Temperature Control of an Oil Cooler System For Machine Tools Using a Fuzzy- Logic-Based Algorithm

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Abstract: Recently, technical trend in machine tools is focused on enhancing of speed, accuracy and reliability. Such high speed usually results in thermal displacement and structural deformation. To minimize such thermal effect, most precision machine tools adopt high precision cooling system. This study proposes a temperature control for an oil cooler system using PI control with fuzzy logic. In a cooler system, the refrigerant flow rate is controlled by rotational speed of the compressor, where the outlet oil temperature is selected as the control variable. The fuzzy control rules iteratively correct PID parameters to minimize the error, difference between the outlet temperature and the reference one. Here, the ambient temperature is used as the reference one. To show the effectiveness of the proposed method, a series of experiments are conducted for an oil cooler system of machine tools, and the results are compared with the ones of a conventional PID control. The experimental results show that the proposed method has advantages of smaller overshoot and smaller steady state error.

Keywords: Fuzzy logic control, Oil cooler system, Compressor speed control, Machine tools

1. INTRODUCTION

Modern machine tools are subject to severe thermal deformation due to high cutting speed and high feed rate during machining processes. Such high speed usually generates heat in their driving unit, which dissipates into the machine tool and results in both non-uniform distribution of the temperature in the structure and thermal deformation in the parts[1]. The thermal deformation usually degrades the machining precision and the reliability of machine tools. In order to prevent the non-uniform distribution of heat, it is required to use an oil cooler to cool down high speed motion parts such as main spindles, ball screws, guide ways, and others.

A conventional cooling method is to supply cold oil from an oil tank to the main spindle regardless of the amount of heat generated in the main spindle. However, this method cannot maintain a temperature of the main spindle at constant. Usually the temperature fluctuates according to change in the load conditions, which cause thermal deformation of the structure. Thus, it is required to actively control the temperature of oil passing through the main spindle to maintain a desired temperature. Such a conventional control method is on-off control. However, this method does not properly respond to external load which continuously changes all the time, also it increases operation cost due to the repeated start and stop of operations.

As an alternative to the on-off control, the speed control of the oil cooler compressor is required. Much research has been carried out on analysis of compressor rotation speed, and the performance and characteristics of electronic expansion valves[2,3,4] for air conditioners and refrigerators. However, few research works on the oil cooler system for machine tools have been reported. Also, it has been known that there are two types in the control of oil cooler system: on-off and PID control. These methods have shown to take long time to be stabilized due to slow response and overshoot.

To overcome such disadvantage, this study proposes a fuzzy-logic-based PI controller which corrects the control parameters in real time, based upon designing the fuzzy control rules for proportional and integral gains, respectively. In this method, the refrigerant flow rate is controlled by a variable-speed compressor driven by an inverter. Also, the flow rate of refrigerant flowing into the evaporator is controlled by the opening angle of an electric expansion valve. It is expected that the error between the reference temperature and the oil outlet temperature is to be minimized, also the response characteristic is to be enhanced. The proposed fuzzy–logic-based PI controller is applied to an industrial oil cooler, and the results show that the proposed method has a faster response and a smaller steady state error than Ziegler-Nichols' PID controller.

2. CONTROL SYSTEM OF OIL COOLERS

2.1 Experiment Set-up

The schematic diagram for an oil cooler of machine tools and it controller is shown in Fig. 1. The oil cooler system consists of a compressor which generates high temperature and high pressure gas by compressing low pressure gas-phase coolant, a condenser which makes high pressure liquid by cooling high temperature and high pressure gas, an expansion valve which makes low temperature and low pressure coolant by lowering the pressure, and an evaporator which makes low pressure gas by absorbing heat from the gas. In this study, a

1kW electric heater, the source of heat, is used as substitute of a machine tool.

