Optimization on Thermostat Location in an Office Room Using the Coupled Simulation Platform in Modelica Buildings Library: a Pilot Study

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SUMMARY

Energy saving technologies commonly used in buildings can largely result into stratified airflow distribution in the space. Determining the best location for a thermostat can be critical. As the Heating, Ventilation, and Air Conditioning (HVAC) system and the thermal comfort of the space are mutually dependent, the location of the thermostat plays an import role in energy performance and thermal comfort. Therefore, this paper proposes an optimization platform to determine its location by integrating a coupled simulation model with an optimization engine. The coupled simulation model can dynamically exchange information between Modelica and fast fluid dynamics, which is used for stratified airflow prediction. Linking a stratified flow to a variable airflow volume terminal box, optimization using GenOpt is carried out to determine the thermostat location that leads to best thermal comfort. Results show that the proposed optimization methodology can determine the thermostat location effectively. Future research is also discussed.

INTRODUCTION

Ventilation techniques with stratified air distribution is found to be able to provide compelling performance in terms of building energy efficiency and indoor air quality (Yuan et al. 1999). The evaluation of those techniques needs coupled simulation between Heating, Ventilation, and Air Conditioning (HVAC) model and airflow prediction enabled by computational fluid dynamics (CFD) model. Du et al. (2015) coupled the TYNSYS with CFD model to seek the optimal thermostat location in terms of energy conservation and predicted mean vote (PMV). However, due to the high demanding of computation time for CFD, the frequency of data exchange is few and thus it is difficult to capture the real dynamics. Moreover, the optimization can only be done over several discrete points. To reduce the time cost for stratified airflow distribution, Kim et al. (2015) proposed to use reduced order model to replace the conventional CFD. One major limitation of this method is that the reduced order model may not be accurate if the query point in the evaluation is outside its training domain. In addition, the reduced order model may need to be reconstructed if the geometry of the space is changed in the design phase.

To overcome the limitations of aforementioned method, this paper proposed to use the coupled simulation model between Modelica and fast fluid dynamics (FFD) model, together with an optimization engine GenOpt (Wetter 2000), to seek optimal solutions in building design and operation. Attaining comparable accuracy, FFD is about 50 times faster than CFD (Zuo and Chen 2009), which is preferable for dynamic control study. In the rest of the paper, we first introduce the methods of FFD, coupled simulation model, and optimization schemes. Then, we describe the numerical case, modeling and optimization setup. At last, we present the results and future research plans.

METHODS

In this section, the mathematical description of fast fluid dynamics model is introduced. Then, the coupled simulation model between Modelica model and FFD model is reviewed. At last, the building optimization strategy and tools are reviewed.

Fast Fluid Dynamics Review

FFD solves the Navier-Stokes equations:

$$\frac{\partial \boldsymbol{U}_i}{\partial t} = -\boldsymbol{U}_j \frac{\partial \boldsymbol{U}_i}{\partial \boldsymbol{x}_j} + \nu \frac{\partial^2 \boldsymbol{U}_i}{\partial \boldsymbol{x}_j^2} - \frac{1}{\rho}\frac{\partial P}{\partial \boldsymbol{x}_i} + \boldsymbol{F}_i \quad (1)$$

where $\boldsymbol{U}_i$ and $\boldsymbol{U}_j$ are the velocity component in $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ directions, respectively, ν is the kinematic viscosity, ρ is the fluid density, P is the pressure, t is the time, and $\boldsymbol{F}_i$ is the source term, such as the buoyancy force. Splitting the Navier-Stokes equation into the following three equations, FFD solves them sequentially:

$$\frac{\partial \boldsymbol{U}_i}{\partial t} = -\boldsymbol{U}_i \frac{\partial \boldsymbol{U}_i}{\partial \boldsymbol{x}_j} \quad (2)$$

$$\frac{\partial \boldsymbol{U}_i}{\partial t} = \nu \frac{\partial^2 \boldsymbol{U}_i}{\partial \boldsymbol{x}_j^2} + \boldsymbol{F}_i \quad (3)$$

$$\frac{\partial \boldsymbol{U}_i}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial \boldsymbol{x}_i} \quad (4)$$

