PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Energy Efficient Room Thermal Control Strategy with Consideration of Occupants' Thermal Comfortability

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Abstract:

In general, any changes to room temperature for energy savings should not impact the occupants' thermal comfortability. Therefore, the thermal control strategy should meet the occupants' thermal comfortability expectations while exploring the energy consumption reduction strategy. The paper presents our preliminary work in developing "people-centered" energy-saving methods. The work starts with building a CFD thermal dynamic model of the room by using an actual kitchen as the prototype. The model can simulate and derive the temperature at any position within the room space and capture its temperature dynamics. Then, a target-tracking people-centered control strategy is proposed. With the occupant's motion and position changes, the model can calculate the room temperature at the point where the occupant is located. The objective of the control is to ensure the occupant's thermal comfortability. The initial simulation study indicates that the target-tracking control strategy could potentially save 23.32% more energy and greatly enhance the occupant's thermal comfort compared to a fixed-position sensor-based control strategy.

Keywords:

Thermal Comfort Control; Energy Efficiency; CFD; Thermal Dynamic Model.

1. Introduction

The UK government has set an ambitious target to reduce emissions by 78% by 2035 compared to the 1990 level [1]. A more ambitious goal is to achieve zero carbon emissions by 2050 [2]. To achieve this target, significant efforts must be made for decarbonizing power generation, heating, and road transportation [3]. Power generation from renewable energy sources has proliferated in the past ten years [4]. However, emissions from heating are almost unchanged. Without decarbonising heating, Net Zero goal has no way to be achieved as heating contributes nearly half of the energy consumption in the UK, in which 57% is used to meet domestic space heating and hot water demands [5]. Electric heating using power from renewable energy sources can promote heating decarbonization and proper electric heating management may support flexible grid operation to allow increased integration of variable renewable energy [6]. Heating electrification in coordination with power generation from renewable energy is considered as feasible way of emission reduction [7].

It is well known that conversion from electricity to heat has an efficiency of 100%. However, the utilisation of the converted thermal energy may not have 100% efficiency while in a heating system. For space heating, temperature distribution and air velocity affect the occupant's thermal comfort level which will lead the variations to energy consumed. A good control strategy for an electric heating system should satisfy the occupants' thermal comfortability while minimising energy consumption.

The room thermal models with high fidelity are essential for thermal comfort control strategies [8]. Room thermal models can be divided into three categories: white, black, and grey box models [9]. The white box model is based on the derivation of physical equations and assigning values to parameters in the model based on empirical knowledge [10]. Jradi et al. [11] developed a dynamic energy performance model for four buildings in Aarhus, Denmark, considering realistically measured physical parameters of components such as roofs, exterior walls, windows, doors, and floors. The model guides the analysis and evaluation of energy retrofits in buildings. The black box model is a purely data-driven model that uses artificial neural networks (ANN) to model the mapping of input parameters to desired output parameters [12]. Attoue et al. [13] proposed an ANN-based indoor temperature prediction model that considers the effects of solar radiation,

https://doi.org/10.52202/069564-0219

historical indoor and outdoor temperatures, and indoor and outdoor humidity on indoor temperature. The grey-box model is a hybrid model that uses physical knowledge to build a mathematical model and uses ANN to mine the relationships between a large amount of actual residential thermal data to obtain the values of the parameters in the model [14]. Hu et al. [15] developed a self-learning grey box room thermal model which uses indoor air and outdoor air temperatures to pre-estimate and scale the model parameters. Case studies show that the model can accurately predict indoor air temperature variations.

However, in these models, the temperature distribution in a space is normally assumed to be uniform. In this way, it is common for occupants to experience differences in thermal comfort in different parts of the room, with some areas feeling hot and others cold, which will affect the occupants' thermal comfortability and may be accompanied by an increase in energy consumption. Focusing on this challenge, this paper explores energy efficiency control strategies for occupant comfort enhancement based on a thermal dynamic model of the room.

The main contributions of the paper present: i) a thermal dynamic model could predict the temperatures of any position point in a room space is built; ii) a target-tracking energy saving control strategy to enhance the occupants' thermal comfortability is proposed; iii) a simultaneously evolving dynamic thermal models and occupant thermal comfort-oriented control strategies is implemented based on a co-simulation multi-platform.

