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INNOVATIVE TWO-PIPE ACTIVE CHILLED BEAM SYSTEM FOR SIMULTANEOUS HEATING AND COOLING OF OFFICE BUILDINGS

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SUMMARY

The aim of this paper was to investigate the energy savings potential of an innovative two-pipe system in an active chilled beam application for heating and cooling of office buildings. The characteristic of the system is its ability to provide simultaneous heating and cooling by transferring energy between zones with one hydronic circuit, operating with a water temperature between 20°C and 23°C. To calculate the energy performance of the system, simulation-based research was developed. The two-pipe system was modelled by using EnergyPlus, a whole building energy simulation program. Hourly heating, cooling and ventilation loads were calculated by the program and an annual energy consumption evaluation of the system was made. Simulation results showed that the innovative two-pipe active chilled beam system used approximately 5% less energy than a conventional four-pipe system.

INTRODUCTION

Buildings constitute the largest energy consuming sector in the world, and account for almost 40% of the total final energy consumption (including HVAC systems, domestic hot water, lighting and appliances) (IEA, 2013). Thus, the potential savings of energy in the building sector would contribute greatly to a society-wide reduction of energy consumption.

Due to the requirements for thermal comfort in buildings, HVAC systems have become an unavoidable asset, accounting for almost half the energy consumed in buildings (Pérez-Lombard et al., 2008). It is clear that the challenge facing engineers and researchers is to design innovative HVAC systems able to achieve high levels of indoor environmental quality while reducing energy consumption. In addition to the global benefits, this task also plays a crucial role for the achievement of nearly zero-energy buildings in the European Community by 2020 (European Union, 2010).

Active chilled beams have been used for more than 20 years, but there are limited data available related to the energy savings potential of these systems. Generally, active chilled beams can save energy in different ways. First of all, they decouple the ventilation load from the space sensible load, handling space cooling and outside air requirements without increasing the airflow rate. Secondly, the use of higher chilled water temperature (13-17°C) than conventional HVAC systems (4-7°C) leads to higher efficiency of the cooling machine

(Kurt et al., 2007). Comparisons of the energy performance of active chilled beams with conventional HVAC systems show that the impact varies considerably depending on the specific project and the climate zone, but energy savings of 8-20% can be achieved (Kurt et al., 2007) (Murphy and Harshaw, 2009).

Conventional active chilled-beam systems have two different configurations: two-pipes or four-pipes. With the two-pipe design, all zones receive either cold water or hot water. The four-pipe design allows some zones to receive cold water for space cooling, while other zones simultaneously receive hot water for space heating (Figure 1). However, when heating and cooling are needed in buildings at the same time, the overlap causes a 5-20% waste of energy, because the two systems are operating simultaneously (Doty et al., 2009).

