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Modeling of a Novel Low-Exergy System for Office Buildings with Modelica

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Abstract

This paper aims to investigate the thermal behavior of a novel low-exergy system for office buildings. The main characteristic of the system is its ability to provide simultaneous heating and cooling by operating one water circuit. Inlet water temperature of about 22 °C is delivered to all the thermal zones in the building, no matter whether a single zone needs heating or cooling. This approach clearly differs from conventional systems where simultaneous heating and cooling is provided by two separated water circuits.

A detailed model of the novel system was developed with Dymola, a modeling and simulation environment based on the Modelica programming language. The system was tested on two single office rooms. In order to evaluate potential energy savings, the energy performance of the novel system was compared with the one of a conventional system for three typical weeks during winter, spring and summer. Simulation results showed that the novel system was able to maintain comfortable levels of indoor air temperature in both rooms for all the three typical weeks. In addition, the novel system used approximately 35% and 7% less energy than the conventional system, respectively for the typical winter and spring week. No energy savings occurred during the summer week.

Keywords - Low-exergy systems; active beam; energy savings; Modelica

1. Introduction

Residential and commercial buildings require approximately 40% of the total end use of energy worldwide [1]. Thus, the potential savings of energy efficiency in the building sector would greatly contribute to a society-wide reduction of energy use.

With the consolidation of the demand for thermal comfort, heating, ventilation and air-conditioning (HVAC) systems have become an unavoidable asset and they represent the largest energy end use both in residential and commercial buildings, accounting for almost half the energy consumed in buildings [2]. It is clear that the challenge facing engineers and researchers is to design innovative HVAC systems able to achieve high levels of indoor climate quality while reducing energy use.

Several studies have been conducted on low-exergy systems for buildings [3],[4],[5]. By providing heating and cooling energy at a temperature close to room temperature, low-exergy systems allow the use of low valued energy, which can be delivered by sustainable energy sources such as heat pumps, solar collectors, waste heat and energy storage [6]. Therefore, the use of low-exergy systems can reduce the environmental impact of buildings, and play a crucial role towards the requirements of nearly zero-energy buildings communities

Previous studies conducted by the authors investigated the energy performance of an innovative low-exergy system for heating and cooling of office buildings. Active beams were integrated into the system as terminal units.

The characteristic of the system is its ability to provide simultaneous heating and cooling with one water circuit. Inlet water temperature of about 22 °C is delivered to all the thermal zones in the building, no matter whether a single zone needs heating or cooling. This approach differs from traditional systems where simultaneous heating and cooling demand is provided by operating two separated water circuits.

The energy performance of the novel system was previously evaluated by simulation-based studies using traditional building performance simulation (BPS) programs. Afshari et al. [7] analyzed the system by using BSim, a program for calculating indoor climate conditions and energy demands in buildings. The use of BSim showed two key limitations. First, BSim does not include any terminal unit clearly defined as active beam. The system was simplified by modeling fan coils for cooling and radiators for heating. Second, BSim treated heating and cooling as two separated processes. Therefore, the energy performance of the system could only be calculated by making some assumptions in a post-processing analysis. Maccarini et al. [8] used EnergyPlus to study the energy performance of the system. Simulations with EnergyPlus allowed a wider understanding of the energy behavior of the system. This was mainly because EnergyPlus includes a specific terminal unit defined as active beam. However, also EnergyPlys considered heating and cooling as two separated processes.

It is clear that a more detailed modeling tool is necessary for a comprehensive investigation of the novel system. Therefore, the main goal of this paper is to develop a model of the innovative system with Dymola, a simulation environment based on the Modelica language. The functioning principles of the system were demonstrated through a simulation case study.

2. Methods

The system was modeled by using basic components of the Modelica *Buildings* library [9], a free open-source library with dynamic simulation models for building energy and control systems. Figure 1 shows the model of the novel system developed with Dymola. The model can be described through four main elements: thermal zones, active beam unit, water system and ventilation system.

