VALIDATION AND REFINEMENT OF A DYNAMIC DIGITAL MODEL OF A FAN COIL HEATING SYSTEM

by

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B.E., Bangalore University, India, 1978

A THESIS

Submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1980

Approved by:

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A2, B2, C2	Weighting factors to compute return air temperature
A7, B7	Weighting factors to compute effective thermostat temperature
A9, B9	Characteristic parameters of valve
CA	Specific heat of air (Btu/lbm °F)
CW	Specific heat of water (BTU/lbm °F)
CF	Specific heat of furniture (Btu/lbm °F)
D	Transit delay of room (hr)
E	Effectiveness of heat exchanger
FLO	Water flow rate (GPM)
HYS	Valve travel correction due to hysterisis
K7	Thermostat gain
K, c	Parameters to relate TEFF and P7
$\dot{M}_w$	Mass flow rate of water through the coil (lbm/hr)
$\dot{M}_{max}$	Maximum mass flow rate of water through the coil (lbm/hr)
P_a	Air density (lbm/ft^3)
P7	Output pressure of thermostat (psi)
P8	Input pressure to valve actuator (psi)
T1, TS	Supply air temperature (°F)
T2, TRM	Average room air temperature (°F)
T3, TR, TRET	Return air temperature (°F)
T4	Temperature of the air entering the fan (°F)
T5	Temperature of the air entering the coil (°F)
T6	Temperature of the air leaving the coil (°F)

TO, TOUT	Annular space temperatures (°F)
TW, TWAL	Wall temperatures (°F)
TEFF	Temperature sensed by the thermostat (°F)
T71	Thermostat time constant (effected by room air) (hr)
T72	Thermostat time constant (effected by wall) (hr)
THWTR	Hot water temperature (°F)
Tai	Temperature of the air entering the duct (°F)
Tao	Temperature of the air leaving the duct (°F)
T_{iw}	Temperature of the water entering the coil (°F)
T_{ow}	Temperature of the water leaving the coil (°F)
U	Slope of the Valve actuator characteristic
UAD	Overall heat transfer coefficient of supply duct (Btu/°F·hr)
V_a	Volume of room (ft^3)
wm	Energy input to the motor (BTU/hr)
X, Y, Z	Weighting factors
a	'y'-intercept of valve actuator characteristic
b, c, d, e	Parameters of valve characteristics
C_o, C_1	Coefficients of coil
h_m	Mechanical efficiency of fan
h_s	Static efficiency of fan
h_t	Overall efficiency of fan
s	Laplace variable
t, T	Time (hr)
δ	Ratio of mass flow rate of return air to ventilation air
Φ	Ratio of pressure drop in return air duct to pressure drop in the system

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CHAPTER 1

INTRODUCTION

This thesis presents results of a part of the project to determine the influence of room equipment and control system dynamics on energy consumption in HVAC systems. This study will help to implement optimal control strategies to save energy. To conduct such a study, it is required to have validated dynamic simulation of room, equipment and control system. Model formulation, digital simulation and experimental validation of the transient thermal response of the room with fan coil heating system has been reported in this thesis.

CHAPTER 2

MODEL FORMULATION

2-1 Introduction

Digital simulation of HVAC systems has been widely accepted by HVAC engineers as a versatile tool to evaluate energy consumption. These simulations can be classified as steady state and dynamic. The dynamic simulations can be further divided into long-term dynamics of the system (hour-by-hour simulation) and those which consider short-term dynamics as well. To evaluate energy consumption in the transient period of the systems operation, it is required to have validated short-term simulation for the HVAC system.

Literature search shows that following people attempted to model various systems of the HVAC system.

Zermuehlen and Harrison [2] modeled room air without thermal capacitance. Their system consisted of dual duct system and thermostat controlled damper to control air temperature. The main objective of their work was to demonstrate principle of control as applied to HVAC system.

Nelson [3] modeled a one storey house and its associated heating and air conditioning plant. He used an analog computer to simulate his model. He concluded that variations in component design could be readily evaluated by computer techniques to get maximum control performance with minimum cost.

Fan, Hwang and Hwang [4] and Nakahisha, Pereira, Fan and Hwang [5] modeled a room heating system. The main objective of their work was to demonstrate the applications of optimal control theory.

Hubbs [6] modeled a room with a unit ventilator system considering only heat flow through the outside wall. He used response factors with a time step of 6 minutes.

A "thermostatic radiator valve/panel radiator/room" system was modeled by Hanby [8]. Thermostat, room air flow, room load and radiator were modeled as first order systems with time delays.

Kaya [9] modeled one zone of a multizoned building and its heating and cooling units. Analysis was carried out by using the Root Locus method.

Miller [10] modeled, analysed and simulated single and multi-zone buildings and associated multi zone heating and cooling units. He concluded that the dynamics of the controls of an HVAC system can have significant effect on reduction of energy usage.

J. R. Anders [12] used analog circuits to model heat flow. His digital simulation predicted room temperatures with an accuracy of 2% and heat fluxes through the walls within 15%.

Thompson and Chen [1] modeled a room with a fan coil heating system. Their model consisted of room air, walls, fan, ducts, and coil. Their control unit consisted of a thermostat, valve, and valve actuator. Experiments were conducted to validate their model. The work reported in this thesis is a refinement of the above model that better matches the experimentally observed behavior of the system. Component parameters were found by the method of least squares and a parameter optimization technique.

2-2 Room Air Model

Room air is modeled to compute the average room air temperature. The model is formulated by carrying out an energy balance of the room.

Zermuehlen and Harrison [2] modeled room air by assuming perfect mixing of air.

Harrison, Hansen and Zelenski [13] included thermal capacitance of the air in their model. They used a combination of mixing and bulk flow of the room air. In their experimental verification they were able to determine a time constant, but no transit delay was observed. They considered an air flow rate of 20 air changes per hour. A possible formulation of the transit delay could be (assuming no mixing)

$$D = \frac{Va\ Pa}{XM1} . \qquad (2\text{-}1)$$

Fan, Hwang and Hwang [4], Pereira [14], Nakanisha, Pereira, Fan and Hwang [5] and Hubbs [6] modeled, the room air as a first order system assuming instantaneous mixing of incoming air with room air.

Chen, Fan, Hwang and Lee [15] used the concept of age distribution to study the air distribution in confined space. They also used statistical analysis to relate age distribution and energy content of air in the room to compute average room air temperature.

Nielsen [16] developed a theoretical model of the motion and temperature of the air in a room. He used the finite difference method to solve the partial differential Navier Stokes, continuity and energy equations.

Thompson and Chen [1] modeled room air assuming perfect instantaneous mixing of incoming air with room air.

For this thesis the room air model is developed by making the following assumptions:

1. Walls can be modeled by layers which are homogenous and have constant thermal properties.
2. One directional conduction is assumed in walls.

3. Heat transfer film coefficients on the inside and outside of the walls remain constant.

4. Windows, doors, and the ceiling tile have negligible thermal capacity.

5. All four walls have the same average temperature.

Figure 1 illustrates the heat flow in a room. The following factors are considered in the heat balance:

1. Heat stored in room air - $PA\cdot VA\cdot CA\cdot\frac{dT2}{dt}$

2. Heat stored in furniture - $XMF\cdot CF\cdot\frac{dT2}{dt}$

3. Heat flow into the room by HVAC system - $XM1\cdot CA\cdot T1$

4. Heat flow into the room by infiltration - $XMO\cdot CA\cdot TO$

5. Heat loss through return air - $XM2\cdot CA\cdot TRET$

6. Heat loss through surfaces with heat storage - QFLO

7. Heat loss through surfaces without heat storage - QCOND

8. Heat gain due to lighting - QLITE

This model does not distinguish between latent and sensible heat. The heat balance equation is

$$Pa\cdot Va\cdot CA\frac{dT2}{dt} + XMF\cdot CF\cdot\frac{dT2}{dt} = XM1\cdot CA\cdot T1 - XM2\cdot CA\cdot TRET + (QFLO + QCOND + QLITE) + XMO\cdot CA\cdot TO \quad (2\text{-}2)$$

This mass balance equation is $XMO = XM2 - XM1$ (2-2a)

The room air temperature is considered to be an average temperature of the air in the room and is representative of the total heat stored in the room. For simplicity furniture is assumed to be at the same temperature as the air. In order to account for the heat leaving the room in the return

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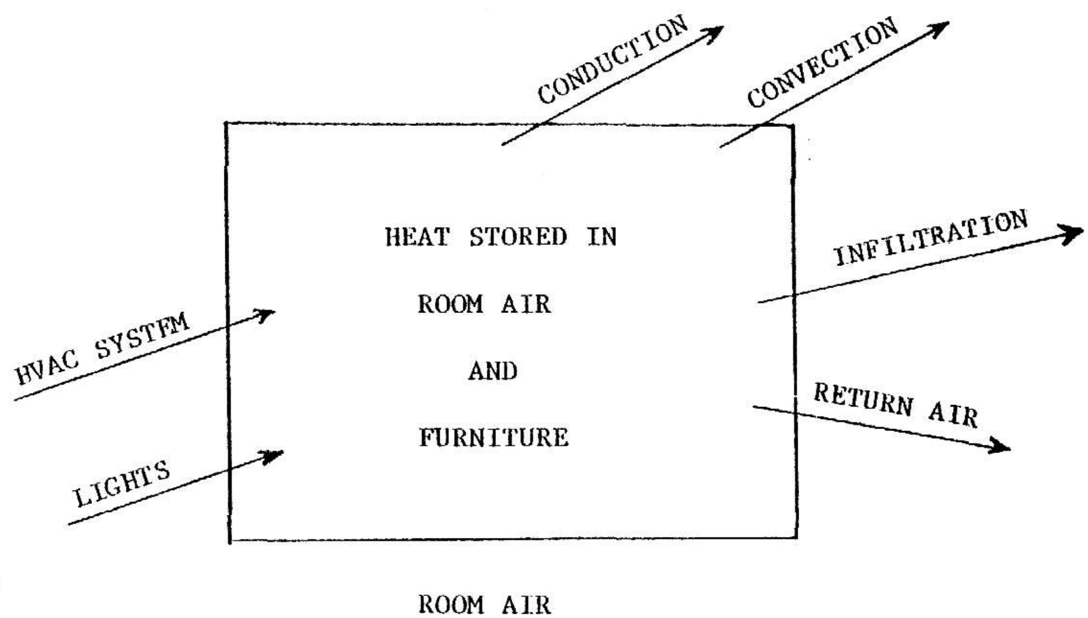

Fig. 1. Room energy balance.

air it is necessary to determine the temperature of the return air. The relationship between the temperatures of the incoming air, the infiltration air, the return air and the average room is dependent upon the kind and location of air diffusers, the shape of the room, the location of heat sources, etc. If experimental data is available the return air temperature may be expressed as

$$TRET = A2 \cdot T1 + B2 \cdot T2 + C2 \cdot TWALL \qquad (2\text{-}3)$$

Using experimental data and applying the method of least squares the weighting factors A2, B2 and C2 were found and implemented in the model.

2-3 Wall Model

The wall model computes the heat loss through walls with thermal capacity. Mitlas and Stephenson [17, 18] introduced the concept of response factors. They carried out their work by assuming one dimensional conduction, homogeneous material, and constant thermal properties. They solved the conduction equation for a unit ramp temperature excitation. The values of this response at discrete time intervals are the response factors.

Calculation of response factors was extended to multilayered structures of various curvatures by Ksuda [19].

Stephenson and Mitlas [20] further developed the response factor method by using Z-transforms for the inversion. This method is usually referred to as the modified response factor method. They also found out that the computation time and computer memory usage were reduced by using this method.

Mitlas and Arseneault [21] developed a computer program which computes either response or modified response factors using either step or ramp inputs.

Thompson and Chen [1] chose the modified response factor method to describe transient heat flow through the walls and floor because:

1. It can be used for multilayered walls.
2. It can be used for periodic and non-periodic temperature excitations.
3. It is quite accurate.
4. Computation time is short compared to other methods.

The ramp approximation requires fewer terms than the step approximation to fit most temperature profiles. But the ramp approximation method requires current temperatures to compute heat fluxes. This step approximation method does not require current temperatures to compute heat fulxes. Thompson and Chen [1] decided to use the step approximation on inside temperatures and the ramp approximation on outside temperatures. The modified response factor equation for computing the heat flow through the j^{th} surface at the n^{th} instant of time is

$$q_j(n) = \sum_{k=1}^{r} X_{jk} \cdot T2(n-k) - \sum_{k=0}^{r} Y_{jk} \cdot T0(n-k) - \sum_{k=1}^{r} Z_{jk} \cdot q_j(n-k) \qquad (2\text{-}4)$$

The temperature on the j^{th} surface is computed by

$$T_j = T2 + q_j / (h_j \; A_j) \qquad (2\text{-}5)$$

2-4 Thermostat Model

The thermostat model relates the temperature sensed by the thermostat to its output pressure.

Hamilton, Leonard and Pearson [22], Thompson and Chen [1] and others have modeled a thermostat with a gain and a single time constant, i.e.

$$\frac{P7(s)}{T7(s)} = \frac{K7}{(T71s+1)} \tag{2-6}$$

where T7 is the effective temperature of the thermostat. Nelson [3], Nelson and Tobias [23], and Kaya [24] modeled T7 as

$$T7 = TEFF = A7 \cdot T2 + B7 \cdot TWAL \tag{2-7}$$

where A7 and B7 are weighting factors. This model did not agree well with the experimental data. The experiment indicated that there is a phase lag between TEFF and T2 and between TEFF and TWALL. In this work the thermostat is modeled as

$$TEFF = \frac{A7 \cdot T2}{(T71s+1)} + \frac{B7 \cdot TWALL}{(T72s+1)} \; . \tag{2-8}$$

In order to match equilibrium conditions we require

$$A7 + B7 = 1 \tag{2-9}$$

The experiment also indicated the existence of a phase lag between TEFF and the output pressure P7. To include this effect TEFF and P7 are related by

$$\frac{P7(s)}{TEFF(s)} = \frac{K \cdot C}{(s+c)} \tag{2-10}$$

Using experimental values for T2, TWALL, TEFF and P7 and applying the parameter optimization technique A7, B7, T71, T72, C and K are evaluated. Details of the parameter optimization technique are given in Appendix D.

2-5 Value Actuator Model

The value actuator is modeled to compute the valve travel. Thompson and Chen [1] modeled the valve actuator as a damped spring-mass system taking hysterisis into account. The values of the coefficients in the model were found experimentally and implemented as

$$Y9 = U \cdot P8 + a \pm HYS \tag{2-11}$$

2-6 Valve (water flow) Model

The valve is modeled to compute water flow rate through the valve. Thompson and Chen [1] proposed a piecewise exponential model of the form

$$\dot{M}_w = \frac{\dot{M}_{max}}{B9} \cdot EXP\ (A9 \cdot Y9) \qquad (2\text{-}12)$$

The coefficients in the above model were to be determined using experimental data. The parameters of the system and the characteristics of the experiment were such that the water flow rate was either zero or near the maximum flow rate during most of the experiment. Very few data points were obtained at lower flow rates. There was not sufficient data distribution to make a suitable evaluation of the above model. A simplified model consisting of a linear function for low flow rates and a power function for higher flow rates was implemented. The simplified model is

$$FLO = b \cdot Y9 \quad , \quad Y9 \leq \lambda \qquad (2\text{-}13)$$

$$FLO = d \cdot Y9^{e} \quad , \quad Y9 > \lambda \qquad (2\text{-}14)$$

where b, d, e, and λ are selected to obtain a suitable match of the experimental data.

2-7 Heat Exchanger Model

The heat exchanger model relates the temperature of the air leaving the coil to the water flow rate through the coil.

Gartner [25] and Tamm and Green [26] modeled heat exchanger with a gain and a time constant.

Boot, Pearson and Leonard [27] obtained algebric expressions to approximate the gain and time constant of a finned, serpentine, cross flow heat exchanger. Calculated values from their algebric approximations had a maximum difference of 6.1% from the theoretical model and fitted their experimental data within a 15% uncertainty.

Gartner [25] proposed a partial differential equation model with time and distance along the tubes as the independent variables. He also solved the partial differential equation and expimentally verified the solution.

Tobias [28] gave a transfer function relating primary fluid outlet temperature to primary fluid inlet temperature.

Thompson and Chen [1] proposed a model based on the effectiveness of the heat exchanger. Effectiveness is defined as

$$E = \frac{\text{Actual Temperature Rise in the Colder Fluid}}{\text{Maximum Possible Temperature Rise of the Colder Fluid}} \qquad (2\text{-}15)$$

Based on this definition the temperatures of the air and water leaving the heat exchanger may be expressed as

$$T6=T5+E\cdot(T_{iw}-T5) \quad , \qquad \dot{M}a\cdot CA\leq\dot{M}w\cdot CW \qquad (2\text{-}16)$$

$$T_{ow}=T_{iw}+E\cdot(T_{iw}-T5)\cdot\dot{M}a\cdot CA/(\dot{M}w\cdot CW) \qquad (2\text{-}17)$$

or

$$T6=T5+E\cdot(T_{iw}-T5)\cdot\dot{M}w\cdot CW/(\dot{M}a\cdot CA) \qquad (2\text{-}18)$$

$$T_{ow}=T_{iw}+E\cdot(T_{iw}-T5) \quad , \qquad \dot{M}a\cdot CA>\dot{M}w\cdot CW \qquad (2\text{-}19)$$

Thompson and Chen suggested fitting the characteristics of a particular heat exchanger with a polynomial in air and water flow rates and inlet air temperature (for a specified inlet water temperature). The model used in this thesis fits the effectiveness of the heat exchanger with a piecewise linear function of water flow rate (the air flow rate is constant).

$$E = C_{i0} + C_{i1}\cdot FLO \quad , \qquad F_{li} \leq FLO \leq F_{hi} \qquad (2\text{-}20)$$

For all but a few data points $\dot{M}a\cdot CA \leq \dot{M}w\cdot CW$ and $T6=T5+E\cdot(T_{iw}-T5)$ gives the temperature of the air leaving the heat exchanger.

2-8 Fan and Duct Model

The fan and duct have significant effect on the temperature of the hot air entering the room. The fan adds some energy to air and the duct loses energy in the form of heat transfer to the surroundings. It is quite difficult to separate the effects of the fan and the duct so they are modeled together.

Tobias [28] modeled a duct as

$$\frac{Tao}{Tai} = EXP\ (-\alpha \cdot L \cdot s) \cdot EXP(-\beta \cdot L) \cdot EXP\ \left[-\alpha L \left(\frac{Td \cdot s}{Tds+1}\right)\ \right] \qquad (2\text{-}21)$$

where the first exponential term is the delay time, the second is the attenuation of air temperature due to the transfer of heat to the duct and the third is the phase shift and attenuation due to the transfer of heat from the duct to the surrounding air.

Thompson and Chen [1] assumed zero phase shift, unity gain and zero time delay because the ducts are short. Analysis of the experimental data indicates the need to include heat loss from the supply duct to the plenum above the ceiling.

Energy is transfered to the air from the fan along the duct as the static pressure head is dissipated by friction. In this model the duct is divided into two sections. One is the duct between the room and the fan inlet and the other is the duct between the fan exit and the room inlet.

The energy balance for the duct between the fan inlet and the room yields

$$T3=T2+\Phi \cdot h_m \cdot h_s \cdot Wm/(XM2 \cdot CA) \qquad (2\text{-}22)$$

The energy balance for the mixing of ventilation air yields

$$T4 = \delta \cdot T_o + (1-\delta) \cdot T3 \qquad (2\text{-}23)$$

The temperature rise across the fan was modeled by writing the energy balance for the fan

$$T5=T4 + h_m \cdot (h_t - h_s) \cdot wm/(XM2 \cdot CA) \tag{2-24}$$

The energy balance for the duct between the fan exit and the room inlet yields

$$T1=T6+(1-\Phi) \cdot h_m \cdot h_s \cdot wm/(XM1 \cdot CA) \tag{2-25}$$

The addition of heat transfer from the duct to the plenum air, the modified return air temperature model, and neglecting the temperature rise across the fan the model for the fan and the ducts is given as

$$TRET = A2 \cdot T1 + B2 \cdot T2 + C2 \cdot TWALL \tag{2-26}$$

$$T3 = TRET + \Phi \cdot h_m \cdot h_s \cdot wm/_{XM2 \cdot CA} \tag{2-27}$$

$$T4 = \delta T_o + (1-\delta)\ T3 \tag{2-28}$$

$$T5 = T4$$

$$XM1 \cdot CA \cdot (T1-T6) = (1-\Phi) \cdot h_m \cdot h_s \cdot wm + UAD \cdot \left(TO - \frac{(T_1+T_6)}{2} \right) \tag{2-29}$$

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3-1 Introduction

An experiment was devised to validate the model of the transient thermal response of a room with a fan coil heating system. Details of the system and experimental procedures are described below.

3-2 Test facility

The test facility consists of a room within a room. The space between the two rooms is used to circulate large quantities of cold air. The test facility is suitably instrumented to obtain data. The details of test facility and instrumentation can be visualised from the photographic Plates 1, 2 and 3.

The plan of the room is as shown in Figure 2. The room measures 19' 10.5"x12'x8'11". It has two wooden doors and one of them has a glass window. The floor is built of wood. The ceiling is Celetex tile. The ceiling has two heat diffusers and four florescent lights. The walls are wood studs (frame), gypsum board, and fiber glass insulation. The construction details with thermophysical properties are given in Table (3-1).

3-3 Heating Circuit

The heating circuit can be divided into two sub-systems:

1. Hot air circuit
2. Hot water circuit.

TABLE 3-1.

Wall Data

Layer	Thickness ft	Conductivity $\frac{BTU}{hr.\ ft.\ ^\circ F}$	Density $\frac{lb}{ft^3}$	Specific heat $\frac{BTU}{lb.\ ^\circ F}$	Heat transfer Coefficient $\frac{BTU}{hr.\ ^\circ F\ ft^2}$
1	0.0	0.0	0.0	0.0	0.833
2	0.417	0.0925	50.0	0.26	0.0
3	0.25	0.026	9.0	0.24	0.0
4	0.0	0.0	0.0	0.0	0.6

Floor Data

Layer	Thickness ft	Conductivity $\frac{BTU}{hr.\ ft.\ ^\circ F}$	Density $\frac{lb}{ft^3}$	Specific heat $\frac{BTU}{lb.\ ^\circ F}$	Heat transfer Coefficient $\frac{BTU}{hr.\ ^\circ F\ ft^2}$
1	0.0	0.0	0.0	0.0	0.6
2	0.125	0.0667	32.0	0.33	0.0
3	0.0	0.0	0.0	0.0	0.6

EXPLANATION OF PLATE 1

North View of Test Facility

D.	Control Valve
E.	Hot Water Reservoir
F.	Coil
G.	Supply "Q"-box
H & I.	Micromanometers
K.	Multimeter (to measure Valve travel)
L.	Power Supply

