THE PERFORMANCE OF PIP-CASCADE CONTROLER IN HVAC SYSTEM

by

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Primitive controllers used in the early version for HVAC systems, like the on-off (Bang-Bang) controller, are inefficient, inaccurate, unstable, and suffer from high-level mechanical wear. On the other hand, other controllers like PI and cascade controllers, overcome these disadvantages but when an offset response (inaccurate response) occurs, power consumption will increase. In order to acquire better performance in the central air-conditioning system, PIP-cascade control is investigated in this paper and compared to the traditional PI and PID, in simulation of experimental data. The output of the system is predicted through disturbances. Based on the mathematical model of air-conditioning space, the simulations in this paper have found that the PIP-cascade controller has the capability of self-adapting to system changes and results in faster response and better performance.

Key words: *PIP-cascade control, traditional control, HVAC system, disturbance rejection*

Introduction

Heating, Ventilation and Air-Conditioning (HVAC) systems are widely used in different environments. HVAC systems are composed of a large number of subsystems, each of which may exhibit time-varying and/or nonlinear characteristics as shown by Jiangjiang et al, [1]. Furthermore, increase in capacitance of building structure raises thermal inertia, as shown in [2]. It would be very difficult to dedicate control system to a specific building due to great variety of building technologies and its dynamical properties. Such these complexities indicated that the use of some simple control schemes (like on-off control that many HVAC systems are using) may not be appropriate for some of the new load-management technologies and systems. Traditional PI controller sometimes doesn't satisfy the control purpose for the object, which has large inertia, delay and nonlinear characteristic and uncertain disturbance factor, like the tall and big space, because of the dissatisfaction of tuning parameters, the effect of dissatisfying performance and the adaptability to different running medium, [3-4]. To overcoming the failing of traditional PI control, we will use cascade control. Cascade control is especially useful in reducing the effect of a load disturbance that moves through the control system slowly, [5]. The inner loop has the effect of reducing the lag in the outer loop, resulting in the cascade system

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responds more quickly with a higher frequency of oscillation. Simulations have illustrated this effect of cascade control, [6-7].

In this study, the heat exchanger and air-conditioning space in the HVAC system are modeled. Then the PIP-cascade control system is presented. Through the simulation in the HVAC system, it is found that the PIP controller enhances the stability and rejects the disturbance and the cascade control increases the response speed and control precision in the HVAC system.

Mathematical model for HVAC system

There are basically two ways of determining a mathematical model of a system: by implementing known laws of nature or through experimentation on the process, [8-9].