2. Description of a target-tracking thermal comfort control system

The target-tracking thermal comfort control system is shown in Figure 1. The aim of the control system developed to achieve energy efficiency while maintaining the occupant's thermal comfort. Three parts form the control system: room CFD thermal dynamic model, occupant location recognition, and control strategy. The parameters and location of the electric heater are fed to the CFD model to simulate heat dissipation and transfer in the room as a heat source. Then, the room temperature distribution will be calculated and updated via the CFD simulation during each simulation time step. By this way, the temperature at different mesh point locations in the room can be obtained. The occupant location recognition is performed by synthesizing the sensors' data so the temperature of the occupant's activity zone can be obtained. The control strategy will be formulated to regulate the heat dissipation power of the electric heater. The study is based on INVENTOR and COMSOL software to build room CFD thermal dynamic model and on COMSOL and SIMULINK software to develop and simulate control strategy. The occupant location recognition part is achieved by an occupant random path generation model based on MATLAB software.

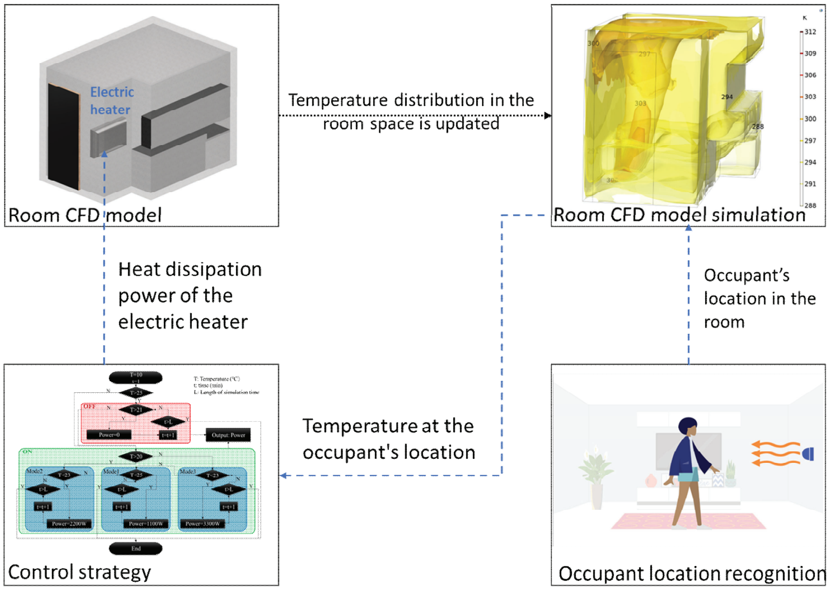

Figure. 1. Target-tracking thermal comfort control system illustration

3. Room CFD thermal dynamic model

Different from the current room thermal models assuming a uniform temperature distribution in the room space, the paper explores the room thermal dynamics and temperature distribution via a CFD simulation which will be performed with the information of room boundary conditions and the heat source (an electric heater in this study); the CFD model will be able to provide the temperature distribution for a different location in the room 3D space, and the resolution depends on the choices of mesh.

The CFD thermal dynamic model is built with the benefits of two software packages: INVENTOR and COMSOL. As shown in Figure 2(a), the laboratory kitchen is chosen as a base space for modelling. Use INVENTOR software to generate a 3D model of the room with consideration of the shapes and spaces of the interior furniture and appliances. The 3D room model is shown in Figure 2(b). The electric heater is the only heat source located in the room to heat up the space. The synchronization of this 3D room model in INVENTOR and COMSOL software is achieved via LiveLink for Inventor interface. In COMSOL, by assigning physical parameters to the components of the 3D room model and adding multi-physics field, the CFD model will obtain the temperature distribution inside the room space. Figure 2(c) shows the room CFD model mesh used in simulation.

