RESEARCH

EVALUATION OF SMART BOOSTER FANS AND DAMPERS FOR ADVANCED HVAC SYSTEMS

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ABSTRACT

There is potential to significantly reduce CO_2 emissions by increasing the efficiency and reducing the duty cycle of HVAC systems by using smart booster fans and dampers. Smart booster fans fit in the vents within a home, operating quietly on low power (2W) to augment HVAC systems and improve their performance. In this study, a prototype duct system is used to measure and evaluate the ability for smart booster fans and dampers to control airflow to different vents for the purpose of increasing the efficiency of HVAC systems. Four case studies were evaluated: an HVAC system (1) without any fans or dampers, (2) with a fan installed in one vent, but without any dampers, (3) with dampers installed at the vents, but without any fans, and (4) with both fan and dampers installed. The results from both the experimental and numerical evaluation show that the smart booster fan and dampers can significantly improve the airflow at a vent that is underperforming. For example, the airflow at the last vent in a ducting branch was increased from 17 to 37 CFM when a smart booster fan was installed at this vent. Results from the numerical analysis show that for the case of an underperforming vent during the winter season the HVAC running time may be reduced from 24 hr/day to 5.6 hr/day. Furthermore, results from the numerical analysis show the HVAC running time is further reduced to 4.5 hr/day for cases 3 and 4.

KEYWORDS

HVAC efficiency, smart booster fans, smart dampers, airflow at HVAC vents, HVAC duty cycles, computational fluid dynamics (CFD)

1. INTRODUCTION

A major portion of the energy consumed in residential buildings is used for heating, ventilation, and air-conditioning (HVAC) systems. In fact, globally, HVAC systems consume more than 50% of the energy used in buildings [1]. Most HVAC systems are powered by natural gas due to the high operating costs of electric-powered HVAC systems [2,3]. Natural gas consumption

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has a negative impact on global warming, and a total of 39.7 metric tons of CO_2 was emitted by natural gas-powered HVAC systems in Canada alone in 2016 [4,5].

Many HVAC systems do not operate efficiently and lose 25–40% of their cooling or heating energy. A significant portion of these loses occur through the HVAC systems duct work. Duct systems may lose energy via heat transfer through the duct walls, or air leakage through damaged or poorly connected sections of the ductwork. Further, duct systems may be inefficient if poorly designed or installed, or if they become dirtied or obstructed over their lifetime.[6] Inadequate ducting systems cause high HVAC duty cycles and unnecessary CO_2 emissions. Improving the energy efficiency of HVAC systems has a large effect on reducing the consumption of fossil fuels, which has motivated research towards improving the efficiency of HVAC systems globally [6–9].

In addition to improving the energy efficiency of HVAC systems, it is also important to achieve proper ventilation rates and comfortable conditions to promote a healthy indoor environment [10,11]. To reduce the energy consumption and heat losses in buildings, Jahantigh et al. [12] investigated a hybrid heating system comprised of a radiant heater and ventilated airflow in a residential building. The conditions and flow field surrounding a manikin were simulated to optimize the system parameters. Their results showed that the hybrid heating system can quickly provide thermal comfort in a residential room and can reduce heating losses through walls by up to 25%. In a numerical and experimental study, to solve the air conditioning problem in winters wherein hot air is collected at the top of the room while colder air resides at the bottom, Delavari et al.[13] used a vertical duct with two fans at each end to circulate the air inside the room. Their result showed that the air conditioning duct inside the room could improve the energy efficiency coefficient from 0.43 to 1.05. Other strategies have focused on sensor-based demand-controlled ventilation [14]. Research directed towards implementing these strategies has focused on CO_2 concentration-based sensors [15], occupant-based sensing [16], and zone temperature-based sensing [17].

In this work, the effects of installing smart booster fans and dampers on the ability to regulate airflow and to reduce the duty cycle of a HVAC system within a residential building is investigated. A smart booster fan fits in the vents within a residential home, operating on low power (~2 W) to augment HVAC systems and improve their performance. A set of smart booster fans installed in vents throughout a home can measure their local temperature and, through wireless communication, operate in concert to optimize airflow to efficiently achieve the desired temperature at different zones throughout a home. Further, smart dampers installed in certain vents within a home may prevent airflow to preserve conditioned airflow for other vents further along the duct-branch. Herein booster fans and dampers were installed in an experimental prototype of a duct-branch system. The airflows at the inlets throughout this ducting system were measured for different cases wherein fans and dampers were situated at certain inlets within the duct-branch. The results from these experiments were used to numerically model the ability of the smart booster fans and dampers to improve airflow, regulate temperature, and reduce energy consumption, with a focus on underperforming inlets at the end of a long duct-branch in a model residential house. The results show that a smart booster fan can improve the airflow in an underperforming vent at the end of a duct-branch such that otherwise unattainable comfortable conditions can be achieved. Furthermore, the results from simulations suggest that smart booster fans and dampers can significantly reduce the running time of HVAC systems that provide conditioned air through underperforming vents.

