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Analysis of the operating parameters of a microchannel beam heat exchanger powered by R290

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ABSTRACT

The paper presents an analysis of the cooling performance of a microchannel beam heat exchanger powered by the combustible refrigerant R290 (propane) as a function of design parameters. R290 is an environmentally friendly refrigerant, in the context of growing concerns about climate change and the need for sustainable cooling solutions. Propane characterized by low global warming potential (GWP = 3) and zero ozone depletion potential (ODP = 0). The studied heat exchanger is dedicated to refrigeration devices where waste heat from mechanical ventilation installations serves as the lower heat source. Performance analyses of the exchanger operating as a condenser in the refrigeration system were conducted based on its design parameters. Several design variations of the exchanger were examined, including different microchannel shapes. Simulation studies were also performed under various operating conditions. The mass flow rate of the refrigerant in the exchanger and the volumetric flow rate of ventilation air were varied. The aim of the conducted research was to reduce the dimensions of the heat exchanger, enabling a reduction in the mass of the combustible refrigerant in the exchanger. Simulation studies were conducted using SolidWorks software with the Flow Simulation library. Over 500 simulations were performed. Based on the obtained results, it was found that using hexagon-shaped or triangle-shaped microchannels with corrugated walls could double the heat transfer rate of the condenser compared to the commonly used square or circular channels.

Keywords: evaporator, microchannel beam heat exchanger, R290, microchannel.

INTRODUCTION

In December 2019, the European Commission presented a package of political initiatives known as the European Green Deal, aimed at achieving climate neutrality by 2050. A key aspect of this energy transition is reducing the use of fossil fuels and replacing them with renewable energy sources to cut CO_2 emissions. Decarbonisation affects all industries, including both residential and commercial heating sectors. The EU energy policy focuses on generating electricity from renewable sources, and devices that produce heat from conventional fuels should be replaced with compressor heat pumps. However, achieving decarbonisation in both residential and commercial heating sectors is challenging due to Regulation (EU) No. 2024/573 on fluorinated greenhouse gases, which came into effect in March 2024 [1]. According to this regulation, a ban has been imposed and a schedule for phasing out synthetic refrigerants with high GWP (global warming potential) has been introduced. Consequently, commonly used synthetic refrigerants must be replaced by natural refrigerants. One of the natural refrigerants set to replace some of the synthetic refrigerants is propane (R290), which has a low GWP and zero ODP (ozone depletion potential). The use of natural refrigerants comes with certain challenges, as they are slightly flammable substances categorised as A2L or flammable substances in category A3. According to Regulation 2024/573 [1], the mass of refrigerant in a refrigeration system must be reduced. For a refrigeration system located in an enclosed space using R290 refrigerant, the refrigerant mass must not exceed

150 grams [2, 3]. Consequently, the energy transition in the residential sector relies on monoblock compressor heat pumps, where the entire refrigeration system is located outside the building. For industrial applications, a similar solution is used, but the devices are custom-designed for each facility. The greatest challenge of decarbonisation is in multi-family residential buildings, especially newly built ones, where there is a need to reduce the thermal load from central heating. In such cases, developers typically require each residential unit to have its own heating source, simplifying administrative procedures related to utility billing. Until recently, condensing gas boilers have been commonly used as a heat source in multi-family residential buildings. However, due to the value of the EP_{H+W} coefficient defined by the Minister of Infrastructure's regulation on the technical conditions buildings must meet, which is ≤ 70 [kWh/m^2/year], this solution is no longer feasible [4]. In newly built multi-family residential buildings, due to stringent values for heat transfer coefficients of building envelopes and their elements as defined by the EN 12831 standard [5], mechanical ventilation with heat recovery must be used. Additionally, the literature review indicates that the global efficiency of natural ventilation is only about 60% [6]. Therefore, the most advantageous solution for replacing a condensing gas boiler is a compressor heat pump that works in conjunction with a ventilation unit. Such a solution, with its compact design, could be used as a heating source for individual residential units in a multi-family residential building. The main construction challenge is reducing the mass of the eco-friendly refrigerant. This paper attempts to address this issue.