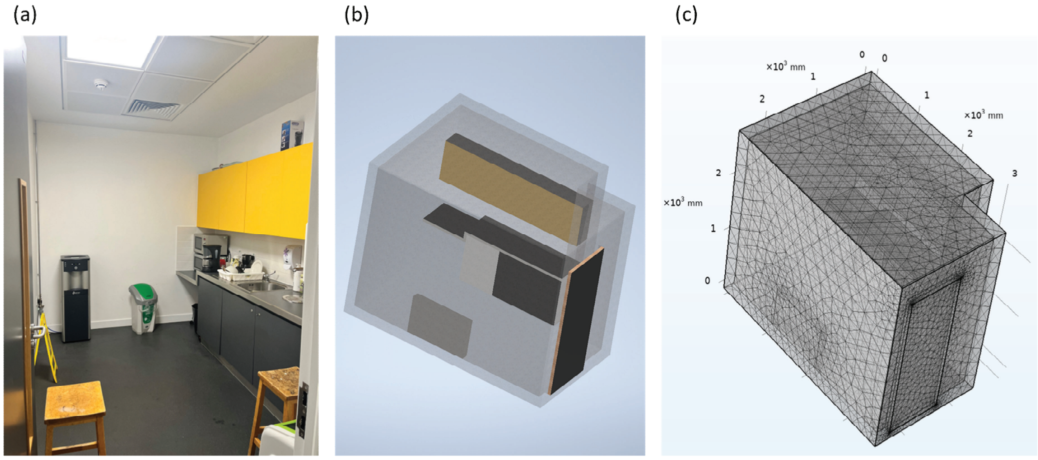

Figure. 2. a) The room, b) 3D model of the room, c) illustration of the room CFD dynamic thermal model mesh

In order to get the information about the temperature distribution inside the room space during the operation of an electric heater, multi-physics field simulations of coupled fluid flow and fluid-solid heat transfer are required in using COMSOL Multiphysics modelling. The laminar flow model is used to simulate the air flow in the room. The thermal model chooses using solid and fluid heat transfer physical fields. The total volume of the room is approximately 26.4 m^3. Physics-controlled mesh, shown in Figure 2(c), was generated automatically with element size set to coarse. The automatically generated mesh contains 127,313 domain elements, 15,887 boundary elements and 1,558 edge elements. Referring to the European National Building Code [16], heat transfer coefficients for the exterior wall and the door are selected to be 2.5 W/m^2K and 3 W/m^2K, respectively to represent the simulating scenario. The initial temperature is set as 10 ℃.

The input variable to this room CFD model is the thermal dissipation power of the electric heater. The state variable is the temperature distribution in the room space. By setting the thermal dissipation power of the electric heater, the temperature distribution in the room space will be updated at each simulation step.

4.Thermal comfort control strategies

A quantum series heater is investigated in this paper. This electric heater is an advanced product in the UK market. The heater used in this paper is model QM150RF, which has three electric heating modules, each operating at 1100 W and one fan, operating at 11W. The heater uses forced convection heat transfer to provide heat to the occupant. The electric heater is well insulated, the heat is released from underneath the heater, and a fan blows from underneath the heater to bring the heat into the room. In this study, the circuit of the electric heater has been modified so that it can now be heated at three levels of power: 1100 W, 2200 W, and 3300 W. The control strategy in this paper has been developed based on these three levels of power.

A commonly used temperature control strategy currently is thermostatic control. Based on the temperature data input from a fixed sensor to maintain the temperature near that sensor in a fixed interval, usually 21-25℃. Control strategies based on feedback from fixed temperature sensors are developed under the assumption that the temperature distribution within a room space is uniform. However, there is a large variation in the temperature distribution within the room space, which leads to erratic performance of control strategies based on fixed temperature sensor feedback. The CFD thermal dynamic model of the room developed in the third part of this paper can provide temperature variations at any location during the operation of the electric heater. LiveLink for Simulink interface enables the joint simulation of this CFD model in COMSOL and SIMULINK software. The development and simulation of the control strategy in this paper is based on the combined operation of SIMLINK and COMSOL software. The target-tracking thermal comfort control system proposed in this paper is shown in Figure 1. The heat dissipation power of the electric heater is the control variable of the strategy and the temperature distribution in the room space is the state variable. The target-tracking thermal comfort control framework is present as follows:

$$\begin{cases} C(t) = f_{cs}(T(t)) \\ T(t) = S(t)|(x,y,z) \\ (x,y,z) = f_{olc}(t) \\ S(t+step) = f_{rtdm}\big(S(t),C(t)\big) \end{cases} \tag{1}$$

where, f_{cs} is the control strategy. $C(t)$ is the control variable at time t. $T(t)$ is the temperature at the occupant's location at time t; $S(t)$ is the state variable at time t, which is a function of the spatial coordinates. f_{olc} is the occupant location recognition model which is a time-dependent function. (x,y,z) is the occupant's spatial location. f_{rtdm} is the room CFD thermal dynamic model. $step$ is the simulation time step.

