Design of Temperature and Humidity Control System for Environmental Testing Apparatus

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Abstract

Environmental testing apparatuses are widely used for testing endurance of industrial products to both temperature and relative humidity (hereinafter called humidity). It means that both of these physical values inside of environmental testing apparatus are changed over a wide range to evaluate the durability of the industrial products. These two physical values are changed automatically, and may be changed separately or simultaneously. The goal of this study is to control these two physical values effectively. In general, commercially available environmental testing apparatuses have pre-installed controllers which are traditional PID control systems to control the two physical values. However, PID controllers cannot control two physical values effectively because it is impossible to design for MIMO (Multiple-Input and Multiple-Output) systems. This means that the PID controller for temperature control disrupts the other PID controller for humidity control and vice versa. In this study, an MPC (Model Predictive Control) was introduced because it can be designed for MIMO systems and has recently become widely used in industrial manufacturing systems because of the simplicity of its design as a PID(1). However, the environmental testing apparatus has two difficulties in controlling the temperature and humidity. One of which is that the refrigerator is always working to cool down and dehumidify, which affects the disturbance factor of the whole control system. The other is that the humidifier works not only to humidify but also as another heater. An accurate model is required to design an MPC with good performance despite these complex difficulties. In this study, an accurate method of modeling the controlled system is proposed. The MPC based on these models is designed using MATLAB® / Simulink® and implemented with a new type of PLC (Programmable Logic Controller)(2). The experimental results show good tracking performance to the changing set-points of the temperature and humidity.

Keywords: model predictive control, PID control, temperature and humidity control, environmental testing apparatus

1. Introduction

This study, started in March 2019, is a collaborative project between The National Institute of Technology, Numazu College, and Co., Ltd. Shin-Reinetsu-Giken (hereinafter called SRG). The principal business of SRG is the maintenance and repair of refrigerating and heating equipment. The purpose of this collaborative project is to make contributions to industrial applications in the field of heat transfer using the new technology which has been investigated and developed in this study. The specific subject of this study is "Simultaneous Temperature and Humidity Control for the Environmental Testing Apparatus". The environmental testing apparatus is an examination device to test the durability or effects of industrial products in a wide range of temperature and humidity. The contribution of SRG in this study is to repair the environmental testing apparatus, improve its performance and add some extra control functions.

In March 2019, SRG donated an environmental testing apparatus to Numazu College. The controller of the donated apparatus did not work well at that time, and SRG intended to repair it in the future. SRG suggested relegating the testing apparatus to Numazu College and replacing the pre-installed controller with a high-performance PLC to implement a controller designed according to modern control theory. In general, the traditional PID controller is still widely applied to control environmental testing apparatuses, even if there are two physical values, temperature and humidity, to be controlled. In that case, two PID controllers work independently, which usually causes inefficiency and makes the control system sluggish. That is the reason why modern control theory has to be introduced to control the two physical values, temperature and humidity, with high accuracy and effectiveness.

There are two difficulties, which were already overcome in this study, in controlling the environmental testing apparatus. One of them is that the refrigerating device is always working while the apparatus is in operation, to cool and dehumidify the inside of the apparatus. This means if only the refrigerating device works and the heater and humidifier are turned off, the temperature inside of the apparatus decreases under the controlled values, which affects the whole control system as a disturbance factor. The other difficulty is that the humidifying device works not only to humidify but also as another heater because it humidifies by boiling water and the evaporator changes the water vapor generated in the humidifier to complete vaporized gas. This means that the humidifying raises the temperature. These two difficulties cause sluggish and inefficient control of the temperature and humidity inside the apparatus when using the pre-installed PID controllers.

MPC, which is a kind of modern control theory, is introduced to overcome the two difficulties and to control the temperature and humidity of the environmental testing apparatus simultaneously and effectively. Not only can MPC be designed for MIMO systems, but it can also deal with the limitation of the control input at the saturated value(3). The difficulty when utilizing an MPC to control the environmental testing apparatus is that an MPC needs an accurate model to be effective because it generates control input signals based on the predictions of the output signals from the controlled model. If the predictions have large errors, the controller cannot perform well. In this study, an accurate modeling method is proposed which is executed in conjunction with the PID controller with auto-tuning function implemented in the new-type of PLC.

MPC has various applications, such as controlling industrial manufacturing systems(4). In this study, a new-type of PLC, Sysmac NJ produced by Omron Corporation, is utilized as the controller, which leads to greater efficiency of the implementation of the controller. Sysmac NJ has a sophisticated function to implement the controller designed with the MATLAB / Simulink software, produced by the MathWorks Corporation. Simulink PLC Coder® can convert the code of the Simulink controller to the ST (Structured Text) code which can be utilized in the ladder program of the PLC as the FB (Function Block)(5). The development time for the controller can be reduced drastically by this implementation function of the Sysmac NJ because the control designer does not have to develop the program for the MPC.

