A Modelica-based Simulation Study for Dynamic HVAC System Performance Degradation: A Case Study of Fouling Faults

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Abstract

Heating, Ventilation, and Air Conditioning (HVAC) systems and equipment are prone to gradual performance degradations, which could lead to sudden collapses of the entire system if such faults are not detected and isolated in time. Due to the challenge of long-period field data collection, there is barely any real building degradation performance data available publicly to support the development of fault detection and prognostics algorithms for degrading failures. To fill the gap, this research develops a Modelica-based modeling framework to investigate the degrading system performance using dynamic system simulation. The effectiveness of the proposed framework is demonstrated by airside and waterside gradual fouling case studies via an annual simulation. Compared to the fault-free condition, the fouling cases show up to a 34% energy consumption variation at the equipment level and a maximum of 5% energy usage difference at the system level.

Introduction

Today's HVAC systems may suffer from both abrupt and degrading faults. When a component fails partially or completely, the whole system would deviate from its normal operating state, which can possibly cause great losses in thermal comfort and economy. Numerous studies exist on developing detection and diagnosis methods to prevent the system from encountering such harsh disadvantages. The fault detection and diagnostics (FDD) algorithm has become one of the most popular topics in recent years as it can identify HVAC faults and provide solutions to address those problems. Furthermore, the fault prognostic concept is also being studied as an extension to the FDD concept to predict potential future system failures based on current performance data. Research on faults with fixed severity were extensively investigated as they are relatively easier to apply in either actual experimental tests or virtual simulation models, and fault impacts could be obtained in a short period of operational time. Although gradually degrading faults have been noticed as one of the reasons causing poor operation or even failures of HVAC systems and equipment (Xiao and Wang, 2009; Sobral and Soares, 2016), degrading faults have not been widely studied yet. Due to the progressively accumulating pattern of the degrading faults, a relatively long period of time is required to reveal the consequences. However, it is very challenging to collect such degradation data in the field or from designed experiments. Thus, to investigate the gradual changing behaviors and resulting impacts of the entire system, creating fault simulation models seems to be an effective way for data generation for such degradation faults.

The fouling phenomena of HVAC heat exchangers can be treated as a typical type of degradation fault due to the gradually accumulated foulant layers. Fouling, which is defined as the formation of undesired material deposits on heat transfer surfaces, generally provides additional resistances to the heat exchanger. The presence of the accumulated deposits constricts the heat exchanging surface area, which results in an increase in thermal resistance. In addition, the foulant layer can also add roughness to the stream path, so the flow resistance is also negatively affected (Bott, 1995). Therefore, in long-term operation, the progressively attached fouling usually causes thermal inefficiency and variances in energy consumption as pumping and fan powers will change to withstand additional hydrodynamic pressure drop. Several studies have reported flow reduction and loss of effective cooling capacities due to over-time fouling based on field measurements (Krafthefer and Bonne, 1986; Haider & Meitz, 1991; Neal, 1992; Parker et al., 1997; Li and Braun, 2007). Furthermore, for fouling occurred on the airside of heat exchangers, especially for those directly in touch with the supply air (e.g., AHU coils), the attachment of microorganisms on moist cool surfaces can also lead to indoor air quality problems (Hugenholtz and Fuerst, 1992).

The fouling phenomena of heat exchangers has attracted great attention in recent decades, and its impact on heat transfer and pressure drop has been extensively investigated at the device level. However, as a critical component in large HVAC systems, how a fouled heat exchanger would alter the overall HVAC equipment and system performance has not been elaborately addressed yet. Fenaughty and Parker (2018) is one of the groups who treated fouling on HVAC heat exchangers as an important factor causing overall system degradation. They collected HVAC operation data in 2-5 years from 56 homes to evaluate system degradation. The estimated median degradation rate was 5.2% per year, which is higher than that mentioned by the Department of Energy (i.e., 3%). Although this study was carried out at the system level, detailed time-varying symptoms and system performance changes deviating from the normal operating conditions were still lacking.