A semi-Lagrangian method (Courant, Isaacson, and Rees 1952) is employed to solve equation (2). The equation (3) is solved by using an implicit scheme. The last equation (4) together with the continuity equation

$$\frac{\partial \boldsymbol{U}_i}{\partial \boldsymbol{x}_i} = 0 \quad (5)$$

is solved using a projection-correction method (Chorin 1967). A similar algorithm is applied to solve the conservation equations of energy and species as equation (6):

$$\frac{\partial \varphi}{\partial t} = -\boldsymbol{U}_j \frac{\partial \varphi}{\partial \boldsymbol{x}_j} + \Gamma \frac{\partial^2 \varphi}{\partial \boldsymbol{x}_j^2} + S \qquad (6)$$

where φ is a scalar variable, Γ is thermal or mass diffusivity, and S is the source term. The detailed implementation of sequential FFD model can be found in (Zuo and Chen 2009; Jin, Zuo, and Chen 2012). One can also refer to the parallelized FFD model by CUDA and OpenCL in these literature (Zuo and Chen 2010; Yang 2013; Tian, Sevilla, and Zuo 2017).

Coupled Simulation Model Review

In a building, systems of different physical domains are essentially coupled to some extent. To address the dynamic interaction between the non-uniform airflow, HVAC, control, and building envelopes, researchers (Zuo et al. 2014; Zuo et al. 2016) have developed a coupled simulation model *cfd* (*Figure 1*) within the Modelica *Buildings* library (Wetter et al. 2015), in which Modelica is used for modeling of HVAC, control, and heat transfer through and between walls, and a fast fluid dynamics (FFD) model programmed in C language is used for stratified airflow simulation.

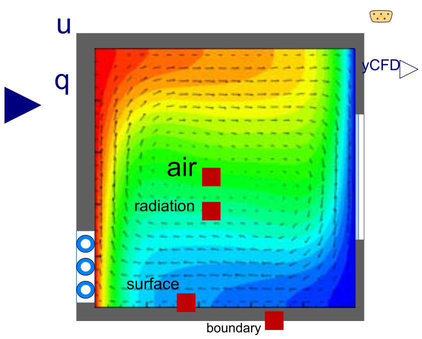

Figure 1. Icon of the coupled simulation model

The coupled simulation model *cfd* can be connected with HVAC models through the fluid ports (blue circle symbol) and thermal ports (red rectangular symbol). The information in those ports then is fed to FFD model, which is compiled as dynamic linker and called externally by *cfd* model. Once FFD finishes the calculation for one data synchronization time step, the averaged value, for example, heat flux through the walls, temperature at thermostat location, will be returned to Modelica. The above procedure repeats until the end of the simulation. For more detailed information of the coupled simulation model, one can refer to the literature (Zuo et al. 2016).

Given that the coupled simulation model *cfd* can only be applied to a single room, Tian, Sevilla, et al. (2017) has extended its application scope from a room to a building with more than one room by linking it with a multizone model (Dols and Walton 2002). Two coupling scenarios are proposed: one is that HVAC model (in Modelica) gives mass flow rate at inlets to FFD while FFD returns the mass flow rate at outlets to multizone models; The other one is that the multizone model gives the total pressure to FFD while FFD returns the mass flow rate to multizone.

Both models have been demonstrated the capability to capture the dynamics of the HVAC system control, which are critical information in both design and operation phases (Wetter 2009). With the capability of dynamic simulation of stratified air distribution and HVAC system, the tool is claimed to be able help control engineers and researchers to study the control of stratified ventilation systems (Zuo et al. 2016).

