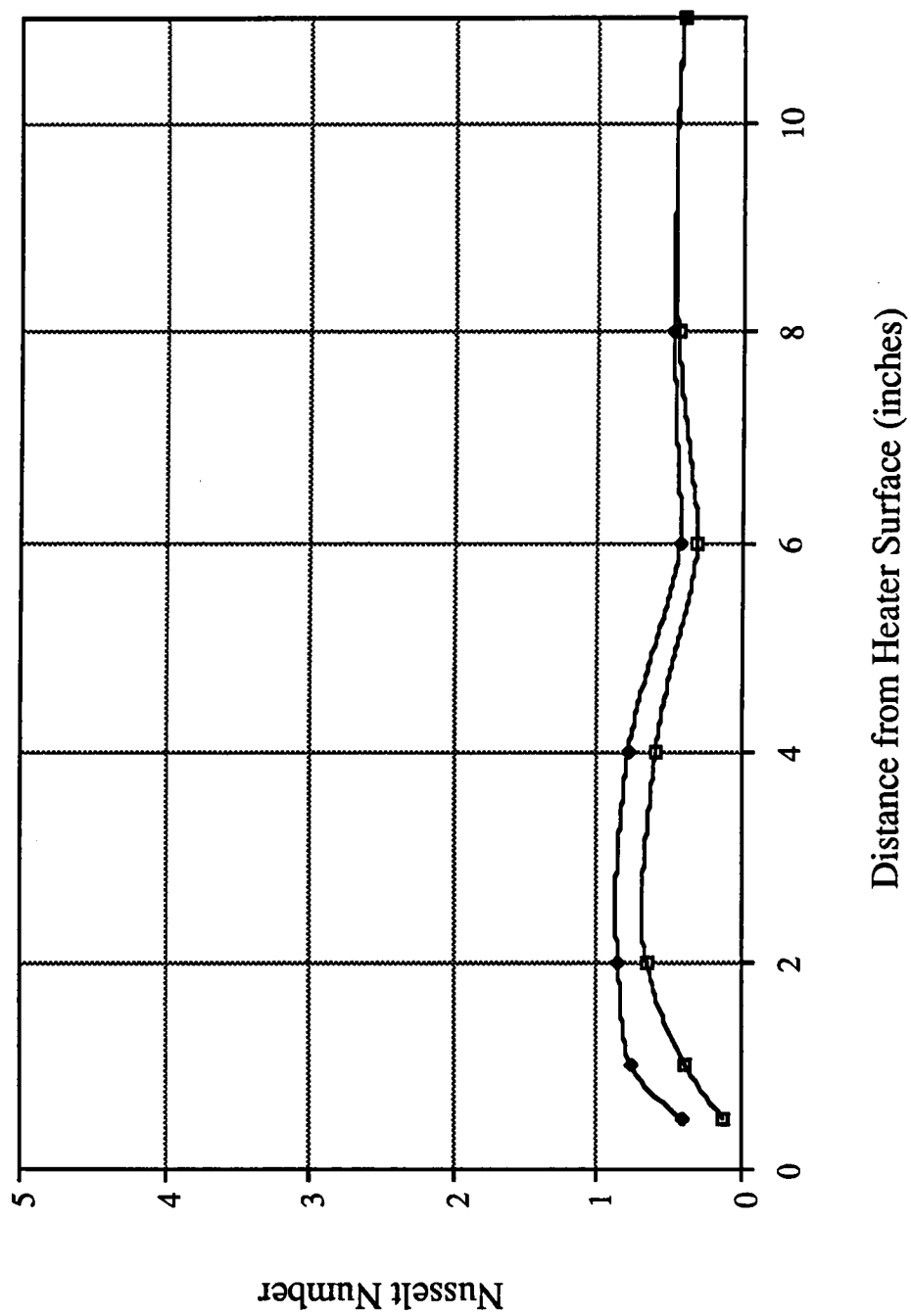


Figure 4.16 Spatial Variation of Nu—6.0 seconds

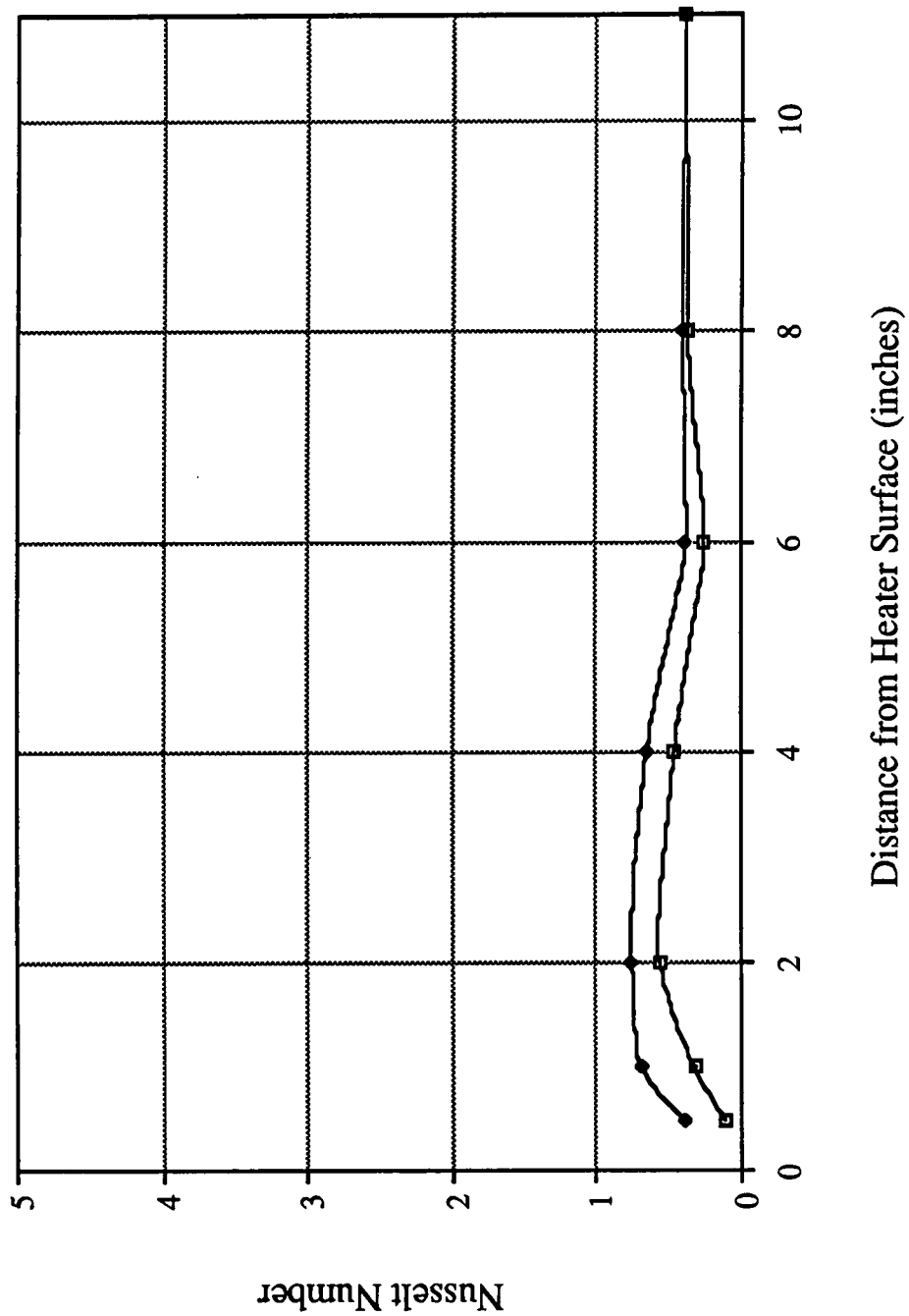


Figure 4.17 Spatial Variation of Nu—7.0 seconds

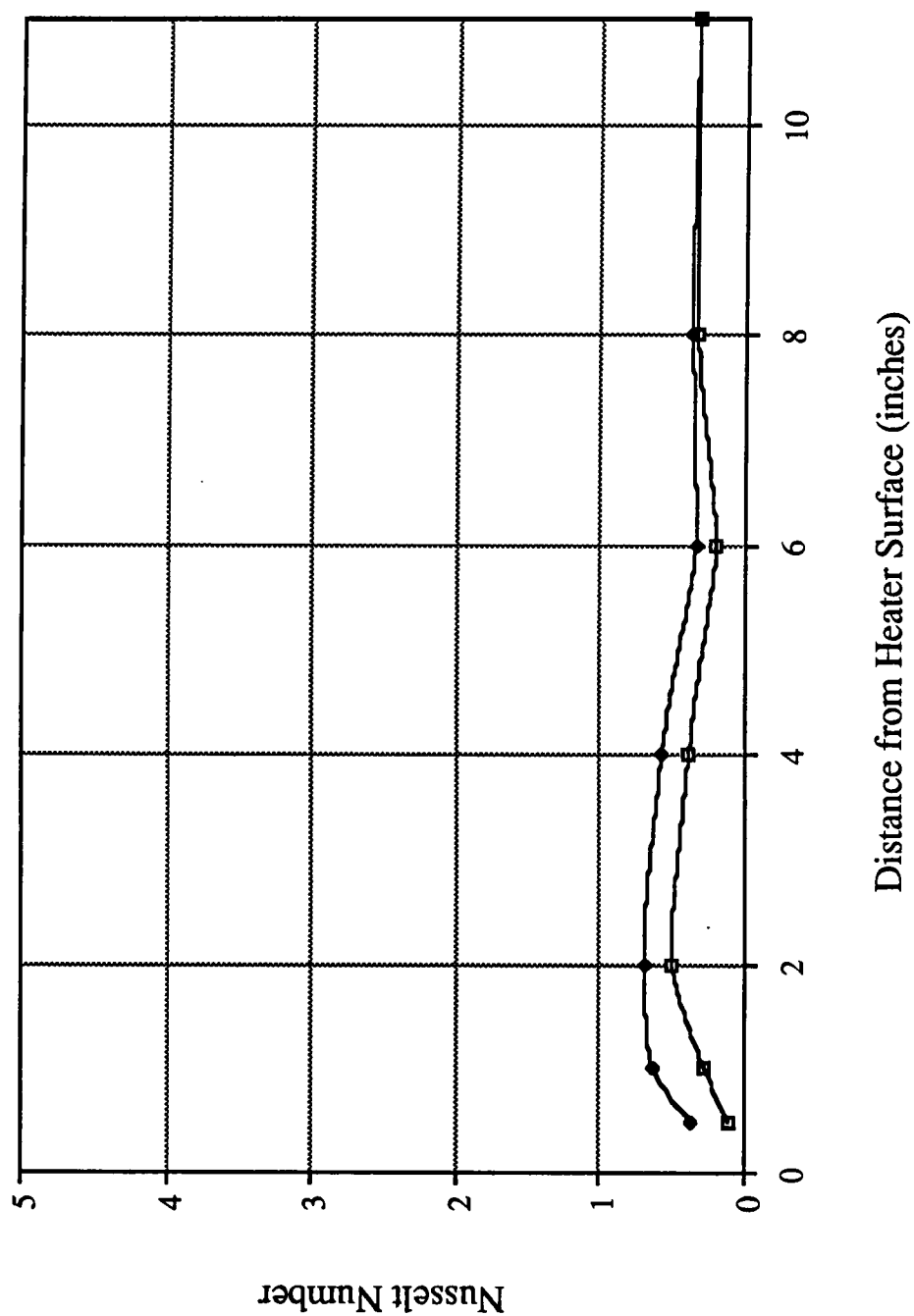


Figure 4.18 Spatial Variation of Nu —8.0 seconds

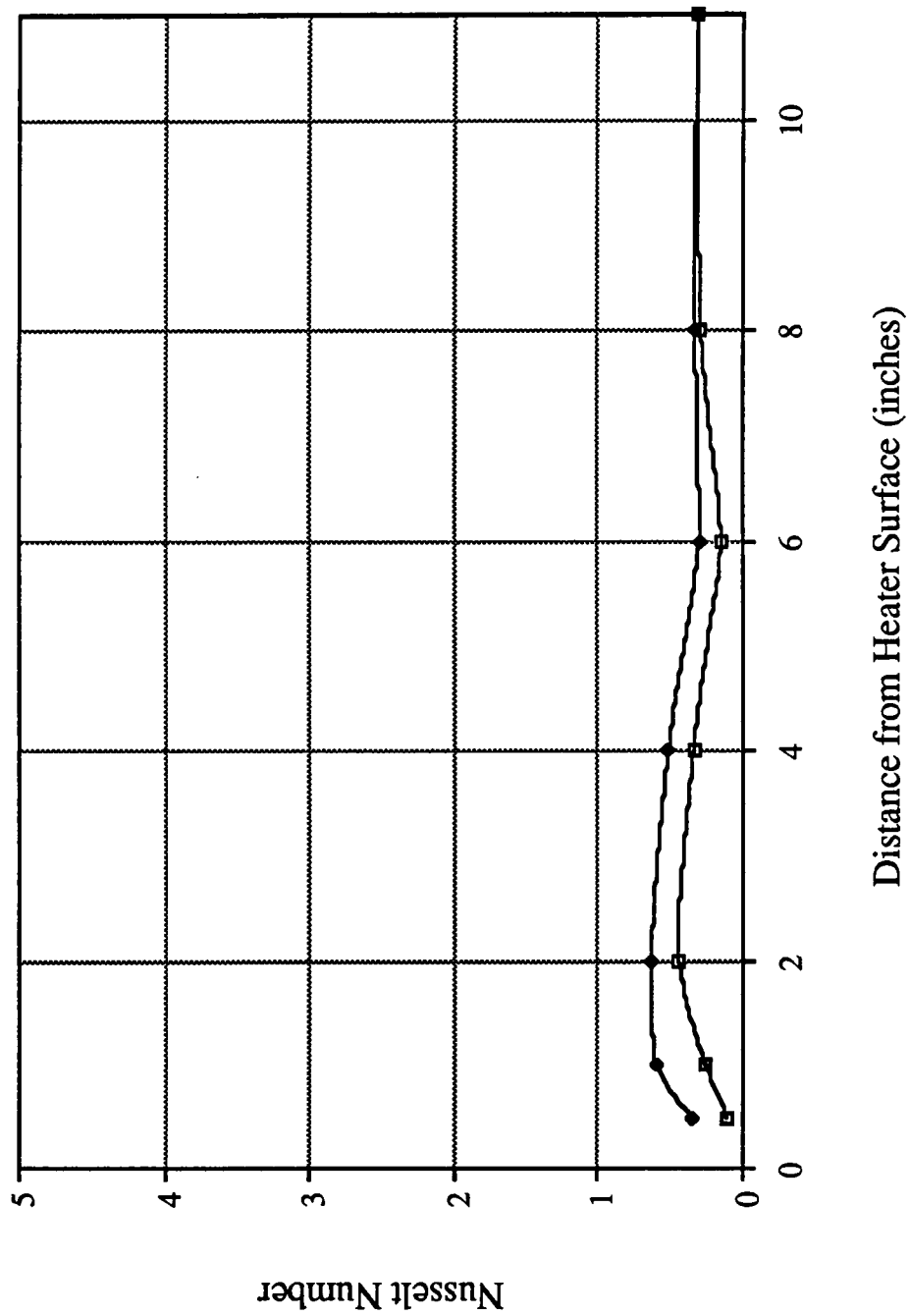


Figure 4.19 Spatial Variation of Nu—9.0 seconds

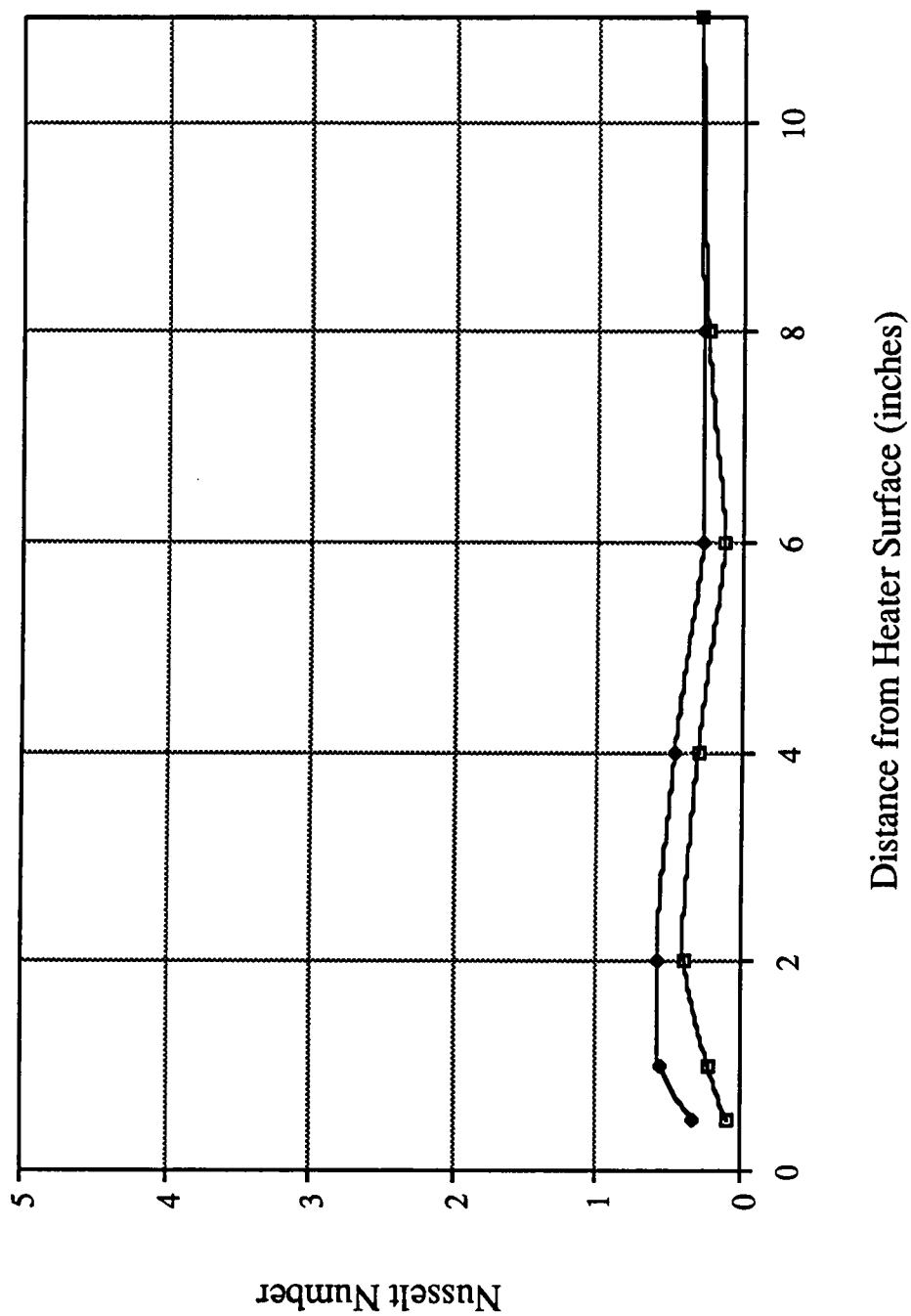


Figure 4.20 Spatial Variation of Nu—10.0 seconds

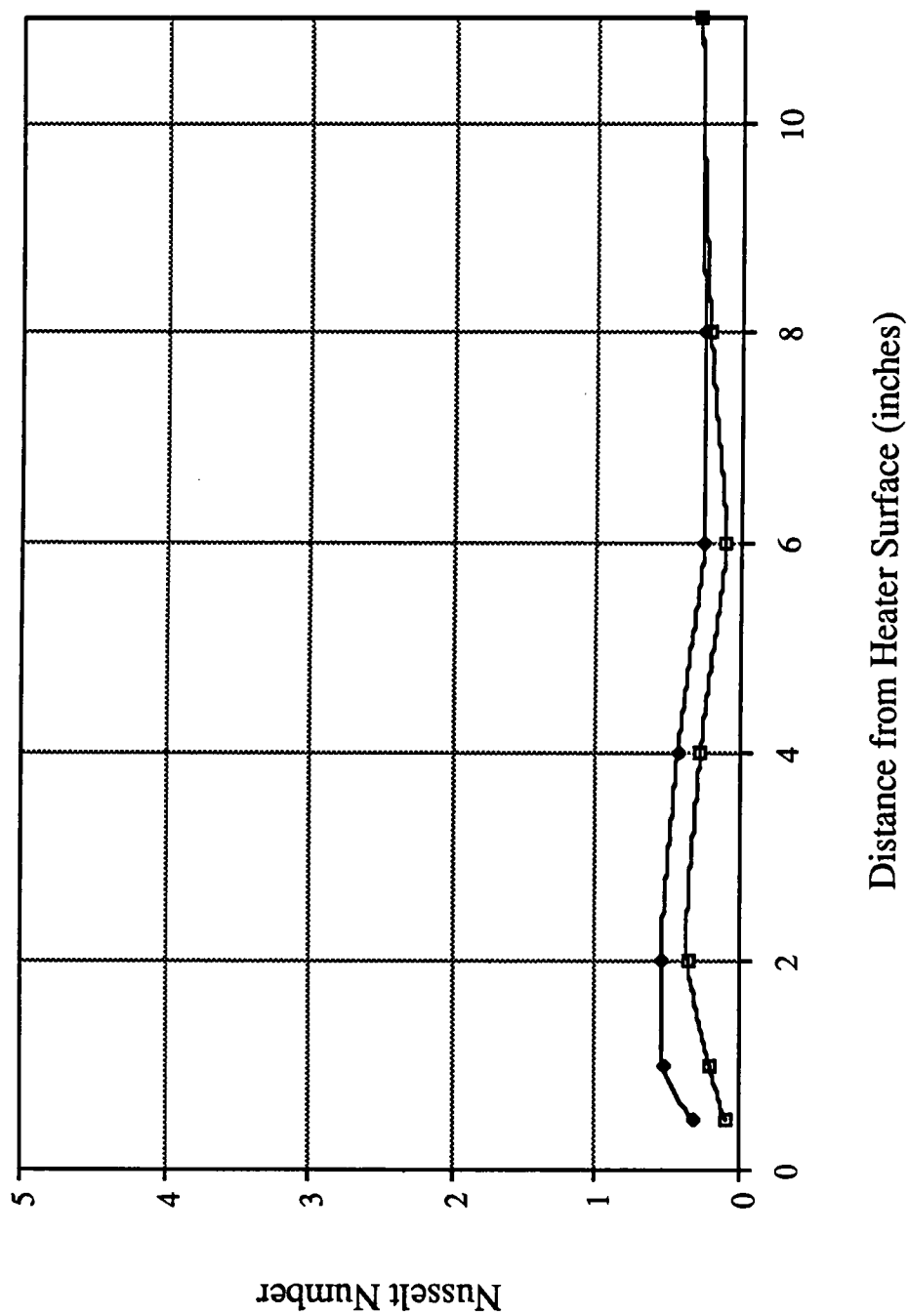


Figure 4.21 Spatial Variation of Nu—11 seconds

important characteristics are illustrated by the following figures. The first is the general shape of the results at any point in time. The second is the manner in which the peak Nusselt number value (or greatest amount of air movement) moves away from the heated boundary with time.

Figure 4.8 presents the results in the form of Nusselt number versus distance from the heater surface 0.5 seconds after the initiation of the test. This figure, though less certain than those presented hereafter, show large values of Nusselt number for the first three thermocouples, followed by significantly lower values for the thermocouples mounted further than 3 inches from the heater.

Figure 4.9 presents the results found after 0.75 seconds have elapsed since the initiation of the test. It is observed that a low Nusselt number of approximately 3, calculated near the heater surface, is followed by higher values up to approximately 7. Thereafter, these values decrease with distance from the surface to a low of 1. These results seem to indicate a peak Nusselt number in the vicinity of thermocouple #2 (approximately 1 inch from the heater surface). The higher values of Nusselt number show a relatively large penetration depth (about 4 inches) of movement of the bulk air.

Figure 4.10 presents the results found at 1.0 second. Again, a lower Nusselt number (approximately 1) near the heater surface is followed by the maximum value (approximately 5) at 1 inch from the heated boundary. Nusselt numbers then decrease more or less linearly

with distance until they reach a low of just over 1 at a distance of 6 inches from the heater. From this point the Nusselt number stays fairly consistent at a value of approximately 1.

Figure 4.11 presents the results found at 1.5 seconds with the same trend as Figure 4.10 but with a maximum Nusselt number of 4. Note the ordinate change first made in this figure. The peak Nusselt number in this figure is found at approximately 1 inch from the heater surface.

Figure 4.12 presents the results after 2.0 seconds have elapsed since the initiation of the test. This figure shows a maximum recorded Nusselt number of 2.7 with the peak moving slightly further away from the heater surface (somewhere between 1 and 2 inches). The penetration depth of air movement remains in the range of about 1 to 4 inches from the surface. As the maximum values of Nusselt number decrease with time, notice the smoothing of the results presented in the upper half of the container.

Figure 4.13 shows that at 3.0 seconds all recorded Nusselt number values fall below a value of 2. It is observed that the Nusselt number peak has now moved to the vicinity of 3 inches from the heater surface. The values presented do not eliminate the possibility of a relative maximum for the Nusselt number occurring between 2 and 4 inches from the heater surface, since no measurements were available at that point. The decreasing of the range of Nusselt number with distance from the surface is the result of the decreasing contribution of

conduction through the thermocouple wires with distance from the heat source.

Figure 4.14 shows that at 4.0 seconds the peak Nusselt number moves even further from the heater (to approximately 4 inches) and decreases to a value of approximately 1.5.

Figures 4.15 through 4.21 are presented for completeness and show similar trends but with much smaller magnitudes of Nusselt number and no further movement of a distinguishable peak. All Nusselt numbers recorded by these figures fall well below 20% of the maximum Nusselt number found at 0.75 seconds and serve to illustrate the rapid decay of the velocity profile with time.

In addition to these measurements attempts were made at recording acoustic signals as a further indication of TAC. A sensitive pressure sensor was placed in the container to record any thermoacoustic oscillations produced. Since the waves generated are of acoustic origin the sensor used to make these measurements was a Brüel-Kjær model 4145 microphone connected with a model 2619 pre-amplifier. The signal was then sent to a model 3347 Brüel-Kjær Real-Time 1/3 Octave Analyzer. The entire apparatus and power supply were placed in a sound proof room to minimize background noise. Even after taking these measures, background and internal electrical noise was measured at 20 decibels. This noise level effectively masked any thermoacoustic signal that may have been generated. Since the recorded pressure traces provided no additional

information on the TAC phenomenon they are not included in the results.

4.3 OPEN AIR RESULTS

Both enclosed and open air tests were performed in order to compare the effects of differing boundary conditions on the TAC phenomenon. Removing the endplate opposite the heater effectively "opens" the lower boundary and eliminates the possibility of pressure waves reflecting off a lower surface. Recalling that the number of thermocouples along the length of the container was decreased to three in the open air tests, Figures 4.22 through 4.24 are presented to illustrate the local variation of Nusselt number with time at three locations within the container. These figures are plotted in the same manner as the first set of figures in the enclosed air results.

The results found for thermocouple #1 given in Figure 4.22 present much the same transient Nusselt numbers found for the enclosed air case in Figure 4.1 (p. 62). The same discussion applies and will not be repeated here. At this small distance from the heater surface (0.5 inch), there seems to be no difference between the enclosed air and open air results.

Figure 4.23 is a plot of the results derived for thermocouple #4. Again these results agree with those derived for thermocouple #4