Despite the existing investigations on the component level, the fouling impacts on the overall HVAC system remain obscure. The lack of understanding of system-level fouling symptoms, such as over-time changes in energy consumption, restricts the development of system failure detection and prediction methods due to the limited available degrading system data source. The data-driven method for fault detection and prognosis is widely used for HVAC systems. The development and validation of such methods heavily rely on data from operational measurements. By learning the operational data pattern and identifying the variances between normal and abnormal conditions, the irregular system performance can be distinguished and the system degradation trend which leads to possible future failures will become foreseeable. Large quantity of data is required for the development and validation of such algorithms to achieve stable and healthy long-term system operations. However, collecting such a large quantity of data from field monitoring is barely possible. To provide sufficient data for abnormal system performance learning and fault diagnostics and prognostics algorithms development, simulation studies are feasible tools to capture long-term system degradation behaviors.

This study aims to provide a Modelica-based simulation framework for modeling and evaluating the effects of gradual degradation faults on building energy systems. This framework is demonstrated through a case study of heat exchanger fouling faults, including both waterside and airside fouling. This paper is organized as follows: first, a literature review is conducted to summarize the heat exchanger fouling patterns from experimental studies and fault simulation tools in current literature. Two types of fouling degradations induced by long-term operation are particularly investigated, which are: gradual airside fouling on the cooling coil fins and gradual waterside fouling within the condenser pipes. The methods section introduces the development of a mid-sized office building HVAC Modelica model as a virtual testbed for investigating the gradual accumulated fouling impacts at the system level. The two fouling degradation mechanisms are then individually implemented in this Modelica-based simulation testbed. The long-term system performance under the fouled conditions is discussed based on the simulation results. Finally, the conclusions and future works are presented at the end.

Literature review

Waterside fouling

Studies on waterside fouling majorly focus on heat exchanging tubes with structured surfaces since they are usually thermally favorable, but the textured surfaces can also provide convenience for particle attachment and deposition. Webb and Li (2000) performed long-term water fouling tests for 7 enhanced tubes to understand the influence of tube internal geometry on heat transfer performance. A maximum fouling resistance was found to be 3.25 times of the design value. Similar experiments have also been conducted by Xu and Zhang (2010) for 4 enhanced tubes and 1 plain tube under fouling conditions. They concluded that the enhanced tubes had higher pressure drops than that of the plain tube, but their heat transfer performance was still much better than the plain tube under the same level of fouling. Likewise, most studies investigated the waterside fouling behaviors with a particular interest in diminished thermal efficiency and fouling resistance evolution. Seldom did the researchers report the pressure drop caused by waterside fouling. Cremaschi et al. (2011) were one of the groups who measured waterside pressure drop. They examined 4 heat exchangers with different configurations by feeding high fouling potential water. The results presented a heat flux reduction in range 4-28% and a pressure drop rising in range 50-250% within test durations varying from 30 to 65 days.

