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To cite this article: Staislavs Gendelis *et al* 2023 *J. Phys.: Conf. Ser.* **2423** 012011

Radiant capillary heat exchangers – power calculation for optimal heating and cooling

Staņislavs Gendelis[1], Jevgēnijs Teličko[1], Andris Jakovičs[1], Indulis Bukans[2]

[1]Institute of Numerical Modelling, Faculty of Physics, Mathematics and Optometry, University of Latvia, Jelgavas Street 3, Riga LV-1004, Latvia
[2]Hydrokapillar Tech, Ltd, 158 Brīvības street, Riga, LV-1012, Latvia

stanislavs.gendelis@lu.lv

Abstract. The issue of switching to renewable energy sources becomes very actual and it is important not only to change the energy source, but also the reduce the final energy needs by improving the energy efficiency of buildings and usage of efficient heating systems. Heat pumps as the most popular renewable energy source are widely used, but their energy efficiency is depending on temperature of the supplied energy carrier. The most efficient are radiant capillary heat exchangers with a large surface area and a low temperature, which typically does not exceed 30°C. Another advantage of radiant capillary heat exchangers is the possibility to operate them in both – heating and cooling modes. Unlike the underfloor heating solution, where the role of thermal convection is very important, the built-in radiant capillary heat exchanger systems provide the energy mainly due to thermal radiation. This study explores two modelling approaches for determination of required power and corresponding area of radiant capillary heat exchangers to be installed in a room to provide heating and cooling: simplified approach, which allows to create the heat balance with a minimum amount of input data and a precise standard-based approach. Calculations were made for three different rooms with variable glazing area and spatial orientation using both approaches. Analysis of the calculation results shows the limits of the simplified method, which overestimates heating need and underestimates cooling need, and the main reason for such differences is simplification of room orientation and subsequent solar heat gains. As the calculated cooling power is less than heating power, therefore the heating estimation is sufficient to estimate the amount of radiant capillary heat exchangers in small/medium rooms for providing both heating and cooling in the climatic conditions of Riga. The use of complex, comprehensive modelling approaches is necessary for rooms with large glazed areas, where the simplified method gives incorrect estimations.

1. Introduction

Due to the recent rise in energy prices in Europe, the matter of switching to renewable energy sources has become very relevant. It is important not only to change energy sources, but also to reduce end-user energy needs by improving the energy efficiency of buildings and usage of highly efficient heating and cooling systems.

Heat pumps are the most popular renewable energy source used for heating, with costs comparable to the natural gas and central heating solutions. Their high efficiency increases with reducing temperature difference between the energy source and the heat exchanger installed in the room. The heat carrier in traditional convectors has temperature above 50°C, the use of underfloor water-based heating system reduces the temperature down to 40°C thanks to larger area [1]. The most effective solutions are radiant capillary heat exchangers (RCHE) [2] with the largest surface areas, allowing to reduce water temperature to 26-30°C while consuming the same amount of power. Another advantage of RCHE is the possibility to operate in both – heating and cooling modes.

Some studies of widespread use of underfloor heating systems showed some more negative effects like the risk of discomfort due to increased floor surface temperature and intensified floor dust spinning [3, 4]. These disadvantages are avoided when using RCHE with lower temperature, integrating them into ceiling and/or wall constructions. Unlike the underfloor heating solution, where the role of thermal convection is very important, the built-in systems provide heating or cooling mainly due to thermal radiation.

As RCHE can also be installed in separate rooms or room groups, the conventional heat balance approach of an entire building or use of data from energy performance certificates for existing buildings in the case of heating system renovation cannot be directly used for determination of the heating (or cooling) power of a locally installed system. The use of standardized heat balance calculation methods like ISO 52016-1 [5] also requires specific knowledge and involvement of an energy auditor. On the other hand, applying some simplification and reasonable assumptions allows one to accurately calculate the heat balance for most of the typical rooms using formulas from the tested and widely used standardized method.

