AN EXPERIMENTAL STUDY ON THE CAPACITY CONTROL OF MULTI-TYPE HEAT PUMP SYSTEM USING PREDICTIVE CONTROL LOGIC

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Abstract: Performance of a water-to-water multi-type heat pump system was investigated by experiment. This system consists of two indoor units and one outdoor unit. Controlled variables are the evaporator outlet pressure of refrigerant and the outlet temperature of secondary fluid at each indoor unit. In this study, capacity control is aimed at controlling the outlet temperature of secondary fluid at each indoor unit using predictive control logic, and test results are compared with those obtained by PID control logic. To find parameters of predictive control, DARMA(Deterministic Auto Regression Moving Average) model was used to describe the system, and on-line parameter estimation method was used to update the parameters. Experiments were carried out when the set temperature was changed and when the load was changed. When the set temperature was changed, both predictive control and PID control gave similar outputs. When one indoor unit was shut off, predictive approach resulted in a better performance.

1. **INTRODUCTION**

As higher standard of living is pursued, there is tendency that more than one air conditioning unit are installed in a house. The cost and space for the installation of air conditioning unit have become a major factor. Multi-type heat pump system which consists of one outdoor unit and multiple indoor units can satisfy the same needs for the installation of several individual units with less space as only one outdoor unit is required. It can handle cooling requirement in summer and also heating requirement in winter. This can further reduce the required space and cost when compared two independent units for heating and cooling. In the respect of cost and space, multi-type heat pump system has much more merits than conventional HVAC system. However, the system's complexity and lack of control strategy on multi-type heat pump system hinder its appearance as a major air conditioning system in the market. Researches on distribution of refrigerant and on the interaction between each component of multi-type heat pump system are being carried out. Multi-type heat pump system should be operated under full load or part load condition and in any case it properly distribute refrigerant to each unit. If each room location is at different, multi-type heat pump system must handle pressure drop caused by their difference in elevation or different tubing length. What system operation logic will be adopted is also a major concern since it has much direct influence on the system performance and efficiency.

In this paper, operational characteristics of multi-type heat pump system with 2 indoor units are investigated. PID control logic and predictive control logic are adopted to show what operational characteristics are yielding under different operation conditions.

2. EXPERIMENTAL APPARATUS AND CONTROL LOGIC

2.1 EXPERIMENTAL APPARATUS

Multi-type heat pump system generally consists of one outdoor unit and multiple indoor units. Figure 1 shows the schematic diagram of experimental apparatus in this study, which has 2 indoor units and 1 outdoor unit. In this paper, proper control parameters which can vary the capacity of indoor units are selected as compressor rotational speed and opening of expansion valves. To change the rotational speed of the compressor, variable open type compressor driven by an inverter was used.