Airside fouling

Fouling is unavoidable neither when air is used as one of the heat transfer media. In general, airside fouling has a more significant effect on pressure drop compared to that on heat transfer performance. (Pak et al., 2005; Yang et al., 2007; Sun et al., 2012). Pak et al. (2005) investigated fouling over six types of coils by introducing ASHRAE standard dust (ASHRAE standard 52.1, 1992) to the air flow. The amount of injected foulant was prepared based on a 1-year deposition of a typical condenser in the field. Results show an increase in pressure drop by up to 37% and a decrease in heat transfer performance by up to 12%. Similar experiments were performed by Yang et al. (2007) on 4 evaporators to examine the dust-capture capability of the air duct filter. ASHRAE standard dust (ASHRAE standard 52.1, 1992) was injected to mimic a 1-year operation condition in the field. They found that the filter could capture most of the dust and therefore allow better coil performance. The coil pressure drops increased by 6-30% for with-filter conditions, whereas for no-filter cases, pressure drops increased by 43-200%. Meanwhile, the heat transfer coefficients decreased by up to 7% for filtered cases and decreased by 6-14% for dusty cases. They also mentioned a slight enhancement in heat transfer under a mild fouled condition as a consequence of an increased turbulence effect. This advantageous improvement in performance has also been reported by Mehrabi and Yuill (2019). Ali and Ismail (2008) have also done dust injection experiments on evaporator coils to study the impact on coefficient of performance (COP) and indoor air quality. Fouling materials collected in the field were injected in 3 doses to imitate 1-year operation conditions. The COP was found to diminish to 67%, 63.4%, and 43.6% of its nominal value for each dose of injections. Sun et al. (2012) also constructed particulate fouling conditions by dust feeding. The foulant was gradually introduced to mimic airborne dust density. Heating mode of the heat exchanger has also been tested under fouled conditions. The result showed that the fouling effect was more obvious under the cooling mode due to the presence of condensed moisture.

Table 1 lists fouling experimental studies with foulants accumulated in certain testing periods reported in the literature. Details of experimental conditions, test durations, and critical results on heat transfer and pressure drop were recorded. These sets of data were collected because they indicate the degree of performance variations for heat exchanger applications in HVAC systems.

Fault modeling

Modeling and simulation of HVAC systems is an efficient way of studying the normal and faulty system performance. There exist hundreds of available HVAC simulation software and programs which makes it easier for modeling HVAC systems with various configurations. Commonly seen programs, such as EnergyPlus, Modelica, TRNSYS, HVACSIM+, are some of the frequently mentioned simulation tools in virtual HVAC studies. However, most of the modeling software is originally designed to mimic normal operating conditions and assess system performance (e.g., energy consumption). Only a few of them have detailed enough physical models that can be used for fault modeling. Several simulation fault models were reported in previous studies. Wen and Li (2011) developed both fault-free and faulty models, which were validated by using experimental data, in HVACSIM+. The investigated faults included temperature sensor bias, damper and valve stuck, fan failures, leaking, control disability, etc. Basarkar (2011) implemented four HVAC faults, including pipe clogging, damper leaking, coil fouling, and temperature sensor offset, in EnergyPlus and evaluated the fault impacts on energy consumption and occupant comfort. Faults were implemented by altering input values on top of the baseline model. For example, the heating coil fouling fault was introduced by altering coil's inlet and outlet temperatures. Zhang and Hong (2017) have also studied fault impact via the EnergyPlus platform by utilizing four native fault objects such as sensor fault, thermostat/humidistat offset, coil fouling, and dirty air filter. Khire and Trcka (2013) developed a fault modeling library in TRNSYS and studied the coupling effect caused by simultaneous appearance of multiple faults. Faults were injected by specifying the according pre-defined fault parameters which represent the occurrence and intensity of the corresponding faults. Padilla and Choiniere (2015) applied temperature sensor bias fault in Modelica and investigated the impact under different fault severities. The fault was implemented by adding a fixed offset value to the sensor output.

Table 1 A summary of experimental conditions, durations, and results from fouling experimental studies in literature