This paper describes the achievement of this study as follows: 1) Modeling of the environmental testing apparatus, 2) MPC design using the modeling results, 3) Modeling of the refrigerator, 4) Comparison of the MPC simulation and experimental results, 5) MPC effectiveness compared with PID control.

2. Experimental Setup

Figure 1 shows the schematic view of the environmental testing apparatus. The heater and humidifier raise the temperature and humidity respectively, and the refrigerator lowers the temperature and humidity, inside the apparatus, allowing the effects on an industrial product specimen to be examined. The evaporator placed above the humidifier heats the moisture generated in the humidifier to convert it to gas completely. The fan circulates the air to mix and homogenize the temperature and humidity inside the apparatus. The controller (PLC) calculates the appropriate values of the control input signals to the heater and humidifier by measuring the output signals from the temperature and humidity sensors. The refrigerator works at constant power

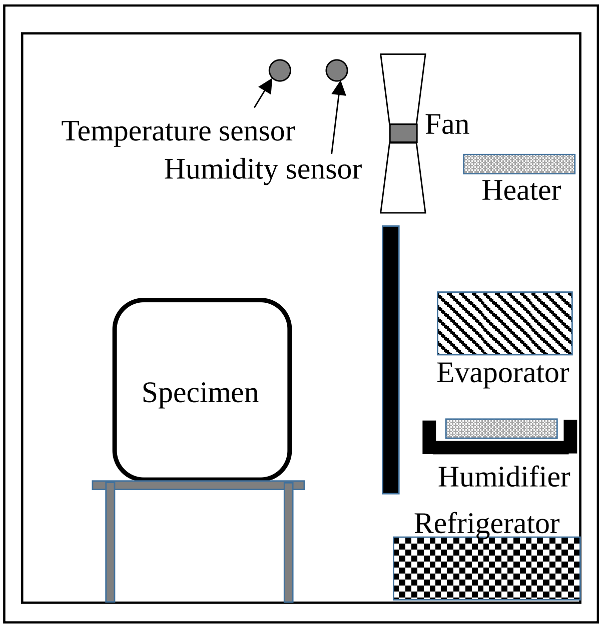
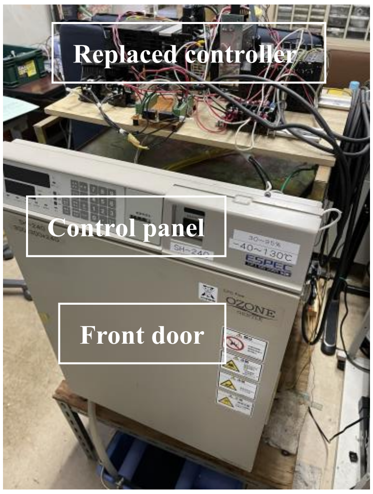
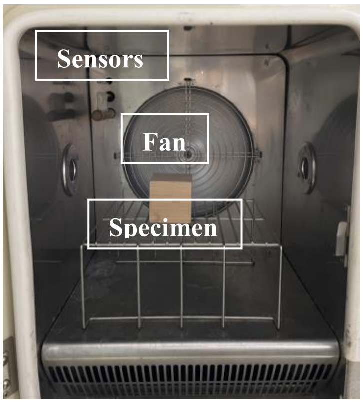


Fig.1. Experimental apparatus



(a) Outside view



(b) Inside view

Fig.2. Photos of the apparatus

during the testing control process.

Figure 2 shows the outside and inside view of the apparatus. As shown in figure (a), the pre-installed PID controllers located at the top of the apparatus were removed and replaced with the new control system which is constructed from the PLC and optional units. They are utilized as a controller in which the proposed MPC is implemented. Accordingly, the front control panel is not available, and alternatively, the apparatus can be controlled from a PC (Personal Computer) connected by a USB cable. Figure (b) shows the inside view of the apparatus which can be accessed by opening the front door. A fan is installed at the center back of the inside chamber and always works while the apparatus is on to mixture the inside gas uniformly. Two thermocouples (sensors) are attached at the top left. They are used as the dry-bulb and wet-bulb thermometers respectively to measure the temperature and humidity. The inside view shows a test block specimen on the stainless-steel rack.