2. MATERIALS AND METHODS

2.1 Experimental Measurements

A duct-branch within a HVAC system was simulated inside the laboratory by designing and building a duct system equipped with an air blower that could be used to perform experiments. Images of the designed and actual experimental set-up are shown in Figures 1a and 1b, respectively. The duct-branch distributes air to four registers, or vents, and is enfolded in a wooden enclosure of size 120 × 233 × 60 cm^3. Flexible ducting made of Aluminum was used. An air blower brings air in through an intake at the bottom left corner of the apparatus. The length of the duct between the blower and the first duct exit boot (vent 1) is 2 m. The duct between the blower and vent 1 has an 8" diameter, while all other ducts in the apparatus have a 4" diameter. The length of ducting from the blower to the second, third and fourth vents is 5 m, 10.6 m and 19.2 m, respectively. The total equivalent length of this ducting system, including additional friction losses due to the curvature of the ducts, is 53.9 m which is comparable with the total equavalent lengh of some duct-branches in a typical residential unit.

Experiments were performed wherein smart booster fans were placed within different vents in the testing apparatus to determine their effect on air flow rates through the vents. By placing a smart booster fan in the vents which is connected to a smart phone, low airflow rates within the vents can be boosted to cool or heat the room much faster. A Vivosun blower with a maximum flow rate of 360 CFM was used to simulate the airflow from a house heater fan. An Extech SDL300 metal Vane Thermo-Anemometer/Data logger was used to record the flow rates during the experiments. Dampers were installed at the boot of vents 1 and 2, to set the air flow through the duct system. The position of the dampers was set such that the air flow through vent 1, 2, and 3 was 90, 59.3 and 55.6 CFM, respectively. Four experiments were conducted to measure the airflow rates through the four vents along the duct-branch. In the first experiment, no fans or dampers were used. In the second experiment dampers were used at vents 1 and 2 to achieve the desired airflow rates through inlets 1, 2 and 3. In the third experiment the dampers were kept in inlet 1 and 2 and a smart booster fan was used at Inlet 4. The fourth experiment was similar to the third, but with the addition of a second smart booster fan at Inlet 3. The

FIGURE 1 (a) Experiment design of duct system (V stands for vent) (b) Experiment duct system (c) Installation of smart booster fan at the vent on the top side of the apparatus.

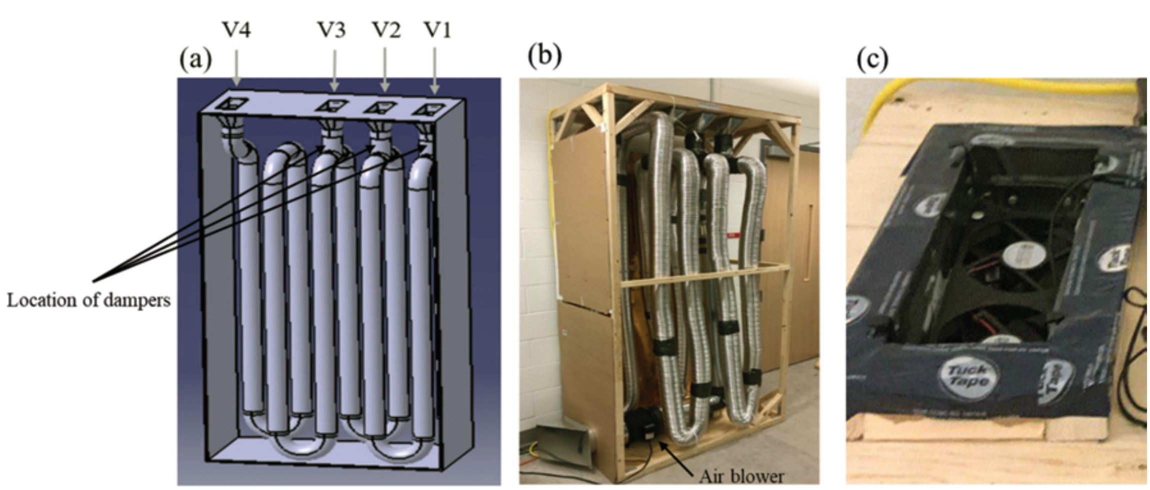


TABLE 1. Operating conditions for experiments one through four.

