Energy System Modeling

Secondary Plant Modeling

Abstract

This report documents the procedure used to model a secondary HVAC plant using previously derived room space models. The plant is modeled as a convective radiator system for heating and a chilled ceiling for cooling. Control of these systems is exercised using two PID controllers that were optimally tuned using the well-known Ziegler Nichols tuning procedure to minimize steady state error.

Matthew Kincaid

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Introduction

The purpose of the Energy System Simulation was to apply the previously derived room space energy models to develop a secondary plant model. The heating system was modeled as a water-based convective radiator system, using radiator properties given by the manufacturer, Myson. Similarly, the cooling system was modeled as a chilled ceiling using data from the manufacturer, Trox. Using the principle of conservation of energy, it was possible to determine the sensible heating and cooling loads in a harsh climate location (Omaha, Nebraska) and a milder climate location (Salem, Oregon). From there, the appropriate heating and cooling equipment were sized and modeled using MATLAB Simulink.

Analysis indicated that the sensible and latent cooling loads could not be met in Omaha Nebraska using a chilled-ceiling alone. It was therefore determined that a dedicated outdoor air system (DOAS) be implemented during hours in which the space was occupied. This DOAS system was modeled to introduce outdoor air at a carbon dioxide level of 400 parts per million.

After the plant was sized, it was desired to control the system using Proportional-Integral-Derivative (PID) controls that would respond to differences in the measured temperature and the specified set point, and then adjust the plan gain accordingly. As with any engineering project, it was desired to optimize the plant performance by effectively tuning the PID controllers for both heating and cooling scenarios.

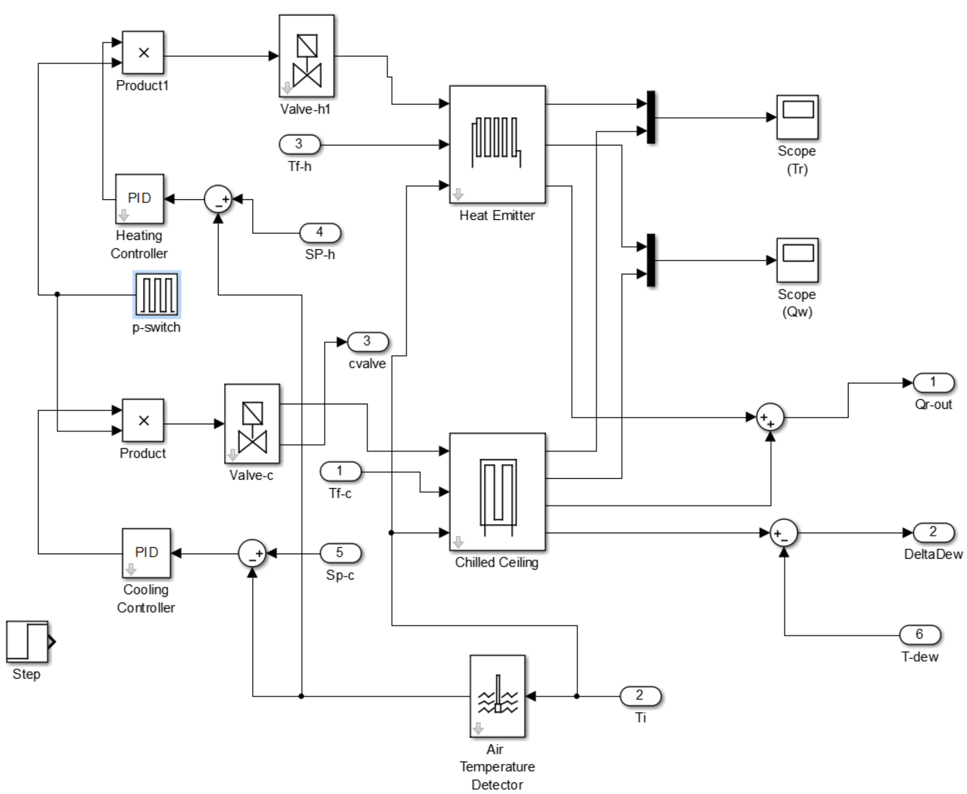

Figure 1.1. Simulink plant model prior to the addition of DOAS system.

System Sizing Calculations

Heating

To aid in the development of the thermal model, HVAC systems were sized based on the weather conditions local to Salem Oregon and Omaha Nebraska. For heating, it was desired to use water based convective radiators to meet the sensible loads. For heat load calculations, the conductive components through the wall and window were considered, along with the heating load due to infiltration. The conducive component was calculated using equations 1, while the infiltration component was determined using equation 2. Subsequent to the rated heating capacity calculation of the selected radiators, it was possible to determine the water mass flow rate required, using equation 3. It was assumed that the entering water temperature in the heating coil was 80°C and the leaving water temperature 70 °C; in accordance with industry convention. The results of these heating load calculations are summarized in table 1.

$$Q_{window\ or\ wall} = UA(T_i - T_o) \quad [1]$$

$$Q_{infil} = (ACH) * V_{room} * \rho_{air} * c_{p,air} * (T_i - T_o) \quad [2]$$

$$\dot{m} = \frac{Q_{tot}}{c_{p,air} * (T_{water,in} - T_{water,out})} \quad [3]$$

Where,

ACH= 1 air change per hour
V_{room}= 630 m^3
Density of air= 1.205 kg/m^3
$C_{p,air}$ = 1000 J/kgK

Table1. 1. Heating load calculation summary table.

Heating Load Calculations		
	Salem	**Omaha**
Internal Design Temp. [C]	23	20
Minimum Outdoor Temperature [C]	-9.3	-35
Q wall (Watts)	879	1578
Q window (Watts)	3256	5846
Q infiltration (Watts)	6811	12231
Safety Factor	1.25	1.25
Q design (Watts)	13,683	24,569
Radiator Selection	30 DPX 160 G	60 DC 200 G
Number of Radiators	12	8
Mean water temperature [C]	75	75
Heat per Radiator (Watts)	1155	3299
Q rated (Watts)	13,960	26,392
Mass flow rate (kg/s)	.33	.63

Cooling

For modeling purposes, the proposed space was to be cooled using a chilled ceiling. This chilled ceiling design was to be implemented using panels manufactured by Trox-technik, Type WK-D-UM. The cooling loads for Salem and Omaha were calculated using the same methodology as heating loads with the aid of equations 1 and 2. This then allowed for the required water mass flow rate to be computed using equation 3. The entering and leaving water temperatures were specified to be 13° C and 15° C, respectively. These values were chosen to keep the coil temperature above the room dew point (12°C) while maintaining a relatively small temperature differential. The results of these computations are shown in table 2.