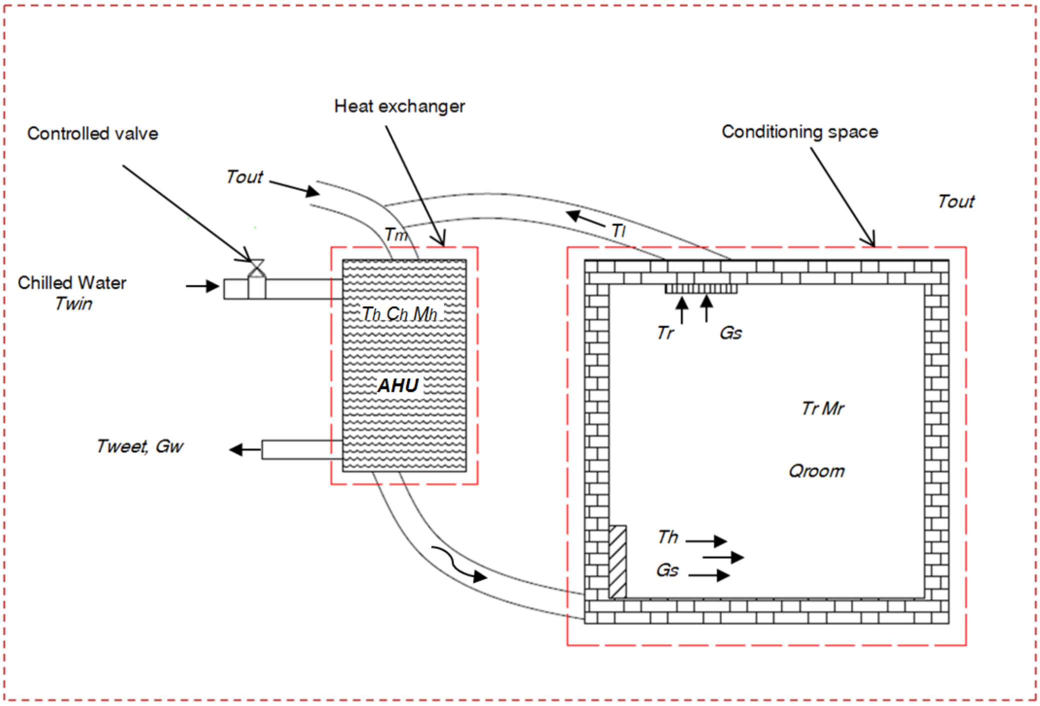

Figure 1. Room-air conditioning system

The first one will take to obtain the mathematical model for HVAC which contain from the first part is the air-processing unit (heating/cooling system) and the second part is the air-conditioning room. These two parts are illustrated in Figure 1.

Heat exchanger model

Based on the law conservation of energy, the thermal balance equation is introduced by Wang et al, [10]:

$$M_h C_h \frac{dT_h}{dt} = G_a C_a (T_m - T_l) - G_w C_w (T_{wout} - T_{win}) \tag{1}$$

The transfer function of air temperature can be derived from (1):

$$\frac{T_l(s)}{\dfrac{G_a C_a T_m}{C_w(T_{wout}+T_{win})}+G_w(s)}=\frac{C_w(T_{wout}+T_{win})}{G_a C_a(\dfrac{M_h C_h S}{G_a C_a}+1)}$$

$$G_1(s)=\frac{T_l(s)}{G_r(s)+G_w(s)}=\frac{K_1}{T_1 S+1}e^{-\tau_1 s} \tag{2}$$

where K_1 is the coefficient of amplify, (C^O.s /kg); T_1 is time constant, (s); τ_1 is the pure time delay of the controlled object, (s); G_r is the disturbance of heat exchanger, (kg/s) where:

$$T_1=\frac{M_h C_h}{G_a C_a},\quad K_1=\frac{C_w(T_{wout}+T_{win})}{G_a C_a},\quad G_r=\frac{G_a C_a T_m}{C_w(T_{wout}+T_{win})}$$

Conditioning space model

The supposition for the temperature control model of air-conditioning space is described as follows: firstly the space is air tight and there is not the direct heat exchange between indoors and outdoors; secondly the temperature in the space is almost equal; thirdly the heat capacity of the door, windows and the goods in the space is ignored. The thermal balance equation is similar to the heat exchanger by Wang etal. (2007a).

$$M_r C_r\frac{dT_r}{dt}=G_a C_a(T_s-T_r)+\frac{T_{out}-T_r}{R}Q_{room} \tag{3}$$

Here, the supply air temperature to room is the handling air temperature after AHU and $T_s=T_l$ .Assumption is that the specific heat capacity of air in air-conditioning room is equal to specific heat capacity of supply air and $C_r=C_a$. The transfer function of conditioning space temperature can be derived from (3).

$$\frac{T_r(s)}{T_s(s)+\dfrac{\dfrac{T_{out}}{R}+Q_{room}}{G_a C_a}}=\frac{G_a C_a}{(G_a C_a+\dfrac{1}{R})(\dfrac{M_r C_a S}{G_a C_a+\dfrac{1}{R}}+1)}$$

$$G_2(s)=\frac{T_r(s)}{T_s(s)+T_f(s)}=\frac{K_2}{T_2 S+1}e^{-\tau_2 s} \tag{4}$$

where K_2 is the amplify coefficient of room, (C^O. s /kg); T_2 is time constant, (s); τ_2 is the pure time delay of the controlled object, T_f (s) is the disturbance to room, which include the disturbances from outdoor and indoor, (C^O). Here,

$$T_2=\frac{M_r C_a}{G_a C_a+\dfrac{1}{R}},\qquad K_2=\frac{G_a C_a}{G_a C_a+\dfrac{1}{R}},\qquad T_f=\frac{\dfrac{T_{out}}{R}+Q_{room}}{G_a C_a}$$