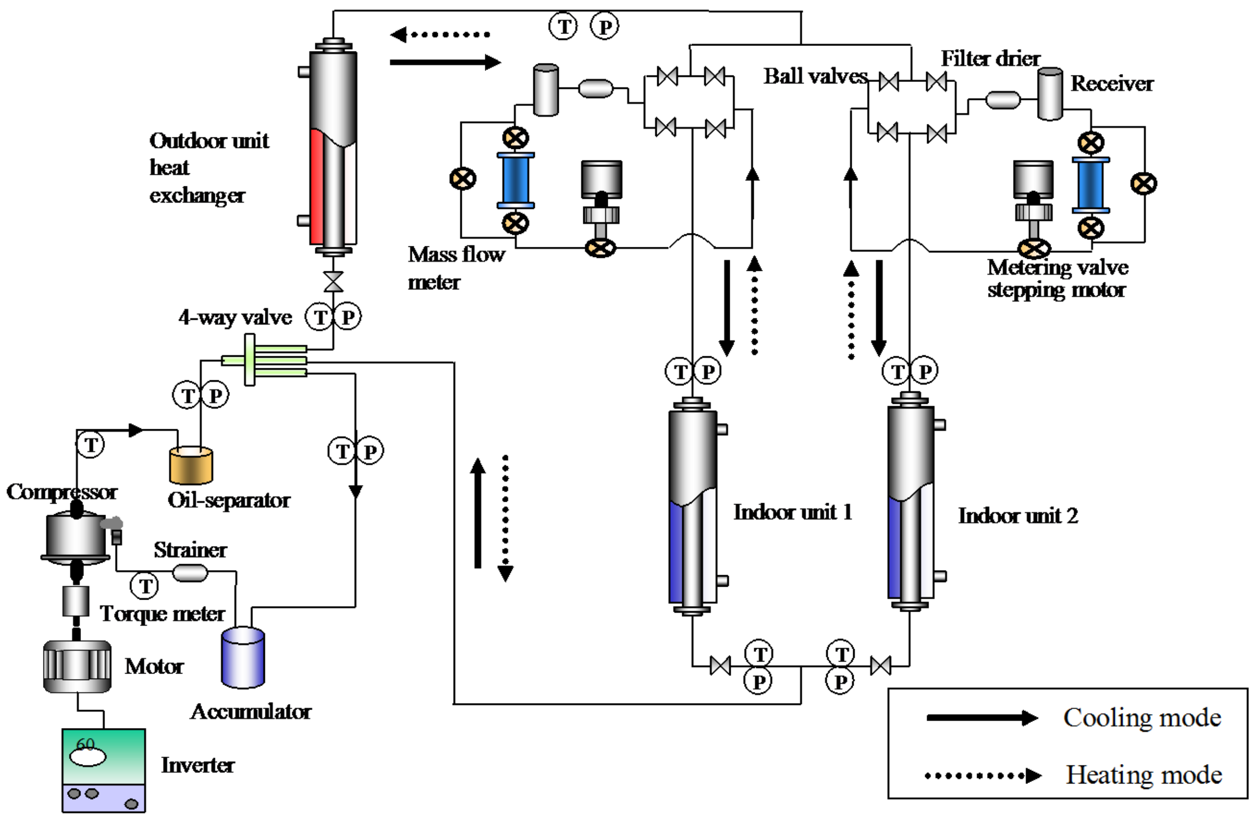

Figure 1. Experimental apparatus of a multi heat pump system with 2 indoor units

To control each indoor unit's capacity, expansion valves are installed at the upstream of each indoor unit to cope with various air conditioning demands. In this study, metering valve operated by a stepping motor is used as an electronic expansion valve. The generated electric pulses are imposed to the stepping motor, and the openings of the expansion valve are determined by how many pulses are imposed to the stepping motor.

As a secondary fluid of indoor units and outdoor unit, pure water was used, and R22 was used as a refrigerant.

2. 2. PREDICTIVE CONTROL

Relations between system input, $u(t)$ and output $y(t)$ in predictive control method can be described as the following mathematical formula. In this equation, white noise is neglected.

$$A(q^{-1})y(t) = B(q^{-1})u(t) \tag{1a}$$

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_m q^{-m} \tag{1b}$$

$$B(q^{-1}) = (b_0 + b_1 q^{-1} + \cdots + b_n q^{-n})q^{-d} \tag{1c}$$

Here q^{-1} represents unit backward shift operator, which represents the value of one time step before. That is, $q^{-1}*y(t)$ means $y(t\text{-}1)$, $q^{-2}*y(t)$ means $y(t\text{-}2)$, so on. The order and coefficients of the above mathematical model are obtained by analyzing system response to a given input. In equation (1), it is assumed that the system is linear and deterministic. However the real multi-type heat pump system cannot be described just by the simple statements in equation (1). Therefore, it is worthy of adopting adaptive control logic to describe the performance of multi-type heat pump system. Following simple projection algorithm is used to update the coefficients of $A(q^{-1})$ and $B(q^{-1})$.

$$\theta(t) = \theta(t-1) + \frac{\phi(t-1)}{\phi(t-1)^T \phi(t-1)}[y(t) - \phi(t-1)\theta(t-1)] \tag{2a}$$

$$\theta(t-1) = [-a_1 \ \cdots \ -a_m \ b_0 \ \cdots \ b_n]^T \tag{2b}$$

$$\phi(t-1) = [y(t-1) \ \cdots \ y(t-m) \ u(t-1) \ \cdots \ u(t-n)]^T \tag{2c}$$

Here $\theta(t)$ is coefficient matrix and $\phi(t-1)$ is matrix of outputs and inputs. When error value is used as a $y(t)$, the desired value of $y(t)$ becomes "0".

