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

by

NAGAMANGALA KRISHNAMURTHY ANAND
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:

[Signature]
Major Professor
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES AND FIGURES</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMENCLATURE</td>
<td>V</td>
</tr>
<tr>
<td>CHAPTER I - INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER II - MODEL FORMULATION</td>
<td>2</td>
</tr>
<tr>
<td>CHAPTER III - EXPERIMENTAL INVESTIGATION</td>
<td>14</td>
</tr>
<tr>
<td>CHAPTER IV - RESULTS AND DISCUSSION</td>
<td>38</td>
</tr>
<tr>
<td>CHAPTER V - RECOMMENDATIONS FOR FURTHER STUDY</td>
<td>52</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>55</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>58</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>78</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>89</td>
</tr>
<tr>
<td>APPENDIX D</td>
<td>90</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>95</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLES</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>15</td>
</tr>
<tr>
<td>3-2</td>
<td>32</td>
</tr>
</tbody>
</table>

**LIST OF PLATES**

<table>
<thead>
<tr>
<th>PLATES</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>17</td>
</tr>
<tr>
<td>2.</td>
<td>19</td>
</tr>
<tr>
<td>3.</td>
<td>21</td>
</tr>
</tbody>
</table>

**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>FIGURES</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>6</td>
</tr>
<tr>
<td>2.</td>
<td>22</td>
</tr>
<tr>
<td>3.</td>
<td>24</td>
</tr>
<tr>
<td>4.</td>
<td>25</td>
</tr>
<tr>
<td>5.</td>
<td>25</td>
</tr>
<tr>
<td>6.</td>
<td>28</td>
</tr>
<tr>
<td>7.</td>
<td>30</td>
</tr>
<tr>
<td>8.</td>
<td>35</td>
</tr>
<tr>
<td>9.</td>
<td>37</td>
</tr>
<tr>
<td>10.</td>
<td>39</td>
</tr>
<tr>
<td>11.</td>
<td>40</td>
</tr>
<tr>
<td>12.</td>
<td>42</td>
</tr>
<tr>
<td>13.</td>
<td>43</td>
</tr>
<tr>
<td>14.</td>
<td>44</td>
</tr>
<tr>
<td>FIGURES</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>15. Wall temperature</td>
<td>45</td>
</tr>
<tr>
<td>16. Effective temperature</td>
<td>47</td>
</tr>
<tr>
<td>17. Output pressure of thermostat</td>
<td>48</td>
</tr>
<tr>
<td>18. Valve travel</td>
<td>49</td>
</tr>
<tr>
<td>19. Water flow rate</td>
<td>50</td>
</tr>
</tbody>
</table>
NOMENCLATURE

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 hysteresis
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/ft³)
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)
Tiw  Temperature of the water entering the coil (°F)
Tow  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)
V2  Volume of room (ft³)
w  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
C0, C1  Coefficients of coil
hm  Mechanical efficiency of fan
hs  Static efficiency of fan
ht  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
DEDICATED TO MY PARENTS
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)

\[ D = \frac{V_a P_a}{X M_1} \]  

(2-1)


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 \(-PA \cdot VA \cdot CA \cdot \frac{dT_2}{dt}\)
2. Heat stored in furniture \(-XMF \cdot CF \cdot \frac{dT_2}{dt}\)
3. Heat flow into the room by HVAC system \(-XM1 \cdot CA \cdot T1\)
4. Heat flow into the room by infiltration \(-XM0 \cdot CA \cdot TO\)
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

\[
PA \cdot VA \cdot CA \cdot \frac{dT_2}{dt} + XMF \cdot CF \cdot \frac{dT_2}{dt} = XM1 \cdot CA \cdot T1 - XM2 \cdot CA \cdot TRET \\
+ (QFLO + QCOND + QLITE) \\
+ XM0 \cdot CA \cdot TO
\]  

(2-2)

This mass balance equation is \(XM0 = XM2 - XM1\)  

(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
THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE. THIS IS AS RECEIVED FROM CUSTOMER.
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

\[ T_{RET} = A_2 \cdot T_1 + B_2 \cdot T_2 + C_2 \cdot T_{WALL} \]  \hspace{1cm} (2-3)

Using experimental data and applying the method of least squares the weighting factors \( A_2, B_2 \) and \( C_2 \) 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 fluxes. 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

\[
q_j(n) = \sum_{k=1}^{r} X_{jk} \cdot T_2(n-k) - \sum_{k=0}^{r} Y_{jk} \cdot T_0(n-k)
- \sum_{k=1}^{r} Z_{jk} \cdot q_j(n-k)
\]  

(2-4)

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

\[
T_j = T_2 + \frac{q_j}{(h_j A_j)}
\]  

(2-5)

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.
\[ \frac{P7(s)}{T7(s)} = \frac{K7}{(T71s+1)} \]  

(2-6)

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

\[ T7 = \text{TEFF} = A7 \cdot T2 + B7 \cdot \text{TWALL} \]  

(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 \( \text{TEFF} \) and \( T2 \) and between \( \text{TEFF} \) and \( \text{TWALL} \). In this work the thermostat is modeled as

\[ \text{TEFF} = \frac{A7 \cdot T2}{(T71s+1)} + \frac{B7 \cdot \text{TWALL}}{(T72s+1)} \]  

(2-8)

In order to match equilibrium conditions we require

\[ A7 + B7 = 1 \]  

(2-9)

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

\[ \frac{P7(s)}{\text{TEFF}(s)} = \frac{K \cdot C}{(s+c)} \]  

(2-10)

Using experimental values for \( T2, \text{TWALL}, \text{TEFF} \) 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 \textbf{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 hysteresis into account. The values of the coefficients in the model were found experimentally and implemented as

\[ Y9 = U \cdot P8 + a \pm \text{HYS} \]  

(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

\[
\dot{M}_w = \frac{M_{\text{max}}}{B9} \cdot \exp(A9 \cdot Y9) \quad (2-12)
\]

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

\[
\begin{align*}
FLO &= b \cdot Y9, \quad Y9 \leq \lambda \quad (2-13) \\
FLO &= d \cdot Y9^e, \quad Y9 > \lambda \quad (2-14)
\end{align*}
\]

where \(b\), \(d\), \(e\), and \(\lambda\) 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.

Booth, Pearson and Leonard [27] obtained algebraic expressions to approximate the gain and time constant of a finned, serpentine, cross flow heat exchanger. Calculated values from their algebraic 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 experimentally 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

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

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

\[
T_6 = T_5 + E \cdot (T_{iw} - T_5) \quad , \quad \dot{M} \cdot \text{C}_{\text{A}} < \dot{M}_w \cdot \text{C}_W \quad (2-16)
\]

\[
T_{ow} = T_{iw} + E \cdot (T_{iw} - T_5) \cdot \dot{M} \cdot \text{C}_{\text{A}} / (\dot{M}_w \cdot \text{C}_W) \quad (2-17)
\]

or

\[
T_6 = T_5 + E \cdot (T_{iw} - T_5) \cdot \dot{M}_w \cdot \text{C}_W / (\dot{M} \cdot \text{C}_{\text{A}}) \quad (2-18)
\]

\[
T_{ow} = T_{iw} + E \cdot (T_{iw} - T_5) \quad , \quad \dot{M} \cdot \text{C}_{\text{A}} > \dot{M}_w \cdot \text{C}_W \quad (2-19)
\]

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).

\[
E = C_{i0} + C_{il} \cdot \text{FLO} \quad , \quad F_{il} < \text{FLO} < F_{hi} \quad (2-20)
\]

For all but a few data points \( \dot{M} \cdot \text{C}_{\text{A}} < \dot{M}_w \cdot \text{C}_W \) and \( T_6 = T_5 + E \cdot (T_{iw} - T_5) \) gives the temperature of the air leaving the heat exchanger.
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

\[
\frac{T_{ao}}{T_{ai}} = \exp(-\alpha L \cdot s) \cdot \exp(-\beta L) \cdot \exp \left(-\alpha_l \frac{T_d \cdot s}{T_d + 1} \right)
\]  

(2-21)

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 transferred 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

\[
T_3 = T_2 + \phi \cdot h_m \cdot h_s \cdot W_m / (X M_2 \cdot C_A)
\]  