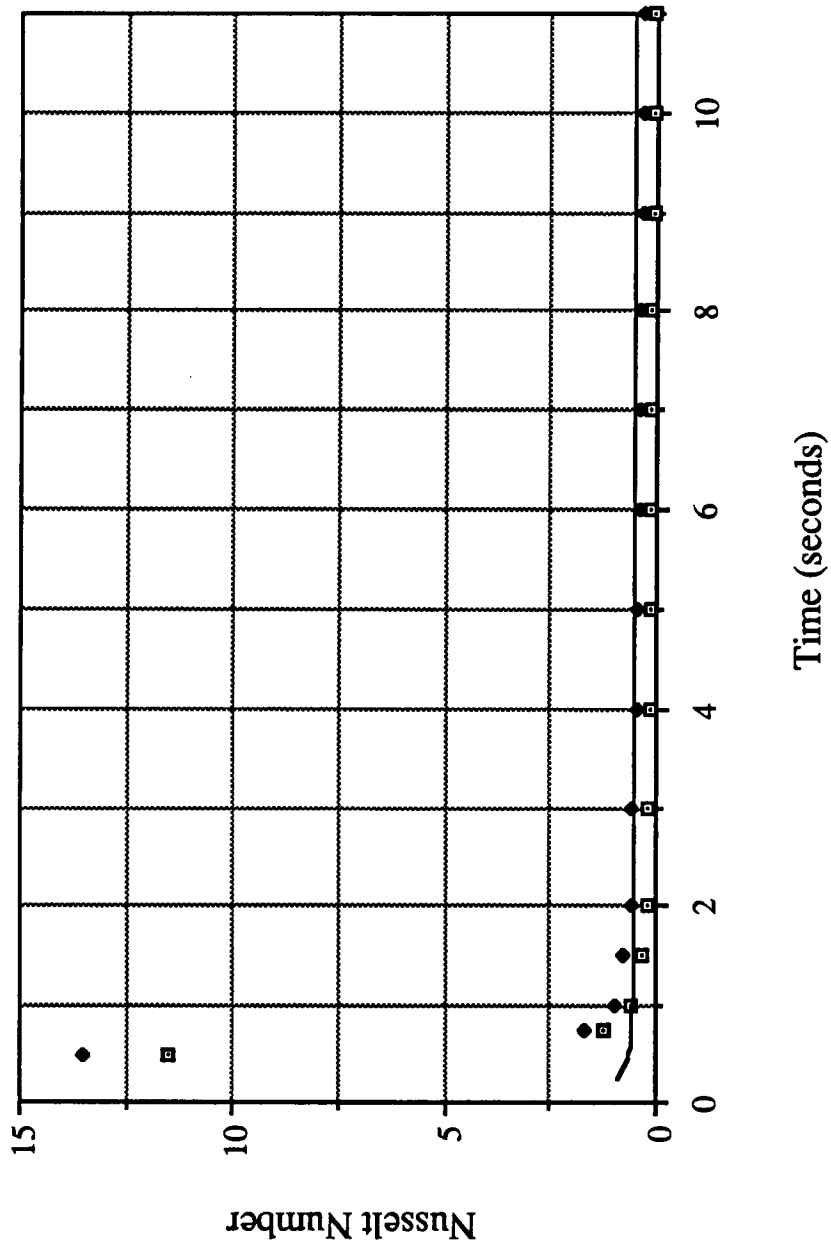


Figure 4.22 Variation of Nu with Time—Thermocouple #1

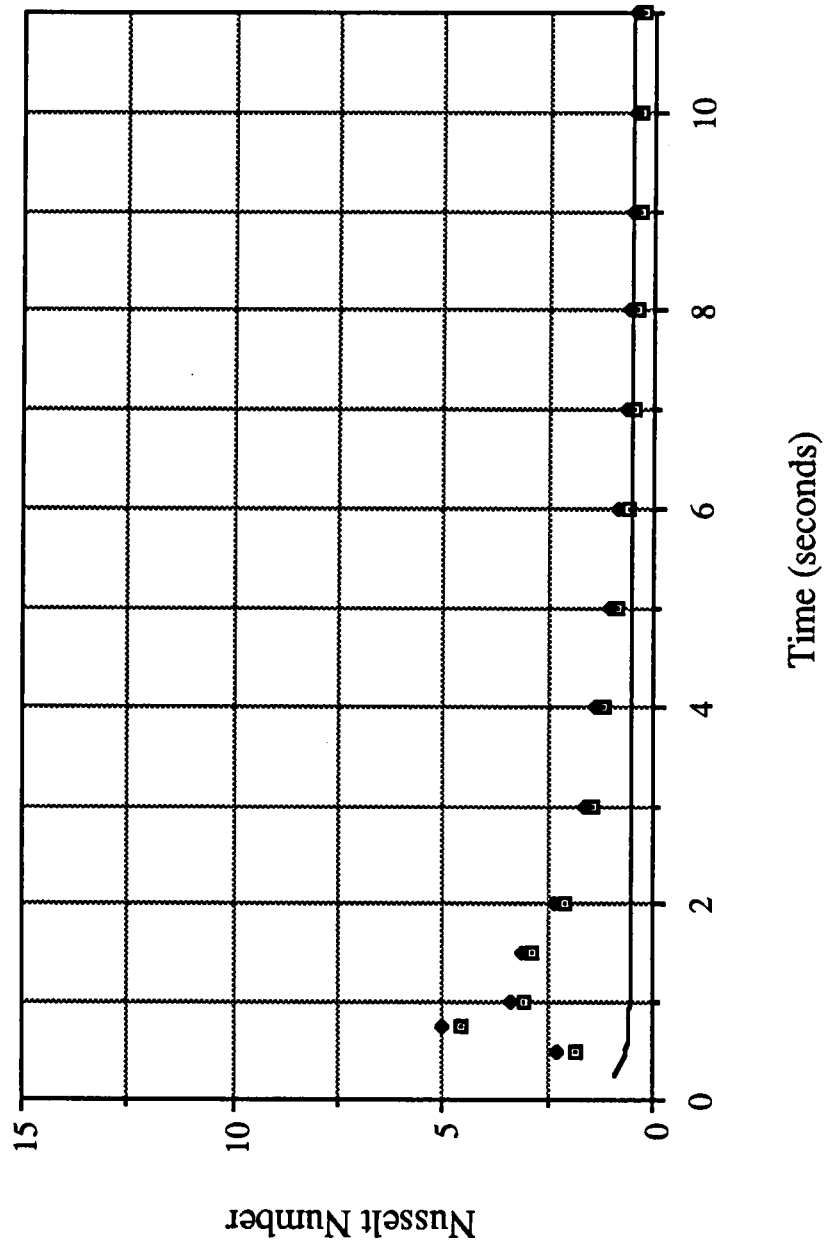


Figure 4.23 Variation of Nu with Time—Thermocouple #4

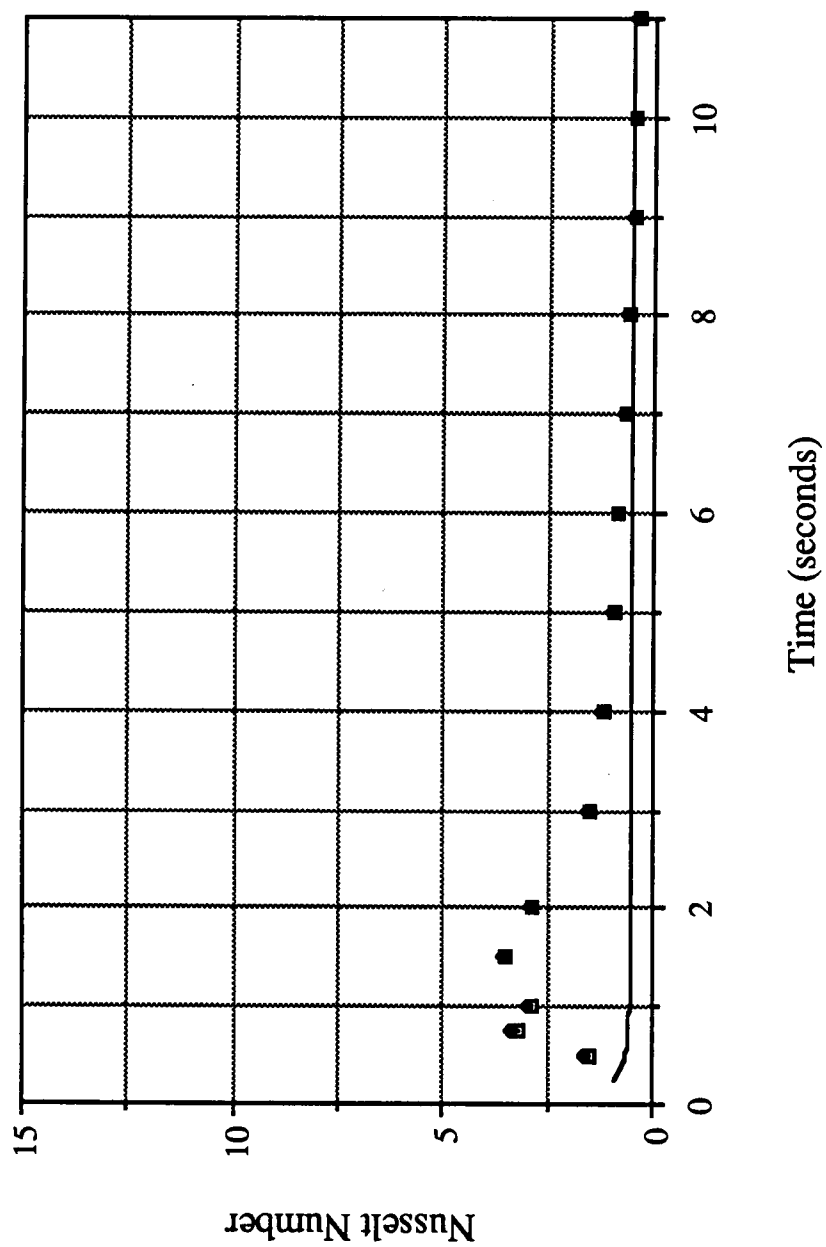


Figure 4.24 Variation of Nu with Time—Thermocouple #6

given in Figure 4.4 (p. 65) for the enclosed air case. Again, there seems to be very little difference between the results found for the enclosed air and open air cases at this location within the container (4 inches from the heater surface).

Figure 4.24 shows the results found for thermocouple #6. This figure represents a significant departure of the open air results from the enclosed air results. Although the trend of the data is generally the same for the two cases, the open air Nusselt numbers are roughly twice those derived in the enclosed air results. This plot shows an initial value of 1.5 for the Nusselt number, increasing to a maximum value of just over 3 at 1.5 seconds then decreasing with time. The full impact of this departure in results is not discovered until the results are examined spatially.

Figures 4.25 through 4.38 present the open air results in the same manner as the second set of figures in the enclosed air results. Nusselt number is plotted as a function of distance from the heater surface at a specific point in time. Though it is difficult to determine the trend of data from a set of three data points, certain comparative observations with the enclosed air results can be made.

Figure 4.25 presents the results found after 0.5 seconds have elapsed since the initiation of the test. Though the curve fitting gives this figure a different look than that found for the enclosed air results, the three points plotted agree quite well with those of Figure 4.8 (p. 71). An increase is noticed at the 8 inch location.