Fouling side	Tested heat exchanger	Remarkable fluid and foulant experimental conditions	Test duration	Experimental results associated with heat transfer	Experimental results associated with pressure drop	Citation
Waterside	Internally enhanced tubes	800 ppm calcium hardness water	2500 h	Maximum fouling resistance increased 3.25 times	N/A	Webb and Li (2000)
	Internally enhanced tubes and a plain tube	Water Reynolds number: 4138-23539	10-27 h	Fouling resistance ration 0.573-0.713 (with plain tube being 1)	N/A	Xu and Zhang (2010)
	Brazed-type heat exchangers	Langelier saturation index (LSI): 1-4	30-65 days	Heat flux decreased 4-28%	Pressure drop increased 10-250%	Cremaschi et al. (2011)
Airside	Plate and spine finned coils	Foulant: ASHRAE standard dust; air velocity: 1.53 m/s	Equivalent to 1-year fouling condition in field	Heat transfer decreased by 4-12% (with upstream filter)	Pressure drop increased by 22-37%	Pak et al. (2005)
	Lanced and wavy finned coils	Foulant: ASHRAE standard dust; air velocity: 2.54 m/s	Equivalent to 1-year fouling condition in field	Airside effective heat transfer coefficient decreased by -4-7% with upstream filter (1); increased by 8-14% without upstream filter	Pressure drop increased by 6-30% with upstream filter; increased by 43-200% without upstream filter	Yang et al. (2007)
	Flat and wave finned coils Fouling Type: particulate fouling	Foulant: Limestone power Foulant injection rate: 11.6 g/min; air velocity: 3 m/s	6.1-21.1 min (2)	Effective heat transfer coefficient of the coil decreased by less than 10% (no filter)	Pressure drop increased by 100%	Sun et al. (2012)

Notes: (1) The negative value indicates an increased heat transfer coefficient case which is caused by an increased turbulence effect; (2) Experiments stopped when pressure drop doubled.

Most of the current fault modeling and simulation studies focus on fixed fault intensity. Time-dependent degradation faults can also be implemented in those simulation tools. For example, Center. I. E. (2003) applied gradual temperature sensor offset fault in HVACSIM+ with the drift increased from 0 to +4 ℃ in two weeks. Kim et al. (2019) modelled several evolutionary faults with specified severities in EnergyPlus including fouling (0 to 50% reduction in air flow rate), temperature sensor bias (-3 to +3K), humidity sensor bias (-10% to +10%), air duct leakage (0 to 30% reduction in air flow rate), HVAC component efficiency reduction (0 to 30%), etc. The common problem in the existing degradation simulation is that, although degradation data can be generated, the level of fault severities was mostly human designed without accounting for real-world degradation rates which could be much slower. It is not clear if any new challenge would be brought up by the realistic evidence of slow-evolving system performance degradation.

The currently available literature does not provide sufficient data for real-would FDD and prognostics algorithms training which can later be used to detect cumulative degradations triggered by long-term system operation. Intensive efforts would be required to collect such long-term data from field or designed experiments. Therefore, as an effort-efficient solution to obtain enormous long-term performance data, degradation simulation models need to be built based on realistic degradation symptoms and patterns of the system components.

Methods

An existing Modelica model for a mid-sized office building, developed by Lawrence Berkeley National Laboratory (Wetter et al., 2014), was adopted to implement degrading faults in this study. The model represents a building with 5 zones and variable-air-volume air handling unit system (VAV-AHU). The system was scheduled to be operated only on workdays from 7am to 7pm. Automatic control strategies were applied to the system to achieve a flexible and energy-efficient operation. The figure of the system model and detailed control strategies were reported in Lu et al. (2021) and Fu et al. (2021).

Modelica, as an object-oriented dynamic modeling solution which creates representations of buildings via mathematical equations. Compared to most of other fault modeling platforms, Modelica is superior for its powerful multi-domain complex system modeling capability as it not only models the physical relationships of the system, but also imitates the effect of automatic local control sequences, which reflects real-world building automation system (BAS) behaviors and heavily influences system and equipment performance. Therefore, modeling faults in Modelica enables observation of actual system reactions and responses. Moreover, Modelica is an open-source modeling language that provides a syntax for convenient component customization, which makes it a great resource for precisely exerting time-dependent degradation on specific locations of relevant devices. In this study, fouling was implemented to the model by directly looking at the device's heat transfer behavior and pressure drop across it. The airside fouling degradation was implemented to the cooling coil, and the waterside fouling degradation was applied to the chiller's condenser.