This study analyses results from two calculation approaches for determination of power and corresponding area of radiant capillary heat exchangers to be installed in rooms for providing necessary heating or cooling power:

- a simplified and very basic approach, which allows to obtain preliminary estimates required for design with a minimum amount of input data;
- a complex and precise approach based on the ISO 52016-1 methodology [5] for the assessment of a building's energy performance.

Calculations were performed for three room types (small room with four outer walls, medium-sized room with one outer wall, spacious room with large, glazed façades). The spatial orientation of the rooms has also changed. The results obtained from both models have been comprehensively analyzed and compared to show the limits of use and the reasons for the difference due to modelling simplifications.

2. Capillary heat exchangers

The invention of capillary heat exchangers started in 1981, when D. Herbst applied patent for this technology "Piping network for warm water surface heating of floors or walls" [6]. Initially, the capillary tube mats were marketed under the brand "*KaRo*" (acronym of the German '*Kapillar Rohr'* meaning 'capillary tube'). Further scientific work created the necessary basic principles on the theory in the applications for capillary tube mats [7]. Today capillary heat exchangers are installed worldwide with annual production of over 400000 m^2 [6]. The biggest companies producing, with slightly different technical nuances, the main element for the capillary heat exchangers technology – the capillary tube mats – are located in Germany (e.g. *Clina*, *Beka*), but there are also a few in Eastern Europe, including the Czech Republic (*Infraclima*) and Latvia (*Wasserkabel*).

The popularity of RCHE is mainly determined by such features and advantages:

- limestone does not accumulate in water capillary mats thanks to the low water temperatures – 32°C for heating and 18°C for cooling (limestone starts to form at 60°C);
- mud (results from corrosion) does not occur in water capillary mats thanks to the use of corrosion-protected components only;
- the safety of a water capillary system is verified with air pressure at 20 bar and water pressure at 10 bar prior to operation;
- water capillary mats can be easily repaired if necessary – a capillary is cut and both ends are welded – with no effect to the heating/cooling output;
- the very first installed water capillary systems demonstrated that they do not require any specific maintenance for dozens of years.

The key element of the RCHE system is the water capillary mat (Fig. 1). The capillary tubes typically are made from polypropylene or polyethylene – an environmentally friendly and safe plastic with good thermal and elasticity properties. The diameters of capillary tubes are range within 3.5–4.5 mm.

Typically, they are integrated in different final finish materials (e.g. plasterboard or limestone), or can be left as exposed construction (Fig. 1.) In case of finish integration, the surface temperature is more homogeneous, but requires slightly higher power due to additional thermal resistance. Our experimental studies [8] show that the specific power output for different types of installation may vary from 25 to 250 W per 1 m^2 of installed capillary mats depending on the temperature difference between water and the room (Fig. 2), with highest power for exposed (free hanging) mats, which are often used for installation in technical rooms with lower architectural requirements. The infrared images of integrated and exposed installations in Fig. 3 display the difference in temperature uniformity.

Fig. 1. Overview and close-up of water capillary mats.

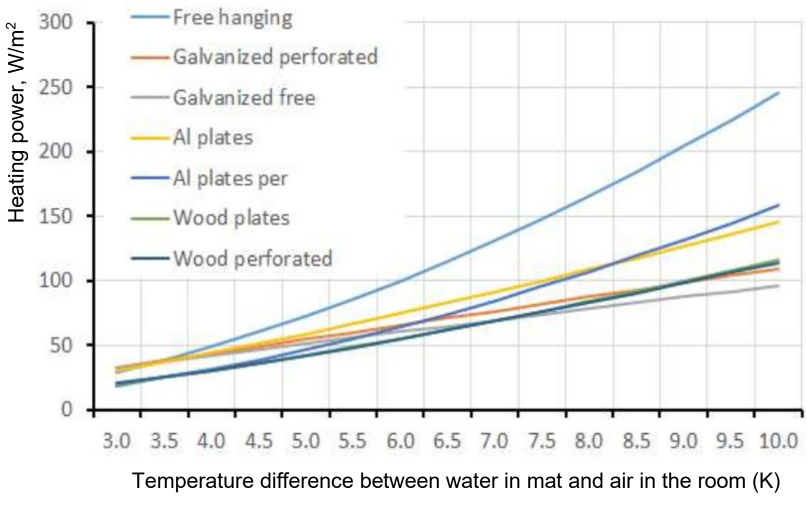

Fig. 2. Measured power (W/m^2) for different installation of capillary mats depending on temperature difference [8].