To determine the required ceiling fraction (f) of the chilled ceiling, equation 4 was used, where k is the overall emission constant for the emitter and was given by the manufacturer to be 8.57 $Wm^{-2}K^{-1}$.

$$f = \frac{Q_{design}}{k * A_{ceiling}(T_{water,avg} - Ti,design)} \quad [4]$$

Table 1.2. Cooling Load calculations summary.

Cooling Load Calculations		
	Salem	**Omaha**
Internal Design Temp [C]	23	23
Max. Outdoor Temp [C]	35	38
Max. Outdoor Sol-Air Temp[C]	55	60
Q wall (Watts)	870	1006
Q window (Watts)	3226	3730
Q infiltration (Watts)	2531	3163
Safety Factor	1.25	1.25
Q design (Watts)	8,284	9,874
Ceiling Fraction	0.5	0.6
Q actual (Watts)	8300	9900
Water Mass Flow Rate (kg/s)	0.993	1.18

Manual Tuning Procedure

Manual tuning of the heating and cooling PID controllers using weather and solar data from both Salem and Omaha. The proportional gain was successively doubled until a sustained oscillation was observed in temperature set point tracking. Once a sustained oscillation was seen, the proportional gain was halved, and thus value was taken to be optimal. The integral gain coefficient was solved for in a similar way, by starting with a small value and doubling until sustained oscillation was observed. It was assumed for this procedure that derivative control would not introduce any appreciable benefits and was therefore set to zero for this analysis. The values attained are shown in table 1.3

Table 1.3

	Proportional Gain	**Integral Gain**
Omaha, Summer	-4	-1/250
Omaha, Winter	16	16/225
Salem, Summer	-2	-8/125
Salem, Winter	8	8/125

Closed Loop System Response Test

Heating Discussion

After the manual tuning process, it was of interest to perform a closed-loop system response test for Omaha to tune the PID controllers using the Ziegler-Nichols procedure. This was done by replacing the weather data with constant values to eliminate disturbances due to climate and solar variation. Specifically,

- Outdoor temperature= 0 ° C
- Solar gains= 0 Watts
- Wind speed= 0 m/s
- Relative humidity= 50%.

A step change was then performed on the heating set point, increasing it from 20° C to 20.5°C. The proportional gain was then increased iteratively to determine the ultimate critical gain (Ku) at which the temperature became unstable, and the associated critical period, Tu. It was then possible to tune that P-only, PI and PID control parameters in accordance with the Ziegler-Nicolas tuning procedure. The selection of these parameters is shown in table 2.1. In order to compare the performance of the P, PI and PID configurations, an integral-squared error function (ISE) was used, as shown by equation 5. Note that the bounds on integration determine the error from the time the step change occurs, to 3 hours after the step change.

$$\int_{t_{step}}^{t_{step}+3hours} [e(t)]dt \qquad [5]$$

Table 2.1

Closed Loop Heating Parameters				
	Kp	**Ki**	**Kd**	**ISE**
P	72	0	0	50.919
PI	64.8	0.111086	0	56.14
PID	86.4	0.246857	7560	55.966
Ku	144			
Tu	700			

The system response for each of these PID tuning configurations is shown on the following pages. The PID controller responded to the step point change most quickly and provided the best control of the three configurations. However, as seen in figure 2.4, the derivative component caused the valve position to behave somewhat erratically, which would cause the valve actuator to ware out more quickly. This must be weighed against the desire for improved control.

Heat Figures

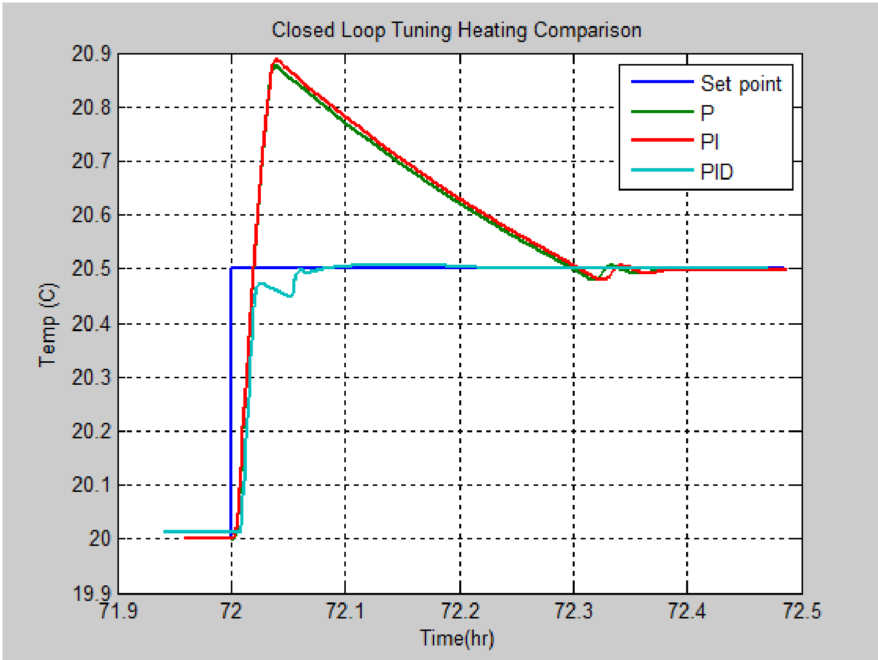

Figure 2.1. Comparison of response to heating set point step change of P, PI and PID configuration.

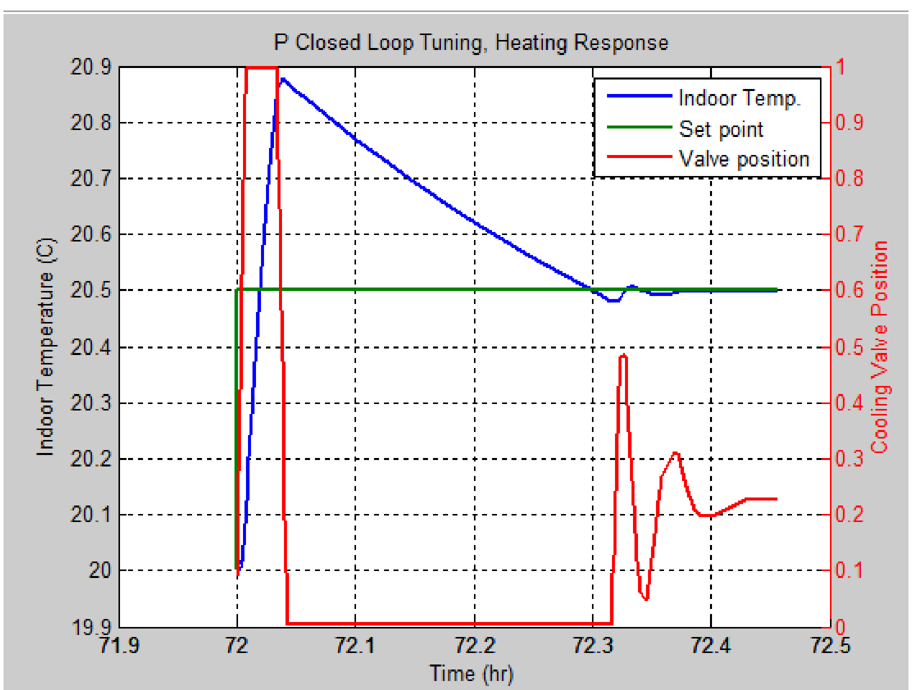

Figure 2.2. Heating valve and temperature response to set point change for P-only controller.