Experiment No.	Inlet 1		Inlet 2		Inlet 3		Inlet 4	
	Fan	Damper	Fan	Damper	Fan	Damper	Fan	Damper
1	x	x	x	x	x	x	x	x
2	x	✔	x	✔	x	x	x	x
3	x	✔	x	✔	x	x	✔	x
4	x	✔	x	✔	✔	x	✔	x

operating conditions for the four experiments are summarized in Table 1. Furthermore, it can be noted that repeated experimental results differed by less than 8%.

2.2 Numerical Simulations

2.2.1 Methods used for evaluating the ability of smart booster fans to improve airflow and heating:

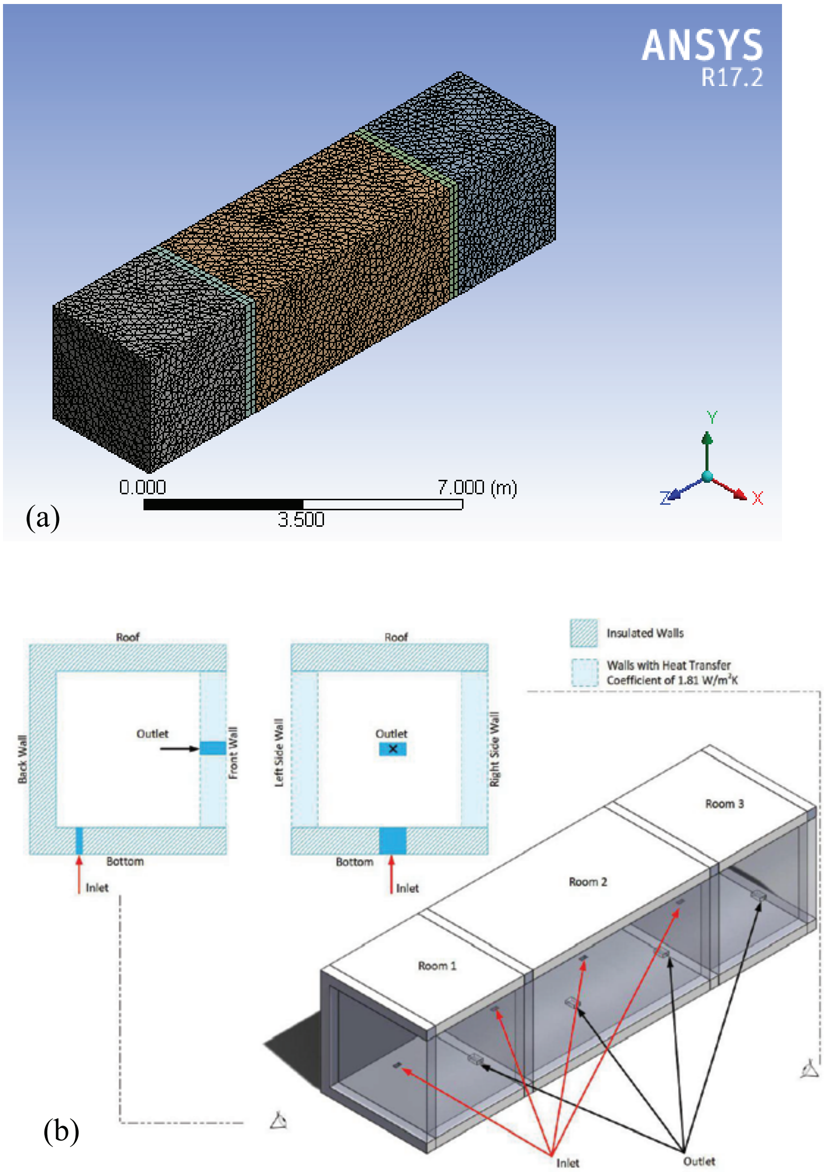
The data attained from the experimental measurements were used to numerically model the ability of the smart booster fans to improve airflow and heating in a residential house. Numerical analyses were performed assuming an initial indoor temperature of 20 °C, and three different cases were considered wherein the outdoor temperature was 5 °C, 0 °C and –10 °C. Computational Fluid Dynamics (CFD) analysis was performed using Ansys software. The modelled house has three rooms of sizes 3×3×3 m^3, 3×6×3 m^3 and 3×3×3 m^3, which are referred to as room 1, room 2 and room 3, respectively. All the walls are considered to have a thickness of 0.3 m. The front, left side, and right-side walls of each room are assumed to be exterior walls with a heat transfer coefficient of 1.81 $W/m^2 \cdot K$. This is typical of a wall made of solid brick with plaster on it. The roof, bottom and back walls are assumed to be interior walls that are perfectly insulated with a heat transfer of 0 $W/m^2 \cdot K$. Rooms 1 and 3 have one inlet and one outlet, and room 2 has two inlets and two outlets, all of size 4×10 in^2. The k-ε model is used with a mesh size of 82,825 tetrahedral elements and element size of 0.39 m having a growth rate of 1.20, skewness of 0.84 and aspect ratio of 1.18, as shown in Figure 2a. A diagram of the model house used for the analysis is provided in Figure 2b. To validate the mesh size, simulations were repeated with 119,411 mesh elements, and the results differed from those produced using 82,825 mesh elements by less than 2%.