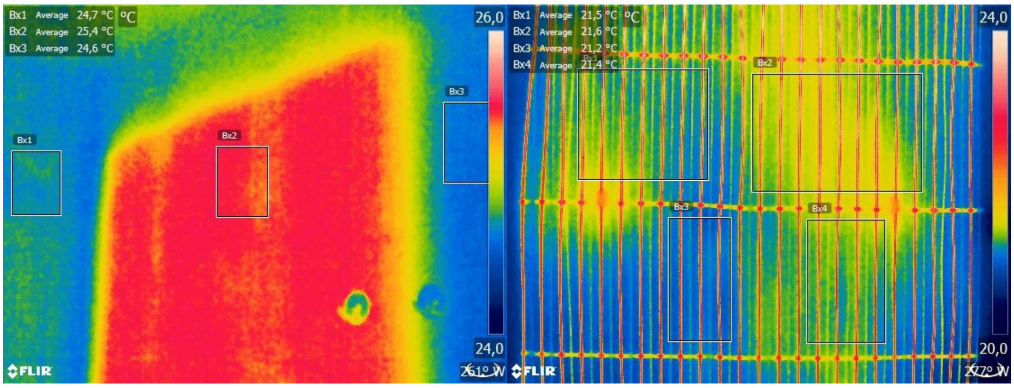

Fig. 3. Infrared images of integrated (left) and exposed (right) installations of water capillary mats.

There are two main places for installation of RCHE in living rooms - ceiling and walls (Fig. 4), where the mats are placed under the plaster or plasterboard with high thermal conductivity. For some cases (e.g., in industrial buildings and shopping centers), installation can also be performed under the decorative grid or metal panels. Underfloor installations are used typically only for heating purposes due to ineffective cooling performance.

Water flow in capillaries can be organized in two different ways – with inlet and outlet along one mat side or using two opposite water connections (Fig. 5). In case of inlet/outlet main pipes placed together, the temperature of capillaries in the middle of the mat is changing alternately (counter-flow adjacent capillaries), in case of separated main pipes the temperature in the adjacent capillaries is equal (co-flow adjacent capillaries) – this effect is visually clearly seen on infrared images (Fig. 6).

Besides the capillary heat exchanger mats and main pipes, the full system also contains the following typical components (Fig. 7): energy source with heat exchanger (heat pumps are recommended), circulation pump, expansion tank and the main control unit (including temperature controller and dew point sensor required for cooling mode).

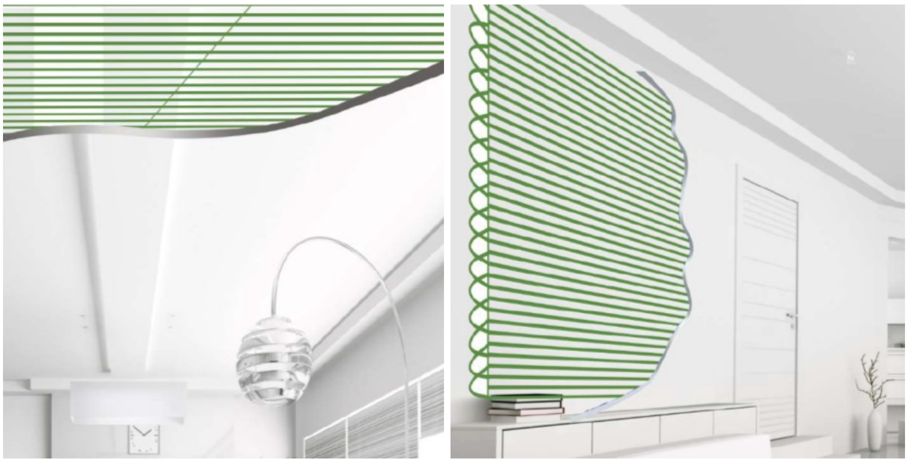

Fig. 4. Typical application of capillary heat exchangers – ceiling (left) and walls (right).