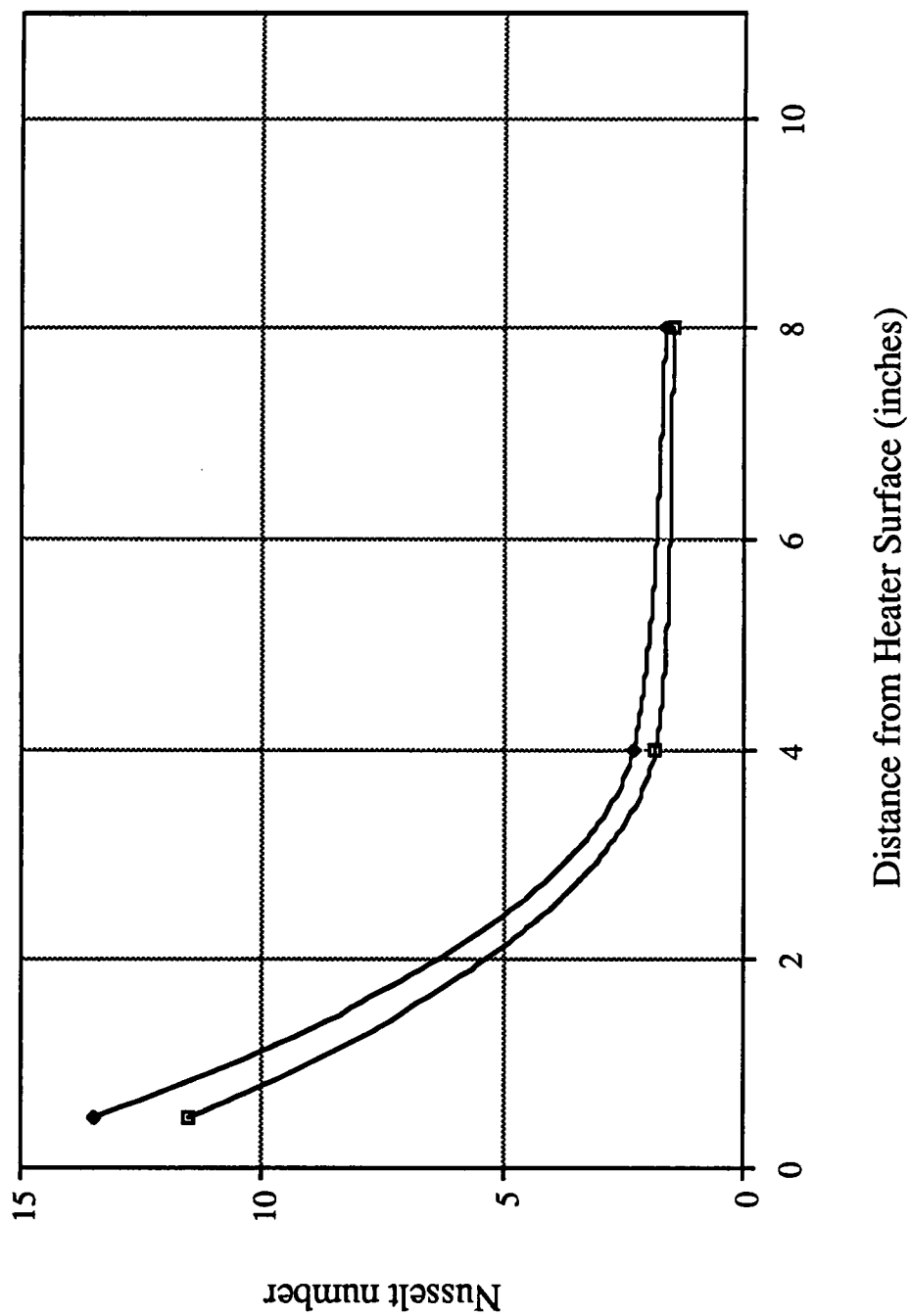


Figure 4.25 Spatial Variation of Nu —0.5 seconds

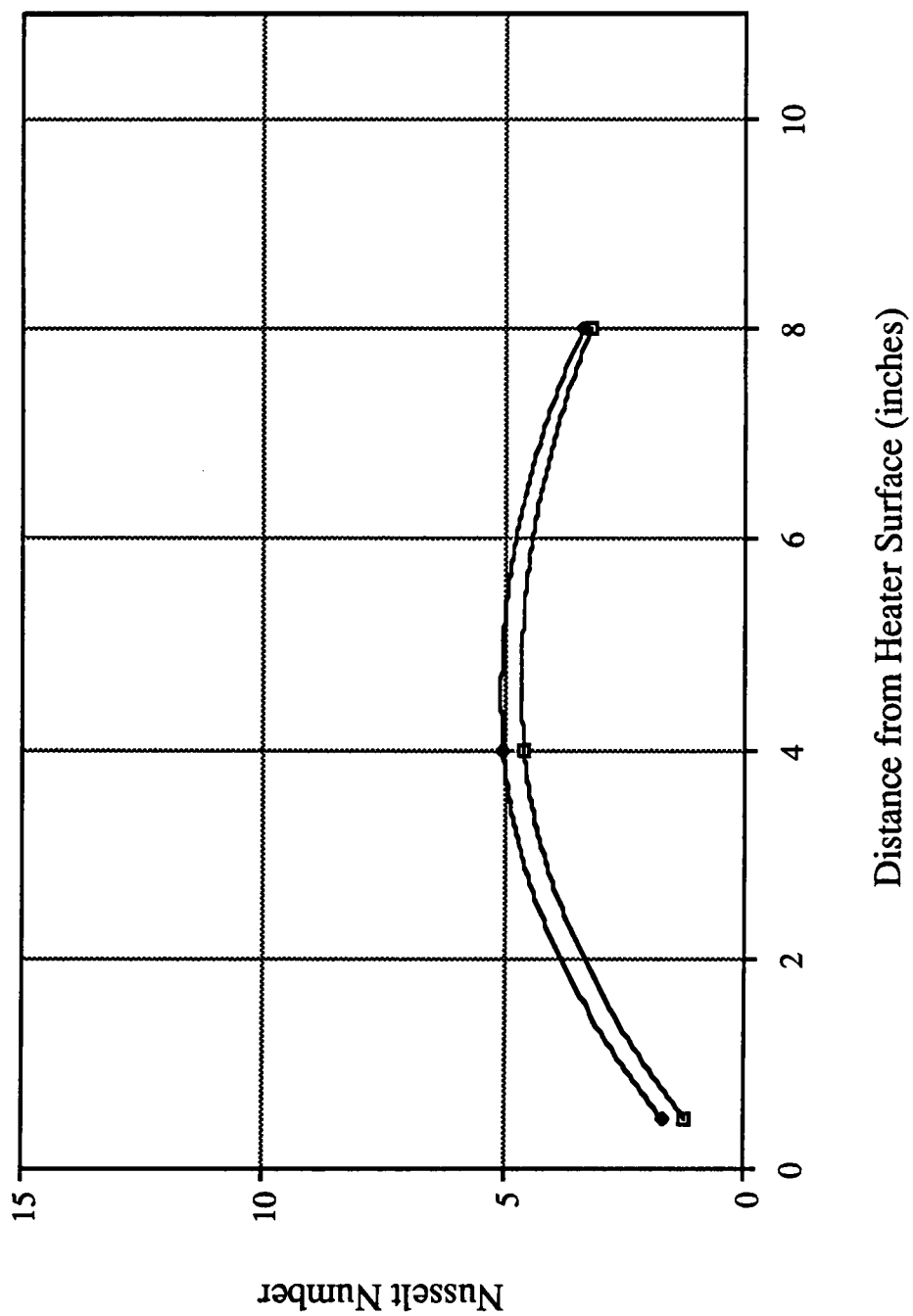


Figure 4.26 Spatial Variation of Nu —0.75 seconds

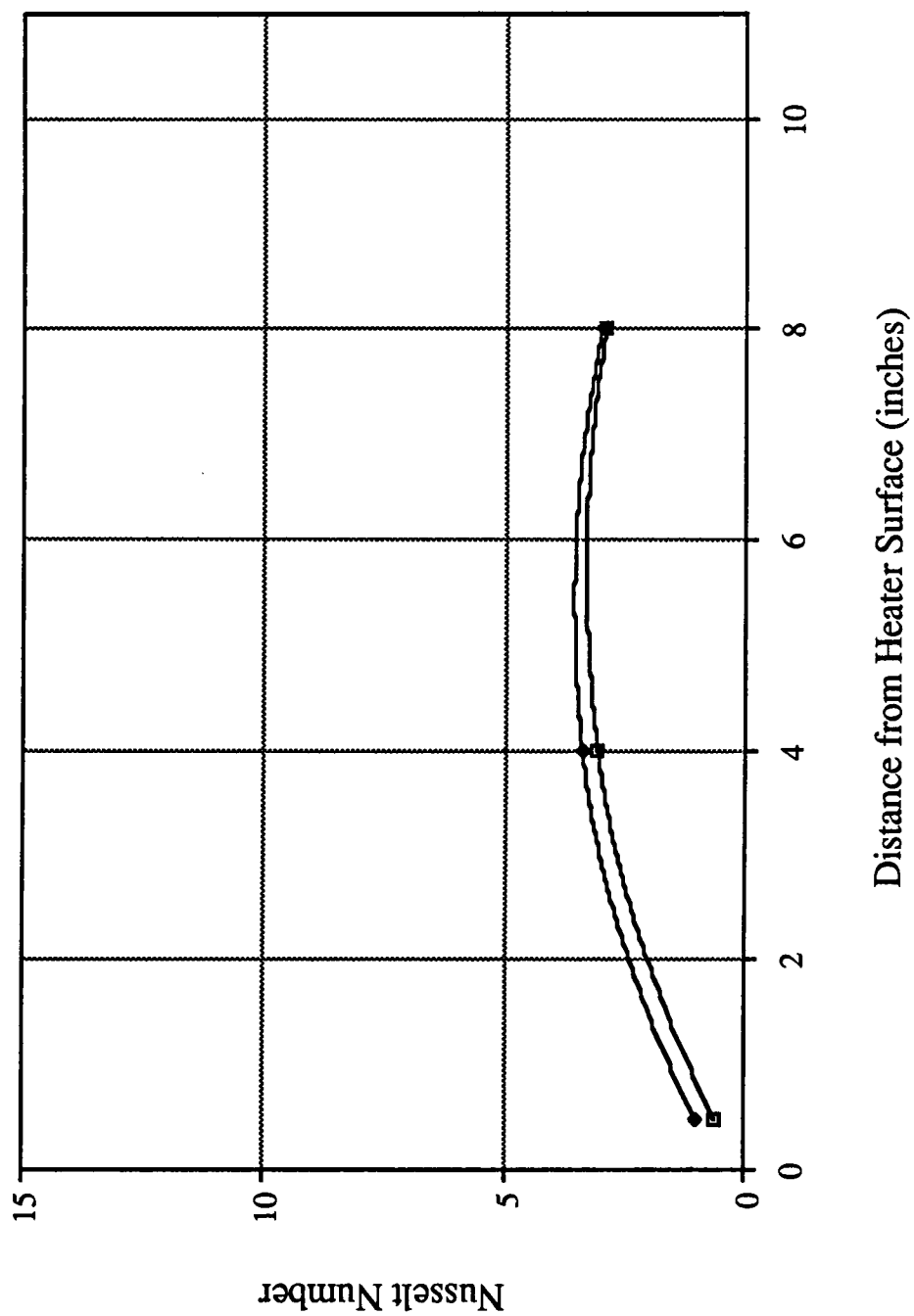


Figure 4.27 Spatial Variation of Nu —1.0 seconds

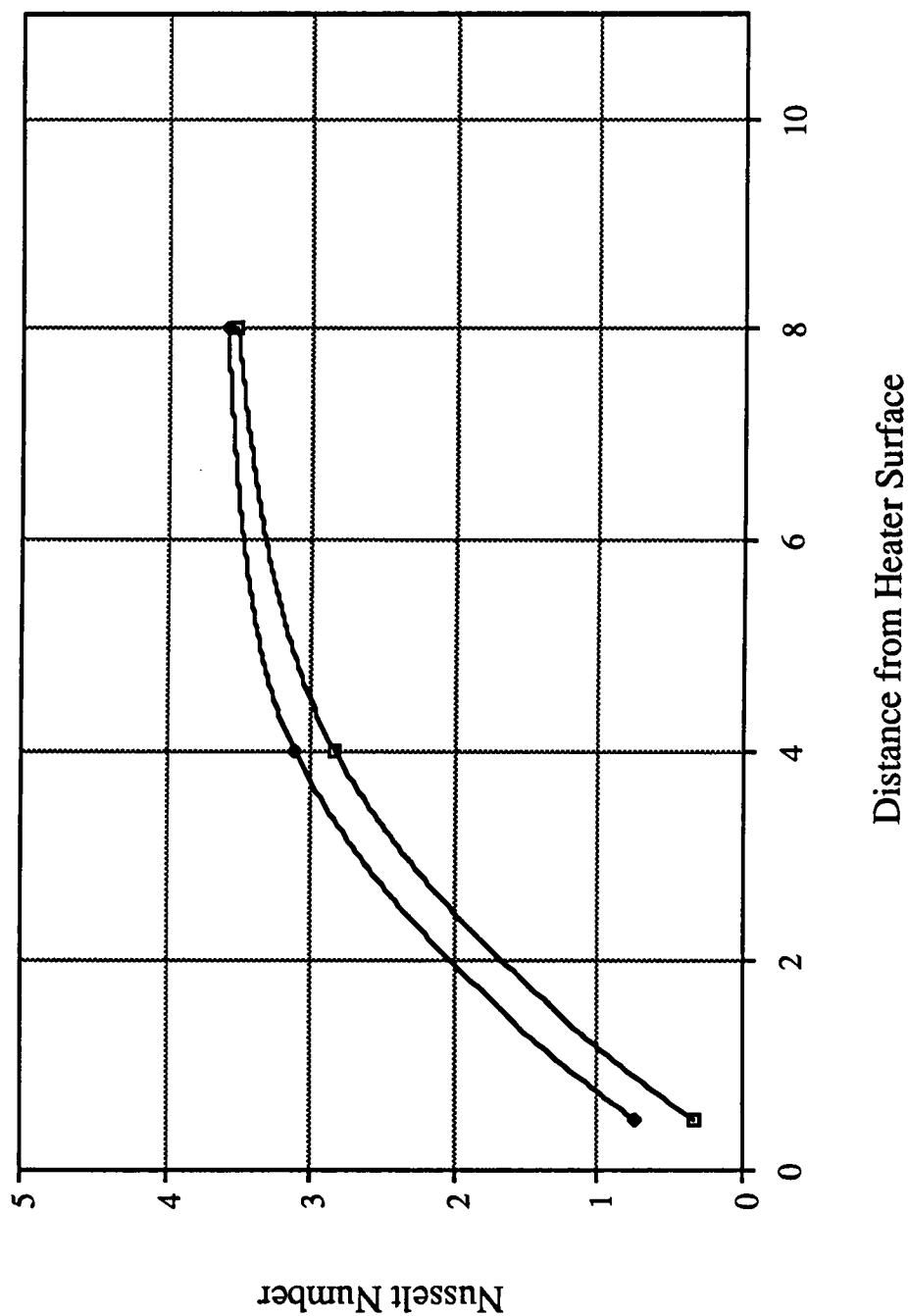


Figure 4.28 Spatial Variation of Nu —1.5 seconds

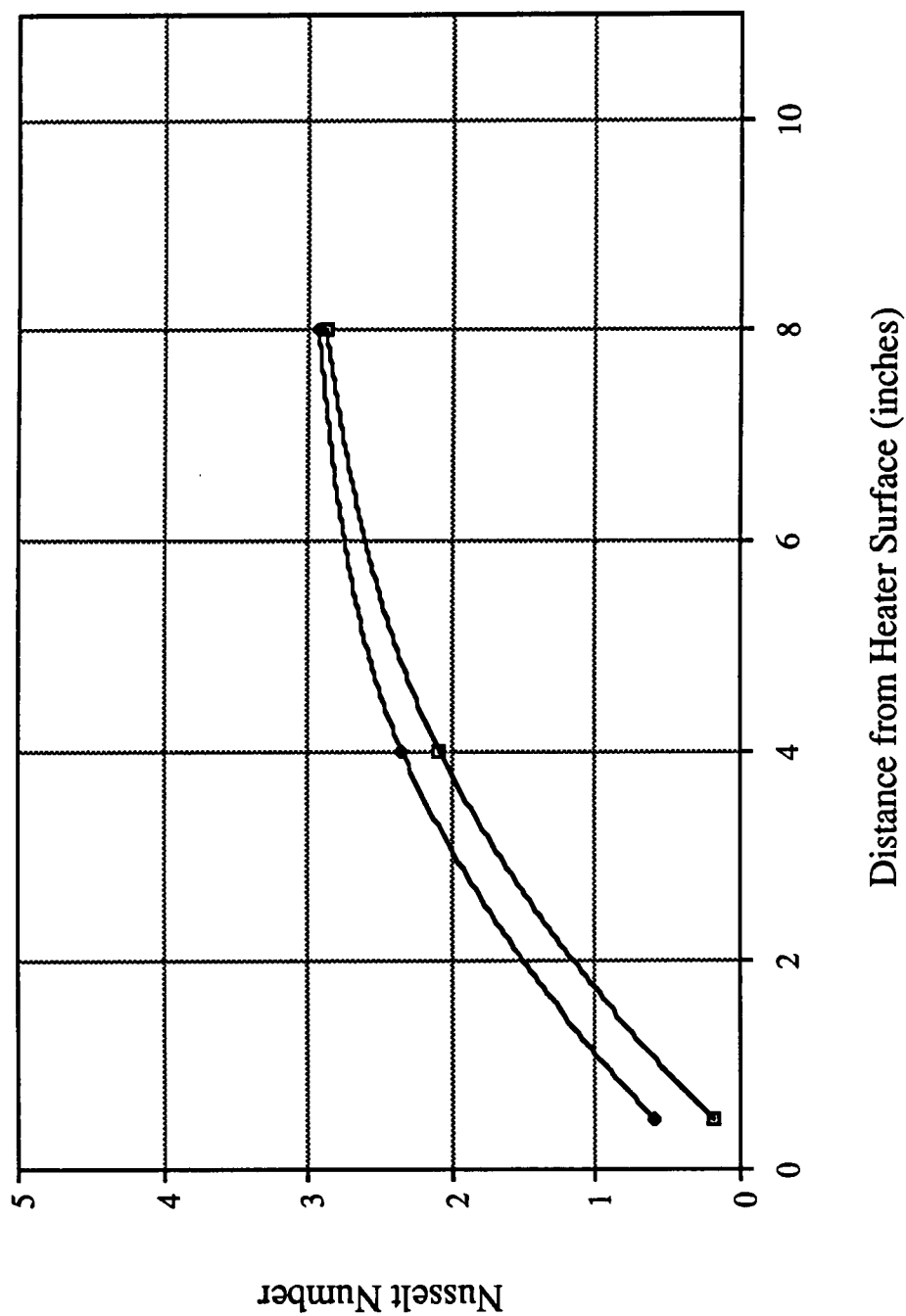


Figure 4.29 Spatial Variation of Nu —2.0 seconds

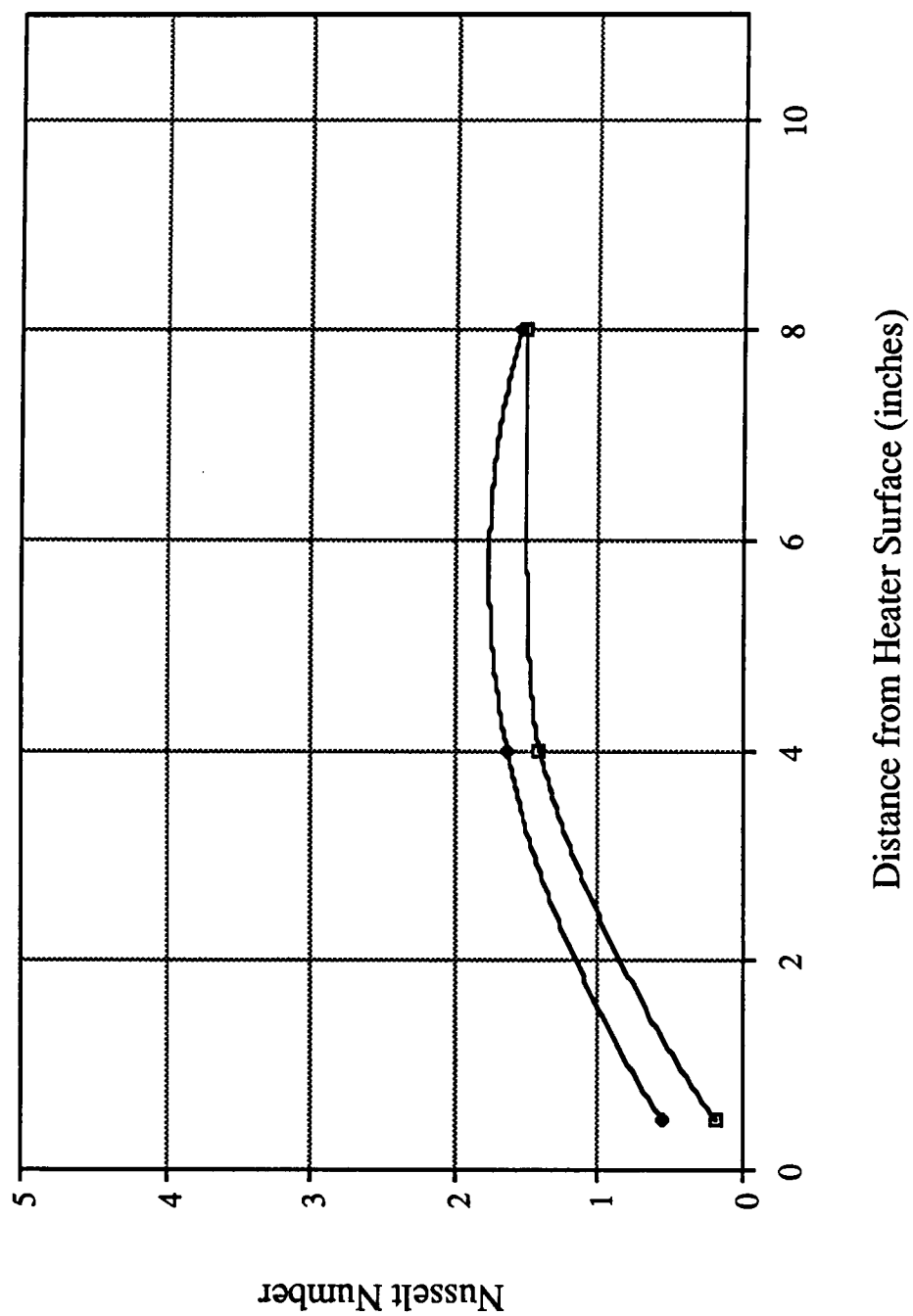


Figure 4.30 Spatial Variation of Nu —3.0 seconds

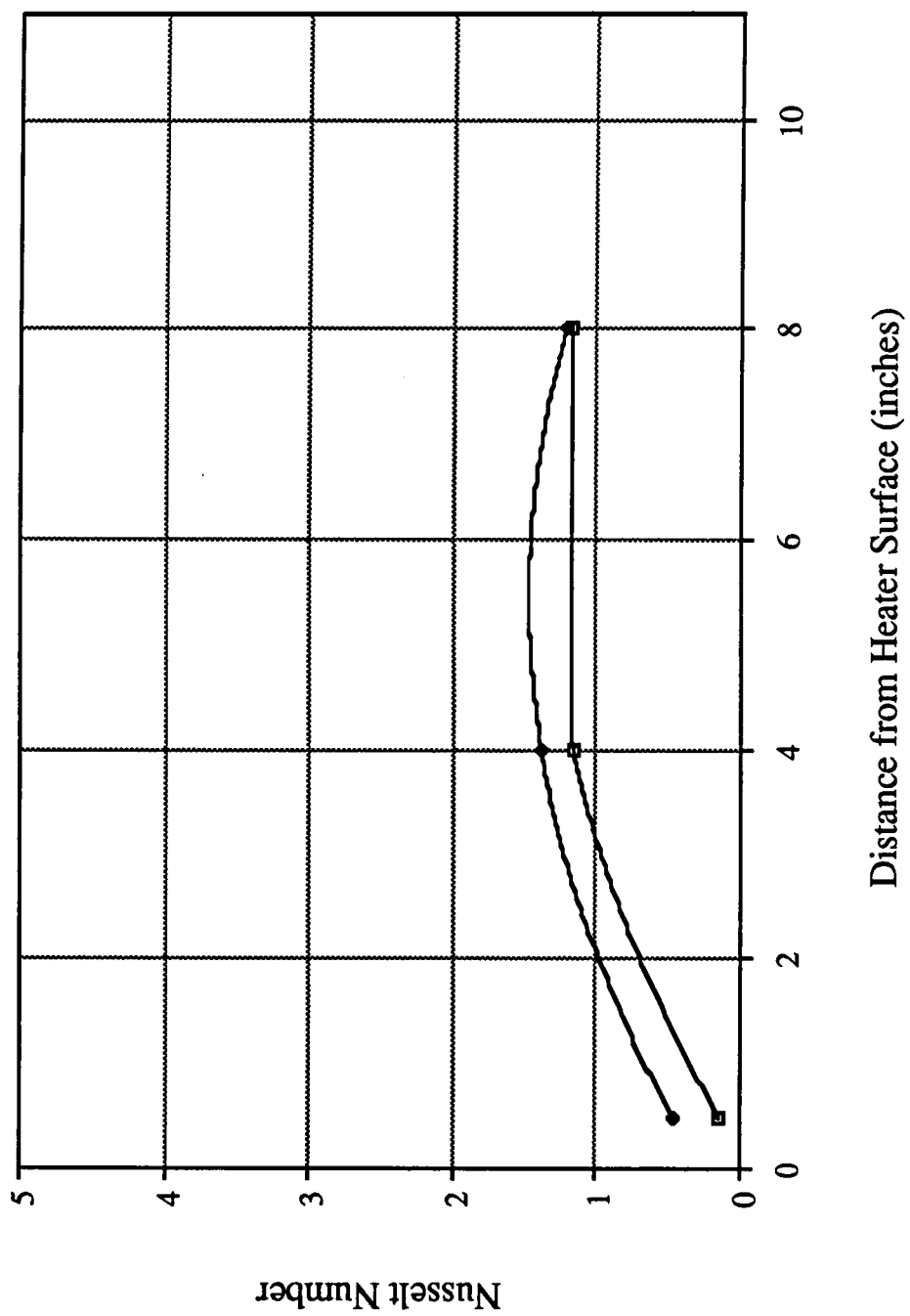


Figure 4.31 Spatial Variation of Nu—4.0 seconds

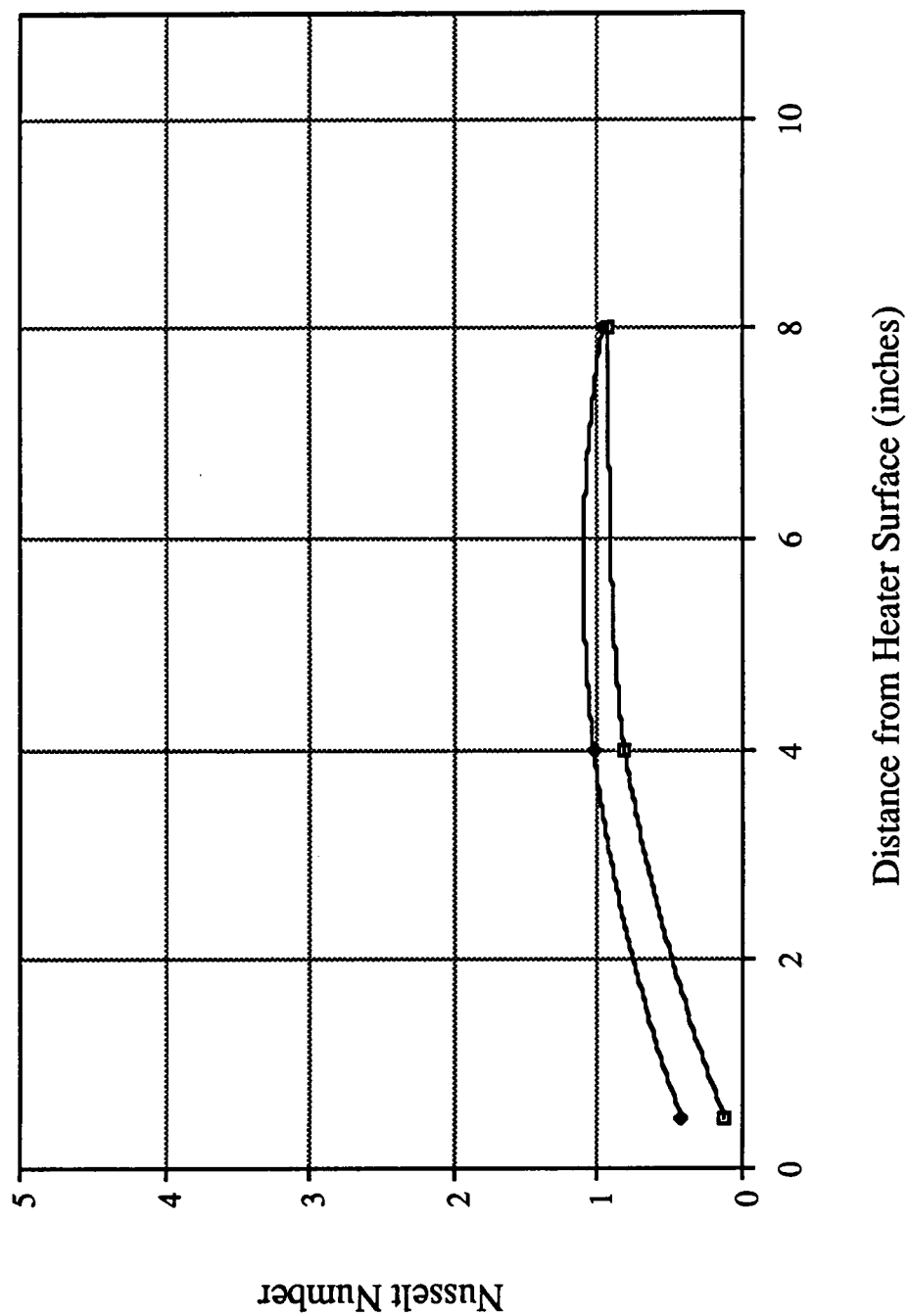


Figure 4.32 Spatial Variation of Nu —5.0 seconds

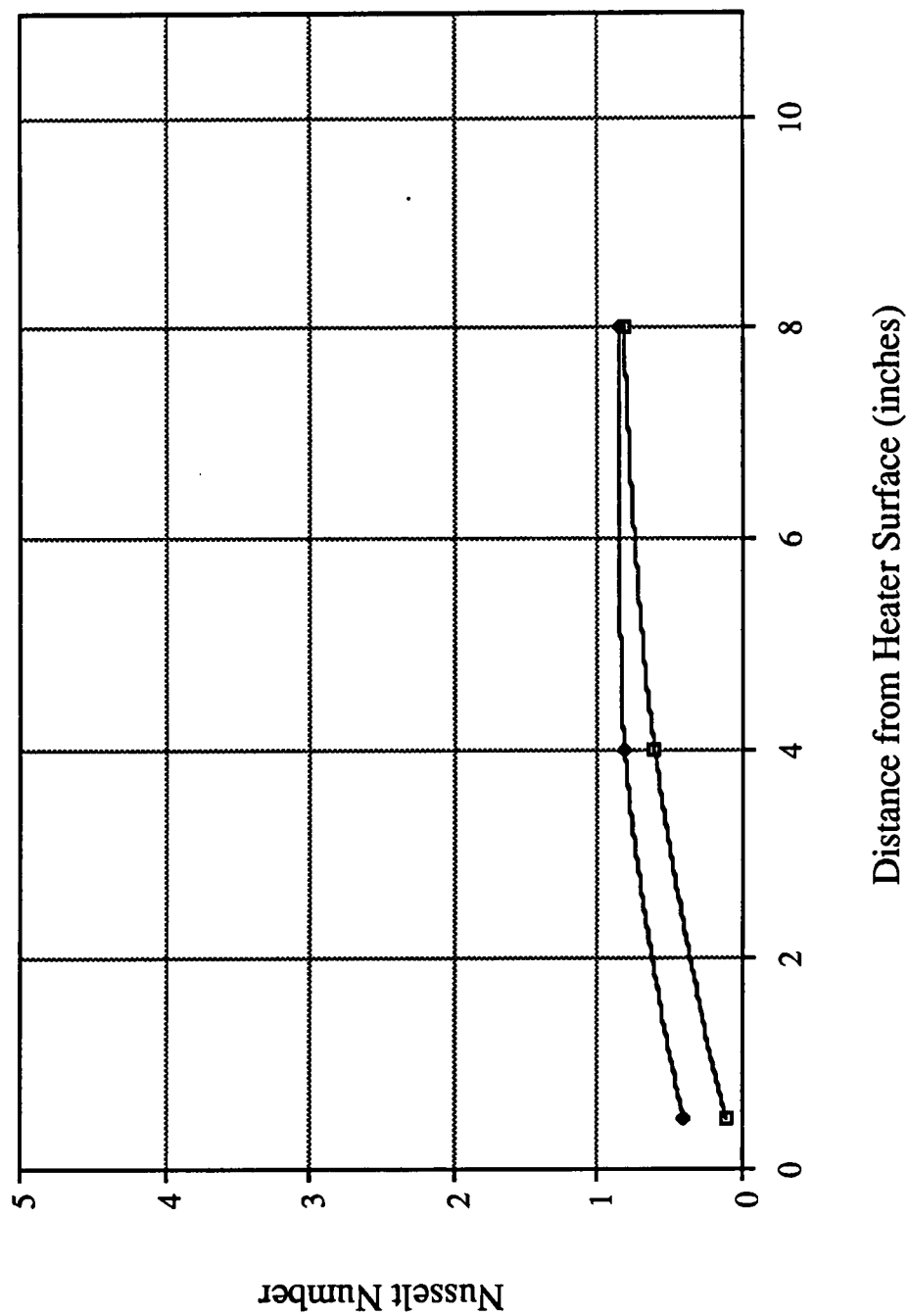


Figure 4.33 Spatial Variation of Nu —6.0 seconds

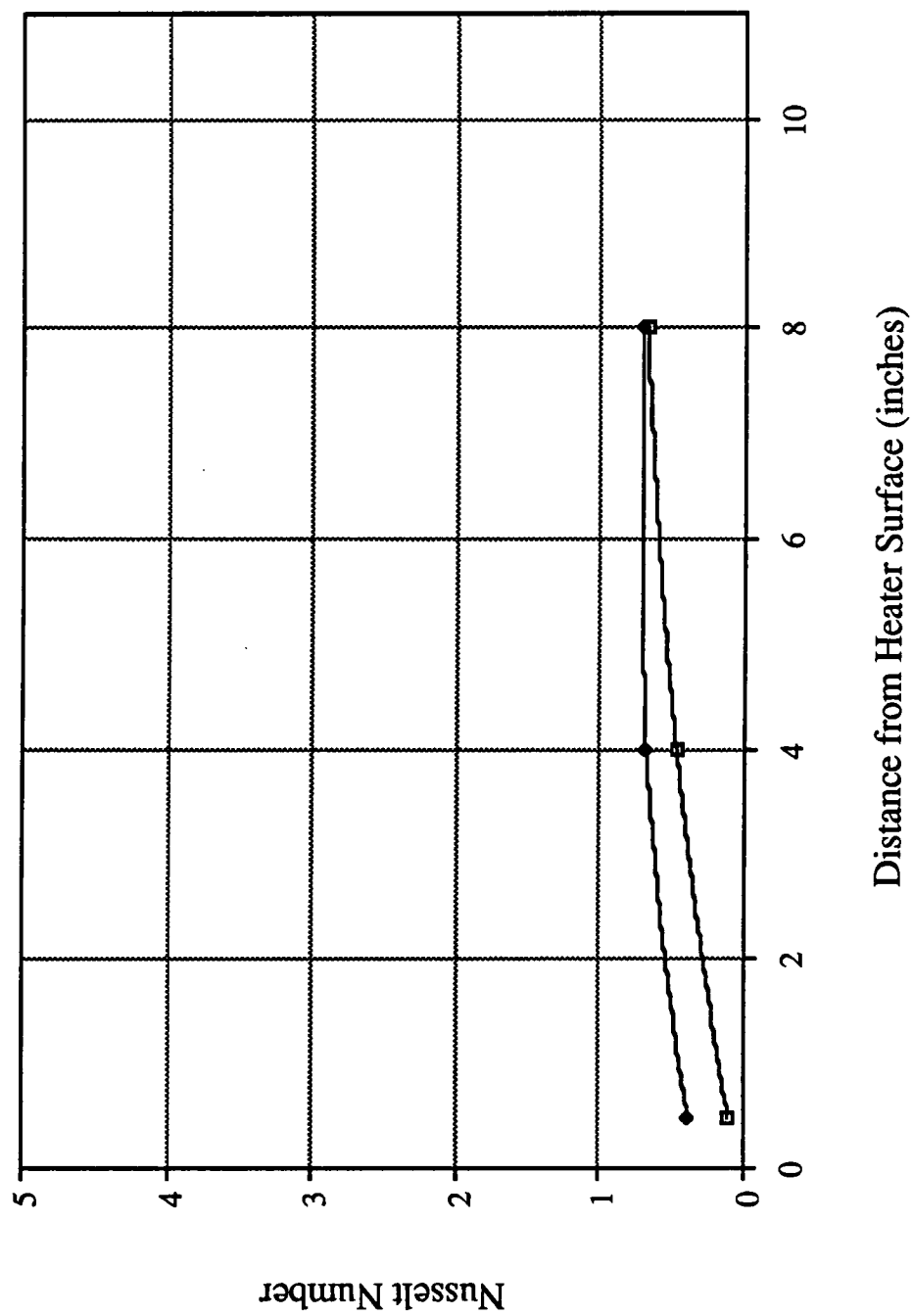


Figure 4.34 Spatial Variation of Nu—7.0 seconds

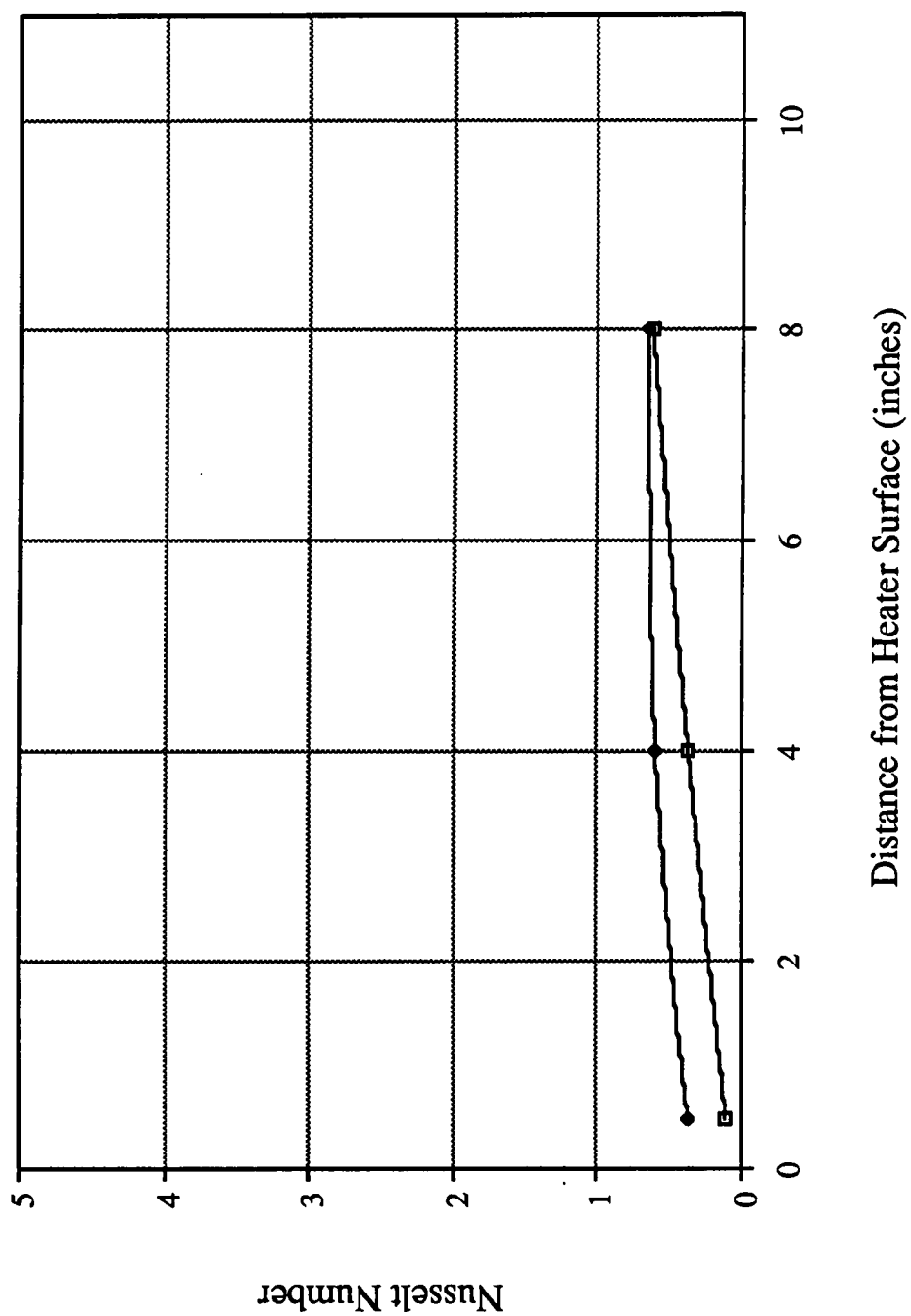


Figure 4.35 Spatial Variation of Nu —8.0 seconds

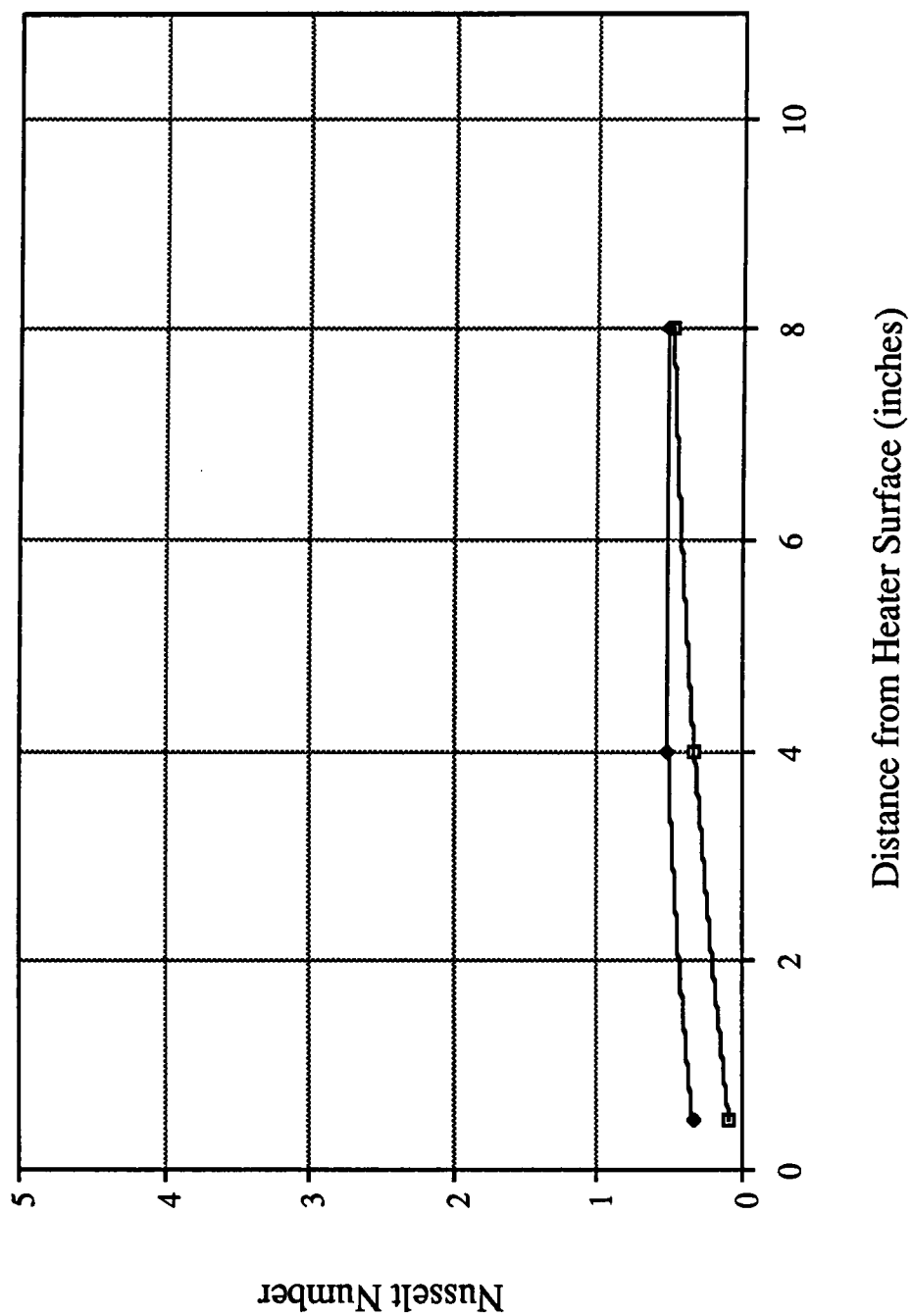


Figure 4.36 Spatial Variation of Nu—9.0 seconds

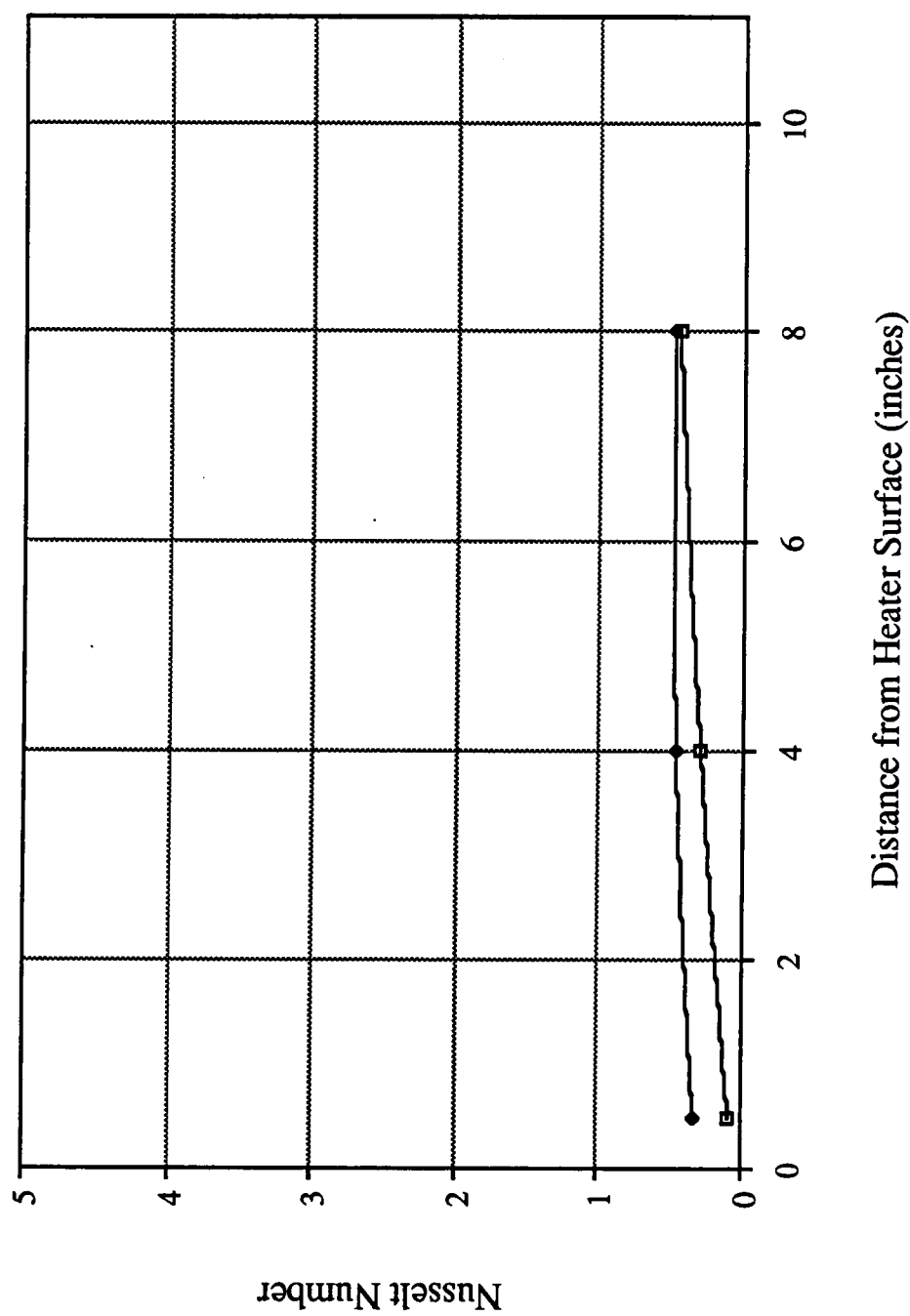


Figure 4.37 Spatial Variation of Nu—10.0 seconds

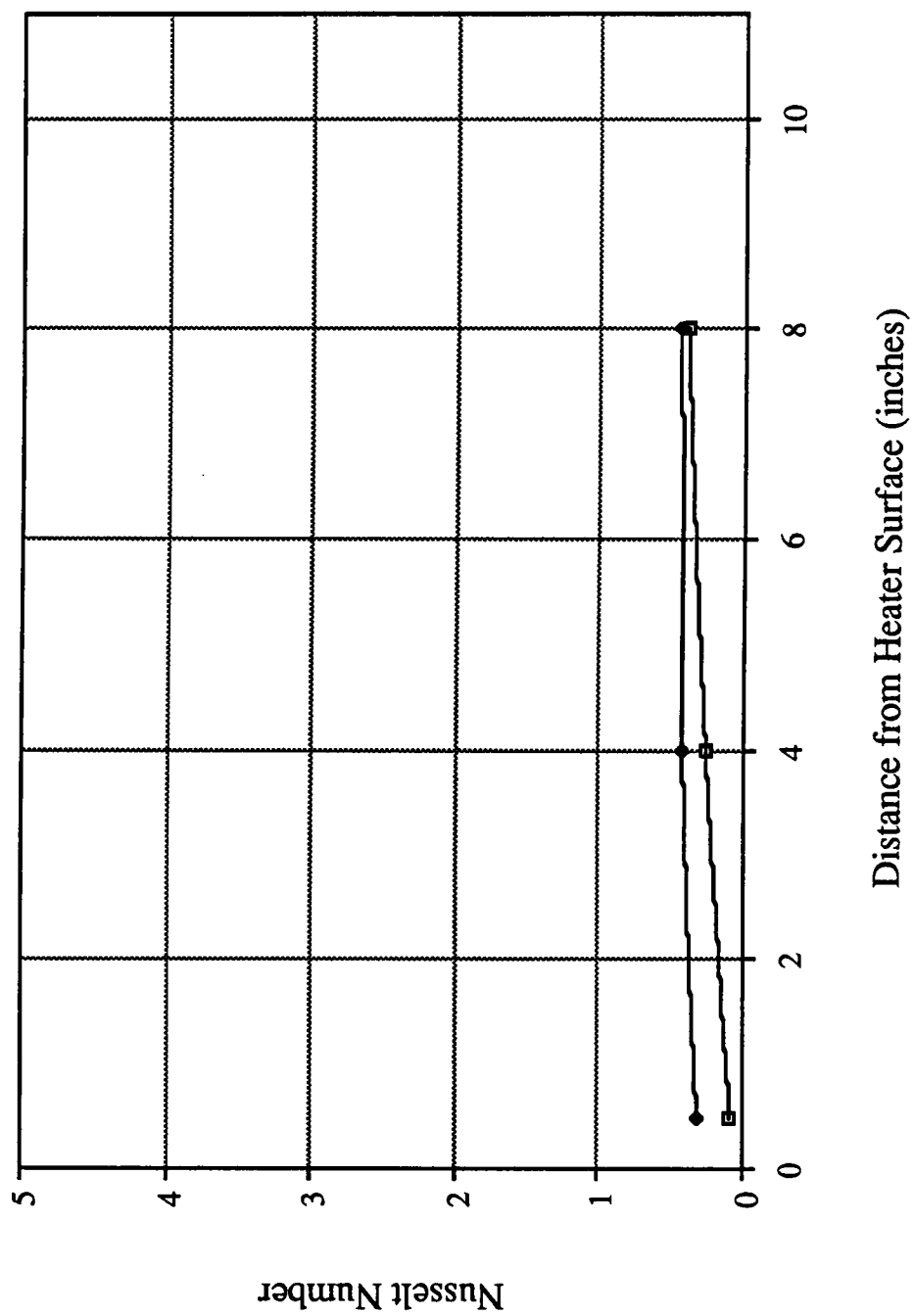


Figure 4.38 Spatial Variation of Nu—11.0 seconds

Figure 4.26 presents the results found after 0.75 seconds have elapsed since the initiation of the test. This figure shows a large difference from the previous figure. The peak has moved further from the heater and is now closer to thermocouple #4. The Nusselt number calculated at 8 inches grows to approximately 3, indicating greatly increased air movement over the enclosed air results at this location.

The spatial Nusselt number band is plotted at 1 second in Figure 4.27. Thermocouple #6, located nearest the exit of the open container, indicates a Nusselt number of just under 3 which has grown to approximately the same as that found for thermocouple #4. The trend of the data, from this time on, portrays the Nusselt number increasing somewhat asymptotically with distance from the surface.

This trend is repeated in Figure 4.28 with thermocouple #6 actually increasing in Nusselt number to exceed those found for the thermocouples closer to the surface. This indicates the greatest magnitude of air movement to now be nearer the exit of the container.

Figure 4.29 supports the results shown in Figure 4.28 with all Nusselt number values decreasing slightly with time. The point of maximum observed air movement is clearly shown to be recorded by the thermocouple located closest to the open end of the container.

Figures 4.30 through 4.38 are presented for completeness and serve to show the same trend of results as presented in the previous two figures. Maximum Nusselt numbers are all found to occur much

closer to the end of the container than the enclosed air results. All values of Nusselt number are shown to continue to decrease with time. As in the enclosed air results, this indicates a dying out of the air movement at all points within the container with time.

4.4 COMPARISON AND DISCUSSION

Some interesting overall observations can be made when examining the complete set of results. For the enclosed air tests, the results exhibit the following general trends:

- a) Nusselt number decreases with time toward a limit of zero after initially large values are observed for all thermocouples. This shows relatively large magnitudes of initial air movement within the container that subside with time.
- b) The values of Nusselt number begin at lower values near the heater surface, increase with distance to maximum values within the first $1/3$ of the length of the container, then decrease to low values from there on. The figures indicate a Nusselt number peak, initially very close to the surface, that decreases in magnitude, moves further from the surface, and broadens or "bubbles out" with time. Likewise, this indicates air movement of an initially high degree, but with the larger degrees of movement indicated penetrating only a short distance into the bulk fluid. As time goes by, the heater continues to affect the

movement of air primarily within the first 5 inches of it, with the relative greatest movement of air moving away from the heater surface. Less air movement is indicated in the latter section of the box and remains minimal to the opposite wall. A lesser degree of air movement in the vicinity of the boundaries is not a surprising result. An interesting observation is that, after about two seconds, the relative air motion in the half of the container closest to the heater assumes the general form of a half sine wave. Since acoustic waves produced in an enclosed container will generate a basic wave form or one of its harmonics, this may be an exhibition of the tendency toward generation of a second harmonic wave form within the cavity. Figures 4.39, 4.40, and 4.41 illustrate this point by overlaying Figures 4.12, 4.13, and 4.14 (pp. 75, 76, 77) with a half sine wave standing between the heater surface and the midpoint of the container's length. The amplitude of the waves are adjusted to best match the results.