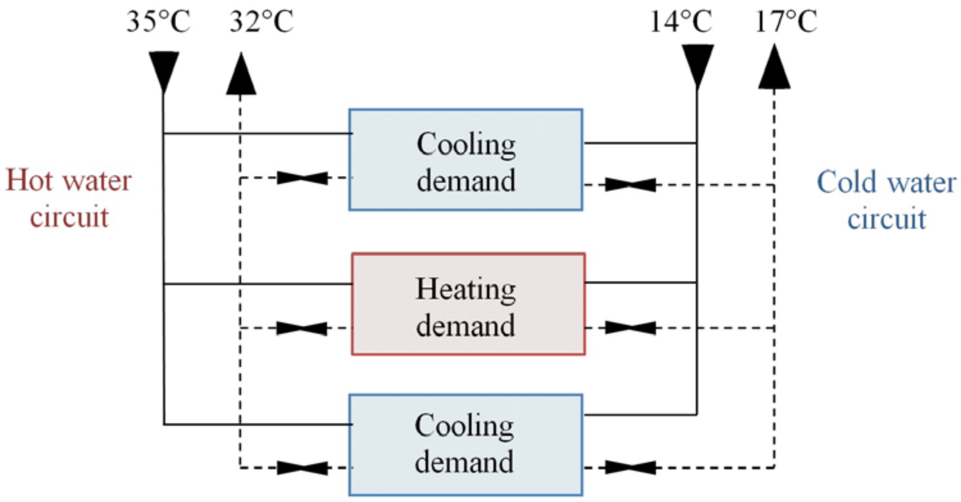

Figure 1. Schematic layout of a four-pipe chilled-beam system for simultaneous heating and cooling. Two zones are served with cooling and one with heating.

The possibility of designing a two-pipe system able to provide simultaneous heating and cooling was explored through previous research conducted at the Danish Building Research Institute in collaboration with Lindab A/S (Afshari et al., 2013). Results showed that this two-pipe configuration uses 3% less energy than a conventional four-pipe one. The system was modelled using BSim, a tool for simulating building energy performance and developed by the Danish Building Research Institute. Simulations with BSim presented some limitations as the tool does not include the capabilities of comprehensive modelling of heating and cooling systems. Further studies were needed in order to develop a more detailed model of the system. Therefore, the main goal of this paper was to simulate and evaluate a model of the two-pipe active chilled beam system with EnergyPlus, a whole building energy simulation program. The use of EnergyPlus allowed a wider understanding of the system and made it possible to simulate a more accurate model.

METHODOLOGIES

Heating and cooling concept

The main characteristic of the system was to use high-temperature cooling and low-temperature heating in one hydronic circuit. Running high-temperature cooling and low-temperature heating in the same circuit actually meant that both heating and cooling had the same inlet water temperature (Figure 2). Output hot and cold water was mixed together and as a result the system only needed to cool or heat the water to reach the inlet temperature once again. By only having to cool or heat the water, no energy was wasted as this was done at the same time.

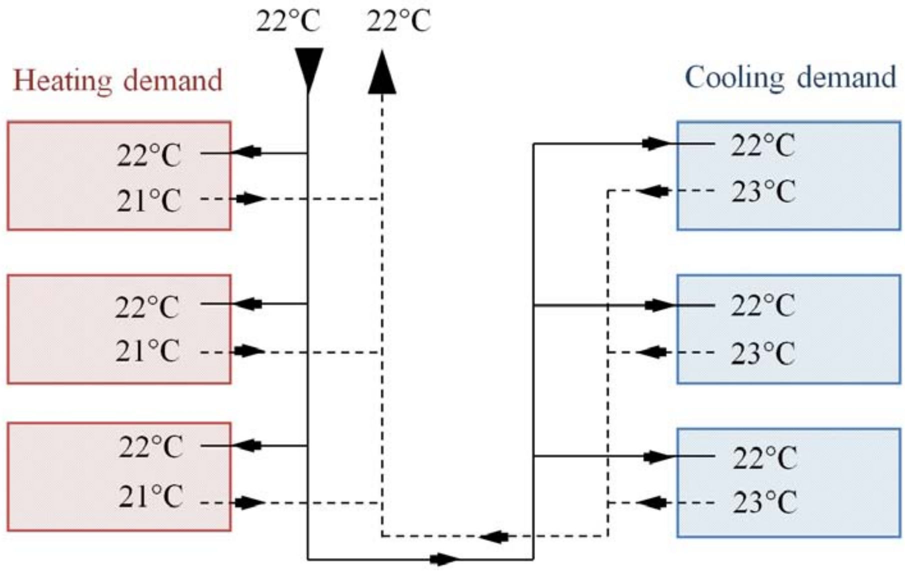

Figure 2. Schematic layout of the active chilled beam system when equal heating and cooling demand occurs.

Depending on the outdoor air temperature, the inlet water temperature varied between 20°C and 23°C. In particular, the inlet water temperature followed the behaviour shown in Figure 3.