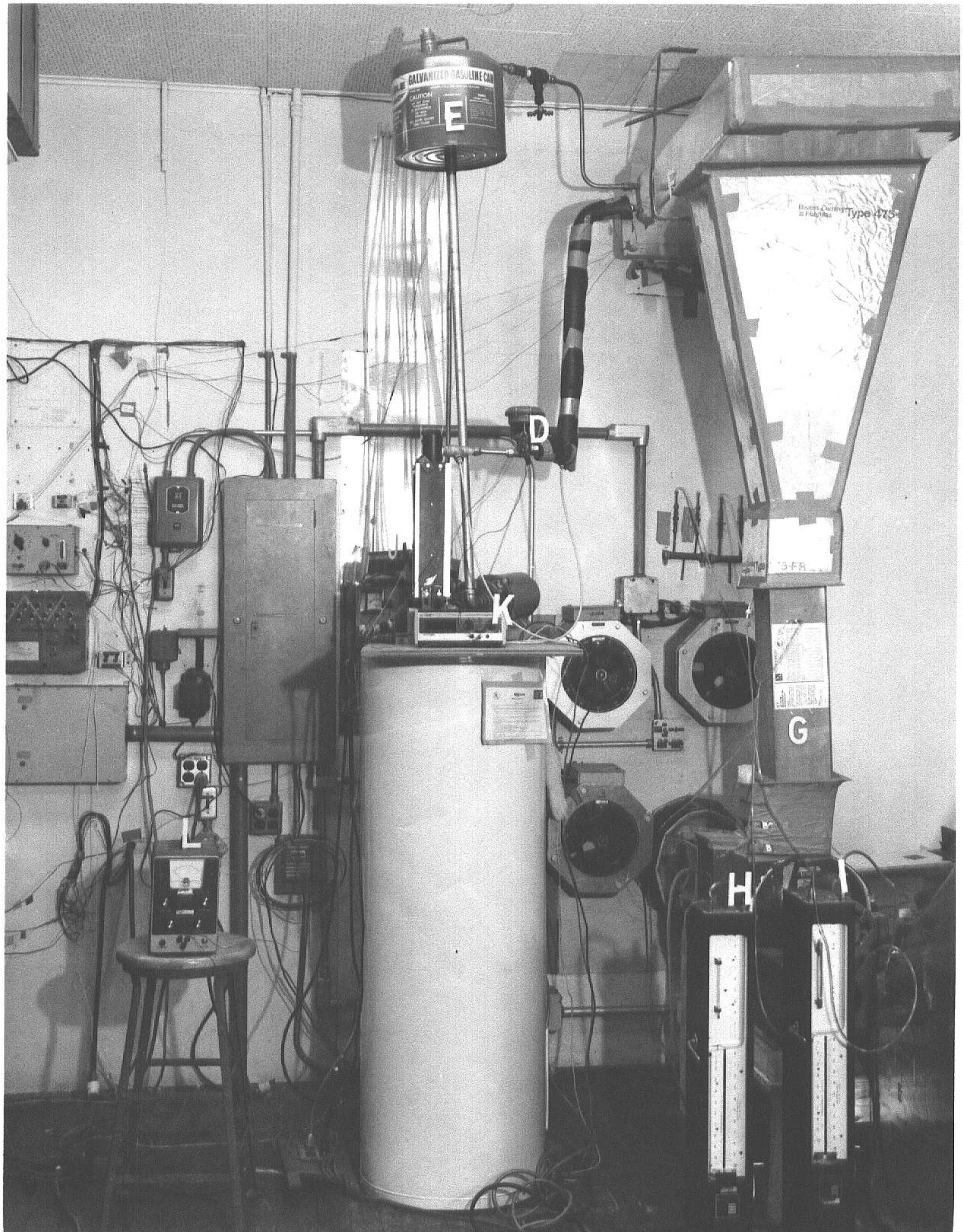

Plate 1

EXPLANATION OF PLATE 2

View of Inside of the Room

O. Thermostat

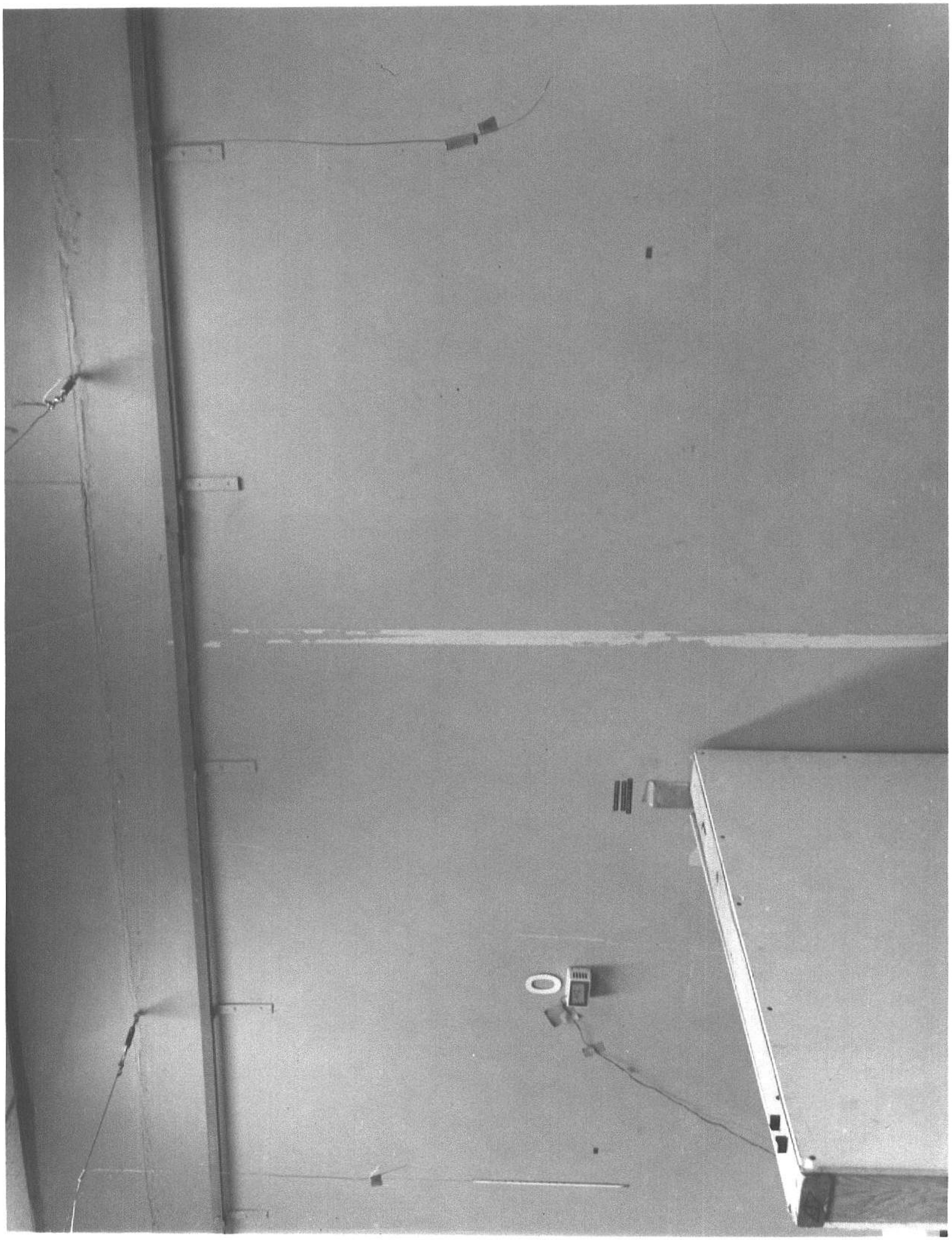

Plate 2

EXPLANATION OF PLATE 3

East View of Test Facility

A. Data acquisition System

B. Multimeter (to measure output pressure from thermostat)

C. Rotameter

F. Coil

J. Multimeter (to measure pressure drop across orifice)

K. Multimeter (to measure valve travel)

L. Power supply

M. Cold Air Fan

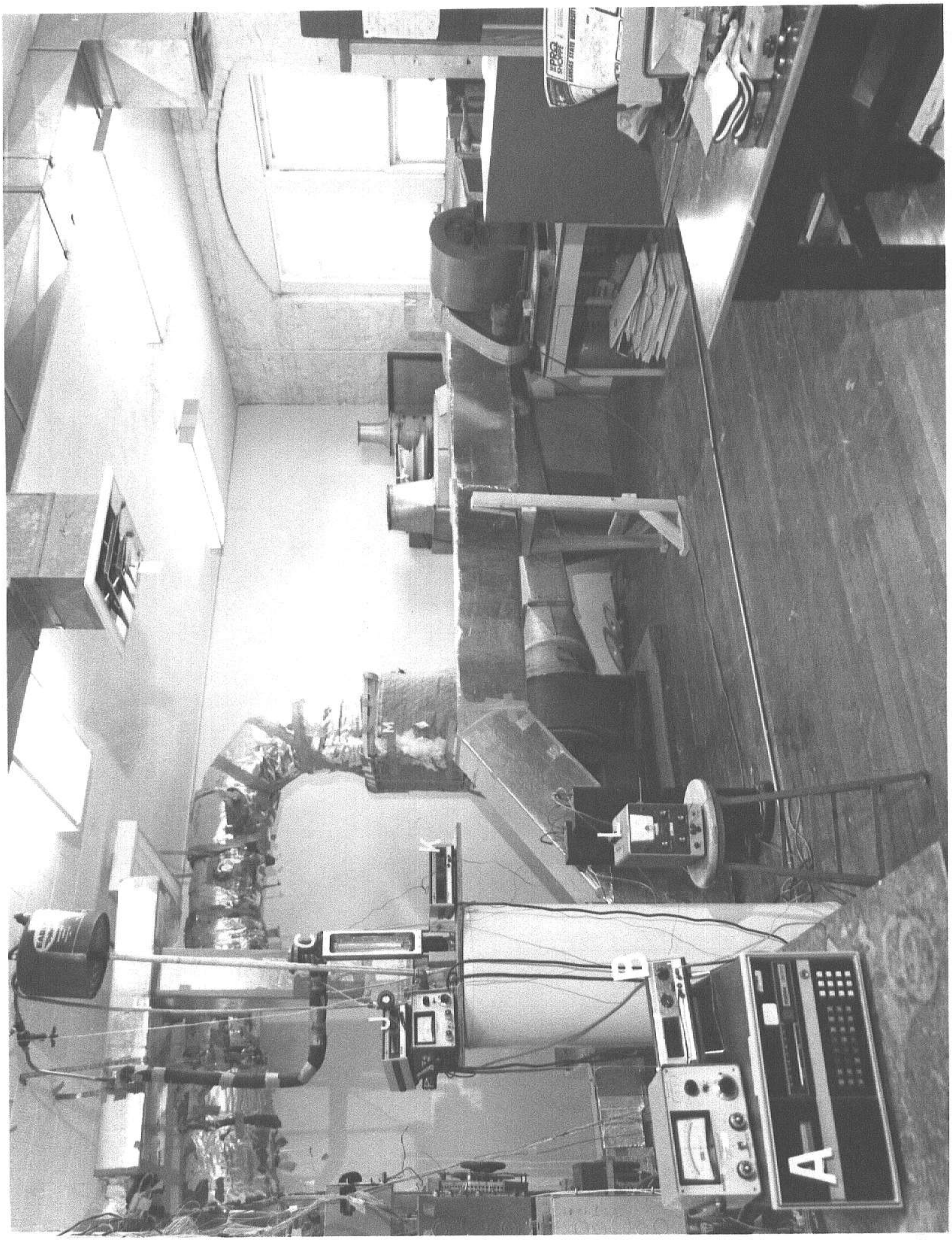

Plate 3

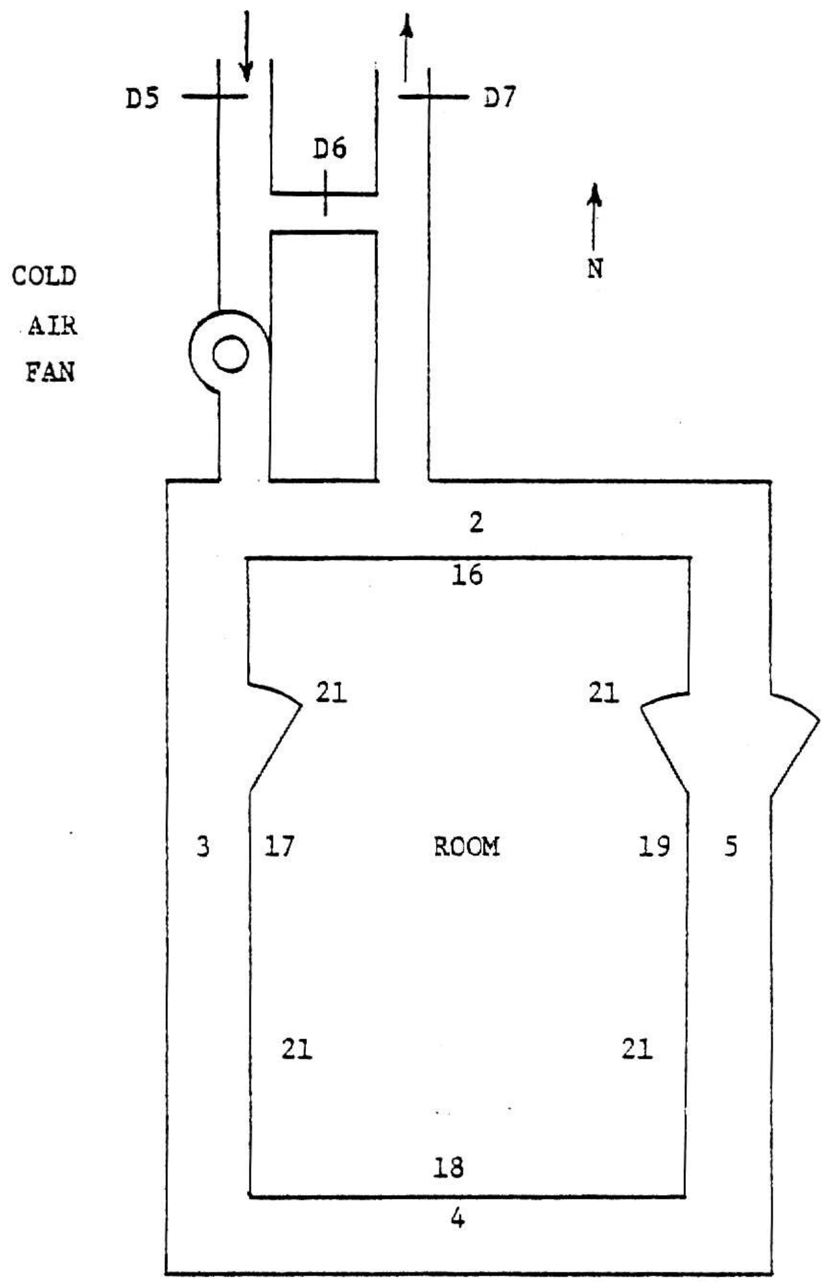

Fig. 2. Schematic diagram of room and cold air circuit. (note: numbers indicate the data acquisition channels assigned to thermocouple locations).

Hot Air Circut

The hot air circuit consisted of insulated duct, heating coil, 'Q'-boxes, dampers, diffusers, and fan.

Figure 3 is the schematic, diagram of the hot air circut. The return duct includes the return 'Q'-box and damper D1. The ventilation duct includes damper D2. These ducts join in mixing box M. The supply duct includes supply 'Q'-box, damper D4, the coil, and the diffusers. The exhaust air duct includes damper D3. Adjustment of dampers D1, D2, D3, and D4 controls the amount of ventilation air admitted to the system, and the supply and return air flow rates. The supply and return air flow rates control the room pressurization which controls the infiltration flow rate. The 'Q'-boxes are used to measure the supply and return air flow rates.

Hot Water Circuit

The hot water circuit consisted of a flowmeter, control valve, bypass valve, coil, pump, water heater, and an orifice plate. Figure 4 is the schematic diagram of the hot water circuit. Water is pumped from the reservoir into the bottom of the water heater. The bypass valve is used to control the pump outlet pressure by permitting some water to flow back to the reservoir. Hot water from the top of the water heater flows through to the flow meter, the pneumatic control valve, the coil, and an orifice into the reservoir. The orifice which is adjustable is used to control the rangability of the control valve.

A rotameter type flowmeter was used to measure the water flow rate in the hot water circuit. It could measure flow rates between 0.2 to 3.0 gpm.

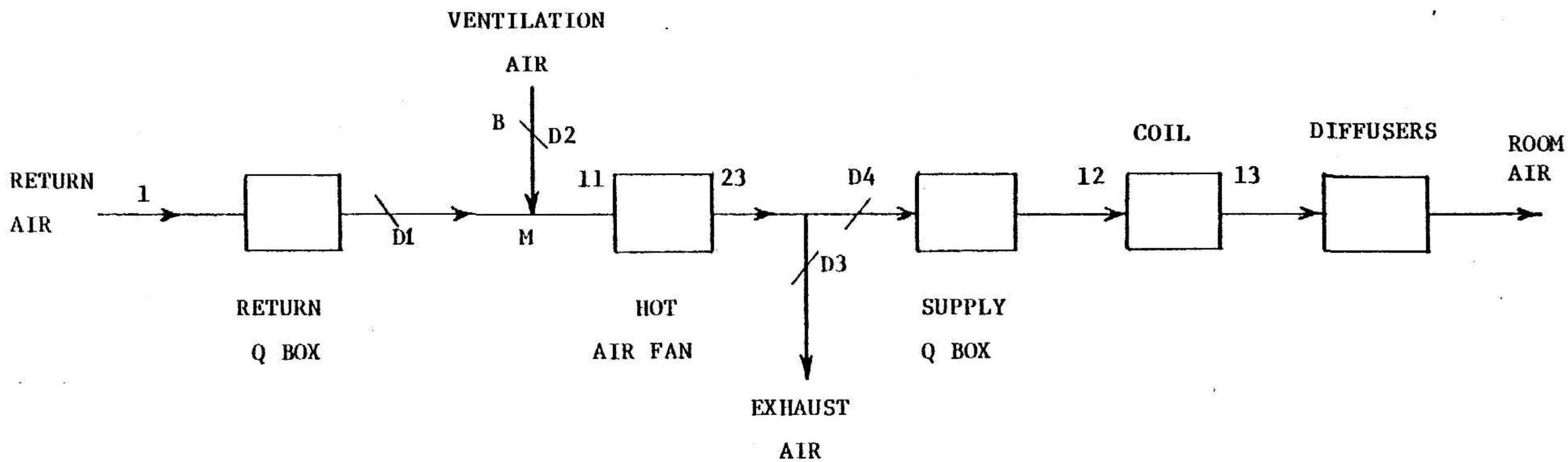

Fig. 3. Schematic diagram of hot air circuit.

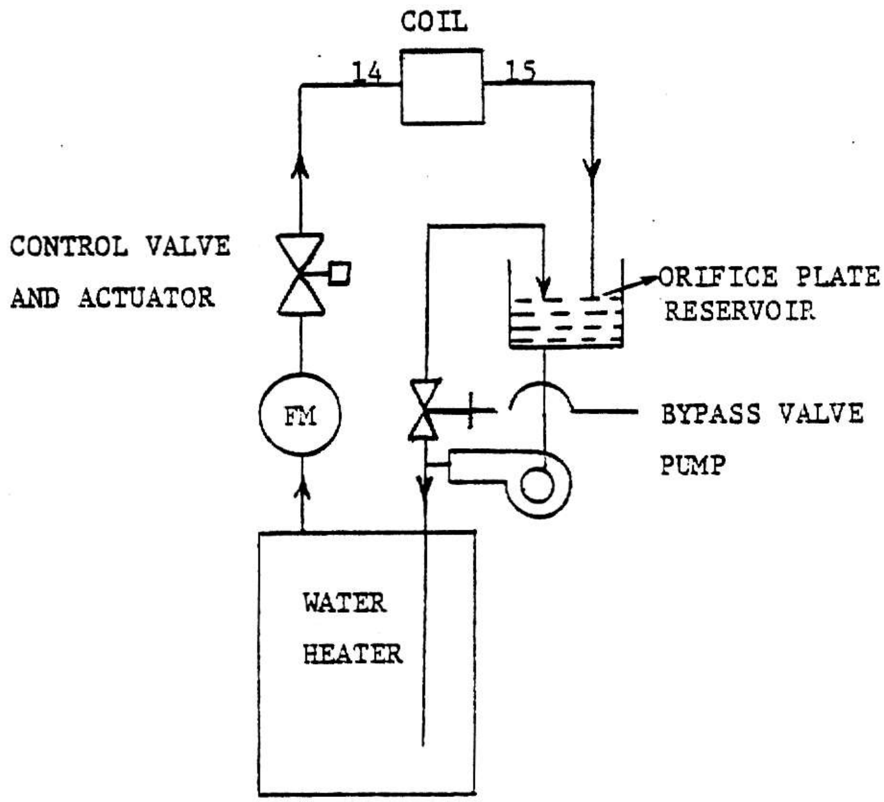

Fig. 4. Schematic diagram of the hot water circuit.

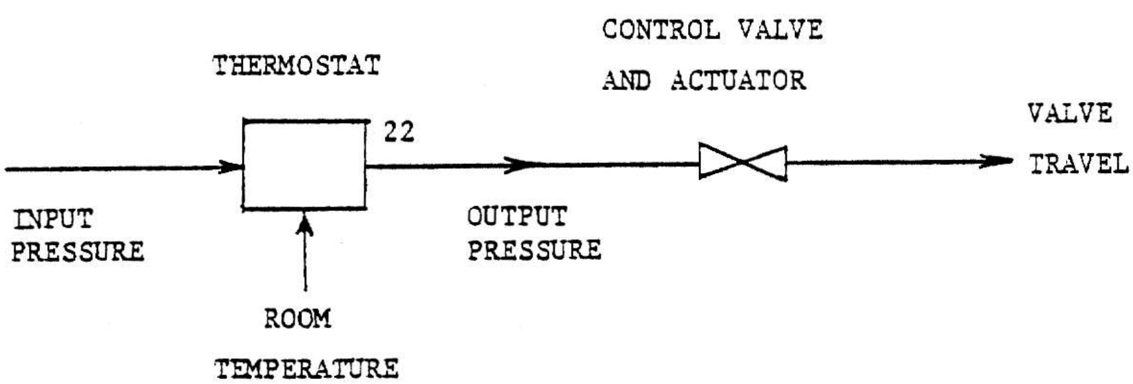

Fig. 5. Schematic diagram of the control circuit.

A Johnson model V-3762 control valve was used to regulate the water flow rate in the hot water circuit. The valve is accurately controlled by an exposed type pneumatic actuator which has a synthetic rubber diaphragm in a die cast aluminum housing. The molded diaphragm design provides a constant effective area throughout the stroke. The complete valve actuator assembly can be removed without disturbing the remainder of the assembly. The valve actuator also gives an equal percentage relationship between valve lift and flow at constant pressure drop.

Alteration of flow in the valve is effected by the movement of the actuator, which is caused by the pneumatic pressure signal from the thermostat.

A single pass, cross flow type heat exchanger was used.

An A. O. Smith model KEN-52 electric water heater was used. Specifications of the water heater are:

Model No.:	KEN-52
Series No.:	860
Maximum power:	4500 watts
Working pressure:	150 psi
Capacity:	52 U.S. gallons
Range of temperature control:	110°F to 170°F

3-4 Control Unit

The purpose of the control unit was to maintain the room at a set temperature. It consisted of a thermostat, pneumatic line and valve actuator. Figure 5 is the schematic diagram of the control circuit.

The thermostat was mounted on one of the walls of the room. A constant pressure air supply was provided to the thermostat. Input pressure to the thermostat was adjusted to P_{set}. The thermostat senses the room temperature and adjusts the output pressure which activates the valve actuator to alter the hot water flow rate. The hot water flow rate controls the temperature of the air delivered to the room.

Johnson Control Co. model T-4752 heating-cooling room thermostat was used. It is a proportional action instrument. Figure 6 is a schematic diagram of the thermostat.

On rising ambient temperature the direct acting bimetallic element bend toward the control port. This causes the pilot chamber pressure to increase. The increasing pressure actuates the instrument relay, allowing air to flow to the control line, thereby increasing the control pressure. The increasing control pressure reduces the valve opening, hence reducing hot water flow rate through the coil, and thus reducing the ambient temperature in the room. Control pressure acting on the feedback diaphragm causes the lever to rotate away from the control port, thus establishing an exact pressure corresponding to the tempature measured by the element.

On decreasing ambient temperature the bimetal element bends away from the control port, allowing the relay pilot chamber pressure to escape through it to the atmosphere. This decrease in the chamber pressure actuates the relay, allowing the control and feed back chamber pressure to decrease. The decreasing pressure on the feed back diaphragm causes the lever to rotate towards the control port and the output pressure is varied in proportion to the ambient temperature measured by the element. The reduced pressure also permits the control valve to open, increasing the flow of hot water to the coil and increasing the room temperature.

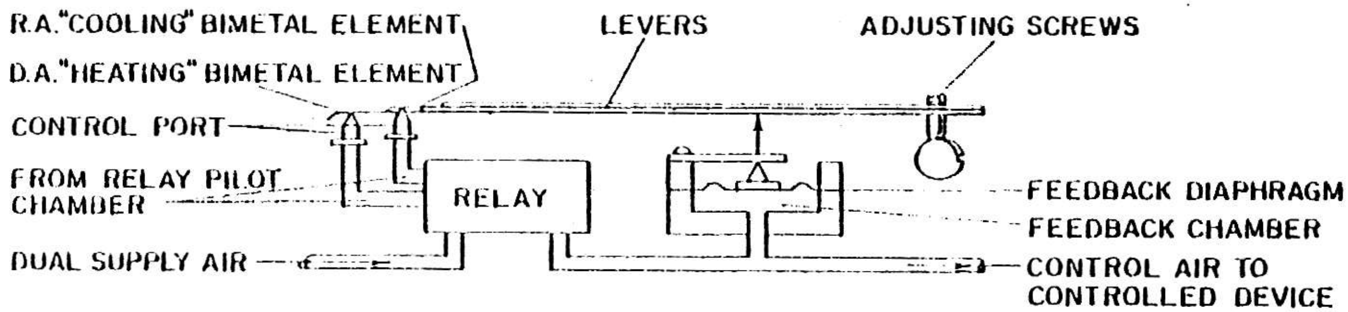

Fig. 6. Schematic Diagram of Thermostat.

3-5 Instrumentation

The instruments used in the experiment are described in this section.

'Q'-box:

'Q'-boxes were used to measure supply and return air flow rate. The 'Q'-boxes were manufactured by Tuttle and Bailey Company. The longitudnal cross section is shown in the Figure 7.

Air flow rate is indicated by the pressure drop across the sieve plate which is measured using a water micromanometer. Calibration of pressure drop vs. velocity of flow in f.p.m. is provided by the manufacturer. Flow rate is found by multiplying the air velocity by the throat area of the box.

Balancing the Air Flow Rates:

The desired air flow rates were obtained by adjusting the dampers in the ducts. The pressure drop corresponding to the desired flow rate was obtained from the calibration. The control levers were adjusted so that the manometers read the required pressure drops thus ensuring the required air flow rates in the system.

Data Acquisition System

During the validation experiment 23 different temperatures were measured every 3 minutes. Copper constantine thermocouples were used. The thermocouples were read by a data acquisition system.

An Easterline Angus P.D. 2064 data acquisition system was used.

The salient features of the P.D. 2064 are:

1. It is a key programmable data acquisition system under the control of a micro-processor. The system can gather either analog or digital data from up to 248 channels. The system prints out the measured values in engineering or scientific units.