3. Modeling of the Heater and Humidifier

It was found in this study that the models of the heater and humidifier can be obtained with accuracy by creating a steady state inside the environmental testing apparatus before executing the modeling process. It is almost impossible to measure the step response of the heater, humidifier, and refrigerator one by one because the temperature goes out of the measurable range if they are operated independently. It was discovered that the experiment to measure step responses of the heater and humidifier is reproducible after the whole system of the apparatus is running steadily so that the temperature and humidity keep constant values.

The new-type of PLC, Sysmac NJ, has a PID control function and it can be used in a ladder program as an FB. Moreover, the PID control parameters can be tuned automatically by using the auto-tuning function provided by the PLC. Therefore, it is easy to put the whole control system of the apparatus in a steady state by using the PID controller under the operation of the refrigerator, that is requiring two PIDs to control temperature and humidity simultaneously despite each disturbing the other as shown in Figure 3. Reference signals r_1 and r_2 are the set-points of temperature and humidity which have measured output signals as y_1 and y_2 respectively. Two control signals u_1 and u_2 are calculated by the two controllers PID$_1$ and PID$_2$ and input to drive the heater and humidifier. Transfer functions G_{11}, G_{12} and G_{21}, G_{22} correspond to the heater and humidifier which affects the temperature and humidity respectively. The first and second indexes of these transfer functions indicate the index numbers of the input and output signals. The effects both of the heater on the humidity and the humidifier on the temperature are considered to be the disturbances for the two PIDs so they are described as d_1 and d_2 in figure 3. The refrigerator causes the subtraction

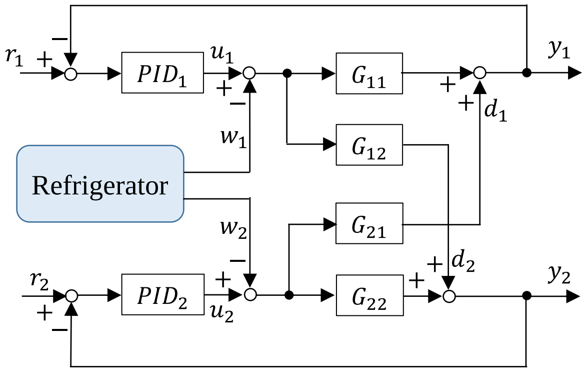


Fig.3. Block diagram of the PID controllers

input signals w_1 and w_2 from u_1 and u_2.

Figure 4 shows the time history of the sensors and control input signals to create a steady state for the preparation of measurement of the step response. Red and blue solid lines indicate the temperature and humidity, and red and blue dashed lines indicate the control input signals to the heater and humidifier respectively. T$_1$ and T$_2$ correspond to the time required for auto-tuning of the heating and humidifying PID control parameters. First of all, the PID controller for the heater is tuned. When the first tuning operation has been finished, the second PID tuning operation for the humidifier is started. After the two auto-tuning processes have been completed, the PID controllers keep the temperature and humidity at their set-points for 20 minutes. After that, the two PID controllers are terminated and a step input signal is added to the control input signal which is generated by the PID controller. Figure 4 shows that the step signal is added to the heater input signal at around 5600 seconds to measure a heat-step response. While the heat-step response is measured, the humidifying input signal is held at the end of the value generated by the PID controller.

Figure 5 shows the step responses obtained by the procedure described above. Figures (a) to (d) are the step responses of four transfer functions G_{11} to G_{22} in figure 3 respectively. The values of the measured responses are all normalized by each amount of the step input signals; they are shown by the thin lines with the numbers 1st to 10th. The models of each transfer function were determined by trial and error to match the measured responses, and the step response of the model is shown as thick solid red lines. The response in figures (a), (b), and (d) are modeled as second-order systems, and figure (c) is modeled as a first-order system respectively.

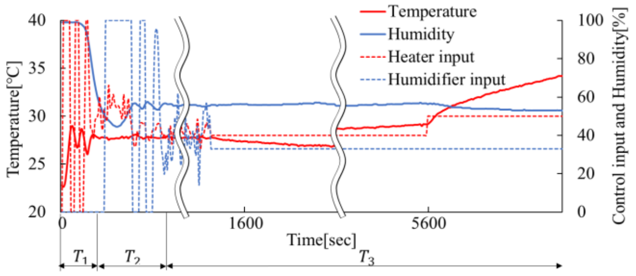
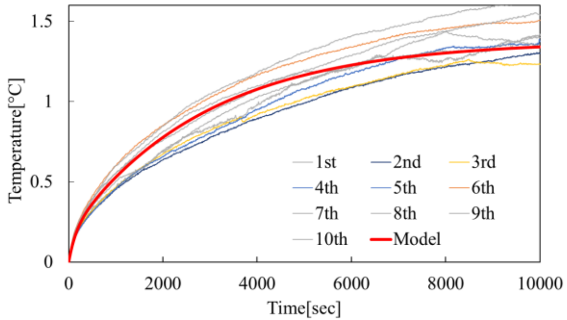
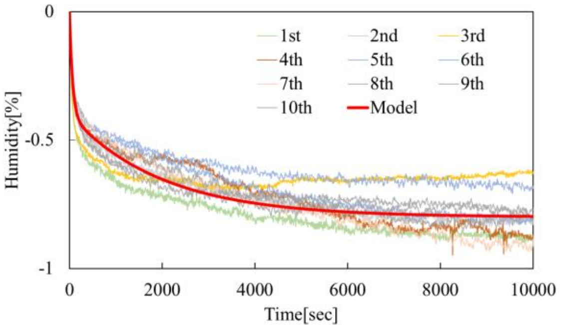