Building Optimization Strategy Review

As to optimization methods, it can be roughly categorized into two types: local and global search methods (Wang and Ma 2008). The local search method, such as hill climbing method, starts exploring the solution space from one solution to another by applying only local changes. With a proper initial point, the local search method can quickly converge on a good solution, which may inversely make it prone to some local optima. On the other hand, the global search method, such as heuristic algorithms, usually focus on finding the maximum or minimum over the whole searching space. To perform the optimization, an optimization tool named GenOpt (Wetter 2000) can be used. It is an open-source program, which includes nearly a dozen of different optimization algorithms, such as generalized pattern search, PSO, a hybrid optimization method combining PSO and Hook-Jeeves, etc. In addition, the users can also develop their own optimization algorithms and implement them into its structure.

NUMERICAL EXPERIMENT SETUP

In this section, we will first describe a stratified airflow (Wang and Chen 2009) to which a variable air volume (VAV) terminal box is hooked. Then, we will explain the Modelica implementation of the system. Lastly, we will show the methodology to integrate an optimization engine GenOpt (Wetter 2008) with the system model to find the optimal thermostat position.

Case Description

This case is initially designed to study the thermal environment of an aircraft cabin, by creating a mixed convection flow (Wang and Chen 2009). As shown in Figure *2*, the room is *2.44 m × 2.44 m × 2.44 m* and at the center a *1.22 m × 1.22 m × 1.22 m* heat blockage is located. The flow is under the influence of the inertia and buoyance forces. In the experiment, the temperature of the box surface, inlet flow, ceiling, floor, and other walls is 36.7 *ºC*, 22.2 *ºC*. 25.8 *ºC*, 26.9 *ºC*, and 27.4 *ºC*, respectively. The inlet velocity is 1.36 m/s. We set the initial temperature as 35 *ºC*. For more details about the experiment setup one can refer to the literature (Wang and Chen 2009).

We further propose to add to the mixed convection flow a VAV terminal box. Since this paper as a pilot study aims to demonstrate the proof of concept, a closer-to-reality HVAC system is therefore not adopted. The VAV terminal box with a reheating coil used in this paper is similar to the one present by Tian, Zuo, et al. (2017). The pressure and temperature of the cold air in the terminal is set as 20 Pa and 16 ℃, respectively. A valve is deployed in the air loop to adjust air volume and a value is place at the water loop of the reheating coil to adjust the water flow rate. A controller module is added to the terminal box to determine the opening position of the valve in cold air and hot water loop.

A pressure-dependent control logic (Liu, Zhang, and Dasu 2012) is used in the controller. Again, as this is a pilot study, we did not try to use a more complex control using in real applications. When the actual temperature approaches the setpoint while being still higher (assuming a cooling season), the controller first attempts to decrease the opening of the valve in air loop until a lower limit of 30% is reached. If 30% is reached, but the actual temperature is lower than the setpoint, the reheating coil will be turned on. To avoid the short cycling of turning on and off the reheat coil, a hysteresis is added in the control loop, which has lower bound of 0.3 and higher bound of 0.4.

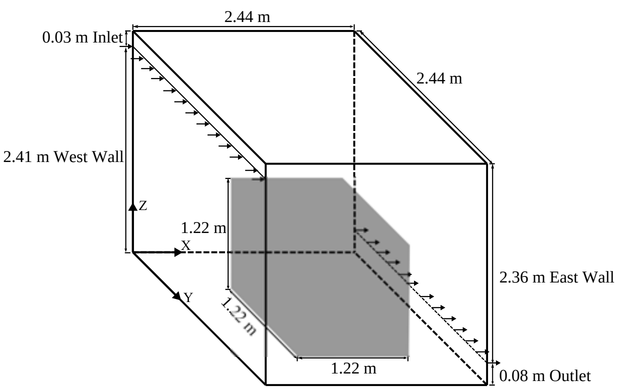

Figure 2. Sketch of numerical case (Tian, Sevilla, and Zuo 2017)

Implementation

The whole implementation can be divided into two parts: the first one is to build the system model which involves the VAV terminal box and FFD representation of the stratified airflow. The other one is to combine the system model with optimization engine GenOpt to performance optimal search.

Figure 3 shows the system model implemented in Modelica. At the center is the instance of *cfd* model, which is used to exchange information between the VAV terminal box model and FFD. The left three blocks show the radiative, convective, and latent heat gain, which are all zeros in this study. Above the cfd model is the VAV terminal box model, whose detailed model is shown in *Figure 4*.