The pressure drop module in Modelica is based on the relationship between pressure drop and mass flow rate. (1) shows this relationship with $\dot{m}$ being the mass flow rate and ΔP being the pressure drop. k is the flow coefficient which is related to the flow resistance. In the degradation-free model, k is a constant determined from the same equation by applying flow rate and pressure drop under the nominal condition. For the gradual fouling process, pressure drop will gradually increase from the clean condition, so a time-dependent pressure drop coefficient ($Coef\_f_{dp}$) is needed to modify (1) into a degradation form. The modified equation for pressure drop under the fouled condition is presented in (2).

$$\dot{m} = k \cdot \sqrt{\Delta P} \tag{1}$$

$$\Delta P = Coef\_f_{dp} \cdot \frac{1}{k^2} \cdot \dot{m}^2 \tag{2}$$

For the heat transfer reduction effect of fouling, modification can be made either directly on the heat flux or on the heat transfer coefficient depending on how the target component model is originally designed and implemented in Modelica. For fouling on the airside, fouling effect was constructed by altering the airside heat transfer coefficient of the cooling coil whose built-in heat exchanging process is determined from (3):

$$\dot{Q} = U_{air} \cdot \Delta T \tag{3}$$

where $\dot{Q}$ represents the convection heat transfer rate, U_{air} represents the conductance of the air, and ΔT designates temperature difference between fluid inlet and outlet. With particles and dust progressively accumulating on the coil surface, heat transfer blocked by the foulants gradually becomes worse over time. To implement the amount of decrease in heat transfer from its original value, a time-dependent heat transfer degradation coefficient ($Coef\_f_{HT}$) is applied. The modification can be seen from (4). Although in the early fouling stage, heat transfer can be slightly improved as the attached foulant layer enhances flow turbulence, the heat transfer would eventually be negatively affected from the sight of long-term operation. In this study, only the heat transfer reduction case was considered.

$$\dot{Q} = Coef\_f_{HT} \cdot U_{air} \cdot \Delta T \tag{4}$$

As for the waterside fouling effect on heat transfer, $Coef\_f_{HT}$ was directly applied to heat flux since the condenser module is not assembled with a detailed heat transfer coefficient. The modified equation for condenser waterside fouling can be taken as (5) indicated:

$$\dot{Q}_{condenser,f} = Coef\_f_{HT} \cdot \dot{Q}_{condenser,c} \tag{5}$$

Table 2 System level fouling simulation severity settings

Case number	Fouling location	Fouling start day	Heat transfer/heat transfer coefficient increase rate	Pressure drop decrease rate	Data source
0	Fouling-free	N/A	N/A	N/A	N/A
1	Cooling coil airside	Day 1	7% / yr	30% / yr	Yang et al. (2007)
2			14% / yr	200% / yr	
3	Condenser waterside	Day 170	4% / 65 days	250% / 65 days	Cremaschi et al. (2011)
4			28% / 30 days	50% / 30 days	

where $\dot{Q}_{condenser,f}$ and $\dot{Q}_{condenser,c}$ represent the heat transfer rates of the condenser under the fouled and the clean conditions, respectively.

Both $Coef\_f_{dp}$ and $Coef\_f_{HT}$ are functions of the elapsed time. Hence the related heat transfer rate and pressure drop also vary with time as the coefficients vary, which establish the gradual altering performance pattern of a fouling fault. The rates of change were obtained based on those test results reported in previous experimental studies as summarized in Table 1.