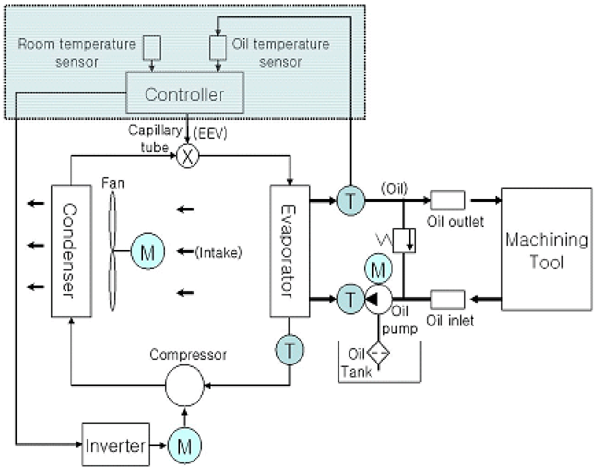

Fig. 1 Oil cooler system and the controller

Oil circulation circuit for a machine tool is shown in Fig. 2 in which the compressor is a speed-variable a high compressive closed rotary type with a three-phase induction motor. The capacity of the inverter is 1.5kW, and the maximum speed of the motor is 1750 rpm. It has a 1- hp rated output, and the control voltage of the inverter is 0 to 10 V. The cooling capacity of the oil cooler is 3024 kcal/h. A u-tube copper tube connects two straight tubes of the condenser, and the evaporator has spiral structures. In addition to the compressor control, it is required to control the flow rate of the refrigerant. For such purpose, a capillary tube can be used, but it has a difficulty in controlling the capacity. As an alternative, an expansion valve is used since it can easily control the flow rate and pressure according to the load conditions.

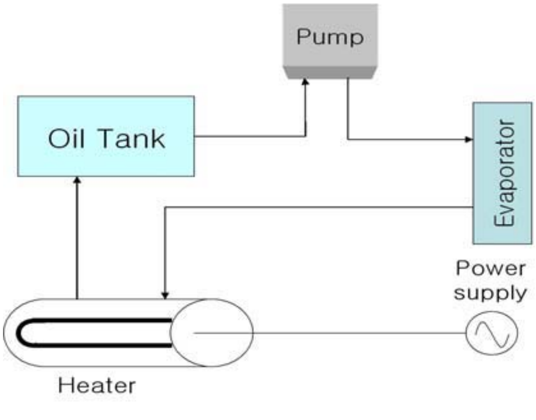

Fig. 2 Cooling oil cycle

2.2 Experiment methods

In this experiment, a metering valve is used for the expansion valve device, and a stepping motor is used to automatically control the opening angle. In order to generate the desired numbers of pulses to rotate the stepping motor, 50 ms pulse is applied to the stepping motor driving circuit. To control the compressor, the PC digital output is converted to DC voltage with DAC(digital-to-analog converter) and DC voltage is applied to the inverter to control the speed of the compressor. The inlet and outlet oil temperature and the ambient temperature are measured with sealed T tube temperature sensors. The measured temperature data are converted to a voltage signal by a transducers and is transmitted to the computer through the interface board. Based upon the outlet oil temperature measured, the control signal is sent to the compressor and the expansion valve through the interface board to control the inverter and stepping motor.

3. CONTROLLER DESIGN

3.1 PID controller

PID controllers are widely used in process control because it is easy to apply and excellent in safety. Also they are usually applied to the air conditioning or heat system. The integral control factor in the PID controller improves steady state response, while the differential control factor increases the stability of the system because it controls the control input which is proportional to the rate of error change signal so that the error signal would not become so big. There are two types of PID controls such as velocity and position types. The position one is expressed by