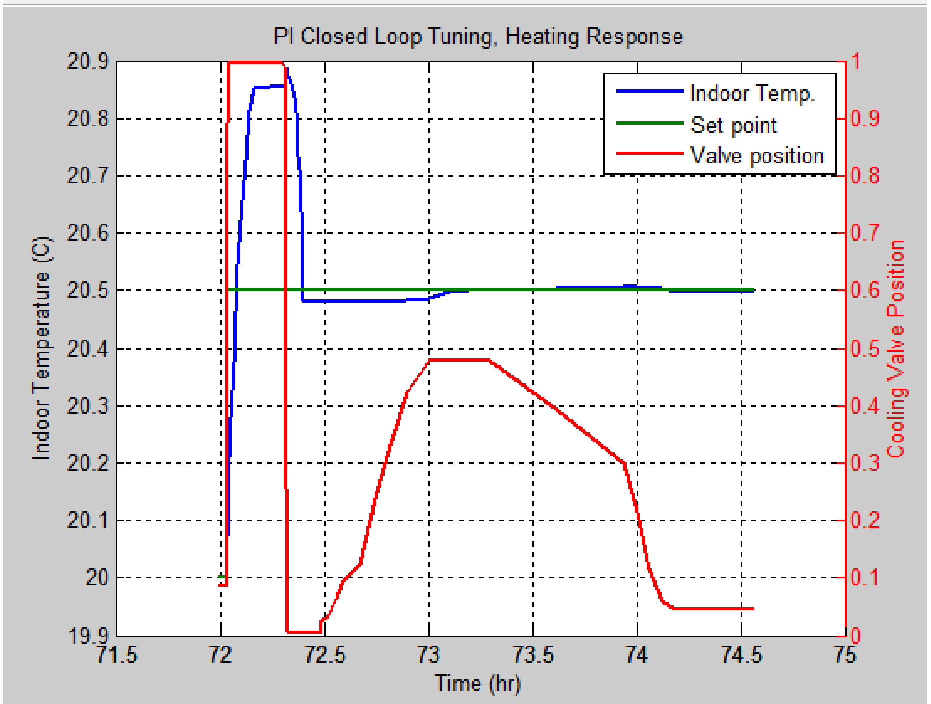

Figure 2.3. Heating valve and temperature response to set point change for PI controller.

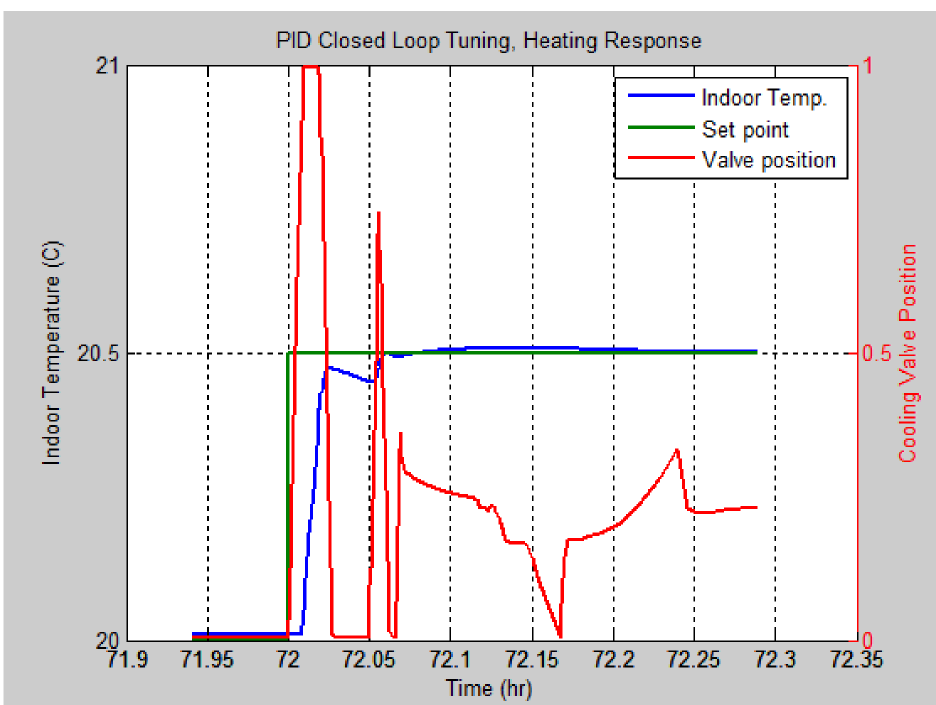

Figure 2.4. Heating valve and temperature response to set point change for PID controller.

Cooling Discussion

The chilled ceiling, PID controller was tuned in a manner similar to heating. Again, weather data was replaced with reasonably constant values, and a step change performed on the set point to analyze the system response. Specifically,

- Outdoor temperature= 35 ° C
- Solar gains= 500 Watts
- Wind speed= 0 m/s
- Relative humidity= 50%.
- Set point decreased from 23°C to 22.5°C

The proportional gain was then increased iteratively to determine the ultimate critical gain (Ku) at which the temperature became unstable, and the associated critical period, Tu. It was then possible to tune that P-only, PI and PID control parameters in accordance with the Ziegler-Nicolas tuning procedure. The selection of these parameters is shown in table 2.2. The integral squared error procedure of equation 5 was then used to compare the performance of each configuration.

Table 2.2

Closed Loop Cooling Parameters				
	Kp	**Ki**	**Kd**	**ISE**
P	32	0	0	60.204
PI	28.8	0.0432	0	62.82
PID	38.4	0.096	3840	81.37
Ku	**64**	-	-	-
Tu	**800**	-	-	-

Similar to the heating system response, the introduction of derivative control led to the valve position to behave erratically (see figure 2.8), which could be undesirable. Further, derivative control resulted in the largest ISE, of the three configurations and is, therefore, not recommended for this application.