(2-22)

The energy balance for the mixing of ventilation air yields

\[
T_4 = \delta \cdot T_o + (1-\delta) \cdot T_3
\]  

(2-23)

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

\[ T_5 = T_4 + h_m \cdot (h_t - h_s) \cdot w_m / (XM_2 \cdot CA) \]  
(2-24)

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

\[ T_1 = T_6 + (1 - \phi) \cdot h_m \cdot h_s \cdot w_m / (XML \cdot CA) \]  
(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

\[ T_{RET} = A_2 \cdot T_1 + B_2 \cdot T_2 + C_2 \cdot TWALL \]  
(2-26)

\[ T_3 = T_{RET} + \phi \cdot h_m \cdot h_s \cdot w_m / XM_2 \cdot CA \]  
(2-27)

\[ T_4 = \delta T_o + (1 - \delta) T_3 \]  
(2-28)

\[ T_5 = T_4 \]

\[ XML \cdot CA \cdot (T_1 - T_6) = (1 - \phi) \cdot h_m \cdot h_s \cdot w_m + UAD \cdot \left[ T_o - \frac{(T_1 + T_6)}{2} \right] \]  
(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 Celotex 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**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (ft)</th>
<th>Conductivity (BTU/hr. ft.°F)</th>
<th>Density (lb/ft³)</th>
<th>Specific Heat (BTU/lb.°F)</th>
<th>Heat transfer Coefficient (BTU/hr.°F ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.833</td>
</tr>
<tr>
<td>2</td>
<td>0.417</td>
<td>0.0925</td>
<td>50.0</td>
<td>0.26</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>0.026</td>
<td>9.0</td>
<td>0.24</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Floor Data**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (ft)</th>
<th>Conductivity (BTU/hr. ft.°F)</th>
<th>Density (lb/ft³)</th>
<th>Specific Heat (BTU/lb.°F)</th>
<th>Heat transfer Coefficient (BTU/hr.°F ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.125</td>
<td>0.0667</td>
<td>32.0</td>
<td>0.33</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>
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
EXPLANATION OF PLATE 2

View of Inside of the Room

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

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 circuit. 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. 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:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model No.</td>
<td>KEN-52</td>
</tr>
<tr>
<td>Series No.</td>
<td>860</td>
</tr>
<tr>
<td>Maximum power</td>
<td>4500 watts</td>
</tr>
<tr>
<td>Working pressure</td>
<td>150 psi</td>
</tr>
<tr>
<td>Capacity</td>
<td>52 U.S. gallons</td>
</tr>
<tr>
<td>Range of temperature control</td>
<td>110°F to 170°F</td>
</tr>
</tbody>
</table>

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 temperature 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 longitudinal 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 proportional 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>
<thead>
<tr>
<th>Channel #</th>
<th>Thermocouple location</th>
<th>Thermocouple #</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Return airduct</td>
<td>1</td>
</tr>
<tr>
<td>02</td>
<td>Air space North</td>
<td>2</td>
</tr>
<tr>
<td>03</td>
<td>Air space West</td>
<td>3</td>
</tr>
<tr>
<td>04</td>
<td>Air space South</td>
<td>4</td>
</tr>
<tr>
<td>05</td>
<td>Air space East</td>
<td>5</td>
</tr>
<tr>
<td>06</td>
<td>Ventilation air</td>
<td>6</td>
</tr>
<tr>
<td>07</td>
<td>Room down stairs</td>
<td>7</td>
</tr>
<tr>
<td>08</td>
<td>Plenum</td>
<td>8</td>
</tr>
<tr>
<td>09</td>
<td>North diffuser</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>South diffuser</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>Fan inlet</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>Air entering coil</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>Air leaving coil</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>Water entering coil</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>Water leaving coil</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>North wall</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>West wall</td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>South wall</td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td>East wall</td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td>Floor</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>Thermostat sensor</td>
<td>22</td>
</tr>
<tr>
<td>23</td>
<td>Outlet of fan</td>
<td>23</td>
</tr>
</tbody>
</table>
and the water flow rate was computed using the formula:

\[ \text{FLO} = \text{FLO}_{\text{max}} \times \text{SQRT}(V3/V3_{\text{max}}) \]

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.

<table>
<thead>
<tr>
<th>Flowrate of water in GPM</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.3</td>
<td>0.115</td>
</tr>
<tr>
<td>0.3 - 0.4</td>
<td>0.788</td>
</tr>
<tr>
<td>0.4 - 0.6</td>
<td>0.790</td>
</tr>
<tr>
<td>0.6 - 0.8</td>
<td>0.7925</td>
</tr>
<tr>
<td>0.8 - 1.0</td>
<td>0.795</td>
</tr>
<tr>
<td>1.0 - 1.2</td>
<td>0.800</td>
</tr>
<tr>
<td>1.2 - 1.4</td>
<td>0.810</td>
</tr>
<tr>
<td>1.4 - 1.6</td>
<td>0.821</td>
</tr>
<tr>
<td>1.6 - 1.8</td>
<td>0.830</td>
</tr>
<tr>
<td>1.8 - 2.0</td>
<td>0.840</td>
</tr>
</tbody>
</table>

**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:

\[
F_{LO} = 2.362 \times Y_9, \quad Y_9 \leq 0.81379
\]

\[
F_{LO} = 1.98 \times (Y_9)^{0.14699}, \quad Y_9 < 0.81379
\]

**Valve Actuator**

The normalized valve travel was related to the input pressure to the valve actuator taking the hysteresis force into account. Experimental
THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE
Fig. 8. Valve (Water Flow) Characteristics.
values of normalized valve travel vs input pressure to the valve actuator are plotted in the Figure 9. The valve travel correction due to hysteresis was found by measuring length DE in Figure 9. From the plot the normalized valve travel is related to the input pressure by:

\[ Y_9 = Y_{\text{MAX}} \cdot (5.11 - 1.23 P + 0.265) \]
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 I.

In the experimental results the following uncertainties are tolerated:

Temperature measurement \(+ 0.5^\circ F\)
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.
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 difference 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. 14. Air Entering the Coil.
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 due 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. 17. Output Pressure of Thermostat.
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 instrumentation 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 used 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 Improvements

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 responses.

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 extended 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.
BIBLIOGRAPHY


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

\[ \dot{x} = -Ax + \phi(t) \]  
(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

\[ x(k+1) = \text{EXP}(-A*T) * x(k) + (\text{1-EXP}(-A*T)) \frac{\phi(k)}{A} \]  
(A-2)

A copy of the simulation program with output results follows.
THIS BOOK CONTAINS NUMEROUS PAGES WITH THE ORIGINAL PRINTING BEING SKEWED DIFFERENTLY FROM THE TOP OF THE PAGE TO THE BOTTOM.

THIS IS AS RECEIVED FROM THE CUSTOMER.
**THIS PROGRAM SIMULATES TRANSIENT THERMAL RESPONSE OF A ROOM WITH FAN, PIPING AND GULF HEATING SYSTEM. SAMPLING INTERVAL IS THREE MINUTES. PROGRAM CONSISTS OF SEVERAL SUBROUTINES WHICH ARE CALLED SEQUENTIALLY BY MAIN PROGRAM. EACH SUBROUTINE CORRESPONDS TO AN INDIVIDUAL ELEMENT OF THE SYSTEM.******************************************************************************

SYMBOLS USED IN EACH SUBROUTINE ARE DEFINED BELOW.

CONSTANTS USED IN THIS SIMULATION ARE GIVEN IN PARENTHESIS.

**SUBROUTINE** RMAIR
**PURPOSE:** TO COMPUTE ROOM TEMPERATURE.

A2, B2, C2 WEIGHTING FACTORS TO COMPUTE RETURN AIR TEMPERATURE.

ADENS RUG AIR DENSITY, LB/FT**3

CA SPECIFIC HEAT OF AIR, BTU/DEG.F. (0.24)

CP SPECIFIC HEAT OF FURNITURE IN THE ROOM, BTU/DEG.F. (1.06)

DT SAMPLING INTERVAL, HR. (0.05)

ISTEP CURRENT TIME STEP.

P2 ROOM PRESSURE, ATM (1.0)

QLET HEAT LOAD DUE TO LIGHTING, BTU/HR. (0.0)

T1 SUPPLY AIR TEMPERATURE, DEG.F.

