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FINAL REPORT – PSO Project n. 348-045

Demonstration af et innovativt 2-rørsbaffelsystem til kontorbygninger

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1. Background

With the consolidation of the demand for thermal comfort, HVAC systems have become an unavoidable asset in buildings. The operation of these systems is, however, responsible for the largest energy end use both in the residential and commercial buildings, accounting for almost half the energy consumed in buildings. Therefore, it is clear that the challenge facing engineers and researchers is to design innovative HVAC systems able to achieve high levels of thermal comfort while reducing energy use.

Low-exergy building energy systems are defined as systems that provide heating and cooling at temperatures close to room temperature. This allows the employment of low valued energy, which can be delivered by sustainable energy sources such as waste heat, river/lake water, solar energy, geothermal applications and heat pumps with a high coefficient of performance (COP). Therefore, the use of low-exergy systems can reduce the environmental impact of buildings.

In the context of low-exergy systems, active beam systems have gained increased recognition over the last decades as a sustainable technology able to provide good thermal comfort and advantages in terms of energy savings. These systems incorporate active beams as terminal units. Active beams are devices able to provide outdoor air, sensible heating and sensible cooling to a space. Figure 1 shows the schematic diagram of a typical active beam. Water is circulated in a heat exchanger placed inside the active beam. The primary air enters the room via a pressure plenum. The high air velocity generated by nozzles reduces the static pressure and induces room air that passes the heat exchanger before it mixes with the primary air. The mixed air is discharged into the room through slots along both sides of the beam.

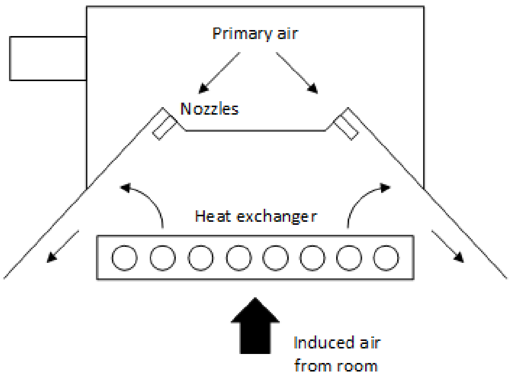


Figure 1. Section view of a typical active beam unit

Conventional active beam systems consist of two main parts: a dedicated outdoor air system (DOAS) to satisfy latent loads and ventilation requirements, and a water circuit to meet sensible heating and cooling loads. The water circuit is typically available in a four-pipe configuration, which allows simultaneous delivery of heating and cooling using two separated loops (Fig. 2 – left).

Recent studies conducted at SBi have investigated the possibility to design a novel active beam system able to provide simultaneous heating and cooling using only a single water loop (Fig. 2 -right). The main characteristic of this novel system is related to the supply water temperature, which is around 22°C all year round. Therefore, a room with an indoor air temperature of 20°C would be heated, while a room at 24°C would be cooled. Return water flows from single zones are mixed and the common return water flow is delivered to the central plant, which will operate in either heating or cooling mode, depending on the average resulting thermal loads in the building.

Beside the advantages in terms of exploitation of sustainable energy sources (due to water temperatures near ambient temperature), this piping configuration opens opportunities for transferring heat among building zones when simultaneous heating and cooling occurs in a building. By mixing the return pipes from individual zones, excess heat can be transferred from warm to cold zones through the water circuit.

In a previous PSO-project (345-010) requirements and conditions for the two-pipe active beam system were investigated by means of modeling and simulation techniques.

The aim of the present PSO-project (348-045) was to analyze the full-scale operation of such system, which was installed for the first time in a real building in Jönköping, Sweden. Aspects such as indoor climate and energy performance of the system were investigated.

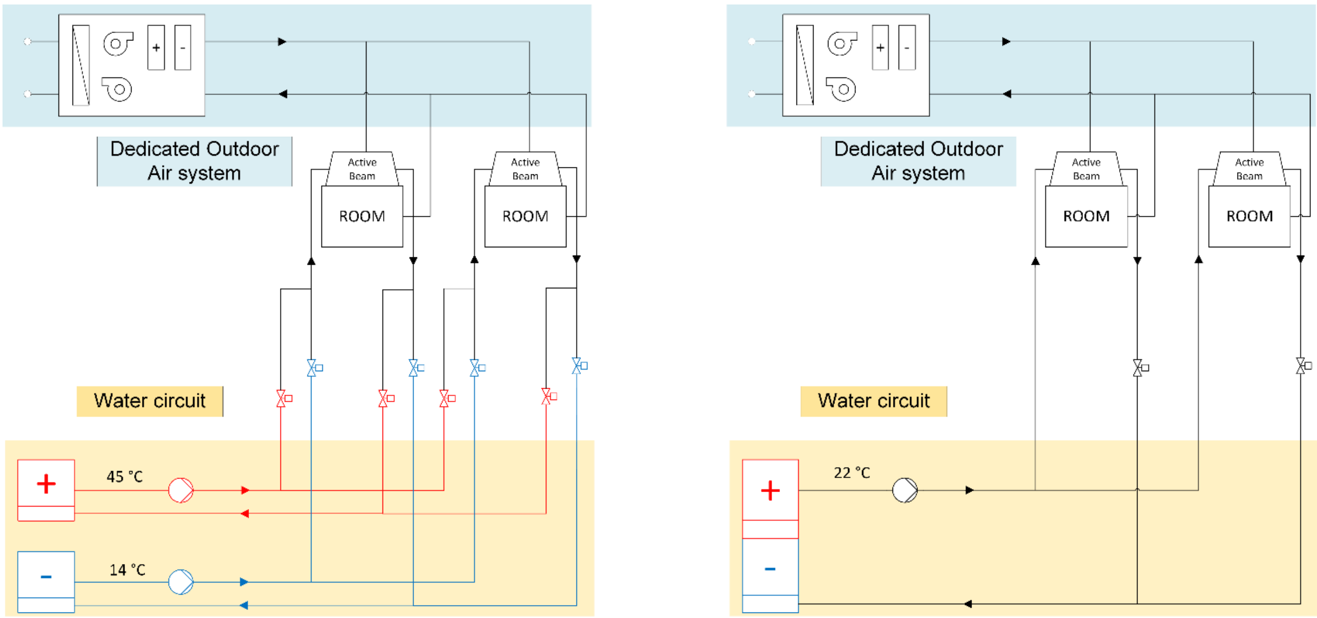


Figure 2. Conventional four-pipe active beam system

2. Methods

The “Runda Huset” is a sixteen-storey office building constructed in 2015 and located in Jönköping, Sweden (Fig.3). This is the first building equipped with the novel two-pipe active beam system proposed. Fourteen floors of the building are dedicated to offices, the ground floor hosts a restaurant and the top floor accommodates conference rooms.

Figure 3. Runda Huset building in Jönköping

2.1 Indoor climate

The indoor climate provided by the two-pipe system was assessed by means of measurements of relevant parameters such as air temperature and air velocity. The work was divided into **two measurement sessions**. In the first session, measurements were carried out in an unoccupied space on the 10th floor. In the second session, measurements were carried out in an occupied space on the 13th floor. Measurements in the unoccupied space allowed to monitor in more detail parameters such as the vertical air temperature difference, while measurements in the occupied space allowed to capture the occupants’ perception concerning thermal comfort conditions. Both tasks were performed for a typical winter day and a typical summer day.