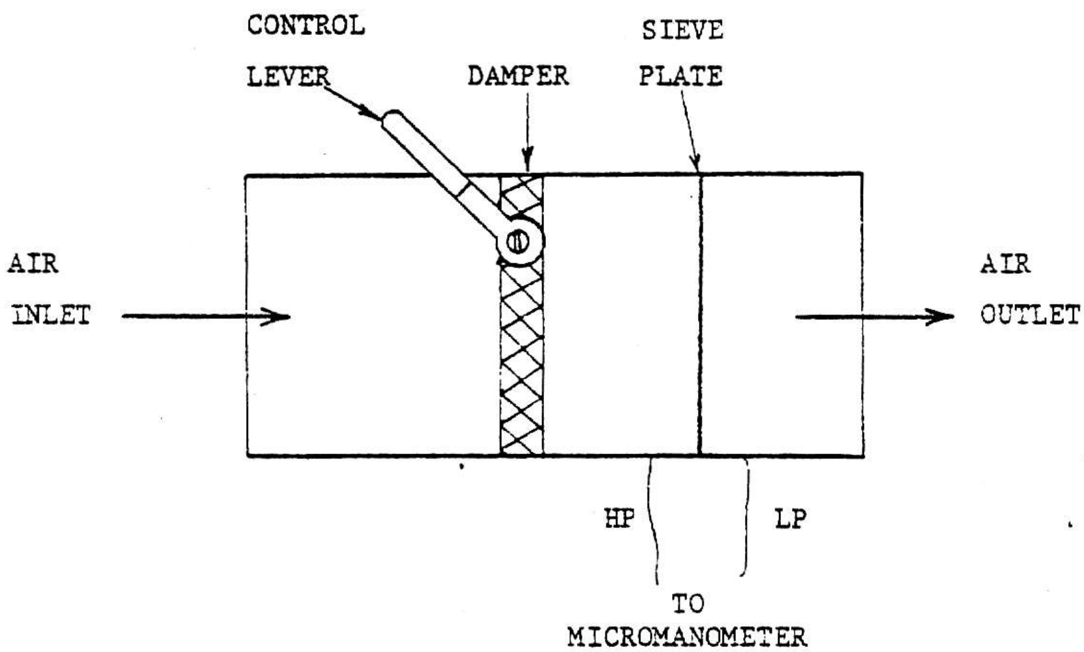

Fig. 7. Schematic Diagram of 'Q' Box.

2. A solid state integrated circuit microprocessor is combined with RAMS, ROMS and PROMS to provide a keyboard programmable system that permits the instrument to scan, measure, collect, identify and record both analog and digital signals.
3. The system provides linearization circuits for up to 4 different thermocouple types. Input circuits for analog signals in the millivolt and volt range and for (BCD) digital signals are provided.

Twenty three channels were used to measure and record temperatures at twenty three different locations. The location and function of the thermocouple attached to each channel given in Table (3-2) and shown in Figures 2, 3, and 4. The data acquisition system was programmed for each channel with following parameters:

Units option: °C

Scan interval: 3 minutes

Channel interval: 1 second.

Data were prepared manually for input to the computer.

Potentiometer

A linear potentiometer was attached to the valve stem and used to measure valve position. The potentiometer voltage which was proportinal to valve position was measured with a digital multimeter.

Pressure Transducers Pace Wiancko model KP-15

A pressure transducers were used to measure the water flow rate in the hot water circuit and the thermostat output pressure. The pressure transducers were calibrated using a dead weight tester.

The water flow rate was obtained by measuring the pressure drop across the orifice plate. The pressure transducer provides a voltage proportional to pressure. At each sampling interval the transducer voltage was recorded

TABLE 3-2.

Channel #	Thermocouple location	Thermocouple #
01	Return airduct	1
02	Air space North	2
03	Air space West	3
04	Air space South	4
05	Air space East	5
06	Ventilation air	6
07	Room down stairs	7
08	Plenum	8
09	North diffuser	9
10	South diffuser	10
11	Fan inlet	11
12	Air entering coil	12
13	Air leaving coil	13
14	Water entering coil	14
15	Water leaving coil	15
16	North wall	16
17	West wall	17
18	South wall	18
19	East wall	19
20	Floor	20
22	Thermostat sensor	22
23	Outlet of fan	23

and the water flow rate was computed using the formula:

$$FLO = FLO_{max} * SQRT(V3/V3_{max})$$

The output pressure from the thermostat was obtained from another pressure transducer. The pressure was obtained by multiplying the transducer voltage by the calibration coefficient.

3-6 Experimental Procedure

The experiment was conducted in the following steps:

1. Inside room lights were turned off.
2. Room doors were closed and sealed with tape.
3. Electrical connections were checked.
4. Dampers D5 and D7 in Figure 2 were closed and Damper D6 was opened.
5. Cold air fan in Figure 2 was turned on to circulate air in the annular space.
6. Water heater temperature was maintained at 160°F.
7. Water pump was started.
8. Hot air fan in Figure 2 was turned on.
9. 'Q'-boxes were balanced as explained earlier. Air flow rate of 95 cfm was maintained in supply 'Q'-box.
10. System was operated until steady state conditions were reached.
11. After steady state conditions were reached dampers D5 and D7 were opened and damper D6 was closed thus subjecting the room to rapidly changing load. Data were obtained at 3 minute intervals. The experiment was continued for 3.2 hours.

3-7 Determination of Coil, Valve and Valve Actuator Characteristics

Characteristics of the coil, valve and valve actuator were determined by using validation experiment data.

Coil

Effectiveness (E) of the coil was related to water flow rate through the coil. The coil characteristics are tabulated below.

Flowrate of water in GPM	Effectiveness
0 - 0.3	0.115
0.3 - 0.4	0.788
0.4 - 0.6	0.790
0.6 - 0.8	0.7925
0.8 - 1.0	0.795
1.0 - 1.2	0.800
1.2 - 1.4	0.810
1.4 - 1.6	0.821
1.6 - 1.8	0.830
1.8 - 2.0	0.840

Valve (water flow)

A plot of water flow rate vs. normalized valve travel is shown in Figure 8. Using the method of least squares the earlier part of the curve was fitted with a linear curve and the later part with a power curve. The parameter values are given below:

$$FLO = 2.362 * Y9, \quad Y9 \leq 0.81379$$

$$FLO = 1.98 * (Y9)^{0.14699}, \quad Y9 < 0.81379$$

Valve Actuator

The normalized valve travel was related to the input pressure to the valve actuator taking the hysteresis force into account. Experimental

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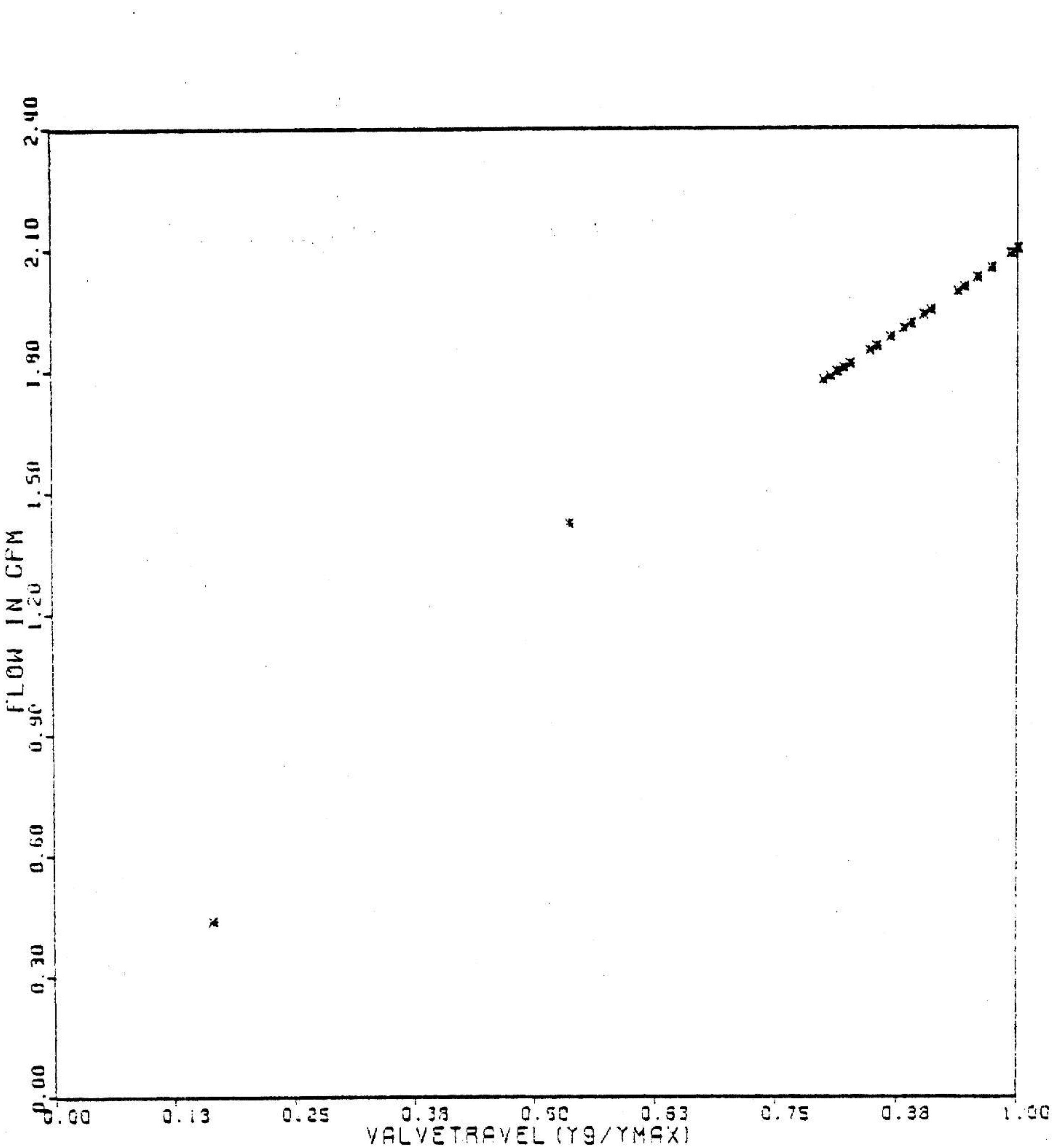

Fig. 8. Valve (Water Flow) Characterstics.

values of normalized valve travel vs input pressure to the valve actuator are plotted in the Figure 9. The valve travel correction due to hysterisis was found by measuring length DE in Figure 9. From the plot the normalized valve travel is related to the input pressure by:

$$Y9 = YMAX \cdot (5.11 - 1.23\ P8 \pm 0.265)$$

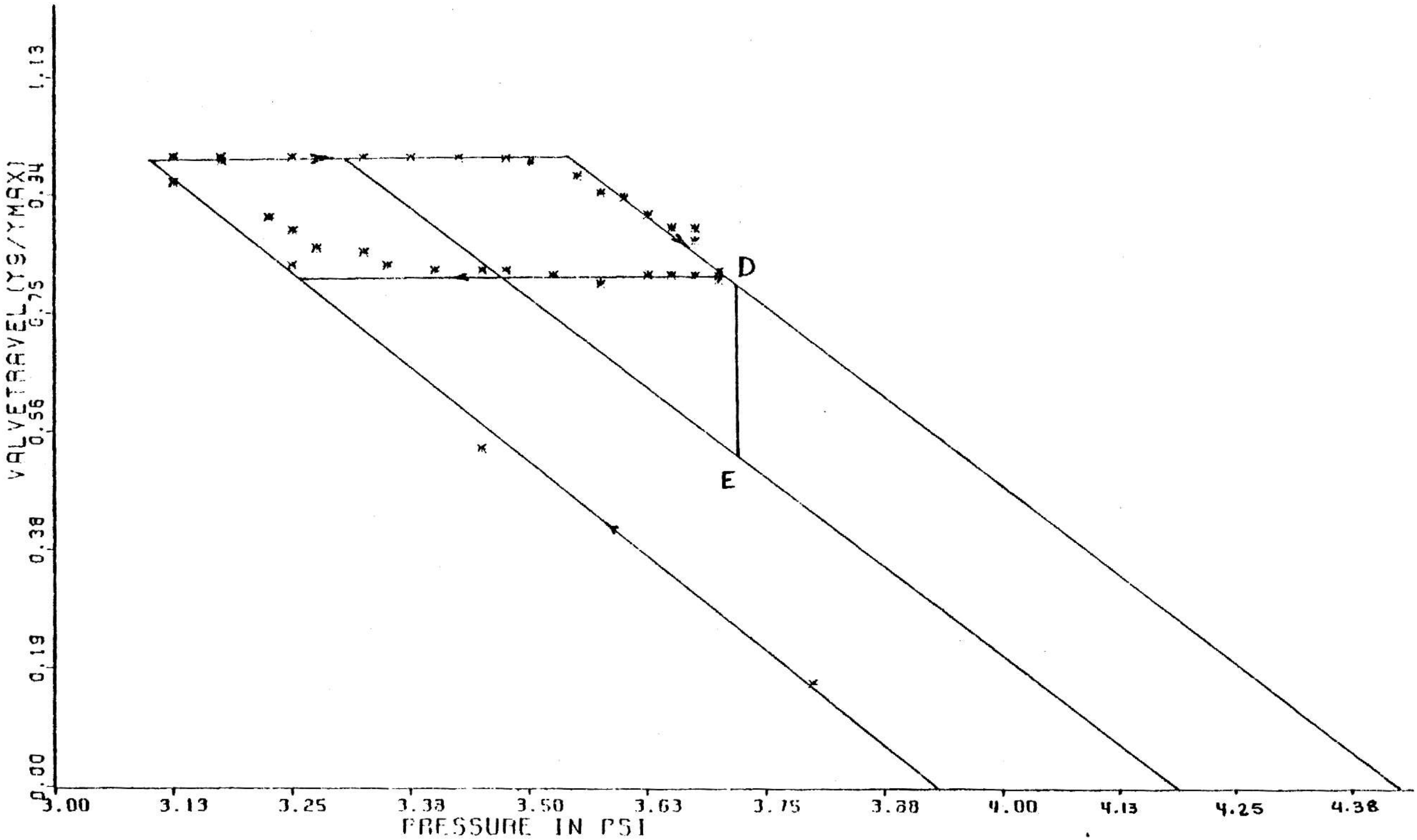

Fig. 9. Valve Actuator Characteristics.

CHAPTER 4

RESULTS AND DISCUSSION

In order to evaluate the simulation, plots of experimental and simulation data are presented. Simulation and experimental values are also presented in the form of tables in Appendix 1.

In the experimental results the following uncertainties are tolerated.

Temperature measurement	$\pm$ 0.5°F
Pressure measurement	$\pm$ 0.28 psi
Water flow rate	$\pm$ 0.01 gpm.

4-1 Room Air

The simulated and the experimental room air temperatures are plotted as in Figure 10. It is evident that the phase lag between the experimental and simulated responses of room temperature is zero. There is an amplitude difference of between 1 and 1.9°F between the two responses. The experimental response is always higher than the simulated response. Part of this difference may be attributed to the uncertainty in temperature measurement. Other factors which may contribute to this difference are the inability of the model to handle radiation effects, return air temperature, etc.

4-2 Supply Air

The experimental and simulated values of the temperatures of the air entering the room are plotted in Figure 11. It may be observed that there is a slight phase lag between the simulation and experiment. This may be the result of neglecting the heat storage capacity of the duct. The slight amplitude difference may be attributed to experimental uncertainty.

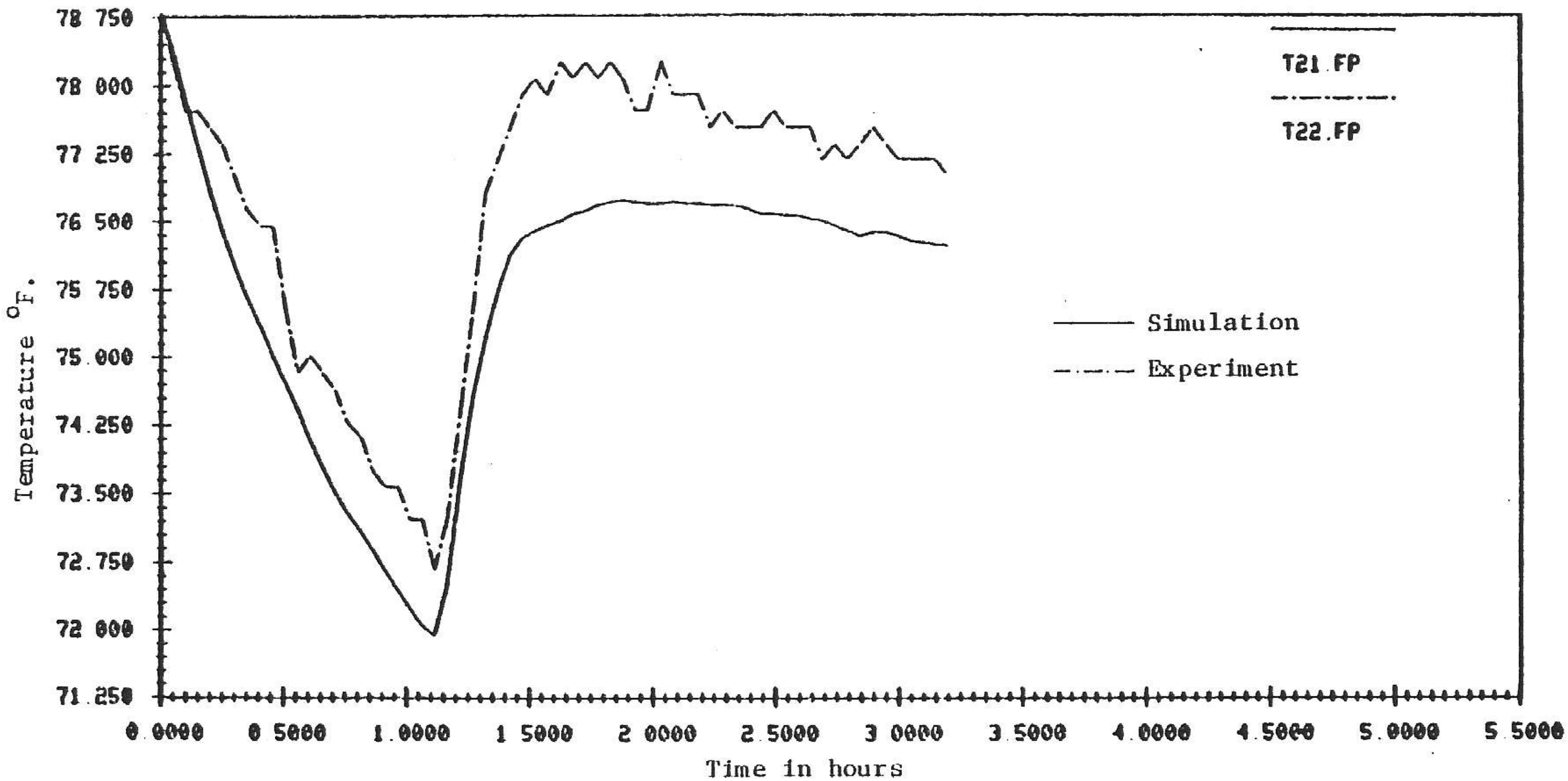

Fig. 10. Room Air.

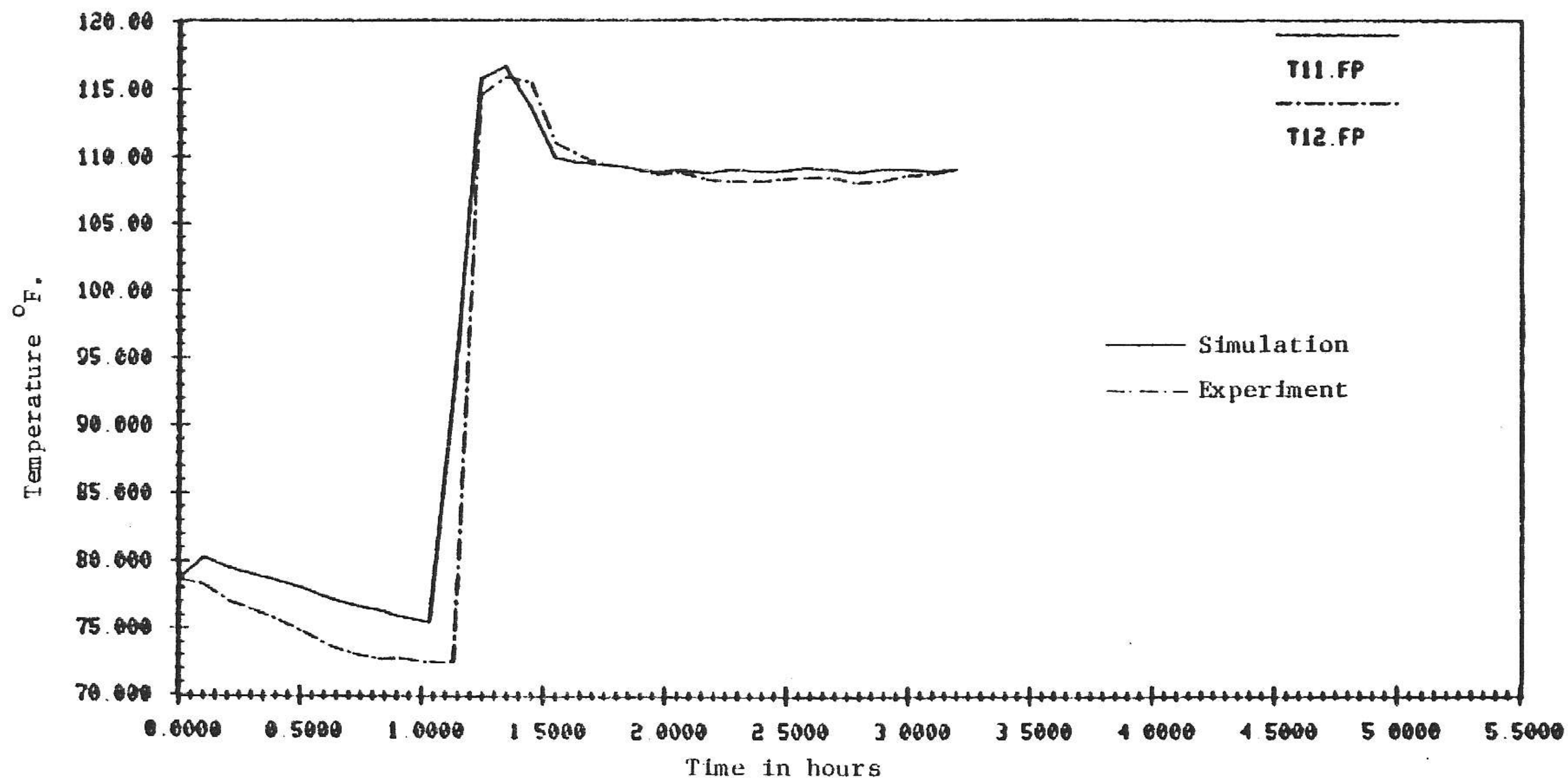

Fig. 11. Supply Air.

4-3 Coil

The simulated and experimental values of the temperature of the air leaving the coil are plotted in Figure 12. The small difference in the amplitude may be attributed to uncertainty in the temperature measurements. The slight phase lag may be the result of neglecting the heat storage capacity of the coil.

4-4 Return Air

The experimental and simulated values of return air temperature are plotted in Figure 13. Part of the difference in amplitude may be attributed to experimental uncertainty. In the model the return air temperature was computed as a weighted sum of supply, room average and wall temperatures. It may be observed that all three of these temperatures are consistently higher than the experimentally measured return air temperature so that the weighted sum will also be consistently higher than the experimental value. The return air model should include the outside air temperature.

4-5 Air Entering the Coil

The simulated and the experimental values of the temperature of the air entering the coil are plotted in Figure 14. Part of the amplitude difference may be attributed to experimental uncertainty. The diffenence in the simulated and experimental values of the return air temperature would also contribute to the observed difference in the temperature of the air entering the coil.

4-6 Wall Temperature

The experimental and simulated values of wall temperatures are plotted in Figure 15. The small difference in the amplitude

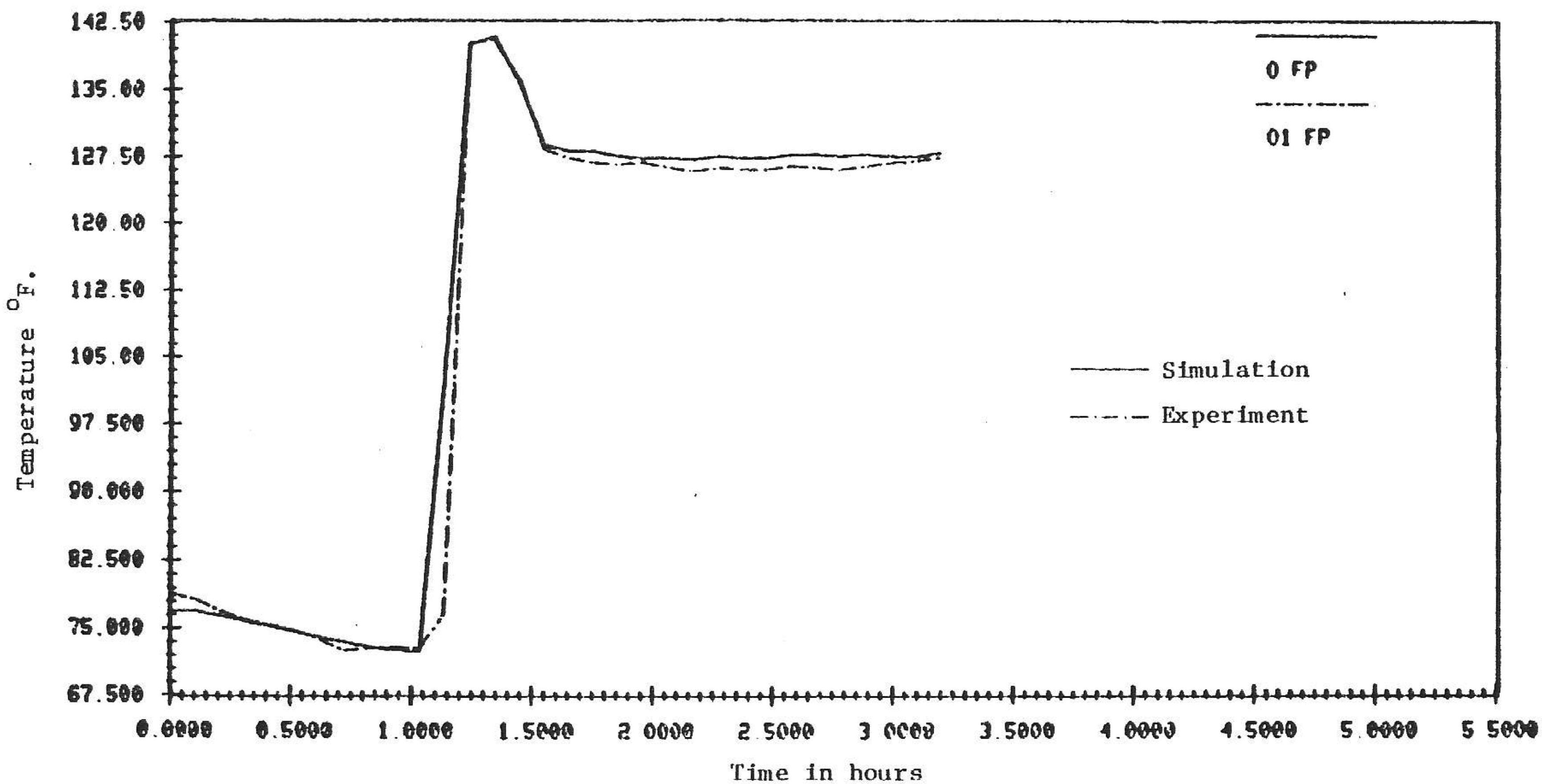

Fig. 12. Coil Output.

