Fault introduction and detection in building HVAC systems

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ABSTRACT
Heating, ventilation and air-conditioning (HVAC) systems play an important role for maintaining a healthy and comfort indoor climate for buildings. Faults in the systems decrease the performance and lead to higher energy consumption or lower thermal comfort level. Researches of the fault detection and diagnosis (FDD) on the building HVAC systems have been presented in recent decades. However, many of them use simulation tools or software to check the behaviour under the faulty condition. Few people introduced real faults into the real systems to get the responses. In this paper, four types of fault are introduced into a test facility of building HVAC systems and the characteristics are analysed for further FDD study.

INDEX TERMS
Fault introduction; HVAC system; Office building; Detection

INTRODUCTION
Heating, ventilation, air-conditioning (HVAC) system in a building is meant to supply suitable conditioned air to the rooms and spaces to maintain an expected temperature and humidity. Meanwhile, it also supplies enough fresh air and drives the polluted air out. Due to the demand of high quality of indoor climate and the rapid development of computer and communication technology, modern buildings increasingly tend to supply increasingly integrated, complicated and intelligent services. Consequently, more control units and building energy management system (BEMS) have been installed in most buildings. Buildings, both commercial and residential buildings, consume every year approximately one-third of the total energy consumption (US Department of Energy, 2002). Furthermore, HVAC systems consume every year more than 60% of the building energy consumption in the USA (Mull, 1997) and more than 50% in Europe (Hughes, 1998).

After more sensors and automatic control loops are installed in HVAC systems, it is getting more complicated to find the fault by feeling. On the other hand, this makes it possible to realize the fault detection and diagnosis automatically by using the digital information. During long time operation, components or devices in the systems may function improperly (under faulty condition). For instance, sensors and actuators degrade and fail, valves and dampers leak and stick, coils become fouled and many other problems may arise. Faults are unavoidable! Faults normally lead to more energy consumption or degradation of comfort level of indoor climate. In the USA, faults in HVAC systems can lead to 30% increase of their energy use (Katipamula and Brambley, 1998). Therefore, fault detection and diagnosis (FDD) on the building HVAC systems is of practical and important issue.

FDD on HVAC system is a subject that has been studied for decades (Yu and Paassen, 2000). However, many of the researches analysed the FDD approach by simulation or model generated faults rather than real faults. In this case, some approved methods may encounter problems when they are applied in reality.

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The responses of the real installation under some faults conditions give very useful information. It gives direct insight for the behaviour of the system and is able to be applied for the validation of model-based FDD.

Four faults on the heating system for an air handling unit are introduced and analysed:

1. Gradual as well as sudden changes of the pump behaviour.
2. Damaged sensors, causing faulty measurements.
3. Changes of the commissioning valve performance.
4. Sticking of the control valve, for example, by a broken actuator.

The following experiments introduce the first five faults to some extent:

1. shutting down the pump at a random moment (fault 1);
2. taking the supply air sensor out and leave it at the laboratory condition (fault 2);
3. close the commissioning valve suddenly (fault 3);
4. fix the control valve position manually (fault 4).

TEST FACILITY

The faults are introduced into a real test facility in the laboratory of Energy Technology at the Delft University of Technology. This test facility consists of an air handling unit (AHU), a cooling unit and boiler, a building management system (BMS) and a climate room, see Figure 1. The AHU consists of two sections containing a cooler, a heater and a steam humidifier. The first section is an emulator to simulate whole year condition at mixing box. The second section is the real air-handling unit to process the air to the supplied condition.