The control strategy is present in Figure 3. The control strategy development draws on the operating model of the actual electric heater. The operating states of an electric heater can be divided into two main categories, off and on. When the heater is on, it can be divided into three operating models, Mode 1 (power = 1100W), Mode 2 (power = 2200W), and Mode 3 (power = 3300W). The control strategy ensures that the temperature around the occupant is always between 21 and 25 ℃. Taking into account the time-dependent nature of heat diffusion and to avoid frequent start/stop of the electric heater, the control strategy is structured in a self-cycling manner for each mode.

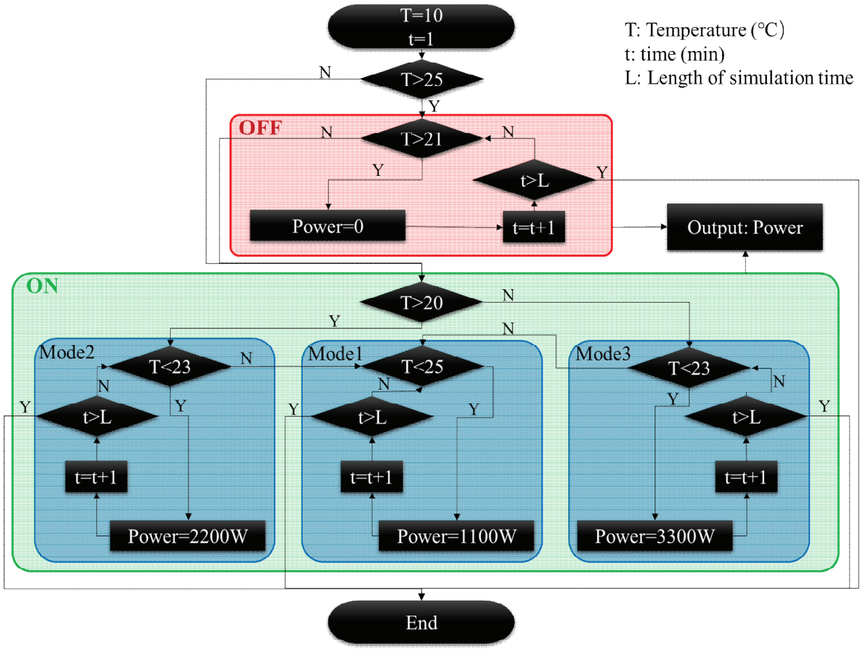

Figure. 3. Thermal comfort control strategy

In order to set the object of comparison, two fixed sensor-based control systems are designed for this study. These are, respectively, a control system based on a temperature sensor fixed to a doorway (TC@d), a control system based on a temperature sensor fixed near the heater (TC@h).

5. Results and discussions

This paper is based on a multi-software platform to complete the development and simulation of a CFD thermal dynamic model of the room and a target-tracking thermal comfort control strategy. The co-simulation flow is shown in Figure 4. During the co-simulation process, the synchronization the 3D room model on INVENTOR and COMSOL platforms via the LiveLink for Inventor interface. The interaction of the input and output data of the room CFD thermal dynamic model on the COMSOL and SIMULINK platforms is accomplished via the LiveLink for Simulink interface.

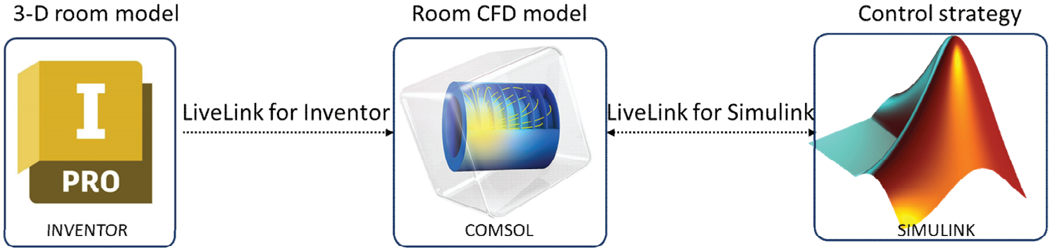

Figure. 4. Multi-platform co-simulation flow

This paper completes all simulations using a computer with an AMD Ryzen 5600H 3.30 GHz Processor, 16 GB of RAM, NVIDIA GeForce GTX 1650 GPU, and a 64-bit Windows operation system. Three temperature control strategies are simulated in this study, two based on fixed position sensor data feedback and the remaining on dynamic occupant activity trajectory temperature feedback. In the room CFD model, a plane one metre above the ground was set up as shown in Figure 5(a). Eight temperature probes were arranged on this plane, as shown in Figure 5(b). In this paper, the occupant's activity range in the room is divided into eight zones. The central temperature of the occupant's activity area is fed to the control strategy. The temperature at the occupant's activity area is always in a suitable range by selecting the appropriate control variables.

