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Dynamic Characteristics of Fluid Temperature

Between Inlet and Outlet of a Room*

(1st Report, The Case of Two-Dimensional Room)

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As the 1st report on the dynamic characteristics of fluid temperature between inlet and outlet of a room, a two-dimensional room with various relative positions of inlet and outlet is treated. First, a mathematical model describing the characteristics of fluid flow in the room is determined experimentally in as simple a form as possible. Next, when the heat transfer into the wall is theoretically added to the above flow model, a mathematical model describing the dynamic characteristics of fluid temperature is obtained. The mathematical model is examined and discussed by experiments. The main results are as follows. The flow model explains well the phenomenon of fluid flow in the room, and parameters in the flow model agree almost with the values estimated by observations of flow patterns. Moreover, the theoretical results of fluid temperature agree well with the experimental ones.

1. Introduction

Recently, the air conditioning has spread rapidly in the forms of heating, cooling, ventilating etc. through the development of its techniques. In order to perform automatic control in the air conditioning system, it is necessary to know the dynamic characteristics of the main components which are the boiler, refrigerator, various kinds of heat exchangers, duct, and room.

The dynamic characteristics of fluid temperature in a duct has been already studied⁽¹⁾. Following this, the dynamic characteristics of fluid temperature between inlet and outlet of a room will be investigated. When an automatic control of fluid temperature in a room is carried out, the fluid temperature at the outlet of the room is often used being regarded as a mean value of fluid temperature in the room, though there is a case where the fluid temperature at a representative point in the room is used. On such a case, there is no systematic research concerning the dynamic characteristics of fluid temperature for various relative positions of inlet and outlet of a room. By use of a model room satisfying the analogy of thermo-fluidic dynamics for an actual room, the dynamic characteristics of fluid tempera-

ture has been discussed in the form of step response by P. Hemmi⁽²⁾.

The object of this paper is to make a fundamental investigation into the dynamic characteristics of fluid temperature in a room. As the 1st report, the dynamic characteristics of fluid temperature is examined for a two-dimensional model room which is laid flat in order to remove the effect of buoyancy and to obtain the mathematical model easily. First, the experiments which determine the characteristics of fluid flow are carried out in detail for a model room having the typical relative positions of inlet and outlet, and it is tried to obtain as simple a mathematical model of fluid flow as possible. Next, by considering the heat transfer into the wall upon the model describing the characteristics of fluid flow (hereafter it is called the flow model), a mathematical model of the dynamic characteristics of fluid temperature between inlet and outlet of the room (hereafter it is called the temperature model) is determined. By use of the temperature model, the dynamic characteristics of fluid temperature is derived in the form of frequency characteristics. On the other hand, the frequency characteristics of fluid temperature is determined experimentally by the pulse response method, and is compared with the above theoretical result.

2. Nomenclature

Main notations used in this paper are listed below.

$a = \lambda_w / (c_w \gamma_w)$: temperature conductivity m^2/h
 A : cross-sectional area m^2
 $c_i, c_i(s)$: density in each representative point and its Laplace transform

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mation, respectively
 $c_g, c_w(s)$: specific heats of air and wall, respectively $\text{kcal/kg}^0\text{C}$
 F : surface area of the inside of room m^2
 F_L, F_r : surface areas of piston flow part and perfect mixing flow part, respectively m^2
 $G(s)$: transfer function
 l : length of fluid flow passage m
 L : dead time s
 q, q_1, q_2 : fluid flow rate, supplied flow rate, and circulating flow rate, respectively m^3/h
 $r=q_2/q_1$
 s : operator of Laplace transformation as to t
 t : time s
 T : time constant s
 v_0 : mean velocity of air in the surroundings of room m/s
 V : volume m^3
 α_i, α_0 : heat transfer rates at the inside and outside of wall, respectively $\text{kcal/m}^2\text{h}^0\text{C}$
 γ_g, γ_w : specific weights of air and wall, respectively kg/m^3
 δ_w : thickness of wall m
 λ_w : thermal conductivity of wall $\text{kcal/mh}^0\text{C}$
 θ_1, θ_2 : temperatures of fluid at the inlet and outlet of room, respectively ^0C
 θ_i, θ_0 : temperatures of fluid in room and of air in the surroundings of room, respectively ^0C
 θ_w : temperature of wall ^0C
 θ_{wi}, θ_{wo} : surface temperatures of the inside and outside of wall, respectively ^0C
 $(\cdot)$: value of $(\cdot)$ at the steady state
 $\Delta(\cdot)$: deviation of $(\cdot)$ from the steady state