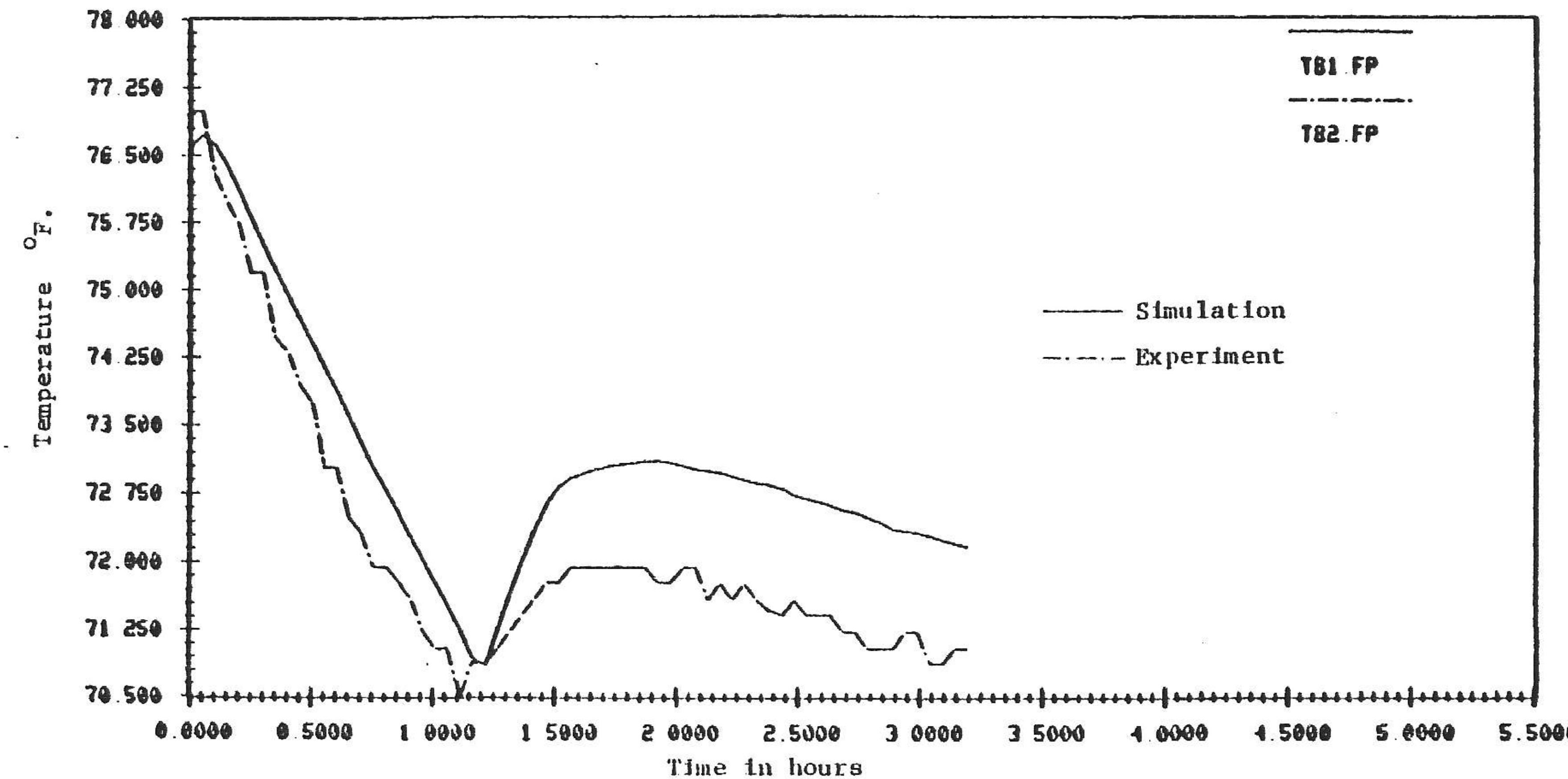

Fig. 13. Return Air.

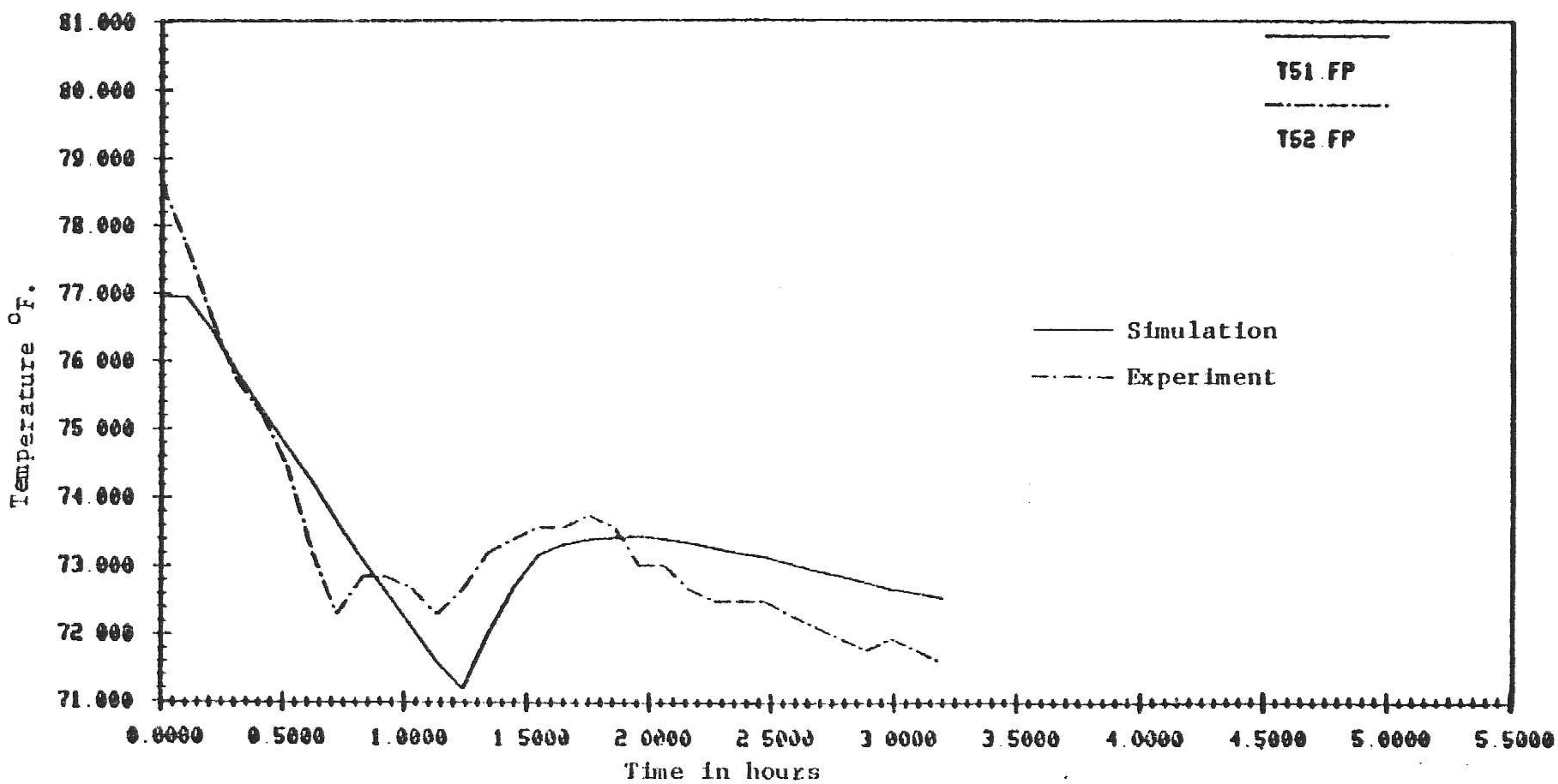

Fig. 14. Air Entering the Coil.

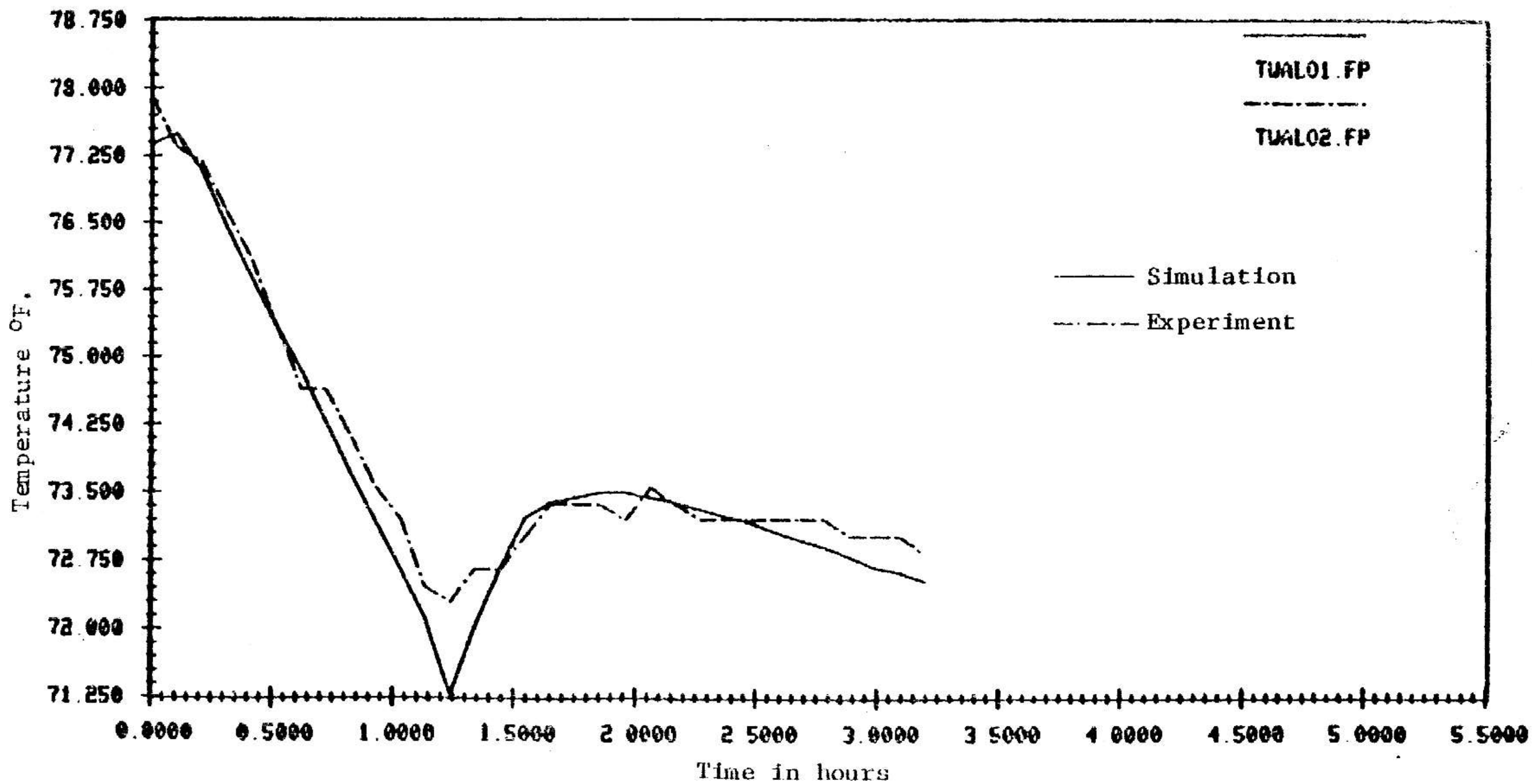

Fig. 15. Wall Temp.

may be attributed to experimental uncertainty.

4-7 Effective Temperature of the Thermostat

The simulated and experimental values of the effective temperatures of the thermostat are plotted in Figure 16. Effective temperature depends on room air temperature and wall temperature. Part of amplitude difference may be due to the differences in room air and wall temperatures and the rest to experimental uncertainty.

4-8 Thermostat Output Pressure

The simulated and experimental values of the thermostat output pressure are plotted in Figure 17. It may be observed that the simulated response tends to attain steady state faster than the experimental response. During the first 1.3 hours of the experiment the thermostat was not within its operating range and the substantial difference in pressure is not considered to be a serious deficiency in the model.

4-9 Valve Travel

The simulated and experimental values of the normalized valve travel are plotted in Figure 18. The simulation valve travel depends completely on the simulated output pressure from the thermostat. It may be observed that once the valve opens in the simulation it does not modulate back like in the experiment. This behavior is do to the difference in the thermostat output pressure.

4-10 Water Flow Rate

The simulated and experimental values of water flow rate are plotted in Figure 19. Note the same difference in response as in the valve

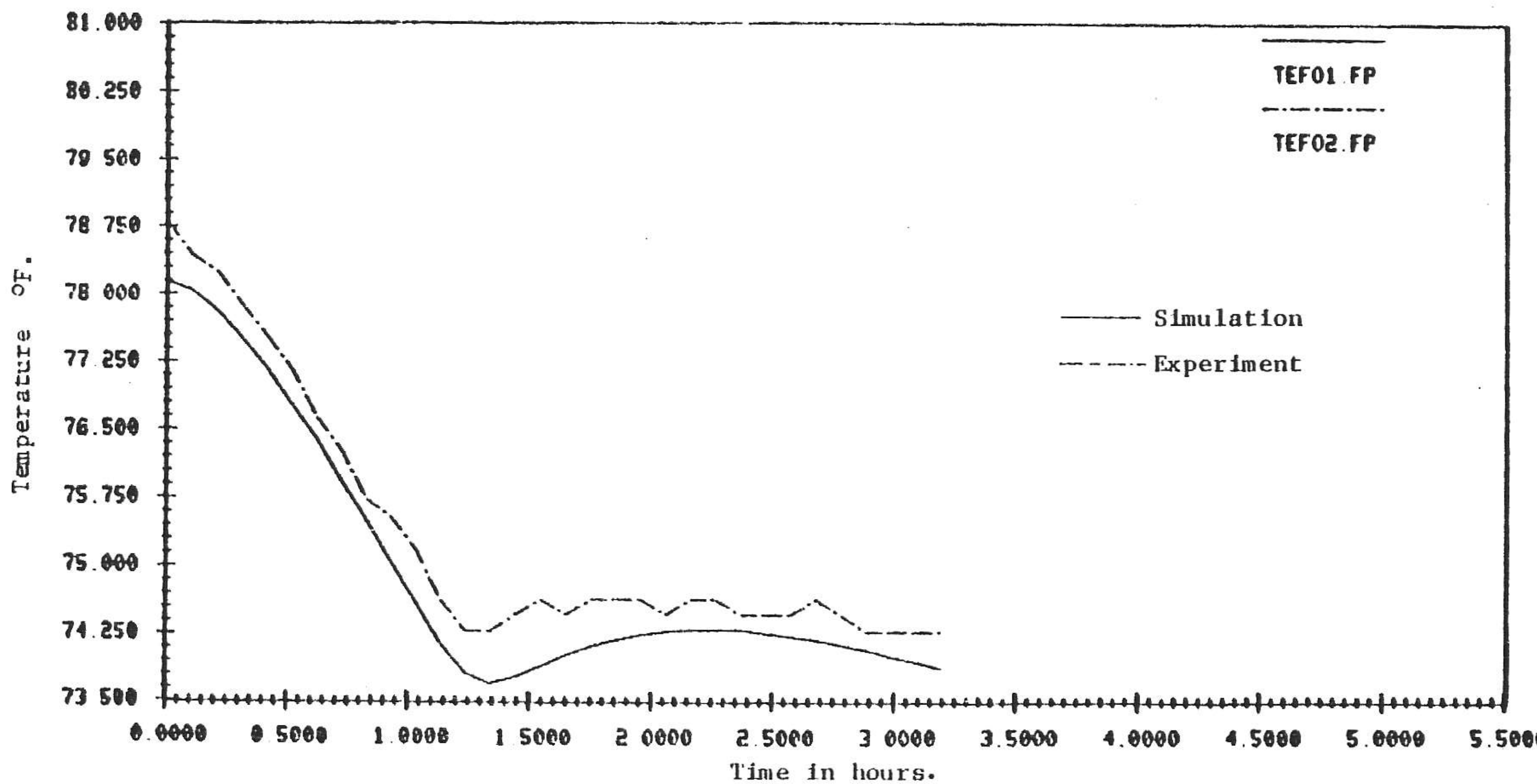

Fig. 16. Effective Temperature.

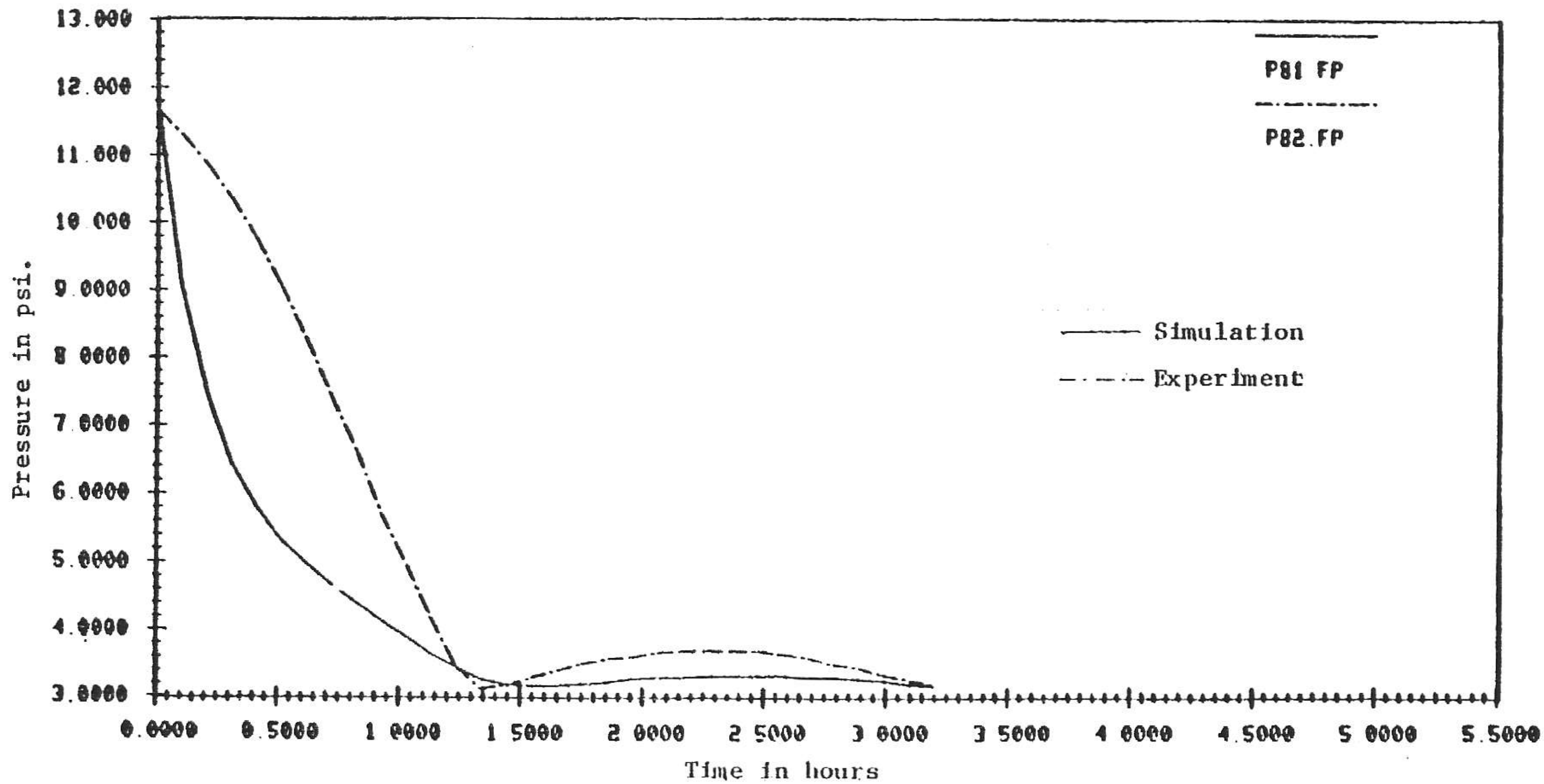

Fig. 17. Output Pressure of Thermostat.

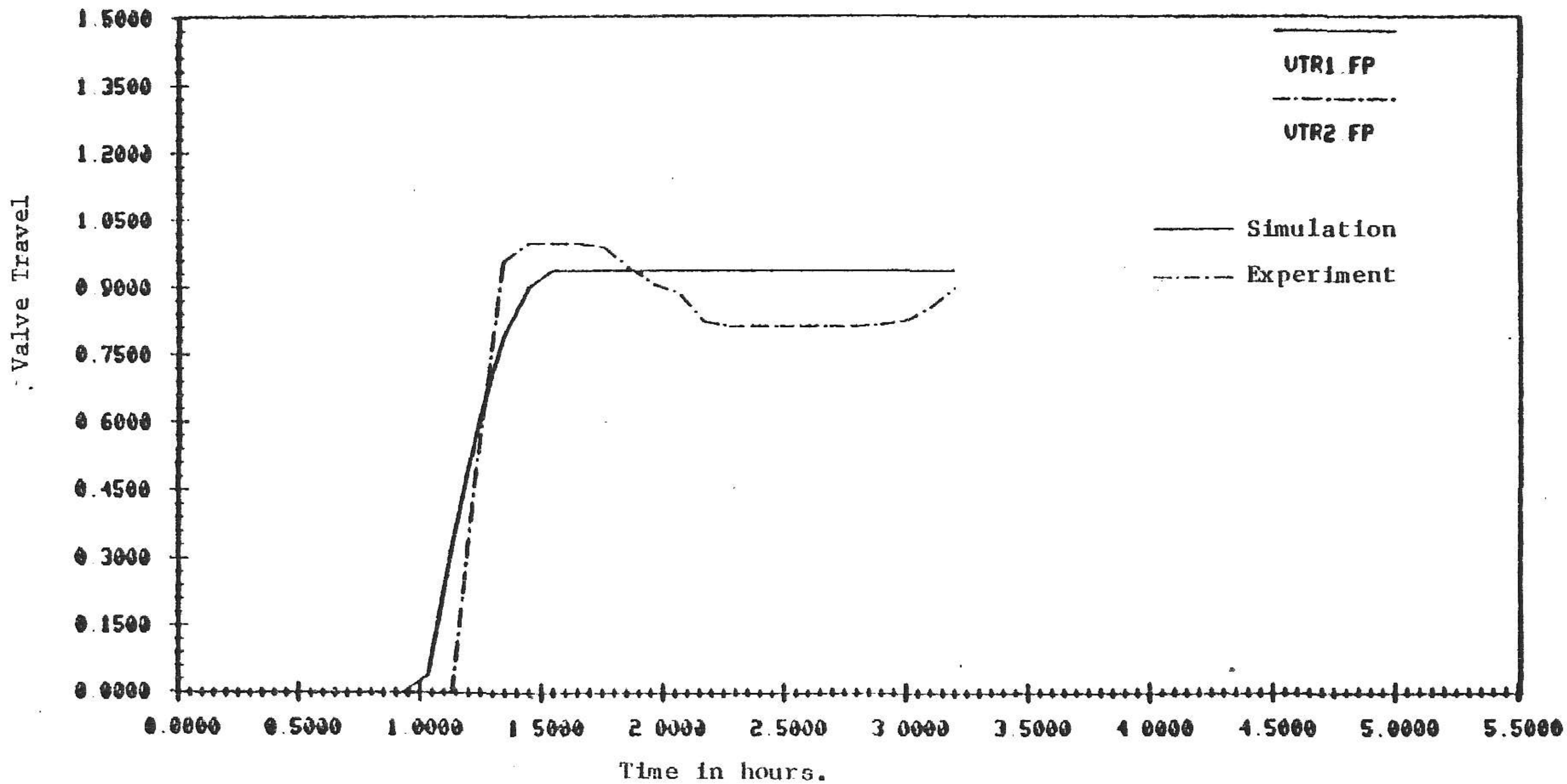

Fig. 18. Valve Travel

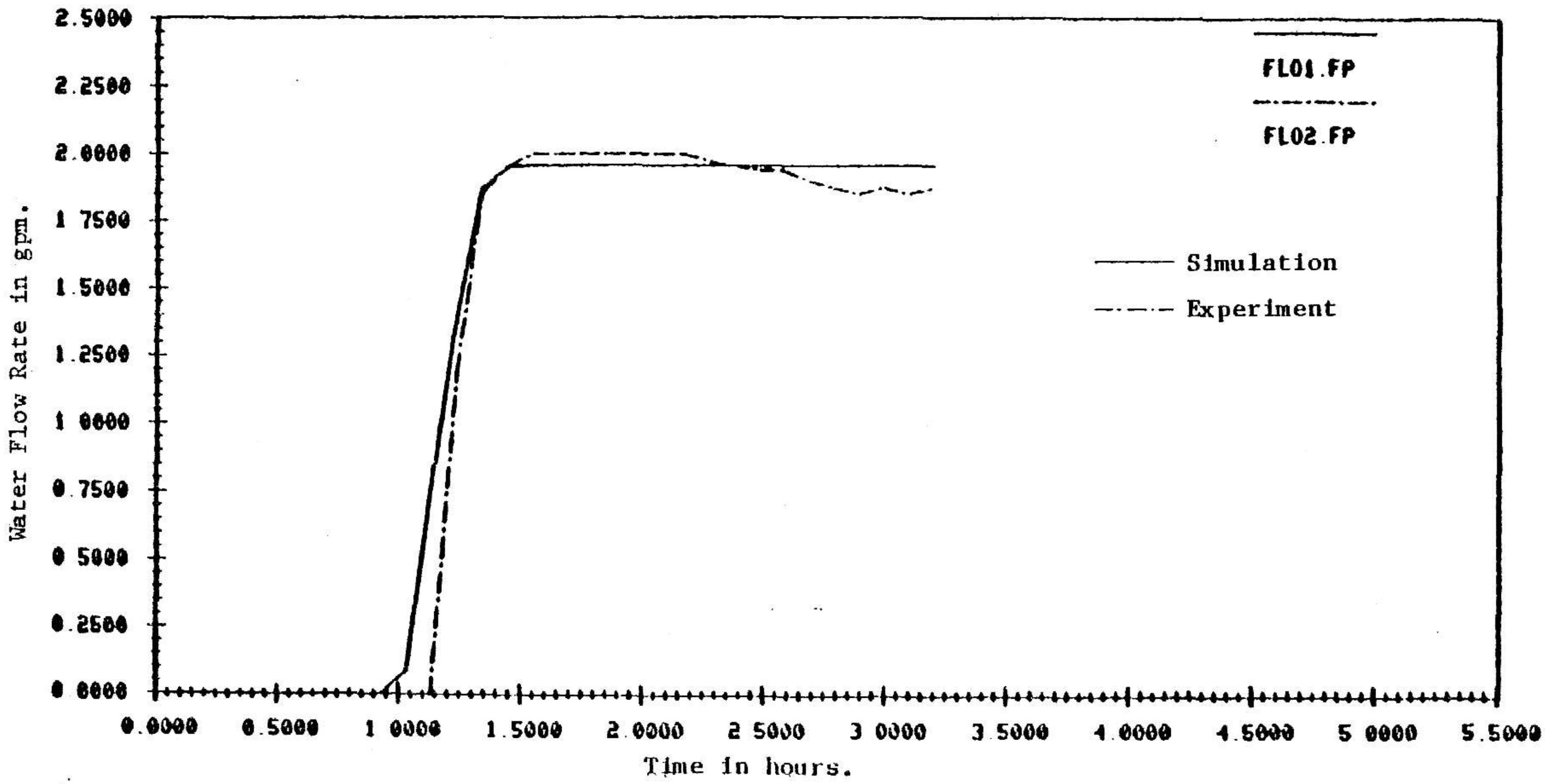

Fig. 19. Water Flow Rate.

travel.