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_a e(t)] \tag{1}$$

$$U_k = K_p e_k + K_i \sum e_k \Delta t + K_d \frac{\Delta e_k}{\Delta t} \tag{2}$$

$$U_{k-1} = K_p e_{k-1} + K_i \sum e_{k-1} \Delta t + K_d \frac{\Delta e_{k-1}}{\Delta t} \tag{3}$$

where U_k and e_k are the output and the error of the controller at time step k, respectively. K_p, K_i, and K_d are the proportion, the integral, and the differential constants which are the parameters of the PID controller. The input U_k to the system can be expressed by the following velocity type equation:

$$\begin{aligned} U_k = {} & K_p(e_k - e_{k-1}) + K_i \sum e_k T_s \\ & + \frac{K_d}{T_s}(e_k - 2e_{k-1} + e_{k-2}) \end{aligned} \tag{4}$$

where Ts is the delay time and equals to Δt in equation (3) and (4). In this experiment, Δt is a sampling time, one cycle of sending an output from the controller, and is equal to 40 ms.

The schematic diagram of the PID controller used to control the flow rate of the coolant is shown in Fig. 3.

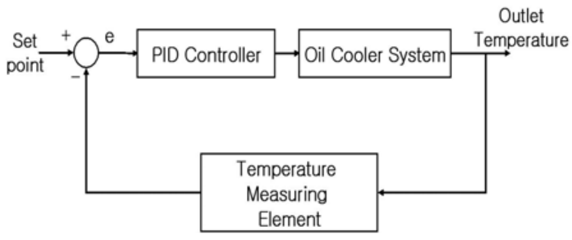

Fig. 3 Block diagram of the compressor speed control system

3.2 Fuzzy logic-based PI controller design

One of the problems of the PID controller is the fact that the controller can not provide a satisfactory control capability in many cases such as when the characteristics of the control object change during the operation and when the operator is not familiar with the control of the PID parameters[4,5]. In this experiment, a fuzzy-logic-based PI controller which corrects the parameters of PID controller in real time is designed so that the PID controller can adapt itself to the change in the environment and the state of the system. Fig. 4 shows the schematic diagram of the proposed control system.

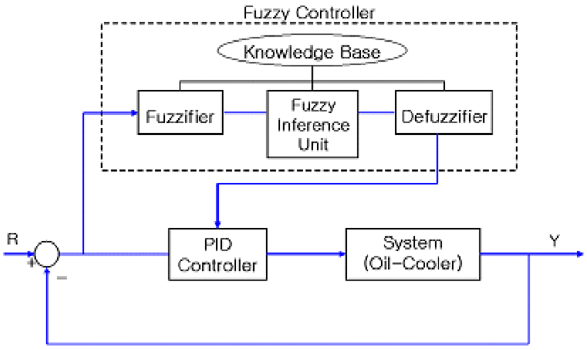

Fig. 4 Block diagram of the proposed fuzzy-logic-based PI controller

As shown in the figure, the fuzzy control process is composed of a fuzzifier, a fuzzy inference system and a defuzzifier. The fuzzifier transforms a crisp input values to a fuzzy value, the fuzzy inference unit carries out evaluation of the fuzzy outputs, and the defuzzifier converts the output to a crisp value. In comparison with PID controllers, the fuzzy controller has advantage that can use experience and knowledge of the expert[6,9]. Thus, it can control much complex system that is difficult to be controlled by conventional controllers. The fuzzy controller involves complex inference processes, but the inference rules can be easily modified[7]. Also, it has a characteristic of robustness. A number of fuzzy PID controllers have been developed : a self tuning fuzzy PID controller, a parallel PID fuzzy controller, and a fuzzy supervision PID controller.

The self-tuning fuzzy PID control method is complex because it requires two rules for the fuzzy PI or fuzzy PD controller and for the increment. The parallel PID fuzzy controller uses fuzzy controller and PID controller in turn, depending on the error and the amount of change of error, also it uses PID when error is small. Thus, there is no difference with the existing PID controller[7,9]. The fuzzy supervisor PID controller has a structure based upon Eq. (1), and increases and decreases the gains of controller by a fuzzy supervisor. It has an enhanced response characteristic.

