Investigation on the performance of the chilled water system with the key sensor fault

J N Liu¹, G N Li², Y P Hu¹*, L Zhou¹, W Chen¹
¹Department of Building Environment and Energy Engineering, Wuhan Business University, Wuhan, 430056, China
²School of Urban Construction, Wuhan University of Science and Technology, Wuhan, 430065, China

*Corresponding author’s e-mail: YunpengHu@wbu.edu.cn

Abstract. Sensors for the role of control ensure the HVAC system operates reliably and optimally. Among them, the readings of some sensors are the key for the whole system since they are the representation of the controlled objects, such as the chilled water outlet temperature, or the room temperature and so on. Unfortunately, sensor fault is unavoidable due to the system error. The system will be misled to the unexpected or even very severe situation by the controller which got the erroneous input. In this paper, a real building model, which was developed in the simulation environment of the EnergyPlus and its external interface, BCVTB, was employed to investigate the performance under the key sensor fault condition. The chilled water outlet temperature sensor, which is in the supply side of the chilled water loop, and the room temperature sensors, which are in the demand side, were introduced different bias fault from negative levels to the positive levels to reveal the performance changing. Results show that the variation of energy consumption with the sensor fault in the demand side is higher than that in the supply side. Some performance parameters, such as COP of the chiller, and the SCOP of the plant, are quite different, while the indoor thermal comfort is stable under the chilled water outlet temperature sensor fault but different under the fault of the room temperature sensors. This simulation model will be combined with the strategy of the sensor fault detection, diagnosis and reconstruction to accomplish the fault-tolerant control in the future.

1. Introduction

Sensor faults are inevitable in the HVAC system for the built environment because of severely working situation. It will cause ineffective control, unsafe operation, unreasonable energy consumption and so on [7, 9] because the erroneous readings trick the control logic and lead the HVAC system to the unexpected situation. Therefore, researches on sensor fault detection, diagnosis, and data reconstruction (FDDR) for HVAC system have been paid more attention to in the last decade [1, 13]. Since the faulty sensor cannot be easily identified, researchers were dedicated in finding novel data-driven methods to get higher accuracy [3, 5, 6, 8, 12, 14].

The controlled objects, such as the chilled water outlet temperature, the room temperature and so on, are represented directly or indirectly by the key sensors involved in the control system. The controller would adjust the action by the deviation between the measured data and its corresponding
setpoint value every control step. When there was a fault in the key sensor, the erroneous deviation would lead the system to the unexpected by the control logic. Therefore, building simulations are employed to investigate the correlation among those sensors significantly [10]. In this paper, a central air-conditioning system with the water-cooled chiller developed by the EnergyPlus [2] and the Building Controls Virtual Test Bed (BCVTB) [11] was employed to investigate the energy consumption and performance under the sensor fault situation.

2. Model description
A building with its chilled-water system was developed in the EnergyPlus software and the BCVTB was employed to introduce the fault and to modify the severity.

2.1. Model Characters
The Energy model of the whole building in SketchUp software was shown in the Figure 1. The thermal character of envelope, the power of indoor electrical devices, the power of light, the occupancy and its corresponding outdoor air mass flow rate were chosen from the National Standard of China, ‘Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015)’. The plant side consisted of a water-cooled chiller, a variable flow rate chilled-water pump, and a cooling tower and a variable flow rate condensed-water pump. The rated COP and cooling ability of chiller are 5.91 and 724kW, respectively. The setpoint of chilled water outlet in the normal operation is 7 ºC, while the room air temperature is 26 ºC.

2.2. Sensor Error Description
The measurement value of a sensor can be simply described as

\[ x^* = \bar{x} + \eta \]  

Where, \( x^* \) is the measured value, \( \bar{x} \) is the real value, \( \eta \) is the fault level. Although there are systemic error and incidental error, in this paper, the bias systemic error was investigated. The room air temperature (\( T_{\text{rm}} \)) and the chilled-water outlet temperature (\( T_{\text{chws}} \)) were introduced different bias fault level from -4 ºC to +4 ºC with 1 ºC interval. \( T_{\text{rm}} \) is the key sensor in demand side for maintaining a specified room air, while \( T_{\text{chws}} \) is the key sensor in supply side for the fixed chilled-water temperature into the fan coil. Both of them are the key in the feedback control logic.

2.3. Data Exchange
BCVTB is a software environment based on the Ptolemy II software environment. BCVTB was employed to exchange the data between EnergyPlus and the Python algorithm which was used to simulate the sensor error. In every simulation step, the detailed data exchange process is: (1) EnergyPlus receives the error sensor \( x^* \) from the last simulation step; (2) EnergyPlus runs a time step with the control instruction by comparing the \( x^* \) with its corresponding set-point; (3) BCVTB gets the
real result, $\bar{x}$, of EnergyPlus when this simulation time step finished and sends it to the Python algorithm which was developed by the authors; (4) the standalone Python algorithm calculates the new measured value $x^*$ of $\bar{x}$ and sends $x^*$ back to BCVTB for the next simulation time step. The step (1) to (4) can exchange the data between EnergyPlus and Python algorithm to simulate the sensor fault well. Also, the MySQL database can be as a middle-ware between EnergyPlus and Python algorithm to simulate the advanced control algorithm.