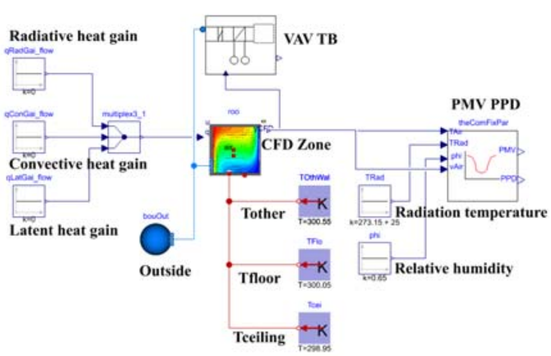

Figure 3. Modelica implementation of system model

Since the VAV terminal box is isolated from the VAV system, the cold air source is represented by a fix boundary with a constant temperature and pressure. The air from the source first goes through an air-to-water heat exchanger (reheating coil). The air flow rate is adjusted by the valve in the air loop, which obtains the opening position signal from controller. The control of valve position for the reheating coil is done similarly. A second order filter is applied to abrupt change of the opening position.

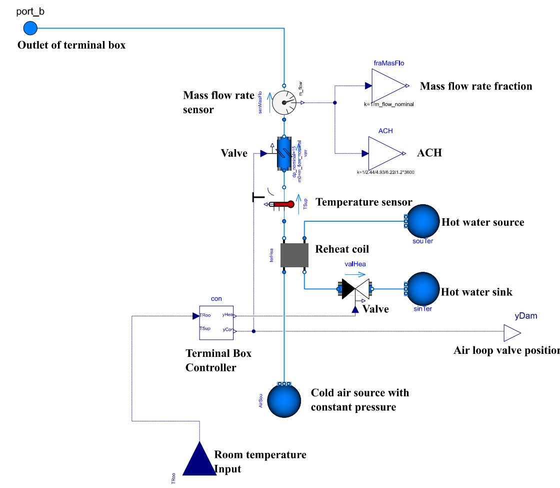

Figure 4. Modelica implementation of VAV terminal box (Tian, Sevilla, et al. 2017)

Once FFD finishes the calculation for one synchronization time step, it feeds back the occupant zone average temperature and speed to the *cfd* model. Those information will be further passed to *Fanger* model (Fanger 1970) to calculate the index of PMV, which indicates the thermal comfort level. Here in the model we assume a constant radiation temperature, which is reasonable as the temperature at the walls are not changed over the time.

After the system model is implemented, the optimization engine GenOpt is connected to the model. The connection establishment is very similar to the literature (Huang and Zuo 2014). GenOpt gives the coordinates of the thermostat to the model while the model gives the PMV value to the GenOpt. GenOpt implemented various optimization schemes to find the optimal values of objective functions (thermal comfort in terms of PMV). Here in this pilot study, we only applied an exhaustive search optimization, to verify the proof of concept.

RESULTS

The validation of FFD on simulation the mixed convection flow described in last section is shown in literature (Zuo et al. 2016). According to the speed and temperature profiles comparison, FFD can capture the flow features in a reasonable accurate manner. The contour plotting (*Figure 5*) shows that the airflow field in this case is stratified, which indicates that putting thermostat in different location may result in different states of HVAC system and thermal comfort. There is a thermal plume formed above the heated blockage. On the right side of the blockage, the temperature is slightly lower than that of the rest area, mainly because the cold jet sinks in that area once hitting the east wall, and the blockage further impedes the airflow circulation.