The following transfer function of heat exchanger and conditioning space can be derived from (2) and (4):

$$G(s) = G_1(s) \times G_2(s) = \frac{K_1 K_2}{[(T_1 S + 1)(T_2 S + 1)]} e^{-\tau s} \tag{5}$$

Control system design

An air-handling unit for a commercial building consists of a fan, heating-coil and discharge air duct to deliver heated/cooled air into the space. In a conditioned space, a temperature sensor measures the temperature and sends signal to temperature controller which controls a steam (or chilled water) valve on the heating coil. Return air from the space is mixed with outdoor air at the inlet to the fan. The fixed ratio of outdoor air to return air is used to meet the requirements for ventilation as shown in Figure 2. In normal operation, the temperature controller does an adequate job of maintaining a stable space temperature. However, in the particular climate of this application, the outside air temperature sometimes drops very rapidly. When it does the mixed air temperature drops, as does the discharge air temperature. This eventually causes a drop in the space temperature. The temperature control loop senses and corrects for this, but because of the large volume of space, it takes an excessively long time to recover to the desired temperature. We can improve the control system to alleviate this problem, by adding an intermediate measurement which is used in an inner feedback loop that will encompass the disturbance, [5].

The inner loop measures the discharge temperature and let that control the steam valve, as shown in Figure 2.When the outside air temperature drops, and consequently the mixed air temperature, the discharge temperature controller will sense this. The discharge temperature control loop will be rapid, in comparison with the space temperature control loop. Hence, the discharge temperature will be maintained approximately constant at its set point, [5].

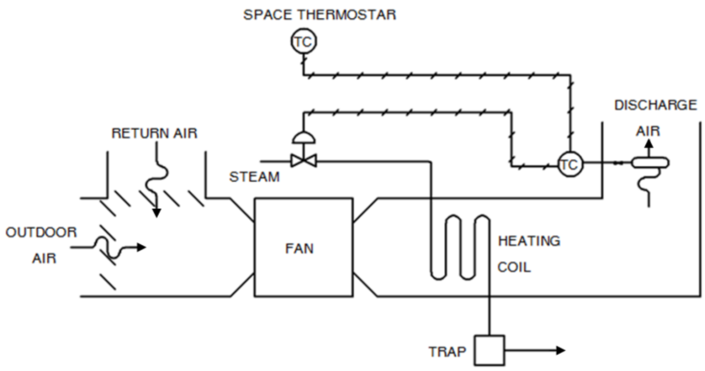

Figure 2. A Cascade Control Application in the HVAC

The design and tuning of the cascade control system and traditional controllers are achieved using Simatic software. Two function blocks are used to simulate the control systems. The FB58 is PID temperature control package containing PID controller with self-tuner. The processes are simulated using FB100 which it can represent processes with third order time lag. The two processes inner heat exchanger and outer room are approximated as first order plus time delay (FOPTD). Two bump tests are conducted to generate the dynamic process response data (process gain, time constant, dead time) needed to design and tune the two controllers in a cascade implementation. A reliable procedure begins with the PI outer primary controller in manual mode as we apply the design and tuning recipe to the P inner secondary controller. The objective for the inner secondary controller is timely rejection of disturbances based on the measurement of secondary process variable. Since we expect the inner secondary controller to respond crisply to the rapid changing set point commands from the output signal of the outer primary controller, the loop is tuned to provide good set point tracking performance. The balance between disturbance rejection and set point tracking capability for the inner secondary controller is considered.

Once implemented, the inner secondary controller literally becomes part of the process from the outer primary controller's view. Therefore, the outer primary controller is tuned approximating the overall process as second order plus time delay (SOPTD).