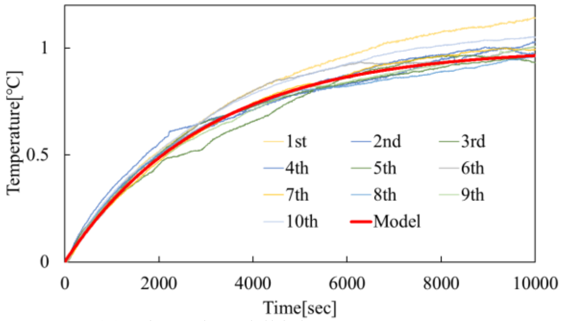
Fig.4. Procedure to measure the heat-step response



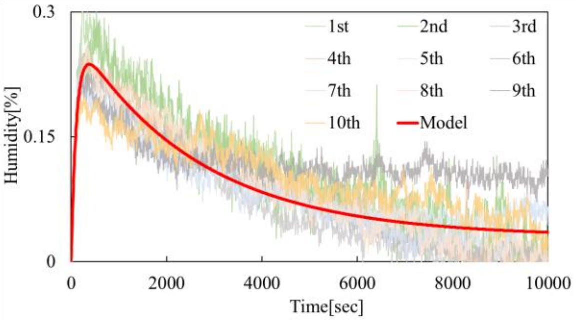
(a) from heating to temperature



(b) from heating to humidity



(c) from humidifying to temperature



(d) from humidifying to humidity

Fig.5. Experimental results and model step response

4. Design of MPC

Nowadays MPC is becoming widely used in manufacturing control systems because MPC can be designed for MIMO systems and as easily utilized as a PID controller. The system used in this study has an interaction between the heater and the humidifier. As a first or second-order approximation, it is enough to consider only the responsivities and gain constants of the heater and humidifier to design the MPC to deal with the interaction. Moreover, the control input signals are applied to the heater and humidifier through SSR (Solid State Relay) generated by PWM (Pulse Width Modulation). It means that the maximum value of the control signal is 100%, so if the controller calculates a value

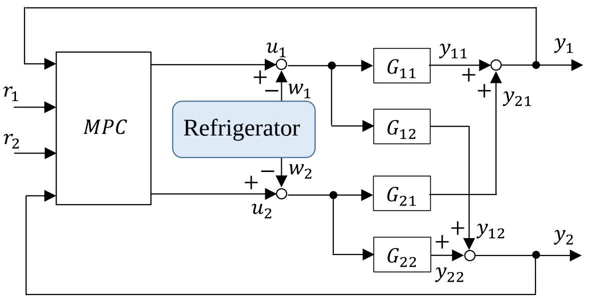


Fig.6. Block diagram of the MPC

over 100%, the control signal is saturated. It is impossible to deal with such a nonlinearity with a PID linear control method. MPC can cope with the restriction of the input signal limitation by predicting the output signals in every sampling time.

Figure 6 shows the MPC system block diagram. MPC can control both temperature (y_1) and humidity (y_2) effectively by the construction of the state-space equation which is corresponding to the whole system of all the four transfer functions $G_{ij};\ i,j = 1{,}2$. MPC can calculate an optimal control input by solving the optimization problem at every sampling time by comparing desired responses and sensor output signals.