In the subscripts of $A, F_L, F_r, G(s), l, L, T, v, V, \alpha_i, \theta_i, \theta_{wi}$, the numbers 1, 11, 12 denote the main flow part; 2, 21, 22 the circulating flow part; and 3 the side capacity part.

Fig.1 Various relative positions of inlet and outlet of a room

Figure 1 shows the relationship of relative position of inlet and outlet of the room which is treated in this paper. In this Figure, (1) shows the case where the fluid flows from left upper inlet to right upper outlet, (2) does the case where it flows from left upper inlet to right lower outlet, (3) does the case where it flows from left upper inlet to left lower outlet, and (4) does the case where it flows from upper central inlet to right lower outlet. The room, whose breadth and height are the

same as those of a three-dimensional model room but whose length is reduced to the width of the inlet or outlet, is called the two-dimensional model room hereafter.

3. Dynamic characteristics of fluid temperature

In the room with various relative positions of inlet and outlet, as shown in Fig.1, the mathematical model of fluid temperature between inlet and outlet will be determined. As physical phenomena taking part in the dynamic characteristics, heat convection in the room and heat transfer into the wall must be considered. Since the former can be identified as the phenomenon of fluid flow in a room, a mathematical model describing the phenomenon of fluid flow in a room is first discussed.

3.1 The flow model

As a physical quantity representing the phenomenon of fluid flow in a room, the density of material (CO_2 gas in the experiments) mixed into the room is taken. The mathematical model describing the dynamic characteristics of density of the mixed material between inlet and outlet is made by considering the phenomenon of fluid flow macroscopically.

In order to simplify the formation of the flow model, the following assumptions are made.

- (1) Since the mixed material in the room is a very small amount, the characteristics of fluid flow is linear and can be described by transfer function.
- (2) The condition of fluid flow in the room is steady and is not accompanied with a chemical reaction.

According to observations of fluid flow which is done by using chinese ink mixed in air of the model room, it is confirmed that patterns of fluid flow consist of the three parts, that is, main flow part, circulating flow part, and side capacity part, in the room with various relative positions of inlet and outlet. Therefore, a systematic expression, as shown in Fig.2, becomes possible for the room with various relative positions of inlet and outlet which are illustrated by Fig.1. The symbol M in Fig.2 shows mixing points, and the mixing at M is assumed to be instantaneous.

The mixing processes in the main flow part (V_1) and the circulating flow part (V_2) are expressed by transfer functions $G_1(s)$ and $G_2(s)$, respectively. (V_3) denotes the side capacity part, but is neglected temporarily because of simplification of model. From Fig.2, when the relations of material balance are described in Laplace transformed form,

$$\left. \begin{aligned} (q_1 + q_2)c_4(s) &= q_1c_1(s) + q_2c_3(s) \\ c_2(s) &= G_1(s)c_4(s), \quad c_3(s) = G_2(s)c_2(s) \end{aligned} \right\} \dots\dots\dots (1)$$

are obtained. By eliminating $c_3(s)$ and $c_4(s)$ from the above equations,

$$\frac{c_2(s)}{c_1(s)} = G(s) = \frac{G_1(s)}{1 + r - rG_1(s)G_2(s)} \dots\dots\dots (2)$$

is obtained, where $r=q_2/q_1$.

As the extreme cases of the mixing process, two fluid flows are considered as follows.