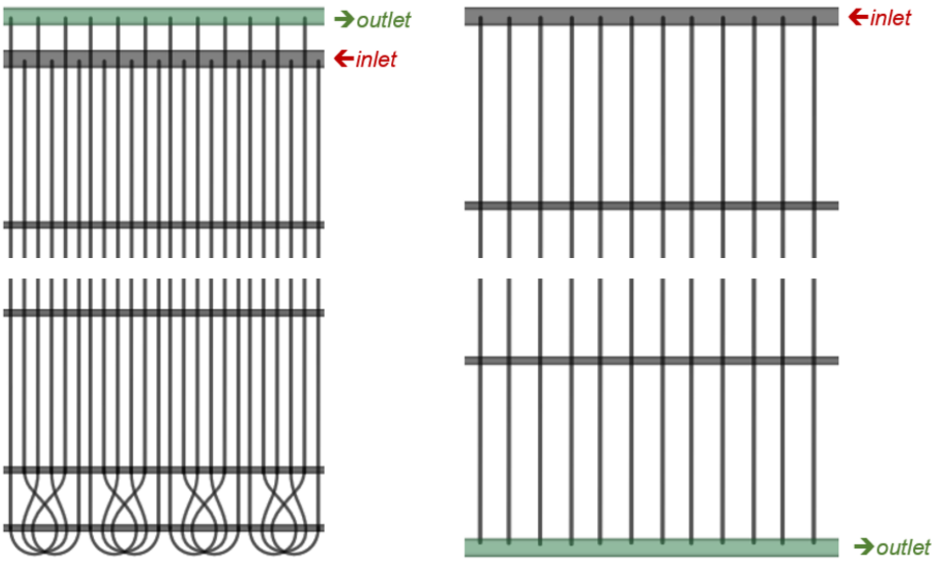

Fig. 5. Two types of capillary mats – with adjacent (left) and separated (right) main inlet/outlet pipes.

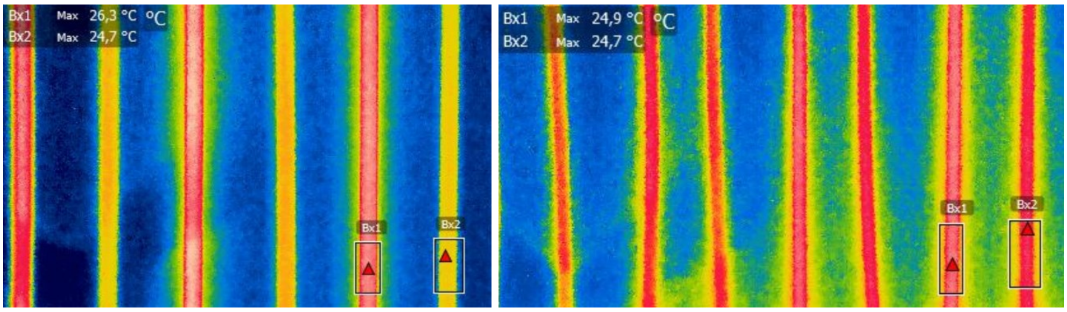

Fig. 6. Temperature of mats with counter-flow (left) and co-flow (right) adjacent capillaries (Fig. 5).