Equation (1) shows the state-space equations for four transfer functions $G_{ij};\ i,j = 1{,}2,$ and they are brought into the whole system as in equation (2). Matrix $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are constructed as shown in equation (3), and matrix $\boldsymbol{D}$ is equal to matrix $\boldsymbol{B}$ because the disturbance signals $\boldsymbol{w}$ act in the same manner as the control inputs as shown in figure 6.

$$\begin{cases} \boldsymbol{x}_{ij}(\boldsymbol{k}+\boldsymbol{1}) = \boldsymbol{A}_{ij}\boldsymbol{x}_{ij}(\boldsymbol{k}) + \boldsymbol{b}_{ij}\boldsymbol{u}_{i\ or\ j} \\ \quad \boldsymbol{y}_{i\ or\ j} = \boldsymbol{c}_{ij}\boldsymbol{x}_{ij}(\boldsymbol{k});\ \ i,j = 1{,}2 \end{cases} \tag{1}$$

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{Ax}(k) + \boldsymbol{Bu}(k) + \boldsymbol{Dw}(k) \\ \quad \boldsymbol{y}(k) = \boldsymbol{Cx}(k) \end{cases} \tag{2}$$

$$\begin{cases} \boldsymbol{A} = \mathrm{diag.}\left[A_{ij}\right];\quad i,j = 1{,}2 \\ \boldsymbol{B} = \begin{bmatrix} \boldsymbol{b}_{11} & \boldsymbol{b}_{12} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{b}_{21} & \boldsymbol{b}_{22} \end{bmatrix}^T = \boldsymbol{D} \\ \boldsymbol{C} = \begin{bmatrix} \boldsymbol{c}_{11} & \boldsymbol{0} & \boldsymbol{c}_{21} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{c}_{12} & \boldsymbol{0} & \boldsymbol{c}_{22} \end{bmatrix} \end{cases} \tag{3}$$

Equation (4) is the model state-space equation to estimate the state variable $\boldsymbol{x}_M(k)$ and output signal $\boldsymbol{y}_M(k)$. In the model equation, the disturbance term is not included because it is an unmeasurable signal. Even if the model were perfect, the calculated state variable $\boldsymbol{x}_M(k)$ and output signal $\boldsymbol{y}_M(k)$ would not be equal to the actual values because of the disturbance. And in general, any model constructed from experiments has normally a certain error so some sort of modification is required to estimate the state value. Equation (5) shows a way to calculate a corrected state value $\boldsymbol{x}_c(k)$, which adds the difference between the actual output and model output to the estimated state value $\boldsymbol{x}_M(k)$ in equation (4), where $\boldsymbol{K}$ is a matrix determined by the characteristic of disturbance or measurement noise, as constructed by the Kalman filter. Finally, the predicted output signal $\boldsymbol{y}_p(k+1)$ is calculated using the corrected state value $\boldsymbol{x}_c(k)$ of equation (5) as shown in equation (6). Matrix $\boldsymbol{A}_\mathrm{f}$ and vector $\Delta\boldsymbol{u}_f(k)$ generate the linear summation of the step response of the future control input signals, and $\boldsymbol{M}$ is the matrix to extract the output signals influenced during the prediction interval. Finally, the predicted output signal $\boldsymbol{y}_p(k+1)$ is derived by adding the effect, caused by the future control input signals, to the current value calculated by the process model.

$$\begin{cases} \boldsymbol{x}_\mathrm{M}(k+1) = \boldsymbol{A}\boldsymbol{x}_M(k) + \boldsymbol{Bu}(k) \\ \quad \boldsymbol{y}_M(k) = \boldsymbol{C}\boldsymbol{x}_M(k) \end{cases} \tag{4}$$

$$\boldsymbol{x}_c(k) = \boldsymbol{x}_M(k) + \boldsymbol{K}\{\boldsymbol{y}(k) - \boldsymbol{y}_M(k)\} \tag{5}$$

$$\boldsymbol{y}_{\boldsymbol{p}}(k+1) = \boldsymbol{MA}\boldsymbol{x}_c(k) + \boldsymbol{A}_f\Delta\boldsymbol{u}_f(k) \tag{6}$$

MPC is designed to minimize the cost function as shown in equation (7) which is composed of the square values of the error between the reference signal $\boldsymbol{r}$ and the predicted output signal $\boldsymbol{y}_p$, plus future control input signal $\Delta\boldsymbol{u}_f$. Both are weighted by matrixes $\boldsymbol{Q}$ and $\boldsymbol{R}$ which are positive definite and usually diagonal matrixes. The control input signal can be derived to minimize the cost function J, and the necessary condition is that the derivation with respect to the input signal $\Delta\boldsymbol{u}_f$ is equal to zero as shown in equation (8). Finally $\Delta\boldsymbol{u}_f$ is derived as shown in equation (9), where $\boldsymbol{K}$ is the designed gain matrix to minimize the cost function by the least-squares method.(6,7)

$$J = \left(\boldsymbol{y}_{\boldsymbol{p}} - \boldsymbol{r}\right)^T \boldsymbol{Q}\left(\boldsymbol{y}_{\boldsymbol{p}} - \boldsymbol{r}\right) + \Delta\boldsymbol{u}_f^T\boldsymbol{R}\Delta\boldsymbol{u}_f \tag{7}$$

$$\frac{\partial J}{\partial\Delta\boldsymbol{u}_f} = \boldsymbol{0} \tag{8}$$

$$\Delta\boldsymbol{u}_{\boldsymbol{f}}(k) = \boldsymbol{K}\{\boldsymbol{r}(k) - \boldsymbol{MA}\boldsymbol{x}_c(k)\} \tag{9}$$