The air velocity measurements attained using the ducting apparatus shown in Figure 1b were used as the input velocity at the vents for the CFD simulations. Vent 1 was located in room 1, vents 2 and 3 were located in room 2, and vent 4 was located in room 3. Data used in the simulation is collected from the experiments under 'with fan' and 'without fan' conditions. The boundary conditions used under 'with fan' and 'without fan' conditions are given in Table 2:

2.2.2 Methods used for evaluating the ability of smart booster fans and smart dampers to improve airflow and heating:

Numerical simulations were performed to investigate the ability of smart booster fans and dampers to regulate the temperature of the building shown in Figure 2b. It is assumed that

FIGURE 2 (a) House model with specified mesh as modeled in ANSYS (b) Diagram of house model.



each room is equipped with its own thermostat and the desired temperature in each room is 22 °C. Further, it is assumed that the HVAC system is turned on and hot air is supplied to the rooms when their temperature drops below 20 °C, and that this hot air supply is not turned off until the temperature of the room reaches 24 °C. Four different cases were considered, and the operating conditions for each case are provided below.

Case 1: There are no fans or dampers present in any of the inlets.

Case 2: Dampers are not present in any of the inlets. A fan is installed in the fourth vent.

TABLE 2. The boundary conditions used under 'with fan' and 'without fan' conditions.

With fan	Inlet 1 (room 1)	Inlet 2 (room 2)	Inlet 3 (room 2)	Inlet 4 (room3)
Airflow (CFM)	90	59	53	37
Without fan	**Inlet 1 (room 1)**	**Inlet 2 (room 2)**	**Inlet 3 (room 2)**	**Inlet 4 (room3)**
Airflow (CFM)	90	59.3	55.6	17
Boundary conditions (same for 'with fan' and 'without fan')				
Inlets airflow temperature (°C)	40 °C			
Outlet air pressure (Pa)	1.2 Pa			
Insulation walls heat transfer	No heat flux			
Wall thickness (m)	0.3 m			
Outer walls heat transfer	1.81 w/m2·K			
Initial interior room temperature (°C)	20 °C			

Case 3: Fans are not present in any of the inlets. Dampers are installed in inlets 1, 2, and 3.

Case 4: Dampers are installed in all four inlets. A fan is installed in inlet 4.

For cases 1 and 2 the state of the HVAC system is determined by the thermostat in room 3. The HVAC system (airflow) turns on if the temperature in room 3 drops below 20 °C, and turns off if the temperature in this room exceeds 24 °C. The airflow rates through all vents when the HVAC system is on for cases 1 and 2 are provided in Table 3.

For cases 3 and 4 each room has its own thermostat. The HVAC system turns on if the temperature in any room drops below 20 °C and turns off if the temperature in every room is 24 °C or higher. When the HVAC system is on for cases 3 and 4 there are two modes of operation. For the first mode, which is in effect when room 1 is being heated to 24 °C, all dampers are in an open position and air flows through all vents. The airflow rates through all vents while operating in mode 1 are shown in Table 3.

The second mode of operation is initiated when room 1 reaches 24 °C. Because the temperature profile of room 1 and room 2 in heating mode are almost the same, the dampers in inlets 1, 2, and 3 close when the second mode of operation is initiated. While in the second mode of operation hot air from the HVAC system is sent exclusively to room 3 via inlet 4. As shown in Table 3, the airflow rates to room 3 when the dampers in inlets 1, 2, and 3 are in a closed position for cases 3 and 4 is 85 and 91 CFM, respectively. Also, the temperature of the airflow at all inlets is assumed to be 45 °C. Other than the airflow rates, as listed in Table 3, and the inlet temperature all model designs and boundary conditions are the same as described in previous sections.

TABLE 3. Airflow at inlets for the four different cases considered.

