

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 important 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 TYNYSYS 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:

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

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

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

$$\frac{\partial \mathbf{U}_i}{\partial t} = \nu \frac{\partial^2 \mathbf{U}_i}{\partial x_j^2} + \mathbf{F}_i \quad (3)$$

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

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

$$\frac{\partial \mathbf{U}_i}{\partial x_i} = 0 \quad (5)$$

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.

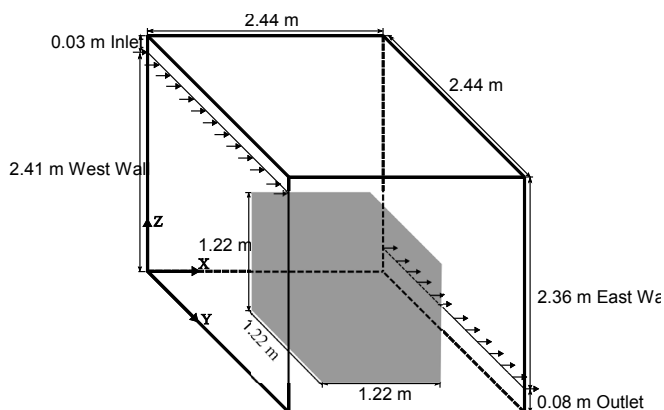


Figure 2. Sketch of numerical case (Tian, Sevilla, and Zuo 2017)

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.

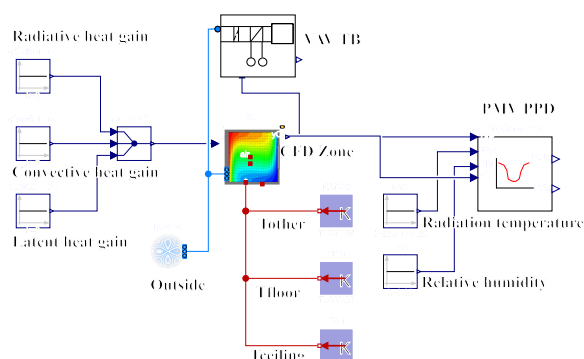


Figure 3. Modelica implementation of system model

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.

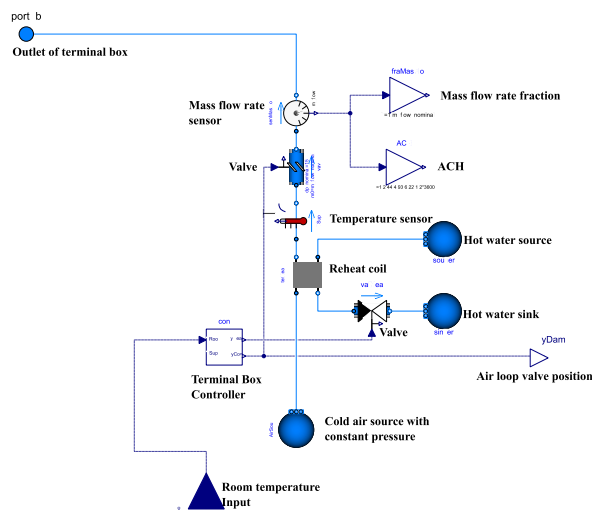


Figure 4. Modelica implementation of VAV terminal box (Tian, Sevilla, et al. 2017)

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.

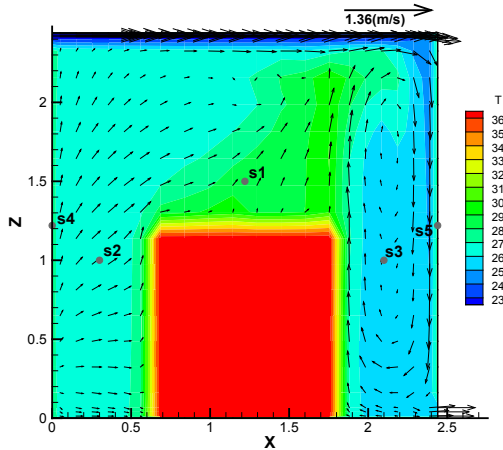


Figure 5 Temperature contour on a cross-section at $Y = 1.22$ m (Zuo et al. 2016)

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 °C, 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 ($Z \leq 1.22$ m) 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

Thermostat #	X (m)	Y(m)	Z(m)	PMV
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