In this study, the outlet temperature of the secondary fluid is controlled by using the compressor with the fuzzy supervisor PI control algorithm proposed by Tzafestas[8,10]. In this method, when overshoot occurred, the integral gain is slightly reduced, and when fine vibration occurred in the steady state, the derivative gain is slightly increased. When the amplitude of the overshoot is large, the proportional gain is reduced so that the transient response is to be enhanced. However, it has a demerit that the system would not converge when three gains are changed to generate overshoot with one fuzzy control matrix. To overcome this problem, the fuzzy control rules for the proportional gain and the integral gain are separately designed in this study. As the input to the fuzzy controller, the error and its change rate are used. Since the time constant of the coolant is large, the response time is long. Thus, when the error and its change rate are large, both the proportional gain and the integral gain are increased, while when they are small the gains are reduced. When overshoot is large, the integral gain is reduced for the output to quickly converge. In this method, Kp and Ki are obtained from the fuzzy inference based upon the error and its derivative at each case. Then, the control is carried out by adjusting Kp and Ki values, the control constants of the PI controller, in real time. In Fig. 5, the temperature error membership function of the outlet oil is shown. The membership function for the error change rate of the outlet temperature is shown in Fig. 6.

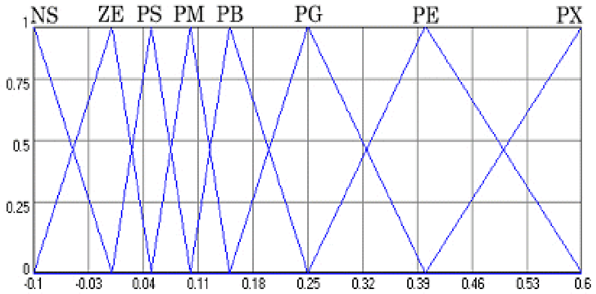

Fig. 5 Membership function for e_k of the outlet temperature

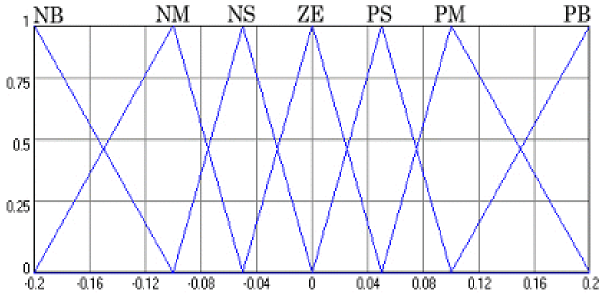

Fig. 6 Membership function for Δe_k of the outlet temperature

The equation of the error and the error change rate are expressed by,

$$e_k = T_{reference} - T_{measured} \tag{5}$$

$$\Delta e_k = e_k - e_{k-1} \tag{6}$$

Using the above membership functions, the fuzzy inference system evaluates the fuzzy output which is defuzzified with the centroid method.

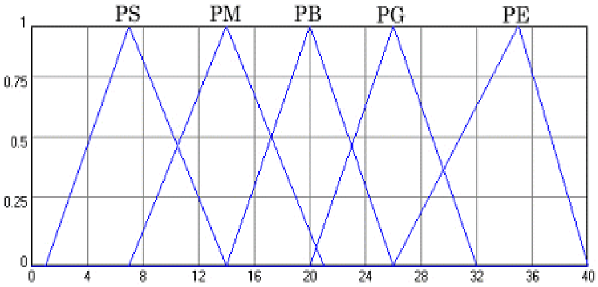

Fig. 7 Membership function for Kp

Table 1 Fuzzy control rule for Kp

Kp		Parameter (E)							
		NS	ZE	PS	PM	PB	PG	PE	PX
Parameter (⊿E)	NB	PS	PS	PS	PS	PM	PB	PG	PE
	NM	PS	PS	PS	PM	PB	PG	PE	PE
	NS	PS	PS	PM	PB	PG	PE	PE	PE
	ZE	PS	PM	PB	PG	PE	PE	PE	PE
	PS	PB	PB	PE	PE	PE	PE	PE	PE
	PM	PG	PE	PE	PE	PE	PE	PE	PE
	PB	PE	PE	PE	PE	PE	PE	PE	PE

