LBNL-1004498

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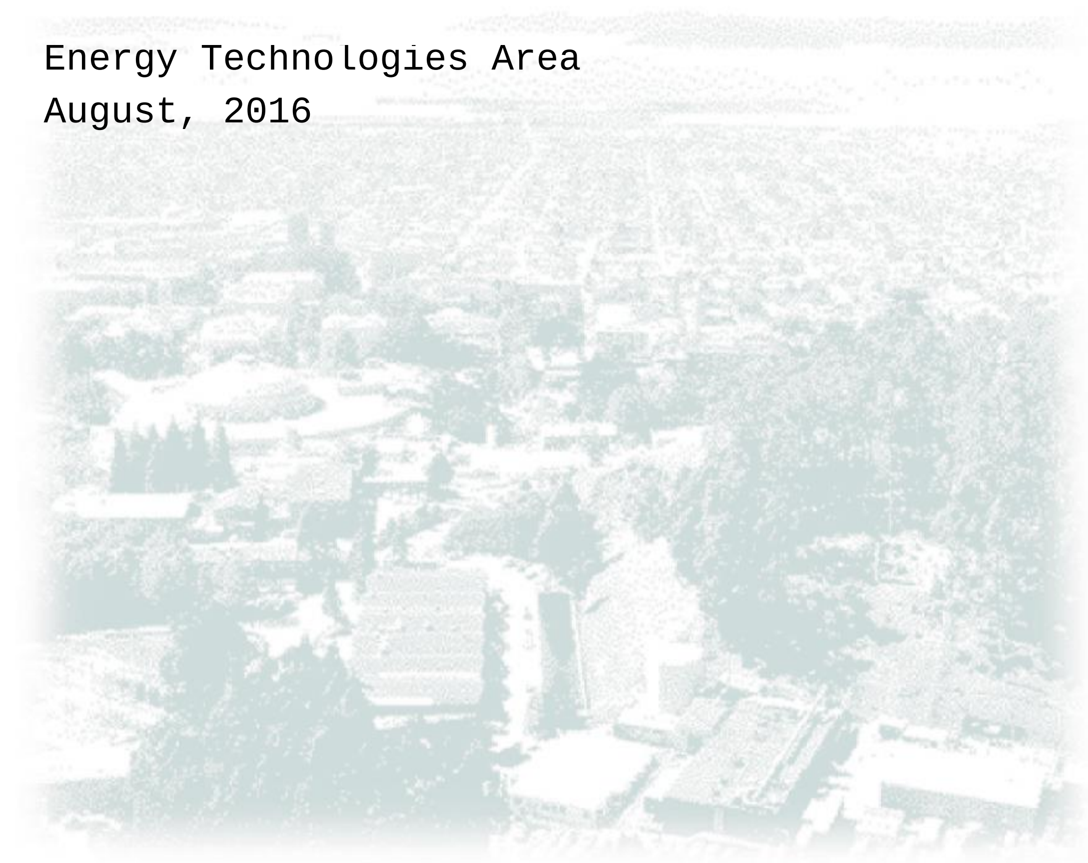
Energy Technologies Area

August, 2016



ASHRAE and IBPSA-USA SimBuild 2016
Building Performance Modeling Conference
Salt Lake City, UT
August 8-12, 2016

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ABSTRACT

HVAC operations play a significant role among various driving factors to improve energy performance of buildings. Extensive researches have been conducted on the design efficiencies and control strategies of HVAC system, but very few focused on the impacts of its operational faults on the building energy efficiency. Modeling and simulation of operational faults can lead to better understandings of the fault impacts and thus support decision making of timely fault corrections which can further benefit the efficient system operation, improve the indoor thermal comfort, and prolong the equipment service life. Fault modeling is also critical to achieve more accurate and reliable model calibrations. This paper introduces the modeling and simulation of operational faults using EnergyPlus, a comprehensive whole building performance simulation tool. The paper discusses the challenges of operational fault modeling, and compares three approaches to simulate operational faults using EnergyPlus. The paper also introduces the latest development of native fault objects within EnergyPlus. As an example, EnergyPlus version 8.4 is used to investigate the impacts of the integrated thermostat and humidistat faults in a typical office building across several U.S. climate zones. The results demonstrate that the faults create significant impacts on the building energy performance as well as occupant thermal comfort. At last, the paper introduces the future development plan of EnergyPlus for the further improvement of its fault modeling capability.

