Investigation on a Temperature Control System Modeled after the Function of the Skin*

(On the Temperature Control System by the Operation of Flow Rate Allotment)

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The contraction and relaxation of muscles located below the skin play an important role to maintain a constant internal body temperature. In this paper, we propose a new temperature control system modeled after the functions of the muscles located below the skin. The most important feature of this system is that the precise control of internal temperature is achieved by the operation of flow rate allotment. Moreover, we used digital adaptive control to improve the performance and flexibility of this system. To verify the validity of this system, the experiments were carried out and it was shown that this system can control the internal temperature within the range of $\pm 0.02^{\circ}\text{C}$.

Key Words: Adaptive Control, Heat Transfer, Digital Control, Valve, Identification

1. Introduction

The internal human body temperature is controlled constantly with high accuracy. It is well known that perspiration and/or biochemical reactions have a marked effect on the internal human body temperature. However, it should be noted that the contraction and relaxation of muscles located below the skin play an important role in controlling the human body internal temperature⁽¹⁾.

The mechanism of internal temperature control by the contraction and relaxation of muscles located below the skin is very interesting. This mechanism is explained as follows⁽¹⁾. If the external temperature is

low, the blood flow rate through the artery located below the skin is decreased by the contraction of muscles. This decrease has an effect of decreasing the heat flux from the body to the atmosphere. Therefore, the decrease of internal temperature is restrained by the contraction of the muscle located below the skin. If the external temperature is high, the blood flow rate through the artery located below the skin is increased by the relaxation of the muscles. This increase has an effect of increasing the heat flux from the body to the atmosphere. Therefore, the increase of internal temperature is restrained by the relaxation of the muscles located below the skin.

In general, the control of flow rate is easier than the control of temperature. Hence, the control mechanism mentioned above is very interesting from the engineering viewpoint and many practical applications are anticipated. However, theoretical or experimental studies on developing this control mechanism have not yet been carried out and there is still much left to be investigated. The final objective of this study is to establish a high-performance temperature control system modeled after the function of the skin. Hence, we fabricated an internal temperature control

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system by the operation of flow rate allotment as a first step and evaluated the basic characteristics of this system. In the human body, the desired internal temperature is constant and does not change with time. However, we include a case where the desired internal temperature changes with time within the scope of the present study from the viewpoint of the engineering applications. It can be easily expected that the change of surrounding conditions will have a strong effect on the performance of the present system. Of course, the system to be in accordance with the changing of surrounding conditions flexibility is desired. Therefore, we introduced the adaptive control system to create this flexible system and the validity of this control scheme is discussed.

2. Experimental Apparatus and Control Methods

2.1 Experimental apparatus

Figure 1 shows the schematic model of the experimental apparatus. The temperature of the test fluid (city water) is kept constant by a constant temperature bath ① and the test fluid is transported to the test section ⑤ by a pump ②. The test section consists of two flow channels and the ratio of flow rate through these channels is controlled by the flow control valve ③. These two channels correspond to the internal artery and the artery located below the skin, but it should be noted that the flow rate and channel geometry are not equivalent to those of the arteries. As we are interested in practical applications, the characteristics of the flow rate and channel geometry are not required to agree with those of the arteries. The spool valve is used as the flow control valve (details are given later). Hence, the ratio of flow rates through these channels is determined by the spool position, which is changed by the stepping motor ④. The test section ⑤ is surrounded by the heat insulator (poly-

styrene form) ⑥ except for one face. The face which is not surrounded by the heat insulator corresponds to the skin and this face is termed the external surface. The copper-constantan thermocouples are attached to the external surface and to the opposite face (internal surface). The data obtained by these thermocouples are digitized by a digital multimeter ⑦, and personal computer ⑧ which determines the signal to control the stepping motor ④ based on the output of digital multimeter ⑦.

As mentioned above, the objective of this study is to establish the high-performance temperature control system modeled after the skin. Of course, it is desirable that this system should work correctly even if the surrounding temperature changes markedly with time. Hence, we placed this apparatus in the student's room, where the room temperature was not kept constant because of the entering and exiting of the students.

Figure 2 shows the model of the flow control valve. This valve is a kind of spool valve and has two outlet ports. The ratio of flow rate through these ports is determined by the position of the spool valve. If we set the origin of the spool valve position at which the ratio of flow rate equals 1.0, the position of the spool valve ranges from -4 mm to 4 mm. The position of -4 mm means that the flow rate through the internal channel equals zero and the position of 4 mm means that the flow rate through the external channel equals zero. Figure 3 shows the cross-sectional view of the test section, which is fabricated of transparent Plexiglas. In general, temperature control with uniform temperature distribution is desired. Hence, we set the cross section of the flow channel as a slit-like rectangle of 2 mm $\times$ 80 mm. This geometry has an advantage that the heat transfer between the

1:constant temp. bath, 2:pump, 3:flow control valve,
4:stepping motor, 5:test section, 6:insulator,
7:digital multimeter, 8:personal computer.