Cooling Figures

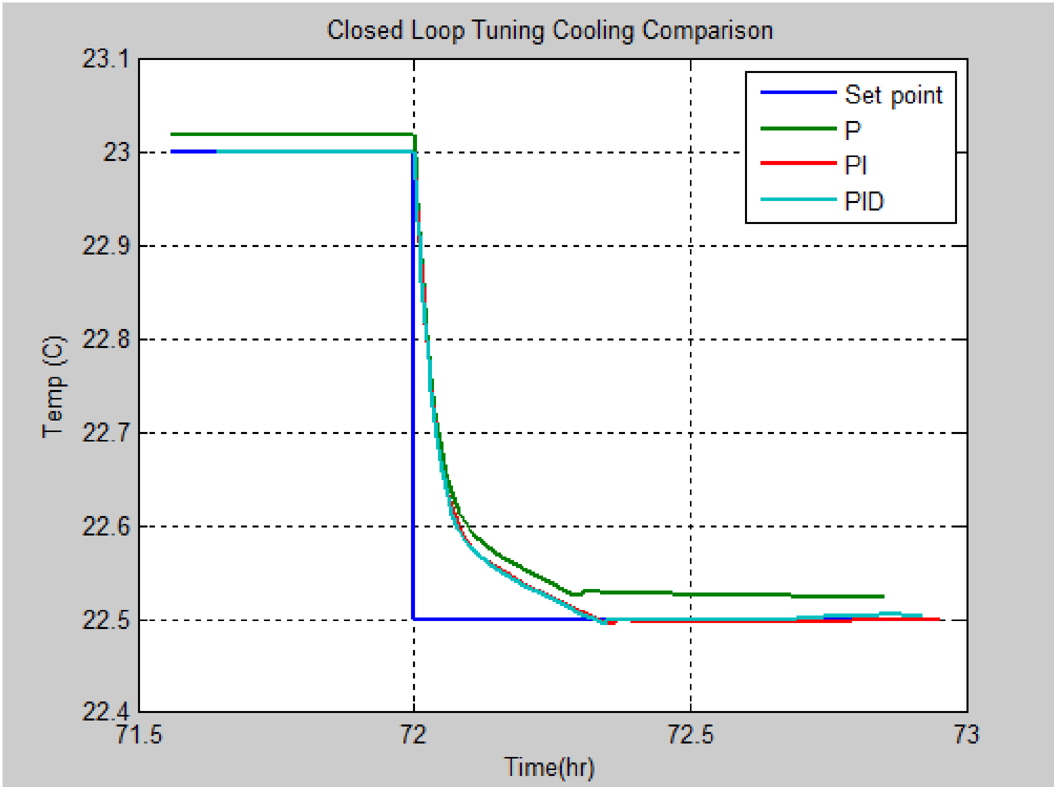

Figure 2.5. Comparison of response to heating set point step change of P, PI and PID configuration.

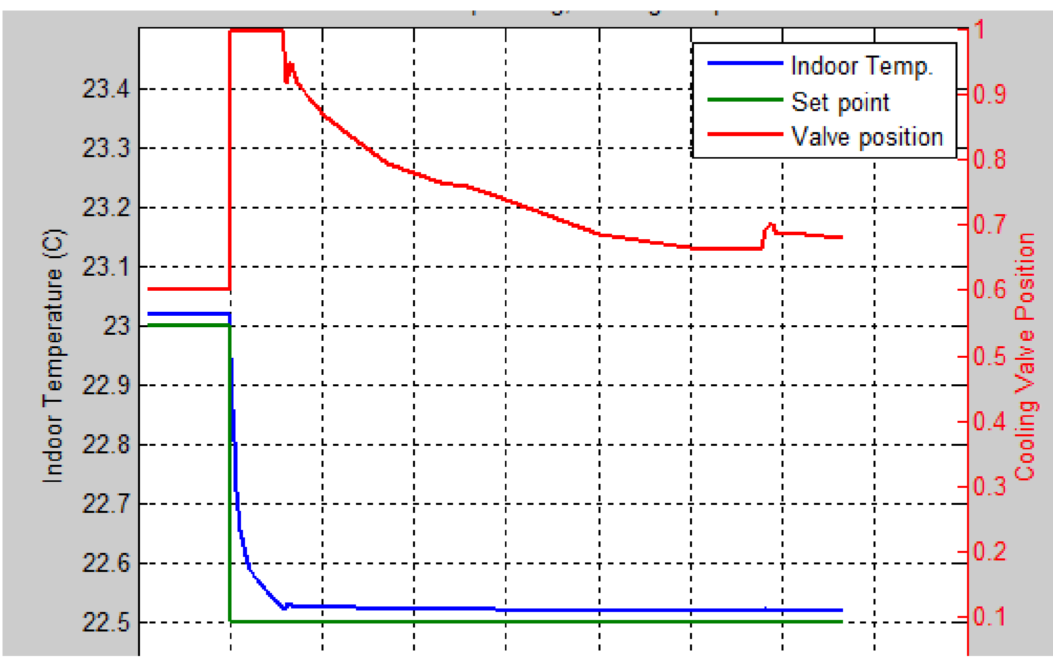

Figure 2.6. Cooling valve and temperature response to set point change for P-only controller.