INTRODUCTION

The building sector has become the largest consumer of end use energy in the world exceeding both the industry and the transportation sectors. According to the US Department of Energy and the European Parliament and Council, buildings (both commercial and residential) account for about 40% of the total primary energy consumption in US and Europe (DOE 2011)(EPC 2010). This not only leads to enormous consumption of fossil fuel resources, but also produces severe environmental impacts such as ozone layer depletion and global warming.

HVAC operations play a significant role among various driving factors to improve energy performance of buildings. However, the operation performance of HVAC systems may be different from the design expectations due to various operational problems such as improper installation, equipment degradation, sensor failures, or control logic problems (Djuric & Novakovic 2009)(Wang et al. 2013). It is estimated that poorly maintained, and improperly controlled HVAC equipment is responsible for 15% to 30% of energy consumption in commercial buildings (Basarkar et al. 2013).

Extensive researches have been conducted on the design efficiencies and control strategies of HVAC system, however, very few focused on the impacts of its operational faults on the building energy efficiency. Modeling and simulation of operational faults can lead to better understandings of the fault impacts. It allows to estimate the severity of common faults and thus support the timely fault corrections which would enable the efficient system operation, improve the indoor thermal comfort, and prolong the equipment service life. Commissioning providers can use the fault models to demonstrate the saving to be expected from fixing faults found in retro-commissioning. The modeling of operational faults is also critical to achieve more accurate and reliable model calibrations, as in reality most buildings have various degrees and types of operational faults.

This paper introduces the modeling and simulation of operational faults using EnergyPlus, a comprehensive whole building performance simulation tool. It discusses the challenges of operational fault modeling using energy simulation programs, and compares three approaches to simulate operational faults using EnergyPlus. This paper also introduces the latest development of native fault objects within EnergyPlus, as well as the future development plan to further improve the fault modeling capability of EnergyPlus.

CHALLENGES OF FAULT MODELING

To model and quantify the impacts of operational faults in a specific building energy system, the following issues need to be taken into account and well addressed.

Firstly, building energy system is usually a complex system implementing numerous interrelated equipment components and sophisticated control logics. The operational faults of a single component can further affect the operations of many other related components and therefore makes it complex to quantify its overall impacts on the whole building energy performance. For example, the supply airflow reduction due to the degradation of fans may affect the heat transfer performance of coils and thus its energy consumption.

Secondly, the operational fault may present diverse impacts on different aspects of the building performance. For instance, a positive offset of the thermostat (i.e., the zone air temperature reading is higher than the actual value) will generate different influence on both the energy consumption and thermal comfort levels at different seasonal periods. During heating season, it reduces the heating energy consumption by maintaining the room temperature at lower levels, but meanwhile it deteriorates the indoor thermal comfort conditions. During cooling seasons, the energy consumption will increase and over-cooling may present. This is another reason that makes it complex to quantify the overall impacts of faults.

Thirdly, one particular operational fault may present very different characteristics and need to be handled separately. Take the temperature sensor offset for example, it can be:

(1) a static fault, if the offset is a constant value throughout the analysis period,

(2) an abrupt fault, if the offset arises suddenly during the analysis period and keeps at a constant level after occurrence,

(3) a degradation fault, if the sensor offset drifts over time.

These different cases need to be carefully distinguished and modeled in various methods which may use different features of the modeling tools.

In addition, operational faults may play different roles at different building simulation steps, and hence need to be handled differently. For example, the thermostat or humidistat offset fault should only be introduced during the weather simulation case, not the sizing case where maximum loads are calculated to determine capacity of HVAC equipment. Since the offsets are unknown during the design phase, they should not affect the sizing of the system. This requires fairly flexible and capable modeling capacities of the modeling tools.

FAULT MODELING APPROACHES USING ENERGYPLUS

EnergyPlus is a whole building performance simulation tool that can be used to investigate operational faults. It is the flagship building simulation engine supported by the United States Department of Energy. It can model heating, ventilation, cooling, lighting, water use, renewable energy generation and other building energy flows, by including many innovative simulation capabilities including sub-hourly time-steps, modular systems and plant integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, renewable energy systems, and user customizable energy management system (DOE 2015a). Each release of EnergyPlus is continually tested extensively using more than four hundred example files and the test cases are defined in the ASHRAE Standard 140. It is a powerful tool that supports building professionals, scientists and engineers in optimizing building design and operations, and thus helps to reduce energy and water consumption (Crawley et al. 2001).