Table 2 Fuzzy control rule for Ki

Ki		Parameter (E)							
		NS	ZE	PS	PM	PB	PG	PE	PX
Parameter (⊿E)	NB	ZE	ZE	ZE	PM	PB	PG	PG	PE
	NM	ZE	ZE	PS	PB	PG	PG	PE	PE
	NS	ZE	PS	PB	PG	PG	PE	PE	PE
	ZE	PS	PB	PG	PG	PE	PE	PE	PE
	PS	PM	PG	PG	PE	PE	PE	PE	PE
	PM	PG	PE	PE	PE	PE	PE	PE	PE
	PB	PE	PE	PE	PE	PE	PE	PE	PE

The fuzzy control rules for Kp and Ki are shown in Table 1 and Table 2. Fig. 7 shows the fuzzy control rule for Kp, while Fig. 8 shows the rule for Ki.

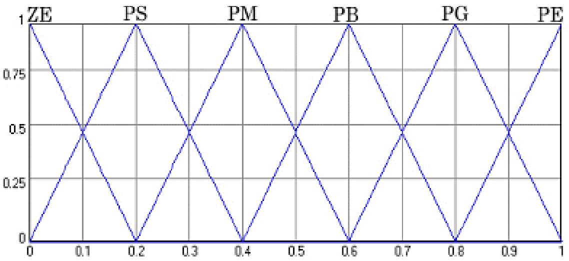

Fig. 8 Membership function for Ki

4 EXPERIMENT RESULTS AND DISCUSSION

To show the performance of the proposed fuzzy-logic-based PI controller, a series of experiments were carried out for an industrial oil cooler system. In the experiment, the outlet oil temperature of the secondary fluid is controlled, while the flow rate is controlled by adjusting the opening of the expansion valve proportional to the compressor speed and the load.

The conventional on-off control is to cool down the oil by operating the oil cooler compressor when the oil temperature is higher than the reference temperature. When the temperature of the oil is same or lower than the reference one, the compressor does not operate, and let the oil itself circulated. This on-off control method increases the operation cost due to the increased electricity consumption owing to the repeated start and stop operations which may cause out of order of the compressor due to the repeated contact of the compressor driving relay. Fig. 9 shows the result of the on-off control experiment at the reference temperature of 28℃ with the initial oil temperature of 31℃. As shown in the figure, it takes 600 seconds to reach to the reference temperature with the error deviation of ±0.5℃, and the error deviation becomes -0.4℃ after the oil temperature reaches the reference temperature.

Fig. 10 shows the result of the experiment carried out at the set temperature of 28℃ using PID control. It take 450 seconds to reach the reference temperature with the error deviation of ±0.35℃. Fig. 11 shows the outlet oil temperature error after carrying out experiment at 28℃ using the proposed method at the same conditions as the on-off control and the PID control. The figure shows that it take 400 seconds to reach the reference temperature and the temperature error is ±0.2℃, which shows the lowest steady state error, small overshoot and stable control capability. Fig. 12 shows the comparison of the temperature error among the on-off control, the PID control and the fuzzy-logic-based PI control. As shown in the figure, the proposed fuzzy-logic-based PI control has the fastest response characteristics and the most stable one.

Fig. 13 shows the result of the on-off control when the ambient temperature is set to the reference one, where the initial outlet oil temperature is 26℃. The figure shows that the difference between the outlet oil temperature and the ambient temperature is 0.7℃. Fig. 14 shows the results of the PID control under the same experiment condition. The figure shows that the average outlet oil temperature error is 0.35℃.