After all modifications have been completed, fouling simulation was performed in a 1-year duration (Started on January 1st and ended on December 31st). The weather profile was taken from Typical Meteorological Year, version 3 (TMY3) data set for the city of Tuscaloosa, AL. For fouling cases on each side, two runs were conducted with various degradation severities. Since the cooling plant only works on relatively hot days, the chiller/condenser keeps inactive at the beginning of the year, followed by irregularly partial switch-on as needed in the shoulder season, and becomes fully alive on daily service during the cooling season. The trend inverses as the weather gradually goes back to the winter season again. Thus, no waterside fouling was considered until a certain hot day. However, for the airside fouling case, fouling was introduced at the beginning of the simulation as conditioned air always goes through the same path where both cooling and heating coils are installed, despite coil working status. Four fouled cases (case 1-4) and their severity settings are listed in Table 2. Case 1 and case 2 were designed to examine airside fouling of the cooling coil, while case 3 and case 4 focused on waterside fouling appearing in the chiller's condenser. The testing rates of change were adopted from Yang et al. (2007) and Cremaschi et al. (2011). One baseline case (case 0) which is free from fouling was also performed for comparison purposes. To scale the degradation impacts, electricity consumption of the major components was specifically examined and compared to the baseline operation case.

Results and discussions

For fouling on the cooling coil airside, increase in energy consumption can be observed in the supply fan and the chilled water pump performance. Compared to the baseline, case 1 result shows a 2.2% and a 3.1% energy consumption increase in supply fan and chilled water pump, respectively. As for case 2 which experienced a more severe fouling condition, the supply fan consumed 12.6% more electricity compared to the baseline and the chilled water pump excessed the baseline usage by 6.3%. Minor consumption increases (less than 1%) also occurred in the chiller compressor and condenser water pump for both airside fouling cases. The increase in supply air fan electricity usage can be explained as a compensation of extra flow resistance caused by airside fouling. Fan speed was adjusted over time to accommodate the increased pressure drop but keep the air flow rate at a relatively stable level. Meanwhile, the effective heat transfer area of the cooling coil became partially blocked as foulant gradually accumulates on fins. Airside heat transfer rate degrades over time, and thus supply air temperature cannot reach as low as it is supposed to if the chilled water system has no reaction to this change. To deal with the loss of heat transfer effectiveness and maintain the indoor environment at a relatively stable condition, more chilled water delivery would be requested to send to the coil. Figure 1 shows zone temperature, fan power, and chilled water pump power under clean and fouled conditions in a typical summer week. Although no significant thermal comfort penalty was noticed at the zone level, changes at the upstream levels are not negligible. The amount of change is not so massive since the applied degradation was not severe and the system is still capable of handling this change. But the increasing trend which would lead to a worse scenario cannot be ignored as operating time increases.

System performance was quite different for the cases where fouling was implemented on the waterside of the condenser. Instead of additional electricity consumption, the waterside fouling results show a negative change in required power for cooling tower fan and condenser water pump. The amount of electricity expended by the cooling tower fan was 13.8% and 34% lower than that would expect for a clean condition for case 3 and case 4, respectively, while for results of the condenser water pump, a 6.1% decrease in case 3 and a 2.3% decrease in case 4 were presented in their energy usages. The energy utilization for the chiller compressor decreased by 1.4% in case 4, whereas negligible change was found in case 3. This decrease in compressor consumption was triggered by insufficient heat removal at the condenser. No distinct changes were observed in other energyconsuming components. Unlike the speed-varying fan, the condenser water pump is a fixed-speed pump and cannot adjust its working point according to the increase of the pressure drop. As a penalty, the water flow rate decreased. In reality, this decrease in flow rate can be further aggravated by the accumulated foulant layer and can even lead to full blockage of the water path as mentioned in some previous experimental studies (e.g., Cremaschi et al., 2011). Therefore, decline in flow rate was more obvious for waterside fouling cases than that of the airside cases, and diminished power was needed to pump this smaller amount of water. In addition, less heat was transferred to the condenser water with the increment of foulant, so the temperature of the condenser water that came out of the chiller and went towards the cooling tower gradually decreased. The low temperature and diminished flow of the incoming water triggered the decrease in cooling tower fan work as less fan power was required to cool the water to the desired condition. Even though the zone temperatures were not obviously affected, consumption changes can be observed in the condenser water pump and the cooling tower fan. Figure 2 indicates clean and fouled performance at zone level and equipment levels in a typical summer week.