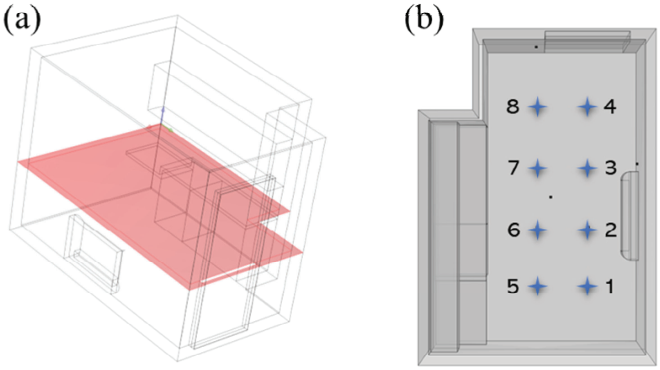

Figure. 5. Occupant activity zones: a) the plane, b) temperature probes

During the simulation, the occupant's activity trajectory needs to be given to verify the strategies' performance. After random sorting, one of the occupant's activity traces was obtained as: 6->3->7->8->5->1->2->4. It is assumed that the occupant spends a half hour in each zone. This paper adds two-time blocks of one hour each to this time location path. During these two-time blocks, the occupant leaves the room. Therefore, the final path obtained for the occupant's location over time is shown in Figure 6. This activity trajectory takes a total of 6 hours.

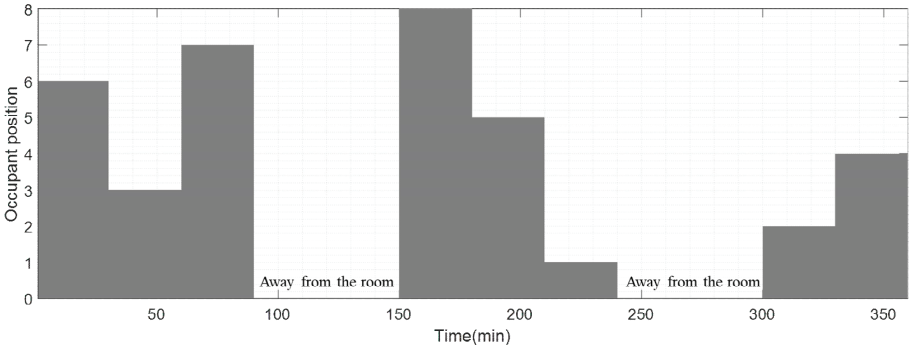

Figure. 6. Map of the location of occupant over time

A simulation analysis of three control strategies is carried out in this paper. These are, respectively, a thermal comfort control strategy for user target-tracking (TC@u), a thermal comfort control strategy based on a sensor fixed to a doorway (TC@d), a thermal comfort control strategy based on a sensor fixed near a heater (TC@h). Figure 7 shows the simulation results for the TC@u strategy. The position of the occupant during each half hour and the temperature at that position before the occupant moves can be clearly obtained from the figure. The temperature at the occupant's location prior to movement is around 25 ℃. This shows that regardless of the temperature when the occupant enters this location, the TC@u strategy adjusts the temperature at the occupant's location to the set range, thus keeping the occupants thermally comfortable at all times.

