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FUZZY CONTROL FOR THE PRECISION WATER BATH OF THE HEAT EXCHANGE CALORIMETER

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Fuzzy inference approach was applied to select the control input for the precision water bath of the heat exchange calorimeter used at a non-air-conditioned laboratory. The thermal fluctuation of the bath water was necessary to be kept within a narrow range. The cooling water or coolant kept at a temperature lower than the set temperature was circulated in the bath. The deviation corresponding to the difference between the set temperature and the observed temperature was observed as the input signal. The output or control input to be given to the heather element in the water bath was calculated by the fuzzy modus. The output function was simplified by means of circulating the cooling water. The contribution of each membership function was changed according to the thermal progress of the observed temperature of the water. The whole system including the control programs was examined by a practical water bath, and fairly good results were obtained. Reasonable recoveries were also shown for external thermal disturbances given to the controlled system.

Keywords: heat exchange calorimeter

Introduction

In the heat exchange calorimetry [1], sample and reference vessels are fixed differentially in a water bath. The heat evolved in the vessel is exchanged freely with the ambient water. Temperature change in the sample solution detected by the thermistor installed in each vessel is transferred to electric signals via a Wheatstone bridge, from which rate of heat evolution and total heat effect are estimated by means of analog treatments and/or digital calculations. The thermal behaviour, such as heat of solution, between liquid and liquid or solid can be measured simply by the calorimetry. The measuring temperature may be selected arbitrarily by changing the temperature of the bath water. However, the differential treatment of observed signals is necessary for estimating the rate of heat evolution. Since noisy signals lower the measuring precision, the thermal fluctuation of the bath water should be kept within a narrow range. For the precision

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water bath the modified PID (proportional, integral and derivative) control system [2] was reported. However, most of parameters in the programs depended on the experimental conditions to be controlled, such as volume of the water and its set temperature. Many constants should be changed for the empirically selected values according to the experimental conditions. Then, the problem involving specific values of parameters was improved by the automatic selection method of optimal control inputs [3] which was recommended for the practical use owing to the simple algorithm and the versatility for the experimental conditions.

In the present report, fuzzy inference approach was applied to select the control input for a precision water bath which may be used at a non-air-conditioned laboratory. The cooling water kept at a temperature lower than the set temperature was circulated in the water bath. The input signal or deviation corresponding to the difference between the set temperature and the observed temperature was fed into a microcomputer, and then control input given to the system was calculated by the fuzzy modus. The output functions were simplified by only adding the heat effect.

Algorithm

The heat evolved in the vessel is exchanged freely with the surrounding bath water in the heat exchange calorimeter. Heat from motor-driven agitators and magnetic stirrers placed in the water bath also conducts into the bath water. In general, the temperature of the water may be elevated gradually, if it is not controlled. On the other hand, the temperature of the bath water was lowered by circulating the cooling water kept at a temperature lower than the set temperature. The difference T_{dev} between the set temperature and the observed temperature was observed and acquired in a microcomputer. The output value or control input H necessary for keeping the temperature of the bath water at the set temperature was calculated by means of fuzzy modus, and given as H_{out} to the heater element via the power amplifier circuit from the microcomputer. As only the heating may be taken into consideration, membership functions were treated simply.

The rule of fuzzy control was set by if-then statements in BASIC. When input and output values are written by x and y, respectively, two example sets may be considered for input and output fuzzy variables as shown in Rules (1) and (2).

Rule (1): if x is A_1 then y is B_1

Rule (2): if x is A_2 then y is B_2

The output value of y_o was calculated from fuzzy inference for input x_o in three steps. The process is demonstrated in Fig. 1 [4, 5].

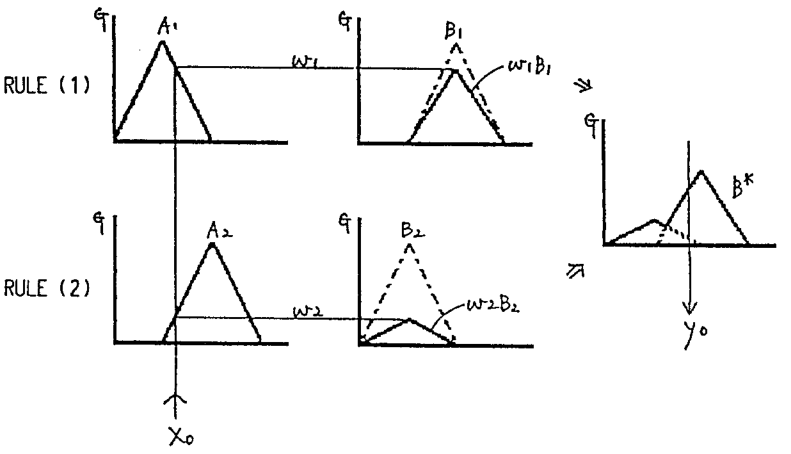

Fig. 1 Calculation process by the fuzzy inference

Step (1):
The grade w_i was calculated by Eq. (1) for each input value, where i = 1 and 2 as shown in rules (1) and (2)