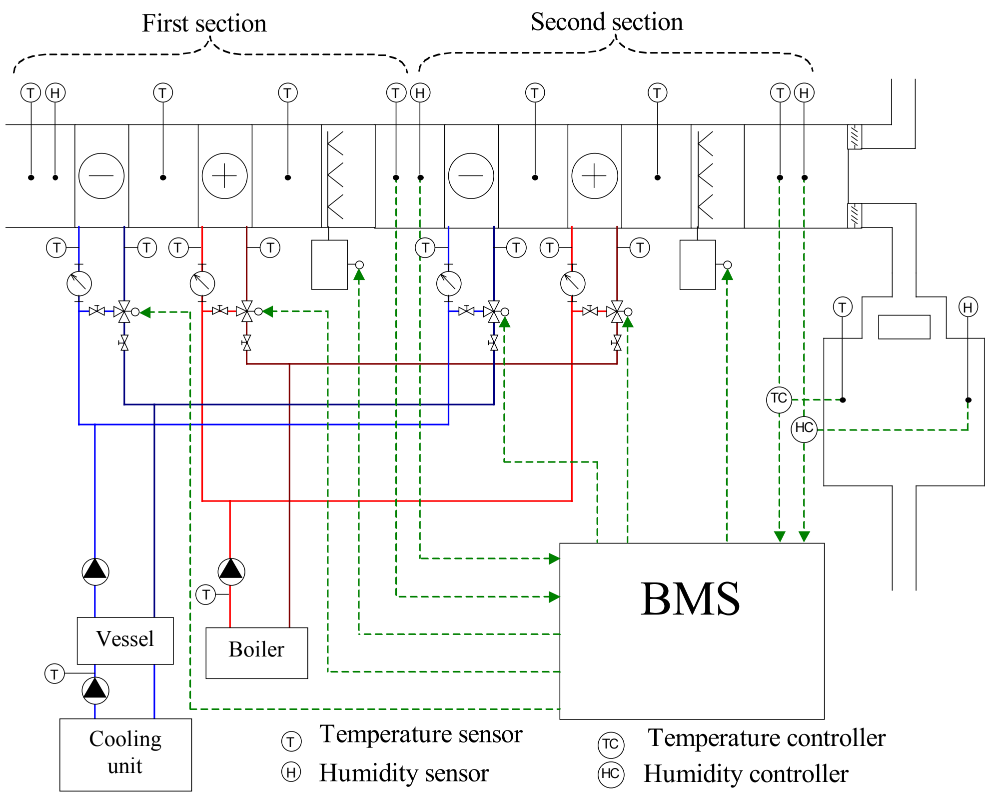

Figure 1 Scheme of the test facility.

The first section (emulator) of the AHU, which is used to generate the mixing point conditions, will be switched on during the experiments. Two sets of experiments have been done with different mixing point conditions (**Table 1**). The mixing point conditions are the conditions when the return air from the buildings is mixed with outside fresh air.

Table 1 Conditions for the two sets of experiments

	First set	Second set
Mixing point air temperature (after emulator)	16°C	15°C
Mixing point humidity	Free	Free
Supply air flow rate	600 m^3/h	600 m^3/h
Redundant air flow rate	600 m^3/h	900 m^3/h
Room air temperature	23°C	23°C
Room relative humidity	50.1%	50.1%

In both sets, the setpoint for the boiler is 80°C and the setpoint of the cooling unit is 5°C. Before starting each experiment, the system is stable. Different phenomena are discussed in the following sections.

Fault 1: Shutting Down Pump

In this experiment, the pump is shut down at random moment. The boiler itself is controlled as normal. The fault is introduced at 600 s.

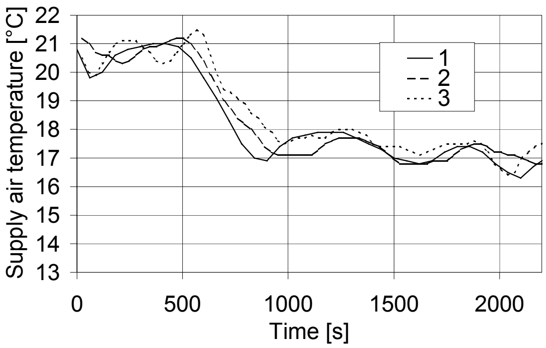

Figure 2 Response of the supply air temperature to shutting down the pump; first set of three experiments.