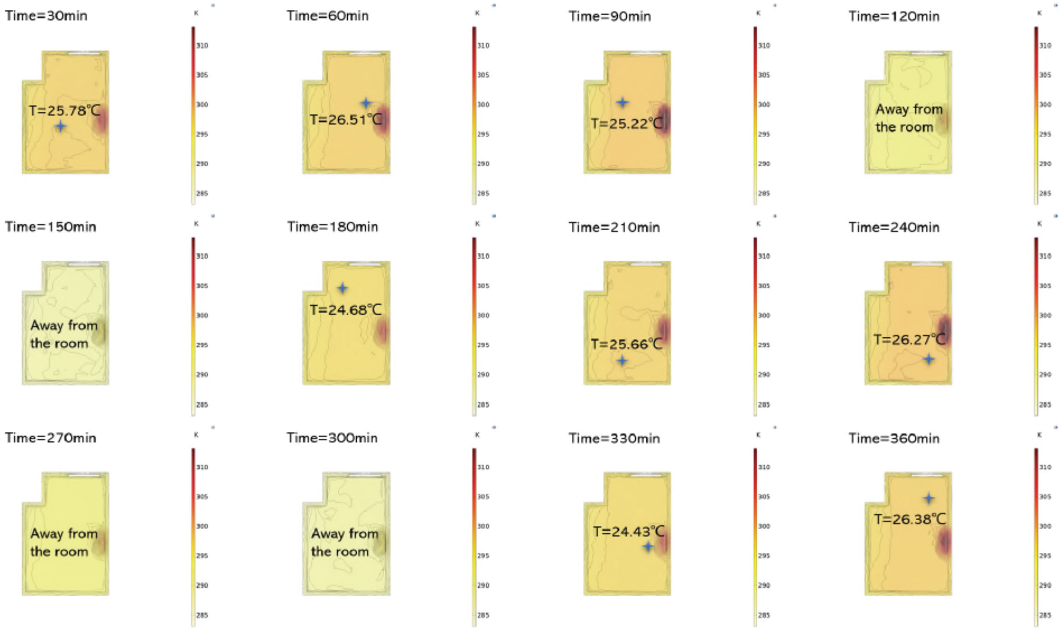

Figure. 7. The position of the occupant during each half hour and the temperature at that position before the position movement under TC@u strategy

Figure 8 shows the simulation results for the TC@h strategy. Prior to the move, the temperature at the occupant's location often exceeded 25 ℃, and even 30 ℃ in some locations. This shows that strategy TC@h does not guarantee the thermal comfortability of the occupants. Occupants tend to feel overheated.

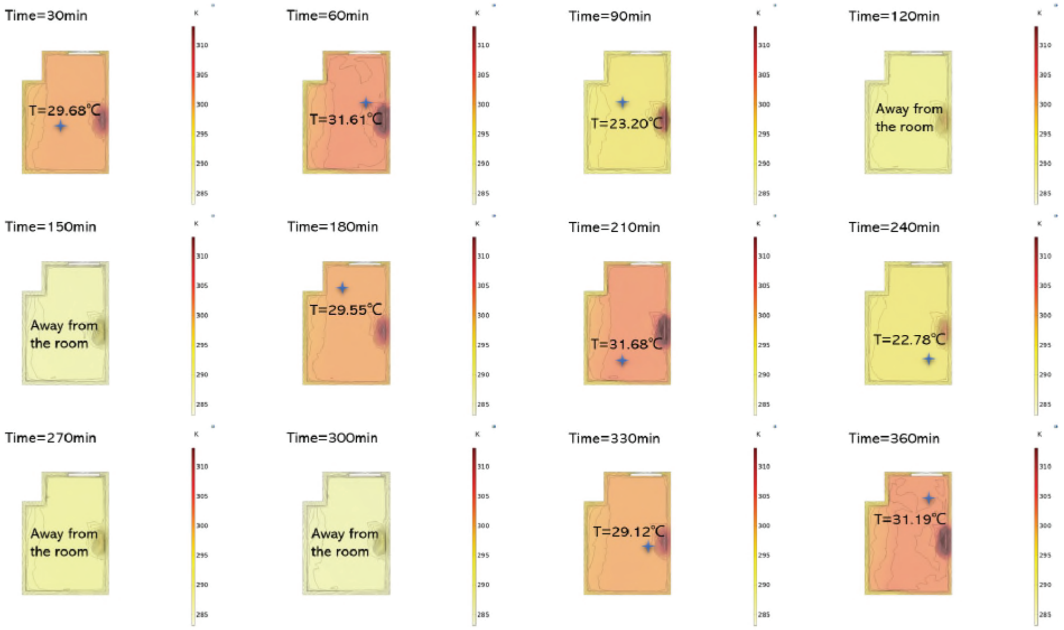

Figure. 8. The position of the occupant during each half hour and the temperature at that position before the position movement under TC@h strategy

The simulation result for the TC@d strategy is shown in Figure 9. Compared to TC@h strategy, the occupant's perception of the high temperature is much reduced in TC@d strategy. However, at 60min, 90min, 240min and 360min, the temperature around the occupant has reached 27 ℃, which has affected the occupant's thermal comfortability. Therefore, based on the simulation results in Figures 7, 8 and 9, TC@u strategy performs best in terms of occupant thermal comfortability.