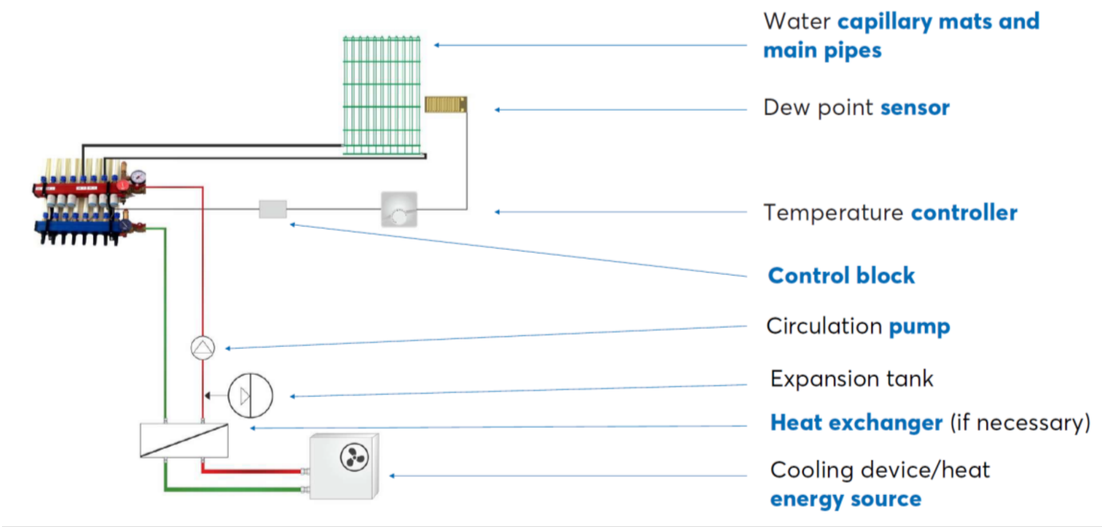

Fig. 7. Outline of a radiant capillary heat exchanger system.

3. Modelled rooms

To select the correct number of capillary mats, it necessary to determine the heating or cooling power (W) for the room with an installed RCHE system. As described above, the corresponding area of heat exchangers depends on the installation type and planned temperature difference; therefore, calculations must include two phases:

- heat balance of the room at set indoor and outdoor temperatures, obtaining the heating/cooling power;
- calculation of the number or total area of capillary mats based on experimental data [8] (Fig. 2) of provided power depending on installation type and target temperature difference between heat carrier and indoor air;
- to analyze the influence of input data specificity and potential variations in results, two different modeling approaches are used for modeling necessary heating or cooling power;
- a simplified and very basic approach, which allows to obtain preliminary estimates required for design with a minimum amount of input data;
- a complex and precise approach based on the ISO 52016-1 methodology [5] for the assessment of a building's energy performance.

Both approaches use the same mathematical equations, but the simplified method involves many simplifications, ignoring less influential factors. A special user-friendly webpage (Fig. 8) was created for implementing the simplified calculation method [9]. For standard calculations, the internet-based application www.heatmod.lv [10] was used (Fig. 9). Both products were developed at the Institute of Numerical Modelling of University of Latvia.

The main assumptions used in the simplified method are as follows:

- internal heat gains (including occupants, equipment and lighting) are considered depending only on the room's type, which is limited to three – dwelling, office and other;
- a room's spatial orientation is not considered, assuming an equal distribution of windows across the facades (used for calculation of solar heat gains);
- only one type of each boundary structure is possible (walls, windows, ground floor, roof) with a limited list of base materials having predefined properties (clay blocks, aerated concrete, bricks, timber frame, sandwich panels etc.) and thickness of insulation material with thermal conductivity of 0.04 W/m/K;
- the type of windows and doors can be selected from a list of four predefined U-values from 0.8 to 2.5 W/m2/K;
- thermal bridges are not included in the calculations;
- it is possible to select natural or mechanical ventilation with three pre-set intensities – low, medium or high with corresponding values of air exchange rate;
- the calculations are made on an annual basis using the average temperature difference;
- the calculations can be performed only for one thermal zone.

Of these assumptions and simplifications, the most important one is neglecting the spatial orientation with the ensuing inaccurate estimation of solar heat gains.