(1) Perfect mixing flow in which a macroscopic mixing occurs perfectly:

$$G(s) = 1/(1+Ts) \quad (3)$$

(2) Piston flow in which a macroscopic mixing does not occur at all:

$$G(s) = e^{-Ls} \quad (4)$$

Since actual mixing process is considered to have an intermediate property between (1) and (2), $G_1(s)$ and $G_2(s)$ in Eq. (2) are appropriately given by the following forms.

$$G_1(s) = e^{-L_1s}/(1+T_1s), \quad G_2(s) = e^{-L_2s}/(1+T_2s) \quad (5)$$

By substituting Eq.(5) into Eq.(2), the mathematical model describing the characteristics of fluid flow in the room can be obtained. The content of Eq.(2) is shown by a block diagram of Fig.3. This mathematical model is called the flow model I. The parameters L_1 , T_1 , L_2 , and T_2 mean the residence time of fluid, and hence these are closely related to the values of q_1 , q_2 , V_1 , and V_2 as follows.

$$V_1 = q_1(1+r)(L_1+T_1), \quad V_2 = q_1r(L_2+T_2) \quad (6)$$

A more accurate flow model is considered, as shown in Fig.4, by adding the side capacity part to the flow model given in Fig.2. The transfer function of each side capacity part is assumed to be the same. In general, when N side capacity parts ($N=3$ in Fig.4) are considered, and the relation of material balance is applied for Fig.4, assuming that symbols in Fig.4 are used in the same way as in Fig.2, then the transfer function of density between inlet and outlet of the room becomes

$$\frac{c_2(s)}{c_1(s)} = G(s) = \frac{G_{11}(s)G_{12}(s)\{1+r_2-r_2G_3(s)\}^N}{(1+r_1)\{1+r_2-r_2G_3(s)\}^N - r_1G_{12}(s)G_3(s)} \quad (7)$$

where $r_1=q_2/q_1$, $r_2=q_3/q_2$. Similarly, the mixing processes of each flow part can be approximated by

$$\begin{aligned} G_{11}(s) &= \exp(-L_{11}s), \\ G_{12}(s) &= \exp(-L_{12}s)/(1+T_{12}s), \\ G_2(s) &= G_{21}(s)G_{22}(s)G_{23}(s)G_{24}(s) \\ &= \exp(-L_{2s})/(1+T_{2s}), \\ G_3(s) &= 1/(1+T_3s) \end{aligned}$$

This mathematical model is called the flow model I'.

Next, for the flow pattern of (4) in Fig.1, a model which may express the phenomenon of fluid flow more adequately is given in Fig.5. As before, the transfer function of density between inlet and outlet becomes

$$\frac{c_2(s)}{c_1(s)} = G(s) = \frac{G_1(s)}{\{1+r_1-r_1G_{21}(s)\}\{1+r_2-r_2G_{22}(s)\}} \quad (8)$$

where $r_1=q_{21}/q_1$, $r_2=q_{22}/q_1$. Similarly, the following transfer functions can be assumed for each flow part.

$$\begin{aligned} G_1(s) &= G_{11}(s)G_{12}(s) = \exp(-L_{1s})/(1+T_{1s}), \\ G_{21}(s) &= 1/(1+T_{21s}), \\ G_{22}(s) &= \exp(-L_{22s})/(1+T_{22s}) \end{aligned}$$

The mathematical model described by Eq.(8) is called the flow model II.

3.2 The temperature model

The dynamic characteristics of fluid temperature between inlet and outlet of the room will be determined using the flow model obtained in Section 3.1. The temperature model is determined only for the flow model I, since they can be easily calculated in the same way as for other flow models. By adding heat transfer to the wall to Eq.(2), the temperature model is obtained. The following are assumed.

Fig.2 A systematic description of model for the flow patterns of (1)-(4) in Fig.1

Fig.3 Block diagram of the flow model I

Fig.4 A developed description of the model shown in Fig.2

Fig.5 Another developed description of the model corresponding to (4) in Fig.1

(1) Fluid temperature in each flow part of the room is uniform in the section perpendicular to the direction of stream.

(2) Mean velocity of each flow part is constant. Therefore, the flow rate and the heat capacity of fluid are constant.

(3) Heat conduction of wall is taken into account only in the direction of thickness. Heat insulation of the wall is imperfect. Temperature of air in the surroundings of room is constant.

(4) Thermal conductivity is constant, but heat transfer rate is different in each flow part.

The effects of heat transfer to the wall are first considered for both the perfect mixing flow and the piston flow which are the extreme flows, as was explained when the flow model was determined.