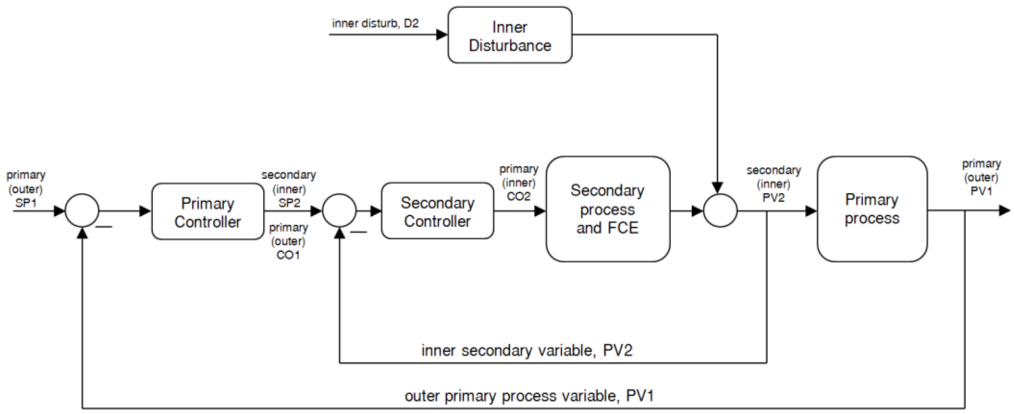

Figure 3. Block diagram of cascade PIP control

To accomplished fair comparison between the cascade and traditional controllers performance (set-point tracking, disturbance rejection, load parameters variations) in HVAC system, all controllers are moderately tuned. Table 1 shows the all controllers parameters which are used to produce the acceptable performance of the control systems.

Table 1. Controller design and tuning parameters

Controller	Proportional gain (K_C)	Integral time (T_I)	Derivative time (T_D)
Cascade secondary(P)	12		
Cascade Primary (PI)	10	50 s	
Traditional (PI)	0.3	110 s	
Traditional(PID)	0.4	90 s	1 s

Simulation

The parameters of the HVAC system are as follows: the volume of air conditioning room is 8m length, 6m width and 4m height; the air specific heat capacity is C_a=1.0 kJ/kg^{0}C; the water specific heat capacity is C_w=4.18 kJ/kg^{0}C and for heat exchanger C_h=0.5 kJ/kg^{0}C.The quality of heat exchanger is M_h=80 kg and for air conditioning room M_r=416 kg. Based on the criterion in the heating, ventilation and air-conditioning field, and the number of taking a breath in air-conditioned room, the calculation of the supply air is G_a=1.0 kg/s, the heat resistance of wall is 1/R=0.3 KW/^{0}C and the temperature error of supply hot-water and back-water to the heat exchanger in winter is T_{win}-T_{wout}=5 ^{0}C. Lastly, the parameters of the middle process, heat exchanger, are calculated as following: K_1= 20.9 ^{0}Cs/kg, T_1=40s. The parameters of air-conditioned room are calculated as follows: K_2=0.8 ^{0}Cs/kg, T_2=320 s. So the controlled object G_1(s) and G_1(s) can be expressed as, [10]:

$$G_1(s) = \frac{20.9}{40S+1} e^{-\tau_1 s} \tag{6}$$

$$G_2(s) = \frac{0.8}{320S+1} e^{-\tau_2 s} \tag{7}$$

and the disturbances from outdoor and indoor can be expressed as:

$$G_r(s) = 0.048 T_m$$
$$T_f(s) = 0.3 T_{out} + Q_{room}$$

Simulation (1): The comparison curves of three controllers are shown in Figure (4). It can be seen that the setpoint response of the PIP-cascade control system has accurate quicker response and while the traditional controllers have offset and slow response and large settling time.