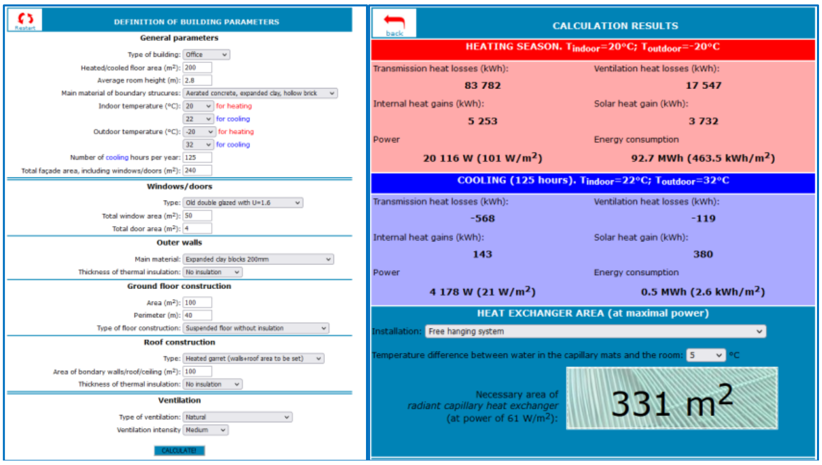

Fig. 8. Webpage used for simplified heat balance calculations (http://www.modlab.lv/SKS/).

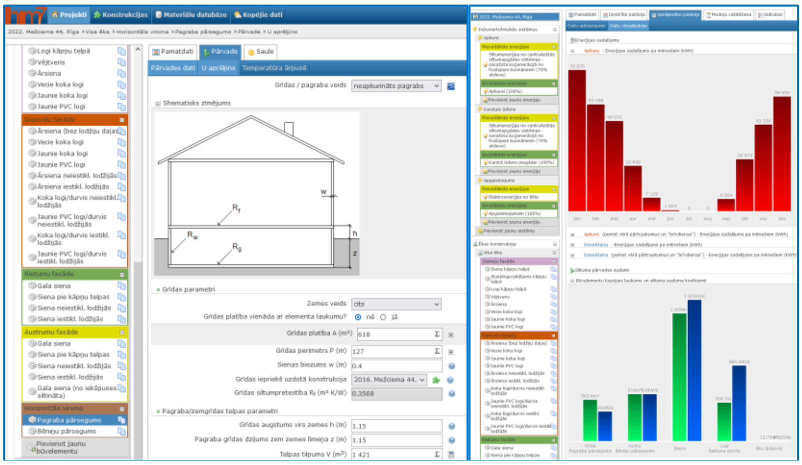

Fig. 9. Webpage used for full heat balance calculations according to ISO 52016-1 (http://www.heatmod.lv/).

The use of the simplified calculation approach is very easy and saves time, no specific knowledge or data is needed in order to quickly simulate the energy consumption for the most common rooms. Therefore, it is recommended for approximate estimations of installed RCHE mats.

To show the possible limits of this approach due to applied assumptions, three rooms are selected for calculation using both methods and further comprehensive analysis:

- small room with four outer walls and no glazing (e.g. test buildings described in [11]);
- medium room with one outer wall and three small windows (Fig. 10);
- large room with two large, glazed façades and two indoor walls (Fig. 10).

The orientation for rooms with glazing was changed from North to South, producing two different calculation sub-variants. All the rooms were defined as offices with double-glazed windows and target indoor temperatures of 20°C for heating and 23°C for cooling. Outer walls consist of reinforced concrete with a 10 cm thermal insulation layer. Outdoor temperature used for calculations corresponds to average values of the five coldest/hottest days in Riga, -20°C and +25.5°C accordingly [12]. Natural ventilation with medium intensity (air exchange rate 0.5 h^{-1}) is used. Other important input data are summarized in Table 1. Therefore, there are 5 room variants, each of them is calculated using both approaches – simplified and full.

Fig. 10. Overview of the medium-sized (left) and large (right) modeled rooms.