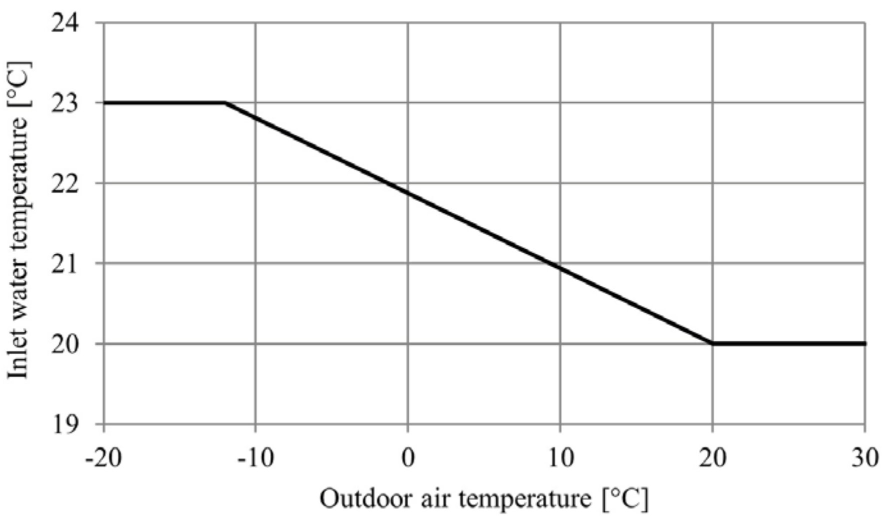

Figure 3. Inlet water temperature in the circuit as a function of outdoor air temperature.

Simulation

The two-pipe active chilled beam system was modelled using EnergyPlus. The energy performance of the system was studied through its integration into an office building (Figure 4). The geometry of the building was created with OpenStudio, a Google SketchUp plug-in that allows the generation of a 3D model of the building and then exporting it as an EnergyPlus file. The building consisted of five floors with a total floor area of 1471.5 m^2. The building was located in Copenhagen (Denmark) and the corresponding weather file was used for the simulation.