Fig. 15 shows the results of the proposed fuzzy-logic-based PI control under the same experiment condition. The results show that the error is 0.15℃, which is minimum among three control methods.

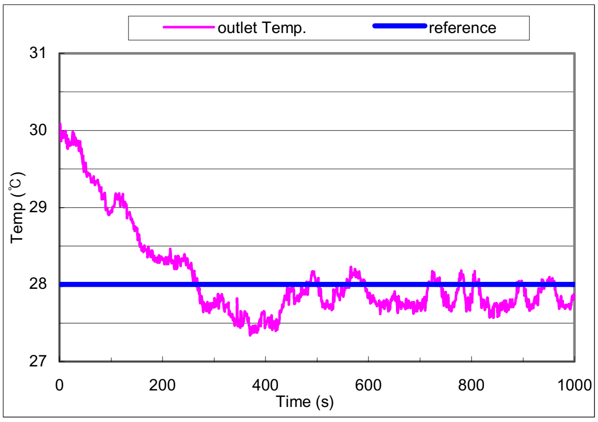

Fig. 9 Outlet oil temperature using an on-off control

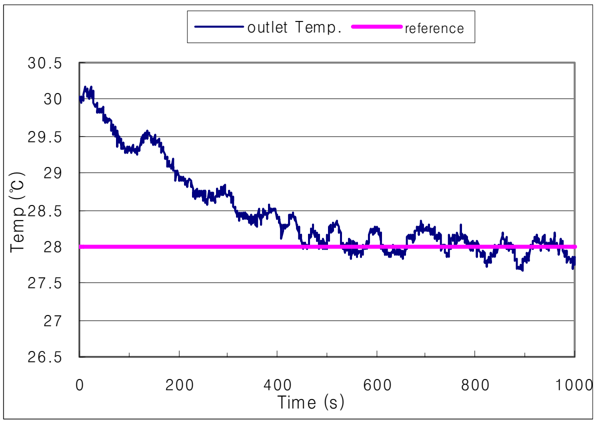

Fig. 10 Outlet oil temperature using a PID control

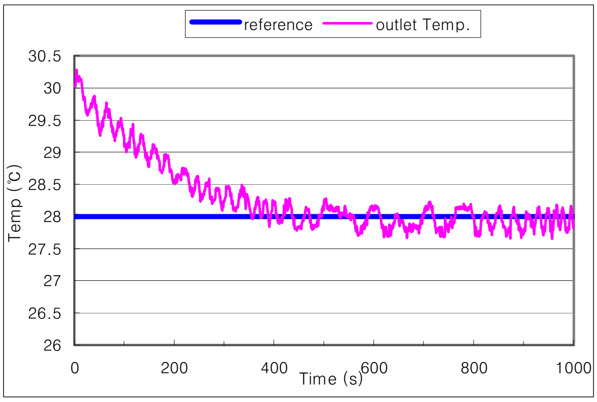

Fig. 11 Outlet oil temperature using the proposed fuzzy-logic-based PID control

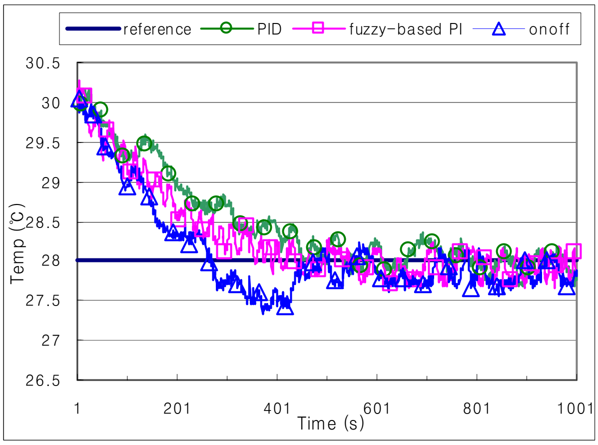

Fig. 12 Comparison of the Outlet oil temperature among three control methods

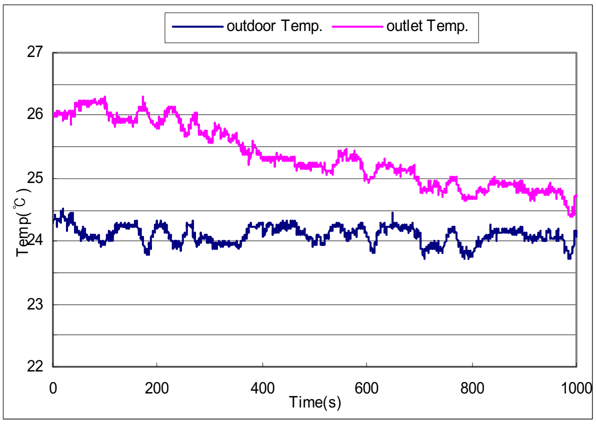

Fig. 13 Change in the outlet oil temperature using an on-off control when outlet oil temperature is controlled to be same as the ambient temperature

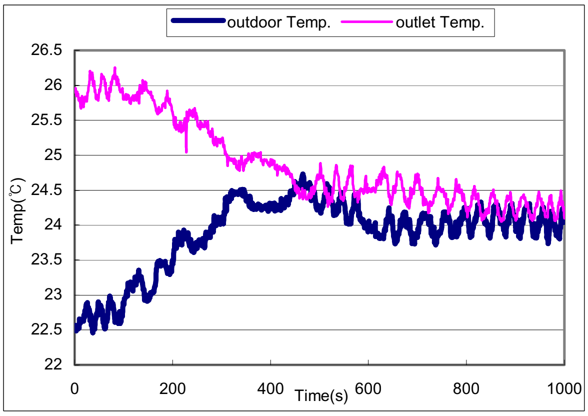

Fig. 14 Change in the outlet oil temperature using a PID control condition is the same as Fig.13

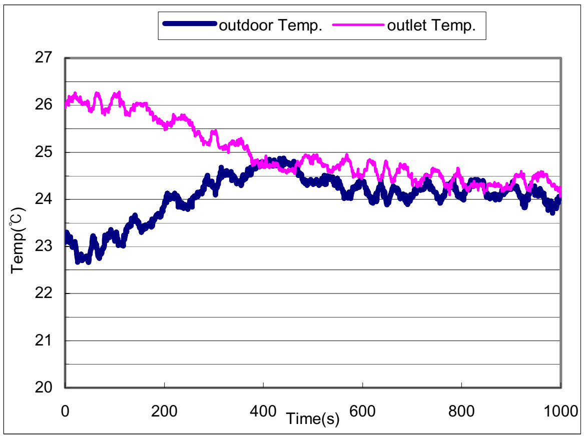

Fig. 15 Change in the outlet oil temperature using the proposed fuzzy-logic-based PID control Condition is the same as Fig.13

5. CONCLUSION

This study proposed a fuzzy-logic-based PI control algorithm to control the temperature of the oil in cooling systems for machine tools. The outlet temperature of oil is the control variable, and a constant temperature or the ambient temperature is set to the reference, desired temperature. The compressor of the oil cooler is the actuator to be controlled, and the rotating speed of the compressor is controlled by the proposed fuzzy-logic-based control algorithm. From the understanding of the PI gains in real time, the fuzzy rules are constructed; the rules for the P gain and the I gain are designed separately. The proposed control algorithm was applied to an industrial oil cooler, and the results are compared with the ones of an on-off control and a conventional PID controller. From the experiments, it is shown that the proposed control method has a faster response and a smaller steady state error than the on-of control and the PID one. Therefore, it is concluded that the proposed fuzzy-logic-based PI control algorithm can be applied to a high precision oil cooler system for high-speed and super-precision machine tools.

ACKNOWLEDGEMENT

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