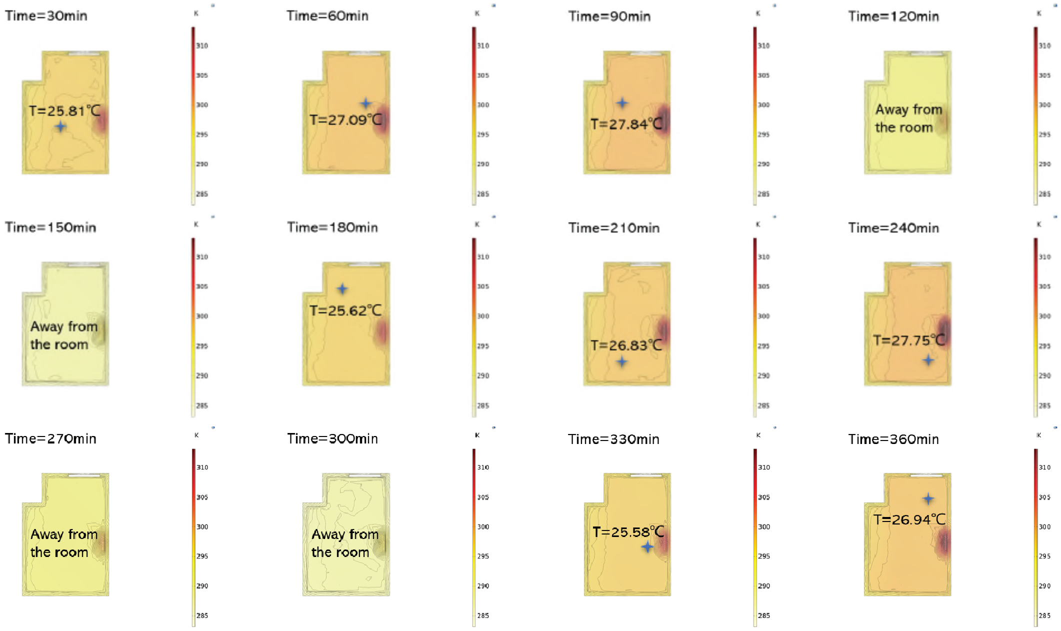

Figure. 9. The position of the occupant during each half hour and the temperature at that position before the position movement under TC@d strategy

Figure 10 shows the temperature variation for the three control strategies at the occupant's actual time location. Strategies TC@h and TC@d cause the occupant to be in the hot zone periodically, and the occupant tends to feel overheated. Strategy TC@u performs reasonably well, with the temperature at the occupant's activity trajectory remaining between 21-25 ℃ for most of the time. However, Strategy TC@u will occasionally experience high-temperature overshoot, as heat is a process quantity that will expand into the surrounding space over time. In subsequent studies, the control strategy needs to be tailored to address this high-temperature overshoot phenomenon.

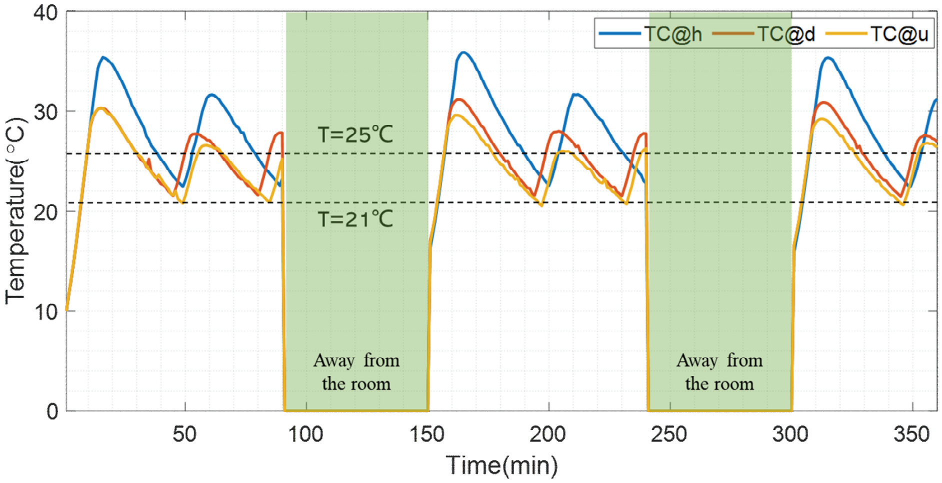

Figure. 10. Temperature at occupant activity trajectories with different temperature control strategies

In addition to comfortability, another indicator that occupants care about is the operating economy. The thermal energy consumption under the three temperature control strategies is shown in Figure 11. After six hours of operation, the energy consumptions under strategies TC@h, TC@d, and TC@u are 2.9887kWh, 2.5300kWh, and 2.2917kWh, respectively. Compared to strategies TC@h and TC@d, the economy of strategy TC@u is improved by 23.32% and 9.42%, respectively. Therefore, TC@u strategy ensures occupants' thermal comfortability while reducing energy consumption. It is a promising strategy for energy-efficient temperature control.