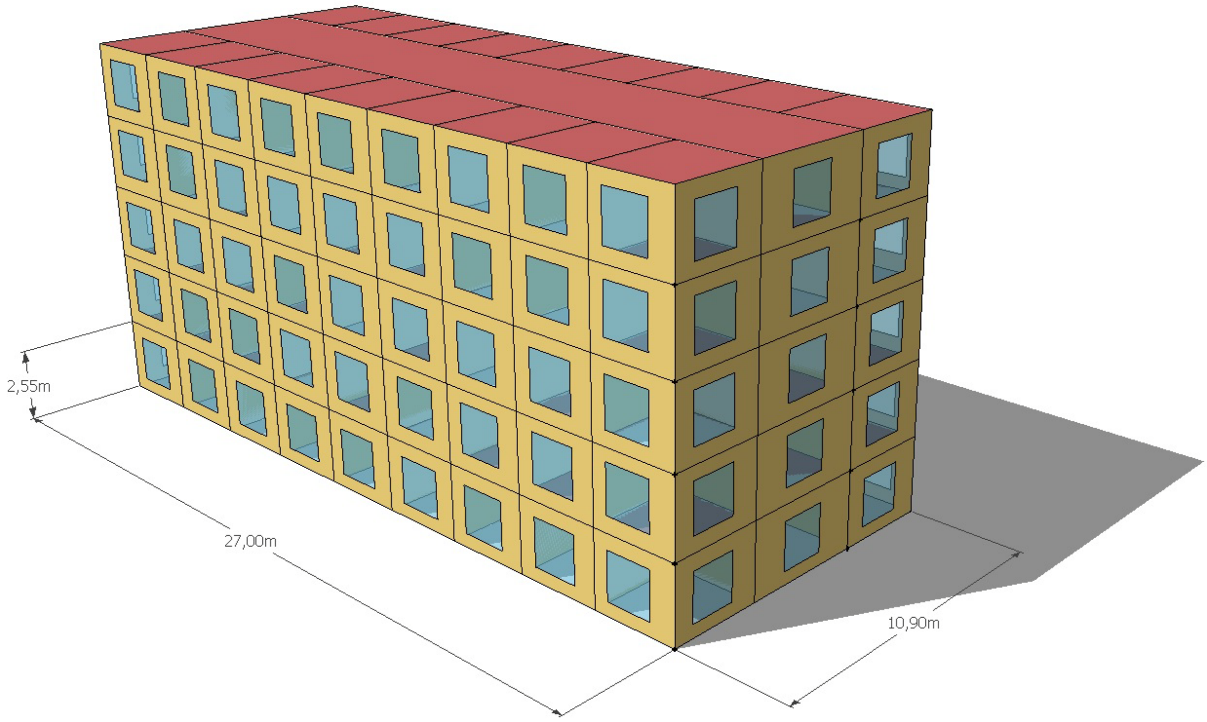

Figure 4. Geometry of the building energy model (OpenStudio plug-in for Google SketchUp).

U-value and thickness of the construction elements were selected according to the Danish Building Regulations and are shown in Table 1. Windows included shading elements controlled by a sensor measuring solar radiation on the window. If the solar radiation exceeded 125 W/m^2, the shading system was activated.

Table 1. Properties of the building envelope elements

	U-value [W/m^2]	Thickness [m]
Roof	0.161	0.37
Ground floor	0.169	0.347
External walls	0.251	0.345
Windows	1.273	-

Seven thermal zones were created. Three zones were located on the south facade (meeting room, occupied offices and unoccupied offices), three zones on the north facade (meeting room, occupied offices and unoccupied offices) and one zone for corridors. Working hours were set at 8:00-17:00, Monday to Friday, for corridors and offices while they were assumed to be 10:00-11:00 and 14:00-15:00 for meeting rooms. Internal heat gains due to lighting were assumed to be 7 W/m^2 during working hours in all seven thermal zones. Lighting was controlled by a sensor measuring the illuminance [lux]. When illuminance exceeded 400 lux, lighting was turned off. Internal heat gains due to equipment (e.g. computers, printers and coffee machines) were assumed to be 150 W in occupied offices, 600 W in meeting rooms and 1000 W in corridors during working hours. Unoccupied offices had no internal heat gains. The number of occupants was set to one, zero, six and one during working hours respectively for occupied offices, unoccupied offices, meeting rooms and corridors. Heat loads from occupancy were assumed to be 100 W per person.

The HVAC system included a ventilation system, a heating system and a cooling system. The ventilation system was comprised of a constant volume fan, a heat exchanger, a heating coil and a cooling coil. The constant volume fan provided an average airflow rate per square meter floor area of 2.3 l/s m^2, corresponding to an average air change rate of 3.25 h^{-1}. Heating and cooling coils were sized to meet the supply air temperature set point according to Table 2.

Table 2. Air supply temperature throughout the year.

	Winter			Spring and autumn			Summer		
Time	0-7	7-17	17-24	0-7	7-17	17-24	0-7	7-17	17-24
Air supply temperature [°C]	18	22	18	14[1]	21	18	14[1]	20	-

[1]If outdoor air temperature is below 14°C, the air supply temperature is set to 14 °C. If the outdoor air temperature is above 14°C, the air supply temperature is equal to the outdoor air temperature (the coils of the ventilation system are off).

The heating system consisted of a boiler and a heating coil while the cooling system consisted of a chiller and a cooling coil. Coils were designed to provide sensible heating and cooling to spaces. Set point temperatures were controlled by thermostats according to Table 3.

Table 3. Set point temperatures for heating and cooling throughout the year.