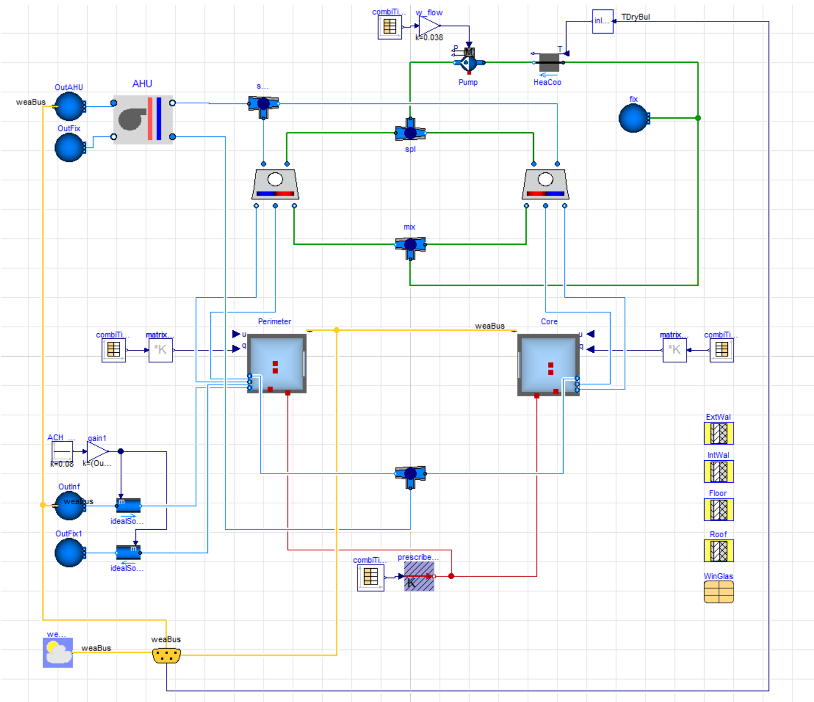

Fig. 1 Model of the novel system with Dymola. The water and air fluid circuits are illustrated respectively in green and blue color

Thermal zones

The system was studied through its integration into two thermal zones that represented two single office rooms. Typically, office buildings have two different kinds of thermal zones: perimeter and core. Perimeter zones refer to areas of the building that have at least one vertical surface facing the outdoor environment, while core zones represent areas located in the middle of the building. Therefore, a perimeter and a core office room were chosen for the simulation case study.

Both rooms had the following dimensions: 4 m length, 4 m width and 3 m height. The perimeter zone was assumed to have an external wall (north orientation), a floor and a roof. A double pane window of 3.6 m^2 was placed on the external wall. The core zone was assumed to have a floor and a roof. Internal walls were considered adiabatic. Table 1 shows the thermal properties of the constructions elements.

Tab. 1 Thermal properties of construction elements

Construction element	**U-value (W/m^2K)**
External Wall	0.31
Roof	0.18
Floor	1.83
Window (SHGC=0.4)	2.37

Infiltration rate was set equal to 0.08 air change hour for the perimeter zone. Internal heat gains were selected to be equal to 8.83 W/m^2 for lighting, 8 W/m^2 for equipment and 6.46 W/m^2 for occupants during working hours (7 am-6 pm). It is worth mentioning that the values of the thermal properties for construction elements and internal heat loads were defined according to the medium office building model prototype described in [10] and developed in accordance with the design and construction requirements of AHSRAE standard 90.1-2013. The climatic boundary conditions of Copenhagen (Denmark) were chosen for simulations.

Active beam unit

Active beams are terminal units for heating, cooling and ventilation of buildings. This means that they are connected to both the supply air ductwork and the water circuit. They consist of a primary air plenum, a mixing chamber, a heat exchanger and several nozzles. The primary air is discharged to the mixing chamber through the nozzles. This generates a low-pressure region which induced air from the room up through the heat exchanger. The conditioned induced air is then mixed with primary air, and the mixture descents back to the space.

Currently, no active beam model is included in the Modelica *Buildings* library. Therefore, a new Modelica model was developed. A comprehensive description of the active beam model used in this work is provided in [11]. The model encapsulates empirical equations derived by a specific active beam terminal unit named *Solus*, manufactured by Lindab A/S. This unit was designed to operate with low-temperature heating and high-temperature cooling systems.

Water and ventilation system

As previously mentioned, the novel system integrated only one water circuit for both heating and cooling. Therefore, the supply water should have temperature levels similar to indoor thermal comfort conditions. A controller regulated the supply water temperature between 23 °C and 20 °C based on outdoor air temperature. Fig. 2 shows the relationship between water and outdoor air temperature.