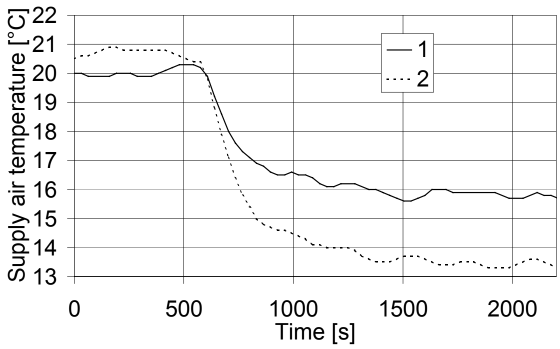

Figure 3 Response of the supply air temperature to shutting down the pump; second set of two experiments.

When the pump stops running, the following will happen:

1. The supply air temperature (Figures 2 and 3) decreases, because there is no water flow through the heater anymore.
2. The control valve of the heater opens to maintain the supply air temperature at the setpoint. This will not succeed of course, because there is no flow to control.
3. The room air temperature decreases because of the decreasing supply air temperature.
4. The setpoint of the supply air temperature increases in order to maintain the room air temperature at the setpoint.
5. The control valve of the heater opens even more, if it was not already fully opened.

The change in supply air temperature is quite clear as can be seen in Figures 2 and 3. The drop in the second set is bigger than that in the first set because the mixing point temperature for the second set is lower than that for the first. The difference between the first and second experiment of the second set (Figure 3) is caused by the cooler of the secondary part. In the second experiment, the cooler was on because the air needs to be dehumidified. In the first experiment, the cooler was off.

Fault 2: Taking Out the Supply Air Sensor

The supply air temperature sensor was taken out of the AHU casing and was put on the top of it. The hole in the AHU was filled with a piece or cloth. The fault is introduced at 600s and the temperature in the lab is higher than the supply air temperature.

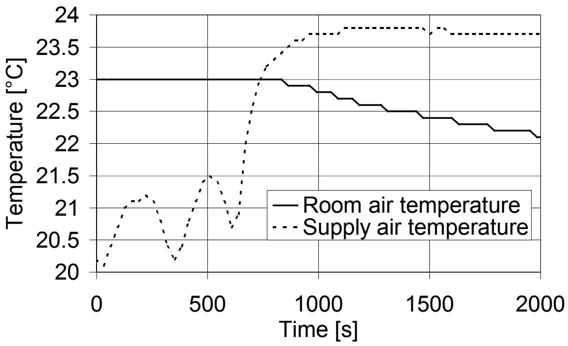

Figure 4 Behaviour of room and supply air temperature when taking out the supply air sensor; first experiment, first set.

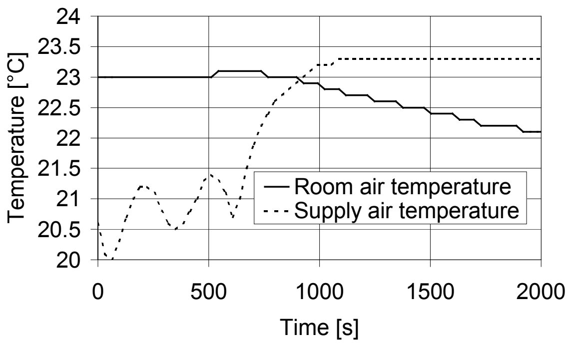

Figure 5 Behaviour of room and supply air temperature when taking out the supply air sensor; second experiment, first set.

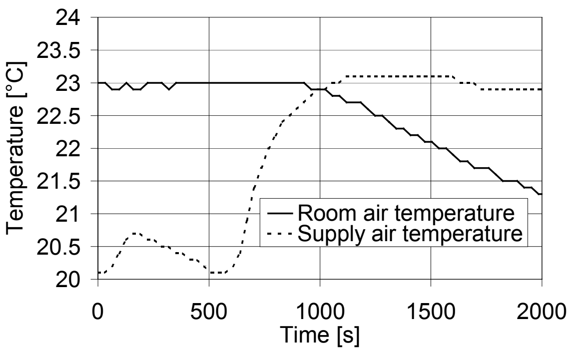

Figure 6 Behaviour of room and supply air temperature when taking out the supply air sensor; first experiment, second set.