	Winter			Spring and autumn			Summer		
Time	0-7	7-17	17-24	0-7	7-17	17-24	0-7	7-17	17-24
Heating [°C]	18	22	18	18	21	18	18	20	-
Cooling[°C]	22	23	-	21	22	-	20	21	-

In order to model a two-pipe operation, the same inlet water temperature was set for both the heating and the cooling system. An Energy Management System program (EMS) was written with a simple programming language called EnergyPlus Runtime Language (Erl). EMS is an advanced feature of EnergyPlus and it provides a way to develop custom control and modelling routines for EnergyPlus models. The EMS program had the aim to schedule the inlet water temperature depending on the outdoor air temperature (Figure 3) by applying equation 1:

$$T_{water\_inlet} = \begin{cases} 23 & if\ T_{outdoor\_air} < -12°C \\ 21.875 - 0.09375 * T_{outdoor\_air} & if\ -12°C < T_{outdoor\_air} < 20°C \\ 20 & if\ T_{outdoor\_air} > 20°C \end{cases} \quad (1)$$

To calculate hourly heating, cooling and ventilation loads, an annual energy simulation was run.

Calculation method for energy transfer between spaces

As mentioned, the two-pipe system was designed with the ability to transfer energy between thermal zones when heating and cooling were needed simultaneously in the building. The energy behaviour of the building was divided into three categories: only heating (OH), only cooling (OC) and simultaneous heating and cooling (SHC). OH and OC represented hourly periods during the year when all the seven thermal zones needed only heating or only cooling energy, respectively. SHC represented hourly periods during the year when at least one thermal zone needed cooling while simultaneously the other thermal zones needed heating, or vice versa. In particular, the total annual energy consumption of the two-pipe system was calculated by equation 2:

$$E_{two-pipe} = \sum_{i=1}^{8760} E_{OH} + \sum_{i=1}^{8760} E_{SHC} + \sum_{i=1}^{8760} E_{OC} \quad (2)$$

where E_{OH} is the heating energy demand during OH periods, E_{OC} is the cooling energy demand during OC periods and E_{SHC} was expressed by equation 3:

$$\sum_{i=1}^{8760} E_{SHC} = \sum_{i=1}^{8760} |E_{SH} - E_{SC}| \quad (3)$$

where E_{SH} is the heating energy demand during SHC periods and E_{SC} is the cooling energy demand during SHC periods.

RESULTS AND DISCUSSION

In order to evaluate the energy savings potential, a traditional four-pipe configuration was simulated and compared with the two-pipe system. The annual energy demand of the systems for heating, cooling and ventilation is shown in Figure 5. The annual energy demand for the two-pipe system was 54.2 kWh/m^2 while it was 57.1 kWh/m^2 for the four-pipe system. Energy demand for ventilation, heating and cooling during OH and OC periods were, as expected, the same. Conversely, during periods of simultaneous heating and cooling (SHC), the energy demand of the systems differed. The four-pipe system provided heating and cooling with two independent circuits, requiring 9 kWh/m^2 of energy (4.1 kWh/m^2 for heating and 4.9 kWh/m^2 for cooling). The two-pipe system consisted of only one water circuit and needed 6.1 kWh/m^2 for simultaneous heating and cooling. Consequently, when comparing the innovative two-pipe system with a traditional four-pipe system, annual energy savings of 5.1 % could be achieved.

Figure 6 shows the number of hours when a simultaneous need of heating and cooling occurred in the building each month. Spring and autumn represented the period with the best opportunities for redistributing thermal energy in the building. The typical external thermal loads of these months resulted in a need for cooling in part of the building and a need for heating in another part for a considerable number of hours. Simultaneous heating and cooling occurred quite frequently also during the winter season. High internal gains, which are typically observed in office buildings, created hot spots where cooling was needed, despite the low outdoor temperatures. As a result, energy savings could be achieved also during winter. Conversely, summer did not leave much possibility for recycling the thermal energy, as cooling was necessary most of the time while heating only for a short time. Depending on geographical location, energy savings may still be obtained as free cooling may be available. Due to the high inlet temperatures in the water circuit, free cooling can be gained at a relatively high outdoor temperature.