$$w_i = A_i(x) \tag{1}$$

Step (2):
Result of inference by the ith rule was obtained as 'y is w_iB_i'

$$w_iB_i(y) = w_i \times B_i(y) = w_i \wedge B_i\, y \tag{2}$$

Step (3):
As a whole, the final result y_o was calculated from the center of gravity of B^* by Eqs (3) and (4).

$$B^* = w_1B_1 \cup w_2B_2 \tag{3}$$

$$y_o = \frac{\int B^*(y)\, y\, dy}{\int B^*(y)\, dy} \tag{4}$$

Input signal T_{dev} acquired to a microcomputer via interface circuits was in the range from −1999 to 1999, and output signal or control input H_{out} from 0 to 1000 was given from the microcomputer to the heater element soaked in the bath water via the power amplifier circuit. However, these signals were normalized between −1 and +1 in the calculations of fuzzy inference. The normalized values, T and H, are shown as abscissa in Figs 2 and 3, respectively.

Seven fuzzy variables and the defined membership functions were used as follows: NB; Negative Big, NM; Negative Medium, NS; Negative Small, ZO; Zero, PS: Positive Small, PM; Positive Medium, and PB; Positive Big. Input T was given by input fuzzy variables from NB to PB. Zero in T corresponded that the

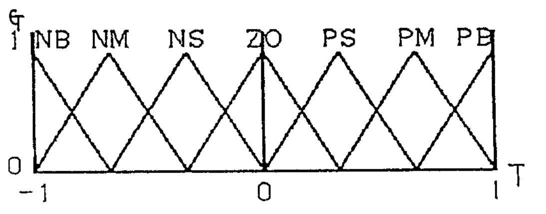

Fig. 2 Relation of fuzzy functions and the membership functions for input value T

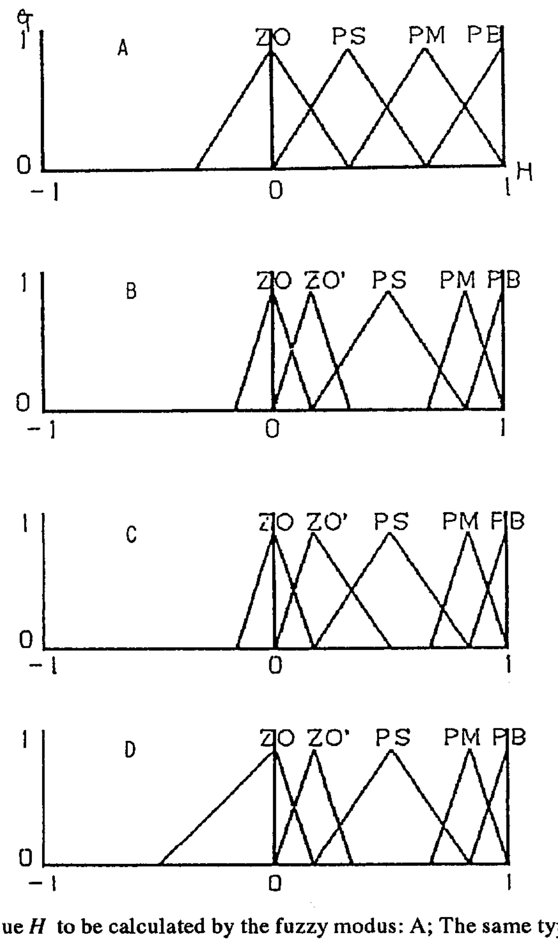

Fig. 3 Output value H to be calculated by the fuzzy modus: A; The same type as T, B; Normal pattern, C; Increase in the heating, D; Decrease in the heating

observed temperature was equal to the set temperature. Output H was also given by output fuzzy variables from ZO to PB. Relation of fuzzy variables and membership functions to grade G is demonstrated for T and H in Figs 2 and 3, respectively, where T and H of the abscissa are indicated between −1 and +1, and the ordinate G means the grade of membership function between 0 and 1 as usual.