4-11 Conclusion

After a careful study of the results it is concluded that the mathematical model is quite adequate for analysis and design purposes. However, further improvements in the model, which are beyond the scope of this project, are suggested in the next chapter.

CHAPTER 5

RECOMMENDATIONS FOR FURTHER STUDY

Recommendations for further study are given in three parts:

1. Experimental Work
2. Model Improvements
3. Model Extensions

5-1 Experimental Work

The experimental facility used for this project requires outside air to provide the thermal load on the system. Because of delays in getting some of the materials and instrumation used in the project only a limited number of days of sufficiently cold weather were available to conduct the experimental tests. The facility has been retained and it is recommended that a few additional tests be conducted to provide additional data under different conditions to more extensively verify the model. Based on our experience with the experimental results the following suggestions are made for future experimentation:

1. In the experiment 'Q'-boxes were uesd to measure the supply and return air flow rates. As this type of measurement depends on the perfection of the calibration of the 'Q'-box and on water micro-manometer, the chances of making erroneous measurements are high. It is suggested that a "Velometer" type instrument be used to check the 'Q'-boxes in further work.
2. It was found that a very high air infiltration rate existed in our experiment. Because of the dominance of infiltration more energy was required to maintain the room temperature. It is suggested that door gaps be taped and wall cracks be

taken care of properly thereby more nearly duplicating the practical case and saving energy.

3. In the experiment the valve travel, water flow rate and output pressure from the thermostat were measured manually. To avoid this tediousness, it is suggested to connect these transducers to the data acquisition system in future experiments.

4. In the experiment, the heat exchanger was operated in the saturation region. As a result, the mathematical model for the heat exchanger is almost flat (relation between effectiveness and water flow rate). It is, therefore, quite insensitive to changes in water flow rate. It is suggested that in future experiments care should be taken not to operate the coil in the saturation region.

5-2 Model Improvemtns

After a careful study of the simulated and experimental results, the following improvements in the mathematical model are suggested:

1. In the present model the return air temperature is taken as a linear combination of supply, room, and wall temperatures. It was observed that the simulated values were consistently higher than the experimental values. It is suggested that the return air temperature be modeled by adding the effect of the outside air temperature.

2. The room air and wall models may be improved by accounting for the convection film effect in the room air model rather than in the wall model. The same change should be made at

the outside surface of the walls. These changes are suggested for the following reasons:

a. Radiation effects may be handled more directly.

b. Changes in air flow conditions will cause the inside and outside convection film coefficients to vary. In the existing method these coefficients are included in the response factors and cannot easily be changed during the calculation. In the suggested method the coefficients appear directly and they can be changed during the calculations as needed.

3. It is suggested that the heat storage capacity of the coil be included in the model to overcome the small phase lag between the simulated and the experimental respones.

5-3 Model Extensions

The scope of this project was limited to the consideration of a fan coil heating system of a single room. The results of this project are encouraging and it is recommended that the work be extened to include additional types of heating and cooling systems and components and to include more than one room. Many important questions of the effect on energy consumption of system dynamics can be explored if alternative system types can be considered and if the interactions of rooms in a zone and zones in the system are included in the model.

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APPENDIX A

SIMULATION PROGRAM

The transient thermal response of a room with a fan coil heating system was simulated on a digital computer. The computer program was written in FORTRAN IV and run on an ITEL/AS5 machine.

The program consists of a main program and several subroutines. Subroutines are sequentially called by the main program. Each subroutine represents an individual component in the system. The program prints the simulated results along with the experimental results for easy comparison.

Integration Procedure

The room air and the thermostat models consist of linear differential equations with constant coefficients. They are of the form

$$\dot{x} = -Ax + \Phi(t) \qquad \text{(A-1)}$$

where

x : state variable

A : constant

$\Phi(t)$: forcing function

Assuming the forcing function to be constant over the sampling interval, equation (A-1) may be integrated in closed form as

$$X(k+1) = EXP(-A*T) *X(k) + (1-EXP(-A*T)) \frac{\cdot\Phi(k)}{A} \qquad \text{(A-2)}$$

A copy of the simulation program with output results follows.

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$JOB           NKA,TIME=(0,20),PAGES=50
C
C     ************************************************************************
C     THIS PROGRAM SIMULATES TRANSIENT THERMAL RESPONSE OF A ROOM WITH
C     FAN,PIPE AND COIL HEATING SYSTEM.
C     SAMPLING INTERVAL IS THREE MINUTES.
C     PROGRAM CONSISTS OF SEVERAL SUBROUTINES WHICH ARE CALLED SEQUENTIALLY
C     BY MAIN PROGRAM.
C     EACH SUBROUTINE CORRESPONDS TO AN INDIVIDUAL ELEMENT OF THE SYSTEM.
C     ************************************************************************
C
C
C     SYMBOLS USED IN EACH SUBROUTINE ARE DEFINED BELOW.
C
C     CONSTANTS USED IN THIS SIMULATION ARE GIVEN IN PARENTHESIS.
C
C     SUBROUTINE     RMAIR
C     PURPOSE:       TO COMPUTE ROOM TEMPERATURE.
C
C     A2,B2&C2       WEIGHTING FACTORS TO COMPUTE RETURN AIR TEMPERATURE.
C     ADENS          ROOM AIR DENSITY,LB/FT**3
C     CA             SPECIFIC HEAT OF AIR,BTU/DEG.F*LB. (0.24)
C     CF             SPECIFIC HEAT OF FURNITURE IN THE ROOM,BTU./DEG.F. (0.8)
C     DT             SAMPLING INTERVAL,HRS. (0.05)
C     ISTEP          CURRENT TIME STEP.
C     P2             ROOM PRESSURE,ATMS. (1.0)
C     QLITE          HEAT LOAD DUE TO LIGHTING,BTU/HR. (0.0)
C     T1             SUPPLY AIR TEMPERATURE,DEG.F.
C     T2             AVERAGE ROOM AIR TEMPERATURE,DEG.F.
C     TOUT           AIRSPACE TEMPERATURES,DEG.F.
C     TAU2           ROOM TIME CONSTANT,HRS.
C     VRM            VOLUME OF ROOM,FT**3 (2126.6)
C     XM1            MASS FLOW RATE OF AIR ENTERING THE ROOM,LB./HR. (427.5)
C     XM2            MASS FLOW RATE OF RETURN AIR,LB./HR. (776.5)
C     XMO            MASS FLOW RATE OF INFILTERED AIR INTO ROOM,LB./HR. (349.0)
C     XMF            MASS OF FURNITURE IN THE ROOM,LB. (100)
C
C     SUBROUTINE     SFLUX
C     PURPOSE:       TO COMPUTE HEAT LOSS THROUGH THE SURFACES WITH HEAT STORAGE.
C
C     CO(1)          CONDUCTANCE  OF OUTSIDE WALL,BTU/HR.FT**2.DEG.F. (0.08850)
C     CO(2)          CONDUCTANCE OF FLOOR,BTU/HR.DEG.F.FT**2 (0.3253)
C     FLUX           HEAT FLUX THROUGH SURFACE I AT TIME ISTEP
C     HTFLO          TOTAL HEAT LOSS THROUGH THE SURFACE WITH HEAT STORAGE
C     NSURF          NUMBER OF SURFACES WITH HEAT STORAGE. (2)
C     NX,NY,NZ       NUMBER OF COEFFICIENTS FOR WALL AND FLOOR.
C     SAREA(1)       SURFACE AREA OF OUTSIDE WALL,FT**2 (531.8)
C     SAREA(2)       SURFACE AREA OF FLOOR,FT**2 (531.8)
C     XS,YS,ZS       COEFFICIENTS FOR SURFACES WITH HEAT STORAGE.
C
C     SUBROUTINE     HFLUX
C     PURPOSE:       TO COMPUTE INSIDE HEAT FLUX OF SURFACE WITH HEAT STORAGE.
C
C
C     SUBROUTINE     WLTEMP
C     PURPOSE:       TO COMPUTE INSIDE WALL TEMP. ON WHICH THERMOSTAT IS MOUNTED.
C
C     TWALL          WALL TEMPERATURE,DEG.F
C     HWALL          HEAT TRANSFER COEFFICIENT OF WALL,BTU/HR.DEG.F.FT**2 (0.6)
C
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C       SUBROUTINE     WTRFLO
C       PURPOSE:       TO COMPUTE WATER FLOW RATE IN GPM.
C
C       FLO(ISTEP)     WATER FLOW RATE AT TIME ISTEP
C       FLCMAX         MAXIMUM WATER FLOW RATE,GPM (2.0)
C
C       SUBROUTINE     FNDC1
C       PURPOSE:       TO COMPUTE AIR TEMPERATURE AT FAN EXIT.
C
C       ARATIO         RATIO OF VENTLN. AIR TO RETURN AIR (0.0)
C       ETAM           MECH. EFFICIENCY OF MOTOR DRIVING HOT AIR FAN (0.5)
C       ETAS           FAN STATIC ENERGY/ENERGY TO FAN SHAFT
C       T5             AIR TEMP. ENTERING COIL,DEG.F
C       T8             RETURN AIR TEMPERATURE,DEG.F.
C
C       SUBROUTINE     FNDC2
C       PURPOSE:       TO COMPUTE SUPPLY TEMP.
C
C       PHI            PRESSURE DROP IN RETURN DUCT/DROP IN ENTIRE SYSTEM (0.2)
C       UAD            OVERALL HT COEFFICENT OF SUPPLY PIPE, BTU/HR.DEG.F.FT**2
C                      (52.0)
C
C       SUBROUTINE     COIL
C       PURPOSE:       TO COMPUTE TEMP. OF AIR LEAVING THE COIL,DEG.F.
C
C       G6             EFFECTIVENESS OF COIL
C       GPM            WATER FLOW RATE IN THE COIL
C
C       SUBROUTINE     THRMST
C       PURPOSE:       TO COMPUTE THE OUTPUT PRESSURE FROM THE THERMOSTAT.
C
C       A7687          WEIGHTING FACTORS TO COMPUTE EFFCTIVE TEMP. (0.725,0.275)
C       PSET           SET PRESSURE,PSI (3.45)
C       TAU71          TIME CONSTANT EFFECTED BY WALL
C       TAU72          TIME CONSTANT EFFECTED BY ROOM AIR.
C       TEFF           EFFECTIVE TEMP. OF THRMST.
C       P7             OUTPUT PRESSURE FROM THRMST.
C       TSET           SET TEMP. OF THRMST. (74.5)
C       P7 AND TEFF ARE RELATED BY GAIN AND A TIME CONSTANT.
C       1/P            TIME CONSTANT,HRS. (0.19)
C       PK             GAIN (0.508)
C
C       SUBROUTINE     COND
C       PURPOSE:       TO COMPUTE HEAT LOSS THROUGH SURFACES WITHOUT HT.STORAGE.
C
C       U              OVER ALL HT. COEFFICIENTS OF SURFACES W.O.T. HT. STORAGE.
C       AREA           AREAS OF SURFACES W.O.T. HT. STORAGE,FT**2
C
C       SUBROUTINE     VALACT
C       PURPOSE:       TO COMPUTE NORMALIZED VALVE TRAVEL.
C
C       Y9             NORMALIZED VALVE TRAVEL
C       YMAX           MAXIMUM VALVE TRAVEL, INCHES. (0.256)
C       HYS            VALVE TRAVEL CORRECTION DUE TO HYSTERISIS. (0.265)
C
1       DIMENSION XS(2,30),YS(2,30),ZS(2,30),SAREA(2),
       1TOUT(3,100),T1(100),T2(100),GMO(30,100),TMO(30,100),
       2  NX(2),NY(2),NZ(2),
       3TM(30,100),GM(30,100),CO(2),FLUX(2,100),
       4GPM(10),G6(10),CAREA(3),U(3),TMX(100),
```

```
      5                          P8(100),P8A(100),T60(100),
     6Y9EX(100),V1(100),V2(100),V3(100),P8EX(100),FLEX(100),
     7Y9(100),FLO(100),P7(100),P7EX(100)
C     READ NUMBER OF INTERVALS
      READ 1,IEND
C     READ INITIAL ROOM TEMPERATURE AND TEMPERATURE OF THERMOSTAT
      READ 6, T2(1),TEFF
C     READ OUTSIDE TEMPERATURE PROFILES.
      DO 111 J=1,IEND
      READ 1000,M,N,L,A,B,V1(J),V2(J),V3(J)
 1000 FORMAT(3I2,5F6.2)
      READ 1001,(TM(I,J),I=1,12)
 1001 FORMAT(12F6.2)
      READ 1002,(GM(I,J),I=1,11)
 1002 FORMAT(11F6.2)
      TOUT(1,J)=(TM(2,J)+TM(3,J)+TM(4,J)+TM(5,J))/4.0
      TOUT(2,J)=TM(7,J)
      TOUT(3,J)=TM(8,J)
  111 CONTINUE
C     READ IN ROOM DATA :
      DO 10 I=1,12
      DO 10 J=1,IEND
      TMC(I,J)=TM(I,J)*1.8+32.0
   10 CONTINUE
      DO 11 I=1,11
      DO 11 J=1,IEND
      GMC(I,J)=GM(I,J)*1.8+32.0
   11 CONTINUE
      READ 1, NSURF
      READ 3, (NX(I),NY(I),NZ(I), I=1,NSURF)
      READ 6,(CO(I),SAREA(I),I=1,NSURF)
      DO 200 I=1,NSURF
      MM=NX(I)
      READ 700,(XS(I,J),J=1,MM)
      MM=NY(I)
      READ 700, (YS(I,J),J=1,MM)
      MM=NZ(I)
      READ 700,(ZS(I,J),J=1,MM)
  200 CONTINUE
      READ 5,VRM
      READ 5, HWALL
      READ 1,NWL
      READ 1, INF
      READ 6, XMF,CF
      READ 6,CA,P2
      READ 6,GLITE,DT
      READ 5,PO
C     DATA FOR SURFACES WITH NEGLIGIBLE HEAT STORAGE :
      DO 20 I=1,3
      READ 6, U(I),CAREA(I)
   20 CONTINUE
C     FAN-DUCT DATA :
      READ 6,WM,ETAM,ETAT,ETAS
      READ 6, ARATIO,PHI
      READ 5, XM1
      READ 5,FLOMAX
C     THERMOSTAT DATA :
      READ 6,PS,TSET
      READ 6, TAU71,TAU72
      READ 6,A7,B7
```

```
C      COIL DATA :
       READ 6,(GPM(I),G6(I),I=1,10)
       READ 5,THWTR
       READ 1005,UAD
 1005  FORMAT(F5.2)
       READ 1006,XM2
 1006  FORMAT(F10.5)
       XMO=XM2-XM1
       CFM=XM1/60./0.075
C      VALVE DATA :
       YMAX=0.256
       HYS=0.265
C      CONVERT TEMPERATURE INPUT TO DEGREE  F .
       DO 100 I=1,3
       DO 100 J=1,IEND
       TOUT(I,J)=TOUT(I,J)*9./5.+32.
  100  CONTINUE
       T2(1)=T2(1)*9./5.+32.
       TEFF=TEFF*9./5.+32.
       PRINT 530
  530  FORMAT(7X,'T6',9X,'T6*',8X,'TWALO',6X,'TWALC*',
      15X,'TEFO',7X,'TEFO*',6X,'T8',9X,'T8*',8X,'T5',9X,'T5*',//)
C
C      THE FIRST LOOP INITIALIZES ALL VARIABLES (ISTEP=1)
C      EACH FOLLOWING LOOP COMPUTES ALL VARIABLES AT THE END OF THE TIME INTERVAL
C
       DO 70 ISTEP=1,IEND
       IF(ISTEP.EQ.1) GO TO 60
C
       CALL RMAIR(TOUT,T1,T2,DT,VRM,CA,CF,XMF,XM1,XM2,CLITE,HTFLO,
      1QCOND,P2,TAU2,INF,ISTEP,TWALL,TEMP,S)
C
   60  CALL SFLUX(T2,TOUT,XS,YS,ZS,NX,NY,NZ,NSURF,SAREA,CO,FLUX,
      1HTFLO,ISTEP)
       DMY1=FLUX(NWL,ISTEP)
       DMY2=T2(ISTEP)
       X1=FLUX(NWL,ISTEP)
       X2=T2(ISTEP)
C
       CALL WLTEMP(X1,X2,HWALL,TWALL)
C
       CALL THRMST(X2,TWALL,A7,B7,TEFF,TSET,P8,PS,
      1TAU71,TAU72,D7,DT,ISTEP,GMC)
       QCOND=0.0
       X3=TOUT(1,ISTEP)
       DO 25 I=1,2
       X4=U(I)
       X5=CAREA(I)
C
       CALL COND(X2,X3,X4,X5,X6)
       QCOND=QCOND+X6
   25  CONTINUE
C
       QCOND=QCOND+U(3)*CAREA(3)*(TOUT(3,ISTEP)-T2(ISTEP))
C
       CALL        VALACT(P7EX,V2,YMAX,Y9,P8,HYS,ISTEP)
C
       CALL        WTRFLO(Y9,FLO,YMAX,FLOMAX,ISTEP)
C
       CALL FNOQ1(T1,T2,T3,T4,T5,T6,TOUT,XMO,XM1,XM2,
```

```
     1ETAT,ETAM,ETAS,WM,CA,PHI,ARATIO,ISTEP,INF,1,UAD,TWALL,T8)
C
      CALL COIL(GFM,G6,FLO,GMO,TMO,T6,ISTEP,T5)
C
      CALL FNCO2(T1,T2,T3,T4,T5,T6,TOUT,XM0,XM1,XM2,ETAT,ETAM,ETAS,
     1WM,CA,PHI,ARATIO,ISTEP,INF,2,UAD)
C
      IF(ISTEP.GT.1) GO TO 30
      CALL RMAIR(TOUT,T1,T2,DT,VRM,CA,CF,XMF,XM1,XM2,CLITE,HTFLO,
     1UCOND,P2,TAU2,INF,ISTEP,TWALL,TEMP,S)
   30 T30=T3
      T50=T5
      T60(ISTEP)=T6
      T10=T1(ISTEP)
      TWALO=TWALL
      TEFO=TEFF
      PRINT 531,ISTEP,T60(ISTEP),GMO(1,ISTEP),TWALO,GMO(7,ISTEP),
     1TEFO,GMO(10,ISTEP),T8,TMO(1,ISTEP),T5,TMO(12,ISTEP)
  531 FORMAT(2X,I2,2X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2,
     15X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2)
   70 CONTINUE
      PRINT 600
  600 FORMAT(1H1,7X,'T1',9X,'T1*',7X,'T2',9X,'T2*',//)
      DO 80 I=1,IEND
      TMX(I)=(TMO(9,I)+TMO(10,I))/2.0
   80 PRINT 601,I,T1(I),TMX(I),T2(I),GMO(9,I)
  601 FORMAT(2X,I2,2X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2)
      PRINT 500
  500 FORMAT('1')
    1 FORMAT(I5)
    3 FORMAT(3I5)
    5 FORMAT(F10.5)
    6 FORMAT(2F10.5)
    8 FORMAT(4F10.5)
  700 FORMAT(D23.16)
      PRINT 900
  900 FORMAT(1H1,7X,'VTR',7X,'VTR*',7X,'P8',7X,'P8*',
     15X,'FLO1',6X,'FLO1*',//)
      DO 90 ISTEP=1,IEND
      IF(V3(ISTEP).LE.0.0) V3(ISTEP)=0.0
      IF(V1(ISTEP).GT.4.95) V1(ISTEP)=5.0
      IF(V1(ISTEP).EQ.3.88) V1(ISTEP)=3.82
      X9=-0.17655*V1(ISTEP)+0.88275
      Y9EX(ISTEP)=X9/YMAX
      P8EX(ISTEP)=2.5*V2(ISTEP)
      FLEX(ISTEP)=2.0*SQRT(V3(ISTEP)*2.0)
   90 PRINT 49,ISTEP,Y9(ISTEP),Y9EX(ISTEP),P8(ISTEP),
     1P8EX(ISTEP),FLO(ISTEP),FLEX(ISTEP)
   49  FORMAT(2X,I2,2X,F6.2,5X,F6.3,4X,F6.2,3X,
     1F6.2,3X,F6.2,4X,F6.2)
C
C
C              KEY TO OUTPUT
C
C
C     ALL LABELS STARTING WITH ALPHABET 'T' ARE TEMPERATURES IN FAHRENHIET SCALE
C     T6       AIR LEAVING THE COIL (SIMULATION)
C     T6*      AIR LEAVING THE COIL (EXPERIMENT)
C     TWALO    WALL TEMP (SIMULATION)
C     TWALO*   WALL TEMP (EXPERIMENT)
```

```
C     TEFC      THERMOSTAT EFFECTIVE (SIMULATION)
C     TEFFD*    THERMOSTAT EFFECTIVE (EXPERIMENT)
C     T3        RETURN AIR (SIMULATION)
C     T3*       RETURN AIR (EXPERIMENT)
C     T5        AIR ENTERING COIL (SIMULATION)
C     T5*       AIR ENTERING COIL (EXPERIMENT)
C     T1        AIR ENTERING ROOM (SIMULATION)
C     T1*       AIR ENTRING ROOM (EXPERIMENT)
C     T2        ROOM AVERAGE (SIMULATION)
C     T2*       ROOM AVERAGE (EXPERIMENT)
C
C     VTR       NORMALIZED VALVE TRAVEL (SIMULATION)
C     VTR*      NORMALIZED VALVE TRAVEL (EXPERIMENTAL)
C
C     P6        OUTPUT PRESSURE IN PSI FROM THERMOSTAT (SIMULATION)
C     P6*       OUTPUT PRESSURE IN PSI FROM THERMOSTAT (EXPERIMENT)
C
C     FLO1      WATER FLOWRATE IN GPM (SIMULATION)
C     FLO1*     WATER FLOWRATE IN GPM (EXPERIMENT)
C
      STOP
      END