The rotational speed of compressor and opening of expansion valves are changed to control the capacity of the multi-type heat pump system. These become the inputs $u(t)$ of equation (2). As outputs, evaporator outlet pressure of refrigerant and outlet temperature of secondary fluid of indoor unit were adopted for compressor rotational speed and opening of

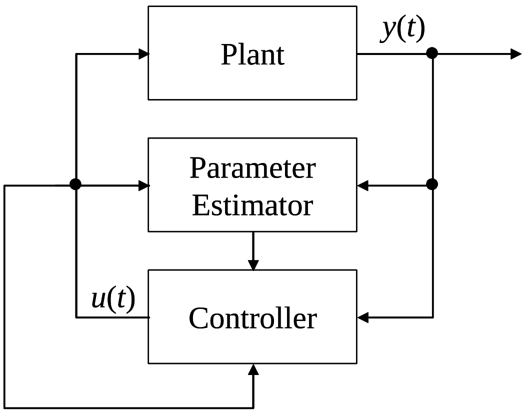

Figure 2. Block diagram of predictive control

expansion valve as inputs, respectively.

Figure 2 shows the block diagram of predictive control. Output of plant was used as an input to the parameter estimator and the controller. In the parameter estimator, parameters are updated to make a desired system output and these parameters are sent to the controller to provide a proper output value.

3. RESULT

3.1. CAPACITY CONTROL AT COOLING MODE

Figure 3 shows temperature change versus time when setting temperature of indoor unit 1 decreased from 19 °C to 17 °C. PID and predictive controls were applied under the same condition. Both control logics showed that the outlet temperature of indoor units reached a

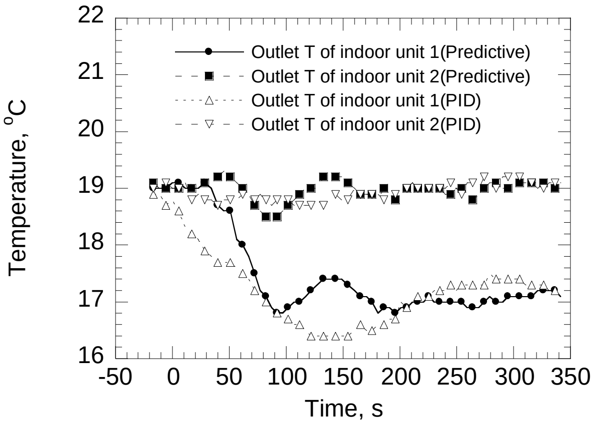

Figure 3. Secondary fluid outlet temperature of indoor units when setting temperature was changed from 19 °C to 17 °C at cooling mode

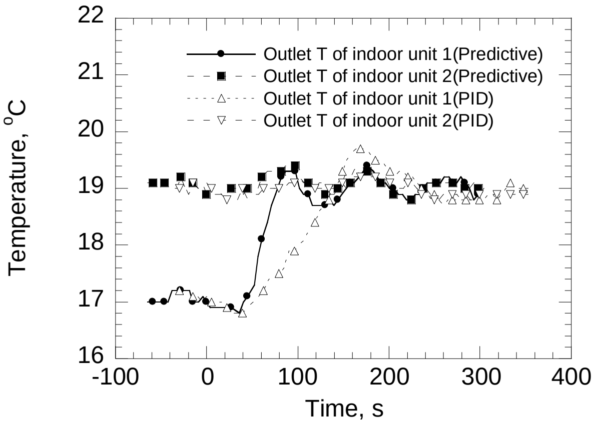

Figure 4. Secondary fluid outlet temperature of indoor units when setting temperature was changed from 17 °C to 19 °C at cooling mode

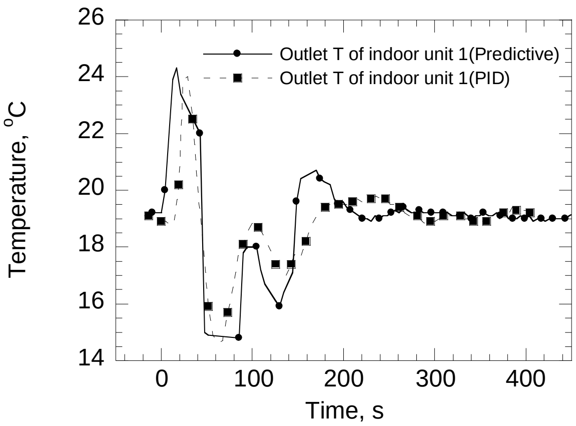

Figure 5. Secondary fluid outlet temperature of indoor unit 1 when indoor unit 2 was turned on at cooling mode