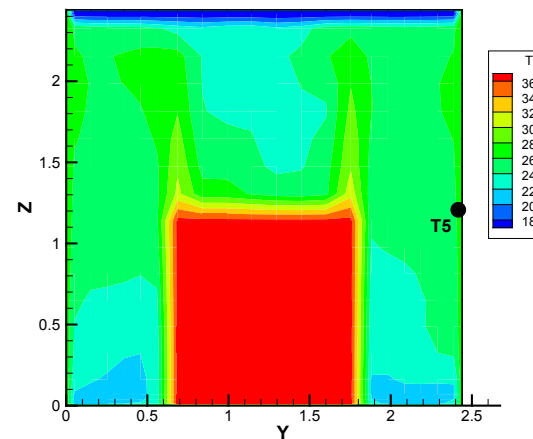


Figure 6 Temperature contour on a cross-section at $X = 1.22$ m when thermostat is put at location 5

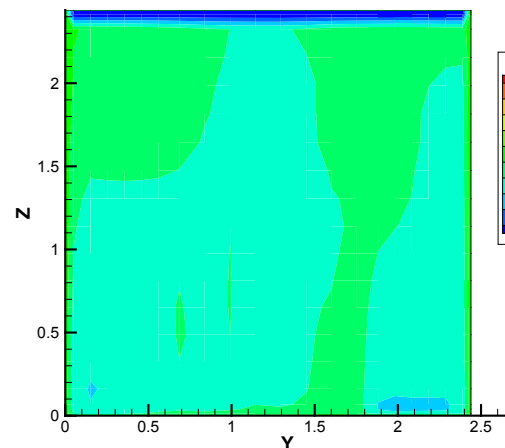


Figure 7 Temperature contour on a cross-section at $X = 0.3$ m when thermostat is put at location 5

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 °C. As the cold air keeps injecting from the inlet, the average temperature gradually approaches to the room temperature set point of 25 °C. 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.

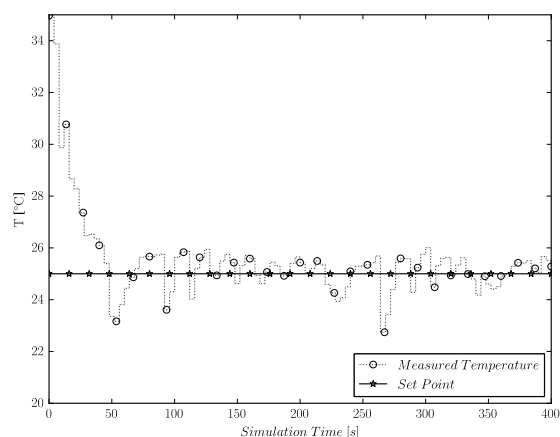


Figure 8 Temperature control when thermostat is put at location 5

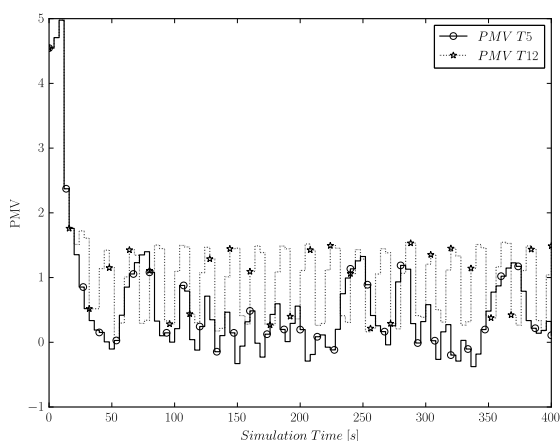


Figure 9 PMV changing along with time when thermostat is put at location 5 and 12

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 multi-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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REFERENCE

- Chorin, A. J. 1967. "A Numerical Method For Solving Incompressible Viscous Flow Problems." Review of. *Journal of Computational Physics* 2 (1):12-26.
- Courant, Richard, Eugene Isaacson, and Mina Rees. 1952. "On the solution of nonlinear hyperbolic differential equations by finite differences." Review of. *Communications on Pure and Applied Mathematics* 5 (3):243-55.
- Dols, W Stuart, and George N Walton. 2002. *CONTAMW 2.0 user manual: multizone airflow and contaminant transport analysis software*: US Department of Commerce, Technology Administration, National Institute of Standards and Technology.
- Du, Zhimin, Peifan Xu, Xinqiao Jin, and Qiaoling Liu. 2015. "Temperature sensor placement optimization for VAV control using CFD-BES co-simulation strategy." Review of. *Building and Environment* 85:104-13.
- Fanger, Poul O. 1970. "Thermal comfort. Analysis and applications in environmental engineering." Review of. *Thermal comfort. Analysis and applications in environmental engineering*.
- Huang, Sen, and Wangda Zuo. 2014. Optimization of the water-cooled chiller plant system operation. Paper presented at the 2014 ASHRAE/IBPSA-USA Building Simulation Conference.
- Jin, Mingang, Wangda Zuo, and Qingyan Chen. 2012. "Improvements of fast fluid dynamics for simulating air flow in buildings." Review of. *Numerical Heat Transfer, Part B: Fundamentals* 62 (6):419-38.