Experimental

Apparatus

The heat exchange calorimeter, whose essential parts were similar to those reported previously [2], was assembled. The temperature control system of the water bath is shown in Fig. 4, from which all the equipments for calorimetric measurements, such as the sample and reference vessels, the magnetic stirrers fixed to each vessel, the aluminium frame in order to fix both vessels and stirrers, and the titrant reservoirs for thermal equilibrium, were omitted for simplicity.

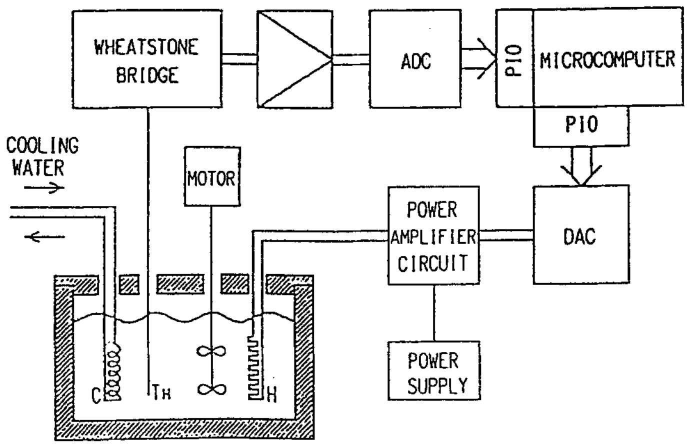

Fig. 4 The temperature control system

A glass box of 23 × 30 × 27 cm^3 in size was used as the water bath which was covered with 5-cm thick Styrofoam insulator boards, and filled with about 16 dm^3 of water which was agitated by a motor-driven stirrer (35 W, PS–1, Yamato Kagaku Co., Tokyo). The cooling water or coolant was kept about 2°C lower than the given set temperature of 25°C with an electric cooler (CTE–200 and CTR–220, Komatsu Electronics Co., Tokyo), and circulated in the water bath by using a glass spiral tubing shown as C in Fig. 4 at a flow rate of 1.5 dm^3·min^{-1}.

The set temperature was given on the operation panel by selecting two kinds of variable resistors which were comprised in one of a Wheatstone bridge. Details of the resistor assembly were reported previously [2]. Temperature of the bath water was measured by a thermistor (NLB, Shibaura Denshi Co., Tokyo) shown as Th in Fig. 4. The resistance R at 25°C and the B constant defined as $R = -A\exp(B/T)$ were 2.371 k(Ω) and 3199 K, respectively, where A is a constant and T temperature. The thermistor was also composed in another arm of the Wheatstone bridge. The relation of the temperature to the resistance was calibrated by a commercially available standard thermometer. The unbalanced voltage corresponding to the deviation T_{dev} was adjusted by a preamplifier (PM–17A, Toa Dempa Co., Tokyo) and acquired to a small microcomputer (M5, SORD Co., Tokyo) operated with Z–80A CPU (central processing unit), Zilog Co. The input and output interface circuits of the microcomputer were composed of a programmable input-output (PIO) (i8255, Intel Co.), an analog-to-digital converter (ADC) (AD–80–12, Analog Devices), and a digital–to–analog converter (DAC) (DAC–80–12, MicroNetwork). The temperature change in the bath water of $1.5 \cdot 10^{-5}$ °C corresponded to 1 digit. The input value of T_{dev} to the ADC was within the range of ±2 V and to the microcomputer ±1999 digit. The output value of H_{out} to the power amplifier circuit was in the maximum 1 V or between 0 and 1000 digit. The power amplifier circuit involving a power transistor and the heater element shown as H in Fig. 4 was almost the same as reported previously [2]. The temperature of the bath water was recorded on a Y–t recorder (R–02, Rika Denki Co., Tokyo).

Software

All the necessary programs were written in BASIC. They were composed of initialization of the control system, data acquisition, calculations from Eqs (1) to (4) of the fuzzy inference using membership functions, and output of control signals. The membership functions were selected in trial and error so as to keep smaller fluctuation range. To eliminate offset temperature and to respond speedily to temperature change, the latest T and the difference ΔT between the T and that just before were taken into consideration.

Procedure

The set temperature was selected on the operation panel. The sample and reference vessels contained equal amount of water for the examination, and were set in each frame to fix in the water bath. The water bath was filled with water, and circulation of the coolant and execution of the temperature control program were started. The temperature of the water was monitored on the Y–t recorder.

Results and discussion

As for the control input to be given to the temperature control system, only the heating signals were needed in the present report. When membership functions shown in Fig. 3A were used to calculate the output or control input H given to the heater element, the controlled temperature of the bath water was stabilized with offset value at a temperature lower than the set temperature. Even if the control input multiplied by 1.5 or 2 was supplied, the results were not improved. Small overshoot followed by oscillations was obtained in both cases.