T2 AVERAGE ROOM AIR TEMPERATURE, DEG.F.

TOUT AIRSFACE TEMPERATURES, DEG.F.

TAU2 ROOM TIME CONSTANT, HR.

VRM VOLUME OF ROOM, FT**3 (2126.6)

XM1 MASS FLOW RATE OF AIR ENTERING THE ROOM, LB./HR. (42.8)

XM2 MASS FLOW RATE OF RETURN AIR, LB./HR. (77.6)

XM0 MASS FLOW RATE OF INFILTRATED AIR INTO ROOM, LB./HR. (134.9)

XMF MASS OF FURNITURE IN THE ROOM, LB. (100)

**SUBROUTINE** SFLUX
**PURPOSE:** TO COMPUTE HEAT LOSS THROUGH THE SURFACES WITH HEAT STORAGE.

C0(1) CONDUCTANCE OF OUTSIDE WALL, BTU/HR.FT**2.DEG.F. (0.0285)

C0(2) CONDUCTANCE OF FLOOR, BTU/HR.FEET**2 (0.323)

FLUX HEAT FLUX THROUGH SURFACE 1 AT TIME ISTEP

HT901 TOTAL HEAT LOSS THROUGH THE SURFACE WITH HEAT STORAGE

NSURF NUMBER OF SURFACES WITH HEAT STORAGE.

NX,NY,NZ NUMBER OF COEFFICIENTS FOR WALL AND FLOOR.

SAREA(1) SURFACE AREA OF OUTSIDE WALL, FT**2 (531.8)

SAREA(2) SURFACE AREA OF FLOOR, FT**2 (531.8)

XSY,ZSY COEFFICIENTS FOR SURFACES WITH HEAT STORAGE.

**SUBROUTINE** HFLUX
**PURPOSE:** TO COMPUTE INSIDE HEAT FLUX OF SURFACE WITH HEAT STORAGE.

**SUBROUTINE** HTEMP
**PURPOSE:** TO COMPUTE INSIDE WALL TEMP. ON WHICH THERMOSTAT IS MOUNTED.

TNWALL WALL TEMPERATURE, DEG.F.

HNWALL HEAT TRANSFER COEFFICIENT OF WALL, BTU/HR.FEET**2 (0.0)
SUBROUTINE FTRFLO
PURPOSE: TO COMPUTE WATER FLOW RATE IN GPM.
FLO(ISTEP) WATER FLOW RATE AT TIME ISTEP
FLCMAX MAXIMUM WATER FLOW RATE, GPM (2.0)

SUBROUTINE FNOC1
PURPOSE: TO COMPUTE AIR TEMPERATURE AT FAN EXIT.
ARATIO RATIO OF VENTLN. AIR TO RETURN AIR (0.0)
ETAM MELT EFFICIENCY OF MOTOR DRIVING HOT AIR FAN (0.5)
ETAS FAN STAT. ENERGY/ENERGY TO FAN SPFT
T5 AIR TEMP. ENTERING CCIL, DEG.F.
T8 RETURN AIR TEMPERATURE, DEG.F.

SUBROUTINE FNOC2
PURPOSE: TO COMPUTE SUPPLY TEMP.
PHI PRESSURE DROP IN RETURN DUCT/DRIP IN ENTIRE SYSTEM (0.2)
UAD OVERALL HT COEFFICIENT OF SUPPLY PIPE, BTU/HR DEG.F. FT**2

SUBROUTINE COIL
PURPOSE: TO COMPUTE TEMP. OF AIR LEAVING THE CCIL, DEG.F.
G6 EFFECTIVENESS OF CCIL
GPM MAX FLOW RATE IN THE CCIL

SUBROUTINE THERMT
PURPOSE: TO COMPUTE THE OUTPUT PRESSURE FROM THE THERMOSTAT.
AT277 WEIGHTING FACTORS TO COMPUTE EFFECTIVE TEMP. (1.725, 0.275)
PSET SET PRESSURE, PSI (3.45)
TAUT1 TIME CONSTANT EFFECTED BY WALL
TAUT2 TIME CONSTANT EFFECTED BY ROOM AIR.
TEFF EFFECTIVE TEMP. OF THERMT.
PT OUTPUT PRESSURE FROM THERMT.
TSET SET TEMP. OF THERMT. (74.5)
PT AND TEFF ARE RELATED BY GAIN AND A TIME CONSTANT.
1/P TIME CONSTANT, MIN. (0.19)
PK GAIN (0.50)

SUBROUTINE CCND
PURPOSE: TO COMPUTE HEAT LOSS THROUGH SURFACES WITHOUT HT. STORAGE.
U OVER ALL HT. COEFFICIENTS OF SURFACES W.C.T. HT. STORAGE.
AREA AREAS OF SURFACES W.C.T. HT. STORAGE, FT**2

SUBROUTINE VALACT
PURPOSE: TO COMPUTE NORMALIZED VALVE TRAVEL.

VY NORMALIZED VALVE TRAVEL
YMAX MAXIMUM VALVE TRAVEL, INCHES (0.256)
YCS VALVE TRAVEL CORRECTION DUE TO HYSTERESIS (0.263)

DIMENSION XS(2,36),YS(2,30),ZS(2,30),SAREA(2),
LGTU(3,100),TLU(100),ZTU(100),SMO(30,100),TMU(30,100),
2 N(32,40),NY(32,40),N2(12),
3T(30,100),OM(30,100),CO2(1),FLUX(2,100),
4GPM(100),G6(100),CAREA(31),ULU(5),TMU(100),

C REAL NUMBER OF INTERVALS
2 READ 1, IEND
L READ INITIAL ROOM TEMPERATURE AND TEMPERATURE OF THERMOSTAT
3 READ G, T2(I), TEFF
C READ OUTSIDE TEMPERATURE PROFILES.
4 LC I11 J=1, IEND
5 READ 1000, KMN, L, A, B, V1(J), V2(J), V3(J)
6 1000 FORMAT(312, 5F6.2)
7 READ 1001, (TM(1, J), I=1, 12)
8 1001 FORMAT(12F6.2)
9 READ 1002, (SM(I, J), I=1, 1)
10 1002 FORMAT(11F6.2)
11 TOUT(1, J) = (TM(2, J) + TM(3, J) + TM(4, J) + TM(5, J)) / 4.0
12 TOUT(2, J) = TM(7, J)
13 TOUT(3, J) = TM(9, J)
14 111 CONTINUE
C READ IN ROOM DATA:
15 DC 10 I=1, 12
16 DC 10 J=1, IEND
17 TM(1, J) = TM(1, J) * 1.6 + 32.0
18 10 CONTINUE
19 DC 11 I=1, 11
20 DC 11 J=1, IEND
21 GMI(I, J) = GM(I, J) * 1.6 + 32.0
22 11 CONTINUE
23 READ 1, NSURF
24 READ 3, (NX(I), NY(I), XZ(I), I=1, NSURF)
25 READ 4, (CO(I), SAREA(I), I=1, NSURF)
26 DC 200 ) = 1, NSURF
27 MM = NX(I)
28 READ 700, (XS(I, J), J=1, MM)
29 MM = NY(I)
30 READ 700, (YS(I, J), J=1, MM)
31 MM = XZ(I)
32 READ 700, (ZS(I, J), J=1, MM)
33 200 CONTINUE
34 READ 5, VM
35 READ 5, W
36 READ 1, NNL
37 READ 1, NINF
38 READ 6, XM, CF
39 READ 6, CP2
40 READ 5, VLM, UT
41 READ 5, P0
C DATA FOR SURFACES WITH NEGLIGIBLE HEAT STORAGE:
42 DC 20 I=1, 3
43 READ 0, U(11), CAREA(1)
44 20 CONTINUE
C FAN-DUCT DATA:
45 READ 0, M, ETAM, ETA1, ETA5
46 READ 0, AA10, PHI1
47 READ 5, XM1
48 READ 5, P2
C THERMSAT DATA:
49 READ 0, PSATSET
50 READ 6, TAL72, TAU72
51 READ 6, A72, B72
C CALL DATA :
  52 READ 6,(GPM(1:6),G6(1:1),I=1,10)
  55 READ 5,10,10R
  56 READ 100, I=1,10R
  58 FORMAT(F5.2)
  59 REAL XM, XM2
  60 READ 100, XM
  61 FORMAT(A3,25)
  64 IF XM2=XMVIW=1
  65 DO K=1,10R
    TOUT(K)=TOUT(K)*9./5.32.
    75 CONTINUE
  78 PRINT 530
  81 C C THE FIRST LOOP Initializes ALL VARIABLES (ISTEP=1)
  82 C C EACH Following LOOP Computes ALL VARIABLES at THE END of THE TIME INTERVAL
  83 DO 70 I=1,10R
    70 J=ISTEP+1,10R
    CALL MWK(XM,X1,F,CA,CF,XM1,XM2,VM1,VM2,IP,ILT,HTF,CL,,I,J,K)
  73 DO 60 CALL 3,FLUX1,FLUX2,TOUT1,XS1,Y12,NSCA,SCA,SCB,FLUX,1,
                    HTF,1,ISTEP)
  76 CALL KALL (X1,2,Y1,2,MMX,1,MMY,1,MMZ)
  77 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  78 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  79 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  80 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  81 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  82 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  83 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  84 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  85 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  86 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  87 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  88 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  89 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  90 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
  91 CALL KALL (X1,2,2,Y1,2,1,MMX,1,MMY,1,MMZ)
CALL CCLIGFM, S, FLG, GMC, TMC, To, ISTEP, T5)