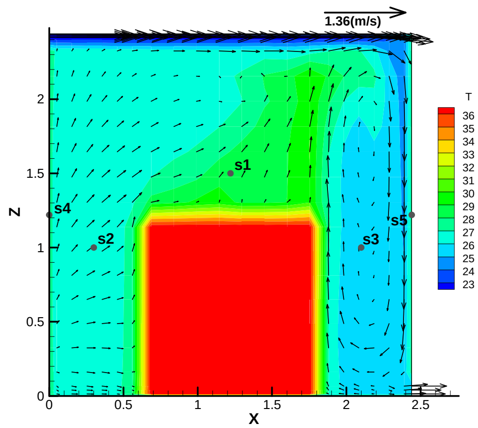

Figure 5 Temperature contour on a cross-section at Y = 1.22 m (Zuo et al. 2016)

Table 1 shows the optimization results by the exhaustive search methods. The search domain contains 12 discrete points at height of 1.22 m (Z = 1.22 m). The distance between two points on each wall is about 0.61 m. The thermostat detects the temperature at the adjacent fluid cell other than the temperature at the solid wall. From the nature of PMV index, PMV that is close to zero indicates a comfortable environment. From the perspective of the walls on which the thermostat is located, the east wall (X=2.44) is the least appropriate plane to put the thermostat, as this region has relatively lower temperature than rest of the area, due to the mixing of cold and hot stream, as well as the existing of the blockage. As the temperature reaches the set point of 25 *ºC,* the rest of the area in the occupant zone might have higher temperature. This explains why thermostat at point 11, 12, 13, results into slightly higher value of PMV, which indicates warm thermal sensation. On the other hand, the thermostat put on the rest of points generally results in better results in terms of the PMV. Specially, the thermostat located at position 5 is the best, as the PMV of 0.10834 is closest to zero.

Figure 6 shows the temperature contour at plane X = 1.22 m where the thermostat at location 5 is identified. Again, we can observe the thermal plume above the heat blockage, and the upper zone has relatively higher temperature. As expected, the temperature at the location 5 is roughly the same level compared to the average occupant zone (Z <= 1.22m) temperature, as it is less affected by the cold jet due to the existing of the blockage. Similarly, *Figure 7* shows the temperature distribution at plane that is not intersected with the blockage. A higher temperature is still observable in the upper zone, which further supports our assumption that the temperature stratification forms in the space.

Table 1. Position of thermostat and its associated PMV

Thermostat #	X (m)	Y(m)	Z(m)	PMV
1	0.61	0	1.22	0.815221
2	1.22	0	1.22	0.491478
3	1.83	0	1.22	0.331682
4	0.61	2.44	1.22	1.08229
5	1.22	2.44	1.22	0.10834
6	1.83	2.44	1.22	0.155018
7	0	0.61	1.22	0.654682
8	0	1.22	1.22	0.317413
9	0	1.83	1.22	0.549786
10	2.44	0.61	1.22	1.12858
11	2.44	1.22	1.22	0.453708
12	2.44	1.83	1.22	1.487672

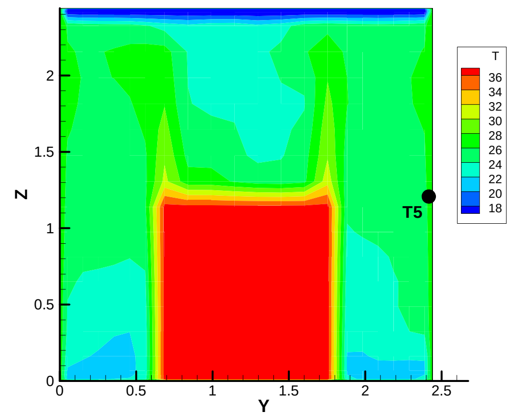

Figure 6 Temperature contour on a cross-section at X = 1.22 m when thermostat is put at location 5

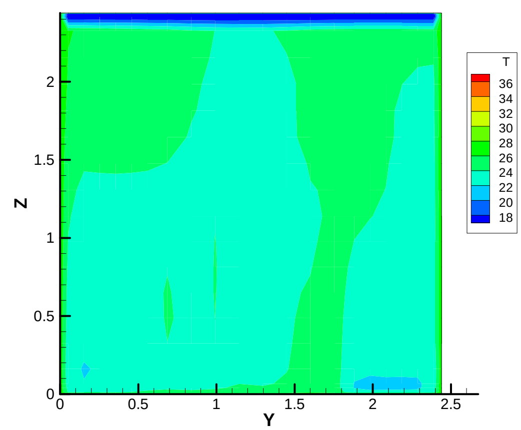

Figure 7 Temperature contour on a cross-section at X = 0.3 m when thermostat is put at location 5