(i) For the case of the perfect mixing flow:

Referring to Fig. 6, the following heat balance equation is obtained.

$$V \rho c_p \frac{d\theta_2(t)}{dt} = q \gamma c_p (\theta_1(t) - \theta_2(t)) - \alpha_i F_T (\theta_2(t) - \theta_{wi}(t)) \quad (9)$$

Now, each variable is taken as a deviation from the steady state as follows.

$$\left. \begin{aligned} \theta_1(t) &= \bar{\theta}_1 + \Delta\theta_1(t), & \theta_2(t) &= \bar{\theta}_2 + \Delta\theta_2(t), \\ \theta_{wi}(t) &= \bar{\theta}_{wi} + \Delta\theta_{wi}(t) \end{aligned} \right\} \quad (10)$$

From the Laplace transformation of Eqs. (9) and (10), the transfer function of fluid temperature between inlet and outlet of the room is given by

$$\frac{\Delta\theta_2(s)}{\Delta\theta_1(s)} = G_T(s) = \frac{1}{1 + Ts + K_{wT}(1 - G_{wi}(s))} \quad (11)$$

where

$$T = V/q, \quad K_{wT} = \alpha_i F_T / (q \gamma c_p),$$

$$G_{wi}(s) = \Delta\theta_{wi}(s) / \Delta\theta_2(s)$$

(ii) For the case of the piston flow:

Referring to Fig. 7, the following heat balance equation is obtained.

$$\begin{aligned} \frac{V}{l} dx \rho c_p \frac{\partial \theta_i(x, t)}{\partial t} &= q \gamma c_p \left[\theta_i(x, t) - \left\{ \theta_i(x, t) + \frac{\partial \theta_i(x, t)}{\partial x} dx \right\} \right] \\ &- \alpha_i [\theta_i(x, t) - \theta_{wi}(x, t)] \frac{F_L}{l} dx \quad (12) \end{aligned}$$

In the same way as in the above case, from both the Laplace transformation as to t of Eq. (12) and the boundary conditions $x=0: \Delta\theta_i(0, s) = \Delta\theta_1(s)$, $x=l: \Delta\theta_i(l, s) = \Delta\theta_2(s)$, the transfer function is given by

$$\frac{\Delta\theta_2(s)}{\Delta\theta_1(s)} = G_L(s) = \exp[-Ls - K_{wL}(1 - G_{wi}(s))] \quad (13)$$

where

$$L = l/v, \quad K_{wL} = \alpha_i F_L / (q \gamma c_p),$$

$$G_{wi}(s) = \Delta\theta_{wi}(s) / \Delta\theta_i(s)$$

$G_{wi}(s)$ in Eqs. (11) and (13) are the transfer functions of temperature between surface of the inside of the wall and fluid in the room. By referring to Fig. 8, and using both the following equation of heat conduction

$$\frac{\partial \theta_w(y, t)}{\partial t} = a \frac{\partial^2 \theta_w(y, t)}{\partial y^2} \quad (14)$$

and the following boundary conditions

$$\left. \begin{aligned} y=0: & \alpha_i (\theta_i(t) - \theta_w(t)) = -\lambda_w [\partial \theta_w(0, t) / \partial y] \\ y=\delta_w: & \alpha_o (\theta_{wo}(t) - \theta_w(t)) = -\lambda_w [\partial \theta_w(\delta_w, t) / \partial y] \end{aligned} \right\} \quad (15)$$

similarly, the transfer function is given by

$$\frac{\Delta\theta_{wi}(s)}{\Delta\theta_i(s)} = G_{wi}(s) = \frac{1}{1 + \sqrt{2T_{ws}} \left(1 - \frac{2(P - \alpha_o)}{(P - \alpha_o) + (P + \alpha_o)R^2} \right)} \quad (16)$$

where

$$P = \lambda_w \sqrt{s/a}, \quad R = \exp(\delta_w \sqrt{s/a}),$$

$$T_w = c_w \lambda_w \gamma_w / (2\alpha_i^2)$$

By substituting Eq. (6) into Eqs. (11) and (13), the transfer functions of fluid temperature including the effect of heat transfer to the wall are determined for the perfect mixing flow and the piston flow, respectively. Since actual fluid flow is considered to have an intermediate property, the transfer function is given by the combined form of Eqs. (11) and (13). Figure 9 shows a block diagram in which the effect of the wall is considered on the flow model I.