CALL FNCC2 (T1, T2, T3, T4, T5, To, TCU1, XM1, XM2, ETAT, ETAM, ETAS, 
IM, CA, PH1, ATRIG, ISTEP, INF, 2, UAD, TALL, T5)

C

IF (ISTEP > 10) GO TO 30

CALL KM41R (TJUT, TI, T2, JX, VR, CA, CF, XM, XM1, XM2, GLTE, FFLG, 
UCM, F2, JAJ, INF, ISTEP, TALL, TEMP, 5)

30 T5G = T3

T5D (ISTEP) = To

TIC = T1 (ISTEP)

TEMP = TEPF

PRINT 541, ISTEP, T5D (ISTEP), GMC1 (ISTEP), TM41, GMC1 (7, ISTEP), 
ISTEP, 15, TMC1 (ISTEP), T5, TMC1 (12, ISTEP)


7C CONTINUE

PRINT 560

600 FORMAT (T1ML, 7X, 'T1=', 7X, 'T2=', 9X, 'T3=', 7X, 'T4=', 9X, 'T5=', //)

100 DC 90 I = 1, 10, 0

150 TMC (1) = TMC (1) / 2.0

80 PRINT C12, T1 (I), T5A (I), T2 (I), GMC (9, I)


111 PRINT 560

112 5CC FORMAT (15)

113 1 FORMAT (15)

114 2 FORMAT (315)

115 5 FORMAT (150, 5)

116 6 FORMAT (2F10.5)

117 2 FORMAT * (F10.5)

118 70C FORMAT (023, 16)

119 PRINT 960

120 5CC FORMAT (15, 7X, 'VTR=', 7X, 'VTR=', 7X, 'PB=', 7X, 'PB=', 
15X, 'FLG=', 6X, 'FLG1=', //)

121 DC 90 ISTEP = 1, 10

122 IF (V31 (ISTEP) = 0.01 V31 (ISTEP) = 1.0

123 IF (V11 (ISTEP) = LT 4.95 V11 (ISTEP) = 5.0

124 IF (V11 (ISTEP) .EQ. 3.0) V11 (ISTEP) = 3.82

125 C = -.17655 V11 (ISTEP) C 68275

126 Y11 (ISTEP) = Y11 (ISTEP)

127 P31 (ISTEP) = 2.5 V21 (ISTEP)

128 P11 (ISTEP) = 2.0 * SRT (V31 (ISTEP) = 2.0)

129 5D PRINT 15, ISTEP, Y11 (ISTEP), Y11 (ISTEP), PB (ISTEP), 
P11 (ISTEP), FLG (ISTEP1), FLEX (ISTEP)

130 49 FLXMAT (2X, 12, 2, X, F6.2, 5X, F6.2, 4X, F6.2, 3X, 
15X, F6.2, 5X, F6.2, 4X, F6.2)

C

KEY TO OUTPUT

ALL LABELS STARTING WITH ALPHAS IT ARE TEMPERATURES IN FAHRENHEIT SCALE
To AIRM LEHUNG THE CEIL (SIMULATION)
To AIRM LEHUNG THE CEIL (EXPERIMENT)
TALL MALL TEMP (SIMULATION)
TALL MALL TEMP (EXPERIMENT)
STOP
END

SUBROUTINE FMAIR(TOUT, T1, T2, DT, VRM, CA, CF, XM, XM1, XM2, QLITE, 
                  FLUX, TCGO, PT, TAU2, INF, ISTEP, TVALL, TEMP, S)

DIMENSION TOUT(1, ICG), T1(ICG), T2(ICG)

A2=0.00436273
B2=.0.1012
C2=0.0625
K=ISTEP-1

IF(I1=1) K=1

IF(I1=1, 1)

TEMP=T2(I1)

IF(I1=1)

GC TC 94

A0=14.05*14.0*P2/53.352/146.0*T2(K)

XM=XM2-XM1

TAU2=142*(2.5*CA-CF)/(XM2*CA)

TC=1.0/TAU2

S1=1.0-CA-A2*XM2*CA

S2=-XM0*TOUT(1, ISTEP)/((XM2*U2)

S3=(CC0+MFLUX*QLITE)/(XM2-CA)

S4=-IC2*TVALL)/U2

S5=1.0*IC2*TVALL)/U2

TEMP=EXP(-TC*CT)+(1.0-EXP(-TC*CT))*S

T2(ISTEP)=TEMP

RETURN

SUBROUTINE SFUX(T2, TCUT, XS, YS, ZS, NX, NY, NZ, NSURF, SAREA, CG, FLUX, 
                  HTFL, ISTEP)

DIMENSION XA(2), NY(2, ICG), ZS(2, 3C), YS(2, 3C), XS(2, 3C), 
                  T2(I2, ICG), XCG, YCG, ZCG, SAREA(2), CO(2)

IF(I1=1, 1)

GO TO 10

DO 100 I=1, NSURF

CALL HFLUX(XS, YS, ZS, T2, TOUT, FLUX, NX, NY, NZ, ISTEP, 1)

100 CONTINUE

RETURN

10 CONTINUE K=1

DO 200 I=1, NSURF

FLUX(I1, I)=CG(I)*(TOUT(I, I)-T2(I, I))
HTFC=HTFLC*SAREA(I)=CO(I)*(TCUT(I,1)-T2(I,1))

2C CONTINUE

RETURN

END

SUBROUTINE MFLUX (XS,YS,ZS,T2,TCUT,FLUX,NAX,NY,NZ,ISTEP,K)

DIMENSION NAX(2),NY(2),NZ(2,30),XS(2,30),YS(2,30),ZS(2,30),T2(100),
TCUT(3,100),FLUX(2,100)

IF (K.LE.0) I=1

K=NAX(1)

IF (I.LE.0) I=1

IF (I.LE.0) I=1

RETURN

END

SUBROUTINE MTEMP (FLUX,T2,FWALL,FT2)

RETURN

END

SUBROUTINE MFLUX (YE,YZ,FMAX,FLOPAX,ISTEP)

DIMENSION YZ(100),FLOU(100)

GOTO 650

RETURN

END

SUBROUTINE MFLUX (XG,XT,T1,T2,T3,T4,T5,T6,TCUT,AX,AP1,AX2,ETAT,ETAM,
IETAS,MP1,MP2,MP3,ARAT1,T2,ISTEP)

DIMENSION TCUT(3,100),T1(100),T2(100)

T1(I,1)=T2(I,1)

K=ISTEP-1

RETURN

END
SUBROUTINE TNGCRG(TL,T2,T3,T4,T5,T6,TGT,XT1,XM1,XM2,ETA1,ETAN)
LETSMAX(C,PHI,ATIG,ISTEP,INF,1,WJG)
DIMENSION TOUT(3,LO),TL(100),T1(100)
GENMAX(C,CA=UA0,C,S)+1.0-PHI)*ETAN
I=ETAS*W+UA0*TOUT(3,ISTEP)/DTH
RETURN
END