      SUBROUTINE RMAIR(TOUT,T1,T2,DT,VRM,CA,CF,XMF,XM1,XM2,QLITE,
     1HTFLO,QCOND,P2,TAU2,INF,ISTEP,TWALL,TEMP,S)
      DIMENSION TOUT(3,100),T1(100),T2(100)
      A2=0.0041388273
      B2=0.1012
      C2=0.8825
      K=ISTEP-1
      IF(K.LT.1) K=1
      IF(ISTEP.EQ.1) TEMP=T2(1)
      IF(ISTEP.EQ.1) GO TO 94
      ADENS=14.696*144.0*P2/53.352/(460.0+T2(K))
      XM0=XM2-XM1
      TAU2=(ADENS*VRM*CA+XMF*CF)/(XM2*CA*B2)
      TC=1.0/TAU2
      S1=(XM1*CA-A2*XM2*CA)*T1(K)/(XM2*CA*B2)
      S2=(XM0*TOUT(1,ISTEP))/(XM2*B2)
      S3=(QCOND+HTFLO+QLITE)/(XM2*CA*B2)
      S4=-(C2*TWALL)/B2
      S=S1+S2+S3+S4
      TEMP=TEMP*EXP(-TC*DT)+(1.0-EXP(-TC*DT))*S
   94 T2(ISTEP)=TEMP
      RETURN
      END

      SUBROUTINE SFLUX(T2,TOUT,XS,YS,ZS,NX,NY,NZ,NSURF,SAREA,CO,FLUX,
     1HTFLO,ISTEP)
      DIMENSION NX(2),NY(2),NZ(2),XS(2,30),YS(2,30),ZS(2,30),
     1T2(100),TOUT(3,100),FLUX(2,100),SAREA(2),CO(2)
      HTFLO=0.0
      IF(ISTEP.EQ.1) GO TO 10
      DO 100 I=1,NSURF
      CALL HFLUX(XS,YS,ZS,T2,TOUT,FLUX,NX,NY,NZ,ISTEP,I)
      HTFLO=HTFLO+FLUX(I,ISTEP)*SAREA(I)
  100 CONTINUE
      RETURN
   10 DO 20 I=1,NSURF
      FLUX(I,1)=CO(I)*(TOUT(1,1)-T2(1))
```

```
      HTFLO=HTFLO+SAREA(I)*CO(I)*(TOUT(I,1)-T2(1))
   20 CONTINUE
      RETURN
      END

      SUBROUTINE HFLUX (XS,YS,ZS,T2,TOUT,FLUX,NX,NY,NZ,ISTEP,K)
      DIMENSION NX(2),NY(2),NZ(2),XS(2,30),YS(2,30),ZS(2,30),T2(100),
     1TOUT(3,100),FLUX(2,100)
      FTEMP=0.0
      KK=NX(K)
      DO 10 I=1,KK
      II=ISTEP-I+1
      IF(II.LE.0) II=1
      FTEMP=FTEMP+XS(K,I)*TOUT(K,II)
   10 CONTINUE
      KK=NY(K)
      DO 20 I=1,KK
      II=ISTEP-I+1
      IF(II.LE.0) II=1
      FTEMP=FTEMP-YS(K,I)*T2(II)
   20 CONTINUE
      KK=NZ(K)
      DO 30 I=2,KK
      II=ISTEP-I+1
      IF(II.LE.0) II=1
      FTEMP=(FTEMP-FLUX(K,II)*ZS(K,I))/ZS(K,1)
   30 CONTINUE
      FLUX(K,ISTEP)=FTEMP
      RETURN
      END

      SUBROUTINE WLTEMP(FLUX,T2,HWALL,TWALL)
      TWALL=FLUX/HWALL+T2
      RETURN
      END

      SUBROUTINE WTRFLO(Y9,FLO,YMAX,FLOMAX,ISTEP)
      DIMENSION Y9(100),FLO(100)
      IF(Y9(ISTEP).LE.0.81379) GO TO 650
      FLO(ISTEP)=1.98*(Y9(ISTEP)**0.14659)
      GO TO 600
  650 FLO(ISTEP)=2.362*Y9(ISTEP)
  600 RETURN
      END

      SUBROUTINE FNDC1(T1,T2,T3,T4,T5,T6,TOUT,XM0,XM1,XM2,ETAT,ETAM,
     1ETAS,WM,CA,PHI,ARATIO,ISTEP,INF,I,UAD,TWALL,T8)
      DIMENSION TOUT(3,100),T1(100),T2(100)
      T1(1)=T2(1)
      K=ISTEP-1
      IF(K.LT.1) K=1
      A2=0.0041388273
      B2=0.1013
      C2=0.8825
      T8=A2*T1(K)+B2*T2(ISTEP)+C2*TWALL
      T3=T8+PHI*ETAM*ETAS*WM/XM2/CA
      T4=ARATIO*TOUT(INF,ISTEP)+(1.0-ARATIO)*T3
      T5=T4
      RETURN
      END
```

```
      SUBROUTINE FNDC2(T1,T2,T3,T4,T5,T6,TOUT,XM0,XM1,XM2,ETAT,ETAM,
     1ETAS,WM,CA,PHI,ARATIO,ISTEP,INF,I,UAO)
      DIMENSION TOUT(3,100),T1(100),T2(100)
      DEN=XM1*CA+UAO*0.5
      T1(ISTEP)=(T6*(XM1*CA-UAO*0.5)+(1.0-PHI)*ETAM
     1*ETAS*WM+UAO*TOUT(3,ISTEP))/DEN
      RETURN
      END

      SUBROUTINE COIL(GPM,G6,FLO,GMO,TMO,T6,ISTEP,T5)
      DIMENSION GPM(10),G6(10),FLO(100),GMO(30,100),TMO(30,100)
      IF(FLO(ISTEP).EQ.0.0) T6=T5
      IF(FLO(ISTEP).GT.0.0.AND.FLO(ISTEP).LE.GPM(1))
     1T6=G6(1)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(1).AND.FLO(ISTEP).LE.GPM(2))
     1T6=G6(2)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(2).AND.FLO(ISTEP).LE.GPM(3))
     1T6=G6(2)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(3).AND.FLO(ISTEP).LE.GPM(4))
     1T6=G6(3)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(4).AND.FLO(ISTEP).LE.GPM(5))
     1T6=G6(4)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(5).AND.FLO(ISTEP).LE.GPM(6))
     1T6=G6(5)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(6).AND.FLO(ISTEP).LE.GPM(7))
     1T6=G6(6)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(7).AND.FLO(ISTEP).LE.GPM(8))
     1T6=G6(7)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(8).AND.FLO(ISTEP).LE.GPM(9))
     1T6=G6(8)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(9).AND.FLO(ISTEP).LE.GPM(10))
     1T6=G6(9)*(GMO(2,ISTEP)-T5)              +T5
      IF(FLO(ISTEP).GT.GPM(10)) T6=G6(10)*(GMO(2,ISTEP)-T5)+T5
      RETURN
      END

      SUBROUTINE THRHST(T2,TWALL,A7,B7,TEFF,TSET,P7,PSET,
     1TAU71,TAU72,G7,DT,ISTEP,GMO)
      DIMENSION GMO(30,100),P7(100)
      P=5.2446
      PK=0.5081702
      IF(ISTEP.EQ.1) GO TO 410
      PLAST=P7(ISTEP-1)
      TLAST1=TEFF1
      TLAST2=TEFF2
      TEFF1=TLAST1*EXP(-DT/TAU72)+T2         *(1.0-EXP(-DT/TAU72))
      TEFF2=TLAST2*EXP(-DT/TAU71)+TWALL      *(1.0-EXP(-DT/TAU71))
      TEFF=TEFF1*B7+TEFF2*A7
      GO TO 420
  410 TEMP1=GMO(9,ISTEP)
      TEFF1=TEMP1
      TEMP2=GMO(7,ISTEP)
      TEFF2=TEMP2
      TEFF=TEFF1*B7+TEFF2*A7
      P7(1)=11.65
      GO TO 7000
  420 P7(ISTEP)=PLAST*EXP(-P*DT)+(1.0-EXP(-P*DT))*(PK*TEFF
     1-74.5*PK+3.45)
 7000 IF(P7(ISTEP).LE.0.0) P7(ISTEP)=0.0
      RETURN
```

```
      END

      SUBROUTINE COND(T2,TOUT,U,AREA,FLUX)
      FLUX=U*AREA*(TOUT-T2)
      RETURN
      END

      SUBROUTINE VALACT(P7EX,V2,YMAX,Y9,P8,HYS,ISTEP)
      DIMENSION P8(100),Y9(100),P7EX(100),V2(100)
      IF(ISTEP.GT.1) GO TO 750
      FHYS=-HYS
      DP=2.0*HYS/1.23
      GO TO 710
  750 IF(FHYS.EQ.(-HYS).AND.P8(ISTEP).LE.PTEMP) GO TO 710
      IF(FHYS.EQ.HYS.AND.P8(ISTEP).GE.PTEMP) GO TO 710
      IF(FHYS.EQ.(-HYS).AND.P8(ISTEP).GT.PTEMP.AND.P8(ISTEP).
     1LT.(PTEMP+DP)) GO TO 790
      IF(FHYS.EQ.(-HYS).AND.P8(ISTEP).GT.PTEMP.AND.P8(ISTEP).
     1GE.(PTEMP+DP)) GO TO 760
      IF(FHYS.EQ.HYS.AND.P8(ISTEP).LT.PTEMP.AND.P8(ISTEP).
     1GT.(PTEMP-DP)) GO TO 790
      IF(FHYS.EQ.HYS.AND.P8(ISTEP).LT.PTEMP.AND.P8(ISTEP).
     1LE.(PTEMP-DP))  GO TO 770
  760 FHYS=HYS
      GO TO 710
  770 FHYS=-HYS
  710 Y9(ISTEP)  =-1.23*P8(ISTEP)+5.11 +FHYS
      PTEMP=P8(ISTEP)
      GO TO 715
  790 Y9(ISTEP)=Y9(ISTEP-1)
  715 IF(Y9(ISTEP).LE.0.0) Y9(ISTEP)=0.0
      IF(Y9(ISTEP).GE.1.0) Y9(ISTEP)=1.0
      RETURN
      END
```

The data listed below are the system parameters required to run the program. This data is input to the program starting with the READ statement on program card number 23, and ending with the READ statement on program card number 56.

```
 2
 10   11   11
 8    8    8
 0.0885  531.8
 0.3253  238.5
 0.68862679031278510-06
-0.30996379920068830-05
 0.58242555774954545D-05
-0.43171982690859590-05
 0.14669481155800440-04
 0.21900144757469760-04
 0.16177128713489330-04
 0.40063661916006720-05
 0.38111924418514570-06
 0.12350742441526670-07
 0.84624580440711950 00
-0.33404945477338540 01
 0.53762235326070840 01
-0.45491896442130010 01
 0.21839565155370930 01
-0.60315271165134000 00
 0.94098750981777220-01
-0.79660205212950240-02
```

0.34107477522726800-03

-0.65589831463874750-05

0.48195846202858660-07

0.10000000000000000D 01

-0.35012118791928480D 01

0.49102786126184670D 01

-0.35385255400992860D 01

0.14044671410470420D 01

-0.30879014694345910D 00

0.36554889082225220D-01

-0.21968916380153150D-02

0.59937601133541270D-04

-0.62060125342744600D-06

0.20120428221314240D-08

0.22813727970638630D-05

0.41909605698370410D-04

0.94585495184182980D-03

0.21915223931573730D-02

0.10567865226635250D-02

0.11308542015943300D-03

0.24195941702720440D-05

0.80178657602125710D-08

0.12391049075091520D 01

-0.28846647725316430D 01

0.23129684279504920D 01

-0.75092022205562380D 00

0.91224994044520660D-01

-0.33912090867211480D-02

```
 0.3180740957264838D-04
-0.6537668806316738D-07
 0.1000000000000000D 01
-0.2129753138219186D 01
 0.1538636158169764D 01
-0.4386928051206221D 00
 0.4438956503173424D-01
-0.1201533462399290D-02
 0.5820901523719435D-05
-0.3276510267828186D-08
2126.6
   0.6
    1
    1
 100.0        0.8
   .24        1.
   0.0        0.05
   1.0
   0.646     31.3
   0.73       2.0
   0.8      206.
1060.0         .5          .6          .6
   0.0         .2
 427.5
   2.
   3.45      74.5
   0.571      0.260
```

0.725	0.275
0.3	0.115
0.4	0.788
0.6	0.79
0.8	0.7925
1.0	0.795
1.2	.80
1.4	.81
1.6	.821
1.8	.83
2.0	.84
155.0	
52.0	
776.5	

$ENTRY

	T6	T6*	TWALO	TWALO*	TEFO	TEFO*	T8	T8*	T5	T5*
1	76.95	78.80	77.40	77.90	78.15	78.80	76.61	77.00	76.95	78.62
2	77.08	78.80	77.59	77.54	78.11	78.62	76.73	77.00	77.08	78.44
3	76.96	78.26	77.51	77.36	78.04	78.44	76.62	76.28	76.96	77.72
4	76.73	77.54	77.31	77.09	77.95	78.26	76.39	75.92	76.73	77.00
5	76.46	77.00	77.07	77.18	77.83	78.26	76.12	75.74	76.46	76.64
6	76.15	76.46	76.76	76.82	77.69	78.08	75.81	75.20	76.15	76.28
7	75.86	76.10	76.48	76.64	77.53	77.90	75.52	75.20	75.86	75.74
8	75.57	75.74	76.19	75.92	77.36	77.54	75.23	74.48	75.57	75.38
9	75.28	75.38	75.90	76.10	77.18	77.54	74.94	74.30	75.28	75.20
10	75.02	75.20	75.64	76.10	76.99	77.54	74.67	73.94	75.02	75.02
11	74.75	74.84	75.37	75.38	76.80	77.18	74.41	73.76	74.75	74.48
12	74.49	74.30	75.12	74.66	76.60	77.00	74.15	73.04	74.49	73.94
13	74.23	73.76	74.86	74.66	76.39	76.64	73.89	73.04	74.23	73.22
14	73.94	73.22	74.57	74.30	76.17	76.46	73.60	72.50	73.94	72.68
15	73.67	72.68	74.29	74.66	75.95	76.28	73.33	72.32	73.67	72.32
16	73.38	72.68	73.99	74.30	75.73	76.10	73.04	71.96	73.38	72.68
17	73.12	72.86	73.72	74.12	75.51	75.74	72.78	71.96	73.12	72.86
18	72.87	73.04	73.46	73.76	75.29	75.74	72.53	71.78	72.87	72.86
19	72.63	73.04	73.21	73.59	75.06	75.56	72.28	71.60	72.63	72.86

20	72.37	73.04	72.95	73.40	74.84	75.38	72.03	71.24	72.37	72.86
21	72.42	72.86	72.69	73.22	74.61	75.20	71.78	71.06	72.12	72.68
22	74.07	72.68	72.44	72.86	74.39	75.02	71.54	71.06	71.88	72.50
23	101.75	76.64	72.16	72.50	74.17	74.66	71.28	70.52	71.62	72.32
24	138.08	137.84	71.65	72.59	73.96	74.48	70.96	70.88	71.30	72.68
25	139.90	140.18	71.29	72.32	73.82	74.30	70.86	70.88	71.20	72.68
26	140.61	140.90	71.65	72.32	73.74	74.30	71.27	71.06	71.61	72.86
27	140.84	140.54	72.04	72.68	73.72	74.30	71.67	71.24	72.02	73.22
28	140.16	139.82	72.38	72.68	73.74	74.48	72.03	71.42	72.38	73.22
29	135.58	136.04	72.71	72.68	73.79	74.48	72.36	71.60	72.70	73.40
30	130.19	129.74	73.02	72.86	73.85	74.49	72.64	71.78	72.98	73.58
31	128.94	128.30	73.25	73.04	73.91	74.66	72.84	71.78	73.18	73.58
32	128.51	127.76	73.35	73.04	73.97	74.48	72.93	71.96	73.27	73.58
33	128.22	127.40	73.41	73.40	74.03	74.66	72.99	71.96	73.33	73.58
34	128.22	127.04	73.44	73.22	74.08	74.66	73.02	71.96	73.37	73.76
35	128.08	126.86	73.48	73.40	74.12	74.66	73.06	71.96	73.40	73.76
36	127.79	127.04	73.50	73.40	74.17	74.66	73.08	71.96	73.43	73.58
37	127.64	126.68	73.52	73.40	74.20	74.66	73.10	71.96	73.44	73.58
38	127.34	126.32	73.52	73.53	74.24	74.66	73.11	71.96	73.45	73.22
39	127.49	126.86	73.53	73.22	74.26	74.66	73.11	71.78	73.45	73.04
40	127.49	126.32	73.51	73.22	74.28	74.48	73.10	71.78	73.44	72.86
41	127.48	126.32	73.47	73.58	74.30	74.66	73.06	71.96	73.40	73.04
42	127.33	126.32	73.43	73.40	74.31	74.66	73.02	71.96	73.37	72.86
43	127.18	125.96	73.42	73.40	74.31	74.66	73.01	71.60	73.35	72.68
44	127.17	125.96	73.38	73.40	74.32	74.66	72.98	71.78	73.32	72.86
45	127.61	126.32	73.35	73.22	74.31	74.66	72.95	71.60	73.29	72.50
46	127.61	126.32	73.30	73.40	74.31	74.66	72.91	71.78	73.25	72.68
47	127.45	126.14	73.26	73.22	74.30	74.48	72.87	71.60	73.21	72.50
48	127.30	125.96	73.24	73.22	74.29	74.48	72.85	71.42	73.19	72.32
49	127.44	126.14	73.20	73.22	74.28	74.48	72.81	71.60	73.15	72.50
50	127.28	125.96	73.13	73.40	74.26	74.66	72.75	71.42	73.09	72.32
51	127.87	126.59	73.09	73.22	74.24	74.48	72.71	71.42	73.05	72.32
52	127.86	126.86	73.04	73.22	74.22	74.66	72.66	71.42	73.00	72.14
53	127.71	126.32	73.00	73.22	74.20	74.66	72.63	71.24	72.97	72.14
54	127.55	126.14	72.95	72.86	74.17	74.48	72.58	71.24	72.92	71.96
55	127.55	126.14	72.92	73.22	74.15	74.48	72.55	71.06	72.89	71.56
56	127.39	125.96	72.87	72.86	74.12	74.30	72.50	71.06	72.84	71.60
57	127.83	126.50	72.81	73.04	74.09	74.30	72.44	71.06	72.78	71.78
58	127.81	126.50	72.73	73.22	74.05	74.48	72.37	71.24	72.71	71.56
59	127.66	126.86	72.70	73.04	74.02	74.30	72.34	71.24	72.68	71.96
60	127.66	126.50	72.68	72.86	73.99	74.30	72.32	70.88	72.66	71.60
61	127.65	127.04	72.65	73.04	73.96	74.30	72.29	70.88	72.63	71.78
62	127.49	127.04	72.60	72.86	73.93	74.30	72.25	71.06	72.59	71.78
63	127.94	127.40	72.56	72.86	73.89	74.30	72.21	71.06	72.55	71.60
64	127.93	127.94	72.53	72.86	73.86	74.30	72.18	70.88	72.53	71.60

	T1	T1*	T2	T2*
1	78.80	78.71	78.80	78.80
2	80.48	78.89	78.34	78.26
3	80.26	78.26	77.82	77.72
4	79.84	77.45	77.31	77.72
5	79.60	77.09	76.82	77.54
6	79.35	76.82	76.40	77.36
7	79.10	76.46	76.01	77.00
8	78.78	75.74	75.66	76.64
9	78.54	75.65	75.34	76.46
10	78.23	75.29	75.03	76.46
11	78.00	74.84	74.73	75.56
12	77.48	74.03	74.42	74.84
13	77.33	73.85	74.10	75.02
14	77.01	73.40	73.81	74.84
15	76.85	73.13	73.53	74.66
16	76.61	72.77	73.30	74.30
17	76.45	72.86	73.09	74.12
18	76.15	72.77	72.89	73.76
19	75.94	72.77	72.66	73.58
20	75.71	72.77	72.46	73.58
21	75.59	72.59	72.26	73.22
22	76.58	72.50	72.07	73.22
23	92.85	72.50	71.95	72.68
24	114.56	102.56	72.50	73.22
25	115.79	114.53	73.74	74.48
26	116.36	114.17	74.59	75.56
27	116.64	115.88	75.23	76.82
28	116.38	116.42	75.75	77.18
29	113.73	115.61	76.14	77.54
30	110.53	112.46	76.33	77.90
31	109.92	111.02	76.39	78.00
32	109.66	110.39	76.45	77.90
33	109.56	110.12	76.51	78.26
34	109.56	109.67	76.58	78.08
35	109.40	109.40	76.63	78.26
36	109.30	109.22	76.68	78.08
37	109.21	109.13	76.71	78.26
38	109.04	108.95	76.73	78.08
39	108.98	108.68	76.72	77.72
40	109.05	108.59	76.69	77.72
41	109.12	108.77	76.69	78.26
42	108.96	108.50	76.72	77.90
43	108.87	108.32	76.70	77.90
44	108.86	108.12	76.69	77.90
45	109.05	108.23	76.67	77.54
46	109.12	108.41	76.67	77.72
47	108.96	108.23	76.67	77.54
48	108.72	108.14	76.64	77.54
49	108.95	108.32	76.59	77.54
50	108.85	108.73	76.58	77.72
51	109.21	108.41	76.56	77.54
52	109.13	108.41	76.56	77.54
53	109.11	108.41	76.53	77.54
54	108.87	108.14	76.51	77.18
55	108.87	108.05	76.45	77.36
56	108.70	107.87	76.39	77.18
57	109.11	108.23	76.34	77.36

58	109.10	108.50	76.37	77.54
59	109.01	108.50	76.37	77.36
60	108.86	109.32	76.34	77.18
61	108.93	108.68	76.29	77.18
62	108.91	108.68	76.27	77.18
63	109.10	109.04	76.25	77.18
64	109.02	109.04	76.22	77.00

	VTR	VTR*	PA	PB*	FLOI	FLOI*
1	0.00	0.000	11.65	11.65	0.00	0.00
2	0.00	0.000	10.18	11.50	0.00	0.00
3	0.00	0.000	9.04	11.30	0.00	0.00
4	0.00	0.000	8.16	11.10	0.00	0.00
5	0.00	0.000	7.46	10.85	0.00	0.00
6	0.00	0.000	6.91	10.63	0.00	0.00
7	0.00	0.000	6.47	10.35	0.00	0.00
8	0.00	0.000	6.11	10.05	0.00	0.00
9	0.00	0.000	5.81	9.75	0.00	0.00
10	0.00	0.000	5.56	9.40	0.00	0.00
11	0.00	0.000	5.34	9.05	0.00	0.00
12	0.00	0.000	5.15	8.68	0.00	0.00
13	0.00	0.000	4.98	8.25	0.00	0.00
14	0.00	0.000	4.82	7.87	0.00	0.00
15	0.00	0.000	4.68	7.43	0.00	0.00
16	0.00	0.000	4.54	7.00	0.00	0.00
17	0.00	0.000	4.40	6.60	0.00	0.00
18	0.00	0.000	4.28	6.18	0.00	0.00
19	0.00	0.000	4.15	5.72	0.00	0.00
20	0.00	0.000	4.03	5.35	0.00	0.00
21	0.04	0.000	3.91	4.97	0.09	0.00
22	0.18	0.000	3.79	4.55	0.43	0.00
23	0.33	0.000	3.67	4.18	0.77	0.00
24	0.47	0.166	3.56	3.80	1.10	0.40
25	0.60	0.538	3.45	3.45	1.41	1.20
26	0.71	0.828	3.36	3.25	1.67	1.65
27	0.79	0.959	3.29	3.13	1.88	1.85
28	0.86	1.000	3.24	3.13	1.94	1.94
29	0.90	1.000	3.21	3.18	1.95	1.96
30	0.93	1.000	3.19	3.25	1.96	1.98
31	0.94	1.000	3.18	3.32	1.96	2.00
32	0.94	1.000	3.18	3.38	1.96	2.02
33	0.94	1.000	3.19	3.42	1.96	2.02
34	0.94	1.000	3.20	3.48	1.96	2.02
35	0.94	0.993	3.21	3.50	1.96	2.02
36	0.94	0.972	3.23	3.55	1.96	2.02
37	0.94	0.945	3.24	3.58	1.96	2.02
38	0.94	0.938	3.26	3.60	1.96	2.02
39	0.94	0.910	3.28	3.62	1.96	2.02
40	0.94	0.890	3.29	3.65	1.96	2.00
41	0.94	0.870	3.30	3.68	1.96	2.00
42	0.94	0.869	3.31	3.68	1.96	2.00
43	0.94	0.807	3.32	3.70	1.96	2.00
44	0.94	0.821	3.33	3.70	1.96	1.98
45	0.94	0.814	3.34	3.70	1.96	1.98
46	0.94	0.814	3.34	3.70	1.96	1.96
47	0.94	0.814	3.34	3.70	1.96	1.96
48	0.94	0.814	3.34	3.70	1.56	1.96
49	0.94	0.814	3.34	3.70	1.96	1.94
50	0.94	0.814	3.34	3.68	1.96	1.92
51	0.94	0.814	3.33	3.65	1.96	1.94
52	0.94	0.814	3.33	3.65	1.96	1.92
53	0.94	0.814	3.32	3.62	1.96	1.90
54	0.94	0.800	3.31	3.58	1.96	1.90
55	0.94	0.814	3.30	3.52	1.96	1.88
56	0.94	0.821	3.29	3.48	1.96	1.90
57	0.94	0.821	3.28	3.45	1.96	1.85

58	0.94	0.821	3.27	3.40	1.96	1.88
59	0.94	0.828	3.25	3.35	1.96	1.88
60	0.94	0.848	3.24	3.32	1.96	1.88
61	0.94	0.855	3.22	3.28	1.96	1.85
62	0.94	0.883	3.21	3.25	1.96	1.88
63	0.94	0.903	3.19	3.22	1.96	1.88
64	0.94	0.993	3.18	3.18	1.96	1.85

APPENDIX B

DATA OF TESTS 1&2