3. Results
The simulation data of Energy Consumption, the performance, and the indoor thermal comfort were sorted to find the trend in the faulty condition.

3.1. Energy Consumption
The energy consumption chiller and the chilled-water pump were compared to the normal operation with different bias fault in levels in $T_{rm}$ and $T_{chws}$, since the consumption of other devices is changing very little. The influence in the chiller energy consumption was shown in the Figure 2.

![Figure 2. The energy consumption percentile of the chiller in faulty condition to the normal operation](image)

With the bias fault of $T_{chws}$, there is only $\pm 5\%$ changing rate, while there is $\pm 40\%$ changing rate with $T_{rm}$ error. That means $1 \degree C$ bias fault in the demand side would cause nearly $8\%$ changing of normal operation. On the contrary, the bias fault in the supply side influenced the energy consumption much less.

The changing in the chilled-water pump energy consumption was shown in the Figure 3. Since the chilled water pump is variable, the energy consumption under $+4 \degree C$ bias of $T_{rm}$ is five times of that in the normal operating situation. Due to $T_{rm}$ error changes the cooling load demand, the trends of energy consumption of chiller and chilled-water pump are similar under the $T_{chws}$ bias condition, but the trends of these two in $T_{chws}$ are opposite since the demand side is steady.

3.2. Plant Side Performances
The coefficient of performance (COP) and the system coefficient of performance (SCOP) were illustrated in Figure 4.
When the bias levels are varying from the negative to the positive, COP and SCOP are decreased with the $T_{chws}$ fault due to the real evaporator temperature downside. On the contrary, COP and SCOP are increased with the $T_{rm}$ bias from -4 °C to +4 °C.

In order to demonstrate the performance in detail, the part load ratio (PLR) and its corresponding COP was shown as separated scatter plots in Figure 5 and Figure 6 with different bias fault levels in $T_{rm}$ and $T_{chws}$, respectively. In $T_{rm}$ fault condition, the weight center of PLR is from high to low when the bias from +4 °C to -4 °C, so that COP is decreased since the demand cooling load is less and less. On the contrary, the PLR is steady with $T_{chws}$ fault condition, while COP change with the evaporator temperature.

![Figure 4. The COP and SCOP in the $T_{rm}$ and $T_{chws}$ faulty condition](image)

![Figure 5. The scatter plot for the PLR and COP in the $T_{rm}$ faulty condition](image)
3.3. Indoor Thermal Comfort

The Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [4] were introduced to compare the results of the indoor thermal comfort with different bias levels for these two faulty sensors. Since PMV and PPD are time-varying, the four statistical characters, the 25% percentile number, the mean, the median, and the 25% percentile number, were used to analyze the influence of PMV and PPD for indoor thermal comfort. The values of PMV and PPD with different bias fault levels in $T_{rm}$ and $T_{chws}$ were shown in the Table 1 and Table 2, respectively. Although the $T_{chws}$ is erroneous, the values of PMV and PPD did not change. However, the values of PMV become lower with the fault levels from the negative bias to the positive bias. What’s more, the thermal sensitivity of people is changing from very unsatisfied to very pleased according to the median of PPD from 90.35% to 7.96%. Since the error of $T_{rm}$ would estimate the variable cooling load by the indoor air temperature control logic, the real room air temperature will from 30 °C to 22 ºC with the bias levels from -4 ºC to +4 ºC. When the error occurs in the $T_{chws}$, the PMV and PPD would be steady since the demand side cooling load would not change.

Table 1. PPD of different bias fault levels in $T_{rm}$ and $T_{chws}$

| Fault Level | $T_{rm}$ | $T_{chws}$ |
|-------------|----------|------------|
| °C | P25 Mean Median P75 | P25 Mean Median P75 |
| -4 | 77.13 80.89 90.35 | 95.43 44.48 35.81 |
| -3 | 66.92 74.16 80.67 | 88.53 44.44 35.79 |
| -2 | 53.71 64.99 66.77 | 77.87 44.43 35.78 |
| -1 | 39.48 54.53 51.19 | 65.59 44.46 35.78 |
| 0  | 26.01 44.48 35.78 | 55.47 44.48 35.78 |
| 1  | 15.80 36.09 22.74 | 46.89 44.51 35.77 |
| 2  | 8.84 29.98 13.15 | 38.55 44.56 35.76 |
| 3  | 5.57 26.14 7.13 | 31.35 - - |
| 4  | 5.52 25.65 7.96 | 29.09 - - - |
Table 2. PMV of different bias fault levels in $T_{rm}$ and $T_{chws}$