The open air test results are found to exhibit the following general trends and seem to agree well with the results found for the enclosed air tests:

- a) For all of the thermocouples, Nusselt number decreases with time toward a limit of zero after indicating initially larger values. As in the enclosed air tests, this is indicative of a larger initial movement of the air that subsides with time.
- b) The values of Nusselt number initially begin at lower values near the heater surface, increasing then slightly decreasing along the length

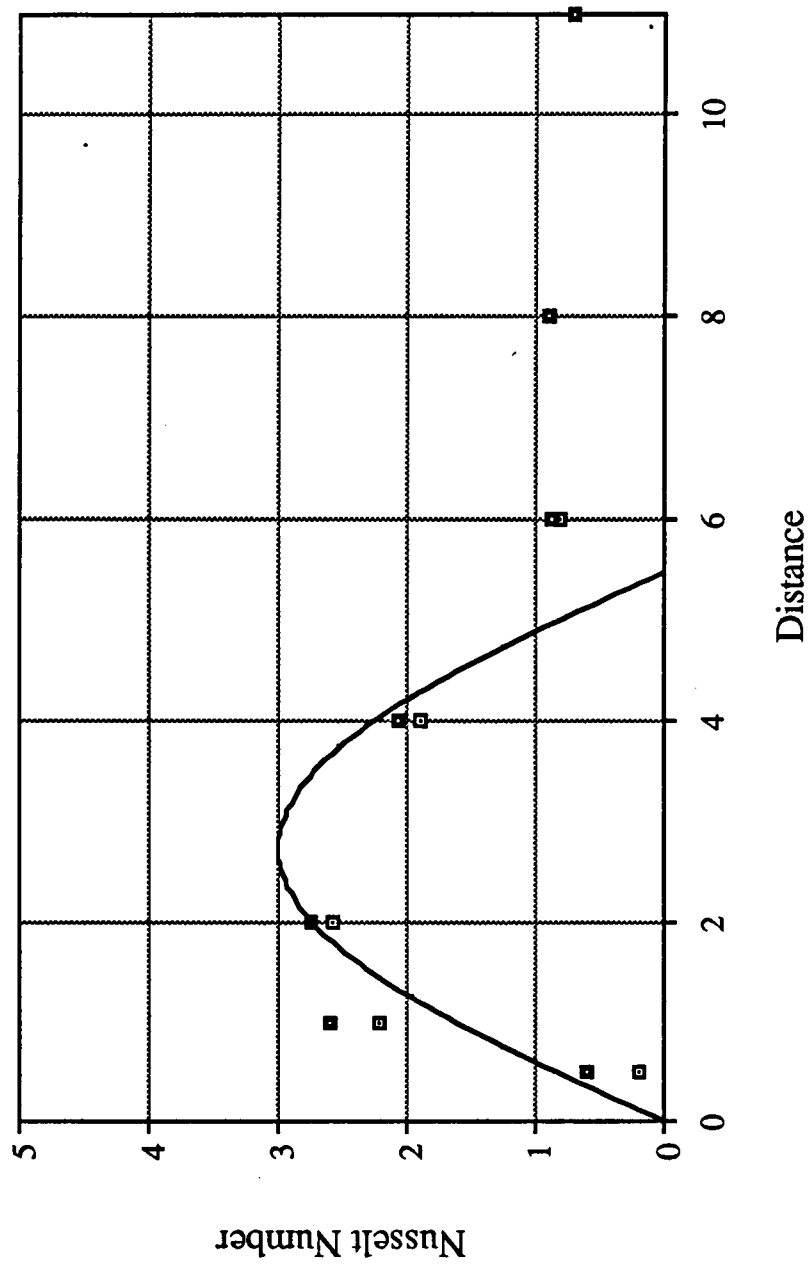


Figure 4.39 Spatial Variation of Nu with Sine Wave—2.0 seconds

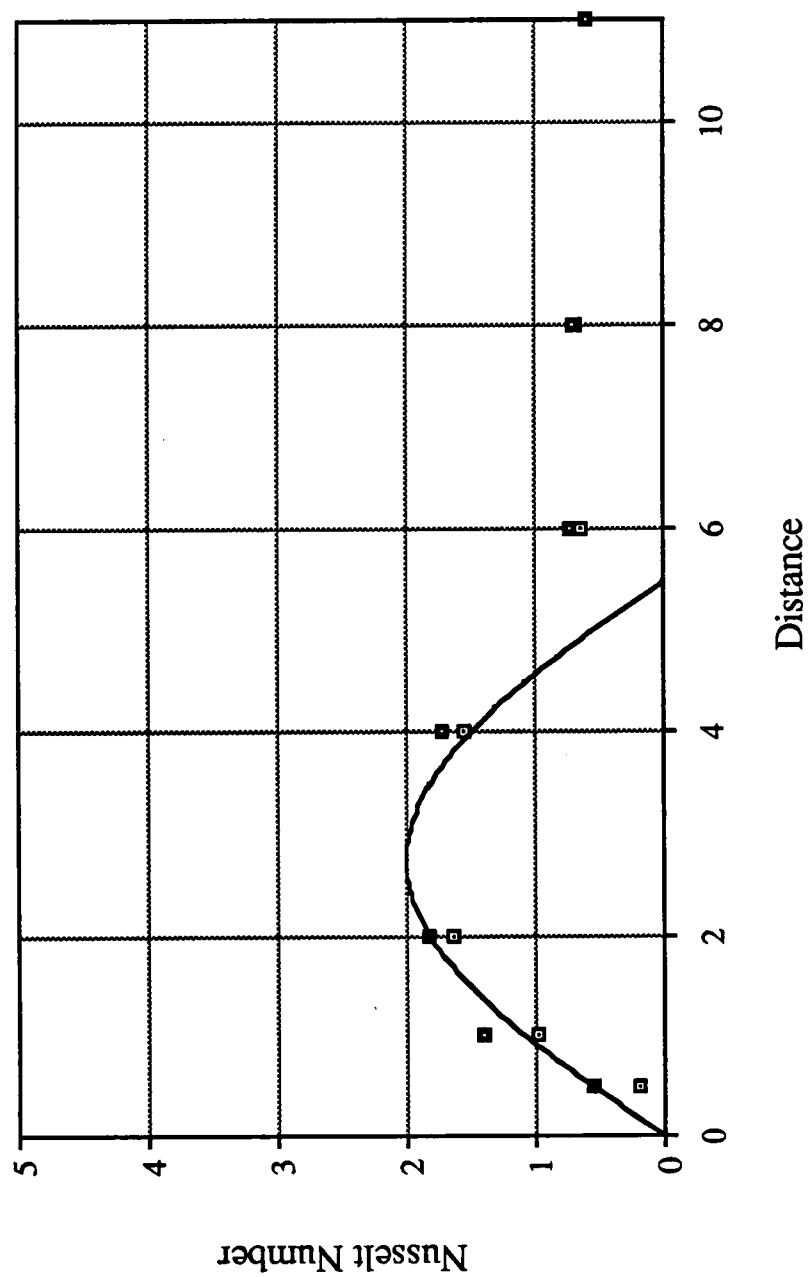


Figure 4.40 Spatial Variation of Nu with Sine Wave—3.0 seconds

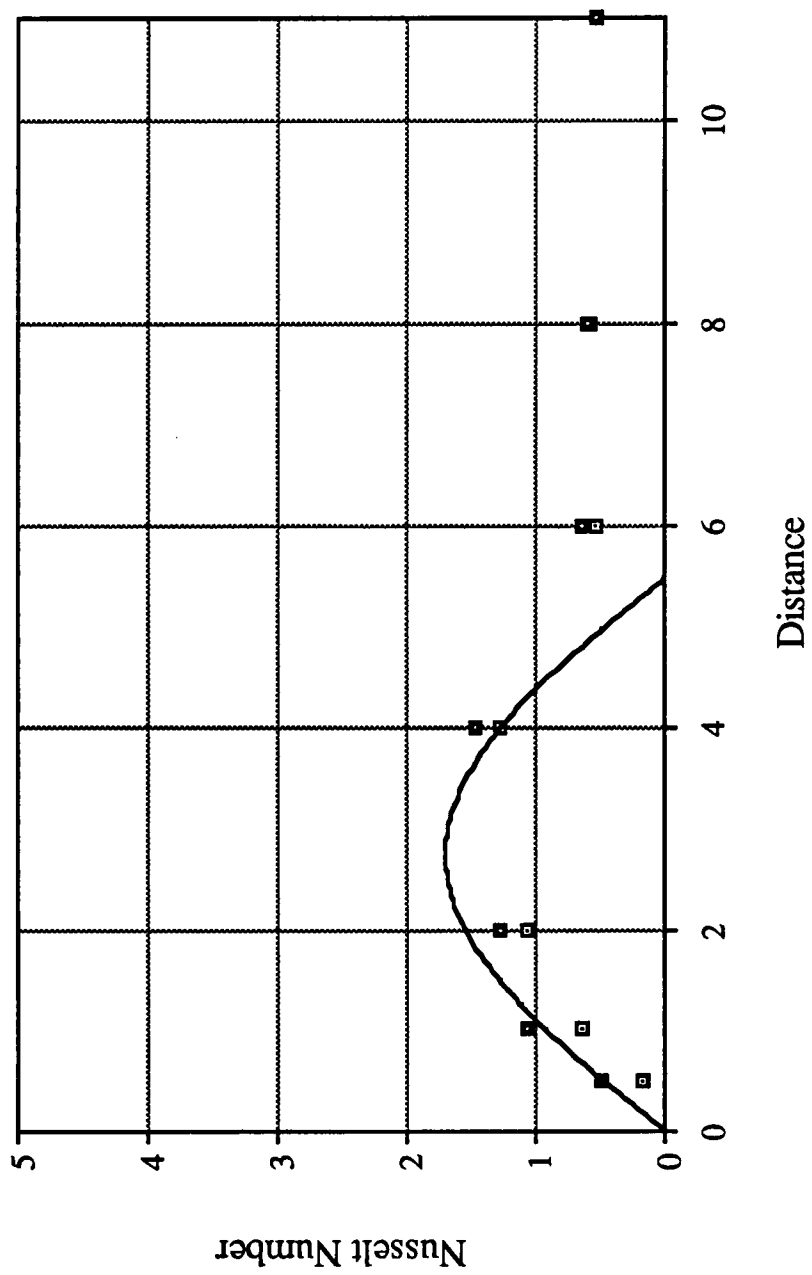


Figure 4.41 Spatial Variation of Nu with Sine Wave—4.0 seconds

of the container. After a short time (approximately 1.0 second), the value of Nusselt number found for the thermocouple furthest from the heater increases relative to the other values and gives the figures the appearance of an open end quarter sine wave. This is an interesting trend since it would indicate that the air movement initiated at the heater surface is less restricted since the opposite boundary has been removed. The movement of air would seem to establish a standing acoustic wave with a displacement node at the heater surface boundary and a pressure node (or displacement anti-node) at the open end of the container. This point is illustrated by Figures 4.42, 4.43, and 4.44 which presents the results of Figures 4.28, 4.29, and 4.30 (pp. 96, 97, 98) overlaid with quarter sine waves for comparison purposes.

Comparison with Kassoy Model

Kassoy's model portrays some interesting characteristics which will now be discussed and compared with the experimental results found. Although the geometry of the Kassoy model is different from the experimental container used and the boundary conditions are not similar, qualitative comparisons concerning the characteristics of TAC can be made. Kassoy's model describes a velocity distribution in the core fluid that decays with time. He also predicts a velocity maximum that moves away from the heated boundary as its magnitude decreases. The experimental results exhibit, qualitatively, these same characteristics. It is also interesting to note that his results also exhibit

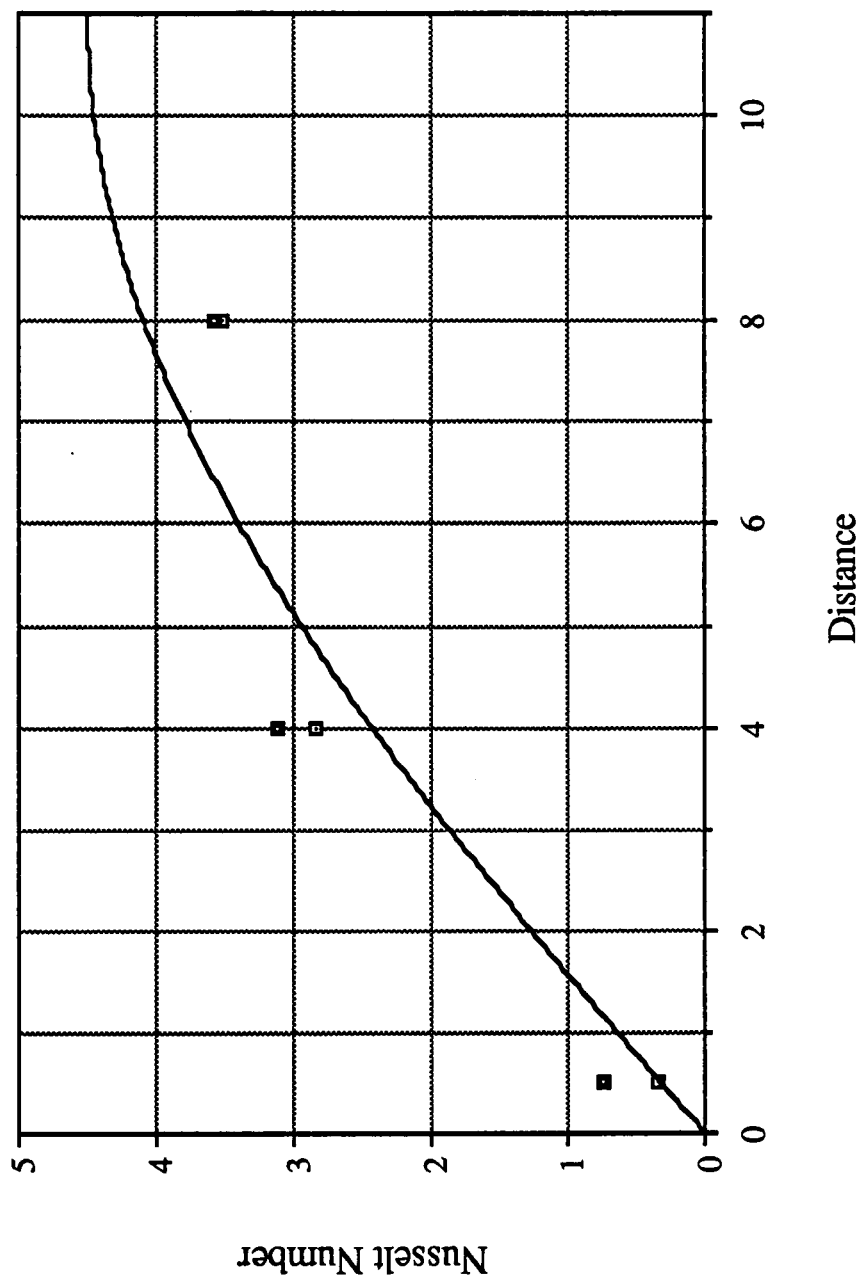


Figure 4.42 Spatial Variation of Nu with Sine Wave—1.5 seconds

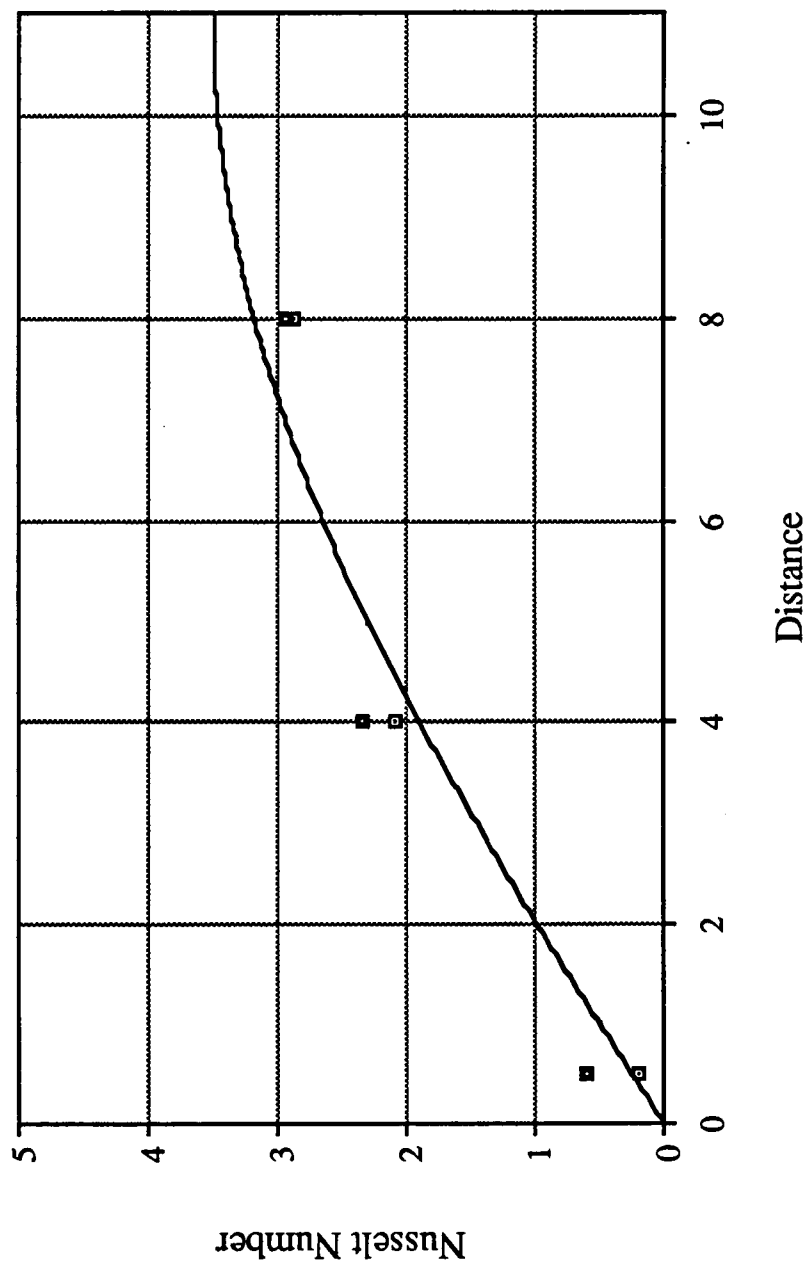


Figure 4.43 Spatial Variation of Nu with Sine Wave—2.0 seconds

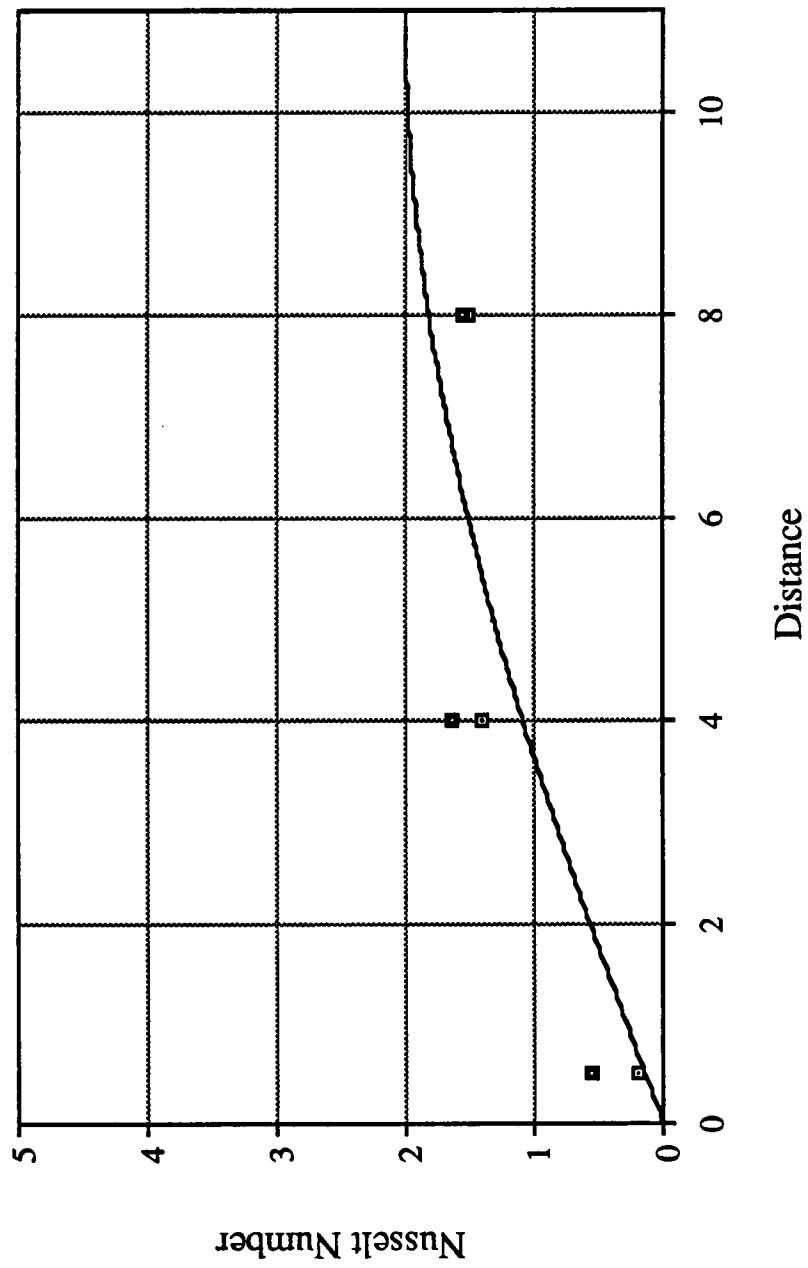


Figure 4.44 Spatial Variation of Nu with Sine Wave—3.0 seconds

a harmonic tendency of the movement of confined gas in his model. Therefore, it may be stated that the Kassoy model agrees qualitatively with the results found experimentally; however, a more detailed comparison with the Kassoy model will require the modification of the boundary conditions to match the experimental model.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This study has as its major objective the detection and determination of TAC effects in both enclosed and open containers using air as the medium. Since thermocouples were used as temperature sensors it was not surprising that they lost energy due to the existence of convective air movement. This cooling effect was proposed as a means of substantiating the TAC phenomenon. The cooling effects on the thermocouples were calculated by performing a transient energy balance on each thermocouple bead. This energy balance included and accounted for radiation exchange with the surrounding cooler surfaces, conduction to the air, and conduction through the thermocouple wires. Ranges of Nusselt number were derived, presented, and discussed as evidence of the bulk air movement induced by TAC. Nusselt number trends were presented as indicators of the variance of the relative magnitudes of bulk air movement and differences between the effects of TAC on a fluid in an enclosed and open cavity were discovered.

The experimental research of TAC would be benefitted if some difficulties could be overcome. One such difficulty is that a

thermocouple measures its own temperature rather than that of the surrounding medium. This difficulty may possibly be overcome by employing alternate means of temperature measurement, such as optical techniques. This temperature measuring technique might also allow for the gathering of data more closely to the heater surface and at shorter intervals of time. Another benefit might lie in avoiding the difficulty of evacuating the container to determine the radiation induced error in the measurements. Since thermal conductivity is a strong function of temperature and generally a weak function of pressure, it may also be possible to perform low temperature experimentation and, thereby, side step the difficulty of conduction to a surrounding medium. Some characteristics of TAC might be more easily researched in the steady state, thereby avoiding some of the problems imposed by working with a transient phenomenon.

Further experimental research is recommended in both enclosed and open mediums, due to the lack of availability of data of the TAC phenomenon. In addition, a reexamination of the microgravity data presented by Salah-Eddine is also called for, noting that vacuum data is not needed to establish a general estimate of the TAC effect. In the same manner as the upper limit Nusselt number was derived in the analysis of Chapter 4, the data recorded in the experiments of Salah-Eddine could be used to determine the Nusselt number recorded in his experiments. Comparisons could then be more accurately made on the effects of gravity on the TAC phenomenon. This would provide for a

very efficient means of research since the experimental data is already available.

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APPENDICES

APPENDIX A

WIRE CONDUCTION TABLES

WIRE CONDUCTION TABLES

(based on the RAD6 data set with $T_{\text{box end}} = 299.8^\circ\text{K}$)

Table A.1 Wire Conduction Table—Thermocouple #1

$T_{\text{tc}} _{\text{VAC}} (^\circ\text{K})$	$T_{\text{foil}} _{\text{VAC}} (^\circ\text{K})$	$dT/dt _{\text{VAC}} (^\circ\text{K/s})$	$q_{\text{COND,wire}} (x10^4 \text{ W})$
302.2	372.1	0	0.04802
350	837.0	94	1.192
400	987.0	145	2.679
450	1039.1	152	3.501
500	1067.6	154	3.972
550	1080.8	122	4.439
600	1085.3	96	4.616
650	1086.9	60	4.775

Table A.2 Wire Conduction Table—Thermocouple #2

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
302.1	372.1	0	.04022
325	778.9	67	.6710
350	899.5	96	1.437
375	966.1	111	2.076
400	1009.0	121	2.570
425	1038.8	121	3.017
450	1059.2	116	3.383
475	1073.0	105	3.699
500	1080.7	94	3.903

Table A.3 Wire Conduction Table—Thermocouple #3

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
302.1	372.1	0	.02743
320	765.7	60	.2589
340	873.0	88	.5788
360	937.1	114	.7980
380	977.8	128	1.012
400	1006.8	134	1.228
420	1030.3	137	1.435

Table A.4 Wire Conduction Table—Thermocouple #4

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
301.6	372.1	0	.01322
310	776.5	30	.1393
320	883.8	48	.2626
330	943.2	58	.3841
340	983.1	61	.5265
350	1008.5	64	.6170
360	1030.2	71	.6579
370	1045.3	73	.7174
380	1057.4	79	.7239

Table A.5 Wire Conduction Table—Thermocouple #5

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
301.4	372.1	0	.007143
310	798.2	23	.03942
320	917.5	33	.1421
330	985.4	39	.2379
340	1027.9	39	.3515
350	1057.1	33	.4960
360	1076.0	27	.6132
370	1082.4	22	.6805

Table A.6 Wire Conduction Table—Thermocouple #6

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
301.1	372.1	0	.004242
305	764.6	13	.008511
310	865.6	21	.01911
315	926.0	27	.03043
320	964.2	31	.04286
325	995.3	34	.06007
330	1018.1	36	.07715
335	1035.8	36	.1071
340	1050.7	36	.1331

Table A.7 Wire Conduction Table—Thermocouple #7

$T_{tc} _{VAC} (^{\circ}K)$	$T_{foil} _{VAC} (^{\circ}K)$	$dT/dt _{VAC} (^{\circ}K/s)$	$q_{COND,wire} (x10^4 W)$
300	372.1	0	0
305	824.0	13	0
310	918.1	19	0
315	971.3	24	0
320	1005.1	30	0

APPENDIX B

TABULATED AIR RESULTS

APPENDIX B.1

THE ENCLOSED AIR RESULTS

ENCLOSED AIR RESULTS (using the data set of TAC20)

Table B.1 Enclosed Air Results—Thermocouple #1 (1/2 inch from heater surface)

time (sec)	$T_{c,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	dT/dt_{AIR} (°K/sec)	$q_{COND,wire}$ (x10 ⁴ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.4	297.8	0	—	—	—	—	—
.5	298.9	593.6	7	0	4916	4916	13.77	13.77
.75	302.0	730.0	37	.04323	1250	1316	3.50	3.69
1.0	317.3	831.4	73	.4094	277	396	.776	1.110
1.5	359.4	955.3	84	1.472	120	252	.335	.707
2.0	401.5	1016.4	62	2.704	70	214	.195	.599
3.0	439.7	1063.7	37	3.332	71	200	.198	.561
4.0	474.6	1083.9	30	3.773	58	175	.163	.489
5.0	503.5	1097.7	25	4.005	51	158	.142	.443
6.0	527.8	1109.0	23	4.232	45	147	.127	.411
7.0	549.4	1117.9	22	4.433	41	138	.114	.386
8.0	570.6	1124.7	18	4.512	39	130	.109	.364
9.0	589.0	1131.7	16	4.577	38	124	.105	.348
10.0	606.4	1137.6	15	4.636	36	119	.101	.333
11.0	621.3	1143.4	13	4.684	35	115	.099	.322

Table B.2 Enclosed Air Results—Thermocouple #2 (1 inch from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.2	297.8	0	—	—	—	—	—
.5	299.2	593.6	4	0	2156	2156	6.04	6.04
.75	300.4	730.0	7	0	2389	2389	6.69	6.69
1.0	302.8	831.4	12	.05950	1872	1943	5.25	5.44
1.5	309.5	955.3	17	.2441	1396	1407	3.91	3.94
2.0	320.0	1016.4	25	.5448	791	928	2.22	2.60
3.0	347.9	1063.7	17	1.373	350	501	.979	1.405
4.0	368.5	1083.9	21	1.910	230	379	.644	1.063
5.0	388.3	1097.7	20	2.339	169	312	.474	.873
6.0	405.7	1109.0	16	2.672	137	274	.385	.767
7.0	421.3	1117.9	13	2.951	116	248	.325	.694
8.0	436.5	1124.7	15	3.185	98	225	.275	.630
9.0	448.5	1131.7	10	3.361	91	213	.254	.598
10.0	461.8	1137.6	12	3.532	80	199	.225	.558
11.0	474.2	1143.4	10	3.689	74	189	.207	.529

Table B.3 Enclosed Air Results—Thermocouple #3 (2 inches from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.5	297.8	0	—	—	—	—	—
.5	298.9	593.6	3	0	3647	3647	10.22	10.22
.75	300.1	730.0	7	0	2169	2169	6.08	6.08
1.0	302.3	831.4	10	.03002	1538	1581	4.31	4.43
1.5	308.3	955.3	11	.1076	1051	1112	2.95	3.11
2.0	313.0	1016.4	10	.1684	916	980	2.57	2.75
3.0	324.4	1063.7	15	.3293	582	652	1.631	1.827
4.0	339.4	1083.9	10	.5692	376	453	1.054	1.268
5.0	352.0	1097.9	13	.7103	288	361	.808	1.012
6.0	364.3	1109.0	12	.8440	236	307	.662	.859
7.0	375.9	1117.9	10	.9681	202	271	.565	.758
8.0	385.0	1124.7	10	1.066	180	248	.505	.694
9.0	396.0	1131.7	10	1.185	158	225	.444	.631
10.0	405.8	1137.6	10	1.288	143	209	.400	.585
11.0	416.0	1143.4	10	1.394	129	194	.362	.545

Table B.4 Enclosed Air Results—Thermocouple #4 (4 inches from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.1	297.8	0	—	—	—	—	—
.5	298.8	593.6	3	0	884	884	2.48	2.48
.75	299.8	730.0	4	0	963	963	2.70	2.70
1.0	300.9	831.4	5	.002713	1025	1030	2.87	2.89
1.5	304.1	955.3	7	.05074	813	860	2.28	2.41
2.0	307.4	1016.4	5	.1003	676	735	1.893	2.06
3.0	311.5	1063.7	5	.1578	552	616	1.546	1.727
4.0	315.2	1083.9	5	.2034	457	522	1.279	1.463
5.0	322.4	1097.7	8	.2918	314	380	.880	1.065
6.0	332.3	1109.0	8	.4169	215	282	.601	.789
7.0	340.7	1117.9	8	.5328	165	234	.462	.654
8.0	347.7	1124.7	8	.5962	140	206	.391	.576
9.0	354.6	1131.7	8	.6358	123	185	.345	.518
10.0	362.0	1137.6	8	.6698	109	167	.307	.468
11.0	368.6	1143.4	8	.7091	99	155	.278	.433

Table B.5 Enclosed Air Results—Thermocouple #5 (6 inches from heater surface)

time (sec)	$T_{tc AIR}$ (°K)	$T_{foil AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.5	297.8	0	—	—	—	—	—
.5	298.9	593.6	2	0	798	798	2.23	2.23
.75	299.7	730.0	5	0	620	620	1.737	1.737
1.0	301.2	831.4	7	.006392	486	499	1.361	1.398
1.5	305.5	955.3	9	.02253	345	363	.967	1.016
2.0	309.8	1016.4	7	.03867	291	310	.816	.869
3.0	315.6	1063.7	4	.09692	229	260	.640	.727
4.0	320.4	1083.9	2	.1459	188	224	.526	.628
5.0	325.6	1097.7	0	.1957	155	195	.434	.545
6.0	332.0	1109.0	5	.2606	113	156	.317	.437
7.0	337.9	1117.9	5	.3276	91	137	.256	.384
8.0	343.8	1124.7	5	.4064	73	122	.204	.342
9.0	350.1	1131.7	6	.4972	56	109	.156	.305
10.0	356.1	1137.6	5	.5675	46	100	.130	.281
11.0	362.3	1143.4	5	.6287	38	92	.107	.259

Table B.6 Enclosed Air Results—Thermocouple #6 (8 inches from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	dT/dt_{AIR} (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.3	297.8	0	—	—	—	—	—
.5	298.7	593.6	2	0	385	385	1.078	1.078
.75	299.4	730.0	3	0	418	418	1.170	1.170
1.0	300.1	831.4	4	.003147	458	467	1.282	1.309
1.5	302.4	955.3	5	.005665	379	386	1.061	1.082
2.0	305.0	1016.4	4	.008511	316	323	.884	.904
3.0	308.7	1063.7	4	.01635	245	253	.686	.710
4.0	311.8	1083.9	3	.02319	206	216	.578	.604
5.0	314.2	1097.7	3	.02862	183	193	.513	.541
6.0	316.6	1109.0	4	.03441	162	172	.453	.482
7.0	320.8	1117.9	4	.04561	133	145	.374	.405
8.0	323.8	1124.7	4	.05594	119	131	.333	.366
9.0	327.3	1131.7	4	.06793	105	118	.294	.330
10.0	332.2	1137.6	4	.09028	88	103	.247	.288
11.0	335.7	1143.4	4	.1107	79	95	.221	.267

Table B.7 Enclosed Air Results—Thermocouple #7 (11 inches from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	298.4	297.8	0	—	—	—	—	—
.5	298.5	593.6	1	0	932	932	2.61	2.61
.75	298.9	730.0	2	0	481	481	1.348	1.348
1.0	299.5	831.4	3	0	391	391	1.096	1.096
1.5	301.4	955.3	4	0	273	273	.766	.766
2.0	303.1	1016.4	3	0	248	248	.695	.695
3.0	305.3	1063.7	2	0	215	215	.602	.602
4.0	306.8	1083.9	2	0	191	191	.535	.535
5.0	308.6	1097.7	2	0	165	165	.464	.464
6.0	310.2	1109.0	2	0	149	149	.418	.418
7.0	311.7	1117.9	2	0	137	137	.383	.383
8.0	314.0	1124.7	2	0	119	119	.333	.333
9.0	315.4	1131.7	2	0	112	112	.314	.314
10.0	317.0	1137.6	2	0	104	104	.292	.292
11.0	317.9	1143.4	1	0	104	104	.292	.292

APPENDIX B.2

THE OPEN AIR RESULTS

OPEN AIR RESULTS (using the data set of OPENAIR8)

Table B.8 Open Air Results—Thermocouple #1 (1/2 inch from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	302.8	300.4	0	—	—	—	—	—
.5	302.9	609.6	14	.06477	4115	4823	11.53	13.51
.75	309.9	740.1	48	.2323	432	602	1.210	1.687
1.0	327.0	843.5	62	.6428	212	355	.593	.995
1.5	364.9	970.2	85	1.635	122	266	.342	.744
2.0	411.6	1030.2	65	2.870	69	213	.192	.597
3.0	448.1	1071.0	35	3.470	70	201	.195	.563
4.0	487.6	1086.0	38	3.855	50	165	.140	.462
5.0	514.5	1093.9	23	4.107	44	151	.124	.422
6.0	529.1	1102.9	23	4.244	42	145	.118	.407
7.0	544.9	1107.2	17	4.391	39	138	.108	.387
8.0	559.9	1113.6	17	4.474	37	133	.104	.371
9.0	579.3	1117.1	20	4.543	33	123	.092	.345
10.0	595.3	1122.4	15	4.599	32	119	.090	.332
11.0	610.5	1124.7	13	4.649	30	113	.084	.317