- Kim, D, JE Braun, EM Cliff, and JT Borggaard. 2015. "Development, validation and application of a coupled reduced-order CFD model for building control applications." Review of. *Building and Environment* 93:97-111.
- Liu, Guopeng, J Zhang, and A Dasu. 2012. "Review of Literature on Terminal Box Control, Occupancy Sensing Technology and Multi-zone Demand Control Ventilation (DCV)." Review of. *US Department of Energy, Tech. Rep.*
- Tian, Wei, Thomas Alonso Sevilla, and Wangda Zuo. 2017. "A systematic evaluation of accelerating indoor airflow simulations using cross-platform parallel computing." Review of. *Journal of Building Performance Simulation* 10 (3):243-55. doi: 10.1080/19401493.2016.1212933.
- Tian, Wei, Thomas Alonso Sevilla, Wangda Zuo, and Michael D. Sohn. 2017. "Coupling fast fluid dynamics and multizone airflow models in Modelica Buildings library to simulate the dynamics of HVAC systems." Review of. *Building and Environment* %@ 0360-1323.
- Tian, Wei, Wangda Zuo, Thomas Sevilla, and Michael Sohn. 2017. Coupled Simulation between CFD and Multizone Models Based on Modelica Buildings Library to Study Indoor Environment Control. Paper presented at the Proceedings of the 12th International Modelica Conference, Prague, Czech Republic, May 15-17, 2017.
- Wang, Miao, and Qingyan Chen. 2009. "Assessment of various turbulence models for transitional flows in an enclosed environment (RP-1271)." Review of. *HVAC&R Research* 15 (6):1099-119.
- Wang, Shengwei, and Zhenjun Ma. 2008. "Supervisory and optimal control of building HVAC systems: A review." Review of. *HVAC&R Research* 14 (1):3-32.
- Wetter, M. 2008. "GenOpt Manual: Generic Optimization Program, Version 2.1. 0." Review of. *University of California (through Lawrence Berkeley National Laboratory), Berkeley.*
- Wetter, Michael. 2000. "Design optimization with GenOpt." Review of. *Building Energy Simulation User News* 21 (19-28).
- Wetter, Michael. 2009. "Modelica-Based Modeling And Simulation To Support Research And Development In Building Energy And Control Systems." Review of. *4th International Conference On Building Energy, Environment of. Journal of Building Performance Simulation* 2 (2):143-61.
- Wetter, Michael, Marco Bonvini, Thierry Noudui, Wei Tian, and Wangda Zuo. 2015. Modelica Buildings Library 2.0. Paper presented at the Abstract submitted to Building Simulation 2015, Hyderabad, India.
- Yang, Pu. 2013. "Real-time Building Airflow Simulation Aided by GPU and FFD." Concordia University.
- Yuan, Xiaoxiong, Qingyan Chen, Leon R Glicksman, Yongqing Hu, and Xudong Yang. 1999. "Measurements and computations of room airflow with displacement ventilation." Review of. *Ashrae Transactions* 105:340.
- Zuo, Wangda, and Qingyan Chen. 2009. "Real-Time Or Faster-Than-Real-Time Simulation Of Airflow In Buildings." Review of. *Indoor Air* 19 (1):33-44.
- Zuo, Wangda, and Qingyan Chen. 2010. "Fast And Informative Flow Simulations In A Building By Using Fast Fluid Dynamics Model On Graphics Processing Unit." Review of. *Building and Environment* 45 (3):747-57.
- Zuo, Wangda, Michael Wetter, Dan Li, Mingang Jin, Wei Tian, and Qingyan Chen. 2014. Coupled Simulation of Indoor Environment, HVAC And Control System by Using Fast Fluid Dynamics and Modelica. Paper presented at the 2014 ASHRAE/IBPSA-USA Building Simulation Conference, Atlanta, GA, Sep. 10-12.
- Zuo, Wangda, Michael Wetter, Wei Tian, Dan Li, Mingang Jin, and Qingyan Chen. 2016. "Coupling indoor airflow, HVAC, control and building envelope heat transfer in the Modelica Buildings library." Review of. *Journal of Building Performance Simulation* 9 (4):366-81.