EnergyPlus can be used to model HVAC operational faults in the following three ways.

The first approach is direct modeling in EnergyPlus IDF file. The advantage of this approach is easy implementation. Users can change the design input parameters or performance curves to describe the faulty operations, run the IDF file in a normal way, and then compare the results with the fault-free cases. Using this approach, however, users can only modify the existing input parameters which are not specifically designed for fault modeling. It is usually limited to address static faults such as outdoor air damper leakage, or the simplified operational issues such as chiller fouling described by an empirical degradation factor (Wang & Hong 2013). It is usually unqualified to handle complex fault models, especially those requiring sophisticated physical calculations. What’s more, users need to be careful to set up the fault models that are not supposed to affect the sizing period in the simulation. Many auto sizing features of EnergyPlus may need to be avoided as a tradeoff of direct modeling of operational faults.

The second approach is to use the energy management system (EMS), an advanced feature of EnergyPlus. It is a scripting language that allows the development of customized supervisory controls to override selected aspects of EnergyPlus modeling (DOE 2015b). Compared with direct modeling approach, EMS provides more flexibility to the user to design or overwrite algorithms in EnergyPlus within the specified aspects of current EMS capability, and is more powerful in handling complex fault models such as dirty filters with increasing pressure drop during simulation periods. This approach, however, only offers users limited access to a pre-selected set of parameters, i.e., EMS sensor and actuator set. It cannot address the fault models requiring parameters out of that set. In addition, users need to program specific logics to describe the fault model for a particular building system. This makes it laborious and inflexible to transfer the fault model to another building model with different system configurations. Moreover, EMS is an advanced feature designed for EnergyPlus professional users. It requires computer programming skills as well as deeper understandings on the connections between faulty component and related objects. This may limit its adoption by common building energy modelers and practitioners.

The third approach is to use native fault objects within EnergyPlus. Compared with the above ones, this approach has remarkable advantages in terms of usability, capability, flexibility, and transferability. Since the developers have full access to all the EnergyPlus parameters in source codes, the complexity of the fault models is no longer a problem. Using this approach, developers can implement substantial generic physical logics in the source codes, e.g., the algorithm calculating the impacts of dirty air filter pressure drop increase on the airflow delivering performance of various types of fans. Therefore, users only need to provide the fault information required in the IDD, without worrying about the description of its calculation logics. This highly reduces the modeling burdens of users compared with the EMS approach. Therefore, this approach can be more widely adopted by both practitioners and energy modeling experts. Moreover, the native fault object is fairly generic for various building system configurations, and thus makes the fault modeling more transferable from one building model to the other. Note that this approach is easy and friendly to the user, but it requires considerable amount of work from the EnergyPlus developers to design and create the objects. As described in the following section, current EnergyPlus V8.4 can only cover four common fault types. More fault types will come in the following EnergyPlus releases in the future.

NATIVE FAULT OBJECTS WITHIN ENERGYPLUS

A review of operational faults in buildings was carried out and a number of common HVAC equipment faults were identified in the previous study (Basarkar et al. 2013). These faults were then ranked according to both the complexity of implementation and the severity of associated energy penalty. Based on the ranking, four types of occurring faults have been implemented in EnergyPlus, including:

(1) Sensor faults with air economizers,
(2) Thermostat/humidistat offset,
(3) Heating and cooling coil fouling,
(4) Dirty air filters.

The symptoms and modeling approaches of these operational faults are introduced in details below.

Economizer Sensor Offset

Symptom:

The sensor readings deviate from the actual air conditions, which leads to inappropriate operations of the air economizer and thus undesired resulting indoor conditions.

Approach:

There are many sensors installed in the economizer to support its proper operations. These sensors may be of different types. In the current EnergyPlus, a number of objects are designed to describe the fault of different types of sensors at various economizer locations, such as FaultModel:EnthalpySensorOffset:ReturnAir and FaultModel:TemperatureSensorOffset:OutdoorAir. These faults further applies to the set-point manager objects such as SetpointManager:SingleZone:Heating.