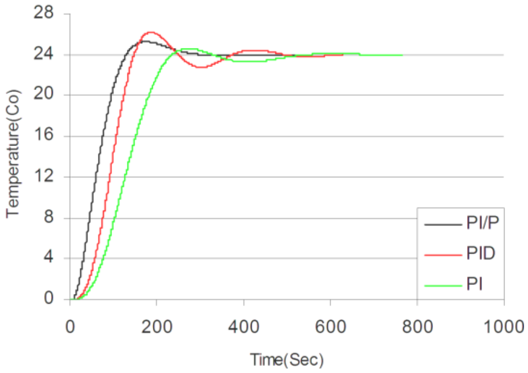

Figure 4. Set-point input response comparison

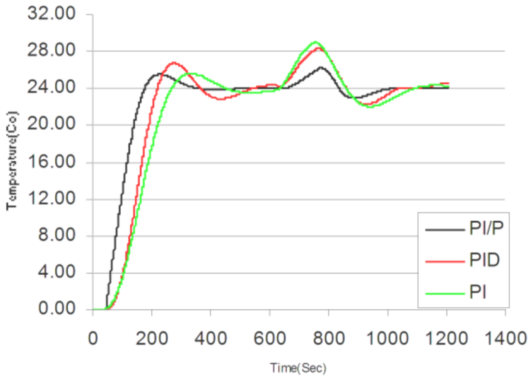

Figure 5. Disturbance input response comparison

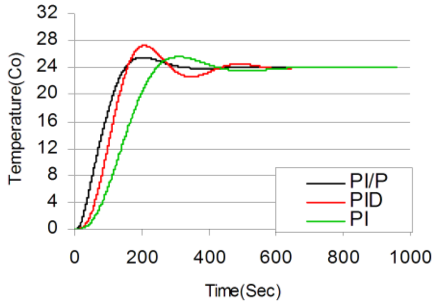

Figure 6. Robustness response comparison

Simulation (2): To certify the robustness of PIP-Cascade control in the HVAC system, the controlled process parameters are changed during simulation while the controllers are kept unchanged. The gains of the controlled process, K_1 =20.9 ^{0}Cs/Kg, K_2 =0.8 ^{0}Cs/Kg are increased to K_1 =22 ^{0}Cs/Kg, K_2 =1 ^{0}Cs/Kg respectively.

The simulation results are shown in Figure (6). It can be seen that the setpoint response is similar to the *Simulation (1).* However, the overshoot of traditional PID control is greater than the *Simulation (1).* Based on this simulation, the robustness of the PIP-Cascade control system has been proven.

Conclusion

The PIP-cascade controller is adopted the constant temperature central air-conditioning system. It has shown better performance than traditional PID and PI control system. Through simulation, PIP-cascade control has shown better robustness and adaptability for nonlinear object. The central air-conditioning system, which is controlled by PIP-cascade controller, has faster response and better performance even with the seasonal outdoor heat disturbance and uncertain indoor heat disturbance compared to the conventional system. The PIP-cascade control can also be applied to objects with large inertia, pure lag, and nonlinear characteristic and uncertain disturbance factor.

Nomenclature

Symbols

M_h The quality of heat exchanger, (kg)
AHU Air handling unit
M_r Air quality of air-conditioning room, (kg)
G_a Supply air flows ,(kg/s)
G_w Hot water (or cold water) flows,(kg/s)
C_a Specific heat capacities of air, (kJ/kg^{0}C)
C_w Specific heat capacities of water(kJ/kg^{0}C)
C_h Specific heat capacities of heat exchanger(kJ/kg^{0}C)
T_m The temperature of mix fresh air, (^{0}C)
T_l The temperature after heat exchanger, (^{0}C)
T_h Surface temperature of heat exchanger,(^{0}C)
T_{win} The temperature of supply water, (^{0}C)
T_{wout} Back-water from heat exchanger, (^{0}C)
Q_{room} Perturbation inside thermal load, (kJ)
T_{out} Uncontrolled outside temperature (^{0}C)
K_1 The amplify coefficient of heat exchanger, (^{0}Cs/kg)
T_1 Heat exchanger time constant, (s)
G_r The disturbance of heat exchanger, (kg/s)
K_2 The amplify coefficient of room, (^{0}Cs/kg)
T_2 Conditioning space time constant, (s)
T_f The disturbance to room, including disturbances from outdoor and indoor, (^{0}C).
T_s The supply air temperature to room, (^{0}C).

Subscripts

H Heat exchanger
r Room
a Air
w Water
m Mixed fresh and return air
l Leaving
W_{in} Water input
W_{out} Water output
room Inside room
out Outside room
1,2 Heat exchanger, room region
f Indoor and outdoor

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