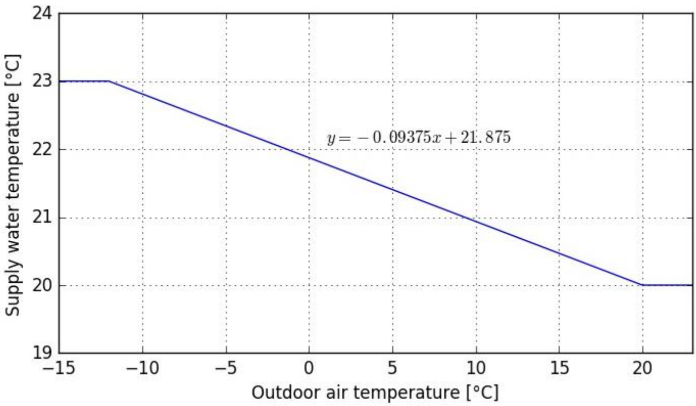

Fig. 2 Supply water temperature vs. outdoor air temperature

A constant water mass flow rate of 0.038 kg/s per each beam was provided by a circulating pump. An ideal heater-cooler was responsible to provide energy to the return water flow to reach the supply temperature set-point. The water system controller was designed to turn on two hours before the beginning of the working day (5 AM) and turn off two hours after (8 PM). The ventilation system consisted of an air handling unit (AHU) made of a fan and two heat exchangers. The latter aimed to maintain a constant supply air temperature of 22 °C. The fan supplied a constant air mass flow rate of 0.03 kg/s per each beam during working hours. A heat recovery unit with efficiency of 0.9 pre-heated outdoor air. The air mass flow rate was reduced by half during non-working hours.

Table 2 shows a summary of the parameters used in the simulations. It is worth mentioning that these values were chosen according to the technical documentation of the *Solus* unit and based on the recommended design values described in the REHVA chilled beam application guidebook [12].

Tab. 2 Parameters of water and ventilation system

Parameter	**Value**
Water system	
Supply water temperature	20-23 °C
Water mass flow rate per beam	0.038 kg/s
Pressure drop	15 kPa
Ventilation system	
Supply air temperature	22 °C
Air mass flow rate per beam	0.03 kg/s
Pressure drop of active beam	100 Pa
Active beam	
Length	1.8 m
Units per office room	1

3. Results and discussion

In order to study the thermal behavior of the novel low-exergy system, dynamic simulations were run for three typical weeks. To evaluate energy savings potentials, a model of a conventional system was developed and used for comparison. The only difference between the two systems referred to the water circuit. The conventional system integrated two separated water circuits with supply water temperatures of 35 °C and 14 °C, respectively for heating and cooling. This means that two ideal plants were modelled, an ideal heater for the heating loop and an ideal cooler for the cooling loop. To present a fair energy comparison, the conventional system was forced to maintain the same indoor air temperatures calculated by the novel system in the office rooms during working hours. This was done by integrating water flow controllers with set-point temperature values equal to the indoor air temperature values obtained in the simulation of the novel system. Therefore, since air temperatures in the rooms and ventilation parameters were exactly the same for the two systems, the energy used by the AHU was neglected in the energy comparison.

Indoor air temperatures

Fig. 3 shows the air temperature profiles of the two office rooms and the supply water temperature during the typical winter week. The minimum and maximum air temperatures during working hours in the perimeter room were respectively 20.2 °C and 21.5 °C. The minimum and maximum air temperatures during working hours in the core room were respectively 22.3 °C and 23.2 °C. It can be noticed that the supply water temperature lies between the perimeter and core air temperature for almost all the working hours.

The air temperature values obtained during the spring week are illustrated in Fig. 4. In this case, minimum and maximum air temperatures during working hours in the perimeter room were respectively 20.9 °C and 21.8 °C. The minimum and maximum air temperatures during working hours in the core room were respectively 22.3 °C and 23.1 °C. During working hours, the supply water temperature is mostly always below both air temperatures. However, there are still periods where the supply water temperature lies between the two air temperatures.

Fig. 5 shows the air temperature profiles for the summer week. The peaks at the beginning and at the end of the weekdays represent the two-hour shift between the operation of the water system and the working hours. The minimum and maximum air temperatures during working hours in the perimeter room were respectively 22.5 °C and 23.1 °C. The minimum and maximum air temperatures during working hours in the core room were respectively 22.7 °C and 23.4 °C. In this case, the supply water temperature lies always below both air temperature profiles.