5. Model of the Refrigerator

One of the most important features of this study is that an exact modeling method for the refrigerator was established. This modeling method can be applied now because of the excellent MPC result. The difficulty of modeling the refrigerator was that it is impossible to measure the step response of the refrigerator in the same manner as a MIMO mechanical system in which all of the control inputs can be applied one by one. If only the refrigerator operates for a while, the temperature quickly falls below zero, so the humidity is out of the measurable range. This means that the refrigerator model has to be identified while the heater or humidifier is working. That is made possible by calculating the effects of the refrigerator using the measurement values at the steady state created by the MPC. That is to say, the cooling and dehumidifying effects, w_1 and w_2 in figure 6, can be derived from the output setpoints and control input signals as follows;

Figure 7 shows the experimental results of an MPC designed by using the method described in section 4. At the beginning of the experiment, following the process of the experiment to measure the step response in section 3, the two PID controllers of the heater and humidifier are tuned and work in sequence. That is why the temperature and humidity (red and blue line) are different from the reference signal (black line) from time 0 to around 4000 seconds. Then, the two PIDs are terminated and MPC starts immediately. At that time, the control input signals of MPC (orange and light blue line) are zeros, which is why the temperature and humidity go down steeply just after the MPC starts, but after that, they asymptotically approach the reference signals and follow them almost exactly. The MPC experimental results at the three specific time values (t_1, t_2, t_3) were used in the modeling of the refrigerator. They are indicated by the dashed lines in figure 7.

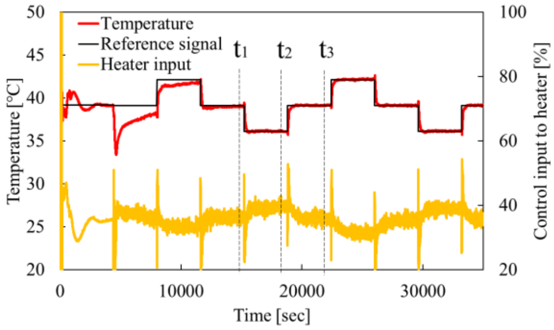
Equation (10) shows that the relationship between the steady-state inputs $\overline{u_1}$, $\overline{u_2}$ and outputs $\overline{y_1}$, $\overline{y_2}$ where $K_{ij}; i,j = 1,2$, are the gain constants of the transfer functions $G_{ij}; i,j = 1,2$. As shown in figure 7, the outputs are almost the same as the reference signals r_1, r_2. All of these signals can be read from figure 7 as constant values, and substituted into equation (10), and then the steady-state inputs $\overline{u_1}$ and $\overline{u_2}$ can be derived as shown in equation (11). These input signals consist of the control inputs and the refrigerator effects, so the refrigerator effect signals w_1 and w_2 are derived as shown in equation (12). That is the method of modeling the refrigerator which was established in this study.

$$\begin{cases} K_{11}\overline{u_1} + K_{21}\overline{u_2} = \overline{y_1} = r_1 \\ K_{12}\overline{u_1} + K_{22}\overline{u_2} = \overline{y_2} = r_2 \end{cases} \tag{10}$$

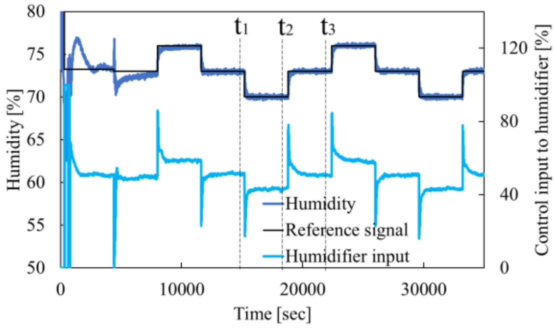
$$\begin{cases} \overline{u_1} = \dfrac{K_{21}r_2 - K_{22}r_1}{K_{12}K_{21} - K_{11}K_{22}} \\ \overline{u_2} = \dfrac{K_{12}r_1 - K_{11}r_2}{K_{12}K_{21} - K_{11}K_{22}} \end{cases} \tag{11}$$

$$\begin{cases} w_1 = u_1 - \overline{u_1} \\ w_2 = u_2 - \overline{u_2} \end{cases} \tag{12}$$