Case 1	Inlet 1 (room 1)	Inlet 2 (room 2)	Inlet 3 (room 2)	Inlet 4 (room3)
Airflow (CFM)	90	59.3	55.6	17

Case 2	Inlet 1 (room 1)	Inlet 2 (room 2)	Inlet 3 (room 2)	Inlet 4 (room3)
Airflow (CFM)	90	59	53	37

Case 3	Inlet 1 (room 1)	Inlet 2 (room 2)	Inlet 3 (room 2)	Inlet 4 (room3)
Airflow for mode 1 (CFM) (room 1 is heating to 24 °C)	90	59.3	55.6	17
Airflow for mode 2 (CFM) (room 1 has reached 24 °C, room 3 is still heating)	0	0	0	85

Case 4	Inlet 1 (room 1)	Inlet 2 (room 2)	Inlet 3 (room 2)	Inlet 4 (room3)
Airflow for mode 1 (CFM) (room 1 is heating to 24 °C)	90	59	53	37
Airflow for mode 2 (CFM) (room 1 has reached 24 °C, room 3 is still heating)	0	0	0	91

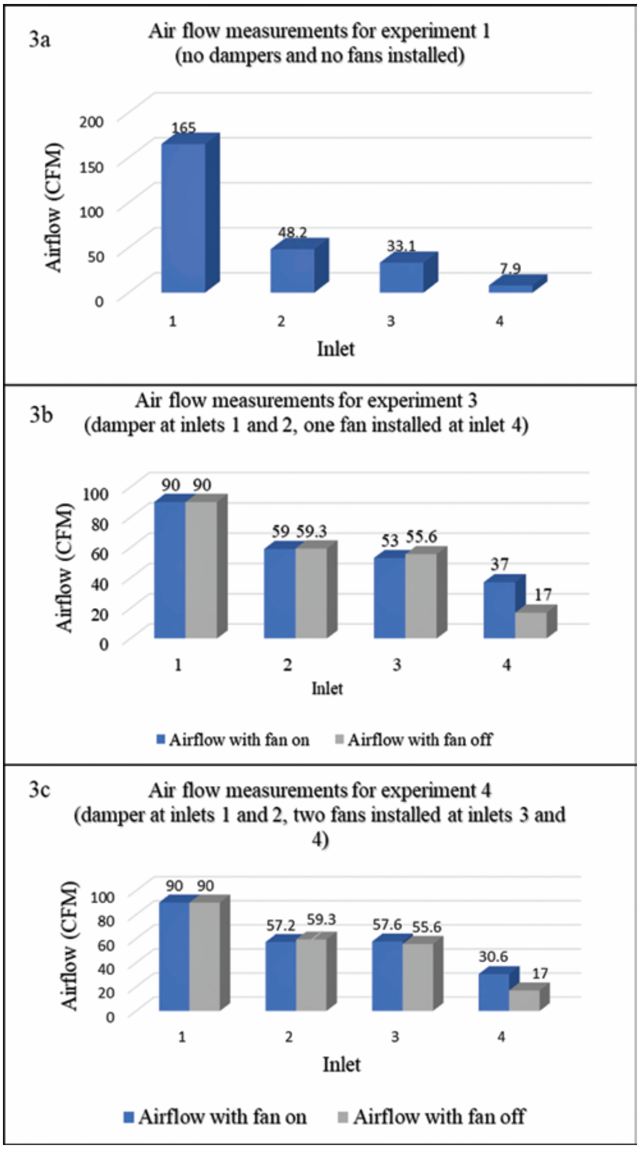
3. RESULTS

3.1 Experimental Results:

The results obtained from airflow measurements for experiments one through four are presented in Figures 3a, 3b, and 3c.

It is observed from Figure 3b that the airflow through the fourth inlet increases from 17 CFM to 37 CFM when one fan is installed at the fourth inlet and dampers are positioned at inlets 1 and 2. It can be noted that the overall airflow through all inlets increases by 7.07 %. Furthermore, as shown in Figure 3c, airflow increased from 17 CFM to 30.6 CFM when smart booster fans are installed at the third and fourth inlets. When smart booster fans are installed at the third and fourth inlets the overall airflow through all inlets increases by 6.03%. Notably, the airflow through the third inlet increased from 55.6 CFM to just 57.6 CFM when the booster fans were installed at both the third and fourth inlets.

FIGURE 3. (a) Air flow measurements for experiment 1 (no dampers and no fans installed) (b) Air flow measurements for experiments 2 and 3 (dampers at vents 1 and 2, one fan installed at vent 4) (c) Air flow measurements for experiment 4 (damper at vents 1 and 2, two fans installed at vent 3 and vent 4). The results from experiment 2 are also shown for comparison.