Table B.9 Open Air Results—Thermocouple #4 (4 inches from heater surface)

time (sec)	$T_{tc AIR}$ (°K)	$T_{foil AIR}$ (°K)	$dT/dt _{AIR}$ (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	301.7	300.4	0	—	—	—	—	—
.5	302.7	609.6	1	.02973	653	817	1.831	2.29
.75	302.7	740.1	3	.02973	1633	1797	4.58	5.03
1.0	304.2	843.5	6	.05224	1093	1207	3.06	3.38
1.5	306.7	970.2	6	.08977	1015	1113	2.84	3.12
2.0	310.2	1030.2	7	.1418	746	838	2.09	2.35
3.0	316.2	1071.0	5	.2157	504	586	1.412	1.641
4.0	319.9	1086.0	5	.2614	415	494	1.163	1.385
5.0	326.7	1093.9	6	.3440	293	368	.820	1.032
6.0	334.0	1102.9	7	.4411	218	293	.611	.821
7.0	341.2	1107.2	7	.5379	168	243	.472	.681
8.0	347.9	1113.6	7	.6716	133	213	.373	.596
9.0	355.8	1117.1	7	.6407	119	184	.333	.515
10.0	362.4	1122.4	7	.6722	106	167	.297	.468
11.0	368.8	1124.7	7	.7103	94	152	.264	.426

Table B.10 Open Air Results—Thermocouple #6 (8 inches from heater surface)

time (sec)	$T_{tc,AIR}$ (°K)	$T_{foil,AIR}$ (°K)	dT/dt_{AIR} (°K/sec)	$q_{COND,wire}$ ($\times 10^4$ W)	h (low) (W/(m ² °K))	h (high)	Nu (low)	Nu (high)
0	301.6	300.4	0	—	—	—	—	—
.5	302.1	609.6	0	.005337	525	583	1.470	1.634
.75	302.1	740.1	1	.005337	1146	1205	3.21	3.38
1.0	302.6	843.5	1	.005884	1034	1066	2.90	2.99
1.5	303.1	970.2	1	.006431	1257	1280	3.52	3.59
2.0	303.9	1030.2	2	.007307	1029	1047	2.88	2.93
3.0	306.6	1071.0	3	.01190	542	555	1.519	1.555
4.0	308.5	1086.0	2	.01593	422	434	1.181	1.217
5.0	310.5	1093.9	2	.02024	334	347	.936	.971
6.0	312.0	1102.9	2	.02364	294	307	.825	.860
7.0	314.3	1107.2	2	.02885	243	255	.680	.715
8.0	315.8	1113.6	2	.03242	221	234	.619	.654
9.0	319.6	1117.1	2	.04187	174	186	.486	.522
10.0	321.3	1122.4	2	.04733	160	174	.449	.486
11.0	323.6	1124.7	2	.05525	143	157	.400	.439

APPENDIX C

MISCELLANEOUS CALCULATIONS

APPENDIX C.1

THE TRANSMITTANCE OF AIR

Calculation of the Transmittance of Air

To provide an absolute upper limit on the value presented for air absorptivity (and, therefore, a lower limit on transmittance) 100% relative humidity is assumed.

$$\Phi = P_v / P_g$$

Substituting in the known values

$$\Phi = 1.00$$

$$P_g = 0.5073 \text{ psi (pressure of saturated steam at } 80^\circ\text{F)}$$

$$P_v = (1.00)(0.5073 \text{ psi}) = 0.5073 \text{ psi} = 0.03452 \text{ atm}$$

Assuming the radiation to be absorbed by a 1 foot thick slab of air (the greatest distance between the heater surface and a thermocouple)

$$P_v L = (0.03452 \text{ atm})(1.0 \text{ ft}) = 0.03452 \text{ atm-ft}$$

From the CRC Handbook¹⁶ Table 2-11, the emissivity of pure water vapor at 40°F and $P_v L = 0.03452 \text{ atm-ft}$ is 0.079 (and decreases with

increasing vapor temperature). This value is then corrected for air containing this amount of water vapor. The CRC Handbook recommends multiplying this value by 0.55 to arrive at the estimated value of air emissivity.

$$\epsilon_{\text{air}} = (0.55)(0.079) = 0.043$$

The absorptivity of air can be estimated as being equal to the emissivity and the transmittance can then be calculated (assuming no reflectivity or scattering effects).

$$\tau_{\text{air}} = 1 - \alpha_{\text{air}} = 0.957$$

APPENDIX C.2

MOLECULAR STEADY STATE CONDUCTION TO THE AIR

Thermocouple #1 is the only thermocouple evaluated since it records the greatest values of $T_{tc} - T_{\infty}$ for all points in time. To serve as an illustration only the data taken at 11 seconds will be analyzed. Again, this provides the largest value of $T_{tc} - T_{\infty}$. This will provide an upper limit on the values determined for the contribution of conduction.

VACUUM CASE

For the vacuum case (low pressure) the mean free path of the air molecules is calculated using the simple equation²²

$$\lambda = 5 \times 10^{-3} / P$$

where λ is the mean free path expressed in centimeters and P is the pressure of air in Torr.

The conduction heat loss per unit surface area is given as²³

$$E_0 = \Lambda_0 a (273/T_i)^{1/2} (T_s - T_i) P$$

With the known values

$$\Lambda_0 = 1.64 \times 10^{-2} \text{ W/cm}^2 \text{ K Torr}$$

$$T_i = T_\infty = 298.4^\circ\text{K}$$

$$T_s = T_{tc} = 621.3^\circ\text{K}$$

$$P = 70 \text{ microns of Hg} = 9.2 \times 10^{-5} \text{ atm} = 0.070 \text{ Torr}$$

$$a = 0.8$$

gives a value for the heat transferred by conduction per unit area of

$$E_0 = 0.284 \text{ W/cm}^2$$

This is equivalent to a total heat transfer by conduction from the thermocouple bead of

$$q_{\text{COND,air}} = A_{tc} E_0 = 5.16 \times 10^{-5} \text{ W}$$

AIR CASE

Conduction to the air at atmospheric pressure is calculated for comparison purposes. The conduction limit for the steady state Nusselt number is 2.

$$Nu = h d_{tc} / k_{air} = 2$$

Solving for h and substituting in the known values gives

$$h = 2 k_{\text{air}} / d_{\text{tc}} = 2(0.0272 \text{ W/mK}) / (7.62 \times 10^{-5} \text{ m}) = 713.9 \text{ W/m}^2\text{K}$$

which results in the steady state heat conduction to the air of

$$\begin{aligned} q_{\text{COND,air}} &= hA_{\text{tc}}(T_{\text{tc}} - T_{\infty}) \\ &= 713.9 \text{ W/m}^2\text{K}(1.82 \times 10^{-8} \text{ m}^2)(621.3 - 298.4)\text{K} \\ &= 4.195 \times 10^{-3} \text{ W} \end{aligned}$$

The steady state vacuum case conduction term was calculated to be almost two orders of magnitude lower than the steady state air case.

This can be shown to always be the case for this experiment.

$$q_{\text{COND,air}}|_{\text{VAC}} = q_{\text{COND,air}}|_{\text{AIR}}$$

$$A_{\text{tc}}E_0 = hA_{\text{tc}}(T_{\text{tc}} - T_{\infty})$$

$$A_{\text{tc}}(\Lambda_0 a (273/T_{\infty})^{1/2} (T_{\text{tc}} - T_{\infty})P) = hA_{\text{tc}}(T_{\text{tc}} - T_{\infty})$$

which can be reduced to

$$\Lambda_0 \alpha (273/T_{\infty})^{1/2} P = h$$

recalling that the conduction limit of h is $713.9 \text{ W/m}^2\text{K}$ and substituting the other unchanging values into the equation gives

$$(1.64 \times 10^{-2} \text{ W/cm}^2 \text{ K Torr})(0.8)(273/298.4)^{1/2} \\ \times (0.07 \text{ Torr})(100 \text{ cm/m})^2 = 713.9 \text{ W/m}^2\text{K}$$

$$8.78 \text{ W/m}^2\text{K} \ll 713.9 \text{ W/m}^2\text{K}$$

Therefore, the steady state vacuum case conduction term will always be almost two orders of magnitude lower than the steady state air case conduction term.

APPENDIX C.3

CONDUCTION TO THE AIR— STEADY STATE VERSUS TRANSIENT

Thermocouple #1 is the only thermocouple evaluated since it records the greatest values of $T_{tc} - T_{\infty}$ for all points in time. This will provide an upper limit on the values determined for the contribution of conduction.

STEADY STATE

The steady state conduction to the air has previously been calculated (see Appendix C.2) and resulted in a value of the heat being conducted from the thermocouple by the air of

$$q_{COND,air} = 4.195 \times 10^{-3} \text{ W}$$

TRANSIENT

At 11 seconds $T_{tc} = 401.5^{\circ}\text{K}$ and $T_{\infty} = 298.4^{\circ}\text{K}$.

$$\begin{aligned} q_{COND,air} &= k_{air} A_{tc} (T_{tc} - T_{\infty}) / (\pi \alpha t)^{1/2} \\ &= (0.0272 \text{ W/m K})(1.82 \times 10^{-8} \text{ m}^2)(621.3 - 298.4)^{\circ}\text{K} \\ &\quad / [\pi (0.2216 \times 10^{-4} \text{ m}^2/\text{s})(11 \text{ s})]^{1/2} \\ &= 5.78 \times 10^{-6} \text{ W} \end{aligned}$$

The transient case gives a value of almost three orders of magnitude lower than the steady state.

Again, this can be shown to always be the case for this experiment.

$$q_{\text{COND,air}}|_{\text{STEADY}} = q_{\text{COND,air}}|_{\text{TRANSIENT}}$$

$$hA_{\text{tc}}(T_{\text{tc}} - T_{\infty}) = k_{\text{air}} A_{\text{tc}} (T_{\text{tc}} - T_{\infty}) / (\pi\alpha t)^{1/2}$$

which can be reduced to

$$h = k_{\text{air}} / (\pi\alpha t)^{1/2}$$

recalling that the conduction limit of h is $713.9 \text{ W/m}^2\text{K}$ and substituting the other unchanging values into the equation gives

$$713.9 \text{ W/m}^2\text{K} = (0.0272 \text{ W/m K}) / [\pi (0.2216 \times 10^{-4} \text{ m}^2/\text{s})(11 \text{ s})]^{1/2}$$

$$713.9 \text{ W/m}^2\text{K} \gg 0.983 \text{ W/m}^2\text{K}$$

Therefore, the transient air case conduction term will always be almost three orders of magnitude lower than the steady state air case conduction term.

APPENDIX C.4

THERMOCOUPLE DIMENSIONS AND PROPERTIES

Thermocouple bead diameter (d_{tc}) 7.62 x 10⁻⁵ m
(given in Omega Temperature Handbook¹⁹ and verified by using a measurement microscope accurate to 1/10000 of an inch—0.003 inches)

Thermocouple bead surface area (A_{tc}) 1.82 x 10⁻⁸ m²
$$A_{tc} = \pi d_{tc}^2$$

Thermocouple bead mass (m_{tc}) 2.01 x 10⁻⁹ kg
$$m_{tc} = (\pi d_{tc}^3 / 6)(\rho_{\text{Chromel}} + \rho_{\text{Alumel}}) / 2$$
$$\rho_{\text{Chromel}} = 8730 \text{ kg / m}^3$$
$$\rho_{\text{Alumel}} = 8600 \text{ kg / m}^3$$

Thermocouple bead specific heat (C) 486 J/kg K
for lack of a better approximation, $C = (C_{\text{Chromel}} + C_{\text{Alumel}}) / 2$
$$C_{\text{Chromel}} = 448 \text{ J/kg K}$$
$$C_{\text{Alumel}} = 523 \text{ J/kg K}$$

APPENDIX C.5

TRANSIENT CONDUCTION TO THE AIR

CONDUCTION TO THE AIR

Thermocouple #1 is the only thermocouple evaluated since it records the greatest values of $T_{tc} - T_{\infty}$ for all points in time. This will provide an upper limit on the values determined for the contribution of conduction.

At 2.0 seconds $T_{tc} = 401.5^{\circ}\text{K}$ and $T_{\infty} = 298.4^{\circ}\text{K}$.

$$\begin{aligned} q_{\text{COND,air}} &= k_{\text{air}} A_{tc} (T_{tc} - T_{\infty}) / (\pi \alpha t)^{1/2} \\ &= (0.0272 \text{ W/m K})(1.82 \times 10^{-8} \text{ m}^2)(103.1^{\circ}\text{K}) \\ &\quad / [\pi (0.2216 \times 10^{-4} \text{ m}^2/\text{s})(2 \text{ s})]^{1/2} \\ &= 4.33 \times 10^{-6} \text{ W} \end{aligned}$$

The experimentally derived heat loss to the air is calculated using the standard convective equation.

$$q_{\text{CONV,air}} = h A_{tc} (T_{tc} - T_{\infty})$$

From the experimental results, h for thermocouple #1 at 2.0 seconds is found to be $70 \text{ W/m}^2\text{K}$.

$$q_{\text{CONV,air}} = 70 \text{ W/m}^2\text{K}(1.82 \times 10^{-8} \text{ m}^2)(103.1^\circ\text{K}) = 1.31 \times 10^{-4} \text{ W}$$

For this particular case, the analytically determined heat loss by conduction is almost two orders of magnitude less than the experimental results for heat loss to the air. Table C.1 gives the transient results of these calculations for thermocouple #1.

THE CONDUCTION LIMIT

Using the equation

$$h = k_{\text{air}} / (\pi\alpha t)^{1/2}$$

the equation representing Nusselt number is found to be

$$\text{Nu} = h d_{\text{tc}} / k_{\text{air}} = d_{\text{tc}} / (\pi\alpha t)^{1/2}$$

Substituting in the unchanging quantities for this experiment gives

$$\text{Nu} = 7.62 \times 10^{-5} \text{ m} / [\pi (0.2216 \times 10^{-4} \text{ m}^2/\text{s})t]^{1/2}$$

$$\text{Nu} = 9.13 \times 10^{-3} / t^{1/2}$$

Table C.1 Air Conduction Versus Experimental Convection

Time (s)	$q_{\text{COND,air}} (\times 10^4 \text{ W})$	$q_{\text{CONV,air}} (\times 10^4 \text{ W})$
0.75	0.00034	0.819
2.0	0.0433	1.31
3.0	0.0484	1.83
4.0	0.0523	1.86
5.0	0.0544	1.90
6.0	0.0556	1.88
7.0	0.0563	1.87
8.0	0.0571	1.93
9.0	0.0575	2.01
10.0	0.0578	2.02
11.0	0.0578	2.06

where t is in seconds. This equation can then be used to define the transient conduction limit of Nusselt number. Table C.2 gives the results of these calculations.

Table C.2 Conduction Limit Nusselt Number

Time (s)	Nusselt number
0.25	0.0183
0.50	0.0129
0.75	0.0105
1.0	0.0091
1.5	0.0075
2.0	0.0065
3.0	0.0053
4.0	0.0046
6.0	0.0037
9.0	0.0030
11.0	0.0028

APPENDIX D

UNCERTAINTY ANALYSIS

Uncertainty in the Measurement of Time

The first degree of uncertainty associated with the measurement of time dealt with the actual initiation of heating with respect to the zero of the time scale. The zero time of the original data corresponds to the initiation of data acquisition by the the computer. Manual initiation of heating occurred at some finite time after the computer signaled the start of data acquisition. Heating is evidenced by a large measured heater circuit current. The resolution of this measurement is once every 0.23 seconds and the first large current measurement was consistently made on the second measurement pass. Therefore, it can be stated that heating began between 0 and 0.23 seconds after the start of data acquisition. It should be considered that this delay in the initiation of heating will have no effect on the results other than a shift of the time axis of not greater than 0.23 seconds. This has no effect on the magnitude of the results presented, since the equations are not explicitly dependent upon time.

The uncertainty of the time measurement process, independent of the initiation uncertainty, is completely dependent upon the accuracy of the internal clock of the Hewlett-Packard computer. The accuracy of the internal clock was given to be $\pm 0.005\%$ of the time measured.

Uncertainty in the Measurement of Temperature

The uncertainty of the temperature measurement process was arrived at by allowing the enclosed air within the container to reach a uniform temperature (accomplished by leaving the apparatus undisturbed for at least 24 hours) and running a test to measure the temperature of the internal air temperature. This resulted in over 100 measurements of the air. The maximum deviation in this data set is $\pm 0.6^{\circ}\text{K}$ which is taken to be the uncertainty in the temperature measurement of the thermocouples. The raw data used to establish this uncertainty is given in at the end of this appendix.

Uncertainty in the Measurement of Thermocouple Location

The uncertainty in the measurement of distance of the thermocouple from the foil was estimated to be ± 0.2 inches. This is a conservative estimate of uncertainty and also includes any slight movement of the foil due to thermal expansion.

Uncertainty in the Measurement of Thermocouple Bead Diameter

The thermocouple bead diameter was given by the manufacturer (Omega) to be approximately three times the diameter of the wire used to create it. Since 0.001 inch wire was used, the estimate of the bead diameter is 0.003 inch. In order to verify this estimate, measurements of the bead diameter were made with a measuring microscope. Each of two thermocouple beads were measured three different times in

three different directions across the bead. The three measurements were averaged to arrive at bead diameters of 0.0029 and 0.0033 inches. The uncertainty in the bead diameter is therefore estimated as ± 0.0003 inches.

THEORNOACOUSTIC RESEARCH - TEMPERATURES IN DEGREES CELSIUS

REFERENCE IS 0 DEGREES AND -0.001075 VOLTS

DC	STC8	TC7	TC6	TC5	TC4	TC3	TC2	TC1
TEMP 0 A	24.4	24.9	24.9	24.7	24.7	24.4	24.5	23.9
TIME .01	.03	.06	.09	.11	.14	.16	.19	.21
TEMP 0 A	24.9	25.1	24.5	25.2	24.6	24.5	24.4	24.1
TIME .24	.26	.29	.32	.34	.37	.39	.42	.44
TEMP 0 A	24.3	25	24.7	25	24.6	24.8	24.3	24.3
TIME .47	.5	.52	.55	.57	.6	.62	.65	.68
TEMP 0 A	24.4	25.1	24.6	25	24.4	24.7	24.3	24.2
TIME .7	.73	.75	.78	.8	.83	.86	.88	.91
TEMP 0 A	24.7	24.6	24.9	24.8	24.7	24.7	24.6	24.4
TIME .93	.96	.98	1.01	1.03	1.06	1.09	1.11	1.14
TEMP 0 A	24.3	24.6	25.1	24.3	24.8	24.5	24.4	24.1
TIME 1.16	1.19	1.21	1.24	1.27	1.29	1.32	1.34	1.37
TEMP 0 A	24.8	24.6	25	24.6	24.9	24.6	24.5	23.7
TIME 1.39	1.42	1.45	1.47	1.5	1.52	1.55	1.57	1.6
TEMP 0 A	24.4	24.8	25	24.6	24.8	24.4	24.6	24
TIME 1.63	1.65	1.68	1.7	1.73	1.75	1.78	1.81	1.83
TEMP 0 A	24.4	25.1	24.4	25.1	24.7	24.5	24.3	23.9
TIME 1.86	1.88	1.91	1.93	1.96	1.98	2.01	2.04	2.06
TEMP 0 A	24.2	25.1	24.6	24.9	24.4	24.7	24.3	24.4
TIME 2.09	2.11	2.14	2.16	2.19	2.21	2.24	2.26	2.29

TEMP 0 A	24.5	24.6	24.9	24.6	24.7	24.7	24.3	24.3	24.3
TIME 2.32	2.34	2.37	2.42	2.39	2.42	2.47	2.45	2.5	2.52
TEMP 0 A	24.3	24.6	24.7	25	24.7	24.7	24.7	24.6	24.4
TIME 2.55	2.57	2.6	2.65	2.62	2.68	2.7	2.73	2.73	2.75
TEMP 0 A	24.5	24.7	24.5	24.8	24.9	24.3	24.4	24	24
TIME 2.78	2.81	2.83	2.88	2.86	2.91	2.93	2.96	2.98	2.98
TEMP 0 A	24.7	24.6	24.6	25	24.9	24.4	24.6	24.1	24.1
TIME 3.01	3.04	3.06	3.09	3.11	3.14	3.16	3.19	3.21	3.21

APPENDIX E

THE COMPUTER INTERFACE

APPENDIX E.1

TEMPERATURE CONVERSION POLYNOMIAL

The temperature conversion polynomial recommended by Hewlett-Packard¹⁵ is as follows:

$$T = P_0 + V(P_1 + V(P_2 + V(P_3 + V(P_4 + V(P_5 + V(P_6 + V(P_7 + V(P_8 + V(P_9))))))))))$$

where V is the referenced voltage measured by each thermocouple and P_0 through P_9 are the coefficients of the polynomial. The coefficients recommended for Chromel-Alumel thermocouples are given as follows.

$$P_0 = -5.115307103 \text{ E-2}$$

$$P_5 = 6.039285524 \text{ E+11}$$

$$P_1 = 2.485028007 \text{ E+4}$$

$$P_6 = -1.910899962 \text{ E+13}$$

$$P_2 = -3.826622822 \text{ E+5}$$

$$P_7 = 3.478234730 \text{ E+14}$$

$$P_3 = 9.966105673 \text{ E+7}$$

$$P_8 = -3.399102821 \text{ E+15}$$

$$P_4 = -1.082062357 \text{ E+10}$$

$$P_9 = 1.382851398 \text{ E+16}$$

APPENDIX E.2

DATA ACQUISTION
COMPUTER PROGRAM


```

170 PRINT
180 I THERMOCOUPLE POLYNOMIAL COEFFICIENTS
190 P0=-5.115307103E-2
200 P1=2.485028007E+4
210 P2=-3.826622822E+5
220 P3=9.966105673E+7
230 P4=-1.082062357E+10
240 P5=6.039285524E+11
250 P6=-1.910899962E+13
260 P7=3.476234730E+14
270 P8=-3.399102821E+15
280 P9=1.382851398E+16
290 FOR I=1 TO 50
300   Ic=V(I,9)*10000
301   Ic=INT(Ic+.5)
310   FOR N=1 TO 9
320     Vt=V(I,N)-R
321     Tet=P6+Vt*(P7+Vt*(P8+Vt*P9))
330     Tc(N)=P0+Vt*(P1+Vt*(P2+Vt*(P3+Vt*(P4+Vt*(P5+Vt*Tet))))
331     Tc(N)=INT(Tc(N)*10+.5)/10
332     T(I,N)=INT(T(I,N)*100+.5)/100
334   NEXT N
336 I PRINT "VOLT ";V(I,9);TAB(15);V(I,8);TAB(23);V(I,7);TAB(31);V(I,6);TAB(39);
V(I,5);TAB(47);V(I,4);TAB(55);V(I,3);TAB(63);V(I,2);TAB(71);V(I,1)
340 PRINT "TEMP ";Ic;"A";TAB(15);Tc(8);TAB(23);Tc(7);TAB(31);"OUT";TAB(41);"OU
T";TAB(47);Tc(4);TAB(57);"OUT";TAB(63);Tc(2);TAB(73);"OUT"
342 PRINT "TIME ";T(I,9);TAB(15);T(I,8);TAB(23);T(I,7);TAB(31);T(I,6);TAB(39);
T(I,5);TAB(47);T(I,4);TAB(55);T(I,3);TAB(63);T(I,2);TAB(71);T(I,1)
350 PRINT
352 OUTPUT @Path_1,Ic

```

```
354   FOR J=8 TO 1 STEP -1
355     OUTPUT @Path_1;Tc(J)
356   NEXT J
357   FOR J=9 TO 1 STEP -1
358     OUTPUT @Path_1;T(I,J)
359   NEXT J
360 NEXT I
361 PRINTER IS 1
370 END
```

APPENDIX E.3

DATA REPRODUCTION COMPUTER PROGRAM

```

1  TACTABLE
10  TACTABLE
11  THIS PROGRAM PRODUCES TABULATED DATA FROM THE TAC DATA FILES
12  DIM M(50,9),Ti(50,9),Mnd(50,9)
13  CREATE EBDAT "TACDAT100",1,5500
14  ASSIGN @Path_1 TO "TACATM100"
15  ASSIGN @Path_2 TO "TACDAT100"
16  PRINTER IS 701
17  PRINT "DATA FILE: TACDAT100"
18  PRINT
19  PRINT
20  PRINT " DC STC0 TC1 TC2 TC3 TC4 TC5 TC6
TC7"
21  PRINT
22  FOR I=1 TO 50
23  FOR J=1 TO 9
24  ENTER @Path_1;M(I,J)
25  NEXT J
26  FOR J=1 TO 9
27  ENTER @Path_1;Ti(I,J)
28  NEXT J
29  PRINT "TEMP ";M(I,1);"A";TAB(15);M(I,2);TAB(23);M(I,3);TAB(31);M(I,4);TA
B(39);M(I,5);TAB(47);M(I,6);TAB(55);M(I,7);TAB(63);M(I,8);TAB(71);M(I,9)
30  PRINT "TIME ";Ti(I,1);TAB(15);Ti(I,2);TAB(23);Ti(I,3);TAB(31);Ti(I,4);TA
B(39);Ti(I,5);TAB(47);Ti(I,6);TAB(55);Ti(I,7);TAB(63);Ti(I,8);TAB(71);Ti(I,9)
31  PRINT
32  NEXT I
33  FOR J=2 TO 9
34  FOR I=1 TO 50
35  OUTPUT @Path_2;Ti(I,J)
36  OUTPUT @Path_2;M(I,J)
37  NEXT I
38  NEXT J
39  PRINTER IS 1
40  END

```

APPENDIX F

ORIGINAL DATA

APPENDIX F.1

THE VACUUM TESTS

DATA FILE: RADMATCH2 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	29.1	28.7	28.7	28.3	28.2	27.6	27.4	25.8
TIME 0	.03	.05	.08	.1	.13	.15	.18	.2
TEMP 214 A	57.9	28.9	26.9	28.5	28	27.7	26.8	25.7
TIME .23	.25	.28	.3	.33	.35	.38	.4	.43
TEMP 198 A	181.5	31.4	31.1	30.1	28.7	27.8	27.4	25.6
TIME .45	.48	.51	.53	.56	.58	.61	.63	.66
TEMP 187 A	294.1	37	35.5	33.6	29.6	29.3	27.7	26.3
TIME .69	.71	.73	.76	.78	.81	.83	.86	.88
TEMP 180 A	395.2	46.4	42.9	40.1	32	31	29	27.2
TIME .91	.93	.96	.98	1.01	1.03	1.05	1.08	1.11
TEMP 175 A	484	58.9	53.9	49.9	38.4	34.2	31.5	28.7
TIME 1.13	1.16	1.18	1.21	1.23	1.26	1.29	1.31	1.34
TEMP 171 A	559.4	75.1	68.3	64	42.7	39.1	34.6	31.4
TIME 1.36	1.39	1.41	1.44	1.46	1.49	1.51	1.54	1.57
TEMP 168 A	621.1	97.8	86.1	82.4	51.4	44.7	39.1	35
TIME 1.59	1.62	1.64	1.67	1.69	1.72	1.74	1.77	1.79
TEMP 166 A	665.9	122.9	105.8	104.2	62.2	51.2	44.8	39.3
TIME 1.82	1.84	1.87	1.9	1.92	1.95	1.97	2	2.02

TEMP 165 A	700.1	149.5	128.6	128.2	74.7	57.8	50.9	44.3
TIME 2.05	2.07	2.1	2.12	2.15	2.17	2.2	2.22	2.25
TEMP 164 A	724.8	176.9	150.3	152.9	87.8	64.1	57	49.7
TIME 2.28	2.3	2.33	2.35	2.38	2.4	2.43	2.45	2.48
TEMP 163 A	741.5	204.5	171.5	177.6	101.3	69.8	63.7	55.2
TIME 2.5	2.53	2.55	2.58	2.61	2.63	2.66	2.68	2.71
TEMP 163 A	753.9	231.3	191.5	201.5	114.9	75.1	69.9	60.6
TIME 2.73	2.76	2.78	2.81	2.83	2.85	2.88	2.91	2.94
TEMP 163 A	760.2	256	209.5	223.6	127.4	79.9	74.9	65.6
TIME 2.96	2.99	3.01	3.04	3.06	3.09	3.11	3.14	3.17
TEMP 162 A	763.2	278.7	225.6	243.7	138.6	83.6	79.7	70
TIME 3.19	3.22	3.24	3.27	3.29	3.32	3.34	3.37	3.4
TEMP 162 A	766.4	299.3	240.4	261.1	149.1	87	84.2	74.4
TIME 3.42	3.45	3.47	3.5	3.52	3.55	3.57	3.6	3.63
TEMP 162 A	768.4	315.3	252.7	276.3	159.5	90	88.4	78
TIME 3.65	3.68	3.7	3.73	3.75	3.78	3.8	3.83	3.85
TEMP 161 A	770.2	330.1	263.6	288.8	166.9	92.7	91.3	81.1
TIME 3.88	3.9	3.93	3.96	3.98	4.01	4.03	4.06	4.08
TEMP 161 A	771.7	342.8	273	299.7	174	95.2	94.1	83.8
TIME 4.11	4.13	4.16	4.18	4.21	4.23	4.26	4.28	4.31
TEMP 161 A	772.4	353.4	291.7	308.4	180.7	97.6	96.7	86
TIME 4.34	4.36	4.39	4.41	4.44	4.46	4.48	4.51	4.54
TEMP 161 A	772.3	362.6	299.5	315.6	186.4	99.7	98.7	87.9
TIME 4.56	4.59	4.62	4.64	4.67	4.69	4.72	4.74	4.77

TEMP 161 A	773.4	370.6	296.5	321.9	191.3	101.8	100.2	89.5
TIME 4.79	4.82	4.84	4.87	4.89	4.92	4.94	4.97	5
TEMP 161 A	774.5	378	303.1	327.1	195.9	103.7	102.2	91.1
TIME 5.02	5.05	5.07	5.1	5.12	5.15	5.17	5.2	5.23
TEMP 161 A	774.4	384	309.1	331.4	199.8	105.5	104	92
TIME 5.25	5.28	5.3	5.33	5.35	5.38	5.4	5.43	5.45
TEMP 160 A	774.5	389.6	314.6	335.2	203.1	107.6	105	92.7
TIME 5.48	5.51	5.53	5.56	5.58	5.61	5.63	5.66	5.68
TEMP 160 A	775.7	395.2	319.9	338.7	205.9	109.3	106	93.5
TIME 5.71	5.74	5.76	5.79	5.81	5.84	5.86	5.89	5.91
TEMP 160 A	777	400.4	325	341.6	208.9	110.9	107.6	94.1
TIME 5.94	5.96	5.99	6.01	6.04	6.06	6.09	6.12	6.14
TEMP 160 A	777.7	405.2	329.8	344	211.1	112.9	108.9	94.6
TIME 6.17	6.19	6.22	6.24	6.27	6.29	6.32	6.34	6.37
TEMP 160 A	778.1	410	334.2	346.3	213.2	114.5	109.6	94.9
TIME 6.4	6.42	6.45	6.47	6.5	6.52	6.55	6.57	6.6
TEMP 160 A	778.1	414.6	338.7	348.4	215.2	116.4	110.5	95.4
TIME 6.62	6.65	6.67	6.7	6.72	6.75	6.78	6.8	6.83
TEMP 160 A	777.7	419.3	342.7	350.5	217	118.1	111.7	95.8
TIME 6.85	6.88	6.9	6.93	6.95	6.98	7.01	7.03	7.06
TEMP 160 A	777.7	423.6	346.9	352.2	218.8	119.7	112.5	95.6
TIME 7.08	7.11	7.13	7.16	7.18	7.21	7.23	7.26	7.29
TEMP 159 A	779.4	427.7	351.2	364.1	220.3	121.3	113.4	95.9
TIME 7.31	7.34	7.36	7.39	7.41	7.44	7.46	7.49	7.51