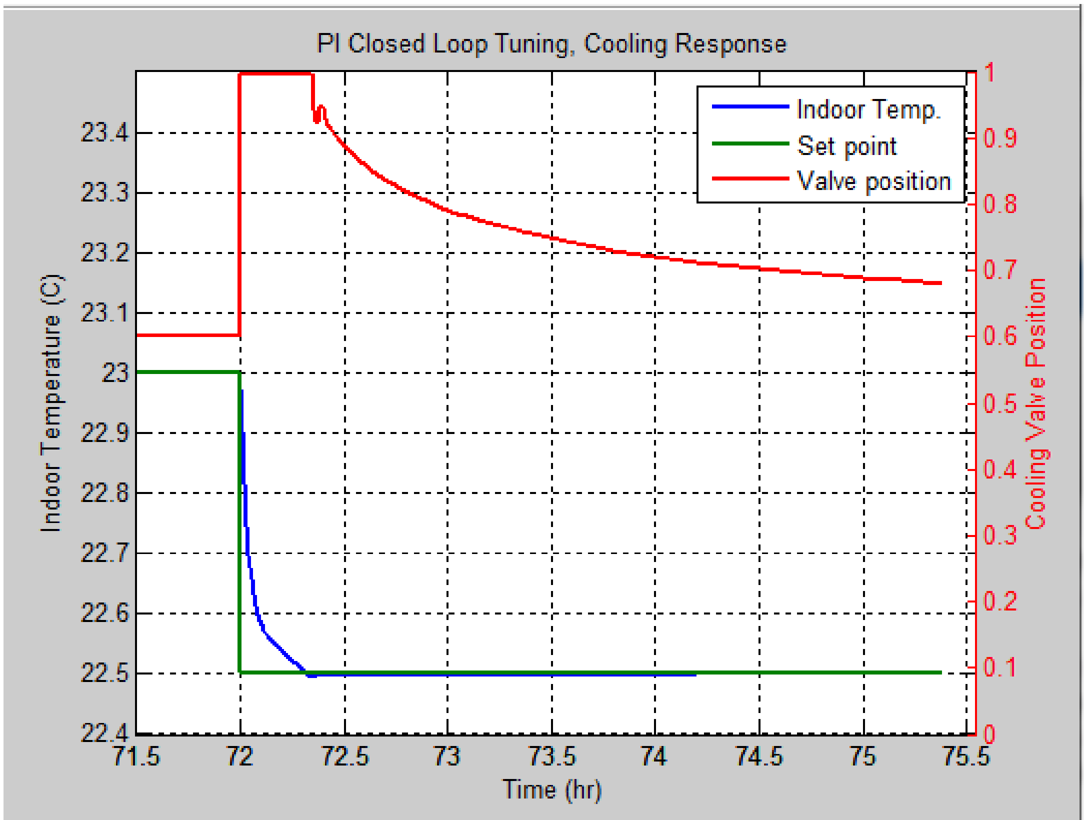

Figure 2.7. Cooling valve and temperature response to set point change for PI controller.

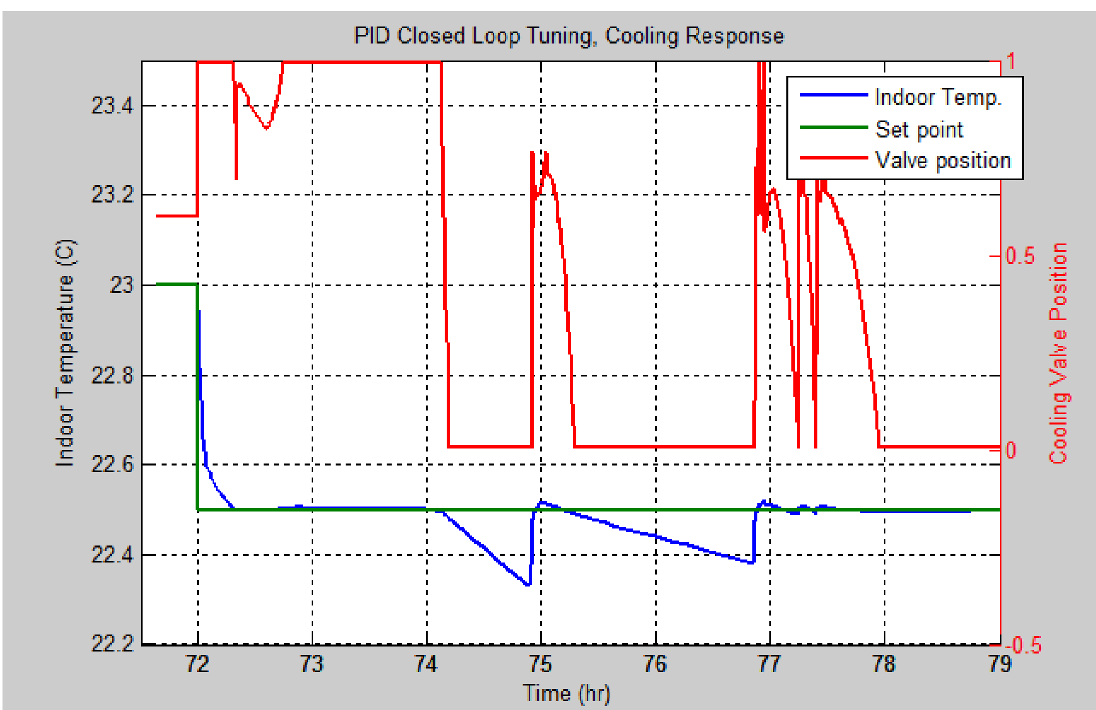

Figure 2.8. Cooling valve and temperature response to set point change for PID controller.

Open-Loop System Response Test

Subsequent to the closed loop tuning procedure, it was of interest to adjust the PID parameters based on the Ziegler-Nichols method for an open control loop. For both heating and cooling scenarios, weather data was replaced with reasonably constant values and a step change was performed on the PID controller output to observe the system response. Specifically, it was possible to observe the system process gain (K), the response dead time (alpha), the response lag time (tau), and the degree of difficulty (S). Ziegler-Nichols was then applied to optimize the PID parameters.

Heating results

Open loop analysis of the heating system was performed by replacing the PID controller output with a step change, increasing from 0.4 to 0.6. The system response was then observed to attain the values in table 3.1. The Ziegler-Nichols procedure was the applied to calculate the values in table 3.2. The PID controller was then reintroduced and a heating set point change was applied to compare the ISE for each configuration.

Table 3.1

System Parameters, Heating	
K	19
Dead time (seconds)	45
Lag Time (seconds)	5792
Degree of Difficulty	0.0078

Table 3.2. Heating PID parameters and the integral squared error.

Open Loop Heating Parameters				
	Kp	**Ki**	**Kd**	**ISE**
P	6.768	0	0	84.2
PI	7.238	0.048	0	57.35
PID	8.122	0.089	184.615	30.4807

The response with each PID configuration is shown on the following pages. Each configuration yielded very similar responses, with the PID option resulting the smallest ISE. It is therefore ideal to implement the PID configuration for this particular system.