Fig. 1 Schematic model of experimental apparatus

Fig. 2 Flow control valve

Fig. 3 Cross-sectional view of test section

fluid and test section is enhanced because of the increased area of the wetting perimeter.

2.2 Controller design

The present temperature control system which appears to have a simple structure at first sight. However, there are many parameters which have a strong effect on the operation characteristics of the present system (example, flow rate and thermal properties of Plexiglas). Of course, the present system can be controlled by using the values of these parameters, but the flexibility is lacking in such a control scheme and we cannot use these schemes for various applications. In this study, we attempt to describe the characteristics of the present system using a simple digitized model to establish the flexible system. The model constants are determined by the techniques of system identification, and the control scheme is derived from this digitized model and the results of the identification. For these reasons, we will first derive the digitized model to describe the present system. The position of the spool valve has a strong effect on the internal temperature. Moreover, the difference between the temperature at the internal surface and the external surface is also thought to have a strong effect on the internal temperature because the ratio of heat flux toward the internal surface to the heat flux toward the external surface is thought to have a strong relationship with the differences in temperature between the internal and external surfaces. In addition, we have to consider the effects of noise and time lag. On the basis of these considerations, the following equation is adopted to describe the behavior of internal temperature.

$$A(z^{-1})t(k) = z^{-m}\{B_0u(k) + C_0w(k)\} + D_0 + \xi(k) \quad (1)$$

where, z^{-1} is a backward shift operator, m is a scalar whose value we must determine in advance, and $A(z^{-1})$ is given by $A(z^{-1}) = 1 - z^{-1}$. Moreover, k is digitized time, $t(k)$ is the internal temperature, $u(k)$ is the spool position, $w(k)$ is the difference of temperature at the internal and external surfaces, $\xi(k)$ is the noise of which the expected value is zero and B_0 , C_0 and D_0 are scalar constants. The values of these

constants are determined by the techniques of identification. The details are given later. Here, we consider the polynomials $R(z^{-1})$ and $S(z^{-1})$ which satisfy the following relationship.

$$1 = S(z^{-1})A(z^{-1}) + z^{-m}R(z^{-1}) \quad (2)$$

This equation is termed Diophantine's equation and it is well known that this equation has one solution⁽²⁾ of $R(z^{-1})$ and $S(z^{-1})$. As the objective of the present study is to follow the internal temperature $t(k)$ to the desired temperature $g(k)$, we introduce the following cost function.

$$J(k) = E[|P(z^{-1})\{t(k+m) - g(k+m)\}|^2] + E[|Q_0\{u(k) - u(k-1)\}|^2] \quad (3)$$

where, $E[\cdot]$ is the expectation, $P(z^{-1})$ is a polynomial of the order $(m-1)$, and Q_0 is a scalar constant. To obtain the optimal spool position which can minimize the value of $J(k)$, we must obtain the optimal estimated internal temperature $t(k+m|k)$ by the usable data. From Eq. (1), the following equation is obtained.

$$A(z^{-1})t(k+m) = B_0u(k) + C_0w(k) + D_0 + \xi(k+m) \quad (4)$$

Multiplying Eq. (2) by $t(k+m)$, we can obtain the following equation.

$$t(k+m) = S(z^{-1})A(z^{-1})t(k+m) + R(z^{-1})t(k) \quad (5)$$

Substituting Eq. (4) into Eq. (5) yields the following equation.

$$t(k+m) = S(z^{-1})\{B_0u(k) + C_0w(k) + D_0 + \xi(k+m)\} + R(z^{-1})t(k) \quad (6)$$

In this equation, the expectation of $\xi(k+m)$ is zero and this function does not have a correlation with other functions. Hence, the optimal estimated internal temperature $t(k+m|k)$ is given by

$$t(k+m|k) = S(z^{-1})\{B_0u(k) + C_0w(k) + D_0\} + R(z^{-1})t(k) \quad (7)$$

Moreover, the cost function $J(k)$ can be rewritten as

$$J(k) = E[|P(z^{-1})\{t(k+m|k) - g(k+m) + e(k+m)\}|^2] + E[|Q_0\{u(k) - u(k-1)\}|^2] \quad (8)$$

where, $e(k+m)$ is given by $e(k+m) = S(z^{-1})\xi(k+m)$. The optimal $u(k)$, which minimizes the value of the cost function, is obtained by the condition of $dJ(k)/du(k) = 0$. That is, the optimal $u(k)$ satisfies the following equation.

$$B_0^2P(z^{-1})S(z^{-1})u(k) + B_0C_0P(z^{-1})w(k) + B_0P(z^{-1})S(z^{-1})D_0 + B_0P(z^{-1})R(z^{-1})t(k) - B_0P(z^{-1})g(k+m) + Q_0^2\{u(k) - u(k-1)\} = 0 \quad (9)$$

The spool position is determined by this equation.