TEMP TIME	159 A 7.54	780.7 7.57	431.7 7.59	355.1 7.62	355.9 7.64	221.9 7.67	123 7.69	114.5 7.72	96.1 7.74
TEMP TIME	159 A 7.77	780.9 7.8	435.8 7.82	358.8 7.85	357.6 7.87	223.5 7.9	124.7 7.92	115.4 7.95	96.2 7.97
TEMP TIME	159 A 8	780.8 8.02	439.8 8.05	362.8 8.07	358.9 8.1	225 8.13	126.3 8.15	116.4 8.18	96.2 8.2
TEMP TIME	159 A 8.23	782.4 8.26	443.4 8.28	366.6 8.31	360.6 8.33	226.3 8.36	127.8 8.38	117.2 8.41	96.6 8.43
TEMP TIME	159 A 8.46	784.1 8.48	447.1 8.51	370 8.53	362.4 8.56	227.5 8.58	129.4 8.61	118 8.64	96.6 8.66
TEMP TIME	159 A 8.69	784.4 8.71	450.7 8.74	373.8 8.76	363.7 8.79	228.8 8.81	131.1 8.84	118.9 8.86	96.5 8.89
TEMP TIME	159 A 8.92	785.2 8.94	453.8 8.97	377.6 8.99	364.8 9.02	230.3 9.04	132.6 9.07	120.1 9.09	96.7 9.12
TEMP TIME	159 A 9.15	786.1 9.17	457.4 9.2	380.9 9.22	366.6 9.25	231.6 9.27	134.1 9.3	120.8 9.32	96.8 9.35
TEMP TIME	158 A 9.37	787.8 9.4	460.6 9.42	384.3 9.45	369.1 9.48	232.7 9.5	135.7 9.53	121.7 9.55	97.1 9.58
TEMP TIME	158 A 9.6	787.9 9.63	464 9.65	387.6 9.68	369.4 9.71	234 9.73	137.3 9.76	122.5 9.78	97.1 9.81
TEMP TIME	158 A 9.83	788 9.86	466.9 9.88	391.1 9.91	370.7 9.93	235.4 9.96	138.8 9.98	123.3 10.01	97.1 10.04
TEMP TIME	156 A 10.06	789.7 10.09	470 10.11	394.2 10.14	372.2 10.16	236.5 10.19	140.2 10.21	124.2 10.24	97.4 10.27

TEMP	158 A	781.2	473.2	397	373.9	237.6	141.7	125.2	97.6
TIME	10.29	10.32	10.34	10.37	10.39	10.42	10.44	10.47	10.49
TEMP	158 A	781.4	475.9	400.3	375.1	239.1	143.3	126.2	97.7
TIME	10.52	10.55	10.57	10.6	10.62	10.65	10.67	10.7	10.72
TEMP	158 A	781.4	478.7	403.3	376.3	240.2	144.6	127	97.7
TIME	10.75	10.77	10.8	10.83	10.85	10.88	10.9	10.93	10.95
TEMP	158 A	782.8	481.3	406.1	377.7	241.4	146.2	127.5	97.9
TIME	10.98	11	11.03	11.05	11.08	11.1	11.13	11.15	11.18
TEMP	157 A	783.8	483.9	409.1	379	242.6	147.5	128.9	98.1
TIME	11.21	11.23	11.26	11.28	11.31	11.33	11.36	11.38	11.41

DATA FILE: RADMATCH3 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	24	24.3	24.2	24.4	24.3	24.3	24.5	24.7
TIME 0	.03	.05	.08	.1	.13	.15	.18	.2
TEMP 231 A	82.1	24.7	24.6	24.7	24.5	24.5	24.7	24.7
TIME .23	.25	.28	.31	.33	.36	.38	.41	.43
TEMP 211 A	227.2	28	27.4	26.7	25.2	25	24.8	24.8
TIME .46	.48	.51	.53	.56	.58	.61	.63	.66
TEMP 198 A	357.2	34.8	33.4	31.6	27	26.6	25.9	25.5
TIME .68	.71	.73	.76	.78	.81	.83	.86	.88
TEMP 190 A	467.2	46.2	42.8	40.3	30.5	30.1	27.6	27.1
TIME .91	.93	.96	.98	1.01	1.03	1.06	1.08	1.11
TEMP 184 A	563.1	62.7	57.3	54.2	37.2	35	31.7	29.9
TIME 1.13	1.16	1.18	1.21	1.23	1.26	1.28	1.31	1.33
TEMP 180 A	639.6	85.8	76.7	74	47	42.4	37.3	34
TIME 1.36	1.39	1.41	1.44	1.46	1.49	1.51	1.54	1.56
TEMP 178 A	697.7	114.2	100.2	99.3	59.8	50.8	44.1	39.7
TIME 1.59	1.61	1.64	1.66	1.69	1.71	1.74	1.76	1.79
TEMP 176 A	739.4	145.8	126.6	128.4	75.5	59.4	52.6	46.3
TIME 1.81	1.84	1.87	1.89	1.92	1.94	1.97	1.99	2.02

TEMP TIME	175 A 2.04	755.7 2.07	178.8 2.09	153.3 2.12	158.8 2.14	92.3 2.17	68 2.2	61.3 2.22	53.7 2.25
TEMP TIME	174 A 2.27	785.8 2.3	212.9 2.32	179.4 2.35	189.9 2.37	109.8 2.4	75.8 2.42	69.5 2.45	61.2 2.47
TEMP TIME	174 A 2.5	800.5 2.53	246.1 2.55	203.8 2.58	220.3 2.6	126.7 2.63	82.5 2.65	77.5 2.68	68.5 2.7
TEMP TIME	173 A 2.73	804.9 2.75	276 2.79	226.2 2.81	248.1 2.83	142.7 2.86	89.4 2.88	85.1 2.91	75.3 2.93
TEMP TIME	173 A 2.96	806.9 2.98	302.7 3.01	245.7 3.03	273 3.06	157.5 3.09	93.2 3.11	91.7 3.14	81.6 3.16
TEMP TIME	173 A 3.19	810.4 3.21	325.9 3.24	263.1 3.26	294.7 3.29	171.2 3.31	97.4 3.34	97.6 3.36	87.6 3.39
TEMP TIME	172 A 3.42	812.9 3.44	345.6 3.47	277.7 3.49	313.1 3.52	183.5 3.54	101.1 3.57	102.9 3.59	92.8 3.62
TEMP TIME	172 A 3.64	813.5 3.67	362 3.69	290.4 3.72	328.2 3.74	194.7 3.77	104.5 3.8	107.7 3.82	97.6 3.85
TEMP TIME	172 A 3.87	813.8 3.9	376 3.92	301.3 3.95	340.8 3.97	204.5 4	107.7 4.02	111.1 4.05	101.5 4.08
TEMP TIME	172 A 4.1	815 4.13	387.5 4.15	310.8 4.18	351.4 4.2	212.8 4.23	110.1 4.25	114.5 4.28	105 4.3
TEMP TIME	172 A 4.33	814.6 4.35	397.4 4.38	319.4 4.4	359.7 4.43	220.4 4.46	112.8 4.48	117.4 4.51	107.6 4.53
TEMP TIME	172 A 4.56	813.9 4.58	405.8 4.61	327.3 4.63	366.4 4.66	227.1 4.69	115.1 4.71	119.9 4.74	110.2 4.76

TEMP 171 A	814.9	412.7	334.2	372.3	232.5	117.3	121.9	112.5
TIME 4.79	4.81	4.84	4.86	4.89	4.91	4.94	4.96	4.99
TEMP 171 A	815.8	419	340.6	377.1	237.4	119.7	124	114.3
TIME 5.01	5.04	5.07	5.09	5.12	5.14	5.17	5.19	5.22
TEMP 171 A	815.6	425.1	346.6	380.9	241.7	121.7	126.1	115.7
TIME 5.24	5.27	5.29	5.32	5.34	5.37	5.4	5.42	5.45
TEMP 171 A	816.5	430.9	352.1	384.4	245.4	124.1	127.3	116.8
TIME 5.47	5.5	5.52	5.55	5.57	5.6	5.62	5.65	5.68
TEMP 171 A	817.5	436.5	357.1	387.4	248.3	125.9	128.4	117.6
TIME 5.7	5.73	5.75	5.78	5.8	5.83	5.85	5.88	5.9
TEMP 171 A	818.8	441.6	362.3	389.8	251.1	128	130.1	118.2
TIME 5.93	5.96	5.98	6.01	6.03	6.06	6.08	6.11	6.13
TEMP 171 A	815.5	446.4	367.2	391.9	253.8	130	131.4	118.6
TIME 6.16	6.18	6.21	6.23	6.26	6.29	6.31	6.34	6.36
TEMP 170 A	817.2	451.4	371.9	394	255.8	131.9	132.3	119.4
TIME 6.39	6.41	6.44	6.46	6.49	6.51	6.54	6.56	6.59
TEMP 170 A	818.3	456	376.4	395.8	258	133.6	133.7	119.7
TIME 6.62	6.64	6.67	6.69	6.72	6.74	6.77	6.79	6.82
TEMP 170 A	818.3	460.4	380.9	397.5	259.7	135.7	134.7	119.9
TIME 6.84	6.87	6.89	6.92	6.94	6.97	6.99	7.02	7.04
TEMP 170 A	819.2	464.8	385.1	399.3	261.4	137.6	135.7	120.2
TIME 7.07	7.1	7.12	7.15	7.17	7.2	7.22	7.25	7.27
TEMP 170 A	820.9	469.2	389.4	400.9	262.8	139.6	136.8	120.5
TIME 7.3	7.32	7.35	7.38	7.4	7.43	7.45	7.48	7.5

TEMP	170 A	821.1	473.2	393.6	402.4	264.4	141.3	138.1	120.4
TIME	7.53	7.55	7.58	7.6	7.63	7.65	7.68	7.7	7.73
TEMP	170 A	821.8	477.2	397.8	403.7	265.8	143.2	138.5	120.5
TIME	7.76	7.78	7.81	7.83	7.86	7.88	7.91	7.93	7.96
TEMP	169 A	823.3	481.3	401.6	405.3	267	145	139.2	120.3
TIME	7.98	8.01	8.03	8.06	8.08	8.11	8.14	8.16	8.19
TEMP	169 A	824.3	485	405.9	406.4	268.5	146.6	140.6	120.4
TIME	8.21	8.24	8.27	8.29	8.32	8.34	8.37	8.39	8.42
TEMP	169 A	824.7	488.5	409.8	407.7	269.7	148.5	141.8	120.3
TIME	8.44	8.47	8.49	8.52	8.54	8.57	8.59	8.62	8.65
TEMP	170 A	824.5	492.1	413.6	409.1	270.8	150.5	142.4	120.4
TIME	8.67	8.7	8.72	8.75	8.77	8.8	8.82	8.85	8.87
TEMP	170 A	825.5	495.7	417	410.5	271.7	152.2	143.3	120.3
TIME	8.9	8.93	8.95	8.98	9	9.03	9.05	9.08	9.1
TEMP	170 A	825.6	498.8	420.6	411.5	273.1	153.7	144.5	120.1
TIME	9.13	9.15	9.18	9.2	9.23	9.25	9.28	9.3	9.33
TEMP	170 A	825.8	501.9	424	412.7	274.1	155.4	145	120.1
TIME	9.36	9.38	9.41	9.43	9.46	9.48	9.51	9.53	9.56
TEMP	169 A	827.6	505.1	427.1	414.1	274.9	157.1	146	120.1
TIME	9.58	9.61	9.63	9.66	9.68	9.71	9.73	9.76	9.79
TEMP	169 A	827.7	506.1	430.6	415.1	276.2	158.8	147.1	119.9
TIME	9.81	9.84	9.86	9.89	9.91	9.94	9.96	9.99	10.01
TEMP	169 A	828.1	510.7	433.8	416.2	277.3	160.5	147.6	120
TIME	10.04	10.06	10.09	10.11	10.14	10.17	10.19	10.22	10.24

TEMP 169 A	830	513.7	435.8	417.5	278	162.1	148.6	120
TIME 10.27	10.29	10.32	10.34	10.37	10.39	10.42	10.44	10.47
TEMP 169 A	830.3	516.4	440	418.3	279.4	163.8	149.6	119.8
TIME 10.49	10.52	10.54	10.57	10.6	10.62	10.65	10.67	10.7
TEMP 168 A	831.5	519.1	443.1	419.3	280.3	165.5	150.1	120
TIME 10.72	10.75	10.77	10.8	10.82	10.85	10.87	10.9	10.92
TEMP 168 A	833.6	522	445.9	420.6	281.3	167	151.2	119.9
TIME 10.95	10.98	11	11.03	11.05	11.08	11.1	11.13	11.15
TEMP 168 A	834.3	524.6	449.2	421.5	282.4	168.8	152.1	119.8
TIME 11.18	11.2	11.23	11.25	11.28	11.31	11.33	11.36	11.38

DATA FILE: RADMATCH4 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	24.4	25.8	25.6	25.8	25.9	25.9	25.7	25.3
TIME 0	.03	.05	.06	.1	.13	.15	.16	.2
TEMP 238 A	135.9	26.7	27	26.6	26.1	25.9	25.8	25.4
TIME .23	.25	.28	.3	.33	.35	.38	.4	.43
TEMP 218 A	292.2	32	30.9	29.9	27.2	27.3	26.4	25.8
TIME .45	.48	.5	.53	.55	.58	.6	.63	.65
TEMP 204 A	429.3	41.3	39.4	37.1	30.4	29.7	28.4	26.9
TIME .68	.7	.73	.75	.78	.8	.83	.85	.88
TEMP 195 A	544	57.5	53	49.9	36.4	35.1	31.7	29.5
TIME .9	.93	.95	.98	1	1.03	1.05	1.08	1.1
TEMP 191 A	639.6	81.6	73.3	70.8	46.3	43.1	37.4	34.3
TIME 1.13	1.15	1.18	1.2	1.23	1.26	1.28	1.31	1.33
TEMP 188 A	710.4	112.7	99.5	96.5	60.4	52.8	45.7	40.5
TIME 1.36	1.38	1.41	1.43	1.46	1.48	1.51	1.53	1.56
TEMP 186 A	759.4	148.5	129.7	131.5	77.9	63.5	55.1	48
TIME 1.58	1.61	1.63	1.66	1.68	1.71	1.74	1.76	1.79
TEMP 184 A	793.4	187.1	160.8	166.7	97.4	73.7	65.2	56.8
TIME 1.81	1.84	1.86	1.89	1.91	1.94	1.96	1.99	2.01
TEMP 183 A	814.6	226.7	191.8	203.1	117.8	83.1	75.7	65.5
TIME 2.04	2.06	2.09	2.11	2.14	2.17	2.19	2.22	2.24

TEMP	183 A	828.2	264.5	220.8	236.2	137.7	91.1	85.4	74.1
TIME	2.27	2.29	2.32	2.34	2.37	2.39	2.42	2.44	2.47
TEMP	183 A	831.8	298.7	247	270.9	156.2	98.2	94.3	82.6
TIME	2.5	2.52	2.55	2.57	2.5	2.52	2.55	2.57	2.7
TEMP	182 A	836.1	329.5	269.3	299.5	173.8	103.7	102.7	90.3
TIME	2.72	2.75	2.78	2.8	2.83	2.85	2.88	2.9	2.93
TEMP	182 A	838.1	353.8	288.4	324	190.1	109	109.8	97.5
TIME	2.95	2.98	3	3.03	3.05	3.08	3.11	3.13	3.16
TEMP	182 A	839.3	375	304.6	344.4	204.5	113.5	115.6	103.9
TIME	3.18	3.21	3.23	3.26	3.28	3.31	3.33	3.36	3.38
TEMP	181 A	841.1	392.4	318.1	361.1	217.3	116.9	121	109.4
TIME	3.41	3.44	3.46	3.49	3.51	3.54	3.56	3.59	3.61
TEMP	181 A	841.1	406.4	330	374.6	228.7	120.3	125.7	114.1
TIME	3.64	3.66	3.69	3.71	3.74	3.77	3.79	3.82	3.84
TEMP	181 A	840.7	418.2	340.6	385.4	238.8	123.4	129.6	118.3
TIME	3.87	3.89	3.92	3.94	3.97	3.99	4.02	4.05	4.07
TEMP	181 A	841.5	427.5	349.6	394.4	247.2	126.3	133	122.1
TIME	4.1	4.12	4.15	4.17	4.2	4.22	4.25	4.27	4.3
TEMP	181 A	843.1	435.7	357.7	401.6	254.8	128.8	136.2	125.2
TIME	4.32	4.35	4.38	4.4	4.43	4.45	4.48	4.5	4.53
TEMP	180 A	843.8	443.4	364.9	407.4	261.1	131.5	139.9	127.7
TIME	4.55	4.58	4.6	4.63	4.65	4.68	4.7	4.73	4.75
TEMP	180 A	845.6	450.4	371.6	412.2	266.5	134.1	140.8	130
TIME	4.78	4.81	4.83	4.86	4.88	4.91	4.93	4.96	4.98

TEMP 180 A	847.2	456.9	377.7	416.2	271.4	136.3	143.1	132
TIME 5.01	5.03	5.06	5.08	5.11	5.13	5.16	5.18	5.21
TEMP 160 A	845.6	463	383.4	419.6	275.5	138.9	145.3	133.4
TIME 5.24	5.26	5.29	5.31	5.34	5.36	5.39	5.41	5.44
TEMP 160 A	845.2	460.9	389	422.6	278.6	141.6	146.5	134.6
TIME 5.46	5.49	5.52	5.54	5.57	5.59	5.62	5.64	5.67
TEMP 179 A	846.9	474.5	394.4	425.3	281.9	143.6	147.9	135.6
TIME 5.69	5.72	5.74	5.77	5.79	5.82	5.85	5.87	5.9
TEMP 179 A	847.6	479.7	399.6	427.4	284.6	145.8	149.7	136.2
TIME 5.92	5.95	5.97	6	6.02	6.05	6.07	6.1	6.12
TEMP 179 A	847.3	484.7	404.9	429.1	287.3	148	150.9	136.8
TIME 6.15	6.18	6.2	6.23	6.25	6.28	6.3	6.33	6.35
TEMP 179 A	849.2	489.6	409.7	431.1	289.3	150.1	152.1	137.3
TIME 6.38	6.4	6.43	6.46	6.48	6.51	6.53	6.56	6.58
TEMP 179 A	850.9	494.2	414.6	432.7	291.2	152.1	153.5	137.7
TIME 6.61	6.63	6.66	6.68	6.71	6.73	6.76	6.78	6.81
TEMP 179 A	851	498.8	419.1	434.3	293	154.3	154.9	137.9
TIME 6.84	6.86	6.89	6.91	6.94	6.96	6.99	7.01	7.04
TEMP 179 A	852.2	503.2	423.7	435.8	294.4	156.4	155.6	138
TIME 7.06	7.09	7.11	7.14	7.16	7.19	7.21	7.24	7.27
TEMP 178 A	854.2	507.4	428.1	437.4	295.8	158.5	156.7	138.2
TIME 7.29	7.32	7.34	7.37	7.39	7.42	7.44	7.47	7.49
TEMP 178 A	854.4	511.7	432.3	439.7	297.4	160.5	158	139.1
TIME 7.52	7.54	7.57	7.6	7.62	7.65	7.67	7.7	7.72

TEMP	176 A	854.2	515.7	436.5	440	298.7	152.7	158.6	138.1
TIME	7.75	7.77	7.8	7.82	7.85	7.87	7.9	7.93	7.95
TEMP	178 A	856.5	519.7	440.5	441.3	299.9	164.5	159.8	138
TIME	7.98	8	8.03	8.05	8.08	8.1	8.13	8.15	8.18
TEMP	178 A	857.4	523.4	444.5	442.6	301.2	165.5	160.9	137.8
TIME	8.2	8.23	8.25	8.28	8.31	8.33	8.36	8.38	8.41
TEMP	178 A	857.7	527.1	448.3	443.8	302.4	168.4	161.8	137.4
TIME	8.43	8.46	8.48	8.51	8.53	8.56	8.58	8.61	8.64
TEMP	178 A	859.3	530.6	452.3	445.1	303.4	170.4	162.4	137.5
TIME	8.66	8.69	8.71	8.74	8.76	8.79	8.81	8.84	8.86
TEMP	178 A	860.5	534	456.2	446.1	304.7	172.2	163.7	137.2
TIME	8.89	8.91	8.94	8.96	8.99	9.02	9.04	9.07	9.09
TEMP	178 A	860.6	537.3	459.7	447.2	306	174.1	164.7	137
TIME	9.12	9.14	9.17	9.19	9.22	9.24	9.27	9.29	9.32
TEMP	178 A	862.3	540.4	463.5	448.2	306.9	176.1	165.5	137
TIME	9.35	9.37	9.4	9.42	9.45	9.47	9.5	9.52	9.55
TEMP	177 A	864.2	543.6	466.8	449.3	308	178	166.5	137
TIME	9.57	9.6	9.62	9.65	9.68	9.7	9.73	9.75	9.78
TEMP	178 A	864.2	546.6	470.2	450.2	309.3	179.8	167.8	136.7
TIME	9.8	9.83	9.85	9.88	9.9	9.93	9.95	9.98	10
TEMP	177 A	865	549.6	473.4	451.6	310.2	181.7	168.5	136.6
TIME	10.03	10.06	10.08	10.11	10.13	10.16	10.18	10.21	10.23
TEMP	177 A	867	552.4	476.8	453	311.2	183.6	169.5	136.6
TIME	10.26	10.28	10.31	10.33	10.36	10.38	10.41	10.43	10.46

TEMP	177 A	867	555.4	479.7	454.3	312.4	185.4	170.5	136.4
TIME	10.49	10.51	10.54	10.56	10.59	10.61	10.64	10.66	10.69
TEMP	177 A	867.2	558.2	482.7	455.2	313.2	187.4	171.2	136.3
TIME	10.71	10.74	10.77	10.79	10.82	10.84	10.87	10.89	10.92
TEMP	177 A	868.9	560.8	485.8	456.1	314.2	189.1	172	136.2
TIME	10.94	10.97	10.99	11.02	11.04	11.07	11.09	11.12	11.15
TEMP	177 A	869.7	563.2	488.8	457	315.4	190.8	173.2	136.1
TIME	11.17	11.2	11.22	11.25	11.27	11.3	11.32	11.35	11.37

DATA FILE: RADMATCHS (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	26.8	27.8	27.5	27.7	27.5	27.6	26.9	26.1
TIME 0	.03	.05	.08	.1	.13	.15	.19	.2
TEMP 253 A	155.3	29.1	29.7	29.7	27.9	27.6	27.3	26.3
TIME .23	.25	.28	.3	.33	.35	.38	.4	.43
TEMP 229 A	331.6	34.8	34	32.6	29.6	29.1	28.4	26.7
TIME .45	.48	.51	.53	.56	.58	.61	.63	.66
TEMP 215 A	479.2	47	44.5	42.2	33.4	33.1	30.3	28.7
TIME .68	.71	.73	.76	.78	.81	.83	.86	.88
TEMP 206 A	602.8	68.1	62.3	59.8	41.9	40.5	35.8	32.6
TIME .91	.93	.96	.98	1.01	1.03	1.06	1.08	1.11
TEMP 201 A	697.6	99.1	88.9	87	55.9	50.9	44.1	38.6
TIME 1.13	1.16	1.18	1.21	1.24	1.26	1.29	1.31	1.34
TEMP 197 A	765.2	138.2	122.1	122.8	74.1	63.4	54.3	47.1
TIME 1.36	1.39	1.41	1.44	1.46	1.49	1.51	1.54	1.57
TEMP 195 A	809.7	181.8	158.1	162.6	96.1	75.7	66.6	56.9
TIME 1.59	1.62	1.64	1.67	1.69	1.72	1.74	1.77	1.79
TEMP 194 A	835.2	227.7	195.2	204.9	119.8	87.6	79.1	67.3
TIME 1.82	1.85	1.87	1.9	1.92	1.95	1.97	2	2.02

TEMP	193 A	851.4	272.6	229.9	246.9	143	97.7	90.5	77.4
TIME	2.05	2.08	2.1	2.13	2.15	2.18	2.2	2.23	2.25
TEMP	193 A	857.3	312.6	261.3	285.4	164.9	106.2	101.3	87.4
TIME	2.28	2.31	2.33	2.36	2.38	2.41	2.43	2.46	2.48
TEMP	192 A	862.5	347.2	287.5	318.8	185.4	113	110.6	96.6
TIME	2.51	2.54	2.56	2.59	2.61	2.64	2.66	2.69	2.71
TEMP	191 A	864.6	375.8	309.6	346.8	204.4	118.9	119.2	104.8
TIME	2.74	2.76	2.79	2.82	2.84	2.87	2.89	2.92	2.94
TEMP	191 A	865.2	388.8	327.7	369.4	221.1	123.7	126.3	111.9
TIME	2.97	2.99	3.02	3.04	3.07	3.09	3.12	3.15	3.17
TEMP	191 A	865.9	417.5	342.9	387.6	235.5	127.8	131.9	118.4
TIME	3.2	3.22	3.25	3.27	3.3	3.32	3.35	3.37	3.4
TEMP	190 A	866.2	432.4	356	401.9	248.5	131.4	137.3	124.3
TIME	3.42	3.45	3.48	3.5	3.53	3.55	3.58	3.6	3.63
TEMP	190 A	865.8	443.8	366.6	413.3	259.5	134.7	142	128.9
TIME	3.65	3.68	3.71	3.73	3.76	3.78	3.81	3.83	3.86
TEMP	190 A	865.4	453.6	375.8	422.1	268.7	137.9	145.3	133
TIME	3.88	3.91	3.93	3.96	3.98	4.01	4.03	4.06	4.09
TEMP	189 A	866	462.4	384	429.2	276.3	140.7	146.3	136
TIME	4.11	4.14	4.16	4.19	4.21	4.24	4.26	4.29	4.32
TEMP	189 A	867.3	469.9	391.2	434.5	282.9	143.3	151.3	138.7
TIME	4.34	4.37	4.39	4.42	4.44	4.47	4.49	4.52	4.54
TEMP	189 A	866.5	475.5	398	438.7	288.6	146	153.8	141
TIME	4.57	4.6	4.62	4.65	4.67	4.7	4.72	4.75	4.77

TEMP 188 A	866.7	483	404	442.3	293.4	148.5	155.9	143
TIME 4.8	4.82	4.85	4.87	4.9	4.93	4.95	4.98	5
TEMP 188 A	868.6	489.2	409.9	445.3	297	151.2	157.8	144.6
TIME 5.03	5.05	5.08	5.1	5.13	5.15	5.18	5.2	5.23
TEMP 188 A	868.9	494.9	415.5	447.8	300.6	153.5	159.4	145.7
TIME 5.25	5.28	5.31	5.33	5.36	5.38	5.41	5.43	5.46
TEMP 188 A	868.6	500.5	421	449.8	303.6	155.9	161	146.4
TIME 5.49	5.51	5.54	5.56	5.59	5.61	5.64	5.66	5.69
TEMP 187 A	870.3	505.9	426.2	451.8	306	158.3	162.2	147.1
TIME 5.71	5.74	5.76	5.79	5.81	5.84	5.87	5.89	5.92
TEMP 187 A	871.9	510.9	431.7	453.6	308.3	160.8	163.7	147.8
TIME 5.94	5.97	5.99	6.02	6.04	6.07	6.1	6.12	6.15
TEMP 187 A	872.5	515.9	436.4	455	310.5	162.8	165.4	148
TIME 6.17	6.2	6.22	6.25	6.27	6.3	6.32	6.35	6.37
TEMP 187 A	873	520.7	441.2	456.3	312.1	165.2	166.1	148.2
TIME 6.4	6.43	6.45	6.48	6.5	6.53	6.55	6.58	6.6
TEMP 187 A	874.5	525.4	445.9	457.8	313.5	167.4	168.9	149.1
TIME 6.63	6.65	6.68	6.71	6.73	6.76	6.78	6.81	6.83
TEMP 187 A	875.5	529.7	450.5	459	315	169.5	168.4	148.1
TIME 6.86	6.88	6.91	6.93	6.96	6.98	7.01	7.03	7.06
TEMP 187 A	875.8	534	455	460	316.6	171.7	169.4	147.8
TIME 7.09	7.11	7.14	7.16	7.19	7.21	7.24	7.26	7.29
TEMP 187 A	877.6	538	459.5	461.4	317.6	173.9	170.2	147.9
TIME 7.32	7.34	7.37	7.39	7.42	7.44	7.47	7.49	7.52

TEMP	186 A	678.9	542.2	463.4	462.9	318.5	176	171.2	147.6
TIME	7.55	7.57	7.6	7.62	7.65	7.67	7.7	7.72	7.75
TEMP	186 A	879.7	546	467.6	463.7	319.7	178.1	172.3	147.3
TIME	7.77	7.8	7.82	7.85	7.88	7.9	7.93	7.95	7.98
TEMP	186 A	880	549.5	471.9	464.5	320.8	180.2	173.7	147
TIME	8	8.03	8.05	8.08	8.1	8.13	8.16	8.18	8.21
TEMP	186 A	881.7	553.2	475.7	465.7	321.9	182.4	174.2	146.6
TIME	8.23	8.26	8.29	8.31	8.33	8.36	8.39	8.41	8.44
TEMP	186 A	882.8	556.9	479.4	466.8	322.6	184.3	175.1	146.3
TIME	8.46	8.49	8.51	8.54	8.56	8.59	8.62	8.64	8.67
TEMP	186 A	884.1	560.2	483.2	467.7	323.7	186.1	176.6	146.5
TIME	8.69	8.72	8.74	8.77	8.79	8.82	8.84	8.87	8.9
TEMP	186 A	884.8	563.3	486.9	468.8	324.9	188.3	177.6	146
TIME	8.92	8.95	8.97	9	9.02	9.05	9.07	9.1	9.12
TEMP	185 A	885.7	566.6	490.4	470.3	325.8	190.3	178.2	145.6
TIME	9.15	9.18	9.2	9.23	9.25	9.28	9.3	9.33	9.35
TEMP	185 A	887.6	569.7	493.6	471.7	326.7	192.4	179.2	145.6
TIME	9.38	9.4	9.43	9.45	9.48	9.5	9.53	9.56	9.58
TEMP	185 A	887.8	572.9	497	472.5	327.7	194.3	180.3	145.3
TIME	9.61	9.63	9.66	9.68	9.71	9.73	9.76	9.78	9.81
TEMP	185 A	888	575.6	500.2	473.1	328.7	196.4	181.5	144.8
TIME	9.84	9.86	9.89	9.91	9.94	9.96	9.99	10.01	10.04
TEMP	185 A	889.5	578.5	503.7	474	329.7	198.3	182.6	144.8
TIME	10.06	10.09	10.11	10.14	10.17	10.19	10.22	10.24	10.27

TEMP	185 A	891.5	581.2	506.6	475.4	330.5	200.4	183.8	144.8
TIME	10.29	10.32	10.34	10.37	10.4	10.42	10.45	10.47	10.5
TEMP	185 A	891.6	583.7	509.7	476.4	331.9	202.1	184.9	144.5
TIME	10.52	10.55	10.57	10.6	10.62	10.65	10.67	10.7	10.73
TEMP	185 A	891.7	586.5	512.4	477.7	332.7	204	185.8	144.3
TIME	10.75	10.78	10.8	10.83	10.85	10.88	10.9	10.93	10.96
TEMP	185 A	893	588.8	515.6	479.3	333.8	205.9	186.9	144.4
TIME	10.98	11.01	11.03	11.06	11.09	11.11	11.13	11.16	11.19
TEMP	184 A	894.5	591.3	518.1	481.1	334.7	207.9	187.8	144.3
TIME	11.21	11.24	11.26	11.29	11.31	11.34	11.36	11.39	11.42

DATA FILE: RADMATCH6 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	28.4	28.6	28.7	28.5	28.5	28.5	27.7	26.8
TIME 0	.03	.05	.09	.1	.13	.15	.18	.2
TEMP 229 A	99.1	29.2	29.1	29.1	28.6	28.4	28.1	27
TIME .23	.25	.28	.3	.33	.35	.38	.4	.43
TEMP 211 A	243.3	32.9	32	31.4	29.3	29.3	28.2	27.4
TIME .45	.48	.51	.53	.56	.58	.61	.63	.66
TEMP 199 A	375.5	40.4	39.3	36.7	31.3	30.9	29.6	27.9
TIME .68	.71	.73	.76	.78	.81	.83	.86	.88
TEMP 191 A	487.3	52.4	49.2	46.1	35.8	34.7	31.8	29.8
TIME .91	.93	.96	.98	1.01	1.03	1.06	1.08	1.11
TEMP 186 A	582.9	71.3	64.6	62	42.9	40.5	36.2	33.1
TIME 1.13	1.16	1.18	1.21	1.23	1.26	1.28	1.31	1.33
TEMP 182 A	657.8	96.2	85.9	83.9	53.9	48.4	42.4	37.8
TIME 1.36	1.38	1.41	1.43	1.46	1.48	1.51	1.54	1.56
TEMP 180 A	713.7	126.8	111.4	111.4	67.9	57.2	50.1	43.6
TIME 1.59	1.61	1.64	1.66	1.69	1.71	1.74	1.77	1.79
TEMP 178 A	753.3	160.2	139.1	142.2	84.4	66.5	58.6	50.9
TIME 1.82	1.84	1.87	1.89	1.92	1.94	1.97	2	2.02