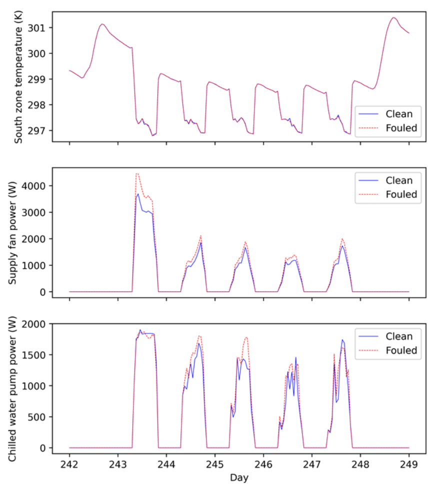

Figure 1 Performance comparison between clean (case 0) and fouled (case 2) conditions for south zone temperature, supply fan power, and chilled water pump power in a typical summer week (Aug. 30th – Sep. 6th).

Figure 3 shows the accumulated annual electricity consumption for all investigated cases. In general, energy consumed by the chiller compressor accounts for the largest portion of the total consumption in all cases, while the hot water pump utilized a minimum amount of energy compared to other categories. For fouling occurring on the airside of the cooling coil (case 1 and case 2), the annual electricity consumption of the entire HVAC system increased by 0.4% for case 1 and 1.7% and case 2, which indicates a moderate level of fouling after a year of operation. Whereas for the waterside fouling cases (case 3 and case 4), decrease in energy consumption of the components caused an overall HVAC consumption reduction of 2.7% in case 3 and 5% in case 4 over a one-year period. A result summary can be seen in Table 3.

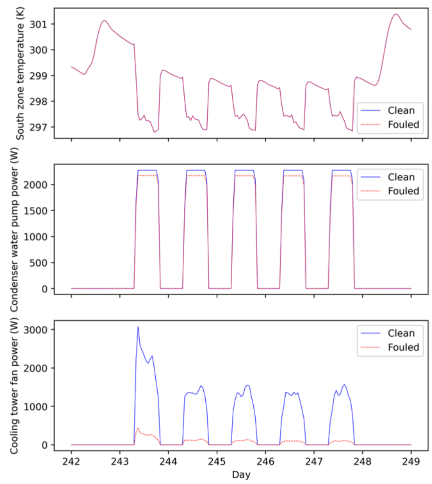

Figure 2 Performance comparison between clean (case 0) and fouled (case 4) conditions for south zone temperature, condenser water pump power, and cooling tower fan power in a typical summer week (Aug. 30th – Sep. 6th).

Table 3 A summary of the simulation results

Case #	**Variations in power consumption ('+' indicates increase; '-' indicates decrease)**		
	Equipment level		**System level**
1	Supply air fan	+2.2%	+0.4%
	Chilled water pump	+3.1%	
2	Supply air fan	+12.6%	+1.7%
	Chilled water pump	+6.3%	
3	Cooling tower fan	-13.8%	-2.7%
	Condenser water pump	-6.1%	
4	Cooling tower fan	-34%	-5%
	Condenser water pump	-2.3%	
	Chiller compressor	-1.4%	

Differences can also be observed between cases under the same type of fault as distinct fault intensities were employed. For the airside fouling scenarios, case 2 has a more severe fouling condition which is compatible to a no upstream filter situation (Yang et al., 2007). The energy consumed by the supply fan and the chiller water pump were both larger. Compared to case 1, case 2 required 10.2% and 3.1% more electricity to operate the supply fan and the chilled water pump, respectively, which resulted in additional energy consumption for both devices in case 2. As for the two waterside fouling cases, the degradation symptoms were not varied in parallel, with case 3 having a higher pressure drop, while case 4 has a more severe effect on heat transfer rate. Distinction of energy usages can also be seen between these two cases. The condenser water pump requested less power in case 3 than that of case 4, while in case 4, a more significant consumption reduction was obtained from the cooling tower fan when compared to that in case 3. This observation indicates the connection between fundamental fouling behaviors and energy used by specific HVAC equipment. The general tendency can be summarized as follows: a lower condenser heat transfer rate causes a greater reduction in cooling tower fan consumption, while a higher condenser water pressure drop leads to a larger decrease in condenser pump consumption. Specifically, when the two investigated fouled cases were compared to each other, 3.9% less electricity was consumed by the condenser water pump in case 3 and 30.6% less energy was utilized by the cooling tower fan in case 4.