Fig. 6 The case of perfect mixing flow

Fig. 7 The case of piston flow

Fig. 8 A sectional view of wall

Thus, the transfer function of fluid temperature between inlet and outlet of the room becomes

$$\frac{\Delta\theta_2(s)}{\Delta\theta_1(s)} = G(s) = \exp[-L_1 s - K_{wL_1}(1 - G_{wi}(s))] \times [1 + T_2 s + K_{wT_2}(1 - G_{wi}(s))] / [(1 + r)[1 + T_1 s]$$

$$\begin{aligned}
& +K_{wT_1}[1-G_{wi}(s)][1+T_2s+K_{wT_2}(1-G_{wi}(s))] \\
& -r \exp[-L_1s-K_{wL_1}(1-G_{wi}(s))] \\
& -L_2s-K_{w2}(1-G_{wi}(s))] \dots\dots\dots (17)
\end{aligned}$$

where

$$\begin{aligned}
K_{wL_1} &= \alpha_{i1} F_{L_1} / [q_1(1+r)\gamma_s c_p], \\
K_{wT_1} &= \alpha_{i1} F_{T_1} / [q_1(1+r)\gamma_s c_p], \\
K_{wL_2} &= \alpha_{i2} F_{L_2} / [q_1 r \gamma_s c_p], \\
K_{wT_2} &= \alpha_{i2} F_{T_2} / [q_1 r \gamma_s c_p]
\end{aligned}$$

$G_{wi1}(s)$ and $G_{wi2}(s)$ are calculated by substituting α_{i1} and α_{i2} , respectively, into α_i of Eq.(16). Moreover, the relations between surface area of each flow part and parameters of the flow model I are established as follows.

$$\begin{aligned}
F_{L_1} &= F_1 L_1 / (L_1 + T_1), & F_{T_1} &= F_1 T_1 / (L_1 + T_1) \\
F_{L_2} &= F_2 L_2 / (L_2 + T_2), & F_{T_2} &= F_2 T_2 / (L_2 + T_2) \\
F &= F_1 + F_2
\end{aligned} \dots\dots\dots (18)$$

Equation (17) is called the temperature model I.

Fig.9 Block diagram of the temperature model where the effect of wall is added to the flow model I in Fig.3

Thus, the mathematical model which gives the dynamic characteristics of fluid temperature between inlet and outlet of the room was obtained. In Eq.(17), ten unknown parameters L_1 , T_1 , L_2 , r , α_{i1} , α_{i2} , α_0 , F_1 , and F_2 are included. Five parameters of them, L_1 , T_1 , L_2 , T_2 , and r are unknown parameters contained in the flow model I. These parameters are determined experimentally by the frequency characteristics of fluid flow, as is stated later. If the flow model is determined, and the lengths of both the main flow part and the circulating flow part are known by observations of smoke etc., then the mean velocity of fluid flow part can be calculated by using Eq.(6) as follows.

$$v_1 = q_1(1+r)/A_1 = l_1/(L_1 + T_1) \dots\dots\dots (19)$$

$$v_2 = q_1 r / A_2 = l_2/(L_2 + T_2) \dots\dots\dots (20)$$

By use of these quantities, the mean heat transfer rate in the surface of the inside of wall may be estimated by using an empirical formula, for example the following Jurges' formula(3)

$$\alpha_i = 6.649 v_0^{0.789} + 5.03 e^{-0.6 v_0} \dots\dots\dots (21)$$

Similarly, the mean heat transfer rate in the surface of the outside of wall may be also given by

$$\alpha_0 = 5.3 + 3.6 v_0 \dots\dots\dots (22)$$

using Jurges' formula(3), where v_0 is the

mean velocity of air in the surroundings of wall. Though the values of α_i and α_0 calculated by Eqs.(21) and (22), respectively, are, exactly speaking, not so accurate, they are used as a temporary standard. In addition, the areas of heat transfers F_1 and F_2 are determined from the flow model by using Eq.(18). Consequently, all parameters of the temperature model are determined, and then the dynamic characteristics of fluid temperature can be obtained.