TEMP TIME	176 A 2.05	780.1 2.07	195.3 2.1	186.8 2.12	174.7 2.15	102.2 2.17	75.1 2.2	67.8 2.22	58.7 2.25
TEMP TIME	175 A 2.28	796.3 2.3	230.6 2.33	193.7 2.35	207 2.38	120.4 2.4	82.8 2.43	76.9 2.46	66.4 2.48
TEMP TIME	174 A 2.51	807.3 2.53	263 2.56	218.5 2.58	237.6 2.61	138 2.63	89.7 2.66	85.3 2.69	74.2 2.71
TEMP TIME	174 A 2.74	808.3 2.76	292.8 2.79	240.3 2.81	265.9 2.84	154.1 2.86	95.3 2.89	92.8 2.92	81.2 2.94
TEMP TIME	174 A 2.97	811.4 2.99	318.4 3.02	259.5 3.04	290.4 3.07	169.4 3.09	100.2 3.12	99.6 3.15	89.1 3.17
TEMP TIME	173 A 3.2	813.6 3.22	340.4 3.25	275.3 3.27	311.6 3.3	183.1 3.32	104.3 3.35	105.3 3.38	94 3.4
TEMP TIME	173 A 3.43	814.4 3.45	358.3 3.48	289 3.5	329 3.53	195.9 3.55	107.6 3.58	110.9 3.61	99.4 3.63
TEMP TIME	173 A 3.66	813.9 3.68	372.9 3.71	300.7 3.73	343.1 3.76	207 3.78	110.9 3.81	115.6 3.83	104.4 3.86
TEMP TIME	172 A 3.89	814 3.91	385.4 3.94	310.6 3.96	355 3.99	216.8 4.01	113.9 4.04	119.2 4.06	108.6 4.09
TEMP TIME	172 A 4.12	814 4.14	396 4.17	319.2 4.19	364.8 4.22	225.3 4.24	116.4 4.27	122.4 4.29	112.2 4.32
TEMP TIME	171 A 4.34	813.6 4.37	404.7 4.39	327 4.42	372.5 4.44	232.9 4.47	118.7 4.5	125.7 4.52	115.3 4.55
TEMP TIME	171 A 4.57	814.3 4.6	411.5 4.62	334.3 4.65	378.7 4.67	239.7 4.7	121.1 4.73	128.5 4.75	118.1 4.78

TEMP TIME	170 A 4.8	815 4.83	418 4.65	340.7 4.98	384.1 4.9	245.4 4.93	123.4 4.95	130.6 4.98	120.6 5.01
TEMP TIME	170 A 5.03	815.4 5.06	424.7 5.08	346.2 5.11	388.6 5.13	250.2 5.16	125.6 5.18	132.3 5.21	122.5 5.24
TEMP TIME	170 A 5.26	816.6 5.29	430.2 5.31	352.1 5.34	392.2 5.36	254.6 5.39	127.4 5.41	134.6 5.44	124.3 5.46
TEMP TIME	170 A 5.49	816.7 5.52	435.4 5.54	357.1 5.57	395.2 5.59	258.5 5.62	129.6 5.64	136.4 5.67	125.8 5.69
TEMP TIME	170 A 5.72	816 5.74	440.5 5.77	361.9 5.79	397.9 5.82	261.8 5.85	131.9 5.87	137.5 5.9	127 5.92
TEMP TIME	169 A 5.95	815.1 5.97	445.5 6	366.5 6.02	400.3 6.05	264.5 6.07	133.6 6.1	138.8 6.13	127.9 6.15
TEMP TIME	169 A 6.19	815.8 6.2	450.1 6.23	371.1 6.25	402.3 6.28	267.1 6.3	135.5 6.33	140.4 6.35	128.5 6.38
TEMP TIME	169 A 6.41	815.6 6.43	454.4 6.46	375.6 6.48	403.8 6.51	269.7 6.53	137.4 6.56	141.5 6.58	129.2 6.61
TEMP TIME	169 A 6.63	816.7 6.66	459.8 6.69	379.8 6.71	405.7 6.74	271.6 6.76	139.3 6.79	142.7 6.81	129.9 6.84
TEMP TIME	168 A 6.86	818.2 6.89	463 6.91	383.8 6.94	407.3 6.96	273.4 6.99	141.1 7.01	143.8 7.04	130.4 7.07
TEMP TIME	168 A 7.09	817.9 7.12	467 7.14	388 7.17	408.6 7.19	275.2 7.22	143 7.24	145.2 7.27	130.7 7.29
TEMP TIME	168 A 7.32	818.1 7.35	470.9 7.37	391.9 7.4	409.9 7.42	276.7 7.45	144.9 7.47	145.7 7.5	131 7.52

TEMP 168 A	818.4	475	395.8	411.4	278	145.5	145.5	131.1
TIME 7.55	7.57	7.6	7.62	7.65	7.67	7.7	7.73	7.75
TEMP 169 A	819.3	478.6	399.6	412.6	279.5	148.3	148	131.2
TIME 7.78	7.8	7.93	7.85	7.88	7.9	7.93	7.95	7.98
TEMP 169 A	820	482.2	403.5	413.7	280.7	149.9	148.8	131.2
TIME 8	8.03	8.06	8.08	8.11	8.13	8.16	8.18	8.21
TEMP 168 A	821.4	485.5	407.4	414.8	281.9	151.7	149.8	131.3
TIME 8.23	8.26	8.28	8.31	8.34	8.36	8.39	8.41	8.44
TEMP 167 A	822.9	489	410.9	416.2	282.9	153.5	150.8	131.4
TIME 8.46	8.49	8.51	8.54	8.56	8.59	8.62	8.64	8.67
TEMP 167 A	822.8	492.4	414.3	417.1	284.1	155.2	151.6	131.3
TIME 8.69	8.72	8.74	8.77	8.79	8.82	8.84	8.87	8.9
TEMP 167 A	822.7	495.6	417.9	418.1	285.2	156.7	152.5	131.2
TIME 8.92	8.95	8.97	9	9.02	9.05	9.07	9.1	9.12
TEMP 167 A	824.4	498.7	421.4	419.4	286.1	158.6	153.1	131.2
TIME 9.15	9.18	9.2	9.23	9.25	9.28	9.3	9.33	9.35
TEMP 167 A	825.7	501.6	424.8	420.4	287.4	160	154.4	131.3
TIME 9.38	9.4	9.43	9.45	9.48	9.5	9.53	9.56	9.58
TEMP 167 A	825.9	504.6	428	421.5	288.4	161.8	155.5	131.3
TIME 9.61	9.63	9.66	9.68	9.71	9.73	9.76	9.79	9.81
TEMP 167 A	826.1	507.5	431	422.6	289.1	163.8	156	131
TIME 9.84	9.86	9.89	9.91	9.94	9.96	9.99	10.01	10.04
TEMP 166 A	827.5	510.4	434.1	423.7	290.2	165.2	155.7	131
TIME 10.07	10.09	10.12	10.14	10.17	10.19	10.22	10.24	10.27

TEMP 166 A	828.7	513	437.4	424.6	291.4	156.6	157.8	131.2
TIME 10.29	10.32	10.35	10.37	10.4	10.42	10.45	10.47	10.5
TEMP 166 A	828.6	515.7	440.3	425.5	292.5	168.4	159.1	131.1
TIME 10.52	10.55	10.58	10.6	10.63	10.65	10.68	10.7	10.73
TEMP 166 A	829.4	518.2	443.1	426.4	293.4	170.3	159.5	131.1
TIME 10.75	10.78	10.8	10.83	10.85	10.88	10.9	10.93	10.96
TEMP 166 A	830.4	520.8	445.8	427.4	294.3	171.7	160.2	130.9
TIME 10.98	11.01	11.03	11.06	11.08	11.11	11.13	11.16	11.18
TEMP 166 A	831.2	523.2	448.8	428.3	295.3	173.2	161.4	130.9
TIME 11.21	11.24	11.26	11.29	11.31	11.34	11.36	11.39	11.41

APPENDIX F.2

THE ENCLOSED AIR TESTS

DATA FILE: TAC20 (TEMPERATURES IN DEGREES CELSIUS)

UC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	24.8	25.4	25.2	25.5	25.1	25.5	25.3	25.4
TIME 0	.03	.05	.08	.1	.13	.15	.18	.21
TEMP 263 A	143.5	25.6	25.4	25.7	25.3	25.7	25.4	25.4
TIME .23	.26	.28	.31	.34	.36	.39	.41	.44
TEMP 236 A	315	25.9	26.4	26	26.1	26.1	26.2	25.8
TIME .47	.49	.52	.54	.57	.59	.62	.64	.67
TEMP 222 A	444.1	29	27.5	27.4	27.1	27.1	26.6	26.2
TIME .69	.72	.75	.77	.8	.82	.85	.88	.9
TEMP 213 A	543.2	42.5	29.8	29.6	28.2	28.8	27.6	25.9
TIME .93	.95	.98	1	1.03	1.06	1.08	1.11	1.13
TEMP 208 A	616.1	63.3	32.8	32.1	30	30.7	28.8	27.8
TIME 1.16	1.19	1.21	1.24	1.26	1.29	1.31	1.34	1.36
TEMP 205 A	669.3	81.3	36	35.2	31.2	32.9	29.7	28.8
TIME 1.39	1.42	1.44	1.47	1.49	1.52	1.54	1.57	1.59
TEMP 202 A	706.6	100.7	40	37.7	32.7	34.6	30.9	29.6
TIME 1.62	1.64	1.67	1.7	1.72	1.75	1.77	1.8	1.82
TEMP 201 A	733	121.7	45	39.6	34.3	36.8	32.2	30.2
TIME 1.85	1.87	1.9	1.93	1.95	1.98	2	2.03	2.05

TEMP	200 A	751.4	137.4	51.4	41.3	35.6	39.4	32.9	30.7
TIME	2.08	2.1	2.13	2.15	2.18	2.21	2.23	2.26	2.28
TEMP	199 A	765.2	148	59.3	43.3	36.4	39.8	33.5	31.5
TIME	2.31	2.33	2.36	2.38	2.41	2.43	2.46	2.48	2.51
TEMP	198 A	775.7	154.6	66.5	45.4	37.1	41.2	34.4	32
TIME	2.54	2.56	2.59	2.61	2.64	2.66	2.69	2.71	2.74
TEMP	199 A	784.2	160.2	72	49.8	39.2	42.1	35.5	32.2
TIME	2.76	2.79	2.82	2.84	2.87	2.89	2.92	2.94	2.97
TEMP	197 A	791.3	168.1	76.2	53.4	38.9	43.4	36.1	32.6
TIME	2.99	3.02	3.04	3.07	3.1	3.12	3.15	3.17	3.2
TEMP	197 A	796.5	173.3	80.3	57.7	39.4	44.3	36.6	32.9
TIME	3.22	3.25	3.27	3.3	3.33	3.35	3.38	3.4	3.43
TEMP	197 A	801.5	187.2	85	61.5	40.2	45.5	37.5	33.6
TIME	3.45	3.48	3.5	3.53	3.56	3.58	3.61	3.63	3.66
TEMP	196 A	805.9	194.2	90.3	64.3	41.5	46.7	38.5	33.7
TIME	3.68	3.71	3.73	3.76	3.79	3.81	3.84	3.86	3.89
TEMP	196 A	809.7	200.3	95.3	66.6	42.4	47.7	39	33.9
TIME	3.91	3.94	3.96	3.99	4.02	4.04	4.07	4.09	4.12
TEMP	196 A	814.2	207.5	99.9	69.1	42.8	49	39.6	34.4
TIME	4.14	4.17	4.19	4.22	4.25	4.27	4.3	4.32	4.35
TEMP	196 A	817.8	215.6	103.7	72	43.7	50.2	39.9	34.9
TIME	4.37	4.4	4.42	4.45	4.48	4.5	4.53	4.55	4.58
TEMP	195 A	820.7	222.3	108.2	75.1	45.9	51.2	40.5	35.2
TIME	4.6	4.63	4.65	4.68	4.7	4.73	4.76	4.78	4.81

TEMP	195 A	823.2	227.5	113.5	78.1	48.9	52.5	41.2	35.7
TIME	4.83	4.86	4.88	4.91	4.93	4.96	4.99	5.01	5.04
TEMP	195 A	825.7	233.2	118.2	81.1	51.7	53.7	41.5	35.8
TIME	5.06	5.09	5.11	5.14	5.17	5.19	5.22	5.24	5.27
TEMP	195 A	827.8	239	122.5	84	54.5	54.9	42.2	36.2
TIME	5.29	5.32	5.34	5.37	5.39	5.42	5.45	5.47	5.5
TEMP	194 A	830.3	245	125.8	86.7	56.5	56.3	42.5	36.5
TIME	5.52	5.55	5.57	5.6	5.63	5.65	5.68	5.7	5.73
TEMP	194 A	833.5	250.2	129.9	89.8	58.3	58.2	43.4	37.2
TIME	5.75	5.78	5.81	5.83	5.86	5.88	5.91	5.93	5.96
TEMP	194 A	836.1	255.8	133.7	92.3	60.2	60.2	44.1	37.4
TIME	5.98	6.01	6.04	6.06	6.08	6.11	6.14	6.16	6.19
TEMP	194 A	838.5	261.1	138	94.9	62.3	61.6	45.2	38
TIME	6.21	6.24	6.27	6.29	6.32	6.34	6.37	6.4	6.42
TEMP	194 A	840.1	266.4	141.8	97.7	64.3	62.9	46.7	38.4
TIME	6.45	6.47	6.5	6.52	6.55	6.58	6.6	6.63	6.65
TEMP	193 A	842.3	270.8	145	100.5	66.2	63.9	47.4	38.4
TIME	6.68	6.7	6.73	6.76	6.78	6.81	6.83	6.86	6.88
TEMP	193 A	844.1	275.5	148.2	103	68	65.3	48.3	38.9
TIME	6.91	6.93	6.96	6.99	7.01	7.04	7.06	7.09	7.11
TEMP	193 A	846.7	280.9	151	105.4	69.3	66.9	48.6	39.4
TIME	7.14	7.16	7.19	7.22	7.24	7.27	7.29	7.32	7.34
TEMP	193 A	849.7	286.2	154.9	107.3	70.9	68.1	49.6	40.1
TIME	7.37	7.4	7.42	7.45	7.47	7.5	7.52	7.55	7.58

TEMP TIME	193 A 7.6	850.2 7.63	291.4 7.65	158.4 7.68	109.1 7.7	72.6 7.73	69.3 7.75	50.3 7.78	40.6 7.81
TEMP TIME	193 A 7.83	851.6 7.86	295.6 7.88	162.1 7.91	111.4 7.94	74.4 7.96	70.8 7.99	50.8 8.01	41.1 8.04
TEMP TIME	193 A 8.06	851.7 8.09	299.5 8.11	165.7 8.14	113.9 8.17	76.3 8.19	71.8 8.22	51.8 8.24	41.5 8.27
TEMP TIME	192 A 8.3	853.8 8.32	303.4 8.35	168.5 8.37	116.9 8.4	77.9 8.42	73.1 8.45	52.3 8.47	41.5 8.5
TEMP TIME	192 A 8.53	855.5 8.55	308 8.58	171.2 8.6	119.1 8.63	79.5 8.65	74.8 8.68	53.2 8.71	42 8.73
TEMP TIME	192 A 8.76	857 8.78	312.6 8.81	173.7 8.83	121.4 8.86	80.9 8.89	76.5 8.91	54 8.94	42.3 8.96
TEMP TIME	192 A 8.99	858.8 9.01	316.7 9.04	176.3 9.07	124.1 9.09	82.4 9.12	78.1 9.14	55 9.17	42.7 9.19
TEMP TIME	192 A 9.22	860.1 9.25	320.6 9.27	179.7 9.3	126.6 9.32	84 9.35	79.6 9.37	56.5 9.4	43.4 9.43
TEMP TIME	192 A 9.45	861.4 9.48	324.7 9.5	182.7 9.53	129 9.55	85.7 9.58	80.9 9.61	57.7 9.63	43.7 9.66
TEMP TIME	192 A 9.68	863 9.71	328.7 9.73	185.9 9.76	131 9.78	87.6 9.81	82.3 9.84	58.7 9.86	44 9.89
TEMP TIME	192 A 9.91	864.2 9.94	332.8 9.96	188.7 9.99	132.9 10.01	89.3 10.04	83.5 10.07	59.6 10.09	44 10.12
TEMP TIME	191 A 10.14	865.8 10.17	336.5 10.19	191.9 10.22	135.3 10.25	90.7 10.27	85 10.3	60.3 10.32	44.2 10.35

TEMP 191 A	867	340.4	194.3	138	91.8	86.3	60.8	44.2
TIME 10.37	10.4	10.42	10.45	10.48	10.5	10.53	10.55	10.58
TEMP 191 A	858.3	343.5	197.5	140.3	93.3	87.9	61.8	44.7
TIME 10.6	10.63	10.66	10.68	10.71	10.73	10.76	10.78	10.81
TEMP 191 A	868.4	346.8	200.1	142.5	95.2	89.2	62.7	45
TIME 10.83	10.86	10.89	10.91	10.94	10.96	10.99	11.01	11.04
TEMP 191 A	871	350	202.8	144.4	97.5	90.5	63.7	45.5
TIME 11.07	11.09	11.12	11.14	11.17	11.19	11.22	11.25	11.27
TEMP 191 A	871.8	353.4	205.4	146.1	99.6	91.8	65.1	45.9
TIME 11.3	11.32	11.35	11.37	11.4	11.42	11.45	11.48	11.5

DATA FILE: TAC21 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC00	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP -1 A	22.3	23	22.8	23.2	22.8	23.1	23.1	23.2
TIME 0	.03	.05	.08	.1	.13	.16	.18	.21
TEMP 264 A	125.2	23.2	23.3	23.2	23.3	23.3	23.7	23.6
TIME .23	.26	.28	.31	.34	.36	.39	.41	.44
TEMP 237 A	299.3	23.8	24	23.8	23.9	23.8	23.7	23.4
TIME .46	.49	.51	.54	.56	.59	.62	.64	.67
TEMP 222 A	430.5	26.3	25	25	24.5	24.7	24	24.1
TIME .69	.72	.74	.77	.79	.82	.85	.87	.9
TEMP 213 A	530.7	37.1	26.9	27	25.6	26.1	25.1	25
TIME .92	.95	.97	1	1.02	1.05	1.07	1.1	1.12
TEMP 207 A	604.7	56.9	29.5	29	27.1	27.9	26.2	25.4
TIME 1.15	1.18	1.2	1.23	1.25	1.28	1.3	1.33	1.35
TEMP 204 A	658.6	74.2	32.7	31.6	28.7	29.8	27.3	26.2
TIME 1.36	1.4	1.43	1.45	1.48	1.5	1.53	1.55	1.58
TEMP 202 A	698.8	93.1	36.1	34.3	29.9	31.8	28.4	27.2
TIME 1.61	1.63	1.66	1.68	1.71	1.73	1.76	1.78	1.81
TEMP 200 A	725.9	113.6	40.6	36.2	31.6	33.7	29.3	27.8
TIME 1.83	1.86	1.88	1.91	1.93	1.96	1.98	2.01	2.04
TEMP 199 A	745.8	131.6	45.9	38.2	32.9	35.3	30.4	28.3
TIME 2.06	2.09	2.11	2.14	2.16	2.19	2.21	2.24	2.26

TEMP 188 A	760.6	142.7	52.8	40.4	33.5	36.9	31	29.4
TIME 2.29	2.32	2.34	2.37	2.39	2.42	2.44	2.47	2.49
TEMP 197 A	771.8	149.8	61	41.7	34.6	38.2	32.1	29.7
TIME 2.52	2.54	2.57	2.59	2.62	2.64	2.67	2.7	2.72
TEMP 196 A	780.9	154.9	66.8	44.1	35.5	39.2	32.7	29.8
TIME 2.75	2.77	2.8	2.82	2.85	2.87	2.9	2.92	2.95
TEMP 196 A	788	161.8	71.2	48.5	36.1	40.3	33.2	30.3
TIME 2.97	3	3.03	3.05	3.08	3.1	3.13	3.15	3.18
TEMP 186 A	794	170.9	75	53	36.6	41.5	34.2	30.7
TIME 3.2	3.23	3.25	3.28	3.3	3.33	3.36	3.38	3.41
TEMP 195 A	798.9	179.6	79.7	56.6	37.6	42.5	35	30.9
TIME 3.43	3.46	3.48	3.51	3.53	3.56	3.58	3.61	3.63
TEMP 195 A	803.8	187.2	84.3	59.5	38.6	43.5	35.7	31.2
TIME 3.66	3.69	3.71	3.74	3.76	3.79	3.81	3.84	3.86
TEMP 195 A	808.5	193.8	88.8	62.5	39.3	44.8	36.1	31.8
TIME 3.89	3.92	3.94	3.97	3.99	4.02	4.04	4.07	4.09
TEMP 195 A	812.1	200.3	93.6	65	39.8	46	36.7	32.1
TIME 4.12	4.14	4.17	4.2	4.22	4.25	4.27	4.3	4.32
TEMP 194 A	816	207.4	98.3	67.3	41.2	47.2	37.7	32.6
TIME 4.35	4.37	4.4	4.43	4.45	4.48	4.5	4.53	4.55
TEMP 194 A	819.9	214.5	102.3	70.2	43.2	48.2	37.8	32.8
TIME 4.58	4.6	4.63	4.65	4.68	4.71	4.73	4.76	4.78
TEMP 194 A	822.4	221.1	106.5	73.5	45.5	49.3	38.1	33.1
TIME 4.81	4.83	4.86	4.88	4.91	4.94	4.96	4.99	5.01

TEMP	194 A	824.5	226.2	111.5	75.6	48.2	50.8	38.9	33.8
TIME	5.04	5.06	5.09	5.11	5.14	5.16	5.19	5.22	5.24
TEMP	193 A	827	231.2	115.8	79.5	50.9	52	39.4	34
TIME	5.27	5.29	5.32	5.34	5.37	5.4	5.42	5.45	5.47
TEMP	193 A	828.7	237	119.8	81.8	53.5	53	40.1	34.1
TIME	5.5	5.52	5.55	5.57	5.6	5.62	5.65	5.68	5.7
TEMP	193 A	830.9	242.2	123.5	84.5	55	54.5	40.8	34.6
TIME	5.73	5.75	5.78	5.8	5.83	5.85	5.88	5.91	5.93
TEMP	193 A	833.6	247.9	127.1	87.5	56.6	56.5	41.2	35
TIME	5.96	5.98	6.01	6.03	6.06	6.08	6.11	6.14	6.16
TEMP	193 A	836.3	253.1	131	89.9	58.4	58	42.3	35.5
TIME	6.19	6.21	6.24	6.26	6.29	6.31	6.34	6.36	6.39
TEMP	193 A	838.9	258.5	135.1	92.3	60.3	59.5	43.8	35.9
TIME	6.42	6.44	6.47	6.49	6.52	6.54	6.57	6.59	6.62
TEMP	192 A	840.9	263.1	138.7	95	62.1	60.8	44.6	36.1
TIME	6.55	6.57	6.7	6.72	6.75	6.78	6.8	6.83	6.85
TEMP	192 A	843	267.1	141.9	97.8	64	62.3	45.4	36.8
TIME	6.58	6.9	6.93	6.95	6.98	7.01	7.03	7.06	7.08
TEMP	192 A	844.6	272.1	144.4	100.6	65.4	63.7	46.1	36.9
TIME	7.11	7.13	7.16	7.18	7.21	7.23	7.26	7.29	7.31
TEMP	192 A	845.2	277.1	147.8	102.7	67	65.3	47	38
TIME	7.34	7.36	7.39	7.41	7.44	7.47	7.49	7.52	7.54
TEMP	192 A	846.7	282.1	151.3	104.5	68.9	66.5	47.7	38.2
TIME	7.57	7.59	7.62	7.64	7.67	7.7	7.72	7.75	7.77

TEMP	192 A	950	286.8	155.2	106.1	70.8	67.5	48.5	38.6
TIME	7.8	7.92	7.85	7.87	7.9	7.93	7.95	7.98	8
TEMP	192 A	951.9	291.1	158.4	108.7	72.6	68.6	48.9	39
TIME	8.03	8.05	8.08	8.1	8.13	8.16	8.18	8.21	8.23
TEMP	191 A	852.4	295.1	161.2	112	73.7	69.8	49.3	39.5
TIME	8.26	8.28	8.31	8.33	8.36	8.38	8.41	8.43	8.46
TEMP	191 A	852.2	299.2	164.3	114.3	75	71.2	50.2	39.8
TIME	8.49	8.51	8.54	8.56	8.59	8.61	8.64	8.66	8.69
TEMP	191 A	854	303.1	167	116.1	76.8	72.8	51.1	40.2
TIME	8.72	8.74	8.77	8.79	8.82	8.84	8.87	8.9	8.92
TEMP	191 A	855.2	307.3	169.5	118.2	78.4	74.2	52.2	40.3
TIME	8.95	8.97	9	9.02	9.05	9.07	9.1	9.13	9.15
TEMP	191 A	857	310.8	172.3	121	80	75.9	53.2	40.7
TIME	9.18	9.2	9.23	9.25	9.28	9.31	9.33	9.36	9.38
TEMP	191 A	858.5	314.8	174.9	123.9	81.2	77.1	54.2	41
TIME	9.41	9.43	9.46	9.48	9.51	9.53	9.56	9.59	9.61
TEMP	191 A	859.7	318.7	177.9	125.9	82.8	78.6	55.5	41.7
TIME	9.64	9.66	9.69	9.71	9.74	9.77	9.79	9.82	9.84
TEMP	190 A	860.9	322.7	180.7	128	84.4	80	56.4	41.8
TIME	9.87	9.89	9.92	9.94	9.97	10	10.02	10.05	10.07
TEMP	190 A	861.5	326.3	184	129.7	86.1	81.1	57.6	41.9
TIME	10.1	10.12	10.15	10.17	10.2	10.23	10.25	10.28	10.3
TEMP	190 A	863.3	330	186.6	132.1	87.7	82.5	58	41.6
TIME	10.33	10.35	10.38	10.4	10.43	10.46	10.48	10.51	10.53

TEMP 190 A	864.3	333.5	189.5	134.6	89.2	83.6	58.7	42
TIME 10.56	10.58	10.61	10.64	10.66	10.69	10.71	10.74	10.76
TEMP 190 A	866.2	336.7	191.9	137.2	90.4	85.1	59.3	42.6
TIME 10.79	10.81	10.84	10.87	10.89	10.92	10.94	10.97	10.99
TEMP 190 A	866.9	340	194.5	139.2	92.4	86.7	60	42.9
TIME 11.02	11.04	11.07	11.09	11.12	11.15	11.17	11.2	11.22
TEMP 190 A	867.6	342.9	197.4	140.8	94.6	87.9	61.6	43.4
TIME 11.25	11.27	11.3	11.32	11.35	11.38	11.4	11.43	11.45

DATA FILE: TAO22 (TEMPERATURES IN DEGREES CELSIUS)

DC	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	21.9	22.3	22.9	22.4	22.8	22.8	22.8	22.8
TIME 0	.03	.05	.08	.1	.13	.15	.18	.2
TEMP 255 A	173	22.8	23.1	22.9	23.1	22.8	23.1	22.9
TIME .23	.26	.28	.31	.33	.36	.38	.41	.43
TEMP 231 A	332.3	23.9	23.4	24	23.2	23.8	23.3	23.7
TIME .46	.48	.51	.53	.56	.59	.61	.64	.66
TEMP 218 A	452.8	27	24.9	25.1	24.4	24.7	24.1	24.2
TIME .69	.71	.74	.76	.79	.81	.84	.86	.89
TEMP 211 A	544.5	41.4	26.8	26.8	25.6	26.2	25	24.4
TIME .92	.94	.97	.99	1.02	1.04	1.07	1.09	1.12
TEMP 206 A	614	60.9	29.8	29.1	27	27.8	25.9	25.4
TIME 1.15	1.17	1.2	1.22	1.25	1.27	1.3	1.32	1.35
TEMP 203 A	666.1	77.6	32.8	31.9	28.2	30.1	26.9	26.5
TIME 1.37	1.4	1.43	1.45	1.48	1.5	1.53	1.55	1.58
TEMP 201 A	703.7	96.8	36.6	34.3	29.8	32	28.3	27.1
TIME 1.6	1.63	1.65	1.68	1.71	1.73	1.76	1.78	1.81
TEMP 200 A	729.8	117.5	41.3	36.3	31.4	33.6	29.2	27.3
TIME 1.83	1.86	1.88	1.91	1.93	1.95	1.98	2.01	2.03

TEMP 198 A	748.4	133.7	47	38.1	32.5	35.4	25.9	28.3
TIME 2.06	2.09	2.11	2.14	2.16	2.19	2.21	2.24	2.26
TEMP 198 A	752.7	143.8	54.5	40	33.4	37	30.8	29
TIME 2.29	2.31	2.34	2.36	2.39	2.42	2.44	2.47	2.49
TEMP 197 A	773.8	150.6	62.1	41.5	34.8	38.1	31.9	29.3
TIME 2.52	2.54	2.57	2.59	2.62	2.64	2.67	2.69	2.72
TEMP 197 A	782.9	156.2	67.2	44.8	35.6	39	32.7	29.7
TIME 2.75	2.77	2.8	2.82	2.85	2.87	2.9	2.92	2.95
TEMP 196 A	790.2	164	71.4	49.5	35.9	40.5	33.3	30.3
TIME 2.97	3	3.03	3.05	3.08	3.1	3.13	3.15	3.18
TEMP 196 A	796.2	173.3	75.5	53.6	36.6	41.5	34	30.6
TIME 3.2	3.23	3.25	3.28	3.31	3.33	3.35	3.38	3.41
TEMP 195 A	801	182	80	56.9	37.9	42.2	34.9	30.6
TIME 3.43	3.46	3.48	3.51	3.53	3.56	3.59	3.61	3.64
TEMP 195 A	805.7	189	85.3	60.1	38.7	43.4	35.6	30.9
TIME 3.66	3.69	3.71	3.74	3.76	3.79	3.82	3.84	3.87
TEMP 195 A	810.3	195.6	89.6	63	39.1	44.7	36.2	31.6
TIME 3.89	3.92	3.94	3.97	3.99	4.02	4.04	4.07	4.09
TEMP 195 A	813.7	201.9	94.4	65.3	39.4	46.1	36.6	31.8
TIME 4.12	4.15	4.17	4.2	4.22	4.25	4.27	4.3	4.32
TEMP 194 A	817.1	209.4	99.1	67.5	40.6	47	37.4	32
TIME 4.35	4.38	4.4	4.43	4.45	4.48	4.5	4.53	4.55
TEMP 194 A	820.9	216.2	103.1	70.5	42.5	48	37.8	32.3
TIME 4.58	4.6	4.63	4.66	4.68	4.71	4.73	4.76	4.78

TEMP	194 A	823.8	222.5	107.5	74	44.9	49.3	38.2	32.9
TIME	4.31	4.83	4.86	4.88	4.91	4.94	4.96	4.99	5.01
TEMP	194 A	825.9	227.8	112.5	76.9	47.6	50.7	38.5	33.3
TIME	5.04	5.06	5.09	5.11	5.14	5.17	5.19	5.22	5.24
TEMP	194 A	827.5	232.8	117.1	79.3	50.7	51.9	39.6	33.5
TIME	5.27	5.29	5.32	5.34	5.37	5.4	5.42	5.45	5.47
TEMP	193 A	830	238.3	120.7	82.1	53.1	53.1	40	33.7
TIME	5.5	5.52	5.55	5.57	5.6	5.63	5.65	5.68	5.7
TEMP	193 A	831.6	243.5	124.4	85	55.1	54.5	40.5	34.2
TIME	5.73	5.75	5.78	5.81	5.83	5.86	5.88	5.91	5.93
TEMP	193 A	834.8	249	127.9	87.9	56.8	56.8	41.2	34.9
TIME	5.96	5.98	6.01	6.03	6.06	6.09	6.11	6.14	6.16
TEMP	193 A	837.1	254.7	131.7	90.3	58.5	58.4	42.1	35.1
TIME	6.19	6.21	6.24	6.26	6.29	6.32	6.34	6.37	6.39
TEMP	193 A	839.2	259.8	136	92.9	60.6	59.5	43.6	35.6
TIME	6.42	6.44	6.47	6.49	6.52	6.55	6.57	6.6	6.62
TEMP	192 A	841.6	264.1	139.4	96	62.4	60.7	44.5	35.7
TIME	6.65	6.67	6.7	6.72	6.75	6.78	6.8	6.83	6.85
TEMP	192 A	843.2	268.6	142.3	98.5	64.3	62	45.4	36.4
TIME	6.88	6.9	6.93	6.95	6.98	7.01	7.03	7.06	7.08
TEMP	192 A	845.3	273.3	145.2	101.1	65.5	63.6	46	37.2
TIME	7.11	7.13	7.16	7.18	7.21	7.23	7.26	7.29	7.31
TEMP	192 A	846.6	278.4	148.6	103	67.3	65.1	46.6	37.5
TIME	7.34	7.36	7.39	7.41	7.44	7.46	7.49	7.52	7.54