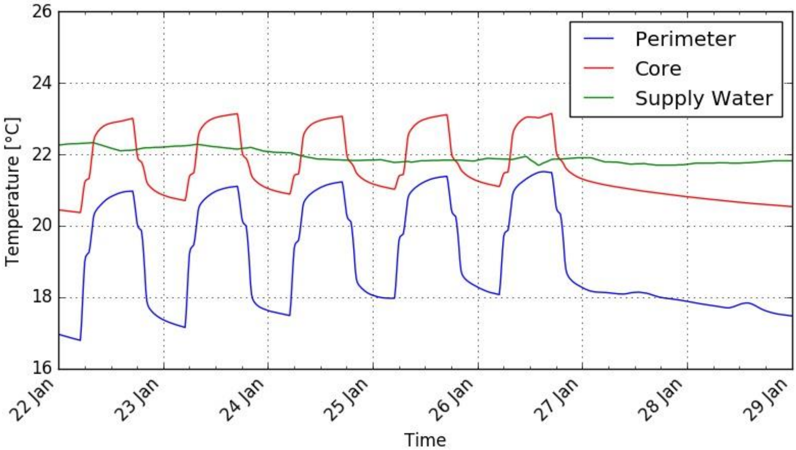

Fig. 3 Temperature profiles during the winter week

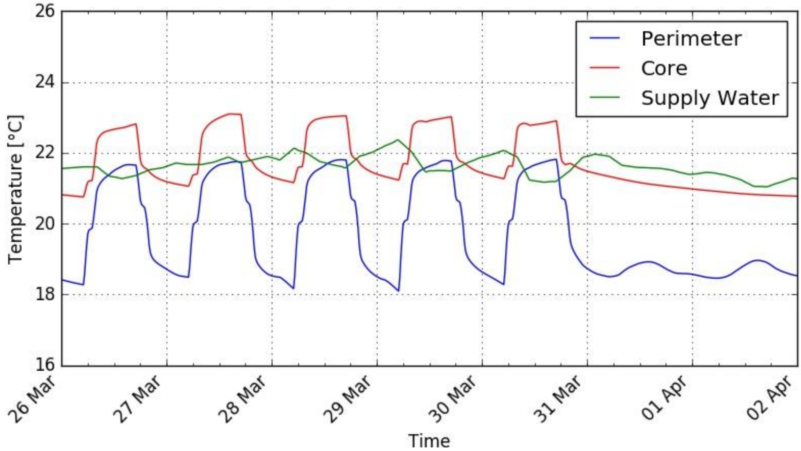

Fig. 4 Temperature profiles during the spring week

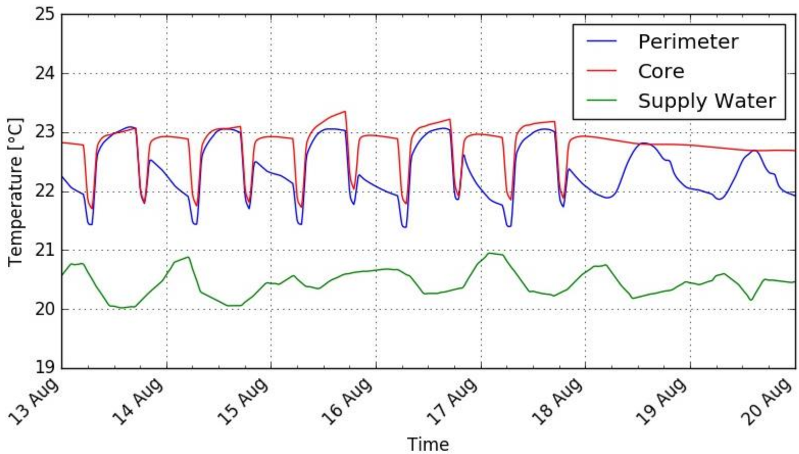

Fig. 5 Temperature profiles during the summer week

Energy use

Fig. 6 shows the energy use for space heating and cooling for the three typical weeks. This energy use represents the heat provided (heating mode) and subtracted (cooling mode) to the return water flows by the ideal heater-cooler plant.

It can be noticed that the novel low-exergy system uses less energy than the conventional system for the winter and spring case. In particular, the energy use of the novel and conventional system during the winter week was, respectively, 6.4 kWh and 9.92 kWh. Therefore, the novel system used approximately 35% less energy than the conventional system to maintain the same indoor air temperatures. Energy savings of about 7% occurred during the spring week. In this case, the novel and conventional system used respectively 8 and 8.64 kWh. Simulations for the typical summer week show exactly the same energy use for both novel and conventional system.

The energy savings computed for the winter and spring weeks are due to the ability of the system in transferring heat between the two zones when the supply water temperature lies between the two air temperature profiles. As shown in Fig. 1, the return water flows from the two rooms are mixed together. Therefore, the total water return temperature has a value equal to the average of the return water temperatures from the two rooms. This means that when simultaneous heating and cooling occurs, the return water has temperature values similar to the supply water, requiring for little or no energy from the heater-cooler plant.

