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

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

$$Q_{shaft,df} = e_{motor} \times Q_{tot,\,df} \qquad (18)$$

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

$$h_{out,df} = h_{in} + Q_{toair,df} \;/\; m_{design,df} \qquad (20)$$

(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.

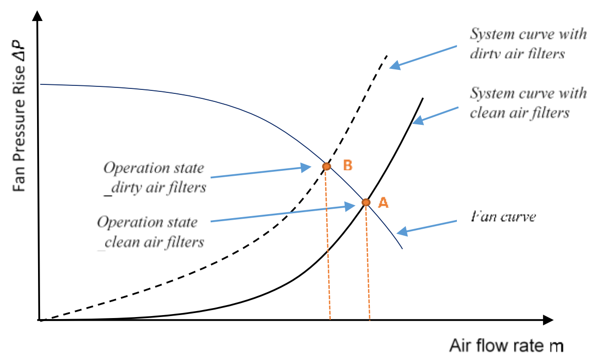

Figure 3 Effect of dirty air filter on constant speed fan operation

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}).

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

$$Q_{shaft,df} = e_{motor} \times Q_{tot,\,df} \qquad (22)$$

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

$$h_{out} = h_{in} + Q_{toair,df} \;/\; m_{df} \qquad (24)$$

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.

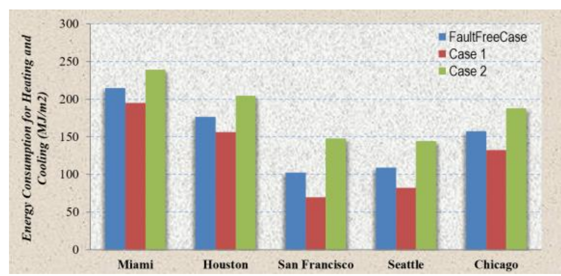

Figure 4 Impact of integrated thermostat/humidistat offset faults on building energy consumption

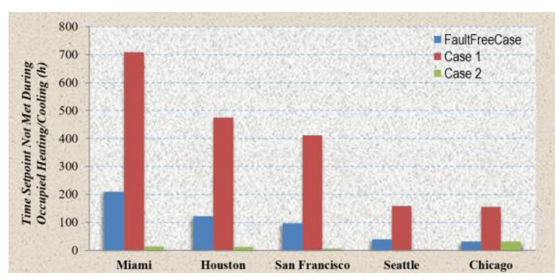

Figure 5 Impact of integrated thermostat/humidistat offset faults on indoor thermal comfort

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

With the new high priority attached by US DOE to retrofit and improve the operations of existing buildings, there is a need to extend the capabilities of EnergyPlus to model existing buildings, including faulty operational faults. 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.

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