4. Apparatus and method of experiment

In order to discuss the propriety of the model basically, experiments are carried out using a two-dimensional model room in which the observations of fluid flow are simple. The breadth, the height, and length of the model room are 0.87 m, 0.365 m, and 0.05 m, respectively. The material is acrylic resin, which is 10 mm in thickness. Size of the inlet and outlet is $0.05 \times 0.025 \text{ m}^2$.

In this paper, in order to eliminate both the effect of difference in specific gravity between CO_2 and fluid and the effect of buoyancy, the experiments are carried out laying flat the model room so that its height becomes 0.05 m. In order to lessen the variation of air temperature in the surroundings of the room, the experiments are performed in a constant temperature room. Figures 10 and 11 show the outlines of experimental apparatus which determine the characteristics of fluid flow and fluid temperature, respectively.

Fig.10 Experimental apparatus for obtaining the characteristics of fluid flow

Fig.11 Experimental apparatus for obtaining the characteristics of fluid temperature

In Fig.10, by a blower installed at the outlet of the room, a regular flow rate of 80 l/min is taken for the convenience of the experiments, since the characteristics of fluid flow does not change so much for the flow rate above a constant value. CO_2 is injected from the inlet of the room, in the pulsed form with height of about 3 %. Detectors of CO_2 are installed at the inlet and outlet of the room, and the densities of CO_2 are measured by a 2 pens-recorder. The frequency characteristics are determined by the pulse response method(4).

In Fig.11, the fluid temperature of inlet is changed in the pulsed form by switchover of duct. In order to obtain the characteristics of fluid temperature with a high accuracy over a wide frequency range, three pulse waves which are 12 min, 30 sec, and 6 sec in width and about 60 °C in height are used. In the same way as before, the frequency characteristics is calculated from the pulse response for each wave, and then the frequency response is determined by combining three frequency characteristics. Fluid temperatures of inlet and outlet are measured as the mean value for five and nine Cu-C thermocouples, respectively, which are 0.1 mmφ in diameter, in each section. Since the measured value of experiment is scattered more or less, several measurements are repeated under the same conditions, and the mean value of them is taken as an experimental value.

5. Experimental results and considerations

Table 1 gives the values of parameters in Eq.(2) of the flow model I, which are determined such as to agree with the experimental values of the two-dimensional model room subject to the constraint that (V_1+V_2) determined by Eq.(6) is under the total volume $V=0.0159 \text{ m}^3$.

L_1	1.08	1.84	3.70	1.20
T_1	0.489	0.795	1.39	0.252
L_2	6.50	3.48	0.153	3.27
T_2	9.03	8.17	4.22	7.18
r	0.605	0.648	0.720	0.878

Table 1 The parameters in the flow model I

Figure 12 shows the comparison on Bode diagram between the experimental values and the calculated values of Eq.(2). The calculated value is denoted by solid line. Broken line shows the frequency characteristics of the case where the fluid in the room is mixed perfectly, i.e., that of the first order lag system with the time constant $T=V/q=11.9 \text{ sec}$. Both results calculated by using the flow model I' for (1)-(4) in Fig.1 and the flow model II for (4) in Fig.1 are neglected. Though better agreements between the mathematical models and

Fig.12 Frequency characteristics of fluid flow

the experimental values are obtained by taking account of the side capacity and by using more accurate and complex models, the effectiveness is not so well recognized. As is known from Fig.12, the characteristics of fluid flow can be expressed satisfactorily and equivalently by the flow model I for all the cases of fluid flow shown in Fig.1. (4) in Fig.1 shows an intermediate flow between (1) and (3). As to (1), (2), and (3) which give the representative fluid flows, more detailed considerations of those parameters give the following results.

If the ratio of the length of the main flow is compared for each flow part, then (1):(2):(3)=1:1.43:2.45. The ratio of dead time L_1 is (1):(2):(3)=1:1.72:3.45. The time constant T_1 becomes large in the order of (3), (2), and (1). Therefore, as the main flow is long, the mean velocity becomes small and the fluid flow wider, and the mixing good. Moreover, since the magnitude of $T_2/(L_2+T_2)$ is larger than that of $T_1/(L_1+T_1)$, the circulating flow part is considered to have better mixing than the main flow part. As is estimated in a practical manner, it is known that the response approaching the first order lag system is in the order of (3), (2), and (1).