| Fault Level | $T_{rm}$ P25 | Mean | Median | P75 | $T_{chws}$ P25 | Mean | Median | P75 |
|-------------|--------------|------|--------|-----|----------------|------|--------|-----|
| -4          | 2.01         | 2.34 | 2.37   | 2.61| 1.00           | 1.46 | 1.21   | 1.58|
| -3          | 1.80         | 2.13 | 2.09   | 2.31| 1.00           | 1.46 | 1.21   | 1.58|
| -2          | 1.55         | 1.91 | 1.80   | 2.02| 1.00           | 1.46 | 1.21   | 1.58|
| -1          | 1.28         | 1.69 | 1.51   | 1.77| 1.00           | 1.46 | 1.21   | 1.58|
| 0           | 1.00         | 1.46 | 1.21   | 1.58| 1.00           | 1.46 | 1.21   | 1.58|
| 1           | 0.71         | 1.23 | 0.92   | 1.43| 1.00           | 1.46 | 1.21   | 1.59|
| 2           | 0.42         | 1.01 | 0.62   | 1.27| 1.00           | 1.46 | 1.21   | 1.59|
| 3           | 0.10         | 0.76 | 0.30   | 1.12| -              | -    | -      | -   |
| 4           | -0.20        | 0.57 | 0.02   | 1.03| -              | -    | -      | -   |

Therefore, the measured temperature data and their corresponding relative humidity in the room air temperature with the bias level from -4 ºC to +4 ºC was shown in the Figure 7. Since the temperature is the measured data, the distribution is quite various from each other. When in the bias of +4 ºC, the readings of $t^{*}_{rm}$ are almost greater than 26 ºC which is the normal condition. On the contrary, nearly all $t^{*}_{rm}$ are less than 26 ºC. In the normal condition, $t^{*}_{rm}$ should be around the 26 ºC. In all different conditions, the relative humidity is not changing greatly. Due to the values of $t^{*}_{rm}$ in the different bias lever are quite various, the PPD and PMV in the room air temperature faulty condition are changing greatly.

4. Conclusion
As the key sensor in the operation control logic, the room air temperature and the chilled water outlet temperature are very significant for the central air-conditioning system. The energy consumption, the performance of devices and the system, and the indoor thermal comfort were investigated under the
two kinds of key sensors with various bias levels by an EnergyPlus model in the Ptolemy environment. Since the error of the room air temperature will cause the demand varying, the energy consumption, the performance, and the indoor thermal comfort would change greatly. Meanwhile, the error of chilled water outlet temperature would cause the chiller and the chilled-water pump operates unequally. This simulation model will be combined with the strategy of the sensor fault detection, diagnosis and reconstruction to accomplish the fault-tolerant control in the future for the performance study.

Acknowledgements
This work is supported by the Natural Science Foundation of Hubei Province, China (2016CFB472), Excellent Young and Middle-aged Talent in Universities of Hubei, China (Q20181110), the Excellent Young and Middle-aged Scientific and Technological Innovative Team in Universities of Hubei, China (T201829), the Innovative Team of Wuhan Business University of China (2018TD003), the Scientific and Technological Innovation Foundation of Wuhan Business University of China (2016KC04), the Doctoral R&D Foundation of Wuhan Business University of China (2016KB001).

References
[1] Bruton K, Raftery P, Kennedy B, Keane M and O Sullivan D T J 2014 Energ. Effic. 7 335-51
[2] Crawley D B, Lawrie L K, Winkelmann F C, Buhl W F, Huang Y J, Pedersen C O, Strand R K, Liesen R J, Fisher D E, Witte M J and Glazer J 2001 Energ. Buildings. 33(4) 319-31
[3] Du Z M, Fan B, Chi J L and Jin X Q 2014 Energ. Buildings. 72 157-66
[4] Fanger P O 1970 Thermal comfort: Analysis and applications in environmental engineering (Copenhagen: Danish Technical Press)
[5] Hu Y, Li G, Chen H, Li H and Liu J 2016 Int. J. Refrig. 63 133-43
[6] Kocyigit N 2015 Int. J. Refrig. 50 69-79
[7] Lee S H and Yik F W H 2010 Energ. Buildings. 42 2-10
[8] Li G, Hu Y, Chen H, Shen L, Li H, Hu M, Liu J and Sun K 2016 Energ. Buildings. 116 104-13
[9] Ma Z and Wang S 2011 Energ. Buildings. 43(1) 153-65
[10] O'Neill Z, Shashanka M, Pang X, Bhattacharya P, Bailey T and Hayes P 2011 Proc. of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, (Sydney) p 474
[11] Wetter M 2011 J. Build. Perform. Simu. 4(3) 185-203
[12] Xiao F, Zheng C Y and Wang S W 2011 Appl. Therm. Eng. 31 3963-70
[13] Yu Y, Woradechjumroen D and Yu D 2014 Energ. Buildings. 82 550-62
[14] Zhao Y, Wen J, Xiao F, Yang X and Wang S 2017 Appl. Therm. Eng. 111 1272-86