The effect of an offset in a sensor whose sole use is for calculation of the difference between the set-point and actual air condition can be modeled as an equal and opposite offset in the set-point:

$$T_f = T_{ff} \pm \Delta T \quad (1)$$

$$RH_f = RH_{ff} \pm \Delta RH \quad (2)$$

$$h_f = h_{ff} \pm \Delta h \quad (3)$$

Where

- $T/RH/h_f$ temperature/humidity/enthalpy value for the faulty sensor case
- $T/RH/h_{ff}$ temperature/humidity/enthalpy value in the fault-free case (design value)
- $\Delta T/RH/h$ difference between faulty sensor reading and the actual value

Note that the economizer sensor set-points are related with two major processes within EnergyPlus: one is the design load calculations and HVAC system sizing, and the other is the HVAC system operations. Only the latter is affected by the economizer sensor offset, while the former is not. Therefore, the two processes are addressed separately in the development of the sensor offset fault model.

Thermostat/Humidistat Offset

Symptom:

The zone air T/RH readings deviate from the actual indoor air T/RH levels due to thermostat/humidistat offset, and thus leads to inappropriate operations of the heating/cooling/humidifying/dehumidifying equipment.

Approach:

The effect of an offset in a thermostat/humidistat whose sole use is for the calculation of difference between the set-points and the design air conditions can be modeled as an equal and opposite offset in the thermostat/humidistat:

$$T_f = T_{ff} \pm \Delta T \quad (4)$$

$$RH_f = RH_{ff} \pm \Delta RH \quad (5)$$

Where

T/RH_f	thermostat/humidistat value in faulty case
T/RH_{ff}	thermostat/humidistat value in the fault-free case (design value)
$\Delta T/RH$	difference between thermostat/humidistat reading and the actual zone T/RH

Note that the humidistat offset faults can be divided into two types: thermostat fault dependent and independent. These two types of the faults need to be addressed differently. For the humidistat that is independent of the thermostat, ΔRH can be simply described by a pre-defined schedule. For the humidistat offset that is caused by the thermostat offset, however, ΔRH is related with both the thermostat offset level as well as the indoor air conditions which are dynamic, and therefore cannot be described with a pre-defined schedule. In this case, the humidistat offset level is calculated at each time step.

$$\Delta RH = RH_{ff} - f(T_{real}, W_f) \quad (6)$$

Where

T_{real}	real-time temperature of the indoor air (real value), °C
W_f	humidity ratio corresponding to $T_{real} \pm \Delta T$ and $RH_{s,ff}$, kg_{Water}/kg_{DryAir}

The thermostat offset fault is described in the FaultModel:ThermostatOffset object and further applies to the following objects in EnergyPlus:

(1) ZoneControl:Thermostat
(2) ZoneControl:Thermostat:TemperatureAndHumidity
(3) ZoneControl:Thermostat:OperativeTemperature

The humidistat offset is described in the FaultModel:HumidistatOffset object and further applies to: ZoneControl:Humidistat.

Fouling Coils

Symptom:

Reduced overall heat transfer coefficient (UA) causes reduced coil capacity, resulting in unmet loads and/or increased water flow rate and decreased water side temperature difference ("low ΔT" syndrome).

Approach:

The fault model is described in the FaultModel:Fouling:Coil object and further applies to the water coils described by:

(1) Coil:Heating:Water,
(2) Coil:Cooling:Water.

The model allows the user to describe the fouling information in either of the two methods: *FouledUARated*, or *FoulingFactor*. In *FouledUARated* method, user specifies the value of UA_{fouled} directly. In *FoulingFactor* method, user specifies air/water side fouling factor, and the UA_{fouled} value is further calculated via:

$$UA_f = (UA_{air}^{-1} + R_{foul} + UA_{water}^{-1})^{-1} \quad (7)$$

Where

UA_{air}	heat transfer coefficient of the coil on the air side, W/K
UA_{fouled}	overall heat transfer coefficient of the fouled coil, W/K
UA_{water}	heat transfer coefficient of the coil on the water side, W/K
R_{foul}	fouling factor, K/W

R_{foul} is determined by:

$$R_{foul} = r_{air}/A_{air} + r_{water}/A_{water} \quad (8)$$

Where

r_{air}	Air side fouling factor, m^2K/W
r_{water}	Water side fouling factor, m^2K/W
A_{air}	Air side coil surface area, m^2
A_{water}	Water side coil surface area, m^2

The pressure drop associated with the fouling is ignored in this implementation, because its impact is usually not significant compared to its impact on the heat transfer performance of the coil.