```
$JOB            NKA,TIME=(0,20),PAGES=50
      DIMENSION V1(64),V2(64),V3(64),GM(12,64),TM(12,64)
     1,TMO(12,64),GMO(12,64)
      READ 1003,IEND
 1003 FORMAT(I3)
      DO 111 J=1,IEND
      READ 1000,M,N,L,P,Q,V1(J),V2(J),V3(J)
 1000 FORMAT(3I2,5F6.2)
      READ 1001,(TM(I,J),I=1,12)
 1001 FORMAT(12F6.2)
      READ 1002,(GM(I,J),I=1,11)
 1002 FORMAT(11F6.2)
 111  CONTINUE
      DO 500 I=1,12
      DO 500 J=1,IEND
      TMO(I,J)=1.8*TM(I,J)+32.0
 500  CONTINUE
      DO 600 I=1,11
      DO 600 J=1,IEND
      GMO(I,J)=1.8*GM(I,J)+32.0
 600  CONTINUE
      PRINT 200
 200  FORMAT(1H1,7X,'V1',7X,'V2',7X,'V3',//)
      DO 12 J=1,IEND
 12   PRINT 100,J,V1(J),V2(J),V3(J)
 100  FORMAT(2X,I2,1X,F6.2,3X,F6.2,3X,F6.2)
      PRINT 201
 201  FORMAT(1H1,7X,'TM1',7X,'TM2',7X,'TM3',7X,'TM4',7X,
     1'TM5',7X,'TM6',7X,'TM7',7X,'TM8',7X,'TM9',7X,
     2'TM10',7X,'TM11',7X,'TM12',//)
      DO 13 J=1,IEND
 13   PRINT 101,J,(TMO(I,J),I=1,12)
 101  FORMAT(2X,I2,2X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,
     14X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,5X,F6.2,5X,F6.2)
      PRINT 202
 202  FORMAT(1H1,7X,'GM1',7X,'GM2',7X,'GM3',7X,'GM4',7X,'GM5',7X,
     1'GM6',7X,'GM7',7X,'GM8',7X,'GM9',7X,'GM10',7X,'GM11',//)
      DO 14 J=1,IEND
 14   PRINT 102,J,(GMO(I,J),I=1,11)
 102  FORMAT(2X,I2,2X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,
     14X,F6.2,4X,F6.2,4X,F6.2,5X,F6.2,5X,F6.2)
C
C
C     DATA OF TEST 1
C
C     V1       VALVE TRAVEL IN VOLTS
C     V2       PRESSURE OUTPUT FROM THERMOSTAT IN VOLTS
C     V3       PRESSURE DROP ACROSS THE ORIFICE IN VOLTS
C
C
C     THESE ARE TEMPERATURES AT VARIOUS LOCATIONS IN THE SYSTEM
C     ALL TEMPERATURES ARE PRINTED IN FAHRENHEIT SCALE
C
C     TM1      RETURN AIR
C     TM2      NORTH AIR SPACE
C     TM3      WEST AIR SPACE
C     TM4      SOUTH AIR SPACE
C     TM5      EAST AIR SPACE
C     TM6      VENTILATION AIR
C     TM7      ROOM DOWNSTAIRS
C     TM8      PLENUM
C     TM9      NORTH DIFFUSER
C     TM10     SOUTH DIFFUSER
C     TM11     INLET OF FAN
C     TM12     AIR ENTERING COIL
C     GM1      AIR LEAVING COIL
C     GM2      WATER ENTERING COIL
C     GM3      WATER LEAVING COIL
C     GM4      NORTH WALL
C     GM5      WEST WALL
C     GM6      SOUTH WALL
C     GM7      EAST WALL
C     GM8      FLOOR
C     GM9      ROOM AVERAGE
C     GM10     THERMOSTAT EFFECTIVE
C     GM11     OUTLET OF FAN
      STOP
      END

$ENTRY
```

	V1	V2	V3
1	5.00	4.66	0.02
2	5.00	4.60	0.03
3	5.00	4.52	0.02
4	4.99	4.44	0.01
5	4.99	4.34	0.01
6	4.99	4.25	0.00
7	4.99	4.14	0.00
8	4.99	4.02	0.00
9	4.99	3.90	0.00
10	4.99	3.76	0.01
11	4.99	3.62	-0.01
12	4.98	3.47	0.00
13	4.98	3.30	0.00
14	4.98	3.15	0.01
15	4.98	2.97	0.02
16	4.98	2.80	-0.01
17	4.98	2.64	0.00
18	4.98	2.47	0.00
19	4.98	2.29	0.01
20	4.98	2.14	0.01
21	4.98	1.99	0.01
22	4.98	1.82	0.01
23	4.99	1.67	0.01
24	4.76	1.52	0.02
25	4.22	1.38	0.18
26	3.80	1.30	0.34
27	3.61	1.25	0.43
28	3.55	1.25	0.47
29	3.55	1.27	0.48
30	3.55	1.30	0.49
31	3.55	1.33	0.50
32	3.55	1.35	0.51
33	3.55	1.37	0.51
34	3.55	1.39	0.51
35	3.56	1.40	0.51
36	3.59	1.42	0.51
37	3.63	1.43	0.51
38	3.64	1.44	0.51
39	3.66	1.45	0.51
40	3.71	1.46	0.50
41	3.71	1.47	0.50
42	3.74	1.47	0.50
43	3.83	1.48	0.50
44	3.81	1.48	0.49
45	3.82	1.48	0.49
46	3.88	1.43	0.48
47	3.88	1.48	0.48
48	3.88	1.48	0.48
49	3.88	1.48	0.47
50	3.88	1.47	0.46
51	3.88	1.46	0.47
52	3.88	1.46	0.46
53	3.88	1.45	0.45
54	3.84	1.43	0.45
55	3.82	1.41	0.44
56	3.81	1.39	0.45
57	3.81	1.38	0.43
58	3.81	1.36	0.44
59	3.80	1.34	0.44
60	3.77	1.33	0.44
61	3.76	1.31	0.43
62	3.72	1.30	0.44
63	3.69	1.29	0.44
64	3.56	1.27	0.43

	TM1	TM2	TM3	TM4	TM5	TM6	TM7	TM8	TM9	TM10	TM11	TM12
1	77.00	69.44	60.72	69.44	69.62	70.34	76.82	80.78	78.62	78.80	77.18	78.62
2	77.00	66.38	61.70	65.30	64.76	66.20	76.92	80.60	78.80	78.98	76.82	78.44
3	76.28	62.06	55.94	60.62	60.26	62.24	76.82	80.24	78.26	78.26	76.46	77.72
4	75.92	59.90	53.42	59.36	57.74	59.54	76.82	79.52	77.36	77.54	76.10	77.00
5	75.74	58.82	52.52	57.20	57.02	58.10	76.82	79.34	77.00	77.18	75.74	76.64
6	75.20	58.10	51.80	56.66	56.12	57.56	76.82	79.16	76.82	76.82	75.38	76.28
7	75.20	57.38	50.54	55.22	55.22	57.20	76.64	78.98	76.28	76.64	75.02	75.74
8	74.48	56.66	50.36	54.32	54.50	56.66	76.82	78.62	75.74	75.74	74.66	75.38
9	74.30	56.30	50.54	54.50	54.50	55.94	76.82	78.44	75.56	75.74	74.30	75.20
10	73.94	55.76	49.46	53.06	53.78	55.22	76.82	78.08	75.20	75.38	73.94	75.02
11	73.76	55.58	49.64	52.70	53.06	54.32	76.82	77.90	74.66	75.02	73.76	74.48
12	73.04	54.68	48.38	50.72	52.16	54.14	76.82	77.00	73.94	74.12	73.22	73.94
13	73.04	55.40	49.10	50.54	52.70	40.46	76.64	77.90	73.76	73.94	72.86	73.22
14	72.50	54.50	48.56	49.64	51.98	38.66	76.64	76.64	73.22	73.58	72.32	72.68
15	72.32	53.78	49.02	49.82	51.44	53.06	76.82	76.64	73.04	73.22	72.14	72.32
16	71.96	53.78	48.38	50.54	52.16	53.42	76.82	75.46	72.68	72.86	72.14	72.68
17	71.96	53.78	48.20	51.08	51.80	52.88	76.64	76.46	72.86	72.86	71.96	72.86
18	71.78	53.06	47.66	50.72	51.26	52.70	76.82	76.10	72.68	72.86	71.78	72.86
19	71.60	52.70	47.66	50.54	51.08	53.42	76.82	75.92	72.68	72.66	71.60	72.86
20	71.24	53.06	47.84	50.36	51.08	52.16	76.82	75.74	72.68	72.86	71.60	72.86
21	71.06	53.06	47.84	49.64	51.26	53.06	76.64	75.38	72.50	72.68	71.24	72.68
22	71.06	53.06	48.02	50.00	51.08	53.24	76.64	75.38	72.50	72.50	71.06	72.50
23	70.52	53.06	48.20	50.00	51.08	52.70	76.46	74.84	72.50	72.50	70.70	72.32
24	70.88	52.88	48.20	50.36	[illegible]	52.88	76.46	75.02	106.52	98.60	70.70	72.58
25	70.88	52.16	47.66	50.36	50.72	52.52	76.46	75.38	122.00	107.06	71.06	72.68
26	71.06	52.16	47.48	49.64	50.54	53.42	76.46	75.74	117.68	110.66	71.24	72.86
27	71.24	52.16	47.30	49.28	50.18	51.62	76.46	76.10	119.30	112.46	71.42	73.22
28	71.42	51.98	47.48	50.00	50.36	52.34	76.64	76.46	119.84	113.00	71.78	73.22
29	71.60	51.80	46.76	48.74	50.00	52.16	76.46	76.64	119.76	112.46	71.96	73.40
30	71.78	51.80	46.94	48.92	50.00	51.98	76.46	76.82	115.34	109.58	71.96	73.58
31	71.78	51.98	47.12	48.74	50.18	51.62	76.46	77.00	113.90	108.14	72.14	73.58
32	71.96	51.62	47.12	48.92	50.18	52.16	76.46	77.00	113.18	107.42	72.14	73.58
33	71.96	51.98	47.66	49.46	50.36	52.16	76.28	77.18	113.00	107.24	72.32	73.58
34	71.96	51.80	47.66	49.64	50.54	51.98	76.46	77.18	112.64	106.70	72.32	73.76
35	71.96	51.98	47.66	49.28	50.36	52.34	76.46	77.18	112.28	106.52	72.32	73.76
36	71.96	51.80	47.84	49.46	50.36	51.98	76.46	77.18	112.10	106.34	72.14	73.58
37	71.96	51.80	47.48	49.64	50.36	51.80	76.28	77.18	112.10	106.16	72.14	73.58
38	71.96	51.62	47.48	49.28	50.18	51.62	76.28	77.18	111.92	105.98	72.14	73.22
39	71.78	51.44	46.76	48.20	49.64	52.34	76.10	76.32	111.56	105.80	71.96	73.04
40	71.78	51.44	46.94	48.74	49.64	51.62	76.10	77.00	111.56	105.62	71.96	72.86
41	71.96	51.44	47.12	48.92	49.64	51.98	76.28	77.18	111.74	105.80	72.14	73.04
42	71.96	51.26	47.30	49.10	49.82	51.06	76.10	77.00	111.38	105.62	72.14	72.86
43	71.60	51.26	46.76	48.56	49.64	51.08	75.92	77.00	111.20	105.44	71.96	72.68
44	71.78	51.26	46.94	48.38	49.64	51.08	76.10	77.00	111.20	105.44	71.96	72.86
45	71.60	51.08	46.76	48.02	49.46	50.72	75.92	76.82	111.23	105.26	71.60	72.50
46	71.78	51.44	46.94	48.92	49.64	50.36	76.10	77.00	111.38	105.44	71.96	72.68
47	71.60	51.08	46.58	48.20	49.28	50.90	75.92	76.82	111.20	105.26	71.78	72.50
48	71.42	51.38	46.58	48.02	49.10	50.12	75.74	76.46	111.02	105.26	71.78	72.37
49	71.60	51.26	46.58	48.20	49.64	50.36	76.10	76.82	111.20	105.44	71.78	72.50
50	71.42	50.72	46.58	47.84	49.10	51.06	75.74	76.32	111.29	105.26	71.60	72.32
51	71.42	51.26	46.40	47.84	48.92	50.18	75.74	76.82	111.38	105.44	71.60	72.32
52	71.42	51.08	46.22	47.12	48.92	49.54	75.92	76.64	111.38	105.44	71.60	72.14
53	71.24	50.54	46.22	47.84	48.92	50.72	75.74	76.82	111.38	105.44	71.42	72.14
54	71.24	50.54	46.04	47.12	48.38	50.00	75.74	76.46	111.02	105.26	71.42	71.96
55	71.06	50.00	45.86	47.48	48.38	50.18	75.74	76.46	111.02	105.06	71.24	71.56
56	71.06	49.82	45.32	46.58	48.32	49.62	75.56	76.28	110.34	104.90	71.24	71.60
57	71.06	50.10	46.04	47.48	48.74	50.72	75.56	76.64	111.20	105.26	71.24	71.78

58	71.24	50.72	46.40	47.66	48.92	50.72	75.74	76.64	111.56	105.44	71.42	71.96
59	71.24	50.36	46.04	47.30	48.56	49.64	75.74	76.64	111.56	105.44	71.42	71.96
60	70.88	49.82	45.32	47.12	48.20	49.64	75.56	76.28	111.38	105.26	71.24	71.60
61	70.88	49.82	45.86	47.30	48.56	50.36	75.74	76.46	111.74	105.62	71.24	71.78
62	71.06	49.82	45.86	47.12	48.56	50.36	75.56	76.64	111.74	105.62	71.06	71.78
63	71.06	49.82	45.32	46.76	48.20	50.36	75.56	76.46	112.10	105.98	71.96	71.60
64	70.88	49.64	45.32	46.40	47.84	49.10	75.74	76.28	112.10	105.98	71.24	71.60

	GM1	GM2	GM3	GM4	GM5	GM6	GM7	GM8	GM9	GM10	GM11
1	78.80	84.20	78.08	77.72	77.90	75.92	77.90	78.26	78.80	79.80	79.34
2	78.80	83.48	77.72	77.36	77.36	75.56	77.54	78.08	78.26	78.62	78.26
3	78.26	82.94	77.36	77.00	77.18	75.02	77.36	78.08	77.72	78.44	78.26
4	77.54	82.04	77.00	76.82	77.00	74.66	77.00	77.72	77.72	78.26	77.54
5	77.00	81.50	76.64	77.00	77.18	74.48	77.18	77.72	77.54	78.26	77.18
6	76.46	80.78	76.10	76.64	76.64	73.94	76.82	77.54	77.36	78.08	76.82
7	76.10	80.06	75.92	76.46	76.46	73.40	76.64	77.36	77.00	77.90	76.28
8	75.74	79.34	75.38	75.74	75.74	72.68	75.92	77.00	76.64	77.54	75.92
9	75.38	78.98	75.20	76.10	75.92	72.68	76.10	77.00	76.46	77.54	75.74
10	75.20	78.44	75.02	75.92	75.74	72.32	76.10	76.82	76.46	77.54	75.38
11	74.84	77.90	74.66	75.38	75.20	71.60	75.38	76.46	75.56	77.18	75.02
12	74.30	77.36	74.30	74.66	74.66	70.88	74.66	76.46	74.84	77.00	74.66
13	73.76	76.82	73.58	74.48	74.48	70.70	74.66	76.10	75.02	76.64	73.58
14	73.22	76.10	73.22	74.30	74.12	70.34	74.30	75.92	74.84	76.46	73.04
15	72.68	75.74	72.86	74.48	74.30	70.52	74.66	75.74	74.66	76.28	73.22
16	72.68	75.38	72.86	74.30	74.12	70.16	74.30	75.56	74.30	76.10	73.58
17	72.86	75.02	72.86	74.12	73.94	69.98	74.12	75.38	74.12	75.74	73.58
18	73.04	74.84	73.94	73.76	73.58	69.62	73.76	75.20	73.76	75.74	73.40
19	73.04	74.84	73.40	73.58	73.40	69.26	73.58	75.02	73.58	75.56	73.22
20	73.04	74.84	73.58	73.40	73.22	69.08	73.40	75.02	73.58	75.38	73.22
21	72.86	74.66	73.58	73.22	73.04	68.90	73.22	74.84	73.22	75.20	73.04
22	72.68	74.66	73.76	73.04	72.86	68.54	72.86	74.66	73.22	75.02	73.04
23	76.64	109.76	73.22	72.50	72.50	68.36	72.50	74.30	72.68	74.66	72.68
24	137.84	155.30	136.04	72.50	72.50	68.18	72.50	74.30	73.22	74.48	72.68
25	140.18	156.02	138.56	72.32	72.32	68.00	72.32	74.30	74.48	74.30	72.68
26	140.90	155.66	139.64	72.32	72.32	68.00	72.32	74.48	75.56	74.30	73.04
27	140.54	154.94	139.46	72.50	72.50	68.00	72.68	74.66	76.64	74.30	73.22
28	139.82	154.04	138.74	72.50	72.50	68.00	72.68	74.84	77.18	74.48	73.40
29	136.04	143.46	135.14	72.50	72.50	68.00	72.68	75.02	77.54	74.48	73.40
30	129.74	141.08	129.32	72.68	72.68	68.18	72.86	75.02	77.90	74.48	73.58
31	128.30	140.36	127.76	72.68	72.68	68.18	73.04	75.02	78.08	74.66	73.76
32	127.76	139.32	127.04	72.68	72.68	68.06	73.04	75.02	77.90	74.48	73.76
33	127.40	139.46	126.50	73.04	73.04	68.54	73.40	75.20	78.26	74.66	73.94
34	127.04	139.46	126.14	72.86	72.86	68.18	73.22	75.20	78.08	74.66	73.58
35	126.86	139.28	125.60	73.04	73.04	68.36	73.40	75.20	78.26	74.66	73.76
36	127.04	138.92	125.78	73.04	73.04	68.36	73.40	75.20	78.08	74.66	73.58
37	125.68	138.74	125.42	73.04	73.04	68.36	73.40	75.20	78.26	74.66	73.58
38	126.32	138.38	125.06	73.22	73.22	68.36	73.58	75.20	78.08	74.66	73.22
39	126.86	138.56	125.24	72.68	72.68	67.82	73.22	75.02	77.72	74.66	72.86
40	125.32	138.56	124.70	72.86	72.86	68.00	73.22	75.02	77.72	74.48	72.86
41	126.32	138.56	124.98	73.22	73.22	68.36	73.58	75.20	78.26	74.66	73.04
42	126.14	138.38	124.52	73.04	73.04	68.00	73.40	75.20	77.90	74.66	73.04
43	125.96	138.20	124.34	73.04	73.04	68.00	73.40	75.20	77.90	74.66	72.86
44	125.96	138.20	124.34	73.04	73.04	68.00	73.40	75.20	77.90	74.66	72.86
45	126.32	138.74	124.70	72.86	72.86	67.64	73.22	75.02	77.54	74.66	72.68
46	126.32	138.74	124.70	73.04	73.04	67.82	73.40	75.02	77.72	74.66	72.68
47	126.14	138.56	124.52	72.86	72.86	67.64	73.22	75.02	77.54	74.48	72.50
48	125.96	138.38	124.34	72.50	72.50	67.46	73.22	74.84	77.54	74.48	72.32
49	126.14	138.56	124.52	72.86	72.86	67.64	73.22	75.02	77.54	74.48	72.32
50	125.96	138.38	124.34	73.04	73.04	67.82	73.40	75.02	77.72	74.66	72.50
51	126.50	139.10	124.88	72.86	72.86	67.64	73.22	74.84	77.54	74.48	72.22
52	126.86	139.10	125.06	72.86	72.86	67.64	73.22	75.02	77.54	74.66	72.14
53	126.32	138.92	124.70	72.86	72.86	67.46	73.22	74.84	77.54	74.66	72.32
54	126.14	138.74	124.70	72.50	72.50	67.10	72.86	74.66	77.18	74.48	71.56
55	126.14	138.74	124.52	72.68	72.68	67.28	73.22	74.66	77.36	74.48	71.96
56	125.96	138.56	124.16	72.50	72.32	66.92	72.86	74.66	77.18	74.30	71.78
57	126.50	139.10	124.88	72.68	72.88	67.28	73.04	74.66	77.36	74.30	71.96

58	126.50	139.10	125.06	72.68	72.68	67.28	73.22	74.84	77.54	74.48	72.14
59	126.86	138.92	125.24	72.68	72.68	67.28	73.04	74.66	77.36	74.30	71.96
60	126.50	138.92	125.24	72.32	72.32	66.92	72.86	74.66	77.18	74.30	71.78
61	127.04	138.92	125.50	72.68	72.50	67.10	73.04	74.66	77.18	74.30	71.78
62	127.04	138.74	125.96	72.68	72.50	67.10	72.86	74.66	77.18	74.30	71.96
63	127.40	139.28	126.50	72.50	72.50	67.10	72.86	74.66	77.18	74.30	71.78
64	127.94	139.28	126.86	72.50	72.50	66.52	72.86	74.66	77.00	74.30	71.60

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$JOB           NKA,TIME=(0,20),PAGES=50
      DIMENSION V1(64),V2(64),V3(64),TM(30,64),GM(30,64),
     1TMO(30,64),GMO(30,64)
      READ 700,IEND
  700 FORMAT(I3)
      DO 111 J=1,IEND
      READ 1000,M,N,L,A,B,V1(J),V2(J),V3(J)
 1000 FORMAT(3I2,5F6.2)
      READ 1001,(TM(I,J),I=1,12)
 1001 FORMAT(12F6.2)
      READ 1002,(GM(I,J),I=1,11)
 1002 FORMAT(11F6.2)
  111 CONTINUE
      PRINT 200
  200 FORMAT(1H1,7X,'V1',7X,'V2',7X,'V3',//)
      DO 12 J=1,IEND
   12 PRINT 100,J,V1(J),V2(J),V3(J)
  100 FORMAT(2X,I2,1X,F6.2,3X,F6.2,3X,F6.2)
      PRINT 201
  201 FORMAT(1H1,7X,'TM1',7X,'TM2',7X,'TM3',7X,'TM4',7X,
     1'TM5',7X,'TM6',7X,'TM7',7X,'TM8',7X,'TM9',7X,
     2'TM10',7X,'TM11',7X,'TM12',//)
      DO 13 J=1,IEND
   13 PRINT 101,J,(TMO(I,J),I=1,12)
  101 FORMAT(2X,I2,2X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,
     14X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,5X,F6.2,5X,F6.2)
      PRINT 202
  202 FORMAT(1H1,7X,'GM1',7X,'GM2',7X,'GM3',7X,'GM4',7X,'GM5',7X,
     1'GM6',7X,'GM7',7X,'GM8',7X,'GM9',7X,'GM10',7X,'GM11',//)
      DO 14 J=1,IEND
   14 PRINT 102,J,(GMO(I,J),I=1,11)
  102 FORMAT(2X,I2,2X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,4X,F6.2,
     14X,F6.2,4X,F6.2,4X,F6.2,5X,F6.2,5X,F6.2)
C
C
C     DATA OF TEST 2
C
C     V1       PRESSURE DROP ACROSS THE ORIFICE IN VOLTS
C     V2       VALVE TRAVEL IN VOLTS
C     V3       PRESSURE OUTPUT FROM THERMOSTAT IN VOLTS
C
C
C     TM&GM ARE TEMPERATURES AT VARIOUS LOCATIONS IN THE SYSTEM
C     ALL TEMPERATURES ARE PRINTED IN FAHRENHEIT SCALE
C
C     TM1      RETURN AIR
C     TM2      NORTH AIR SPACE
C     TM3      WEST AIR SPACE
C     TM4      SOUTH AIR SPACE
C     TM5      EAST AIR SPACE
C     TM6      VENTILATION AIR
C     TM7      ROOM DOWNSTAIRS
C     TM8      PLENUM
C     TM9      NORTH DIFFUSER
C     TM10     SOUTH DIFFUSER
C     TM11     INLET OF FAN
C     TM12     AIR ENTERING COIL
C     GM1      AIR LEAVING COIL
C     GM2      WATER ENTERING COIL
C     GM3      WATER LEAVING COIL
C     GM4      NORTH WALL
C     GM5      WEST WALL
C     GM6      SOUTH WALL
C     GM7      EAST WALL
C     GM8      FLOOR
C     GM9      ROOM AVERAGE
C     GM10     THERMOSTAT EFFECTIVE
C     GM11     OUTLET OF FAN
      STOP
      END

$ENTRY
```