Measurements in unoccupied space

This measurement session was carried out in a test room on the 10th floor of the building. The floor was still unoccupied at the time the experiment was performed and this made it easier to gain access at any time. Key indoor climate parameters were measured using two vertical poles. Along the length of these poles, air temperature and air velocity probes were disposed at four different heights (0.1m, 0.6m, 1.1m and 1.7m) as shown in Fig. 4. Measurements were carried out for a continuous period of 24 hours using 5 min time-averaged values. Local discomfort due to draught and vertical temperature difference was assessed.

The test room was intended to be a double office room. Therefore, a desk with two real computers was placed in the room to simulate the heat loads from office equipment. Heat loads from people were simulated by using dummies. Total heat loads were 50 W/m^2 and they were turned on between 8:00-12:00 and 13:00-17:00.

Air temperature was measured using Indoor Climate Meter (operative range -40 °C to 125 °C, accuracy ± 0.3 °C), and air speed was measured using Dantec 54R103 probes (operative range 0.05 m/s to 5 m/s, accuracy ±

0.02 m/s ±2% of reading). The technical properties of the measurement equipment are compliant with ISO standard 7726 (ISO 7726:1998). Two active beam units were mounted in the room. Each unit has a design capacity of 400 W and 700 W respectively in heating and cooling mode.

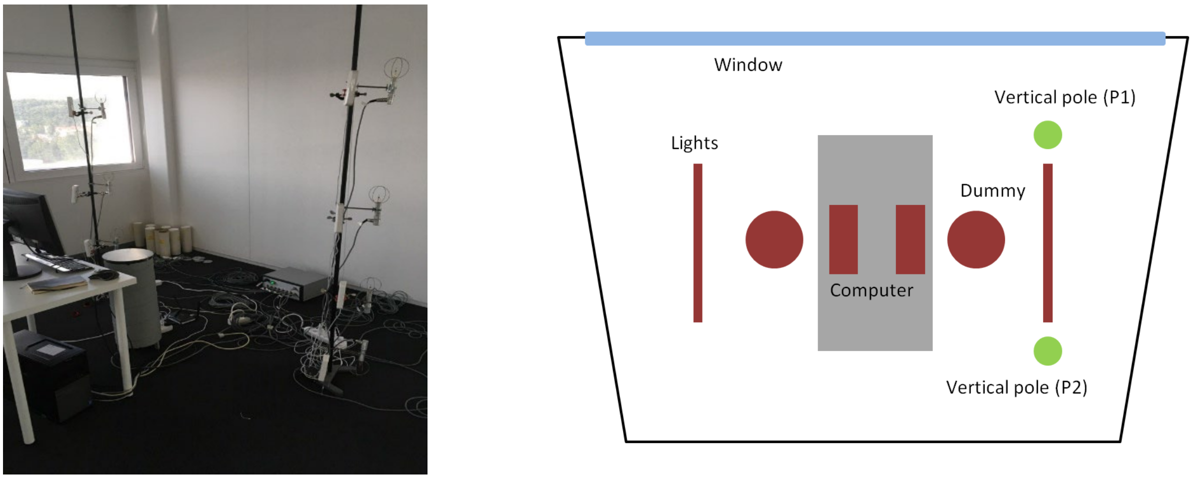


Figure 4. Test room with instruments

Measurements and questionnaire in __occupied space__

This measurement session was carried out on the 13th floor, which was chosen according to access permissions given by the building owner. The floor accommodates a large open office space (approximately 200 m^2), few single office rooms, and a meeting room. Four poles including Indoor Climate Meter sensors and Dantec 54R103 probes were placed in four different locations of the open office space, as illustrated in Fig. 5. The sensors were placed at 1.1 m height. Measurements were collected for a continuous period of 24 hours using 5 min time-averaged values for a typical winter day and a typical summer day.

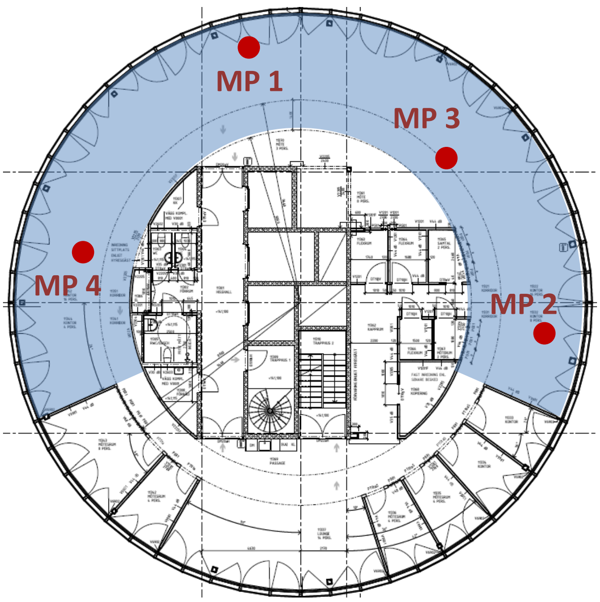
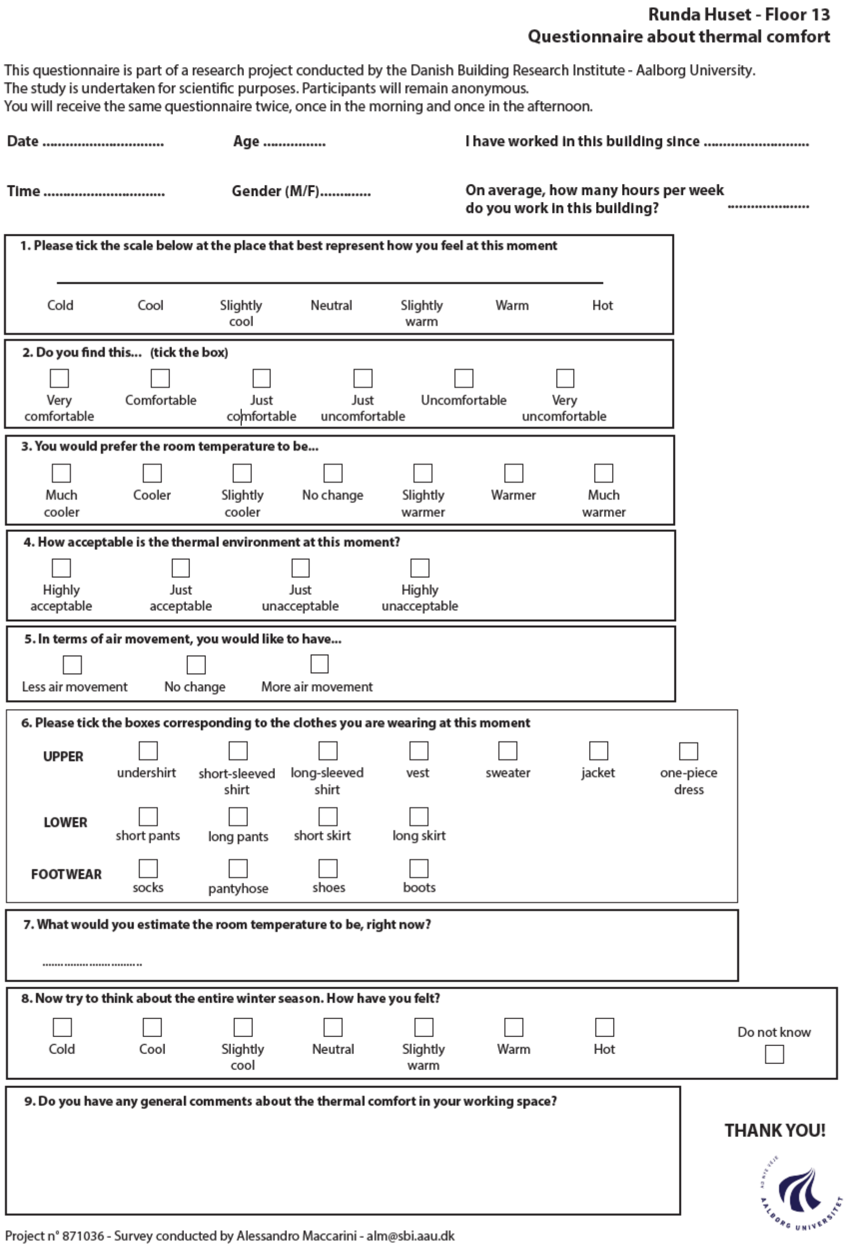