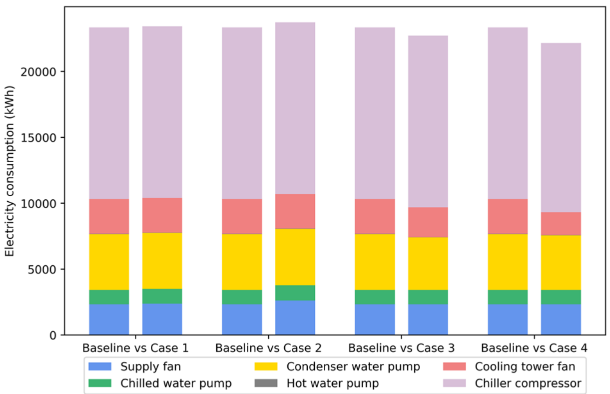

Figure 3 Electricity consumption by end use for baseline and all faulty cases.

Conclusion

Gradually developing faults could occur in HVAC equipment and systems. In real buildings, the gradual varying fault symptoms need to be captured and analysed to determine such gradual system faults so that corrective action can be taken in time and potential abrupt system breakdown can be avoided. Fault modeling and simulation have the ability to generate sufficiently large amounts of building performance data in a cost-efficient way, which benefits the development and validation of fault diagnostics and prognostics algorithms.

A Modelica-based simulation framework was developed for degradation fault simulation. A case study was performed to investigate system performance under degrading faults. Fouling was selected as the representative degrading fault due to the nature of its progressive build-up over time. From the fouling case study, it can be concluded that the over-time degradation of HVAC components would cause variations in system energy consumption. For fouling appearing on the airside of the cooling coil, the effective heat transfer area gradually decreases as particles incrementally load on fins. As a consequence, more fan power is required to compensate for the expanding pressure drop, and more chilled water pumping work is needed to balance the increased thermal resistance at the cooling coil. The overall HVAC power usage also increases with the enhancement of fouling severity. For the case that was tested in this study, a maximum total HVAC power increase of 1.7% was observed due to the implemented airside fouling fault. For the waterside fouling happening on the heat exchanging surface of the chiller's condenser, the amount of water flow is reduced due to the increased pressure drop and partial blockage caused by the foulants. Different from the airside testing results, less pumping power is needed to circulate the diminished condenser water, and the power required by the cooling tower fan is declined accordingly. The overall annual power utilization of the entire HVAC system declined by up to 5% for the cases tested in this study. Unparallel fouling severities were applied on heat transfer and pressure drop for the two testing cases. The simulation results show that a stronger fouling impact on heat transfer would lead to a larger reduction in cooling tower fan consumption, while a more extensive impact on pressure drop would result in less energy requirement of the condenser water pump. Moreover, all investigated fouling scenarios showed no effect on thermal comfort at the zone level, which indicates moderate fouling conditions and resilient performance in a one-year operating period.

The current study does not cover all degradation scenarios that could occur in HVAC systems. More degradation cases need to be investigated and implemented into simulation models to produce more data for the FDD community to motivate the development of gradual fault detection, diagnostics, and prognostics algorithms. Results for this study only indicate system performance variation with degrading faults in a one-year period, some variations are minor, but they are subjected to increase with an extended simulation time and additional new evidences of variation may also emerge.

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