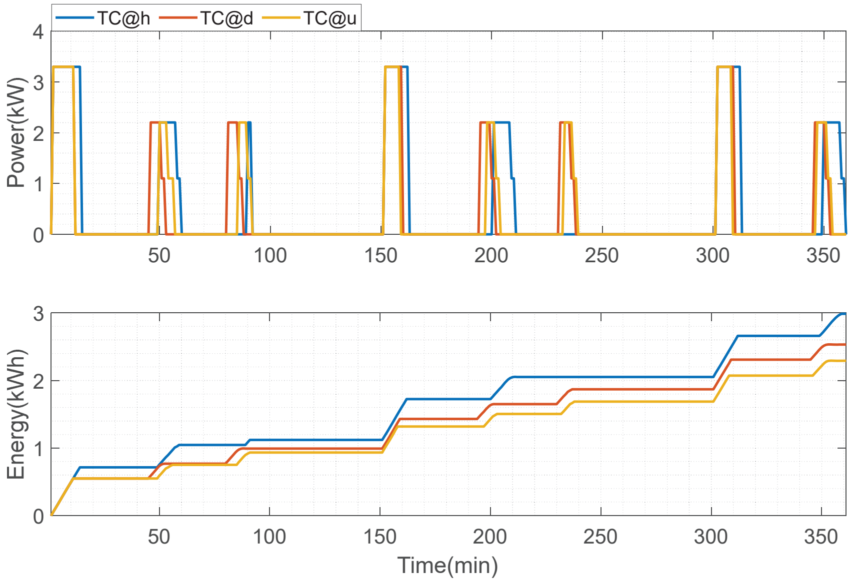

Figure. 11. Thermal energy consumption under different temperature control strategies

6. Conclusion

This paper built a room CFD thermal dynamic model based on the actual kitchen and an electric heater and then proposed a target-tracking thermal comfort control system based on this model. The strategy is developed and simulated through joint simulations on the COMSOL and SIMULINK platforms. The simulation results show that the strategy meets the thermal comfortability of the occupants while considering the economy.

Firstly, a 3D room model based on the INVENTOR platform was built based on the laboratory kitchen. The synchronization of this 3D room model on the INVENTOR and COMSOL platforms was implemented based on LiveLink for the Inventor interface.

Secondly, a room CFD model was created based on the COMSOL platform. The heat dissipation power of the electric heater is the input variable and the temperature distribution in the room space is the state variable. By setting the heat dissipation power of the heater to the model, the temperature distribution in the room space will be updated at each simulation time step.

Finally, a target-tracking thermal comfort control system is proposed and simulated by joint simulations with COMSOL and SIMULINK. The control system aims to achieve energy efficiency while maintaining thermal comfort. It mainly includes three parts: room CFD thermal dynamic model, occupant location recognition and control strategy. The simulation results show that this strategy both meets user comfort and operational economy compared with conventional control strategies.

Acknowledgments

The authors would like to thank the University of Warwick studentship combined with China Scholarship Council (202208060362） and the funding support from UK Engineering and Physical Science Research Council (EP/S032622/1).

Nomenclature

Symbols

$\mathrm{T}(^{\circ}\mathrm{C})$	temperature.
$\mathrm{S}(^{\circ}\mathrm{C})$	state variable, which is the temperature distribution in the room space.
$\mathrm{C}(\mathrm{W})$	control variable, which is the thermal dissipation power of the electric heater.
$\mathrm{f}_{\mathrm{rtdm}}$	room thermal dynamic model.
f_{cs}	control strategy.
f_{olc}	occupant location recognition model.

step	simulation time step.
$(\mathrm{x}, \mathrm{y}, \mathrm{z})$	occupant’s spatial location.

Abbreviation

TC@u	thermal comfort control strategy for user target-tracking.
TC@d	thermal comfort control strategy based on a sensor fixed to a doorway.
TC@h	thermal comfort control strategy based on a sensor fixed near a heater.

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