Figure 5. Open office space with position of sensors

Besides the measurements of physical parameters, a questionnaire was delivered to the occupants in order to assess their perceptions of thermal comfort (Fig. 6). The questionnaire was subdivided into two different parts: a section with the personal data (age, gender and average number of working hours per week) and one about the thermal aspects. The questionnaire was prepared in accordance with the guidelines provided in the DS/EN ISO 10551 standard.

In particular, the thermal sensation was assessed using a continuous 7-degree scale, comprising a central indifference point and three points of increasing intensity going towards "cold" and "hot". Other questions aimed at evaluating the thermal preference, acceptability and judgment about air movement. A short section regarding clothing was also included. A total of 42 and 37 persons responded to the questionnaire for the winter and summer day, respectively.



Runda Huset - Floor 13
Questionnaire about thermal comfort

This questionnaire is part of a research project conducted by the Danish Building Research Institute - Aalborg University.
The study is undertaken for scientific purposes. Participants will remain anonymous.
You will receive the same questionnaire twice, once in the morning and once in the afternoon.

Date .... **Age** .... **I have worked in this building since** ....

Time .... **Gender (M/F)**............ **On average, how many hours per week do you work in this building?** ....

1. Please tick the scale below at the place that best represent how you feel at this moment

Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot

2. Do you find this... (tick the box)

☐ Very comfortable ☐ Comfortable ☐ Just comfortable ☐ Just uncomfortable ☐ Uncomfortable ☐ Very uncomfortable

3. You would prefer the room temperature to be...

☐ Much cooler ☐ Cooler ☐ Slightly cooler ☐ No change ☐ Slightly warmer ☐ Warmer ☐ Much warmer

4. How acceptable is the thermal environment at this moment?

☐ Highly acceptable ☐ Just acceptable ☐ Just unacceptable ☐ Highly unacceptable

5. In terms of air movement, you would like to have...

☐ Less air movement ☐ No change ☐ More air movement

6. Please tick the boxes corresponding to the clothes you are wearing at this moment

UPPER ☐ undershirt ☐ short-sleeved shirt ☐ long-sleeved shirt ☐ vest ☐ sweater ☐ jacket ☐ one-piece dress

LOWER ☐ short pants ☐ long pants ☐ short skirt ☐ long skirt

FOOTWEAR ☐ socks ☐ pantyhose ☐ shoes ☐ boots

7. What would you estimate the room temperature to be, right now?

....

8. Now try to think about the entire winter season. How have you felt?

☐ Cold ☐ Cool ☐ Slightly cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot — Do not know ☐

9. Do you have any general comments about the thermal comfort in your working space?

THANK YOU!

Project n° 871036 - Survey conducted by Alessandro Maccarini - alm@sbi.aau.dk

Figure 6. Questionnaire delivered to occupants

2.2 Energy performance

The energy performance of the system was monitored through a number of sensors placed along system. Relevant physical parameters were measured and data were available through an online platform. Since the novelty of the system is represented by the water circuit configuration, the monitoring campaign focused on the acquisition of measurement data regarding supply and return water temperature using temperature sensors placed along the circuit. The monitoring campaign lasted for one year (October 2017 to September 2018) and data were available hourly. Figure 7 shows the water circuit schematic, including the two sensors for supply (S1) and return (S2) water temperature (accuracy ±0.2°C).

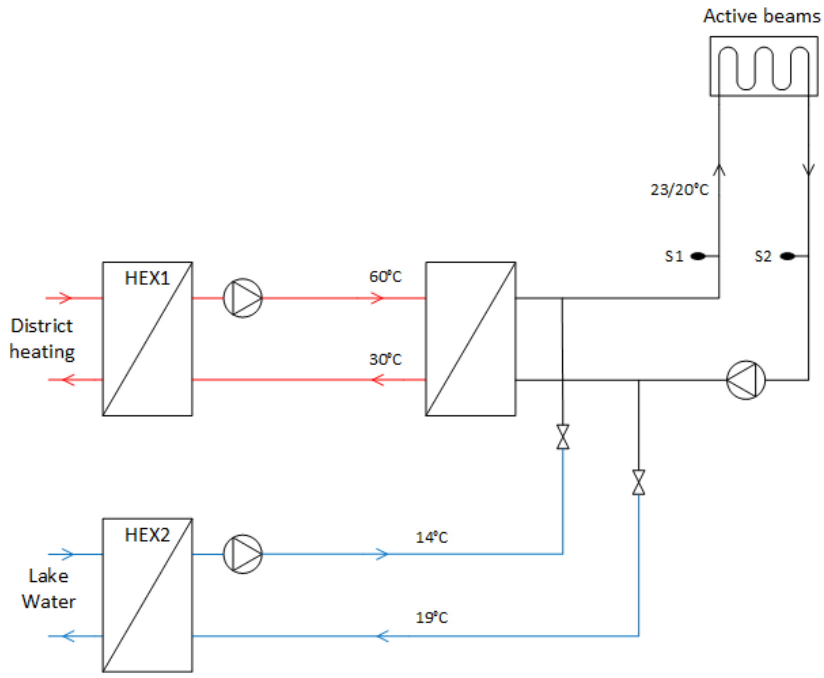


Figure 7. Scheme of the water circuit including sensors

Heating is provided by the local district heating system, while cooling by a nearby lake. The heat exchanger HEX1 connects the district heating network to an intermediate hot water circuit with temperatures of 60-30°C. HEX2 connects the lake water network to an intermediate chilled water circuit with temperature of 14-19°C. The desired supply water temperature in the active beam system is obtained by mixing the hot and chilled water flows according to the curve represented in Fig. 8. In particular, at extreme low outdoor air temperatures, a maximum supply water temperature of 23°C was set. At extreme high outdoor air temperatures, a minimum supply water temperature of 20°C was set. A linear correlation was used between the two extreme points, as illustrated in Fig. 8.

Once supply and return water temperatures are known (through sensors S1 and S2), the heating and cooling energy use of the system was calculated according to the formula:

$$\dot{Q} = \dot{m}c_p\left(T_{sup} - T_{ret}\right)$$

Where $\dot{m}$ is the constant water mass flow rate (equal to approximately 22 kg/s), c_p is the water heat capacity, T_{sup} is the actual supply water temperature (S1) and T_{ret} is the actual return water temperature (S2).