Figure 8 shows the values of the refrigerator w_1 and w_2 which were derived from equation (12) at some different steady-states of the temperature and humidity measured from

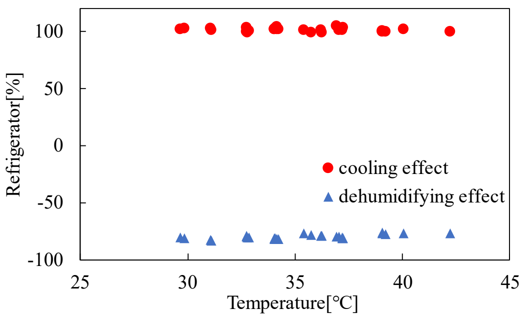


(a) Temperature and humidity

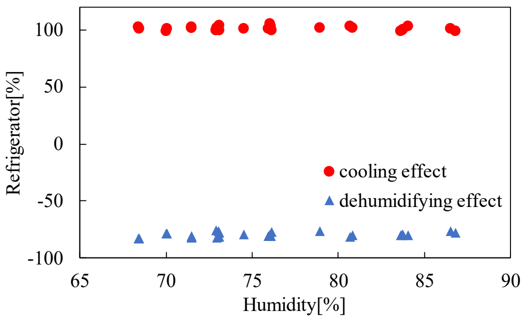


(b) Control input to the heater and humidifier

Fig.7. MPC experimental result



(a) at different temperature



(b) at different humidity

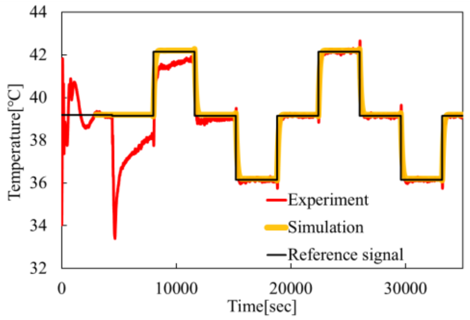
Fig.8. Modeled values of the refrigerator

some MPC experimental results. All of them are almost the same values for both w_1 and w_2, so these values can be considered to be the accurate model of the refrigerator and can be utilized in the design process of the MPC, but it should be noted that the values of the dehumidifying effect are negative. That does not mean the refrigerator humidifies to the same extent as the humidifier. And also it is noted that the values of the cooling effect are almost 100%. That does not mean that the heater cannot rise the temperature even if the heater works at the maximum 100% power. Both w_1 and w_2 have the same effect as the control inputs u_1 and u_2, which means, w_1 and w_2 have effects on both temperature and humidity, and they depend on the gain constants $K_{ij}; i,j = 1,2$.

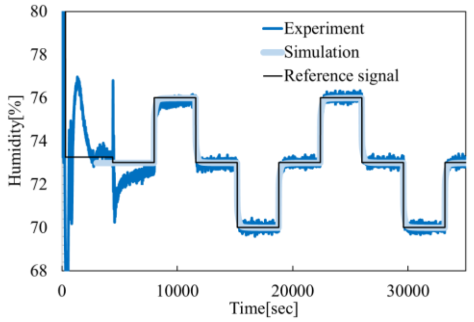
6. MPC experiment

Figure 9 shows the comparison of the MPC experimental and simulation results which include the refrigerator effects derived in section 5. These figures show that the experimental results are similar to the simulation results, which means that the model of the apparatus is accurate. The difference in results from time 0 to around 8000 seconds is caused by the PID auto-tuning period and the transient response of the MPC as mentioned in section 5. After that, the experimental humidity is almost the same as the simulation result and completely follows the reference signal as shown in figure (b). The experimental temperature reached the simulation result later than the humidity and also follows the reference signal as shown in figure (a). On the other hand, the experimental control input signals are slightly different from the simulation results, which seems to be caused by the modeling error. But these results show that the simulation can be utilized to predict the MPC result, that is to say, design parameters can be adjusted by referring to the simulation results.