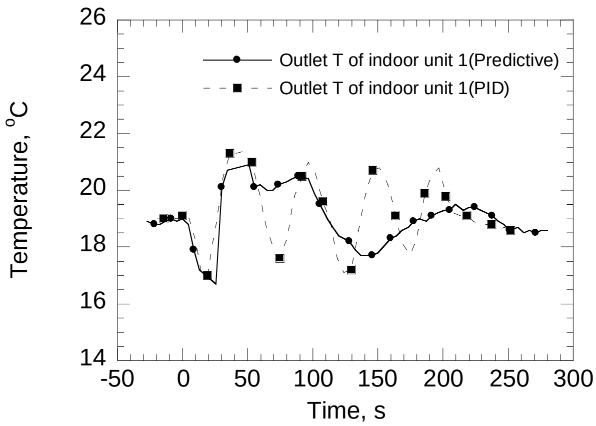

Figure 6. Secondary fluid outlet temperature of indoor unit 1 when indoor unit 2 was turned off at cooling mode

steady state after 250 s. However, predictive control gave less temperature fluctuation than PID. Temperature variation in one indoor unit showed to have little influence on the temperature variation of the other indoor unit. Figure 4 is showing the temperature change versus time when setting temperature increased from 17 ^{o}C to 19 ^{o}C. Figure 5 shows temperature variation to maintain indoor unit 1's secondary fluid outlet temperature at 19 ^{o}C when indoor unit 2 started its operation from non-operating state. Due to a sudden increase in cooling demand, the system undergoes relative lack of cooling capacity. So there was a sudden increase in the outlet temperature of secondary fluid. After 300 s, the outlet temperature of secondary fluid reached a steady state.

When one of indoor units suddenly stops its operation, system may undergo a sudden decrease in cooling demand, so temporary surplus of cooling capacity is expected. Figure 6 shows this situation when indoor unit 2 is turned off. The setting temperature of indoor unit 1 was 19 ^{o}C but the sudden decrease in cooling demand caused the sudden decrease in outlet temperature of secondary fluid. When predictive control logic was used to control outlet temperature of secondary fluid, the system reached a steady state in 300 s. However, when PID control logic was used, the system seemed hard to reach a steady state.

3.2 CAPACITY CONTROL AT HEATING MODE

When setting temperature of each indoor unit is changed, the system shows slightly different behavior from that of cooling mode. Figure 7 shows the temperature variation when setting temperature of indoor unit 1 was changed from 28 ^{o}C to 26 ^{o}C in heating operation. After 800 s, both PID control and predictive control reached a steady state. Seeing that the time needed to reach a steady state is about 250 s in cooling operation, this 800 s is a relatively large value.

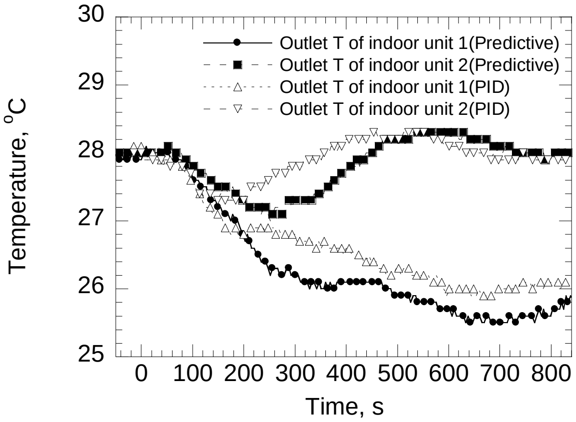

Figure 7. Secondary fluid outlet temperature of indoor units when setting temperature was changed from 28 ℃ to 26 ℃ at heating mode

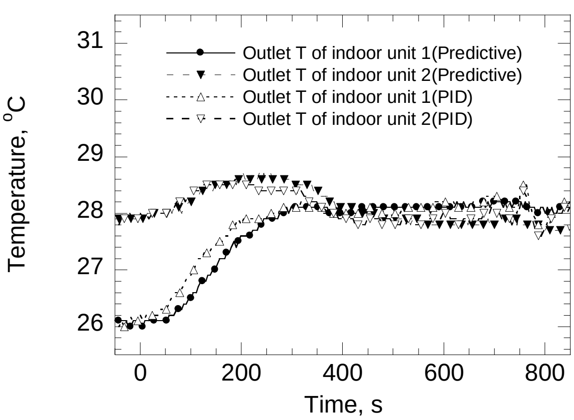

Figure 8. Secondary fluid outlet temperature of indoor units when setting temperature was changed from 26 ℃ to 28 ℃ at heating mode