	V1	V2	V3
1	4.46	13.20	-0.27
2	4.94	12.00	-0.42
3	4.89	10.80	-0.52
4	4.45	9.12	-0.66
5	3.23	7.53	1.86
6	2.33	6.43	7.36
7	1.58	5.40	13.10
8	1.06	4.54	16.71
9	0.42	3.79	16.70
10	0.04	3.29	16.70
11	0.00	2.21	16.70
12	0.00	1.72	16.70
13	0.00	1.20	16.73
14	0.00	0.69	16.81
15	0.00	0.28	17.49
16	0.00	0.17	17.55
17	0.00	0.13	17.80
18	0.00	0.13	17.90
19	0.00	0.12	17.87
20	0.00	0.12	17.85
21	0.00	0.12	17.33
22	0.00	0.12	17.82
23	0.00	0.12	17.76
24	0.00	0.11	17.75
25	0.00	0.11	17.74
26	0.00	0.11	17.72
27	0.00	0.11	17.70
28	0.00	0.11	17.56
29	0.00	0.11	19.90
30	0.00	0.11	19.90
31	0.00	0.11	19.90
32	0.00	0.11	19.90
33	0.00	0.11	19.90
34	0.00	0.11	19.90
35	0.00	0.11	19.90
36	0.00	0.11	20.00
37	0.00	0.10	20.00
38	0.00	0.00	0.00
39	0.00	0.10	6.80
40	0.00	0.10	20.10
41	0.00	0.10	20.10
42	0.00	0.10	20.10
43	0.00	0.10	20.10
44	0.00	0.10	20.10
45	0.00	0.10	20.10
46	0.00	0.10	20.10
47	0.00	0.10	20.10
48	0.00	0.10	20.10
49	0.00	0.10	20.10
50	0.00	0.10	20.10
51	0.00	0.10	20.10

	TM1	TM2	TM3	TM4	TM5	TM6	TM7	TM8	TM9	TM10	TM11	TM12
1	81.50	69.80	65.12	69.80	69.98	72.50	69.80	81.68	84.02	84.02	81.50	81.86
2	81.14	65.66	60.08	65.30	65.12	66.92	69.80	81.32	82.58	82.76	81.14	80.24
3	81.14	63.40	57.56	63.32	62.96	64.58	70.16	81.14	81.32	81.50	80.78	79.34
4	80.60	61.88	55.58	61.16	60.62	62.78	70.16	80.60	91.40	87.26	80.42	78.62
5	80.06	61.52	54.32	59.54	59.18	60.62	70.16	80.24	115.88	107.78	79.88	77.90
6	79.86	59.90	53.78	58.82	58.46	60.62	70.16	80.24	121.82	114.08	79.70	77.54
7	80.06	59.00	52.70	57.38	57.38	59.90	70.34	80.42	123.62	116.06	79.70	77.18
8	80.24	58.82	52.70	56.66	57.02	59.18	70.16	80.42	125.78	118.04	79.88	76.82
9	80.42	57.56	51.62	56.12	56.10	58.28	70.16	80.60	127.76	119.48	80.06	76.64
10	80.60	57.74	51.80	55.58	56.30	57.74	70.16	80.78	128.84	120.38	80.06	76.28
11	80.78	56.66	51.26	54.50	55.22	57.20	70.16	80.60	129.38	121.10	80.06	76.28
12	80.78	56.66	51.08	54.14	54.68	57.02	70.16	80.78	130.28	121.44	80.06	76.10
13	[illegible]	56.12	50.36	53.42	54.70	56.30	69.98	80.78	130.82	122.00	79.88	75.74
14	80.78	55.94	50.00	53.42	54.14	56.84	70.16	80.96	131.54	122.72	80.06	75.74
15	80.78	55.22	50.00	53.06	53.96	55.94	70.16	80.78	132.08	123.38	79.88	75.56
16	80.78	55.22	50.18	53.06	53.78	55.58	70.34	80.96	132.62	123.62	80.06	75.74
17	80.78	55.04	49.82	53.06	53.24	55.04	70.16	80.96	133.16	123.98	80.06	75.38
18	80.96	54.86	49.46	52.16	53.24	55.22	70.16	81.14	133.70	124.52	80.06	75.38
19	80.78	54.14	49.28	52.34	52.88	55.40	70.16	81.14	133.70	124.52	80.06	75.38
20	81.78	54.14	48.92	52.52	52.88	54.50	70.16	81.32	133.70	124.70	80.06	75.38
21	80.60	54.14	49.10	51.44	52.70	54.86	69.98	81.14	129.20	121.28	80.06	75.02
22	80.96	54.14	49.28	52.52	52.88	54.14	70.16	81.14	125.60	118.04	80.96	75.20
23	80.96	53.60	49.10	51.26	52.16	54.86	70.34	81.14	124.52	116.96	80.24	75.20
24	80.76	53.24	48.92	51.26	52.16	54.50	70.16	81.14	124.16	116.42	80.06	75.02
25	80.60	53.06	49.38	50.72	51.80	53.60	70.16	81.14	123.80	116.06	80.06	75.02
26	80.42	52.70	48.20	50.72	51.80	54.32	70.16	80.78	123.62	115.88	79.88	75.02
27	80.42	53.06	48.92	50.72	52.16	53.96	70.34	80.78	123.44	115.70	79.70	74.64
28	80.06	52.70	48.74	50.72	51.98	53.78	70.16	80.78	123.26	115.70	79.70	74.66
29	80.06	52.88	48.92	50.72	51.80	54.50	69.98	80.78	123.80	115.88	79.52	74.66
30	80.06	52.70	48.56	50.72	51.80	53.96	69.98	80.60	123.80	116.06	79.52	74.66
31	80.06	52.88	48.74	51.08	52.16	53.60	69.98	80.78	123.62	115.88	79.34	74.66
32	79.88	52.52	48.74	51.08	51.62	53.78	69.98	80.60	122.90	115.34	79.34	74.48
33	79.88	52.70	48.74	50.72	51.62	53.96	69.98	80.60	123.44	115.52	79.34	74.48
34	79.88	52.52	48.74	50.72	51.26	53.96	69.98	80.42	124.88	116.78	79.16	74.30
35	79.70	52.16	48.38	50.60	51.26	53.60	69.80	80.42	126.14	117.68	78.98	74.30
36	79.70	52.16	48.74	50.18	51.26	53.60	69.98	80.60	127.04	118.58	79.16	74.30
37	79.70	52.34	48.56	50.36	51.44	53.24	69.80	80.60	127.94	119.48	78.98	74.30
38	79.52	52.16	48.56	50.00	51.44	53.42	69.80	80.60	129.02	120.20	78.98	74.12
39	79.70	52.52	48.56	50.00	51.44	53.24	69.98	80.60	[illegible]	117.50	79.16	74.30
40	79.52	52.52	48.74	50.36	51.44	53.78	69.80	80.60	[illegible]	121.10	78.98	74.48
41	79.34	52.34	48.56	50.36	51.26	53.78	69.80	80.24	132.26	122.72	78.80	74.30
42	79.34	52.34	48.56	50.54	51.26	53.78	69.98	80.60	127.04	119.30	78.96	74.12
43	79.70	52.70	49.10	50.90	51.62	54.14	70.16	80.60	124.70	116.96	78.98	74.30
44	79.34	52.70	49.64	51.08	51.98	53.78	70.34	80.42	123.98	116.24	78.98	74.12
45	79.34	52.52	49.10	50.18	51.62	54.14	70.16	80.42	123.62	115.88	78.80	74.12
46	79.52	52.70	49.28	50.72	51.80	54.14	70.16	80.24	123.44	115.52	78.62	74.12
47	79.34	52.52	49.28	50.72	51.98	54.32	70.52	80.42	123.26	115.52	78.80	74.30
48	79.34	52.88	49.46	50.90	51.98	53.96	70.52	80.24	122.90	115.16	78.62	73.94
49	79.34	52.88	49.28	50.90	51.98	54.14	70.70	80.42	122.18	114.62	78.44	74.12
50	79.16	52.34	48.92	50.36	51.62	53.24	70.52	80.06	122.54	114.80	78.62	73.94
51	78.98	52.70	49.64	51.26	51.98	53.06	70.52	80.06	124.34	116.06	78.26	73.74

	GM1	GM2	GM3	GM4	GM5	GM6	GM7	GM8	GM9	GM10	GM11
1	82.76	117.14	87.44	79.52	79.34	78.26	80.06	77.90	82.58	82.22	81.66
2	81.32	113.00	86.00	79.34	79.16	77.90	79.88	77.72	81.86	81.86	80.06
3	80.24	110.12	85.10	79.70	79.52	77.90	80.24	77.90	81.68	81.68	79.34
4	129.20	155.66	122.18	79.70	79.34	77.18	80.06	77.72	81.14	81.14	79.26
5	143.24	158.54	142.52	79.34	78.98	76.64	79.70	77.54	81.50	80.60	77.54
6	144.68	157.64	145.22	79.34	78.98	76.28	79.70	77.54	82.76	80.42	77.36
7	144.14	156.62	145.40	79.16	78.62	75.92	79.34	77.72	83.48	80.42	77.18
8	146.30	157.92	147.92	79.16	78.80	75.56	79.34	77.72	83.66	80.24	77.00
9	147.38	158.72	149.18	79.16	78.62	75.20	79.34	77.54	83.84	80.06	76.64
10	148.10	159.26	150.06	79.16	78.62	75.02	79.34	77.72	84.20	80.06	76.64
11	149.82	160.52	150.98	79.16	78.62	74.66	79.34	77.54	84.38	79.88	76.46
12	149.36	160.88	151.52	79.34	78.62	74.66	79.34	77.72	84.56	79.70	76.46
13	150.08	161.78	152.06	79.16	78.44	74.30	79.16	77.54	84.56	79.70	76.28
14	150.80	162.32	152.78	79.16	78.62	74.12	79.34	77.72	[illegible]	79.52	76.10
15	151.34	163.40	153.50	79.34	78.80	74.12	79.34	77.72	[illegible]	79.34	76.10
16	152.06	164.12	153.22	79.52	78.80	74.12	79.52	77.90	84.92	79.52	76.10
17	152.60	164.84	154.94	79.34	78.80	73.94	79.52	77.90	84.92	79.34	75.92
18	152.96	165.20	155.12	79.52	78.98	73.94	79.52	77.90	85.10	79.34	75.74
19	152.78	164.84	154.76	79.34	78.80	73.76	79.52	77.90	85.10	79.34	75.74
20	152.24	164.12	154.40	79.70	78.98	73.94	79.70	78.08	85.10	79.16	75.74
21	141.62	151.34	143.24	79.52	78.98	73.58	79.52	77.90	84.92	78.98	75.56
22	139.10	149.30	143.90	79.52	78.98	73.58	79.70	77.90	84.92	78.98	75.74
23	138.92	148.82	143.72	79.70	79.16	73.76	79.88	78.08	84.74	78.98	75.74
24	138.74	148.64	140.54	79.52	78.98	73.40	79.52	77.90	84.56	78.80	75.38
25	134.56	148.46	140.54	79.70	78.98	73.40	79.52	77.90	84.56	78.80	75.38
26	133.56	148.46	140.36	79.52	78.98	73.22	79.34	77.72	84.20	78.62	75.20
27	138.38	148.28	140.18	79.70	78.98	73.40	79.70	77.90	84.20	78.62	75.20
28	138.62	148.10	140.00	79.34	78.80	73.04	79.34	77.72	84.02	78.26	75.02
29	138.62	147.92	141.62	79.34	78.80	73.04	79.34	77.72	84.02	78.26	75.02
30	138.74	147.56	141.44	79.16	78.62	72.86	79.16	77.72	83.84	78.26	74.84
31	139.20	147.02	140.90	79.16	78.62	72.68	78.98	77.54	83.66	77.90	74.66
32	135.68	144.14	138.20	79.16	78.62	72.86	79.16	77.54	83.84	77.90	74.66
33	139.10	148.10	141.60	79.16	78.62	72.68	79.16	77.54	83.66	77.90	74.66
34	141.26	150.98	144.14	78.98	78.62	72.68	78.98	77.54	83.48	77.72	74.48
35	142.70	152.60	145.58	78.98	78.44	72.50	78.98	77.36	83.48	77.72	74.48
36	143.96	154.04	147.02	78.80	78.26	72.50	78.80	77.54	83.66	77.72	74.48
37	145.22	155.12	148.10	78.98	78.44	72.50	78.98	77.54	83.66	77.72	74.48
38	146.30	155.84	149.72	78.98	78.62	72.68	78.98	77.54	83.84	77.72	74.30
39	143.24	150.90	142.52	78.98	78.62	72.68	78.98	77.72	84.02	77.90	74.30
40	151.34	161.36	155.30	78.80	78.44	72.32	78.80	77.54	83.66	77.54	74.30
41	150.98	160.34	154.76	78.62	78.26	72.32	78.62	77.54	83.66	77.54	74.30
42	138.56	146.12	141.44	78.62	78.26	72.32	78.80	77.36	83.84	77.54	74.12
43	138.02	145.58	141.08	78.62	78.26	72.32	78.80	77.54	83.84	77.72	74.30
44	137.84	145.58	140.90	78.44	78.26	72.32	78.62	77.36	83.66	77.54	74.30
45	137.66	145.40	140.72	78.44	77.90	72.14	78.62	77.18	83.48	77.36	74.12
46	137.48	145.22	140.72	78.44	78.08	72.14	78.44	77.18	83.30	77.18	74.30
47	137.30	145.04	140.54	78.62	78.26	72.32	78.62	77.18	83.30	77.36	74.48
48	136.58	144.32	139.82	78.44	78.08	72.14	78.62	77.18	83.30	77.18	74.12
49	135.14	142.34	138.02	78.44	78.98	72.14	78.62	77.18	83.30	77.18	74.30
50	137.48	145.76	141.08	79.26	77.90	71.96	78.26	77.18	82.94	77.00	74.12
51	140.00	148.28	143.42	78.26	77.72	71.96	78.26	77.00	92.94	77.00	73.94

APPENDIX C

STATISTICAL RELATION BETWEEN RETURN, WALL, ROOM, AND SUPPLY AIR TEMPERATURES

A linear relation between return, room, wall, and supply air temperatures was assumed of the form

$$TR(k) = A2 \cdot TS(k) + B2 \cdot TRM(k) + C2 \cdot TW(k), \qquad k=1,2,\ldots N$$

and A2, B2, and C2 were evaluated by the method of least squares as follows:

$$J = \sum_{k=1}^{N} (TR_{exp} - TR_{model})^2 \qquad \text{(C-1)}$$

For best fit $\frac{\partial J}{\partial A2} = 0$, $\frac{\partial J}{\partial B2} = 0$, and $\frac{\partial J}{\partial C2} = 0$. Applying these conditions yields:

$$A2 \sum_{k=1}^{N} TS \cdot TS + B2 \sum_{k=1}^{N} TRM \cdot TS + C2 \sum_{k=1}^{N} TW \cdot TS = \sum_{k=1}^{N} TS \cdot TR \qquad \text{(C-2)}$$

$$A2 \sum_{k=1}^{N} TS \cdot TRM + B2 \sum_{k=1}^{N} TRM \cdot TRM + C2 \sum_{k=1}^{N} TW \cdot TRM = \sum_{k=1}^{N} TR \cdot TRM \qquad \text{(C-3)}$$

$$A2 \sum_{k=1}^{N} TS \cdot TW + B2 \sum_{k=1}^{N} TRM \cdot TW + C2 \sum_{k=1}^{N} TW \cdot TW = \sum_{k=1}^{N} TR \cdot TW \qquad \text{(C-4)}$$

This set of simultaneous equations was solved using a FORTRAN-Program and the value of the constants were found to be;

A2 = 0.0041388273

B2 = 0.10132271

C2 = 0.38259590

In order for the model to satisify the steady state condition where all the temperatures are equal the constants should satisfy

$$A2 + B2 + C2 = 1. \qquad \text{(C-5)}$$

The constants A2, B2 and C2 do satisfy this condition.

APPENDIX D

OPTIMIZATION OF THE PARAMETERS OF THE THERMOSTAT

The model of the thermostat is of the form

$$TEFF = \frac{A \cdot a \cdot TRM}{(s+a)} + \frac{(1-A) \cdot b \cdot TW}{(s+b)} \tag{D-1}$$

$$(P7-PSET) = \frac{K \cdot c}{(s+c)} \cdot (TEFF - TSET) \tag{D-2}$$

Using the experimental values of TRM, TW, PSET, TSET, and P7 the parameters A, a, b, c and K were found by the method shown below.

Consider Equation D-1 and let

$$X1 = \frac{a \cdot TRM}{(s+a)}$$

and (D-3)

$$X2 = \frac{b \cdot TW}{(s+b)} \qquad TEFF = A \cdot X1 + (1-A) \cdot X2$$

Equation D-3 may be written

$$\dot{X}1 = - a \cdot X1 + a \cdot TRM \tag{D-4}$$

$$\dot{X}2 = - b \cdot X2 + b \cdot TRM \tag{D-5}$$

Equations D-4 and D-5 are linear differential equations with constant coefficients. Assuming the forcing functions to be constant over the sample interval the solutions of D-4 and D-5 may be written

$$X1\ (k+1) = e^{-a \cdot T}\, X1(k) + (1-e^{-a \cdot T}) \cdot TRM(k) \tag{D-6}$$

$$X2(k+1) = X2(k) \cdot e^{-b \cdot T} + (1-e^{-b \cdot T}) \cdot TW(k) \tag{D-7}$$

Since the system is initially at steady state the initial conditions may be found from Equations D-4 and D-5.

$$X1\ (0) = TRM\ (0)$$

$$X2\ (0) = TW\ (0)$$ (D-8)

Defining the performance index J

$$J(A,\ a,\ b) = \frac{1}{2} \sum_{k=1}^{N} (T_{em} - T_{ex})^2 \qquad \text{(D-9)}$$

where

T_{em} = TEFF model

T_{ex} = TEFF experimental.

The constants A, a and b are determined to minimize value of J.

Consider

$$\frac{\partial J}{\partial A} (A,\ a,\ b) = \sum_{k=1}^{N} (T_{em}-T_{ex}) \cdot (X1-X2)$$

$$= \sum_{k=1}^{N} (A \cdot (X1-X2) + X2 - T_{ex}) \cdot (X1-X2) \qquad \text{(D-10)}$$

Let

$$F_A (A,\ a,\ b) = \frac{\partial J}{\partial A} (A,\ a,\ b) = 0$$

$$F_a (A,\ a,\ b) = \frac{\partial J}{\partial a} (A,\ a,\ b) = 0 \qquad \text{(D-11)}$$

$$F_b (A,\ a,\ b) = \frac{\partial J}{\partial b} (A,\ a,\ b) = 0$$

The set of Equations D-11 are non-linear in A, a, and b. They may be solved by an iterative "steepest decent" method.

The new value of A may be obtained by solving D-10

$$A_{new} = - \sum_{k=1}^{N} (X2-T_{ex}) \cdot (X1-X2) / \sum_{k=1}^{N} (X1-X2)^2 \qquad \text{(D-12)}$$

then

$$\delta A = A_{new} - A \qquad \text{(D-13)}$$

Expanding F_a and F_b in Taylor's series, neglecting higher order terms, and equating to zero yields

$$0 = F_a + \frac{\partial F_a}{\partial A} \cdot \delta A + \frac{\partial F_a}{\partial a} \cdot \delta a + \frac{\partial F_a}{\partial b} \cdot \delta b \qquad \text{(D-14)}$$

$$0 = F_b + \frac{\partial F_b}{\partial A}\cdot\delta A + \frac{\partial F_b}{\partial a}\cdot\delta a + \frac{\partial F_b}{\partial b}\cdot\delta b \qquad \text{(D-15)}$$

These two equations are to be solved for δa and δb.

Let

$$F_a = \frac{\partial J}{\partial a} = \sum_{k=1}^{N} (A\cdot(X1-X2) + X2 - T_{ex})\cdot A\cdot V1 \qquad \text{(D-16)}$$

and

$$F_b = \frac{\partial J}{\partial b} = \sum_{k=1}^{N} (A\cdot(X1-X2) + X2 - T_{ex})\cdot(1-A)\cdot V2 \qquad \text{(D-17)}$$

where

$$V1 = \frac{\partial X1}{\partial a} \quad \text{and} \quad V2 = \frac{\partial X2}{\partial b} \qquad \text{(D-18)}$$

Then let

$$G_a = \frac{\partial F_a}{\partial a} = \sum_{k=1}^{N} (T_{em}-T_{ex})\cdot U1 + A\cdot V1^2 \qquad \text{(D-19)}$$

$$G_b = \frac{\partial F_b}{\partial b} = \sum_{k=1}^{N} (T_{em}-T_{ex})\cdot U2 + (1-A)\cdot V2^2 \qquad \text{(D-20)}$$

and

$$G_{ab} = \frac{\partial F_a}{\partial b} = \sum_{k=1}^{N} A\cdot(1-A)\cdot V1\cdot V2 \qquad \text{(D-21)}$$

where

$$U1 = \frac{\partial V1}{\partial a} \quad \text{and} \quad U2 = \frac{\partial V2}{\partial b} \qquad \text{(D-22)}$$

Equations D-4 and D-5 may be solved as illustrated in Appendix A

$$X1(k+1) = X1(k)\cdot e^{-a\cdot T} + TRM(k)\cdot(1-e^{-a\cdot T})$$

and (D-23)

$$X2(k+1) = X2(k)\cdot e^{-b\cdot T} + TW(k)\cdot(1-e^{-b\cdot T})$$

Applying the definitions of V1 and V2 to Equations D-23. yields

$$V1(k+1) = V1(k)\cdot e^{-a\cdot T} - T\cdot(X1(k) - TRM(k))\cdot e^{-a\cdot T}$$

and (D-24)

$$V2(k+1) = V2(k)\cdot e^{-b\cdot T} - T\cdot(X2(k) - TW(k))\cdot e^{-b\cdot T}$$

Applying the definitions of U1 and U2 to Equations D-24 yields

$$U1(k+1) = U1(k) \cdot e^{-a \cdot T} - 2 \cdot T \cdot V1(k) \cdot e^{-a \cdot T} + T^2 \cdot (X1(k) - TRM(k)) \cdot e^{-a \cdot T}$$

and (D-25)

$$U2(k+1) = U2(k) \cdot e^{-b \cdot T} - 2 \cdot T \cdot V2(k) \cdot e^{-b \cdot T} + T^2 \cdot (X2(k) - TW(k)) \cdot e^{-b \cdot T}$$

The initial conditions for Equations D-23, D-24, and D-25 are

$$X1(0) = TRM(0), \quad V1(0) = 0, \quad U1(0) = 0$$

$$X2(0) = TW(0), \quad V2(0) = 0, \quad U2(0) = 0 \qquad \text{(D-26)}$$

From Equations D-16 and D-17 define

$$G_{aA} = \frac{\partial F_a}{\partial A} = \sum_{k=1}^{N} (2 \cdot A \cdot (X1-X2) + X2 - T_{ex}) \cdot V1 \qquad \text{(D-27)}$$

and

$$G_{bA} = \frac{\partial F_b}{\partial A} = \sum_{k=1}^{N} - ((2 \cdot A - 1) \cdot (X1-X2) + (X2 - T_{ex})) \cdot V2 \qquad \text{(D-28)}$$

From Equations D-14 and D-15 δa and δb may be found

$$\delta a = ((G_{ab} \cdot F_b - G_b \cdot F_a) + (G_{ab} \cdot G_{bA} - G_b \cdot G_{aA}) \cdot \delta A) / (G_a \cdot G_b - G_{ab}{}^2)$$

and (D-29)

$$\delta b = -(F_b + G_{bA} \cdot \delta A + G_{ab} \cdot \delta a) / G_b .$$

Computation begins by selecting initial values of A, a, and b. Equations D-23, D-24, and D-25 are solved for X1, X2, V1, V2, U1, and U2 starting with initial conditions D-26. These values are used to find F_a, F_b, G_a, G_b, G_{ab}, G_{aA}, G_{bA}, and A_{new} from Equations D-16, D-17, D-19, D-20, D-21, D-27, D-28, and D-12 respectively. δA is found by Equation D-13. δa and δb are found from Equation D-29. New values of A, a, and b are found from the old values by

$$A_{new} = A_{old} + \delta A$$

$$a_{new} = a_{old} + \delta a \qquad \text{(D-30)}$$

and

$$b_{new} = b_{old} + \delta b$$

Using the new parameter values, the proceedure is repeated. The iteration continues until the values of δA, δa, and δb are all sufficiently small. This proceedure was programmed in the Basic language on a Z-80 microcomputer. Values of A, a, and b were found to be

$$A = 0.2753377$$

$$a = 3.848994$$

$$b = 1.7507167$$

A similar procedure was developed for finding K and c in Equation D-2. The values of PSET = 3.45 psi and TSET = 74.5°F were observed from the experiment. The values of K and c found by the above procedure were

$$K = 5.2446$$

and

$$c = 0.5081702.$$

ACKNOWLEDGEMENT

The author wishes to express his deep sense of appreciation and gratitude to his Major Professor, Dr. J. G. Thompson, for the continuous guidance and help.

The author also expresses his sincere thanks to Dr. N. Z. Azer for the timely advice and for being on the examining committee.

Thanks are also due to Dr. L. E. Fuller for having served on the examining committee.

Finally, the author extends his thanks to ASHRAE and to the Mechanical Engineering Department for the financial aid provided during the period of this investigation.

VALIDATION AND REFINEMENT OF A DYNAMIC DIGITAL
MODEL OF A FAN COIL HEATING SYSTEM

by

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AN ABSTRACT OF A THESIS

Submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

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1980

ABSTRACT

Experimentally validated mathematical model for the transient thermal response of a room with fan coil heating system is presented in this thesis.

The objective of this project was to have an experimentally validated model of the transient thermal response of a room with a fan coil heating system, so that one could apply optimal control strategies to the control equipment in the HVAC system to minimize energy consumption.

Experimental data were obtained by subjecting the room to a change in the load. The temperatures at various locations in the room were recorded each 3 minutes (sampling interval) for a period of 3.2 hours. Other necessary details; like valve travel, water flow rate, and thermostat output pressure were also recorded each 3 minutes.

Models for the individual components were formulated and combined into a closed loop feedback control system. The closed loop system was simulated on a digital computer. The computer program was written in Fortran.

The simulation results and experimental results were compared by plotting them on a common time axis. The agreement between the simulation and the experiment was good. Reasons for certain deviations were discussed. Based on the experience with the experimental facility and results obtained, recommendations for further study are also provided.