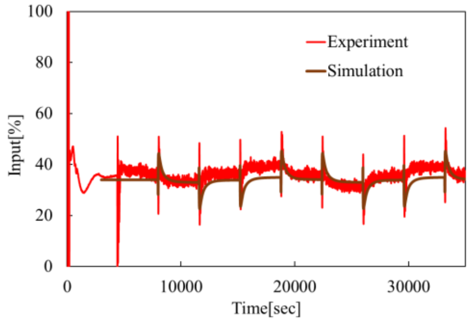
Figure 10 shows the comparison of the PID and MPC experimental results. The two PID controllers for the temperature and humidity have been tuned by the auto-tuning function of the PLC over 0 to around 4000 seconds. There are small overshoots in the result of temperature controlled by PID, and large opposite direction responses appear in the response of the humidity at the changing of the reference signal. On the other hand, the MPC response does not have any overshoot and such an opposite direction response, and almost follows the reference signal. That means MPC control both temperature and humidity effectively with considering their interruption. But both of the control input signals are larger than PID at the reference signal changing points, especially in the humidifier. Moreover, the input signal to the heater changes both sides in a very short period of time. That seems to be caused to suppress such the overshoot and the opposite direction response with the difference of the rise time of the four transfer functions.



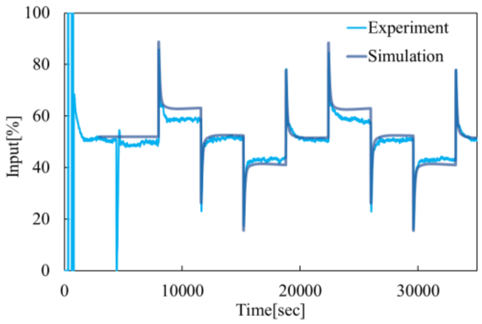
(a) Temperature



(b) Humidity

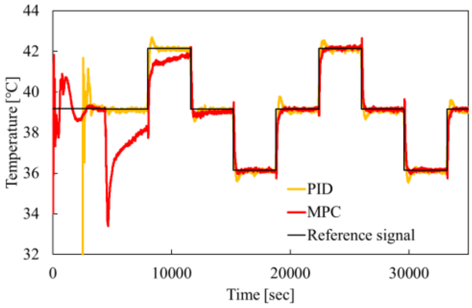


(c) Control input to the heater

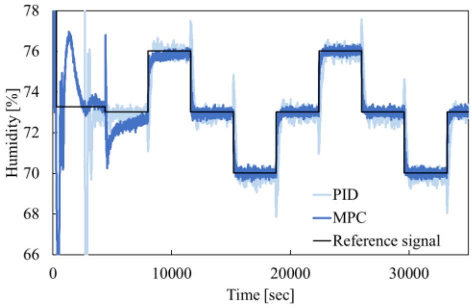


(d) Control input to the humidifier

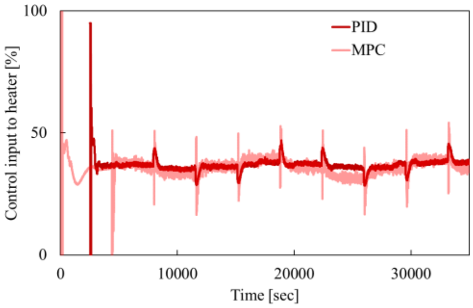
Fig.9. MPC results of experiment and simulation



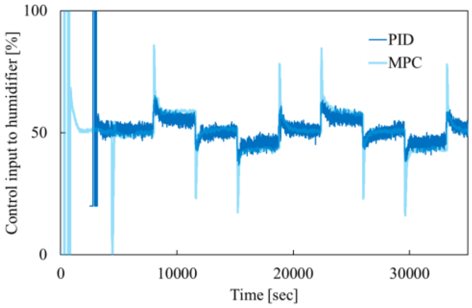
(a) Temperature



(b) Humidity



(c) Control input to the heater



(d) Control input to the humidifier

Fig.10. Comparison of PID and MPC results

7. Conclusions

MPC was introduced to control both the temperature and humidity of the environmental testing apparatus. Simulation and experiment show that the designed MPC successfully controlled the two physical values simultaneously and effectively. The success of the MPC depends to a large extent on the accurate method of modeling the environmental testing apparatus which was proposed in this paper. To obtain such an accurate model, it is important to prepare a temperature and humidity steady-state while the refrigerator is running. This method was developed through many trial-and-error of experiments as part of this study. However, the model of the apparatus which is obtained by the proposed method is not always accurate because the heating and humidifying characteristics are varying slowly under the influence of changing the temperature and humidity outside of the apparatus. This fact became evident when the difference in the step responses in figure 5 was noted, and by the fact that the PID control parameters changed each time the auto-tuning experiments were run. That is to say, the control performance of the MPC with constant gains might not always be able to meet the control design specification. Some robust controllers or adaptive controllers should be introduced to address such issues in future work.

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