Heating Figures

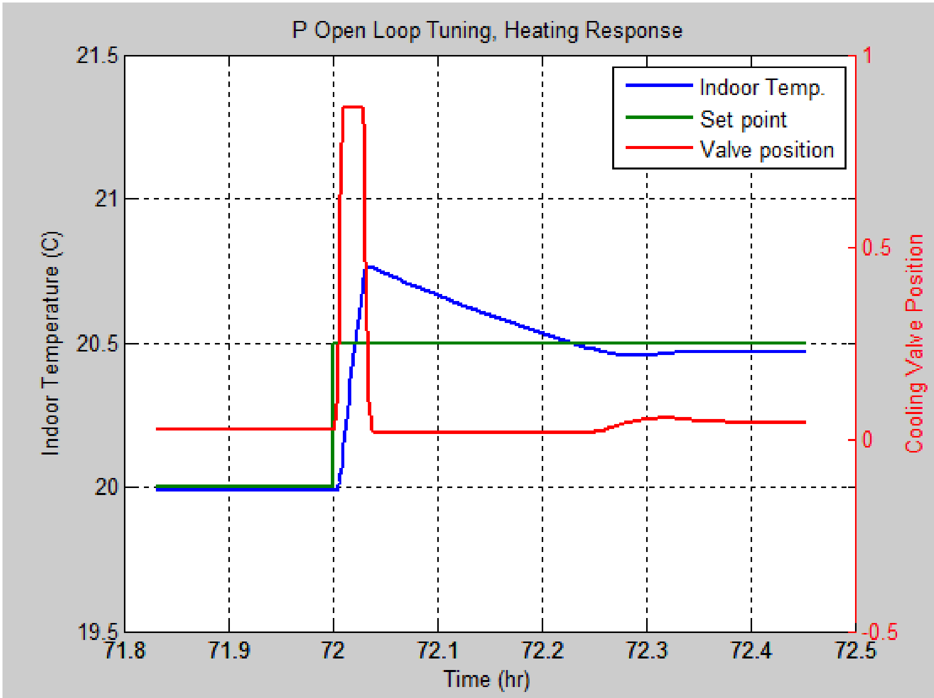

Figure 3.1. Heating valve and temperature response to set point change for open loop P-only controller.

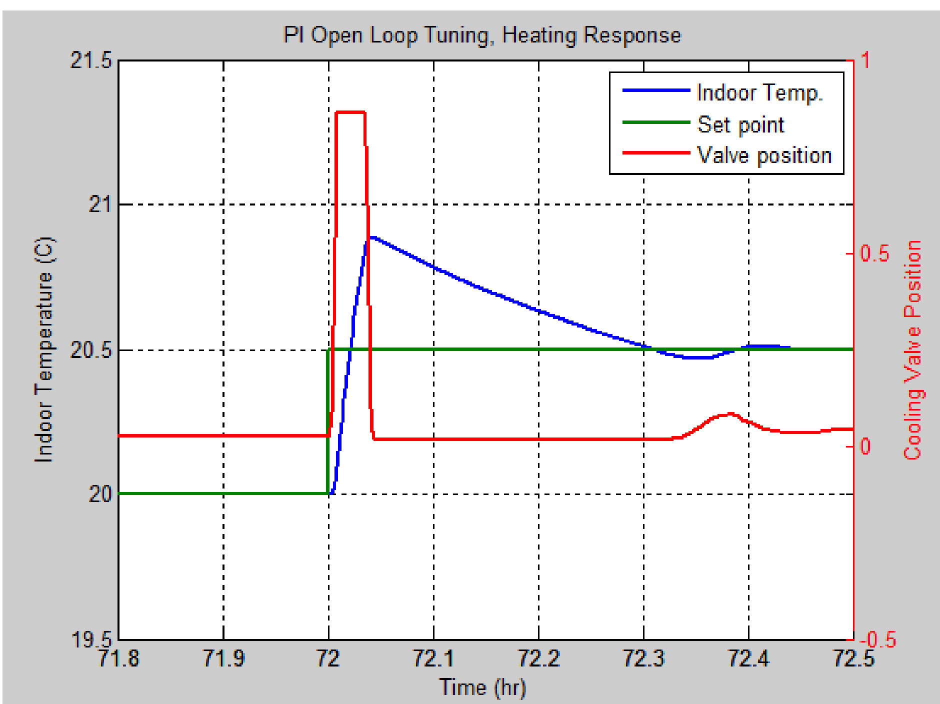

Figure 3.2. Heating valve and temperature response to set point change for open loop PI controller.

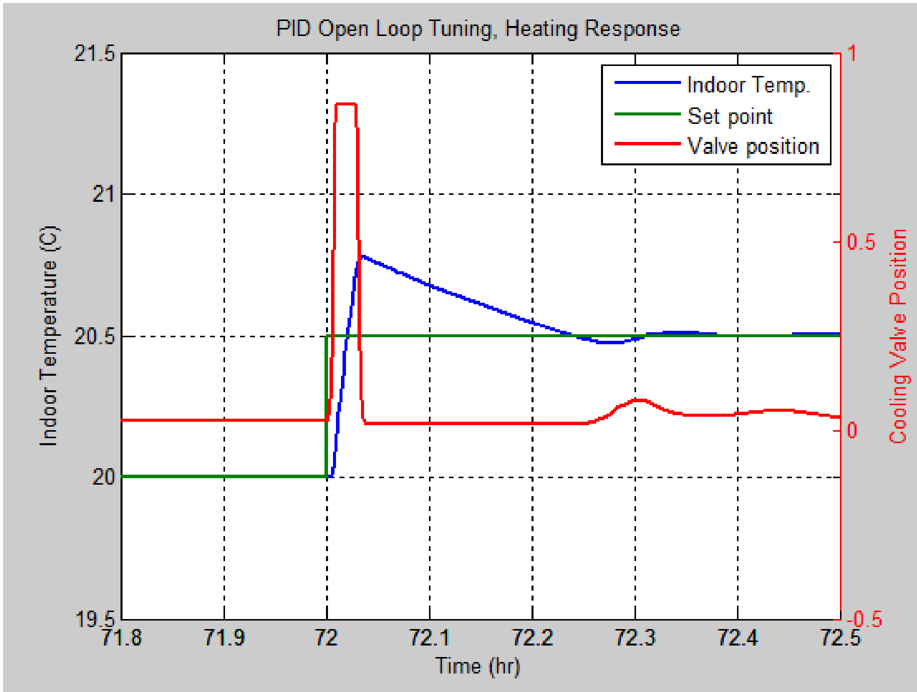

Figure 3.3. Heating valve and temperature response to set point change for open loop PID controller.

Cooling results

Open loop analysis of the heating system was performed by replacing the PID controller output with a step change, increasing from 0.4 to 0.6. The system response was then observed to attain the values in table 3.3. The Ziegler-Nichols procedure was the applied to calculate the values in table 3.4. The PID controller was then reintroduced and a cooling set point change was applied to compare the ISE for each configuration.

Table 3.3.

System Parameters, Cooling	
K	-10
Dead time (seconds)	16
Lag Time (seconds)	1286
Degree of Difficulty	0.013

Table 3.4

Open Loop Cooling Parameters				
	Kp	**Ki**	**Kd**	**ISE**
P	-7.67	0	0	645
PI	-4.85	-0.09	0	21.36
PID	-9.21	-0.28	-75.79	901

The PI configuration resulted in the best control of the three different parameter settings, by a significant margin. The introduction of the derivative component had the effect of creating instability in the system, as evidenced by the sustained oscillation seen in figure 3.6. This is likely due to the fact that the Ziegler-Nichols procedure is recommended primarily for systems with a degree of difficulty between 0.1 and 1.0. This system had a degree of difficulty of 0.013, possibly indicated that Ziegler-Nichols is not appropriate and therefore resulted in less than optimal tuning. For the purpose of Simulink modeling, both open and closed loop tuning are equally practical. However, in the field, closed loop tuning is more practical because it requires only and adjustment to the thermostat and measurements of the interior temperature (both of which are easy to do). Open-loop tuning, however, would require the manual adjustment of a PID controller which might be difficult or dangerous to do.