SUBROUTINE CLIL(UPM,Go,FLC,SMG,TMG,T0,ISTEP,T5)
DIMENSION UPM(LO),Go(10),FLC(LO),SMG(10,LO),TMG(30,LO)
IF (FLC(ISTEP),TEU,0.0) T0=T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(1)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(2)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(3)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(4)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(5)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(6)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(7)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(8)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(9)+SMG(2,ISTEP)-T5
IF (FLC(ISTEP).GT.0.0 AND .NOT.(FLC(ISTEP).LE.0.0))
LT=GO(10)+SMG(2,ISTEP)-T5
RETURN
END

SUBROUTINE THRST(T2,TWALL,AT7,AT7,TEFF,TSET,PT,PCST,
LTAU1,TAU2,TOT,ISTEP,GMG)
DIMENSION GMG(30,100),PT(100)
P=5.23400
PA=5.23400
TAU1=528.1702
ISTEP,FLC,L1 GO TO 410
PLST=PT(ISTEP)+1
TLAST=TEFF
TLAST2=TEFF
TEFFL=TLAST*EXP(-O/T/TAU72)+T2 = (1.0-EXP(-O/T/TAU72))
TEFF2=TLAST2*EXP(-O/T/TAU71)+TWALL = (1.0-EXP(-O/T/TAU71))
TEFF=TEFFL*BT*TEFF2*AT
GO TO 420
410 TEMPL=GMG(9+ISTEP)
420 PT(ISTEP)=PLST*EXP(-P*GTT)+(1.0-EXP(-P*GTT))*(PA*TEFF
L=7.0-PK+3.95)
7000 IF (PT(ISTEP).LT.0.01) PT(ISTEP)=.02
RETURN
SUBROUTINE VELACT(PTEX, V2, YMAX, Y9, P6, HY5, ISTEP)
FLUX=U*AREA*(TCUT-TZ)
RETURN
END

SUBROUTINE VALACT(PTEX, V2, YMAX, Y9, P6, HY5, ISTEP)
DIMENSION P6(100), Y9(100), PTEX(100), V2(100)
IF (ISTEP.GT.1) GC TO 750
P5S=HY5
DP=2.0*HY5/1.23
GU TO 710
750 IF (P5S.EQ.(-HY5).AND.P6(ISTEP).LE.PTEMP) GC TO 71C
751 IF (P5S.EQ.(-HY5).AND.P6(ISTEP).GT.PTEMP) GC TO 71C
752 LT=(PTEMP+DP) GC TO 79D
753 IF (P5S.EQ.(-HY5).AND.P6(ISTEP).ST.PTEMP.AND.P6(ISTEP). LT=(PTEMP+DP) GC TO 79D
754 IF (P5S.EQ.(-HY5).AND.P6(ISTEP).LT.PTEMP.AND.P6(ISTEP). LT=(PTEMP+DP) GC TO 79D
755 IF (P5S.EQ.(-HY5).AND.P6(ISTEP).LT.PTEMP.AND.P6(ISTEP). LT=(PTEMP+DP) GC TO 77D
756 700 P5S=HY5
757 GC TO 710
770 P5S=HY5
710 Y9(ISTEP) = -1.23*P6(ISTEP)+5.11*PHYS
715 PTEMP=P6(ISTEP)
720 GC TO 71B
725 Y9(ISTEP)=Y9(ISTEP-1)
730 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
6 8 6
0.0835 531.8
0.3253 238.5
0.68862579031278513-06
-0.3099037992006830-05
0.58242557749545450-05
-0.43171982690859590-05
0.14609431155800440-04
0.21900144757469700-04
0.16177128713489330-04
0.40063661916006720-05
0.38111924418514570-06
0.1235074241526570-07
0.44624680440711750 00
-0.33404945477336540 01
0.53762235326070640 01
-0.4549180642140010 01
0.21839565155370930 01
-0.50316271165134000 00
0.94098750981777220-01
-0.7966020521250240-02
<table>
<thead>
<tr>
<th>Value</th>
<th>0.3180740957264838D-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.6537668806316788D-07</td>
</tr>
<tr>
<td>Value</td>
<td>0.1000000000000000D 01</td>
</tr>
<tr>
<td>Value</td>
<td>-0.2129753138219186D 01</td>
</tr>
<tr>
<td>Value</td>
<td>0.1538638158169764D 01</td>
</tr>
<tr>
<td>Value</td>
<td>-0.4380928551208221D 00</td>
</tr>
<tr>
<td>Value</td>
<td>0.4438956503173424D-01</td>
</tr>
<tr>
<td>Value</td>
<td>-0.1201533462399290D-02</td>
</tr>
<tr>
<td>Value</td>
<td>0.5820901523714435D-05</td>
</tr>
<tr>
<td>Value</td>
<td>-0.32765102678281d60-03</td>
</tr>
</tbody>
</table>