Additional measurements were performed in the Air Handling Unit (AHU) regarding the electricity use of fans. In particular, the electricity use of supply and return fans was measured for a typical week. Since the weekly operation of fans is constant throughout the year, a one-week monitoring session was enough for the assessment of the annual electricity use.

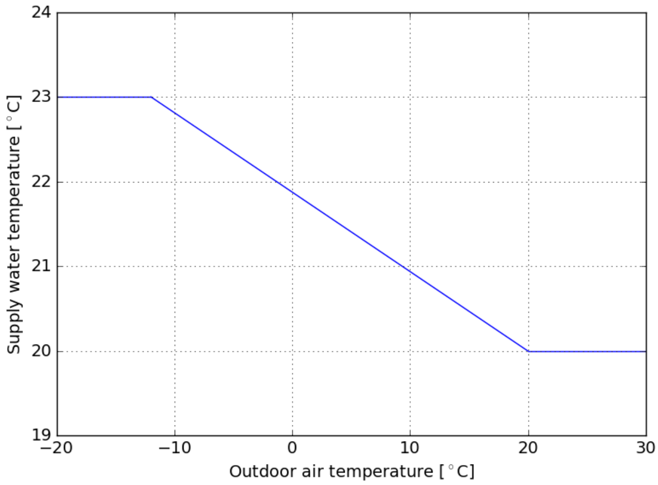


Figure 8. Regulation of supply water temperature

3. Results

3.1 Measurements in unoccupied space

Figure 9 shows the air temperature values recorded during the winter day for both vertical poles. The minimum air temperature was 20.9 °C and was obtained for P1 in the early morning at 0.1 m height. The maximum air temperature was 22.8 °C and was obtained for P1 in the late afternoon at 1.1 m height.

Figure 10 shows the air temperature values recorded during the summer day for both vertical poles. The minimum air temperature was 21 °C and was obtained for P1 in the early morning at 1.7 m height. The maximum air temperature was 23 °C and was obtained for P1 in the late afternoon at 0.6 m height.

Generally, the room air temperature is always confined between 21 °C and 23 °C. Therefore, it can be concluded that the real operation of the system matches the sizing procedure carried out during the design phase of the system. Note that the low air temperatures observed in summer during non-working hours are due to the continuous operation of the system. At night, water at about 20 °C circulates in the system, providing cooling energy to the building. As a consequence, as shown in Figure 10 for P2, early mornings might be slightly too cold, with room air temperatures below 22 °C.

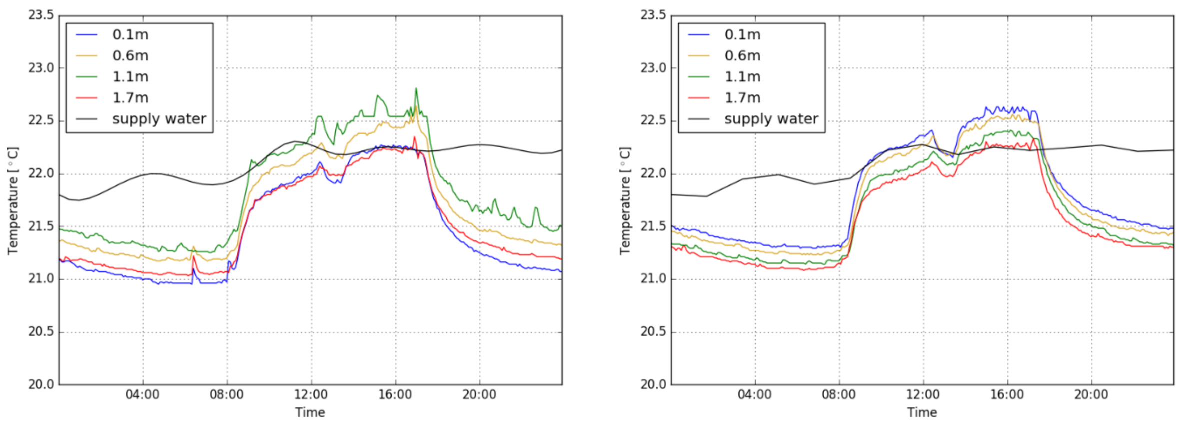


Figure 9. Air temperature profiles for the winter day: P1 (left) and P2 (right)

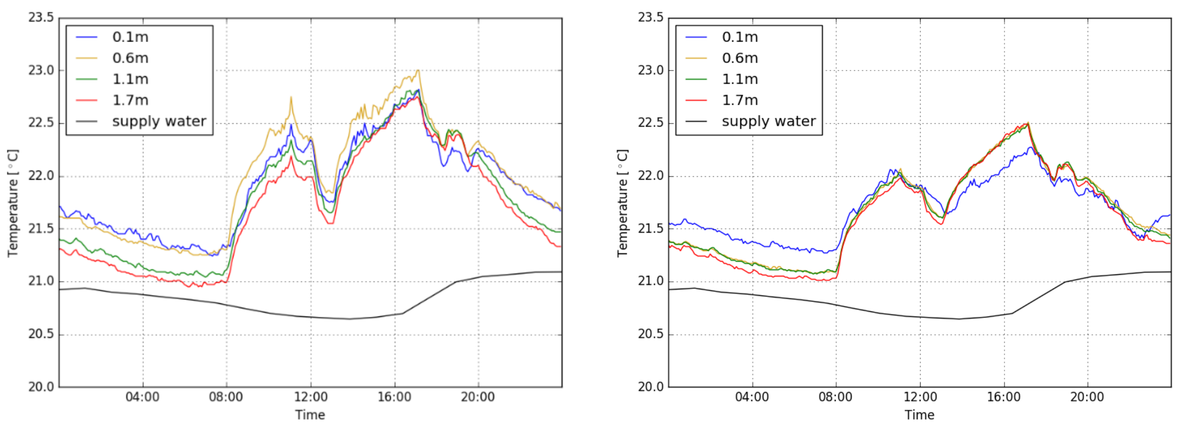


Figure 10. Air temperature profiles for the summer day: P1 (left) and P2 (right)

Thermal stratification that results in the air temperature at the head level being warmer than at the ankle level may cause thermal discomfort. The vertical air temperature difference is shown in Figure 11 for a representing value of air temperature at each height. This representing value is the average temperature occurring during the period 15:00 and 16:00, which was treated as steady-state period (temperature cycles <1 K and temperature ramps <2 K/h).

Considering the difference between head level (1.1 m, seated) and ankle level (0.1 m), it is noted that the temperature increases upward for P1 in winter and for both P1 and P2 in summer. The vertical temperature difference is respectively 0.37 °C, 0.01 °C and 0.25 °C for P1 in winter, P1 in summer and P2 in summer.

Therefore, according to ISO standard 7730, all the three cases fall within the thermal environment defined as category A (vertical air temperature difference less than 2 °C). With regards to P2 in winter, the thermal stratification occurs in the opposite direction. This situation is usually perceived more favorable from occupants, and, therefore, it is not addressed.

Generally, the room is well-mixed, and there is no significant thermal stratification in the space. This is mainly due to the very small temperature difference between water in the beam and room air.