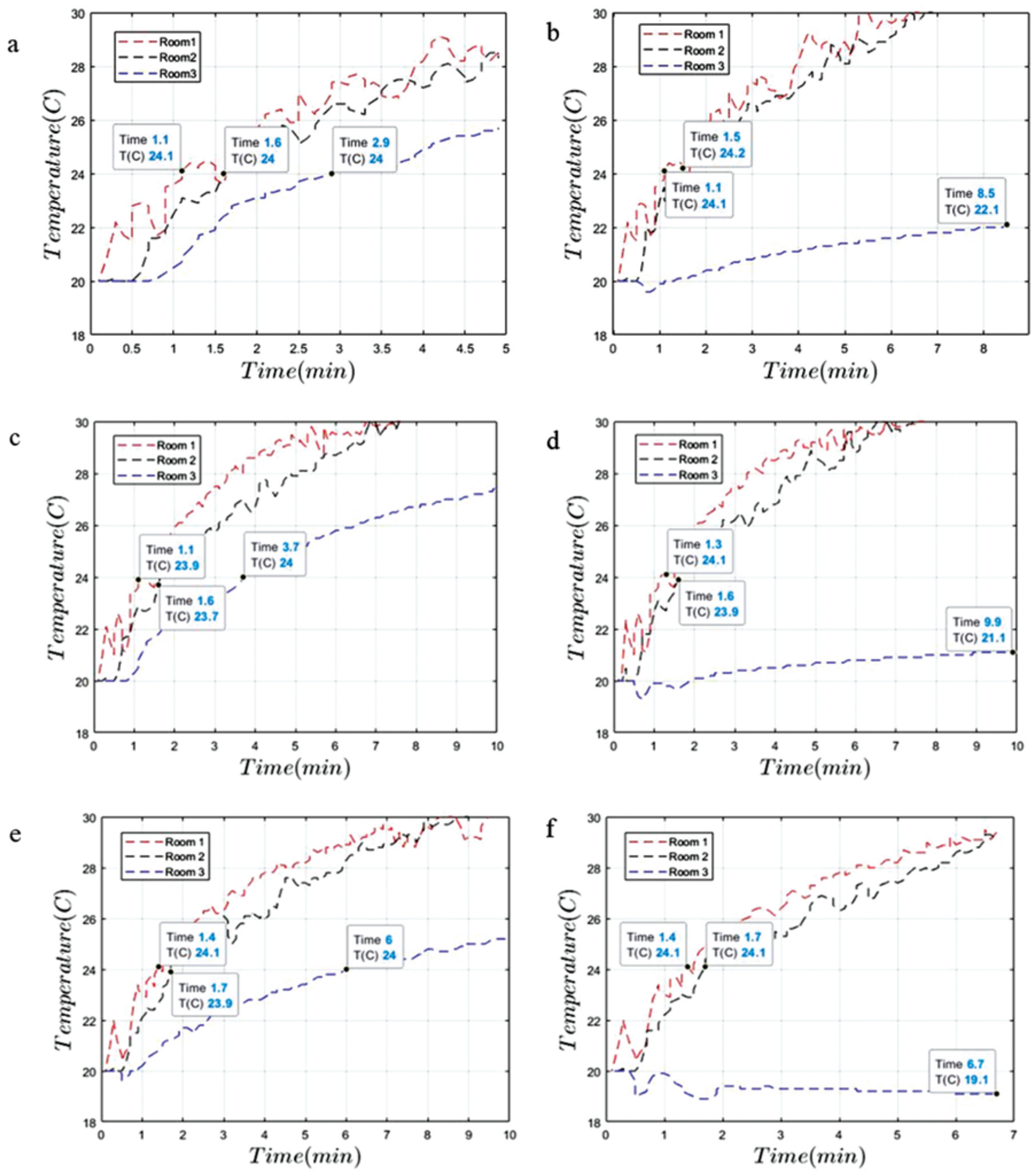


3.2 Simulation Results:

3.2.1 Results from evaluating the ability of smart booster fans to improve airflow and heating:

Figures 4a to 4f plot the temperature in rooms 1, 2 and 3, for the model residence shown in Figure 2b. The initial temperature for all rooms in the house is 20 °C and the ambient temperature is 5 °C for the results shown in Figures 4a and 4b, 0 °C for the results shown in Figures 4c and 4d, and –10 °C for the results shown in Figures 4e and 4f. The amount of time it takes to

FIGURE 4. Simulation results for an outside temperature of 5 °C (a) with fan, and (b) without fan. (c) Simulation results for an outside temperature of 0 °C with fan, and (d) without fan. (e) Simulation results for an outside temperature of –10 °C with fan, and (f) without fan.



heat the rooms from 20 °C to 24 °C with and without a smart booster fan installed within the vent in room 3 is shown for all cases.