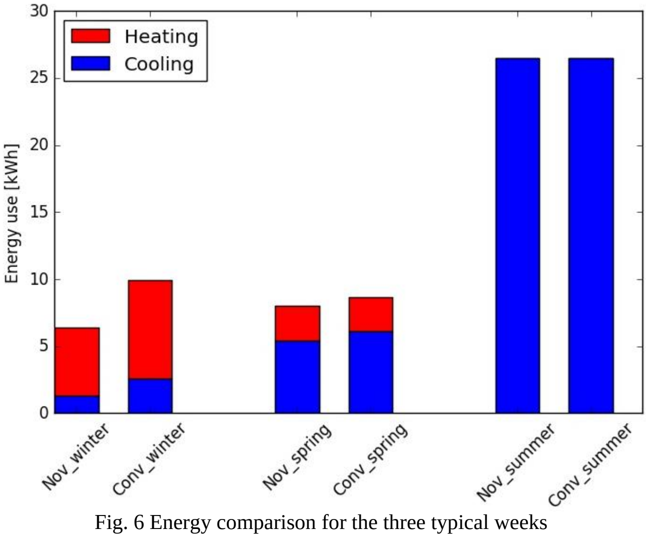

Fig. 6 Energy comparison for the three typical weeks

4. Conclusion

This paper investigated the thermal behavior of a novel low-exergy system for simultaneous heating and cooling of office buildings. A model of the system was developed with Dymola, a modeling and simulation environment based on the Modelica programming language The use of Modelica allowed to overcome the limitations occurred in previous studies where traditional BPS programs were used.

The novel system was tested through its integration into two single office rooms for three typical weeks. Comfortable levels of indoor air temperature were provided by the novel low-exergy system during all the three periods.

In order to evaluate energy savings potentials, a model of a conventional system was developed and used for comparison. The results from the simulations clearly predict that the novel system presented lower energy use for the winter and spring week in terms of space heating and cooling. This was due to the ability of the single water circuit in transferring heat between the two office rooms when simultaneous heating and cooling occurred.

Further studies will involve the modeling of the novel low-exergy system integrated into an entire office building model and simulated for a one-year period. A new controller for the supply water temperature will be developed in order to optimize the energy performance. In addition, a real implementation of the novel system is currently under development in an office building situated in Sweden. This will provide the possibilities for further investigations on energy performance, indoor thermal comfort and cost estimation.

References

[1] International Energy Agency, Transition to Sustainable Buildings - Strategies and opportunities to 2050. 2013.

[2] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (3) (2008) 394–398.

[3] A. Hasan, J. Kurnitski, K. Jokiranta, A combined low temperature water heating system consisting of radiators and floor heating, Energy Build. 41 (5) (2009) 470–479.

[4] K. Zhao, X.-H. Liu, Y. Jiang, Application of radiant floor cooling in a large open space building with high-intensity solar radiation, Energy Build. 66(2013) 246–257.

[5] M. Bejček, Alternative cooling systems for nearly zero-energy buildings, , in: The 4th Climate Change Technology Conference, 25–27 May, 2015, Montreal, Canada.

[6] A. Hepbasli, Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies, Renew. Sustain. Energy Rev. 16 (1) (2012) 73–104.

[7] A. Afshari, R. G. Norouzi, G. Hultmark, C. Niels, Two-Pipe Chilled Beam System for Both Cooling and Heating of Office Buildings, , in: 11th REHVA World Congress and 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, 16–19 June, 2013, Prague, Czech Republic.

[8] A. Maccarini, A. Afshari, N. C. Bergsøe, G. Hultmark, M. Jacobsson, A. Vorre, Innovative two-pipe active chilled beam system for simultaneous heating and cooling of office buildings, , in: 13th International Conference on Indoor Air Quality and Climate, 7–12 July, 2014, Hong Kong.

[9] M. Wetter, W. Zuo, T. S. Nouidui, X. Pang, Modelica Buildings library, J. Build. Perform. Simul. 7 (4) (2014) 253–270.

[10] B. Thornton, M. Rosenber, E. Richman, W. Wang, Y. Xie, J. Zhang, H. Cho, V. Mendon, R. Athalye, B. Liu, Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010, , (2011).

[11] A. Maccarini, G. Hultmark, A. Vorre, A. Afshari, N. C. Bergsøe, Modeling of active beam units with Modelica, Build. Simul. 8 (5) (2015) 543–550.

[12] M. Virta, D. Butler, J. Gräslund, J. Hogeling, E. Kristiansen L., M. Reinikainen, G. Svensson, Chilled Beam Application Guidebook. REHVA, 2004.