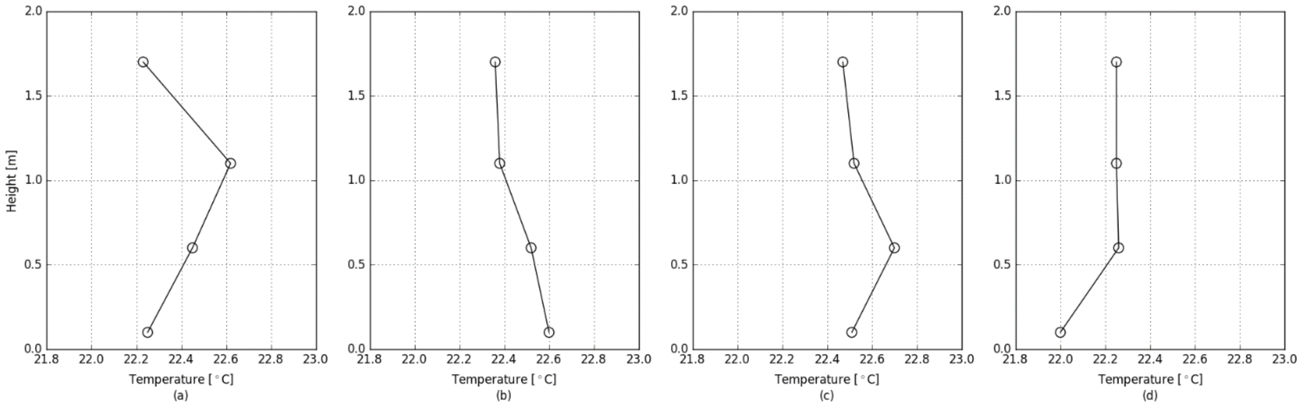


Figure 11. Vertical air temperature differences: P1 winter (a), P2 winter (b), P1 summer (c), P2 summer (d).

Figure 12 shows the air velocity values recorded during the winter day for both vertical poles. The minimum air velocity was 0.045 m/s and was obtained for P2 in the early morning at 0.6 m height. The maximum air velocity was 0.15 m/s and was obtained for P1 in the late afternoon at 0.6 m height.

Figure 13 illustrates the air velocity values recorded during the summer day for both vertical poles. The minimum air velocity was approximately 0.025 m/s and was obtained for P1 in the early morning at 1.1 m height. The maximum air velocity was approximately 0.19 m/s and was obtained for P2 in the afternoon at 0.1 m height. It is noted that the values recorded during the summer day present high fluctuation. This might be due to high turbulence intensity.

Recommendations for air velocity and draught rate (DR) in spaces are given in several international and national documents. ISO standard 7730 (Table A.5) provides following design criteria for office environment:

- Category A (DR 10%): summer 0.12 m/s, winter 0.10 m/s
- Category B (DR 20%): summer 0.19 m/s, winter 0.16 m/s
- Category C (DR 30%): summer 0.24 m/s, winter 0.21 m/s

Therefore, in terms of maximum air speed, the indoor environment provided by the two-pipe system would fall in Category B.

With regard to draught, this is defined as unwanted local cooling of the body caused by air movement. Draught rate (DR) is calculated from the following equation:

$$DR = (34 - T)(\bar{u} - 0.05)^{0.62}(0.37 \cdot \bar{u} \cdot Tu + 3.14)$$

where *T* is the air temperature, $\bar{u}$ is the main air speed and *Tu* is the turbulence intensity.

Table 1 shows the DR for the two vertical poles for both winter and summer days. As previously done for the vertical air temperature, the results were averaged during the period 15:00 and 16:00. It is noted that most of the draught rates fall into category A (<10%). In few cases, the draught rate falls into category B. In particular, these are P1 at 0.6 m in winter and summer, P1 at 1.7 m in summer and P2 at 0.1 m in summer.

Table 1: Draught rates

	P1 winter (%)	P2 winter (%)	P1 summer (%)	P2 summer (%)
0.1 m	8.7	8.4	3	14.3
0.6 m	11.6	8.2	11.1	9.8
1.1 m	8	8	5.8	4.7
1.7 m	8	7.9	10.3	4.4

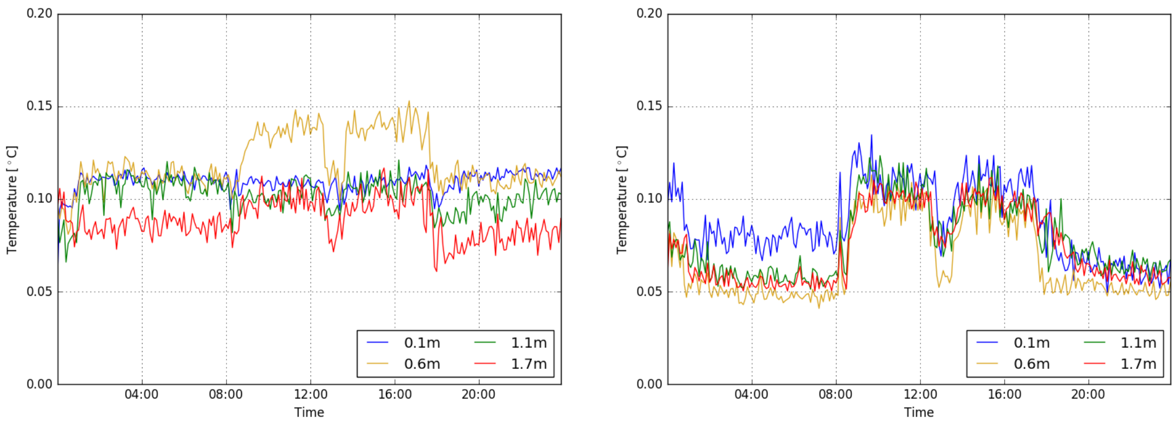


Figure 12. Air velocity profiles for the winter day: P1 (left) and P2 (right)

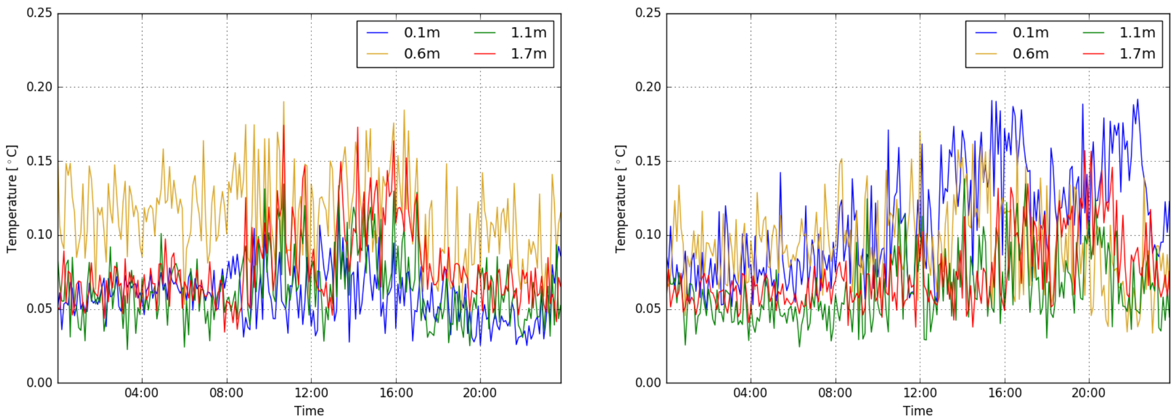


Figure 13. Air velocity profiles for the summer day: P1 (left) and P2 (right)

3.2 Measurements and questionnaire in occupied space

Fig. 14 and 15 shows the daily indoor air temperatures obtained in correspondence of the four locations (M1, M2, M3 and M4) highlighted in Fig. 5. In winter, the indoor air temperature is between 21.2°C and 23°C, while in summer the indoor air temperature is between 21°C and 23.2°C.