It is observed from Figure 4 that it would take 2.9 minutes to heat room 3 from 20 °C to 24 °C with the fan when the outside temperature is 5 °C. However, without a fan installed in room 3 its temperature is just 22.1 °C after 8.5 minutes, and the room will not reach 24 °C in a practical amount of time. When the outside temperature is 0 °C, it would take 3.7 minutes to heat room 3 from 20 °C to 24 °C with the fan installed, but without the fan room 3 does not reach 24 °C (Figure 5). As shown in Figure 6, it would take 6 minutes to heat room 3 from 20 °C to 24 °C with the fan, however, without a fan room 3 is not going to reach 24 °C under an outside temperature of –10 °C. Thus, room 3 will not reach 24 °C in a practical amount of time for any condition considered in this study unless it is equipped with a smart booster fan.

3.2.2 Results from evaluating the ability of smart booster fans and smart dampers to improve airflow and heating:

Simulations were also performed to study the temperature of the rooms in the model house shown in Figure 2b as the airflow through the vents in the house was turned on and off. In these simulations the airflow through the vents was assumed to be set in an "on" or "off" state based on the temperature reading from a thermostat situated in each room. It is assumed the thermostats in each room are set to 22 °C and the dampers (if installed) would close the inlet of the room which reaches 24 °C and the airflow would be directed to the other rooms. For these simulations, because of the similarity of the temperature profile in rooms 1 and 2, the dampers in inlets 1, 2, and 3 are in a closed position when the thermostat in room 1 measures a temperature of 24 °C or higher, such that hot air from the HVAC system is sent exclusively to room 3 via inlet 4. The HVAC system turns off when thermostat in room 3 reaches 24 °C. The system would then remain in the "off" state until the temperature in one of the rooms cools to 20 °C. When the temperature drops to 20 °C, the HVAC system would be turned on until the room 3 temperature was heated to 24 °C. The outside temperature is assumed to be 5 °C for all simulations performed in this section. All assumptions and boundary conditions were kept similar to those used to calculate the results shown in Figure 4, with the exception of the air inlet temperature and airflow for all vents, which is shown in Table 3.

For case 1, as shown in Figure 5a, room 3 does not reach 24 °C while the temperatures of the other rooms are increasing unpleasantly. Figures 5b, 5c and 5d show that the average HVAC system run-time over two rounds of heating and cooling would be 126, 75 and 75 s for cases 2, 3 and 4, respectively, to heat the rooms from 20 °C to 24 °C under an outside temperature of 5 °C. Moreover, it would take 408, 327 and 324 s for the rooms to cool from 24 °C to 20 °C for cases 2, 3 and 4, respectively.

3.3 HVAC running hours

Based on the results shown in Figure 5, the number of hours the HVAC system is expected to run per day in order to maintain the desired temperature of 22 °C, assuming an outdoor temperature of 5 °C, are given in Table 4.

Considering an outside temperature of 5 °C the HVAC system would be required to operate 5.6 hours every day to regulate the temperature of room 3 at 22 °C for case 2, wherein a fan is installed at the fourth inlet, but no dampers are present. However, the temperature of the other rooms would increase unpleasantly. In comparison, the HVAC system is required to run 4.5 hours per day to keep the temperature of rooms at the desire level for cases 3 and 4, wherein dampers are installed in inlets 1, 2 and 3. For case 1, without any fans or dampers present, the HVAC run-time would be 24 h/day to maintain the room 3 temperature at the desire level, while the temperatures of the other rooms are excessively high.

FIGURE 5. Simulation results for heating and cooling under an outside temperature of 5° (a) without any fans or dampers (case 1) (b) with a fan installed in one vent, but without any dampers (case 2) (c) with dampers installed at the vents, but without any fans (case 3) (d) with both fan and dampers installed (case 4).