2126.6

<table>
<thead>
<tr>
<th>Value</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1</td>
</tr>
<tr>
<td>Value</td>
<td>1</td>
</tr>
<tr>
<td>Value</td>
<td>100.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.3</td>
</tr>
<tr>
<td>Value</td>
<td>0.24</td>
</tr>
<tr>
<td>Value</td>
<td>0.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.05</td>
</tr>
<tr>
<td>Value</td>
<td>1.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.640</td>
</tr>
<tr>
<td>Value</td>
<td>31.3</td>
</tr>
<tr>
<td>Value</td>
<td>0.73</td>
</tr>
<tr>
<td>Value</td>
<td>2.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.6</td>
</tr>
<tr>
<td>Value</td>
<td>206.</td>
</tr>
<tr>
<td>Value</td>
<td>1060.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.5</td>
</tr>
<tr>
<td>Value</td>
<td>0.6</td>
</tr>
<tr>
<td>Value</td>
<td>0.6</td>
</tr>
<tr>
<td>Value</td>
<td>0.0</td>
</tr>
<tr>
<td>Value</td>
<td>0.2</td>
</tr>
<tr>
<td>Value</td>
<td>427.5</td>
</tr>
<tr>
<td>Value</td>
<td>2.0</td>
</tr>
<tr>
<td>Value</td>
<td>3.45</td>
</tr>
<tr>
<td>Value</td>
<td>74.5</td>
</tr>
<tr>
<td>Value</td>
<td>0.571</td>
</tr>
<tr>
<td>Value</td>
<td>0.260</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>0.725</td>
<td>0.275</td>
</tr>
<tr>
<td>0.3</td>
<td>0.115</td>
</tr>
<tr>
<td>0.4</td>
<td>0.788</td>
</tr>
<tr>
<td>0.6</td>
<td>0.79</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7925</td>
</tr>
<tr>
<td>1.0</td>
<td>0.795</td>
</tr>
<tr>
<td>1.2</td>
<td>0.83</td>
</tr>
<tr>
<td>1.4</td>
<td>0.81</td>
</tr>
<tr>
<td>1.6</td>
<td>0.821</td>
</tr>
<tr>
<td>1.8</td>
<td>0.83</td>
</tr>
<tr>
<td>2.0</td>
<td>0.84</td>
</tr>
<tr>
<td>52.0</td>
<td>775.5</td>
</tr>
<tr>
<td>ENTRY</td>
<td>16</td>
</tr>
<tr>
<td>-------</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>16.49</td>
</tr>
<tr>
<td>2</td>
<td>17.08</td>
</tr>
<tr>
<td>4</td>
<td>16.15</td>
</tr>
<tr>
<td>5</td>
<td>16.46</td>
</tr>
<tr>
<td>6</td>
<td>16.15</td>
</tr>
<tr>
<td>7</td>
<td>15.86</td>
</tr>
<tr>
<td>8</td>
<td>15.57</td>
</tr>
<tr>
<td>9</td>
<td>15.28</td>
</tr>
<tr>
<td>10</td>
<td>15.02</td>
</tr>
<tr>
<td>18</td>
<td>12.87</td>
</tr>
<tr>
<td>19</td>
<td>12.63</td>
</tr>
<tr>
<td>T1</td>
<td>T1*</td>
</tr>
<tr>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>78.40</td>
</tr>
<tr>
<td>2</td>
<td>80.40</td>
</tr>
<tr>
<td>3</td>
<td>90.26</td>
</tr>
<tr>
<td>4</td>
<td>79.14</td>
</tr>
<tr>
<td>5</td>
<td>79.60</td>
</tr>
<tr>
<td>6</td>
<td>74.35</td>
</tr>
<tr>
<td>7</td>
<td>79.10</td>
</tr>
<tr>
<td>8</td>
<td>90.40</td>
</tr>
<tr>
<td>9</td>
<td>78.54</td>
</tr>
<tr>
<td>10</td>
<td>79.23</td>
</tr>
<tr>
<td>11</td>
<td>79.00</td>
</tr>
<tr>
<td>12</td>
<td>77.40</td>
</tr>
<tr>
<td>13</td>
<td>77.33</td>
</tr>
<tr>
<td>14</td>
<td>77.01</td>
</tr>
<tr>
<td>15</td>
<td>76.85</td>
</tr>
<tr>
<td>16</td>
<td>76.61</td>
</tr>
<tr>
<td>17</td>
<td>76.45</td>
</tr>
<tr>
<td>18</td>
<td>76.15</td>
</tr>
<tr>
<td>19</td>
<td>75.94</td>
</tr>
<tr>
<td>20</td>
<td>75.71</td>
</tr>
<tr>
<td>21</td>
<td>75.59</td>
</tr>
<tr>
<td>22</td>
<td>74.58</td>
</tr>
<tr>
<td>23</td>
<td>72.85</td>
</tr>
<tr>
<td>24</td>
<td>74.56</td>
</tr>
<tr>
<td>25</td>
<td>119.79</td>
</tr>
<tr>
<td>26</td>
<td>116.16</td>
</tr>
<tr>
<td>27</td>
<td>116.84</td>
</tr>
<tr>
<td>28</td>
<td>116.40</td>
</tr>
<tr>
<td>29</td>
<td>113.73</td>
</tr>
<tr>
<td>30</td>
<td>113.53</td>
</tr>
<tr>
<td>31</td>
<td>119.92</td>
</tr>
<tr>
<td>32</td>
<td>119.60</td>
</tr>
<tr>
<td>33</td>
<td>119.56</td>
</tr>
<tr>
<td>34</td>
<td>119.56</td>
</tr>
<tr>
<td>35</td>
<td>119.40</td>
</tr>
<tr>
<td>36</td>
<td>119.30</td>
</tr>
<tr>
<td>37</td>
<td>119.21</td>
</tr>
<tr>
<td>38</td>
<td>119.14</td>
</tr>
<tr>
<td>39</td>
<td>118.98</td>
</tr>
<tr>
<td>40</td>
<td>119.78</td>
</tr>
<tr>
<td>41</td>
<td>119.72</td>
</tr>
<tr>
<td>42</td>
<td>119.76</td>
</tr>
<tr>
<td>43</td>
<td>119.87</td>
</tr>
<tr>
<td>44</td>
<td>119.46</td>
</tr>
<tr>
<td>45</td>
<td>119.95</td>
</tr>
<tr>
<td>46</td>
<td>119.12</td>
</tr>
<tr>
<td>47</td>
<td>118.96</td>
</tr>
<tr>
<td>48</td>
<td>118.72</td>
</tr>
<tr>
<td>49</td>
<td>118.05</td>
</tr>
<tr>
<td>50</td>
<td>118.05</td>
</tr>
<tr>
<td>51</td>
<td>119.21</td>
</tr>
<tr>
<td>52</td>
<td>119.13</td>
</tr>
<tr>
<td>53</td>
<td>119.11</td>
</tr>
<tr>
<td>54</td>
<td>118.81</td>
</tr>
<tr>
<td>55</td>
<td>119.01</td>
</tr>
<tr>
<td>56</td>
<td>118.70</td>
</tr>
<tr>
<td>57</td>
<td>119.11</td>
</tr>
<tr>
<td>28</td>
<td>109.10</td>
</tr>
<tr>
<td>----</td>
<td>--------</td>
</tr>
<tr>
<td>59</td>
<td>109.01</td>
</tr>
<tr>
<td>60</td>
<td>108.96</td>
</tr>
<tr>
<td>61</td>
<td>108.93</td>
</tr>
<tr>
<td>62</td>
<td>108.91</td>
</tr>
<tr>
<td>63</td>
<td>109.10</td>
</tr>
<tr>
<td>64</td>
<td>109.02</td>
</tr>
<tr>
<td>VIR</td>
<td>VIR*</td>
</tr>
<tr>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
</tr>
<tr>
<td>11</td>
<td>0.00</td>
</tr>
<tr>
<td>12</td>
<td>0.00</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>0.00</td>
</tr>
<tr>
<td>18</td>
<td>0.00</td>
</tr>
<tr>
<td>19</td>
<td>0.00</td>
</tr>
<tr>
<td>20</td>
<td>0.00</td>
</tr>
<tr>
<td>21</td>
<td>0.34</td>
</tr>
<tr>
<td>22</td>
<td>0.34</td>
</tr>
<tr>
<td>23</td>
<td>0.33</td>
</tr>
<tr>
<td>24</td>
<td>0.47</td>
</tr>
<tr>
<td>25</td>
<td>0.60</td>
</tr>
<tr>
<td>26</td>
<td>0.71</td>
</tr>
<tr>
<td>27</td>
<td>0.79</td>
</tr>
<tr>
<td>28</td>
<td>0.86</td>
</tr>
<tr>
<td>29</td>
<td>0.90</td>
</tr>
<tr>
<td>30</td>
<td>0.93</td>
</tr>
<tr>
<td>31</td>
<td>0.94</td>
</tr>
<tr>
<td>32</td>
<td>0.96</td>
</tr>
<tr>
<td>33</td>
<td>0.97</td>
</tr>
<tr>
<td>34</td>
<td>0.97</td>
</tr>
<tr>
<td>35</td>
<td>0.97</td>
</tr>
<tr>
<td>36</td>
<td>0.97</td>
</tr>
<tr>
<td>37</td>
<td>0.97</td>
</tr>
<tr>
<td>38</td>
<td>0.97</td>
</tr>
<tr>
<td>39</td>
<td>0.97</td>
</tr>
<tr>
<td>40</td>
<td>0.97</td>
</tr>
<tr>
<td>41</td>
<td>0.97</td>
</tr>
<tr>
<td>42</td>
<td>0.97</td>
</tr>
<tr>
<td>43</td>
<td>0.97</td>
</tr>
<tr>
<td>44</td>
<td>0.97</td>
</tr>
<tr>
<td>45</td>
<td>0.97</td>
</tr>
<tr>
<td>46</td>
<td>0.97</td>
</tr>
<tr>
<td>47</td>
<td>0.97</td>
</tr>
<tr>
<td>48</td>
<td>0.97</td>
</tr>
<tr>
<td>49</td>
<td>0.97</td>
</tr>
<tr>
<td>50</td>
<td>0.97</td>
</tr>
<tr>
<td>51</td>
<td>0.96</td>
</tr>
<tr>
<td>52</td>
<td>0.96</td>
</tr>
<tr>
<td>53</td>
<td>0.96</td>
</tr>
<tr>
<td>54</td>
<td>0.96</td>
</tr>
<tr>
<td>55</td>
<td>0.96</td>
</tr>
<tr>
<td>56</td>
<td>0.94</td>
</tr>
<tr>
<td>57</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>50</td>
<td>0.94</td>
</tr>
<tr>
<td>59</td>
<td>0.94</td>
</tr>
<tr>
<td>60</td>
<td>0.94</td>
</tr>
<tr>
<td>61</td>
<td>0.94</td>
</tr>
<tr>
<td>62</td>
<td>0.94</td>
</tr>
<tr>
<td>63</td>
<td>0.94</td>
</tr>
<tr>
<td>64</td>
<td>0.94</td>
</tr>
</tbody>
</table>
APPENDIX B