Dirty Air Filters

Symptom:

Increased air loop system resistance, resulting in a different system curve. This directly affects the operation of corresponding fans. More specifically, it may lead to an increase in the fan pressure rise, fan energy consumption, as well as the enthalpy of the fan outlet air. It may also lead to a reduction in the airflow rate and thus affects the performance of other system components (e.g., heat transfer performance of heating/cooling coils).

Approach:

The dirty air filter fault is described in the FaultModel:Fouling:AirFilter object and further applies to the following objects:

(1) Fan:ConstantVolume

(2) Fan:OnOff

(3) Fan:VariableVolume

The operating performance of a fan is related with a number of factors, including the fan types, system design and operating conditions. In general, there are three possible situations to be addressed in modeling dirty air filters:

(a) The required airflow rate can be maintained by the variable speed fan running at higher speed.

In this case, the fan operation state changes from point A (intersection of the fan curve corresponding to a lower speed and the system curve with clean filters) to point B (intersection of the fan curve corresponding to a higher speed and the system curve with dirty filters), as shown in Figure 1. Point B corresponds to a higher fan pressure rise than Point A, and the same air flow rate.

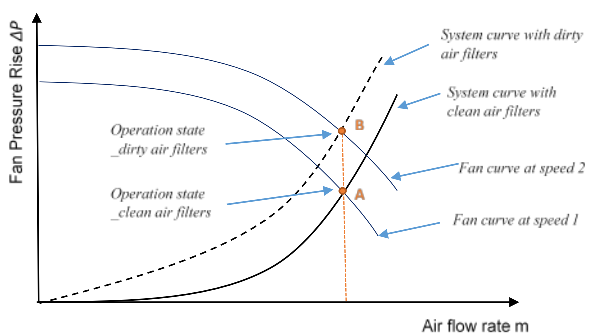

Figure 1 Effect of dirty air filter on variable speed fan operation – flow rate maintained

The required airflow rate m can be maintained while the fan pressure rise ΔP is increased to ΔP_{df}. This leads to higher fan power (Q_{tot}) and higher power entering the air (Q_{toair}), and thus changes the specific enthalpies of the fan outlet air stream (h_{out}).

$$f_{flow,df} = m / m_{design,df} \quad (9)$$

$$f_{pl,df} = c_1 + c_2 \times f_{flow,df} + c_3 \times f_{flow,df}^2 + c_4 \times f_{flow,df}^3 + c_5 \times f_{flow,df}^4 \quad (10)$$

$$Q_{tot,df} = f_{pl,df} \times m_{design,df} \times \Delta P_{df} / (e_{tot} \times \rho_{air}) \quad (11)$$

$$Q_{shaft,df} = e_{motor} \times Q_{tot,\, df} \quad (12)$$

$$Q_{toair,df} = Q_{shaft,df} + (Q_{tot,df} - Q_{shaft,df}) \times f_{motortoair} \quad (13)$$

$$h_{out,df} = h_{in} + Q_{toair,df} \; / \; m \quad (14)$$

Where

e_{motor}	motor efficiency
f_{flow}	flow fraction or part-load ratio
f_{pl}	part load factor
m	air mass flow, kg/s
Q_{tot}	fan power, W
Q_{toair}	power entering the air, W
Q_{shaft}	fan shaft power, W
ΔP	fan pressure increase, Pa
$_{design}$	for the parameters in the design condition
$_{df}$	for the parameters in the dirty filter case.

(b) The variable speed fan cannot increase in speed sufficiently to maintain the required airflow rate.

In this case, the fan operation state changes from point A (intersection of the fan curve corresponding to a lower speed and the system curve with clean filters) to point B (intersection of the fan curve corresponding to a higher speed and the system curve with dirty filters), as shown in Figure 2. Point B corresponds to a higher fan pressure rise and a lower air flow rate than Point A.