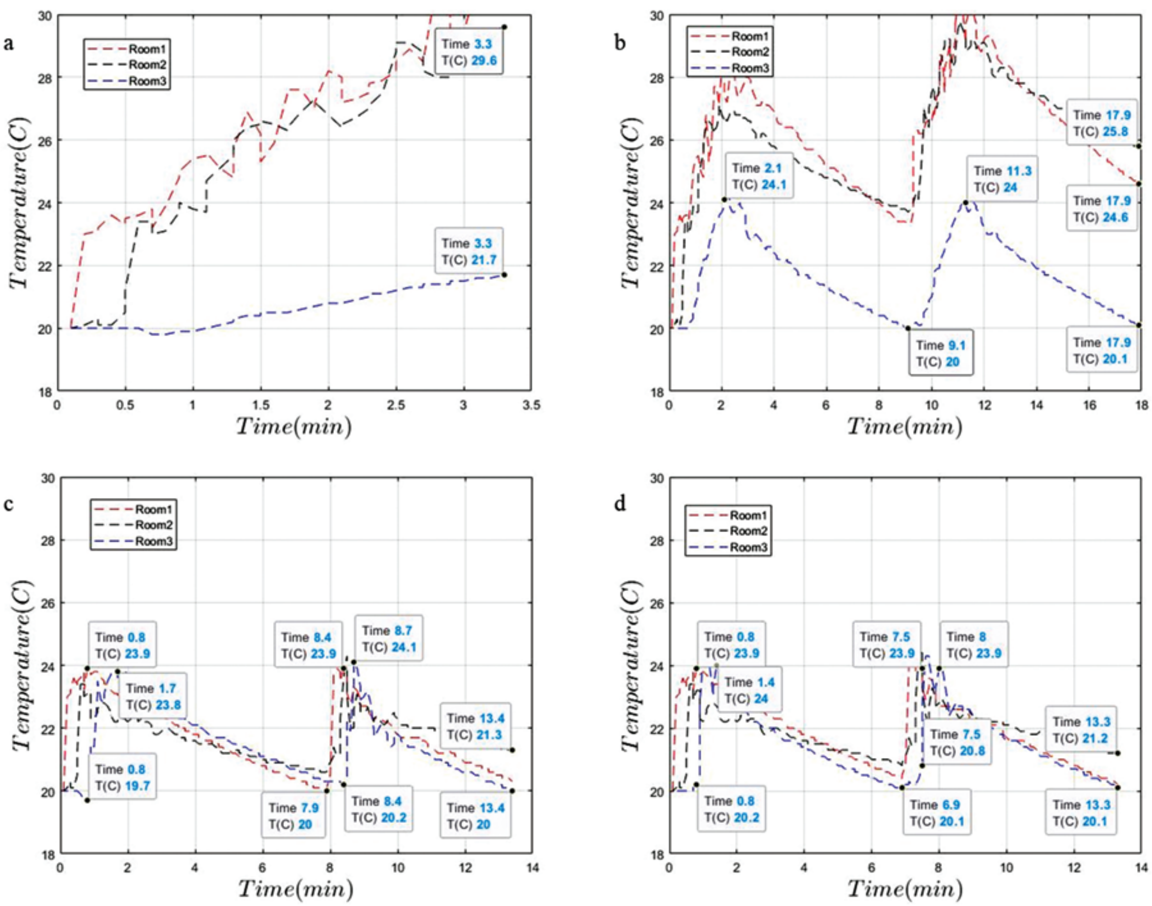


TABLE 4. HVAC run-time and down-time for cases 2, 3 and 4.

Outside temperature 5 °C	Average run-time (s) for heating from 20 °C to 24 °C	Average down-time (s) for cooling from 24 °C to 20 °C	HVAC system run-time (h/day)
Case 2	126	408	5.6
Case 3	75	327	4.5
Case 4	75	324	4.5

4. CONCLUSIONS

In this work we have investigated the ability of smart booster fans and dampers to regulate airflow in a long duct-branch. The poor airflow to the last inlet in the duct-branch is due to friction caused by the length, curvature and other inlets. It should be noted that the case wherein poor airflow is caused by a damaged or leaking duct work is not investigated in this case. Furthermore, regulations pertaining to air ventilation rates and use of dampers in HVAC duct work was not considered.

Airflow measurements on a prototype ducting system were performed to evaluate the ability of a smart booster fan to improve HVAC system performance in residential homes. Results show that the smart booster fan can significantly improve, even by greater than a factor of two, the airflow to a vent at the end of a long duct-branch. Numerical analysis shows that rooms in residential homes that suffer from poor airflow may never reach comfortable conditions during typical winter conditions. However, under typical conditions this problem can be fixed by installing a smart booster fan in this room.

Based on the results attained thus far and those reported herein, it does not appear to be beneficial to simultaneously operate multiple smart booster fans in the same duct branch, although results would vary on a case by case basis. Also, results from simulations show that smart dampers have potential towards enhancing temperature regulation while decreasing the duty cycle of HVAC systems.

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