In winter, there is little difference when comparing the air temperatures in the four locations. In summer, the air temperature closer to the window is higher than at the inner location. This might be attributed to the influence of solar gains. Note that the low air temperatures observed in summer during non-working hours are due to the continuous operation of the system. At night, water at about 20.5°C circulates in the system, providing cooling energy to the building.

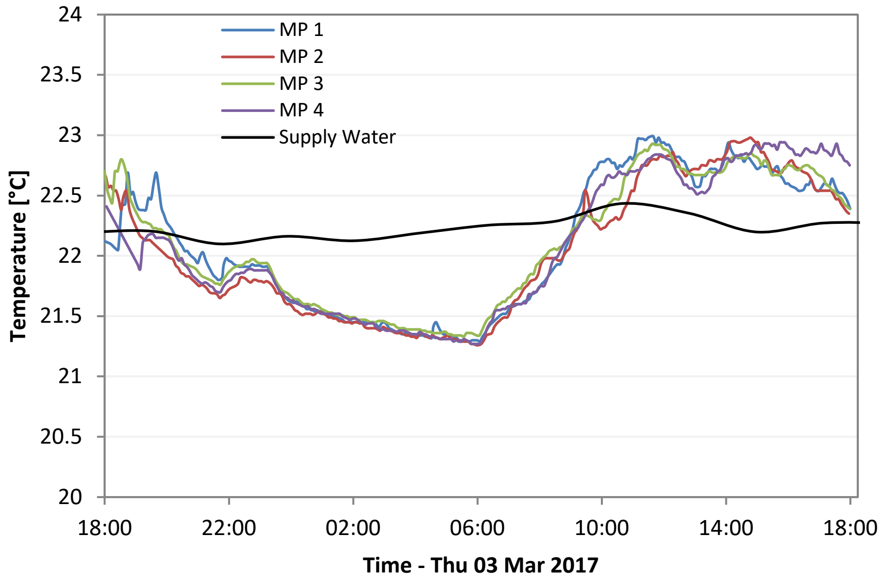


Figure 14. Air temperature profiles for the winter day in the occupied open office space

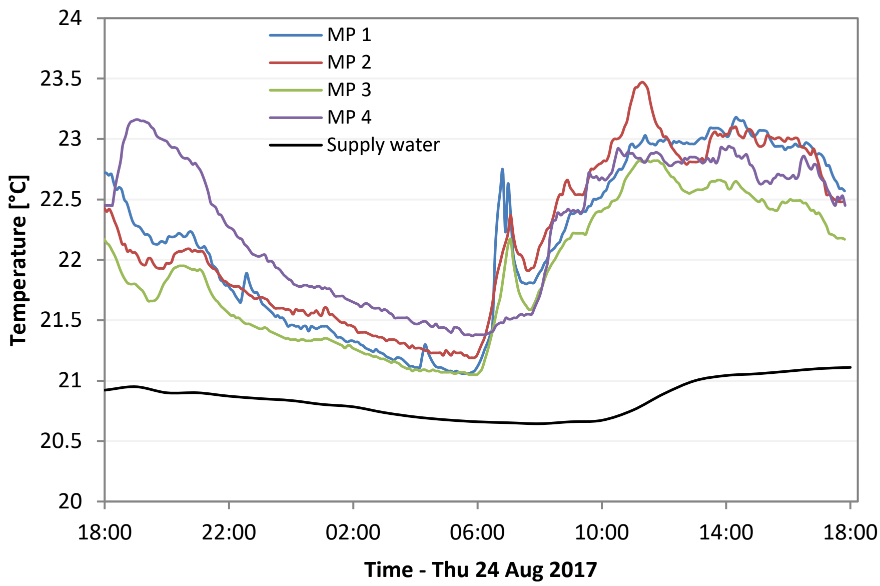
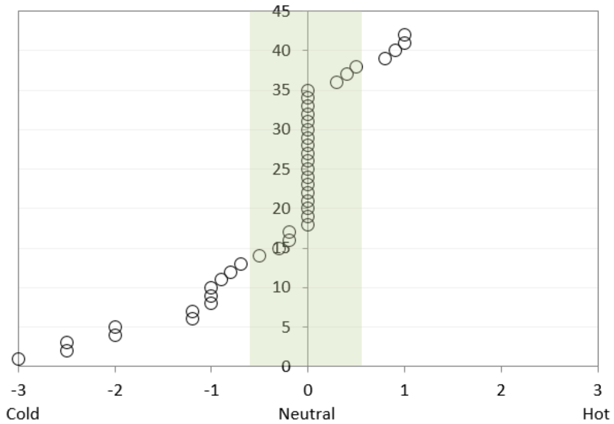


Figure 15. Air temperature profiles for the summer day in the occupied open office space

Regarding the questionnaire, Fig. 16 shows the responses to question n.1 in terms of **thermal sensation** *"Please tick the scale below at the place that best represents how you feel at this moment"*. For the winter case, 60% of the respondents gave an answer related to sensation of thermal comfort (between -0.5 and 0.5), 31% of the respondents provided an answer related to a sensation of cold (<0.5), and 9% of the respondents provided an answer related to a sensation of hot (>0.5).



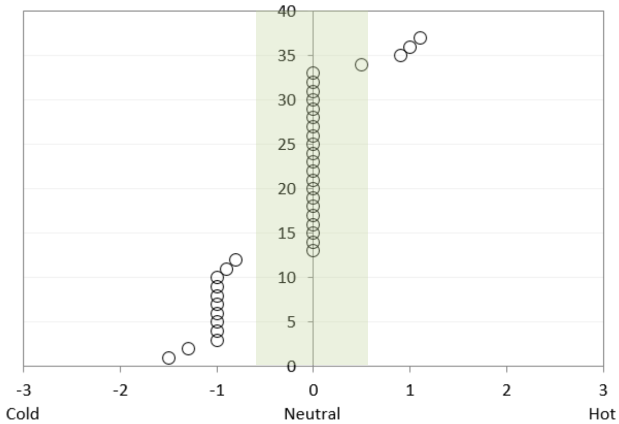


Figure 16. Responses to the questionnaire regarding thermal sensation in winter (left) and summer (right)

For the summer case, 60% of the respondents gave an answer related to a sensation of thermal comfort (between -0.5 and 0.5), 32% of the respondents provided an answer related to a sensation of cold (<0.5), and 8% of the respondents provided an answer related to a sensation of hot (>0.5).

The answers provided in question n.2 reflect the **thermal evaluation**. In the winter case, 71% of the respondents provided an answer related to a comfortable situation (very comfortable, comfortable, just comfortable), while the 29% provided an answer related to an uncomfortable situation (very uncomfortable, uncomfortable, just uncomfortable). In summer, 92% of the respondents provided an answer related to a comfortable situation, while 8% provided an answer related to an uncomfortable situation.