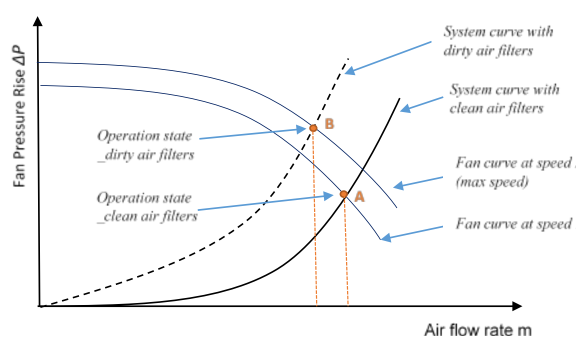

Figure 2 Effect of dirty air filter on variable speed fan operation – air flow rate reduced

The airflow rate m is reduced to m_{df} while the fan design pressure rise ΔP is increased to ΔP_{df}. Similarly to case (a), the fan power (Q_{tot}), the power entering the air (Q_{toair}), and the specific enthalpies of the fan outlet air stream (h_{out}) are all affected. Additionally, the flow fraction f_{flow} becomes 1 in case (b).

$$f_{flow,df} = 1 \quad (15)$$

$$f_{pl,df} = c_1 + c_2 \times f_{flow,df} + c_3 \times f_{flow,df}^2 + c_4 \times f_{flow,df}^3 + \quad (16)$$

$$c_5 \times f_{flow,df}^{\ 4}$$

$$Q_{tot,df} = f_{pl,df} \times m_{design,df} \times \Delta P_{df} / (e_{tot} \times \rho_{air}) \tag{17}$$

$$Q_{shaft,df} = e_{motor} \times Q_{tot,\ df} \tag{18}$$

$$Q_{toair,df} = Q_{shaft,df} + (Q_{tot,df} - Q_{shaft,df}) \times f_{motortoair} \tag{19}$$

$$h_{out,df} = h_{in} + Q_{toair,df} \ / \ m_{\ design,df} \tag{20}$$

(c) The constant speed fan cannot maintain the design airflow rate.

In this case, the fan operation state changes from point A (intersection of the fan curve and the system curve with clean filters) to point B (intersection of the fan curve and the system curve with dirty filters), as shown in Figure 3. Point B corresponds to a higher fan pressure rise and a lower air flow rate than Point A.

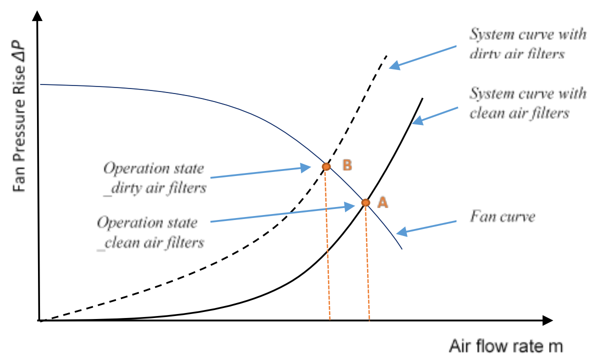

Figure 3 Effect of dirty air filter on constant speed fan operation

Similarly to case (b), the airflow rate m is reduced to m_{df} while the fan pressure rise ΔP is increased to ΔP_{df}. This results in variations of the fan power (Q_{tot}), the power entering the air (Q_{toair}), and the specific enthalpies of the fan outlet air stream (h_{out}).

$$Q_{tot,df} = m_{df} \times \Delta P_{df} / (e_{tot} \times \rho_{air}) \tag{21}$$

$$Q_{shaft,df} = e_{motor} \times Q_{tot,\ df} \tag{22}$$

$$Q_{toair,df} = Q_{shaft,df} + (Q_{tot,df} - Q_{shaft,df}) \times f_{motortoair} \tag{23}$$

$$h_{out} = h_{in} + Q_{toair,df} \ / \ m_{df} \tag{24}$$

IMPACTS OF OPERATIONAL FAULTS: A CASE STUDY

As an example, the impact of integrated thermostat/humidistat offset faults in a typical small-size office building is investigated using the latest EnergyPlus version 8.4.

This building implements a standard VAV system with an outside air economizer, a central chilled water cooling coil, and hot water reheat coils. The central plant includes a single hot water boiler, an electric compression chiller with water cooled condenser, an electric steam humidifier, and a cooling tower. The system controls the high relative humidity set-point of 50% with the chilled water coil and low humidity set-point of 40% with the electric steam humidifier.