DATA OF TESTS 162
DATA OF TEST 1

V1  VALVE TRAVEL IN VOLTS
V2  PRESSURE OUTPUT FROM THERMOSTAT IN VOLTS
V3  PRESSURE DROP ACROSS THE ORIFICE IN VOLTS

T1  ALAS TEMPERATURES AT VARIOUS LOCATIONS IN THE SYSTEM
ALL TEMPERATURES ARE PRINTED IN DEGREES FAHRENHEIT SCALE
T1  RETURN AIR
T2  NORTH AIR SPACE
T3  WEST AIR SPACE
T4  SOUTH AIR SPACE
T5  EAST AIR SPACE
T6  VENTILATION AIR
T7  RECOM DOWSTAIRS
T8  PLENUM
T9  NORTH DIFFUSER
T10 SOUTH DIFFUSER
T11 INLET OF FAN
T12 AIR ENTERING COIL
T13 AIR LEAVING COIL
T14 WATER ENTERING COIL
T15 WATER LEAVING COIL
T16 NORTH WALL
T17 WEST WALL
T18 SOUTH WALL
T19 EAST WALL
T20 FLOOR
T21 ROOM AVERAGE
T22 THERMOSTAT EFFECTIVE
T23 OUTLET OF FAN

STOP
ENTRY
<table>
<thead>
<tr>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>4.04</td>
</tr>
<tr>
<td>2</td>
<td>5.20</td>
<td>4.20</td>
</tr>
<tr>
<td>3</td>
<td>5.20</td>
<td>4.12</td>
</tr>
<tr>
<td>4</td>
<td>4.98</td>
<td>4.16</td>
</tr>
<tr>
<td>5</td>
<td>4.99</td>
<td>4.34</td>
</tr>
<tr>
<td>6</td>
<td>4.99</td>
<td>4.34</td>
</tr>
<tr>
<td>7</td>
<td>4.99</td>
<td>4.34</td>
</tr>
<tr>
<td>8</td>
<td>4.99</td>
<td>4.34</td>
</tr>
<tr>
<td>9</td>
<td>4.99</td>
<td>4.34</td>
</tr>
<tr>
<td>10</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>11</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>12</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>13</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>14</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>15</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>16</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>17</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>18</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>19</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>20</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>21</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>22</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>23</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>24</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>25</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>26</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>27</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>28</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>29</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>30</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>31</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>32</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>33</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>34</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>35</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>36</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>37</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>38</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>39</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>40</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>41</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>42</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>43</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>44</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>45</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>46</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>47</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>48</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>49</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>50</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>51</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>52</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>53</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>54</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>55</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>56</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>57</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>58</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>59</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>60</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>61</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>62</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>63</td>
<td>4.99</td>
<td>3.76</td>
</tr>
<tr>
<td>64</td>
<td>4.99</td>
<td>3.76</td>
</tr>
</tbody>
</table>
DATA OF TEST 1

V1  PRESSURE DROP ACROSS THE ORIFICE IN VOLTS
V2  VALVE TRAVEL IN VOLTS
V3  PRESSURE OUTPUT FROM THERMOSTAT IN VOLTS

TMG1, TMG2 ARE TEMPERATURES AT VARIOUS LOCATIONS IN THE SYSTEM.
ALL TEMPERATURES ARE PRINTED IN FAHRENHEIT SCALE.

TM1  RETURN AIR
TM2  NORTH AIR SPACE
TM3  WEST AIR SPACE
TM4  SOUTH AIR SPACE
TM5  EAST AIR SPACE
TM6  VENTILATION AIR
TM7  ROOM 20STAIRS
TM8  PLENUM
TM9  NORTH DIFFUSER
TM10  SOUTH DIFFUSER
TM11  INLET OF FAN
TM12  AIR ENTERING COIL
GM1  AIR LEAVING COIL
GM2  WATER ENTERING COIL
GM3  WATER LEAVING COIL
GM4  NORTH WALL
GM5  WEST WALL
GM6  SOUTH WALL
GM7  EAST WALL
GM8  PLCCR
GM9  ROOM AVERAGE
GM10 THERMOSTAT EFFECTIVE
GM11 OUTLET OF FAN

ENTRY
<table>
<thead>
<tr>
<th></th>
<th>v1</th>
<th>v2</th>
<th>v3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.46</td>
<td>13.20</td>
<td>-0.27</td>
</tr>
<tr>
<td>2</td>
<td>4.46</td>
<td>12.20</td>
<td>-0.42</td>
</tr>
<tr>
<td>3</td>
<td>4.39</td>
<td>11.80</td>
<td>-0.52</td>
</tr>
<tr>
<td>4</td>
<td>4.55</td>
<td>9.42</td>
<td>-0.66</td>
</tr>
<tr>
<td>5</td>
<td>3.23</td>
<td>7.53</td>
<td>1.66</td>
</tr>
<tr>
<td>6</td>
<td>2.33</td>
<td>6.43</td>
<td>7.34</td>
</tr>
<tr>
<td>7</td>
<td>1.39</td>
<td>5.32</td>
<td>13.19</td>
</tr>
<tr>
<td>8</td>
<td>1.36</td>
<td>4.34</td>
<td>14.71</td>
</tr>
<tr>
<td>9</td>
<td>2.42</td>
<td>3.74</td>
<td>16.70</td>
</tr>
<tr>
<td>10</td>
<td>3.74</td>
<td>3.27</td>
<td>15.30</td>
</tr>
<tr>
<td>11</td>
<td>0.20</td>
<td>2.21</td>
<td>14.70</td>
</tr>
<tr>
<td>12</td>
<td>0.30</td>
<td>1.72</td>
<td>16.70</td>
</tr>
<tr>
<td>13</td>
<td>3.00</td>
<td>1.42</td>
<td>16.70</td>
</tr>
<tr>
<td>14</td>
<td>4.20</td>
<td>3.49</td>
<td>16.31</td>
</tr>
<tr>
<td>15</td>
<td>3.40</td>
<td>4.28</td>
<td>17.05</td>
</tr>
<tr>
<td>16</td>
<td>1.33</td>
<td>2.17</td>
<td>17.55</td>
</tr>
<tr>
<td>17</td>
<td>3.00</td>
<td>1.13</td>
<td>17.83</td>
</tr>
<tr>
<td>18</td>
<td>1.33</td>
<td>1.13</td>
<td>17.92</td>
</tr>
<tr>
<td>19</td>
<td>0.20</td>
<td>0.12</td>
<td>17.87</td>
</tr>
<tr>
<td>20</td>
<td>0.30</td>
<td>0.12</td>
<td>17.85</td>
</tr>
<tr>
<td>21</td>
<td>0.20</td>
<td>0.12</td>
<td>17.83</td>
</tr>
<tr>
<td>22</td>
<td>0.20</td>
<td>0.12</td>
<td>17.82</td>
</tr>
<tr>
<td>23</td>
<td>0.00</td>
<td>0.12</td>
<td>17.73</td>
</tr>
<tr>
<td>24</td>
<td>0.00</td>
<td>0.11</td>
<td>17.74</td>
</tr>
<tr>
<td>25</td>
<td>0.00</td>
<td>0.11</td>
<td>17.72</td>
</tr>
<tr>
<td>26</td>
<td>0.00</td>
<td>0.11</td>
<td>17.71</td>
</tr>
<tr>
<td>27</td>
<td>0.00</td>
<td>0.11</td>
<td>17.69</td>
</tr>
<tr>
<td>28</td>
<td>0.00</td>
<td>0.11</td>
<td>17.60</td>
</tr>
<tr>
<td>29</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>30</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>31</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>32</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>33</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>34</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>35</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>36</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>37</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>38</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>39</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>40</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>41</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>42</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>43</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>44</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>45</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>46</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>47</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>48</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>49</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>50</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
<tr>
<td>51</td>
<td>0.00</td>
<td>0.11</td>
<td>17.50</td>
</tr>
</tbody>
</table>
APPENDIX C

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

A linear relation between return, room, wall, and supply air

\[ TR(k) = A_2 \cdot TS(k) + B_2 \cdot TRM(k) + C_2 \cdot TW(k), \quad k=1,2,...N \]

and \( A_2, B_2, \) and \( C_2 \) were evaluated by the method of least squares as follows:

\[ J = \sum_{k=1}^{N} \left( TR_{\text{exp}} - TR_{\text{model}} \right)^2 \]  \hspace{1cm} (C-1)