Then, a fuzzy function ZO' was added between ZO and PS to decrease fluctuations, and all the membership functions were modified as shown in Fig. 3B. According to magnitude of ΔT which indicates the direction of temperature change, three kinds of membership functions of H were selected as shown by B, C, and D in Fig. 3. When larger output was necessary, membership functions of C in Fig. 3 were suitable. On the other hand, those of D in Fig. 3 were selected for smaller output.

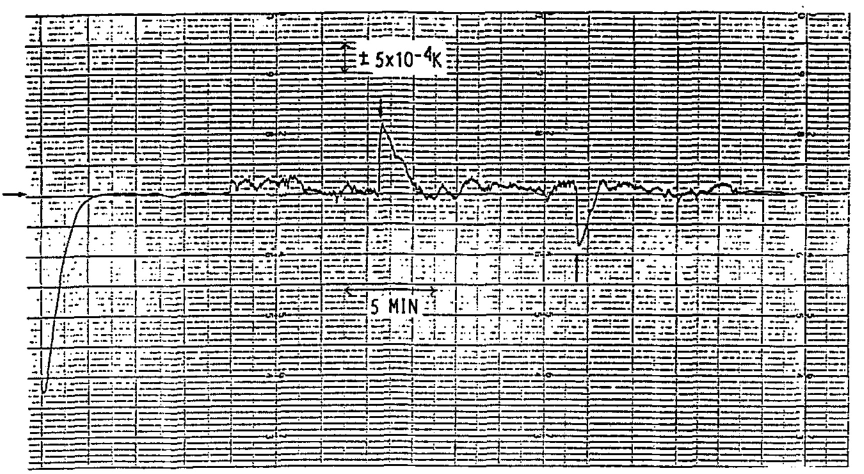

Fig. 5 The recoveries from thermal disturbances in the fuzzy-controlled water

The recoveries from thermal disturbances of ca. 160 J and −120 J were examined at a non-airconditioned room by adding hot and cold water, respectively. The results were shown in Fig. 5, on which downward and upward arrows show the additions of hot and cold water, respectively. The left-hand arrow means the set temperature. The recovery time depended on cooling and heating powers of the control system. At the same time, as the small microcomputer used in the system took time to calculate the output H with BASIC interpreter of floating decimal point, and sampling interval of T_{dev} was every 3 second or more, the recovery from the fairly large thermal change might not be sufficient. The controlled temperature profile was not affected, even if the room temperature changed over a few degrees. When rotation rate of the motor-driven stirrer was decreased, the load to the motor decreased and heat flow from the motor to the water bath also decreased. As expected, the temperature of the bath water lowered, and at the same time became unstable owing to the insufficient agitation.

The fluctuation range of the bath water controlled by the fuzzy modus was within $\pm 5 \cdot 10^{-4}$ K or less, which was adequate range to the heat exchange calorimeter. The performance of temperature control for a water bath of laboratory use was comparable to those reported previously [2, 3]. However, the versatility involving experimental conditions and empirical factors for selection of many constants was much better than the PID method [2]. If more components than T and ΔT in the present work were taken into consideration, more sophisticated control may be possible by the fuzzy inference

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Zusammenfassung — Zur Wahl des Regel-Inputs des Präzisionswasserbades für ein Wärmeaustauschkalorimeter in einem nicht klimatisierten Laboratorium wurde eine Unschärfeschlußnäherung angewendet. Die thermischen Schwankungen des Wassers im Wasserbad müssen in engen Grenzen gehalten werden. Das Kühlwasser oder Kühlmittel mit einer niedrigeren Temperatur als die eingestellte Temperatur wird im Bad zirkuliert. Die Abweichung durch die Differenz zwischen der eingestellten Temperatur und der gemessenen Temperatur wird als Input-Signal beobachtet. Der an das Heizelement im Wasserbad weiterzuleitende Output oder Regel-Input wird mittels des Unschärfe-Modus berechnet. Die Output-Funktion wird durch das Zirkulieren des Kühlwassers vereinfacht. Der Beitrag jeder Teilfunktion wird in Abhängigkeit vom thermischen Verlauf der gemessenen Wassertemperatur geändert. Einschließlich der Regelprogramme wurde das gesamte System an einem praktischen Wasserbad erprobt und man erhielt recht gute Ergebnisse. Akzeptable Diagnosen konnten auch für externe thermische Störeinflüsse gezeigt werden, denen das geregelte System ausgesetzt wurde.