Next, the method to estimate the values of B_0 , C_0 and D_0 in Eq. (1) is given. In the present study, these values are estimated using the techniques of STC (Self Tuning Control)⁽³⁾. Hence, we introduce the following model for the purpose of identification.

$$y(k) = B_0u(k-m) + C_0w(k-m) + D_0 \quad (10)$$

where, $y(k)$ is an output of this identification model. We should determine the values of B_0 , C_0 and D_0 which make the value of $y(k)$ coincide with $A(z^{-1})t(k)$. Hence, we rewrite Eq.(10) as follows.

$$y(k) = \theta(k)^T \zeta(k), \quad (11)$$

where, subscript “ T ” denotes the transposition and $\theta(k)$ and $\zeta(k)$ are given by

$$\begin{aligned} \theta(k) &= (B_0(k), C_0(k), D_0(k))^T, \\ \zeta(k) &= (u(k-m), w(k-m), 1)^T. \end{aligned} \quad (12)$$

As the values of B_0 , C_0 and D_0 change with time, the digitized time k is written explicitly in these equations. There are many algorithms that can bring the value of $y(k)$ close to $A(z^{-1})t(k)$. In the present study, we adopt the algorithm based on the method of least squares⁽⁴⁾, which is known widely and has been extensively used. That is,

$$\Gamma(k) = \frac{1}{\lambda} \left[\Gamma(k-1) - \frac{\Gamma(k-1)\zeta(k)\zeta^T(k)\Gamma(k-1)}{\lambda + \zeta^T(k)\Gamma(k-1)\zeta(k)} \right] \quad (13)$$

$$\begin{aligned} \theta(k) &= \theta(k-1) - \frac{\Gamma(k-1)\zeta(k)}{\lambda + \zeta^T(k)\Gamma(k-1)\zeta(k)} \\ &\quad \times \{\zeta^T(k)\theta(k-1) - A(z^{-1})t(k)\}. \end{aligned} \quad (14)$$

where, $\Gamma(k)$ is a matrix of 3×3 and λ is a forgetting factor which satisfies the condition of $0 \leq \lambda \leq 1$. Finally, we show the values of constants used in this study. The values of m and function $P(z^{-1})$ were set at $m=3$ and $P(z^{-1})=1$ respectively. The value of Q_0 should be determined by the pole-placement method⁽⁵⁾, but this value was determined empirically to simplify the data processing. Moreover, the value of λ was set at $\lambda=1$ and zero vector was used as an initial value of $\theta(k)$. Additionally, the initial value of $\Gamma(k)$ was set at $\gamma I^{(4)}$, where, γ is a constant of the order of 10 000 and I is a unit matrix.

An additional explanation is presented here. It should be noted that the controllable range of the present system has limitations and these limitations are determined by the physical conditions (such as the flow rate and temperature of fluid). Hence, all experiments described in the following section were carried out within these limitations.

3. Results and Discussion

3.1 Results for the constant desired temperature

At first, the experiments were carried out under a constant desired temperature. The change of internal temperature $t(k)$ with time is shown in Fig. 4. In this figure, the desired temperature was set at 37°C . From this figure, we can observe that the fluctuation level of the internal temperature decreases with the progress of time and the internal temperature approaches the desired temperature. When sufficient time has passed, the difference between the internal temperature and

Fig. 4 Time history of internal temperature. The desired temperature is kept constant.

Fig. 5 Time history of B_0 , C_0 and D_0 . The desired temperature is kept constant.

the desired temperature becomes approximately $\pm 0.02^\circ\text{C}$. Here, we present the experimental results under the simple control rule⁽⁶⁾ to show the validity of the present study. That is, we controlled the internal temperature using the following simple rules⁽⁶⁾.

- 1) If the internal temperature is higher than the desired temperature, the flow rate through the internal channel is set at zero.
- 2) If the internal temperature is lower than the desired temperature, the flow rate through the external channel is set at zero.