TEMP 192 A	948.8	292.9	152.3	104.4	69.5	66.2	47.7	38
TIME 7.57	7.59	7.62	7.64	7.67	7.69	7.72	7.75	7.77
TEMP 192 A	950.4	287.9	155.7	106.5	71.3	67.4	48	38.2
TIME 7.8	7.82	7.85	7.88	7.9	7.93	7.95	7.98	8
TEMP 192 A	852	292	159.1	109.2	72.8	68.5	48.8	38.8
TIME 8.03	8.05	8.08	8.11	8.13	8.16	8.18	8.21	8.23
TEMP 191 A	852.7	296.2	161.9	112.5	74	69.9	49	39.3
TIME 8.26	8.28	8.31	8.33	8.36	8.39	8.41	8.44	8.46
TEMP 191 A	852.8	300.4	165	114.7	75.5	71.5	50	39.8
TIME 8.49	8.51	8.54	8.56	8.59	8.62	8.64	8.67	8.69
TEMP 191 A	854.7	304.6	167.5	116.9	76.9	73.1	51.1	40.1
TIME 8.72	8.75	8.77	8.8	8.82	8.85	8.87	8.9	8.93
TEMP 191 A	856	308	170.2	118.9	78.7	74.5	52.2	40.6
TIME 8.95	8.98	9	9.03	9.05	9.08	9.1	9.13	9.16
TEMP 191 A	857.3	311.9	173.1	121.5	80.3	75.8	53.6	40.9
TIME 9.18	9.21	9.23	9.26	9.29	9.31	9.34	9.36	9.39
TEMP 191 A	859.1	315.7	175.9	124	82	77.2	54.6	40.9
TIME 9.41	9.44	9.46	9.49	9.52	9.54	9.57	9.59	9.62
TEMP 191 A	860.1	319.7	178.9	126.2	83.8	78.4	55.6	41.5
TIME 9.54	9.57	9.7	9.72	9.75	9.77	9.8	9.82	9.85
TEMP 190 A	861.9	323.9	181.4	128.7	85	79.9	56.2	41.8
TIME 9.88	9.9	9.93	9.95	9.98	10	10.03	10.05	10.08
TEMP 190 A	862.7	327.7	184.3	130.8	86.3	81.2	57.2	42.3
TIME 10.1	10.13	10.16	10.18	10.21	10.23	10.26	10.28	10.31

TEMP 190 A	864.2	331.2	187.2	133.1	87.9	82.7	57.7	42.3
TIME 10.34	10.36	10.39	10.41	10.44	10.46	10.49	10.52	10.54
TEMP 190 A	865	334.5	190.1	135.1	89.8	83.7	58.6	42.2
TIME 10.57	10.59	10.62	10.64	10.67	10.69	10.72	10.74	10.77
TEMP 190 A	866.5	337.5	193	137.4	91.4	85.1	59.5	42.6
TIME 10.8	10.82	10.85	10.87	10.9	10.92	10.95	10.97	11
TEMP 190 A	867.4	341	195.2	139.8	92.9	86.7	60.1	42.9
TIME 11.03	11.05	11.08	11.1	11.13	11.15	11.18	11.2	11.23
TEMP 190 A	868.6	344.2	197.7	141.9	95	87.9	61.3	43.8
TIME 11.26	11.28	11.31	11.33	11.36	11.38	11.41	11.43	11.46

APPENDIX F.3

THE OPEN AIR TESTS

DATA FILE: OPENAIR6 (TEMPERATURES IN DEGREES CELSIUS)

DC	SIC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	26	29	OUT	OUT	27.8	OUT	28	OUT
TIME 0	.03	.05	.08	.1	.13	.15	.18	.2
TEMP 242 A	117.1	29.4	OUT	OUT	28.1	OUT	28.3	OUT
TIME .23	.25	.28	.31	.33	.36	.38	.41	.43
TEMP 220 A	266.4	28.2	OUT	OUT	29.2	OUT	29	OUT
TIME .46	.48	.51	.53	.56	.58	.61	.63	.66
TEMP 208 A	418.3	30.7	OUT	OUT	28.8	OUT	28.4	OUT
TIME .69	.71	.74	.76	.79	.81	.84	.86	.89
TEMP 199 A	524.9	42.8	OUT	OUT	29.8	OUT	28.8	OUT
TIME .91	.94	.96	.99	1.02	1.04	1.07	1.09	1.12
TEMP 194 A	607	59.2	OUT	OUT	32	OUT	29.8	OUT
TIME 1.14	1.17	1.19	1.22	1.24	1.27	1.29	1.32	1.34
TEMP 191 A	664.4	77.9	OUT	OUT	32.7	OUT	29.4	OUT
TIME 1.37	1.39	1.42	1.45	1.47	1.5	1.52	1.55	1.57
TEMP 188 A	708.9	95.8	OUT	OUT	34.1	OUT	30	OUT
TIME 1.6	1.62	1.65	1.67	1.7	1.72	1.75	1.77	1.8
TEMP 186 A	739.4	119	OUT	OUT	36.6	OUT	31.1	OUT
TIME 1.82	1.85	1.88	1.9	1.93	1.95	1.98	2	2.03

TEMP	165 A	757.7	141.2	OUT	OUT	36.8	OUT	30.8	OUT
TIME	2.05	2.08	2.1	2.13	2.15	2.18	2.2	2.23	2.25
TEMP	183 A	774.4	153.2	OUT	OUT	38.8	OUT	32.2	OUT
TIME	2.28	2.3	2.33	2.35	2.38	2.4	2.43	2.45	2.48
TEMP	183 A	782.8	158.6	OUT	OUT	40	OUT	32	OUT
TIME	2.5	2.53	2.55	2.58	2.61	2.63	2.66	2.68	2.71
TEMP	182 A	790.9	166.9	OUT	OUT	40.7	OUT	32.5	OUT
TIME	2.73	2.76	2.78	2.81	2.83	2.86	2.88	2.91	2.93
TEMP	181 A	797	173.6	OUT	OUT	42.3	OUT	33.4	OUT
TIME	2.96	2.98	3.01	3.03	3.06	3.08	3.11	3.13	3.16
TEMP	181 A	799.8	182.6	OUT	OUT	42.3	OUT	33.2	OUT
TIME	3.18	3.21	3.23	3.26	3.29	3.31	3.34	3.36	3.39
TEMP	180 A	808	190.1	OUT	OUT	44.1	OUT	34.3	OUT
TIME	3.41	3.44	3.46	3.49	3.51	3.54	3.56	3.59	3.61
TEMP	180 A	808.3	199.5	OUT	OUT	45.4	OUT	34.6	OUT
TIME	3.64	3.66	3.69	3.72	3.74	3.77	3.79	3.82	3.84
TEMP	180 A	810	208.5	OUT	OUT	45.3	OUT	33.9	OUT
TIME	3.87	3.89	3.92	3.94	3.97	3.99	4.02	4.04	4.07
TEMP	179 A	815.2	216.1	OUT	OUT	47.3	OUT	35.2	OUT
TIME	4.1	4.12	4.15	4.17	4.2	4.22	4.25	4.27	4.3
TEMP	179 A	816	223.5	OUT	OUT	48.7	OUT	35.7	OUT
TIME	4.32	4.35	4.37	4.4	4.42	4.45	4.47	4.5	4.52
TEMP	179 A	817.3	230.3	OUT	OUT	49.1	OUT	35.5	OUT
TIME	4.55	4.57	4.6	4.63	4.65	4.68	4.7	4.73	4.75

TEMP 178 A	921.6	234.3	OUT	OUT	51.6	OUT	36.9	OUT
TIME 4.78	4.9	4.83	4.55	4.86	4.9	4.93	4.95	4.98
TEMP 178 A	821.5	239.9	OUT	OUT	53	OUT	36.8	OUT
TIME 5	5.03	5.05	5.09	5.11	5.13	5.16	5.18	5.21
TEMP 178 A	823.4	245.3	OUT	OUT	54.5	OUT	37.1	OUT
TIME 5.23	5.26	5.28	5.31	5.33	5.36	5.38	5.41	5.43
TEMP 177 A	826.9	247.2	OUT	OUT	57	OUT	38.5	OUT
TIME 5.46	5.49	5.51	5.54	5.56	5.59	5.61	5.64	5.66
TEMP 178 A	825.8	251.5	OUT	OUT	57.8	OUT	38.4	OUT
TIME 5.69	5.71	5.74	5.76	5.79	5.81	5.84	5.86	5.89
TEMP 177 A	828.3	254.9	OUT	OUT	58.9	OUT	38.4	OUT
TIME 5.92	5.94	5.97	5.99	6.02	6.04	6.07	6.09	6.12
TEMP 177 A	831.5	257.3	OUT	OUT	61.2	OUT	39.6	OUT
TIME 6.14	6.17	6.19	6.22	6.24	6.27	6.3	6.32	6.35
TEMP 177 A	830.6	261.7	OUT	OUT	62.5	OUT	39.6	OUT
TIME 6.37	6.4	6.42	6.45	6.47	6.5	6.52	6.55	6.57
TEMP 177 A	832.4	265.2	OUT	OUT	63.8	OUT	39.6	OUT
TIME 6.6	6.62	6.65	6.67	6.7	6.72	6.75	6.78	6.8
TEMP 176 A	835	267.3	OUT	OUT	66.7	OUT	40.7	OUT
TIME 6.83	6.85	6.88	6.9	6.93	6.95	6.98	7	7.03
TEMP 176 A	834.1	270.6	OUT	OUT	67.8	OUT	40.8	OUT
TIME 7.05	7.08	7.1	7.13	7.16	7.18	7.21	7.23	7.26
TEMP 176 A	836.1	273.7	OUT	OUT	68.9	OUT	40.7	OUT
TIME 7.28	7.31	7.33	7.36	7.38	7.41	7.43	7.46	7.48

TEMP TIME	175 A 7.51	839.2 7.54	276 7.56	OUT 7.59	OUT 7.61	71.3 7.64	OUT 7.66	42 7.69	OUT 7.71
TEMP TIME	176 A 7.74	839.6 7.76	279.9 7.79	OUT 7.81	OUT 7.84	72.6 7.87	OUT 7.89	42.3 7.92	OUT 7.94
TEMP TIME	176 A 7.97	839.5 7.99	284.2 8.02	OUT 8.04	OUT 8.07	73.3 8.09	OUT 8.12	42.2 8.14	OUT 8.17
TEMP TIME	175 A 8.19	841.9 8.22	287.4 8.24	OUT 8.27	OUT 8.29	76 8.32	OUT 8.34	43.7 8.37	OUT 8.39
TEMP TIME	176 A 8.42	840.2 8.45	292.0 8.47	OUT 8.5	OUT 8.52	76.9 8.55	OUT 8.57	43.6 8.6	OUT 8.62
TEMP TIME	175 A 8.65	843.1 8.67	297 8.7	OUT 8.72	OUT 8.75	78.6 8.77	OUT 8.8	44.5 8.82	OUT 8.85
TEMP TIME	175 A 8.87	844.2 8.9	300.8 8.93	OUT 8.95	OUT 8.99	81.4 9	OUT 9.03	45.9 9.05	OUT 9.08
TEMP TIME	175 A 9.1	843 9.13	306.1 9.15	OUT 9.18	OUT 9.2	82 9.23	OUT 9.25	45.7 9.29	OUT 9.31
TEMP TIME	175 A 9.33	845.6 9.36	310.1 9.39	OUT 9.41	OUT 9.43	83.5 9.46	OUT 9.48	46.3 9.51	OUT 9.53
TEMP TIME	174 A 9.56	847.6 9.58	313.3 9.61	OUT 9.64	OUT 9.66	86.1 9.69	OUT 9.71	47.6 9.74	OUT 9.76
TEMP TIME	175 A 9.79	846.1 9.81	317.7 9.84	OUT 9.86	OUT 9.89	86.9 9.91	OUT 9.94	47.4 9.96	OUT 9.99
TEMP TIME	174 A 10.01	848 10.04	321.2 10.07	OUT 10.09	OUT 10.12	88.5 10.14	OUT 10.17	47.5 10.19	OUT 10.22

TEMP	174 A	850.5	323.4	OUT	OUT	91.3	OUT	49	OUT
TIME	10.24	10.27	10.29	10.32	10.34	10.37	10.39	10.42	10.44
TEMP	174 A	848.8	327.5	OUT	OUT	92.2	OUT	48.9	OUT
TIME	10.47	10.5	10.52	10.55	10.57	10.6	10.62	10.65	10.67
TEMP	174 A	850.5	330.8	OUT	OUT	93.6	OUT	49.3	OUT
TIME	10.7	10.72	10.75	10.77	10.8	10.82	10.85	10.88	10.9
TEMP	173 A	853.3	333.1	OUT	OUT	96	OUT	50.5	OUT
TIME	10.93	10.95	10.98	11	11.03	11.05	11.08	11.1	11.13
TEMP	174 A	851.5	337.4	OUT	OUT	96.5	OUT	50.2	OUT
TIME	11.15	11.18	11.2	11.23	11.25	11.26	11.31	11.33	11.36

DATA FILE: OPENAIR6 (TEMPERATURES IN DEGREES CELSIUS)

DO	STC0	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	27.4	29.6	OUT	OUT	26.7	OUT	26.6	OUT
TIME 0	.03	.05	.06	.1	.13	.15	.16	.2
TEMP 234 A	168.6	29.4	OUT	OUT	29.2	OUT	26.9	OUT
TIME 23	.25	.28	.3	.33	.36	.38	.41	.43
TEMP 216 A	325.6	29.6	OUT	OUT	30	OUT	29.4	OUT
TIME 46	.46	.51	.53	.56	.58	.61	.63	.66
TEMP 205 A	449.6	35.6	OUT	OUT	29.6	OUT	26.9	OUT
TIME 66	.71	.73	.76	.78	.81	.84	.86	.89
TEMP 197 A	550.5	50.9	OUT	OUT	31.5	OUT	30	OUT
TIME 91	.94	.96	.99	1.01	1.04	1.06	1.09	1.11
TEMP 193 A	623.9	69	OUT	OUT	32.9	OUT	30.1	OUT
TIME 114	1.16	1.19	1.21	1.24	1.26	1.29	1.31	1.34
TEMP 190 A	678.2	85	OUT	OUT	33.6	OUT	30.1	OUT
TIME 137	1.39	1.42	1.44	1.47	1.49	1.52	1.54	1.57
TEMP 187 A	718	103.9	OUT	OUT	36.2	OUT	31.1	OUT
TIME 159	1.62	1.64	1.67	1.69	1.72	1.74	1.77	1.79
TEMP 186 A	743.6	126.4	OUT	OUT	36.9	OUT	30.9	OUT
TIME 182	1.85	1.87	1.9	1.92	1.95	1.97	2	2.02

TEMP	184 A	753.5	146.4	OUT	OUT	36.2	OUT	31.7	OUT
TIME	2.05	2.07	2.1	2.12	2.15	2.17	2.2	2.22	2.25
TEMP	183 A	776.4	156.6	OUT	OUT	40.1	OUT	32.5	OUT
TIME	2.27	2.3	2.32	2.35	2.37	2.4	2.42	2.45	2.47
TEMP	182 A	764	163.7	OUT	OUT	40.6	OUT	32.4	OUT
TIME	2.5	2.53	2.55	2.58	2.6	2.63	2.65	2.68	2.7
TEMP	181 A	793.1	169.3	OUT	OUT	42.2	OUT	33.3	OUT
TIME	2.73	2.75	2.78	2.8	2.83	2.85	2.88	2.91	2.93
TEMP	181 A	797.7	175.4	OUT	OUT	43.7	OUT	34	OUT
TIME	2.96	2.98	3.01	3.03	3.06	3.08	3.11	3.13	3.16
TEMP	181 A	800.7	184.6	OUT	OUT	43.9	OUT	33.9	OUT
TIME	3.19	3.21	3.24	3.26	3.29	3.31	3.34	3.36	3.39
TEMP	180 A	806.9	194.3	OUT	OUT	45.2	OUT	35	OUT
TIME	3.41	3.44	3.46	3.49	3.51	3.54	3.56	3.59	3.61
TEMP	180 A	808.6	204	OUT	OUT	46.4	OUT	35.5	OUT
TIME	3.64	3.66	3.69	3.71	3.74	3.77	3.79	3.82	3.84
TEMP	179 A	811.4	212.3	OUT	OUT	46.6	OUT	35.5	OUT
TIME	3.87	3.89	3.92	3.94	3.97	3.99	4.02	4.04	4.07
TEMP	179 A	814.6	218.7	OUT	OUT	46.6	OUT	36.5	OUT
TIME	4.09	4.12	4.14	4.17	4.19	4.22	4.25	4.27	4.3
TEMP	179 A	816	225.7	OUT	OUT	48.5	OUT	36.5	OUT
TIME	4.32	4.35	4.37	4.4	4.42	4.45	4.47	4.5	4.52
TEMP	179 A	819.5	231.6	OUT	OUT	50.6	OUT	36.6	OUT
TIME	4.55	4.57	4.6	4.62	4.65	4.67	4.7	4.72	4.75

TEMP	176 A	620.6	236.7	OUT	53.2	OUT	37.5	OUT
TIME	4.78	4.6	4.83	4.65	4.9	4.93	4.95	4.98
TEMP	176 A	620.9	242.9	OUT	54.4	OUT	37.3	OUT
TIME	5	5.03	5.05	5.06	5.13	5.16	5.18	5.21
TEMP	176 A	624.1	246.2	OUT	56	OUT	37.5	OUT
TIME	5.23	5.26	5.28	5.31	5.36	5.38	5.41	5.43
TEMP	177 A	626	249	OUT	59.5	OUT	38.6	OUT
TIME	5.46	5.48	5.51	5.53	5.58	5.61	5.63	5.66
TEMP	176 A	625.9	252.6	OUT	59.2	OUT	38.3	OUT
TIME	5.59	5.71	5.74	5.76	5.81	5.84	5.86	5.89
TEMP	177 A	629.7	255.5	OUT	61.4	OUT	39.5	OUT
TIME	5.91	5.94	5.96	5.99	6.04	6.06	6.09	6.11
TEMP	177 A	630.3	258.2	OUT	63.2	OUT	39.9	OUT
TIME	6.14	6.16	6.19	6.22	6.27	6.29	6.32	6.34
TEMP	177 A	630.5	264.1	OUT	63.8	OUT	39.7	OUT
TIME	6.37	6.39	6.42	6.44	6.5	6.52	6.55	6.57
TEMP	176 A	633.6	267	OUT	66	OUT	40.6	OUT
TIME	6.5	6.62	6.65	6.67	6.72	6.75	6.77	6.8
TEMP	176 A	634.2	269.8	OUT	68	OUT	41.3	OUT
TIME	6.62	6.65	6.67	6.9	6.92	6.96	7	7.03
TEMP	176 A	634.2	273.5	OUT	68.8	OUT	41	OUT
TIME	7.05	7.08	7.1	7.13	7.18	7.2	7.23	7.25
TEMP	176 A	637.9	275.5	OUT	70.9	OUT	41.6	OUT
TIME	7.26	7.3	7.33	7.36	7.41	7.43	7.46	7.48

TEMP	176 A	639.3	276.4	OUT	OUT	73.2	OUT	42.5	OUT
TIME	7.51	7.53	7.56	7.58	7.61	7.63	7.66	7.68	7.71
TEMP	176 A	637.5	283	OUT	OUT	73.9	OUT	42.4	OUT
TIME	7.74	7.76	7.79	7.81	7.84	7.86	7.89	7.91	7.94
TEMP	175 A	640.5	287.1	OUT	OUT	75.6	OUT	43.3	OUT
TIME	7.96	7.99	8.01	8.04	8.06	8.09	8.12	8.14	8.17
TEMP	175 A	641.7	291.1	OUT	OUT	77.6	OUT	44.6	OUT
TIME	8.19	8.22	8.24	8.27	8.29	8.32	8.34	8.37	8.39
TEMP	175 A	641.4	296.3	OUT	OUT	79.5	OUT	44.7	OUT
TIME	8.42	8.44	8.47	8.49	8.52	8.54	8.57	8.59	8.62
TEMP	175 A	644.5	299.7	OUT	OUT	81.2	OUT	46.3	OUT
TIME	8.64	8.67	8.69	8.72	8.75	8.77	8.8	8.82	8.85
TEMP	175 A	643.6	304.7	OUT	OUT	82.8	OUT	46.7	OUT
TIME	8.67	8.9	8.92	8.95	8.97	9	9.03	9.05	9.08
TEMP	175 A	644.6	309.4	OUT	OUT	83.5	OUT	46.8	OUT
TIME	9.1	9.13	9.15	9.18	9.2	9.23	9.25	9.28	9.3
TEMP	174 A	647.6	312.4	OUT	OUT	86.1	OUT	47.6	OUT
TIME	9.33	9.35	9.38	9.4	9.43	9.45	9.48	9.5	9.53
TEMP	175 A	645.6	316.5	OUT	OUT	87.2	OUT	47.8	OUT
TIME	9.55	9.58	9.6	9.63	9.66	9.68	9.71	9.73	9.76
TEMP	175 A	647.6	320.5	OUT	OUT	89.4	OUT	48.1	OUT
TIME	9.76	9.81	9.83	9.86	9.88	9.91	9.93	9.96	9.98
TEMP	174 A	649.8	323	OUT	OUT	90.9	OUT	49.1	OUT
TIME	10.01	10.04	10.06	10.09	10.11	10.14	10.16	10.19	10.21

TEMP	175 A	846.2	327.3	OUT	OUT	91.6	OUT	48.9	OUT
TIME	10.24	10.26	10.29	10.31	10.34	10.36	10.39	10.41	10.44
TEMP	174 A	850.7	330.1	OUT	OUT	93.1	OUT	49.7	OUT
TIME	10.46	10.49	10.52	10.54	10.57	10.59	10.62	10.64	10.67
TEMP	174 A	852.1	333.1	OUT	OUT	95.1	OUT	50.5	OUT
TIME	10.69	10.72	10.74	10.77	10.79	10.82	10.84	10.87	10.89
TEMP	174 A	851.1	337.2	OUT	OUT	96	OUT	50.6	OUT
TIME	10.92	10.95	10.97	11	11.02	11.05	11.07	11.1	11.12
TEMP	174 A	853.8	339.5	OUT	OUT	97.5	OUT	51.2	OUT
TIME	11.15	11.17	11.2	11.22	11.25	11.27	11.3	11.33	11.35

DATA FILE: OPENAIR9 (TEMPERATURES IN DEGREES CELSIUS)

DO	STCO	TC1	TC2	TC3	TC4	TC5	TC6	TC7
TEMP 0 A	26.1	28.5	OUT	OUT	27.4	OUT	27.4	OUT
TIME 0	.03	.05	.08	.1	.13	.15	.16	.2
TEMP 227 A	215.1	28.3	OUT	OUT	27.7	OUT	27.5	OUT
TIME 23	.26	.28	.31	.33	.36	.38	.41	.43
TEMP 211 A	364	26	OUT	OUT	29	OUT	28.3	OUT
TIME 46	.48	.51	.54	.56	.59	.61	.64	.66
TEMP 202 A	477.5	34.4	OUT	OUT	28.6	OUT	27.6	OUT
TIME 69	.71	.74	.76	.78	.81	.84	.86	.89
TEMP 195 A	570.2	53.4	OUT	OUT	30.3	OUT	28.6	OUT
TIME 91	.94	.96	.99	1.01	1.04	1.06	1.09	1.11
TEMP 191 A	636.2	69.6	OUT	OUT	32.1	OUT	28.2	OUT
TIME 114	1.17	1.19	1.22	1.24	1.27	1.29	1.32	1.34
TEMP 186 A	666.4	66.6	OUT	OUT	32.9	OUT	29	OUT
TIME 137	1.39	1.42	1.44	1.47	1.49	1.52	1.55	1.57
TEMP 186 A	723.5	107.4	OUT	OUT	34.6	OUT	30	OUT
TIME 16	1.62	1.65	1.67	1.7	1.72	1.75	1.77	1.8
TEMP 184 A	746.1	129.4	OUT	OUT	36.5	OUT	30.6	OUT
TIME 182	1.85	1.87	1.9	1.92	1.95	1.98	2	2.03

TEMP	164 A	765.2	145.9	OUT	37	OUT	30.6	OUT
TIME	2.05	2.00	2.1	2.13	2.15	2.2	2.23	2.25
TEMP	162 A	777.6	152.9	OUT	38.6	OUT	31.4	OUT
TIME	2.20	2.3	2.33	2.35	2.36	2.43	2.46	2.48
TEMP	162 A	784.6	160.2	OUT	40.1	OUT	31.9	OUT
TIME	2.51	2.53	2.56	2.58	2.61	2.66	2.68	2.71
TEMP	161 A	790.6	167.9	OUT	40.6	OUT	32	OUT
TIME	2.73	2.76	2.78	2.81	2.83	2.88	2.91	2.93
TEMP	160 A	796.9	174.7	OUT	42.5	OUT	33	OUT
TIME	2.96	2.99	3.01	3.04	3.06	3.11	3.14	3.16
TEMP	160 A	798.6	184.3	OUT	42.9	OUT	32.6	OUT
TIME	3.19	3.21	3.24	3.26	3.29	3.34	3.36	3.39
TEMP	160 A	803.4	193.7	OUT	43.7	OUT	33.3	OUT
TIME	3.41	3.44	3.47	3.49	3.52	3.57	3.58	3.62
TEMP	178 A	808.2	202.2	OUT	45.2	OUT	34.4	OUT
TIME	3.64	3.67	3.69	3.72	3.75	3.8	3.82	3.85
TEMP	178 A	809.4	210	OUT	46.3	OUT	34.6	OUT
TIME	3.67	3.9	3.92	3.95	3.97	4.02	4.05	4.08
TEMP	178 A	611	216.7	OUT	46.4	OUT	34.4	OUT
TIME	4.1	4.13	4.15	4.18	4.2	4.25	4.28	4.3
TEMP	178 A	615.4	223.9	OUT	46.7	OUT	35.7	OUT
TIME	4.33	4.35	4.38	4.4	4.43	4.48	4.5	4.53
TEMP	178 A	615.7	230.2	OUT	49.7	OUT	35.8	OUT
TIME	4.55	4.58	4.61	4.63	4.66	4.71	4.73	4.76

TEMP	176 A	617.7	235.7	OUT	50.6	OUT	35.7	OUT
TIME	4.76	4.61	4.63	4.66	4.61	4.64	4.66	4.69
TEMP	177 A	621.3	239.6	OUT	53.5	OUT	36.9	OUT
TIME	5.01	5.04	5.06	5.09	5.14	5.16	5.18	5.21
TEMP	177 A	621.4	243.4	OUT	55.1	OUT	37	OUT
TIME	5.24	5.26	5.29	5.31	5.37	5.39	5.42	5.44
TEMP	177 A	623	247.3	OUT	55.6	OUT	36.7	OUT
TIME	5.47	5.49	5.52	5.54	5.59	5.62	5.64	5.67
TEMP	178 A	626.6	250.1	OUT	59	OUT	37.9	OUT
TIME	5.69	5.72	5.75	5.77	5.82	5.85	5.87	5.9
TEMP	177 A	626.6	253.9	OUT	59.7	OUT	36.2	OUT
TIME	6.32	5.95	5.97	6	6.05	6.08	6.1	6.13
TEMP	177 A	627	256.3	OUT	60.5	OUT	37.6	OUT
TIME	6.15	6.18	6.2	6.23	6.28	6.3	6.33	6.35
TEMP	176 A	630.4	261.1	OUT	62.6	OUT	39.9	OUT
TIME	6.38	6.4	6.43	6.45	6.51	6.53	6.56	6.58
TEMP	176 A	630.7	263.9	OUT	64.6	OUT	39.3	OUT
TIME	6.61	6.63	6.66	6.68	6.73	6.76	6.78	6.81
TEMP	176 A	631.4	267.3	OUT	65.1	OUT	39.2	OUT
TIME	6.63	6.66	6.68	6.91	6.96	6.99	7.01	7.04
TEMP	175 A	634.5	269.3	OUT	67.6	OUT	40.6	OUT
TIME	7.98	7.99	7.11	7.14	7.19	7.21	7.24	7.26
TEMP	176 A	634	272.5	OUT	69.4	OUT	40.9	OUT
TIME	7.29	7.31	7.34	7.37	7.42	7.44	7.47	7.49

TEMP	175 A	834.2	275.5	OUT	OUT	69.9	OUT	40.9	OUT
TIME	7.52	7.54	7.57	7.59	7.62	7.64	7.67	7.7	7.72
TEMP	175 A	837.1	279	OUT	OUT	72	OUT	41.9	OUT
TIME	7.75	7.77	7.8	7.82	7.85	7.87	7.9	7.92	7.95
TEMP	175 A	838	282.8	OUT	OUT	74.1	OUT	42.9	OUT
TIME	7.97	8	8.02	8.05	8.07	8.1	8.13	8.15	8.18
TEMP	175 A	837.7	288	OUT	OUT	74.9	OUT	42.7	OUT
TIME	8.2	8.23	8.25	8.28	8.3	8.33	8.35	8.38	8.4
TEMP	174 A	841.2	291.6	OUT	OUT	77.4	OUT	44	OUT
TIME	8.43	8.45	8.48	8.5	8.53	8.55	8.58	8.61	8.63
TEMP	175 A	840.6	295.9	OUT	OUT	79.2	OUT	44.4	OUT
TIME	8.66	8.68	8.71	8.73	8.76	8.78	8.81	8.83	8.86
TEMP	175 A	840.4	301.3	OUT	OUT	79.9	OUT	44.3	OUT
TIME	8.68	8.91	8.94	8.96	8.99	9.01	9.04	9.06	9.09
TEMP	174 A	843.6	304.5	OUT	OUT	82.5	OUT	45.6	OUT
TIME	9.11	9.14	9.16	9.18	9.21	9.24	9.26	9.29	9.31
TEMP	174 A	843.4	308.6	OUT	OUT	84.3	OUT	45.1	OUT
TIME	9.34	9.36	9.39	9.42	9.44	9.47	9.49	9.52	9.54
TEMP	174 A	842.7	313.4	OUT	OUT	85	OUT	46	OUT
TIME	9.57	9.59	9.62	9.64	9.67	9.7	9.72	9.75	9.77
TEMP	174 A	845.8	318.4	OUT	OUT	87.2	OUT	47.2	OUT
TIME	9.6	9.62	9.65	9.67	9.9	9.92	9.95	9.97	10
TEMP	174 A	845.1	319.5	OUT	OUT	88.9	OUT	47.9	OUT
TIME	10.02	10.05	10.07	10.1	10.12	10.15	10.16	10.2	10.23

TEMP	174 A	645.6	323.6	OUT	OUT	69.5	OUT	47.8	OUT
TIME	10.25	10.28	10.3	10.33	10.35	10.36	10.4	10.43	10.45
TEMP	173 A	649.1	325.9	OUT	OUT	91.6	OUT	45.1	OUT
TIME	10.46	10.5	10.53	10.55	10.58	10.61	10.63	10.66	10.68
TEMP	173 A	648.6	329.6	OUT	OUT	93.2	OUT	45.7	OUT
TIME	10.71	10.73	10.76	10.78	10.81	10.83	10.86	10.88	10.91
TEMP	173 A	649.6	333.3	OUT	OUT	93.7	OUT	45.6	OUT
TIME	10.93	10.96	10.98	11.01	11.03	11.06	11.09	11.11	11.14
TEMP	173 A	651.6	336.1	OUT	OUT	95.6	OUT	50.7	OUT
TIME	11.16	11.19	11.21	11.24	11.26	11.29	11.31	11.34	11.36

VITA

Jeffrey A. Catt was born in Fort Rucker, Alabama to Jack and Doris Catt on October 27, 1963. He graduated from Clarksville High School, Clarksville, Tennessee in 1981. In March, 1986 he received a Bachelor of Science degree in Aerospace Engineering at the University of Tennessee at Knoxville and immediately began work on a graduate degree. On June 18, 1988 he married Julieann Wood of Germantown, Tennessee. In August of that same year he completed the requirements for a Master of Science degree in Mechanical Engineering at the University of Tennessee at Knoxville and accepted a job with General Dynamics in Fort Worth, Texas.