The two-pipe system was assumed to operate with an inlet water temperature ranging between 20°C and 23°C, depending on the outdoor air temperature as expressed by Equation 1. It is worth mentioning that other types of control could have been applied to set the inlet water temperature, possibly leading to different results. Furthermore, a temperature ranging between 20°C and 23°C in the water circuit leads to a small temperature difference between the inlet water temperature and the room temperature. This necessitates the use of active chilled beam components with extremely high efficiency. However, the use of low-temperature heating and high-temperature cooling systems allows taking advantages of sustainable energy sources.

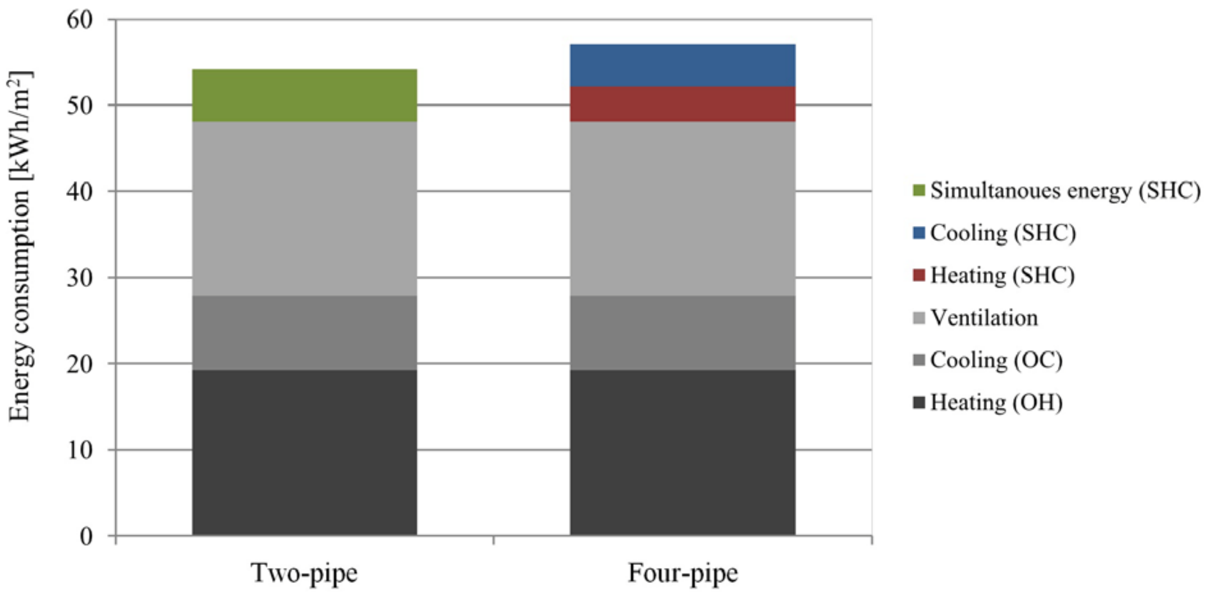

Figure 5. Comparison between annual energy consumption of two-pipe and four-pipe active chilled beam system.