With regards to **air movement** (question n.5), 72% of respondents in winter and 63% of respondents in summer were satisfied with current situation. The 28% of respondents in winter and 37% of respondents in summer would have preferred more air movement. No one preferred less air movement.

3.3 Heating and cooling energy use

Weekly analysis

Fig. 17 shows the hourly values of supply and return water temperatures in the active beam circuit for a typical winter week (from the 29th of January to the 4th of February 2018). The graph also shows the outdoor air temperature. The maximum supply water temperature is 23.2°C and, as expected, it occurs in correspondence of the minimum outdoor air temperature. The minimum supply water temperature occurs in correspondence of the maximum outdoor air temperature and it assumes a value of 22°C. The maximum temperature difference between supply and return water is approximately 1.2 K and it is found in correspondence of the minimum outdoor air temperature. This is because, in case of low outdoor air temperatures, the building requires larger heating demand. Since the system operates with constant water mass flow rate, this results in larger supply/return temperature differences. It is also noticed that the supply water temperature is always higher than the return water temperature, meaning that the building is always in heating demand mode.

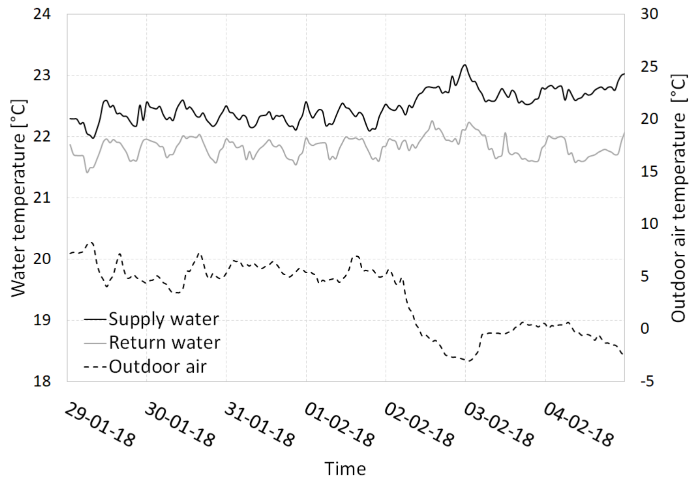


Figure 17. Winter: supply and return water temperatures

Fig. 18 shows the hourly values of supply and return water temperatures for a typical spring week (from the 9th of April to the 15th of April 2018). The maximum supply water temperature is approximately 22.5°C while the minimum supply water temperature is approximately 21.5°C. It is noticed that supply and return water temperatures overlap for most of the time (during daytime), leading to small supply/return temperature differences. This means that heating and cooling loads in the building are balancing each other, and the system is providing simultaneous heating and cooling. At nights, higher supply/return water temperature differences are obtained, meaning that the building is in heating demand mode. The graph also shows how the supply water temperature oscillates according to the outdoor air temperature. During the day, when outdoor air temperatures are higher, the supply water temperature is lower. The opposite behaviour occurs during nights.

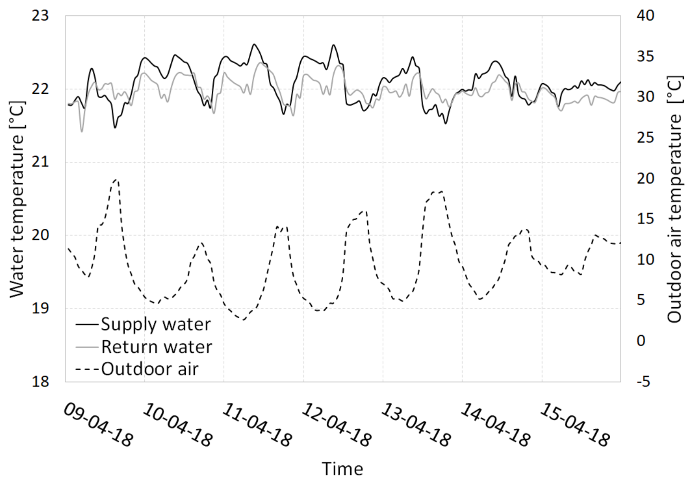


Figure 18. Spring: supply and return water temperatures

Fig. 19 shows the hourly values of supply and return water temperatures for a typical summer week (from the 30th of July to the 5th of August 2018). The maximum and minimum supply water temperatures are 21.5°C and 20°C, respectively. In this case, the overlapping between supply and return water temperature occurs during nights, when the building is unoccupied. During daytime, the supply water temperature is always lower than the return water temperature, meaning that the system is providing cooling energy to the zones. The maximum temperature difference between supply and return water is 1.5 K.

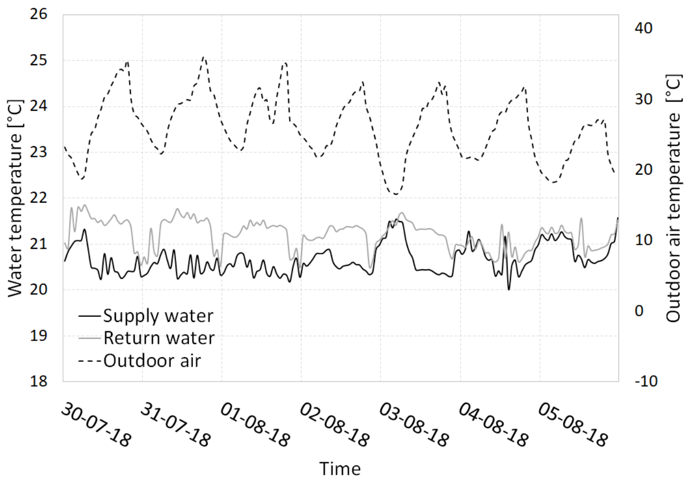


Figure 19. Summer: supply and return water temperatures

Fig. 20 shows the energy use for the three typical weeks provided by the water system. The maximum energy use is found for the winter week and it assumes a value of 1.2 kWh/m2. The minimum energy use is obtained for the spring week and it assumes a value of approximately 0.4 kWh/m2.

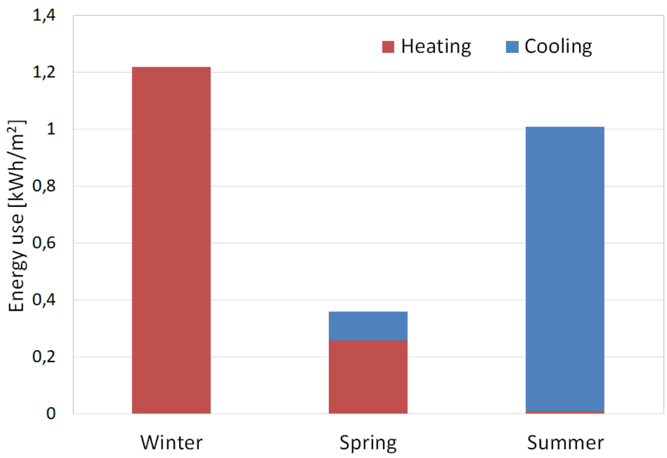


Figure 20. Heating and cooling energy use for the three typical weeks

Annual analysis

Fig 21 shows the supply and return water temperature for a one-year period, from the 1st October 2017 to the 30th September 2018. The graph shows that supply water temperature is between 23.4 °C (February) and 19.6 °C (May). The system operates in heating mode from October to April, and in cooling mode from May to September.