The following two cases are modeled and simulated using the native fault objects introduced above:

- Case 1: humidistat offset caused by dependent thermostat with an offset of 1°C
- Case 2: humidistat offset caused by dependent thermostat with an offset of -1°C

In the study case, the humidistat offset fault is caused by thermostat offset fault and they present a coupling effect to the HVAC system control. Moreover, the humidistat offset is a function of the constant thermostat offset as well as the dynamic indoor air conditions. These make it challenging to estimate the fault impacts on the system operations.

The model was simulated using the weather data from several typical cities located at various U.S. climate regions. The comparisons of the energy consumption and occupant comfort are depicted in Figure 4 and 5, respectively.

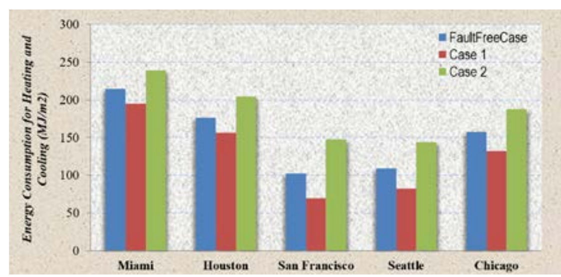

Figure 4 Impact of integrated thermostat/humidistat offset faults on building energy consumption

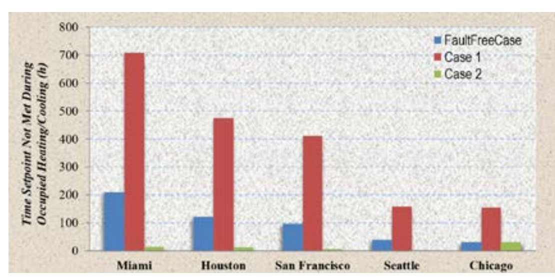

Figure 5 Impact of integrated thermostat/humidistat offset faults on indoor thermal comfort

As can be seen in the Figure 4, both faulty cases lead to remarkable influence on the heating and cooling energy consumptions in all the investigated cities. Case 1 leads to an energy reduction of 8.97-32.04% compared to the fault-free case, while case 2 increases the energy consumption by 11.62-44.05%. Figure 5 shows that the fault also dramatically changes the set-point unmet hours during heating and cooling periods, indicating significant impacts on the occupancy thermal comfort levels.

FUTURE FAULT DEVELOPMENT PLAN

To further expand the fault modeling capacities of EnergyPlus, a number of new fault objects are under development focusing on the operational faults in the plant systems. These faults include:

(1) Boiler performance degradation
(2) Cooling tower scaling
(3) Coil supply/outlet air temperature sensor offset
(4) Chiller water temperature sensor offset

These fault models are expected to come into the coming EnergyPlus release in the near future.

Note that the fault models will be deployed to the corresponding equipment component models existing in the current EnergyPlus. Therefore, they need to be particularly designed taking into account the characteristics of these equipment models. In general, a more physics based equipment model can offer more flexibility to the development of the corresponding fault model, since it allows the manipulation of more operational parameters. For the equipment models that are mainly based on empirical curves, however, there will be less flexibility due to limited access to operational parameters. How to make better use of existing equipment model features and handle various levels of constraints need to be well addressed in the design and implementation of the plant equipment fault models.

CONCLUSION

HVAC operational faults may generate significant impacts on efficient building system operations. Modeling and simulation of operational faults can support the timely fault corrections and benefit model calibration. This paper introduces the modeling and simulation of operational faults using EnergyPlus. It discusses the challenges of operational fault modeling and compares three approaches to simulate operational faults using EnergyPlus. It also presents the latest development of native fault objects within EnergyPlus, including: sensor faults with air economizers, thermostat/humidistat offset, heating and cooling coil fouling, and dirty air filters. The symptoms and modeling approaches of these operational faults are presented. As an example, EnergyPlus version 8.4 is used to investigate the impacts of integrated thermostat/humidistat offset faults in a typical office building across several U.S. climates. The results demonstrate that the faults create significant impacts on the energy performance of HVAC systems as well as occupant thermal comfort. Future work will involve the modeling and implementation of operational faults in the plant systems to further expand the fault modeling capacities of EnergyPlus.

ACKNOWLEDGMENT

The authors would like to thank Jason Glazer, Michael J Witte, Jim Braun, Howard Cheung, Lixing Gu, and Daniel Macumber for all the constructive suggestions and discussions during the development of these fault models. This work was supported by the U.S. Department of Energy under Award No. 00171505.

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