For best fit \( \frac{\partial J}{\partial A_2} = 0, \frac{\partial J}{\partial B_2} = 0, \) and \( \frac{\partial J}{\partial C_2} = 0. \) Applying these conditions

yields:

\[ A_2 \sum_{k=1}^{N} TS \cdot TS + B_2 \sum_{k=1}^{N} TRM \cdot TS + C_2 \sum_{k=1}^{N} TW \cdot TS = \sum_{k=1}^{N} TS \cdot TR \]  \hspace{1cm} (C-2)

\[ A_2 \sum_{k=1}^{N} TS \cdot TRM + B_2 \sum_{k=1}^{N} TRM \cdot TRM + C_2 \sum_{k=1}^{N} TW \cdot TRM = \sum_{k=1}^{N} TR \cdot TRM \]  \hspace{1cm} (C-3)

\[ A_2 \sum_{k=1}^{N} TS \cdot TW + B_2 \sum_{k=1}^{N} TRM \cdot TW + C_2 \sum_{k=1}^{N} TW \cdot TW = \sum_{k=1}^{N} TR \cdot TW \]  \hspace{1cm} (C-4)

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

\[ A_2 = 0.0041388273 \]
\[ B_2 = 0.10132271 \]
\[ C_2 = 0.38259590 \]

In order for the model to satisfy the steady state condition where all the

\[ A_2 + B_2 + C_2 = 1. \]  \hspace{1cm} (C-5)

The constants \( A_2, B_2 \) and \( C_2 \) do satisfy this condition.
APPENDIX D

OPTIMIZATION OF THE PARAMETERS OF THE THERMOSTAT

The model of the thermostat is of the form

\[ \text{TEFF} = \frac{A \cdot a \cdot \text{TRM}}{(s+a)} + \frac{(1-A) \cdot b \cdot \text{TW}}{(s+b)} \]  

\[ (P7-\text{PSET}) = \frac{K \cdot c}{(s+c)} \cdot (\text{TEFF} - \text{TSET}) \]  

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

\[ X1 = \frac{a \cdot \text{TRM}}{(s+a)} \]  

and

\[ X2 = \frac{b \cdot \text{TW}}{(s+b)} \]  

\[ \text{TEFF} = A \cdot X1 + (1-A) \cdot X2 \]  

Equation D-3 may be written

\[ \dot{X1} = -a \cdot X1 + a \cdot \text{TRM} \]  

\[ \dot{X2} = -b \cdot X2 + b \cdot \text{TRM} \]  

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

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

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

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

\[ X1(0) = \text{TRM}(0) \]  

\[ X2(0) = \text{TW}(0) \]  

Defining the performance index J
\[ J(A, a, b) = \frac{1}{2} \sum_{k=1}^{N} (T_{em} - T_{ex})^2 \]  

(D-9)

where

\[ T_{em} = \text{TEFF model} \]
\[ T_{ex} = \text{TEFF experimental} \]

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

\[ \frac{\partial J}{\partial A} (A, a, b) = \sum_{k=1}^{N} (T_{em} - T_{ex}) \cdot (X_1 - X_2) \]
\[ = \sum_{k=1}^{N} (A \cdot (X_1 - X_2) + X_2 - T_{ex}) \cdot (X_1 - X_2) \]  

(D-10)

Let

\[ F_A (A, a, b) = \frac{\partial J}{\partial A} (A, a, b) = 0 \]
\[ F_a (A, a, b) = \frac{\partial J}{\partial a} (A, a, b) = 0 \]  

(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

\[ A_{\text{new}} = - \sum_{k=1}^{N} (X_2 - T_{ex}) \cdot (X_1 - X_2) / \sum_{k=1}^{N} (X_1 - X_2)^2 \]  

(D-12)

then

\[ \delta A = A_{\text{new}} - A \]  

(D-13)

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

\[ 0 = F_a + \frac{\partial F}{\partial A} \delta A + \frac{\partial F}{\partial a} \delta a + \frac{\partial F}{\partial b} \delta b \]  

(D-14)
\[ 0 = F_a + \frac{3F_b}{3a} \cdot \delta a + \frac{3F_b}{3a} \cdot \delta a + \frac{3F_b}{3b} \cdot \delta b \]  
(D-15)

These two equations are to be solved for \( \delta a \) and \( \delta b \).

Let
\[ F_a = \frac{3J}{3a} = \sum_{k=1}^{N} (A \cdot (X_l - X_2) + X_2 - T_{ex}) \cdot A \cdot V1 \]  
(D-16)

and
\[ F_b = \frac{3J}{3b} = \sum_{k=1}^{N} (A \cdot (X_l - X_2) + X_2 - T_{ex}) \cdot (1-A) \cdot V2 \]  
(D-17)

where
\[ V1 = \frac{3X_1}{3a} \quad \text{and} \quad V2 = \frac{3X_2}{3b} \]  
(D-18)

Then let
\[ G_a = \frac{3F_a}{3a} = \sum_{k=1}^{N} (T_{em} - T_{ex}) \cdot U1 + A \cdot V1^2 \]  
(D-19)

\[ G_b = \frac{3F_b}{3b} = \sum_{k=1}^{N} (T_{em} - T_{ex}) \cdot U2 + (1-A) \cdot V2^2 \]  
(D-20)

and
\[ G_{ab} = \frac{3F_{ab}}{3b} = \sum_{k=1}^{N} A \cdot (1-A) \cdot V1 \cdot V2 \]  
(D-21)

where
\[ U1 = \frac{3V1}{3a} \quad \text{and} \quad U2 = \frac{3V2}{3b} \]  
(D-22)

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

\[ X_l(k+1) = X_l(k) \cdot e^{-a \cdot T} + TRM(k) \cdot (1-e^{-a \cdot T}) \]  
(D-23)

and
\[ X_2(k+1) = X_2(k) \cdot e^{-b \cdot T} + TW(k) \cdot (1-e^{-b \cdot T}) \]

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

\[ V1(k+1) = V1(k) \cdot e^{-a \cdot T} - T \cdot (X_l(k) - TRM(k)) \cdot e^{-a \cdot T} \]  
(D-24)

and
\[ V2(k+1) = V2(k) \cdot e^{-b \cdot T} - T \cdot (X_2(k) - TW(k)) \cdot e^{-b \cdot T} \]

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} \\

\text{and} \hspace{2cm} \text{E-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

\begin{align*}
X1(0) &= TRM(0), \quad V1(0) = 0, \quad U1(0) = 0 \\
X2(0) &= TW(0), \quad V2(0) = 0, \quad U2(0) = 0
\end{align*} \hspace{2cm} \text{E-26}

From Equations D-16 and D-17 define

\begin{align*}
G_{aA} &= \sum_{k=1}^{N} (2 \cdot A \cdot (X1-X2) + X2 - T_{ex}) \cdot V1 \\
\text{E-27}

G_{bA} &= \frac{\partial F}{\partial A} = \sum_{k=1}^{N} -((2 \cdot A - 1) \cdot (X1-X2) + (X2 - T_{ex})) \cdot V2 \\
\text{E-29}

\text{From Equations D-14 and D-15} \ \delta a \text{ and } \delta b \text{ may be found}

\begin{align*}
\delta a &= ((G_{ab} \cdot F_a + G_{b} \cdot F_a) + (G_{ab} \cdot G_{b} \cdot C_{aa} - G_{b} \cdot C_{ab}) \cdot \delta A) / (G_{a} \cdot G_{b} - G_{ab}^2) \\
\text{E-29}

\delta b &= - (F_{b} + G_{bA} \cdot \delta A + C_{ab} \cdot \delta a) / G_{b}.
\end{align*}

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. \delta A is found by Equation D-13. \delta a and \delta b are found from Equation D-29. New values of A, a, and b are found from the old values by

\begin{align*}
A_{\text{new}} &= A_{\text{old}} + \delta A \\
\text{E-30}

a_{\text{new}} &= a_{\text{old}} + \delta a
\end{align*}

and

\begin{align*}
b_{\text{new}} &= b_{\text{old}} + \delta b
\end{align*}

Using the new parameter values, the procedure is repeated. The
iteration continues until the values of $\delta A$, $\delta a$, and $\delta b$ are all sufficiently small. This procedure 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 $TSET = 74.5^\circ F$ 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

NAGAMANGALA KRISHNAMURTHY ANAND
B. E., Bangalore University, India, 1978

AN ABSTRACT OF 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
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.