Cooling Figures

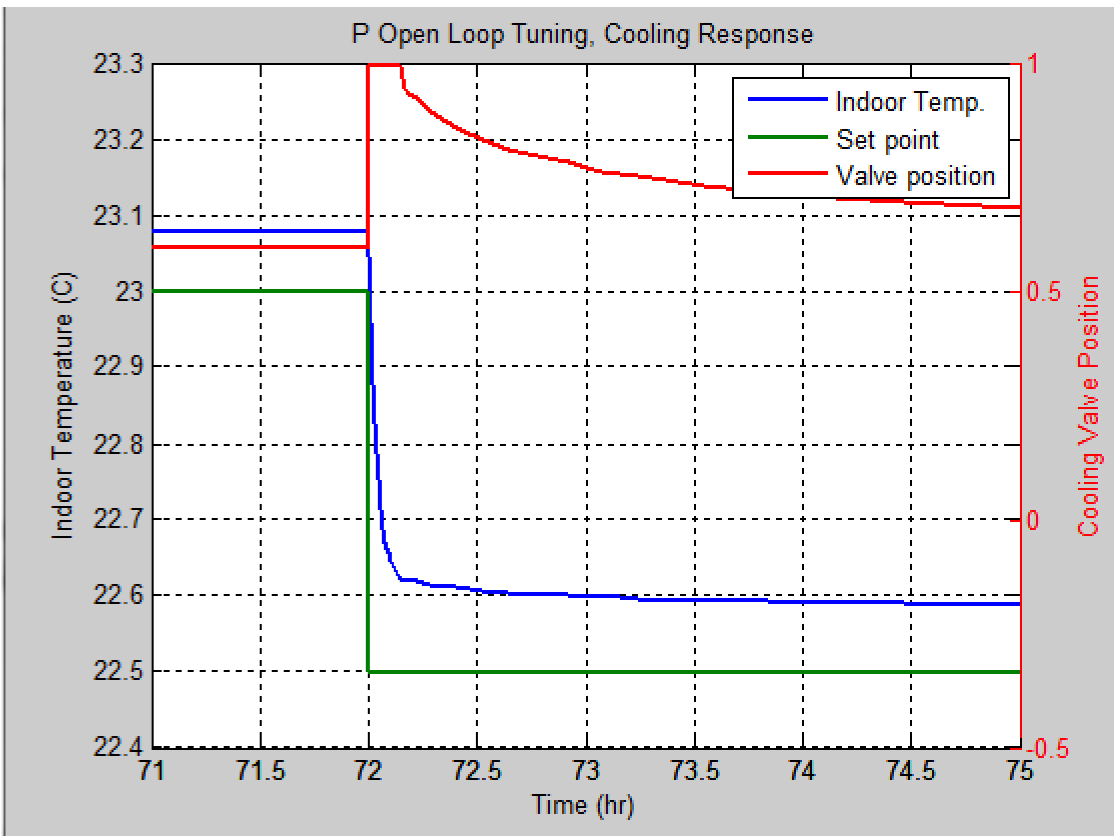

Figure 3.4. Cooling valve and temperature response to set point change for open loop P-only controller.

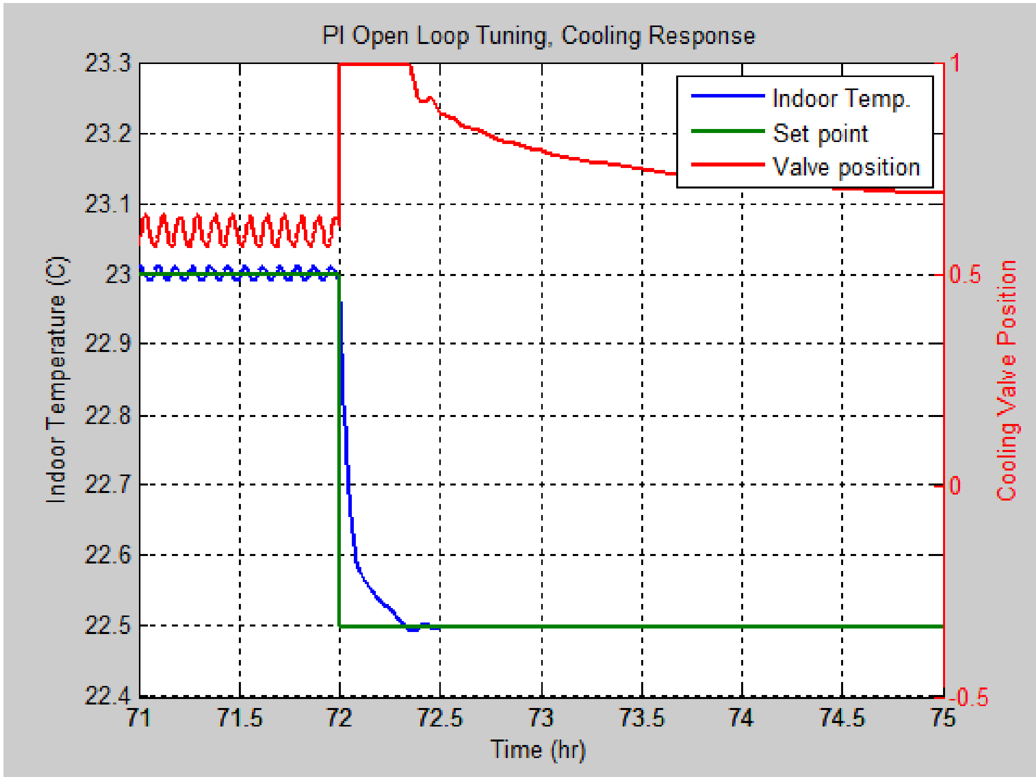

Figure 3.5. Cooling valve and temperature response to set point change for open loop PI controller.