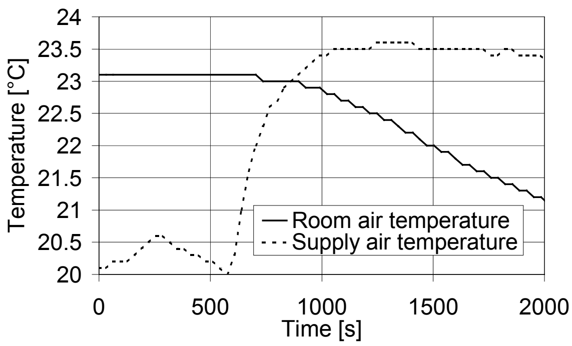

Figure 7 Behaviour of room and supply air temperature when taking out the supply air sensor; second experiment, second set.

The following phenomena will occur, if the supply air sensor is taken out:

1. The measured value for the supply air temperature increases to the lab temperature.
2. The control valve of the heater closes to maintain the supply air temperature setpoint, which will give a lower supply air temperature as a result.
3. The room air temperature decreases because of the lower supply air temperature.
4. The setpoint of the supply air increases to maintain the room air temperature setpoint.
5. The control valve of the heater opens to reach the higher supply air temperature setpoint.
6. The room air temperature increases, because of the higher supply air temperature.

7. The setpoint of the supply air decreases to maintain the room air temperature setpoint.
8. The control valve of the heater closes to maintain the supply air temperature setpoint, which will give a lower supply air temperature as a result.

Points 8 and 2 are the same, which means that the system will get an unstable behaviour. The experiments do not show this unstable behaviour because that will take a lot of time.

All the experiments show the same response when the sensor is taken out (Figures 4–7). Characteristic for this fault is the rising of the measured supply air temperature before the change of other variables like control valve position, supply air temperature setpoint and room air temperature. Of course, the response of the system is depending on the lab temperature, but the characteristic will not change.

Fault 3: Change Position Commissioning Valve

The position of the commissioning valve in the main supply tube is decreased from 4 to 2.5, which means from $k_v = 2.05$ to $k_v = 0.98$. The fault is introduced at 600 s.

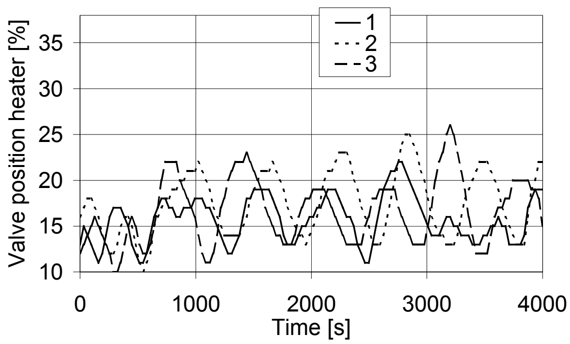

Figure 8 Response of control valve position heater to decreasing commissioning valve position; first set of three experiments.

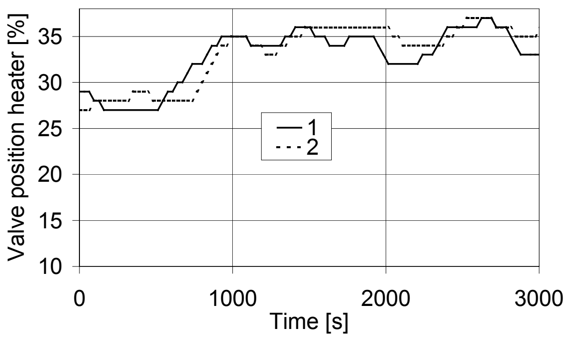

Figure 9 Response of control valve position heater to decreasing commissioning valve position; second set of two experiments.