The experimental results based on this rule revealed that the difference between the internal temperature and the desired temperature is about $\pm 0.1^\circ\text{C}$ ⁽⁶⁾. This difference is considerably greater than the difference in the present study mentioned above. Hence, we can validate the results of the present study based on these considerations. The changes of B_0 , C_0 and D_0 with time are shown in Fig. 5. In the early stage, the changes of these values are marked, but these values become stable with the progress of time because of the accumulation of data. Figure 6 shows the spool position and external temperature. From this figure, we can observe that the position of the spool valve becomes stable with time similar to the other values. Moreover, we can observe that the fluctuation level of the external temperature is much

Fig. 6 Time history of spool position and external temperature. The desired temperature is kept constant.

Fig. 8 Time history of spool position and external temperature. The change of desired temperature is described by the step function. Step width is -0.08°C .

Fig. 7 Time history of internal temperature. The change of desired temperature is described by the step function. Step width is 0.08°C .

greater than that of the internal temperature. Hence, these results show that the present apparatus can control the internal temperature within the range of $\pm 0.02^{\circ}\text{C}$ even if the external temperature changes markedly. Hence, we can understand the importance of the present study.

3.2 Results for the time-varying desired temperature

First, we present the experimental results for the desired temperature variation in a step-like manner. The change of internal temperature with time is shown in Fig. 7. In this figure, the step width of the desired temperature is set at 0.08°C and the sudden increase in the desired temperature occurs after 5 hr. From this figure, we can observe the existence of a

time lag in the internal temperature, but the difference between the internal temperature and desired temperature is small and this result can be considered as satisfactory. Figure 8 shows the results of spool position and external temperature. This figure shows that the spool moves in a complicated manner to compensate the disturbance due to the change of external temperature. This is most probably the reason for the excellent results shown in Fig. 7. Next, we will explain the experimental results shown in Figs. 9 and 10, where the step width of the desired temperature is set at -0.08°C . Moreover, we will also explain the experimental results shown in Figs. 11 and 12, where the step width of the desired temperature is set at 0.12°C . The most interesting results are shown in Figs. 11 and 12. That is, the lower panel of Fig. 12 shows the sudden decrease in the external temperature, but Fig. 11 shows that this change does not have a strong effect on the internal temperature. This result is explained by the movement of the spool valve which compensates the sudden change of external temperature. These results indicate the excellent performance of the present control system. From Figs. 8, 10 and 12, we observe that the sudden movement of the spool valve occurs prior to the sudden change of the desired temperature. This sudden movement of the spool valve has the effect of improving the tracking capacity of the present system by

Fig. 9 Time history of internal temperature. The change of desired temperature is described by the step function. Step width is -0.08°C .

Fig. 11 Time history of internal temperature. The change of desired temperature is described by the step function. Step width is 0.12°C .

Fig. 10 Time history of spool position and external temperature. The change of desired temperature is described by the step function. Step width is -0.08°C .

Fig. 12 Time history of spool position and external temperature. The change of desired temperature is described by the step function. Step width is 0.12°C .

compensating for the time delay of the response. Therefore, this consideration supports the meaning of the present control scheme mentioned in section 2.2.

It can be easily assumed that the present system can track the desired temperature even if the desired temperature shows complicated changes with time. As an example, we present the results in the case of the desired temperature varying in a ramp-like manner. The change of inner temperature is shown in Fig. 13. This figure shows that the desired temperature increases linearly after the lapse of 5 hr. We can observe the weak time lag in this figure, but the difference between the inner temperature and the desired temperature is about $\pm 0.02^{\circ}\text{C}$ and this result

Fig. 13 Time history of internal temperature. The desired temperature is increased linearly after the lapse of 5 hr.

can be considered as satisfactory.

4. Conclusions

In this study, we fabricated the internal temperature control system by controlling the flow rate allotment. Controlling the flow rate is easier than controlling the temperature in general. Hence, this control mechanism has an important implication from the engineering viewpoint. Moreover, we introduced the adaptive control scheme to establish a flexible control scheme. Therefore, we need not to determine the values of all parameters included in this system beforehand. To demonstrate the validity of the present system, the experiments were carried out in the student's room, where the room temperature was not constant. Initially, we kept the desired temperature constant. As a result, we found that the difference between the desired temperature and the internal temperature is about $\pm 0.02^{\circ}\text{C}$. Moreover, the experiment was carried out with the desired temperature varying in a step-like manner or a ramp-like manner. These experimental results revealed that the present apparatus can track the time-varying desired temperature very well and suggested the excellent perfor-

mance of the present apparatus.

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