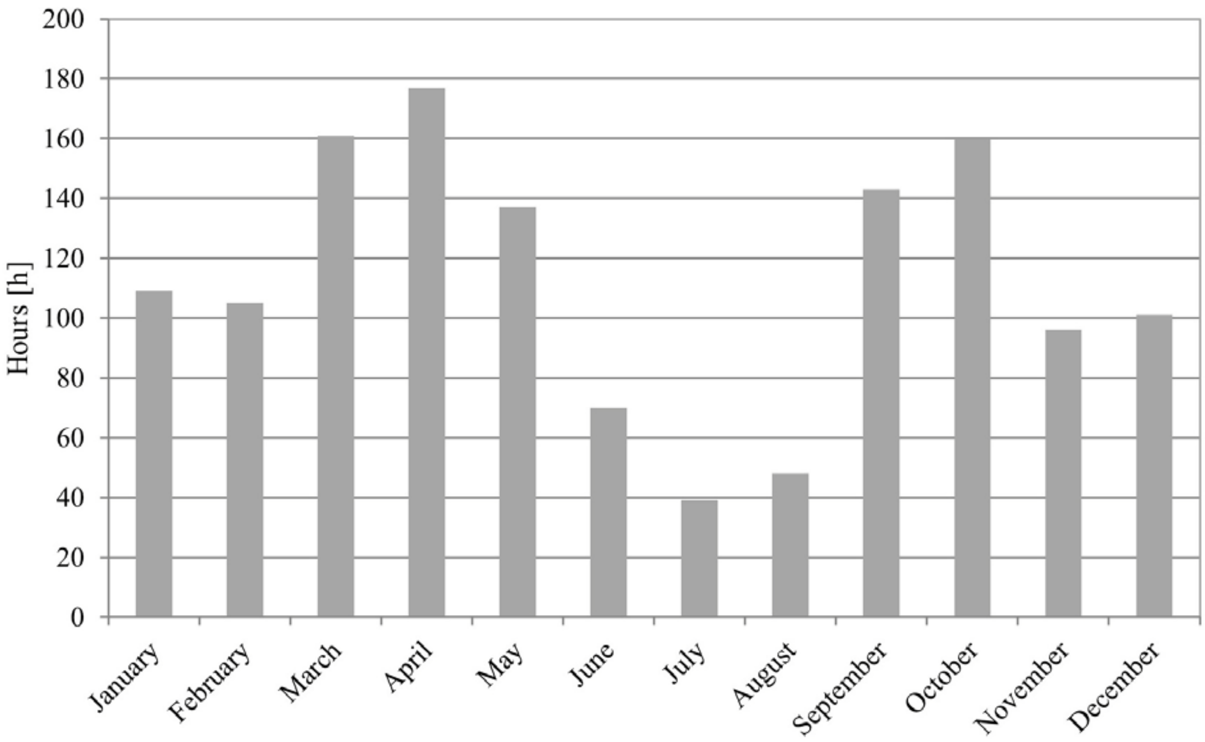

Figure 6. Hours of simultaneous need of heating and cooling in the building.

Further energy savings are related to the water circulation pump. A traditional four-pipe configuration has two pumps, one for the hot water circuit and another one for the cold water circuit. Since the two-pipe configuration constitutes one water circuit, the system needs only one pump. This means that energy is required to drive only one water flow. In addition, the two-pipe system operates with a constant water flow, and therefore no valves and actuators are needed. As a consequence, the system operates with a lower pressure drop and less energy is required to drive the water in the circuit.

CONCLUSION

This paper investigated the energy performance of a two-pipe active chilled beam system for simultaneous heating and cooling of office buildings. An energy model of the system was developed with EnergyPlus and an annual simulation was run in order to calculate hourly ventilation, heating and cooling loads. When comparing the innovative two-pipe system with a traditional four-pipe yearly energy savings of approximately 5% could be achieved. Furthermore, the use of EnergyPlus made it possible to develop a more accurate model of the two-pipe system. Of particular importance was the ability of EnergyPlus to enable the writing of a program in order to set the inlet water supply temperature as a function of the outdoor air temperature.

In conclusion, a real-life implementation of the system seems to be a promising way in order to precisely evaluate all the thermal features of the innovative two-pipe active chilled-beam system. Efforts should also be made to model the system with more advanced simulation tools (e.g. Modelica and Trnsys) that allows the design of every single component of the system.

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