Fig. 22 illustrates the monthly heating and cooling energy use of the two-pipe system. The highest heating energy use occurs in February and it has a value of 5.3 kWh/m2. The highest cooling energy use occurs in July and it has a value of 4.1 kWh/m2.

In total, the system uses approximately 27 kWh/m² for heating and 15 kWh/m² for cooling. Annual energy use for fans was approximately 18.5 kWh/m². Such values agree with simulation results, leading to the conclusion that energy savings of about 15-20% can be achieved in comparison to a conventional four-pipe system.

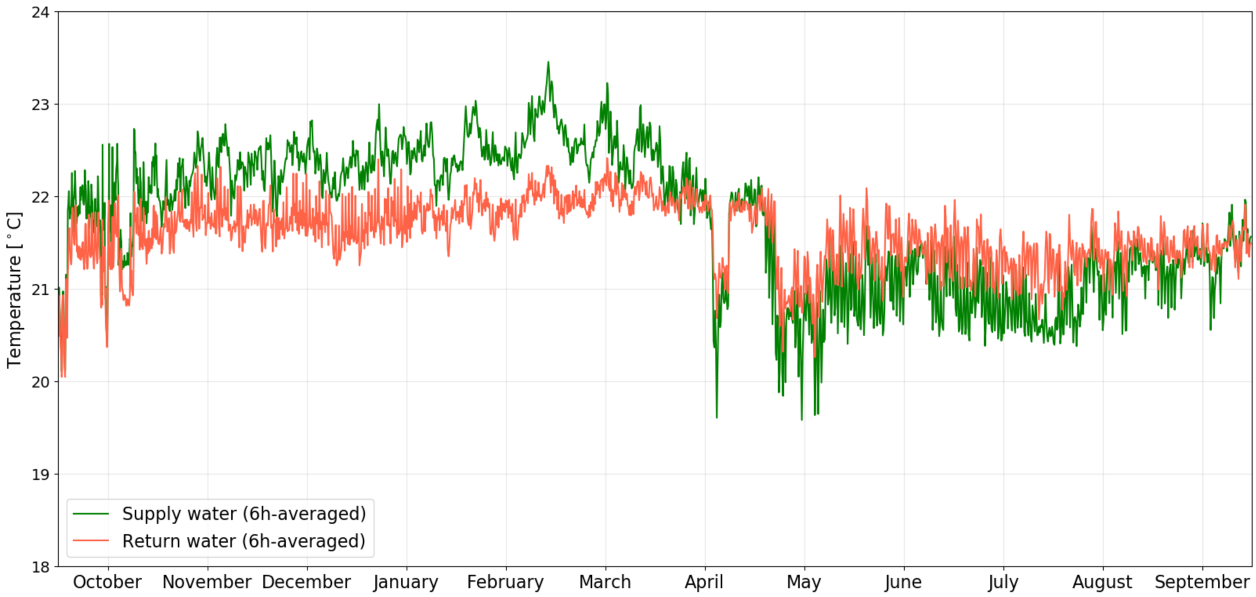


Figure 21. Supply and return water temperature for one-year period

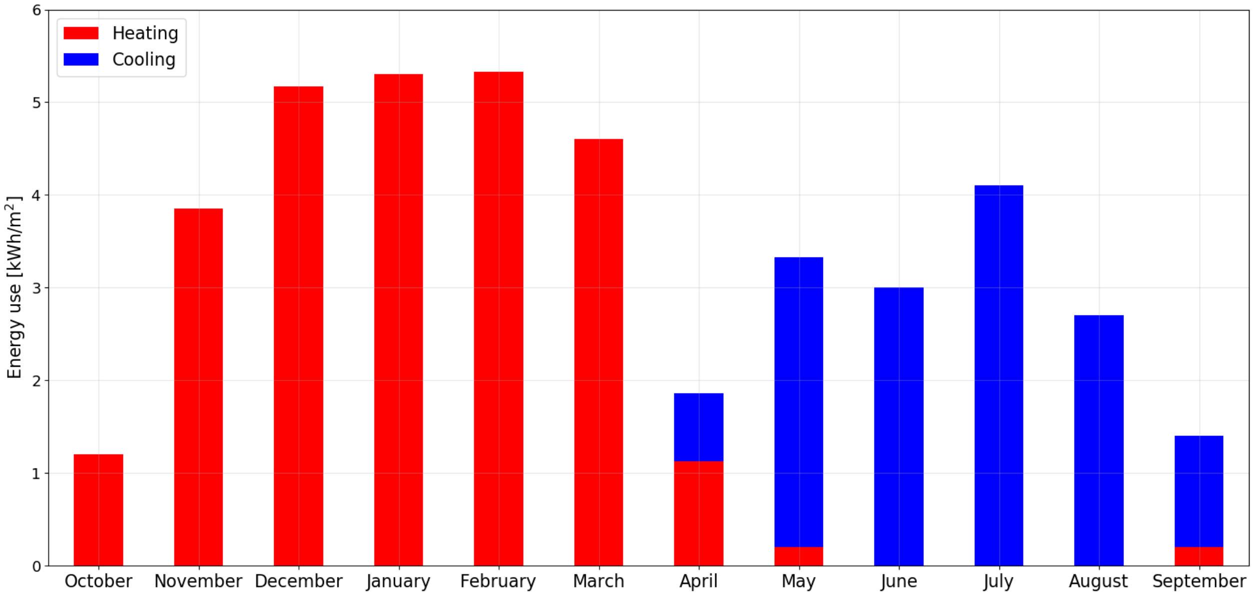


Figure 22. Heating and cooling energy use for one-year period

4. Conclusion

This project aimed at analyzing the full-scale operation of a novel two-pipe system, which was installed for the first time in a real building in Jönköping, Sweden. Aspects such as indoor climate and energy performance of the system were investigated.

Generally, it can be concluded that the two-pipe system is able to maintain a quite constant thermal environment in the space throughout the year (22 °C ±1.5 °C), without the use of any feedback controller. No significant vertical air temperature difference was noticed, and the draught rate was below 10% for most of the cases.

Occupants in the building were satisfied with the thermal conditions provided by the two-pipe system. In winter, 71% of the respondents to the questionnaire provided an answer related to a state of thermal comfort. In summer, 92% of respondents replied to be in a situation of thermal comfort.

In terms of operation and energy use, the two-pipe system operates as designed. The supply water temperature was in the range of 23.4°C (winter) to 19.6°C (summer). Heating and cooling annual energy use were 27 kWh/m^2 and 15 kWh/m^2, respectively.

In conclusion, the two-pipe system represents a valuable alternative to conventional four-pipe systems in office buildings. Besides annual energy saving for heating and cooling, the design of the two-pipe systems allows to save installation cost due to the need of only one water circulation pump, fewer pipes and no control valves.

Thanks to the results provided during this project, the two-pipe system is currently being installed in two other office buildings located in Jönköping. Lindab A/S is also investigating possibilities to install the two-pipe system in Denmark.

This project also resulted in the initiation of a new PSO project (350-013 Energibesparelse til komfortkøling ved anvendelse af PCM i 2-rørs-kølebaffelsystemer), which aims at developing a novel PCM-based heat exchanger that will be able to significantly reduce the cooling energy use of the two-pipe system.