Table 1. summary of modelled rooms

Parameters	Small room	Medium room	Large room
Heated area (m^2)	9	49	96
Height (m)	3	3	4
Volume (m^3)	27	147	384
Outer walls (m^2)	36	14	0
Indoor walls (m^2)	0	70	80
Glazing (m^2)	0	4	80
Glazing orientation	-	North	North+East
		South	South+West

4. Results

The results obtained from simplified and full calculation models for the three different rooms with two glazing orientation sub-variants are summarized in Table 2 and visualized in Fig 11. By analyzing the results, one may highlight a few main points:

- The power needed for heating the small and medium modelled rooms is higher than cooling power and the difference between both models strictly depends on the type of calculation – for heating or cooling. In case of heating, the simplified method overestimates the required power at -20°C, but in case of cooling it underestimates cooling power. The main reason for this is simplification and assumptions about solar heat gains, this is also confirmed by the fact that the smallest difference in results is for the room without windows (only 9% for heating).
- The differences between results are smaller for heating cases and much higher for cooling cases. The reason for this tendency is totally different heat balance composition during the summer (given Riga climatic conditions), where the outdoor temperature is higher that indoor temperature for only a few hours per day, and cooling is not normally necessary during the night. However, the simplified calculation method involves only the accumulated outdoor temperature value, without considering the dynamics of the process. Therefore, the use of a simplified heat balance calculation method for cooling cases is not recommended in general.

- The effect of the rooms' spatial orientation on necessary power is clearly evident, especially for the cooling case, where solar heat gains play an important role and the cooling. For the rooms with glazing the rotation from North to South produces a change in heating power up to 15%, but for cooling calculation this difference exceeds even 50%.
- Nevertheless, the comparison calculated heating and cooling power indicates that heating power for the small and medium rooms in Riga climatic conditions is highest, meaning that only this value should be used for estimating the number of RCHE mats to install. The power needed for cooling is higher for the large room with 100% of glazing facades, therefore the use of simplified method here yields incorrect results.

Table 2. Summary of calculated RCHE power in modelled rooms (see Table 1)

	Small room	Medium room		Large room	
		North	South	North+East	South+West
Heating power (W)					
simplified method	624	1299	1299	4305	4305
full method (%)	565 (-9%)	1158 (-11%)	869 (-33%)	3322 (-23%)	3115 (-28%)
Cooling power (W)					
simplified method	51	480	480	4567	4567
full method (%)	178 (+249%)	608 (+27%)	869 (+81%)	8850 (+94)	10,756 (+136%)

Fig. 11. Comparison of calculated heating/cooling power for different rooms using two modelling approaches.

Conclusion

Analysis of the calculations made for three room types with different geometry, glazing and orientation using simplified and full heat balance modeling approaches showed the limits of the simplified method's use. The simplified method overestimates heating need and underestimates cooling need, and the main reason for such differences is simplification of room orientation and subsequent solar heat gains.

At the same time, the calculated cooling power is less than heating power (except for fully glazed outdoor façades), therefore the heating estimation is sufficient in order to assess the maximum amount of radiant capillary heat exchangers in small/medium rooms for providing both heating and cooling in the climatic conditions of Riga. The use of complex, comprehensive modelling approaches is necessary for rooms with large glazed areas, for which the simplified method yields incorrect estimations.

The calculations performed for different rooms and orientation allow one to conclude that the simplified and very fast method can be used reliably as a first approximation in most cases (especially for rooms with very small window area), slightly overestimating the real need. The results obtained from more detailed calculations will typically reduce the estimated number of mats required.

Acknowledgement
This work is supported by the postdoctoral project "Analysis of the actual energy consumption of zero energy buildings and the development of the necessary energy efficiency improvement solutions" (1.1.1.2/VIAA/3/19/505) and by the European Regional Development Fund project "Development and approbation of complex solutions for optimal inclusion of capillary heat exchangers in nearly zero energy building systems and reduction of primary energy consumption for heating and cooling" (1.1.1.1./19/A/102).

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