However, even in the case of (3), the frequency characteristics deviates from that of the first order lag system in the range of high frequencies.

Figure 13 shows an outline of the flow patterns in the cases of (1), (2), (3) in Fig.1, which are obtained from the photograph of flow in the manner that water is instead of air in the two-dimensional model room and chinese ink is injected in it. In this Figure, A is regarded as the main flow part, B as the circulating flow part, and C, D, E as the side capacity parts. The areas of the main flow part and the circulating flow part, in which the side capacity parts are included, are calculated for various flow patterns as shown in Table 2. When those areas are multiplied by the width of the model room, the estimated values of the volumes V_1 and V_2 in Table 3 are determined for the main flow part and the circulating flow part, respectively. On the other hand, the magnitudes of the volume determined by Eq.(6) by use of the

Fig.13 Flow patterns of (1), (2), (3) in Fig.1

Main flow part	A	A+E	A+D+E
	0.070	0.112	0.221
Circulating flow part	B+C+D+E	B+C+D	B+C
	0.248	0.203	0.097

Table 2 Areas of the main flow part and the circulating flow part for various relative positions of inlet and outlet

	$V_1 \text{ m}^3$		$V_2 \text{ m}^3$	
	C.V.	E.V.	C.V.	E.V.
	0.34×10^{-2}	0.35×10^{-2}	1.25×10^{-2}	1.24×10^{-2}
	0.58 "	0.56 "	1.01 "	1.03 "
	1.17 "	1.11 "	0.42 "	0.48 "

Table 3 The calculated values and estimated values of the volume of the main flow part V_1 and volume of the circulating flow part V_2

parameters obtained by the search are given as the calculated values in Table 3. The calculated value agrees almost with the estimated value of the volume occupied by each flow part. The fact shows that the mathematical model approximates well the characteristics of fluid flow.

Next, the experimental results are stated for the dynamic characteristics of fluid temperature. In Figs.14 and 15, the experimental values of the frequency characteristics of fluid temperature between inlet and outlet are denoted by a circle. Subject to the constraint that the magnitude of F is smaller than the surface area of the room, the parameters α_{11} , α_{12} , α_0 , F_1 , and F_2 of the temperature model I are determined such as to agree with the experimental values. Using these parameters,

Fig.14 Frequency characteristics of fluid temperature

Fig.15 Frequency characteristics of fluid temperature

	C.V.	T.V.	C.V.	T.V.	C.V.	T.V.	C.V.	T.V.
α_{11}	9.15	8.01	8.59	7.50	6.95	7.28	9.21	7.82
α_{12}	3.02	5.85	3.45	5.68	5.40	5.75	2.60	6.03
α_0	8.41	8.90	8.54	8.90	8.93	8.90	10.3	8.90
F_1	0.19	0.19	0.31	0.31	0.59	0.59	0.17	0.17
F_2	0.59	0.57	0.49	0.48	0.19	0.19	0.61	0.59

Table 4 Comparison between calculated values and theoretical values of the parameters in the temperature in the temperature model

the frequency characteristics of Eq.(7) are given by solid line in the Figures as the calculated value. Moreover, the frequency characteristics determined by dotted line as the theoretical value. According to the Figures, the experimental values agree well as a whole with the theoretical values and calculated values. Thus, it is confirmed that the temperature model approximates well the physical phenomenon of fluid temperature. Table 4 gives the parameters which are used in the calculations of both the calculated value and theoretical value, where v_0 is assumed to be 1 m/s. It is known from it that some of the parameters agree well between them.

6. Conclusions

As one of a series of research which discusses systematically the dynamic characteristics of fluid temperature between inlet and outlet of a room with various relative positions of inlet and outlet, in this paper the dynamic characteristics of fluid temperature is determined theoretically and experimentally for the manageable case where

the two-dimensional model room is laid flat. According to the main results, the flow model explains well the phenomenon of fluid flow, and its parameters agree almost with the values estimated by observations of flow patterns. Moreover, the theoretical results explain also well the experimental ones.

The results studied in a similar way for a three-dimensional model room will be presented in another report.

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