Figure 8 shows the occupant zone average temperature varying along the time when the thermostat is put at location 5. The initial temperature of the room is set to be 35 *ºC*. As the cold air keeps injecting from the inlet, the average temperature gradually approaches to the room temperature set point of 25 *ºC*. As expected, the actual temperature is oscillating all the time due to the turbulent essence of the flow. However, the overall controllability of the VAV terminal box by putting the thermostat at location 5 is acceptable, as in the majority of the simulation time, the actual temperature is reasonable close to the setpoint. *Figure 9* shows the comparison of the PMV over the simulation time. Again, since location 12 is within the mixing region where cold jet with hot stream from the blockage, the temperature is relatively lower. Thus, we can clear see that the PMV resulted from putting the thermostat at location 12 is higher, which means less comfortable in terms of the thermal sensation of occupants. As the flow is highly turbulent and temperature is oscillating, the PMV value consequently changes in a similar manner. Overall, location 5 still predominate over location 12 in terms of cultivating the thermal comfort of the room.

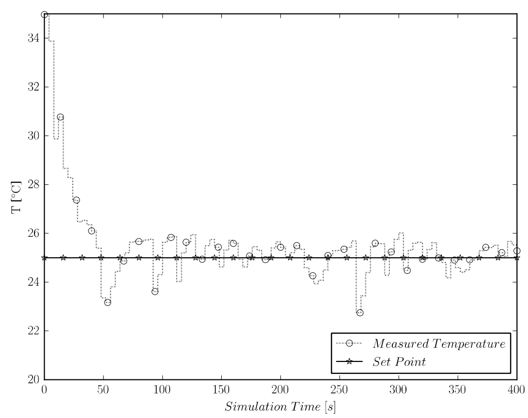

Figure 8 Temperature control when thermostat is put at location 5

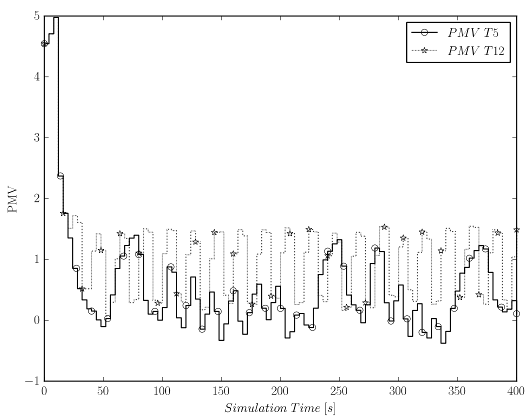

Figure 9 PMV changing alone with time when thermostat is put at location 5 and 12

CONCLUSION

This paper presents a methodology to couple an optimization engine with a coupled simulation model to seek optimal solution for the building design and operation. The coupled simulation model release in the Modelica *Buildings* library can capture the dynamics change of the model by exchanging data between Modelica model and a fast fluid dynamic model. We demonstrated the methodology by applying it in an idealized case to find the best location for thermostat, in order to achieve overall highest thermal comfort. Results show that the proposed methodology is capable to identify the best location, which enable a VAV terminal box to achieve near-to-zero PMV for the thermal environment.

FUTURE WORK

As this paper only reports a pilot study aiming to provide proof of concept, there exists aspects for consideration in the future as follows:

1. Identify more realistic cases. After the idea report in this paper is feasible, the next step is to apply this idea into real application, which may involve more complex thermal environment and HVAC system modelling.
2. Evaluate advanced optimization scheme, both locally and globally. In additional, when a real application is considered, the optimization of mutli-objective functions needs attentions. For example, in the future, it is necessary to consider the PMV and controllability simultaneously.
3. Adapt optimization to the discontinuous search domain. As shown in this paper, the search domain is usually discrete. It is necessary either to improve the optimization scheme designed for continuous search or to improve the selection of search domain to make sure it is continuous.

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