Moreover, variation of outlet temperature in one indoor unit had a greater influence on the outlet temperature of the other unit. Figure 8 shows the temperature change when setting temperature increased to 28 ^{o}C. Figure 9 shows temperature change to maintain indoor unit 1's secondary fluid outlet temperature at 28 ^{o}C when indoor unit 2 is turned on. Due to sudden increase in heating demand, the system undergoes relative lack of heating capacity, which implies there is a sudden decrease in outlet temperature of the secondary fluid. After 600 s, indoor unit 1's outlet temperature reached a steady state.

Figure 10 shows a temperature change when the operation of one indoor unit was stopped. When predictive control logic was used, system reached a steady state in 500 s. When PID was used, the system shows a continuous oscillation in temperature of secondary fluid.

4. CONCLUDING REMARKS

This paper is to investigate the operational characteristics and control characteristics of multi-type heat pump system with one outdoor unit and 2 indoor units where the secondary fluid of indoor unit and outdoor unit is water, and the refrigerant is R22. In order to impose operating conditions, step change of setting temperature of secondary fluid was made. When system underwent a step change of setting temperature, PID control and predictive control showed similar results both in cooling and heating operations. In cooling operation, temperature change in one indoor unit had little influence on the other. But in heating operation, the influence of one indoor unit temperature to the other unit temperature became larger. Also the time needed to reach steady state in heating operation was larger than that in cooling operation. The change of refrigerant flow direction and relative position of each component seem to be the main cause of

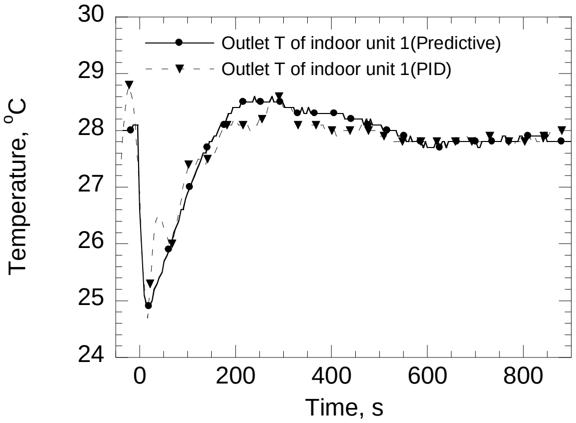

Figure 9. Secondary fluid outlet temperature of indoor unit 1 when indoor unit 2 was turned on at heating mode

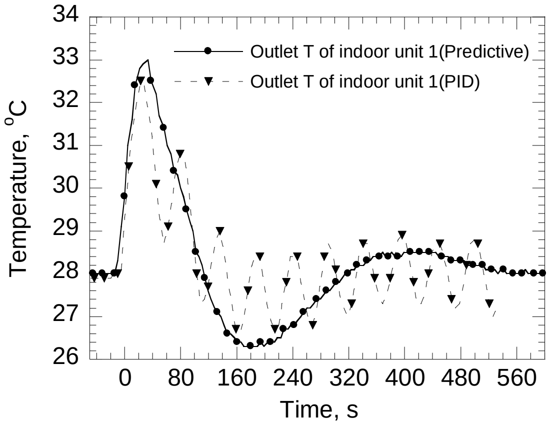

Figure 10. Secondary fluid outlet temperature of indoor unit 1 when indoor unit 2 was turned on at heating mode

this difference in temperature variation for several operation modes.

When number of operation units was changed PID control logic with fixed coefficients failed to achieve a steady state. In using PID control logic with fixed coefficients, it is assumed that system undergoes a little change during operation. This is true when both indoor units operated. But when number of operating units were changed, above assumption is not easily applied, therefore PID control logic considering 2 operating indoor units failed to properly control indoor units. Adaptive control logic which is similar to predictive control logic is needed for better control of the system performance.

NOMENCLATURE

d : time delay [s]

P : pressure [kPa]

q^{-1} : unit backward shift operator

T : temperature[^{o}C]

$u(t)$: input

$y(t)$: output

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