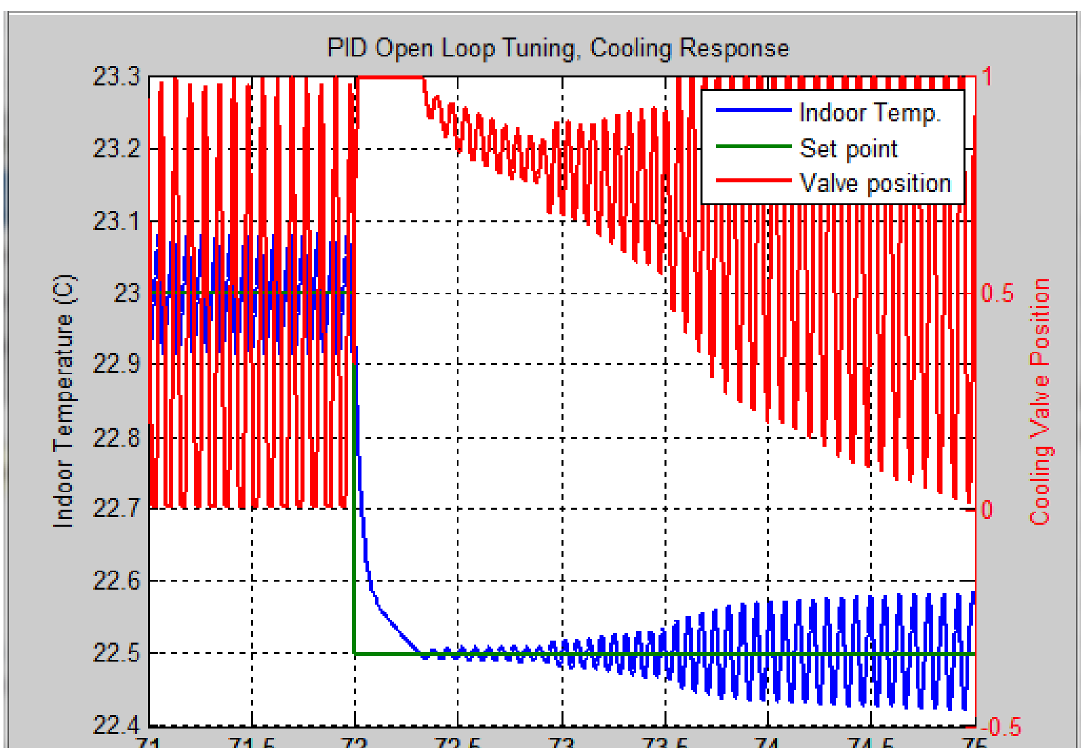

Figure 3.6. Cooling valve and temperature response to set point change for open loop PID controller.

Tuning method comparison

For the cooling scenario, the open-loop method provided the best control, while the closed loop method worked better for heating. The manual comparison had the obvious weakness of subjectivity and the introduction of human error. The closed loop procedure had a similar weakness, in that the proportional gain was determined iteratively and subjectively, which could lead to errors. The response of the best PID parameters found using each tuning method is shown below in figures 4.1 and 4.2.

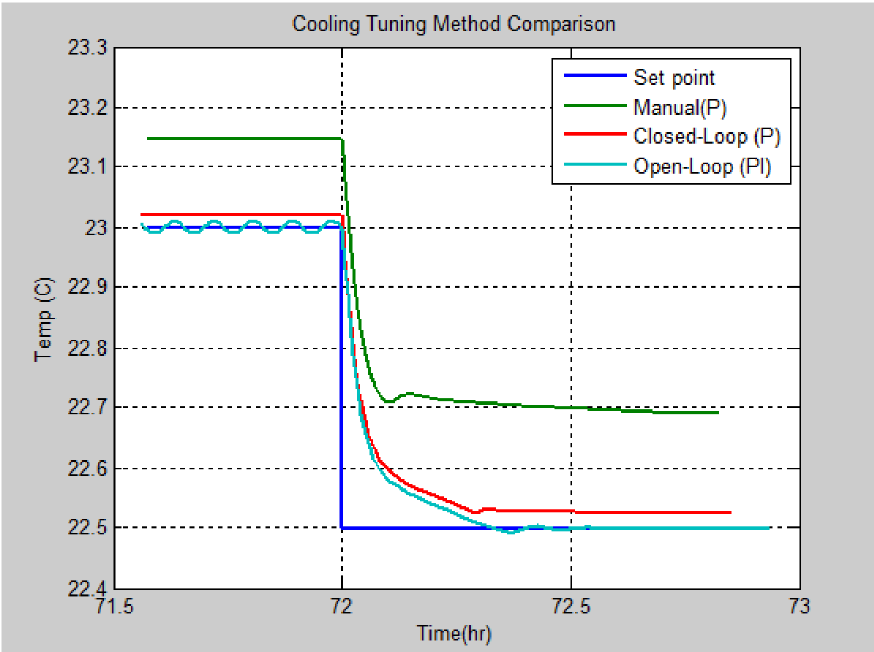

Figure 4.1. Comparison of best PID parameters found for cooling.

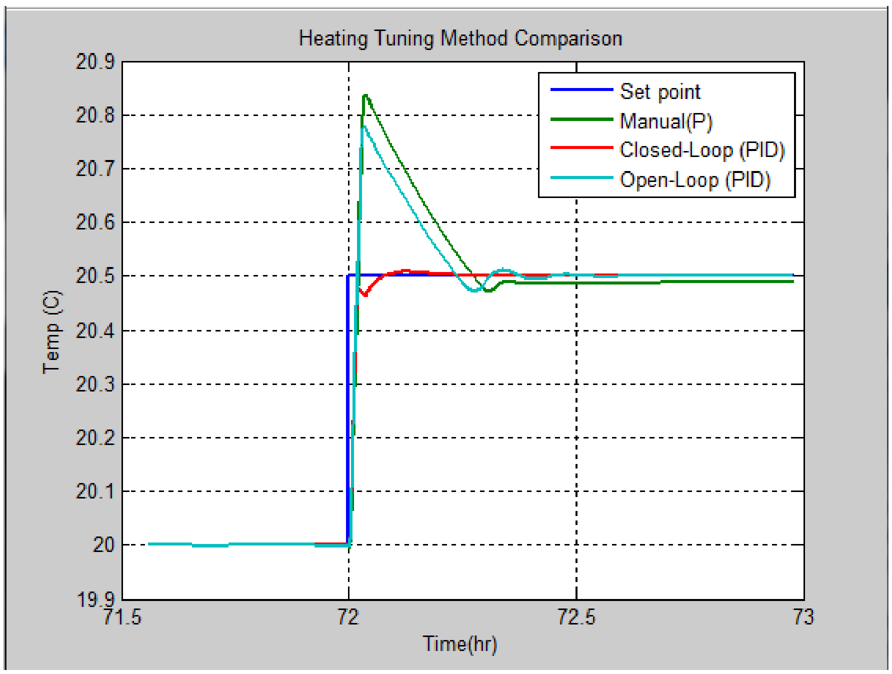

Figure 4.2. Comparison of best PID parameters found for heating.