When the commissioning valve position is decreased, the following will happen:

1. There will be slightly less flow through the heater, because the resistance in the tube has increased.
2. The temperature of the supply air decreases because there is less hot water flowing through the heater.
3. The control valve of the heater opens more to maintain the supply air temperature setpoint.

Figure 9 shows clearly the increase in the position of the control valve of the heater. This phenomenon is less apparent in the first set of experiments (Figure 8). The lower flow through the heater in the first set of experiments is a possible reason for this. Lower flows correspond to lower (control) valve openings. At low openings, the resistance of the control valve is much bigger than the resistance of the commissioning valve and dominating the flow through the heater.

Fault 4: Fix Control Valve

The control valve is fixed at a certain position and moment. With the second set, this moment was picked randomly. In the first experiments, the valve was fixed when the valve position was 16% and increasing. The start of the experiments was around 600 s.

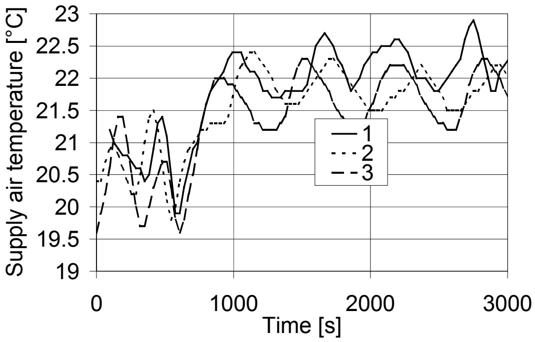

Figure 10 Reaction of supply air temperature when the control valve is fixed; first set of three experiments.

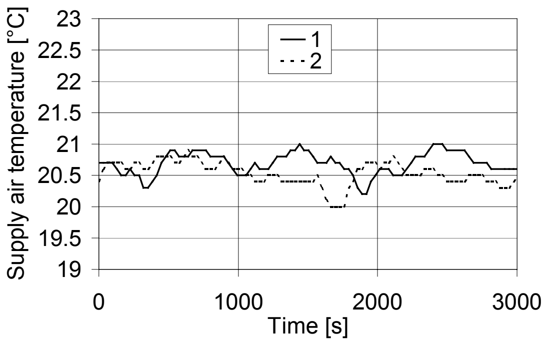

Figure 11 Reaction of supply air temperature when the control valve is fixed; second set of two experiments.

The response of the system when the control valve is fixed is really dependent on the operating conditions (compare Figure 10 with Figure 11). In the first set of experiments, the control valve position fluctuates between 10 and 18%. Fixing the valve at 16% will significantly influence the supply air temperature (Figure 10). From Figure 11, it becomes clear that fixing the control valve position between 25 and 28% has little influence on the supply air temperature.

Furthermore, the actual position at which the control is fixed has a big influence on the response of the system too. Fixing at a high position will cause rising of the supply air temperature, low position will cause decreasing and middle position will not have much influence.

CONCLUSIONS

Faults in the building HVAC system can lead to more energy consumption or less indoor thermal comfort. In order to find useful information for fault detection and diagnosis, four different types of faults are introduced into a real air handling unit. The phenomena for all these faults are discussed. Some characteristics of the responses are raised, and they are supposed to be very useful for further FDD analysis.

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REFERENCES

Hughes, D. (1998). Low energy buildings within the European policy framework, *Proceedings NatVent Conference*, BRE, June.

Katipamula, S. and Brambley, M. (1998). Automated diagnostics: improving building system and equipment performance. *Energy User News* **23** (4).

Mull, T.E. (1997). *HVAC Principles and Applications Manual*. New York: McGraw-Hill.

US Department of Energy (2002). *Energy Information Administration,* Monthly Energy Review August 2002. Washington, DC.

Yu, B. and van Paassen, A.H.C. (2000). State-of-the-art of energy fault diagnosis for building HVAC system. *Proceedings of International Symposium of Air Conditioning in High Rise Buildings '2000—ACHRB '2000*, Shanghai, pp. 162–167.