CONSTRUCTION AND OPERATIONAL PARAMETERS OF A MICROCHANNEL BEAM HEAT EXCHANGER FED WITH R290

Due to the energy transition, the topic of heat pumps is addressed in various aspects by scientific communities. Chua et al. [7] highlight the economic and ecological aspects of using heat pumps. They point out the potential for utilising waste heat as a lower heat source in heat pumps used in industrial processes, as well as in single-family and multi-family heating systems. They emphasise the need for energy savings and improved energy efficiency, identifying heat pumps as a crucial element in energy recovery systems with significant potential and capabilities, and proving that continuous efforts are necessary to enhance their performance and reliability, particularly concerning eco-friendly refrigerants. Cavallini et al. [8] conduct experimental research on heat pumps powered by propane. They note that minimising the refrigerant charge is a priority when designing refrigeration, air conditioning, and heating equipment. To reduce the refrigerant mass in the system, they employed a microchannel shell-and-tube heat exchanger. They demonstrated that the use of microchannels reduces the amount of refrigerant in the system. Fernando et al. [9] confirm these findings by additionally showing that it is possible to minimise the refrigerant charge with an eco-friendly flammable substance while still maintaining the required cooling power necessary for proper operation of the device. Tammaro et al. [10] provide evidence that using propane as a refrigerant in heat pumps in warm and temperate climates increases the device's efficiency. Furthermore, replacing the synthetic refrigerant with R290 always results in a reduction of the refrigerant charge in the system [11]. Simulations of the leakage of flammable refrigerants from refrigeration systems into residential spaces are also being studied [12, 13]. R290 has been recognised as an ideal, environmentally friendly refrigerant. However, Qiu et al. [14, 15] emphasise the need for research to improve the heat exchange process and reduce the refrigerant quantity in the system due to its flammability. It is also highlighted as a viable alternative to HCFC and HFC refrigerants [16]. Many researchers suggest that R290, as a natural refrigerant, can replace other refrigerants in real-world applications due to its excellent environmental and thermophysical properties [17–19]. R290 has a zero ODP, a very low GWP value of 3, and is not harmful to the climate. However, the flammability of R290 limits its mass in the refrigeration system and its wide application. Zhang et al. [20] investigated the explosive properties of propane related to the internal and external units of air conditioning systems by measuring the overpressure resulting from the ignition of R290 in various locations. They demonstrated that the explosion overpressure in internal and external units is low enough not to damage the air conditioning system, making the use of R290 relatively safe. R290 has also been repeatedly compared to other natural refrigerants [21–24]. K. Nawaz et al. [21] indicate that R290 is a better substitute for HFCs than R600a, as unlike R600a, it does not require an increase in compressor size to maintain the cooling capacity of the system. S. Kwon et al. [22] prove that R290 provides better heating performance than R1234yf. According to [23], R290, compared to R134a (used as a baseline in the studies), R152a, R1234yf, R1234ze(E), and R600a, achieves the best results in terms of cooling performance. Furthermore, replacing the R410a refrigerant—the most popular refrigerant used in heat pumps—with R290 enables a 50% reduction in the heat exchange surface area of a conventional fin evaporator while maintaining its efficiency [24]. Analyses presented in [25] show that the largest mass fraction of refrigerant is found in the condenser, evaporator, and compressor. To reduce the refrigerant mass in the system, it is necessary to develop exchanger design solutions that ensure high performance of the evaporator and condenser while simultaneously reducing the refrigerant mass. Currently, the greatest hopes are associated with microchannel heat exchangers. Microchannel heat exchangers are increasingly used in the refrigeration, heating, ventilation, and air conditioning industries [26] due to their higher heat exchange efficiency while maintaining a compact design and lower material usage compared to commonly used plate or fin exchangers.

The rectangular cross-sections of microchannels are small, ranging from hundreds of micrometers to a few millimetres [27]. Due to the complex geometry of microchannels, production costs are higher [28]. Microchannel heat exchangers, due to their small size, hold great potential for use in places with limited space, such as in vehicles [29]. Microchannel heat exchangers are characterised by a high surface-to-volume ratio [30]. Śmierciew [27] points to the use of microchannel heat exchangers as a way to improve the energy efficiency of devices. He focuses on intensifying heat exchange by expanding the heat exchange surface and minimising charge, which further reduces the electrical power demand. It is worth noting the extremely extensive research on these exchangers, including studies involving the combination of several microchannel heat exchangers into a single device to achieve greater system efficiency [31]. It has been proven [32] that the most advantageous combination of microchannel exchangers in terms of thermal power is a series (water) and parallel (refrigerant) circuit. Despite the numerous studies conducted over the years on microchannel heat exchangers, mainly focused on maximising their heat exchange surface while minimising their size, there is still potential for further development of their design and optimization.

RESEARCH PROBLEM

The main objective for a compressor heat pump based on mechanical ventilation with heat recovery, designed for an individual residential unit in a multi-family residential building, is to reduce the refrigerant mass to below 150 g while simultaneously minimising the dimensions of both heat exchangers. During the design phase, it was assumed that the heat source for the heat pump would be the air supplied to the residential unit after heat recovery in a recuperator, while the lower heat source would be the exhaust air from the residential unit after heat recovery in the recuperator. The literature review indicates that the R290 refrigerant has significantly higher efficiency compared to synthetic refrigerants, and its mass in the refrigeration system mainly depends on the volume of the condenser, evaporator, and the length of the liquid line in the refrigeration system. Reducing the length of the liquid line is relatively simple. The main design challenge lies in reducing the volume of the evaporator and condenser while maintaining the required performance and adapting the dimensions of microchannel heat exchangers to allow their integration into the pipes of the mechanical ventilation system.

STUDY OBJECT

The object of the study is a residential unit (Fig. 1) in a multi-family residential building located in Warsaw, within the third climatic zone. The heating load of individual rooms in the model flat was determined using the Audytor OZC software and is presented in Table 1. According to the calculations performed in Audytor OZC, the design heating load of the model flat is 2.997 kW. Therefore, it was assumed that the nominal heating capacity of the designed heat pump would be 3 kW.

ANALYSIS OF THE RECUPERATOR’S PERFORMANCE

As mentioned, the main design assumption for the hybrid heat pump is to utilise exhaust air

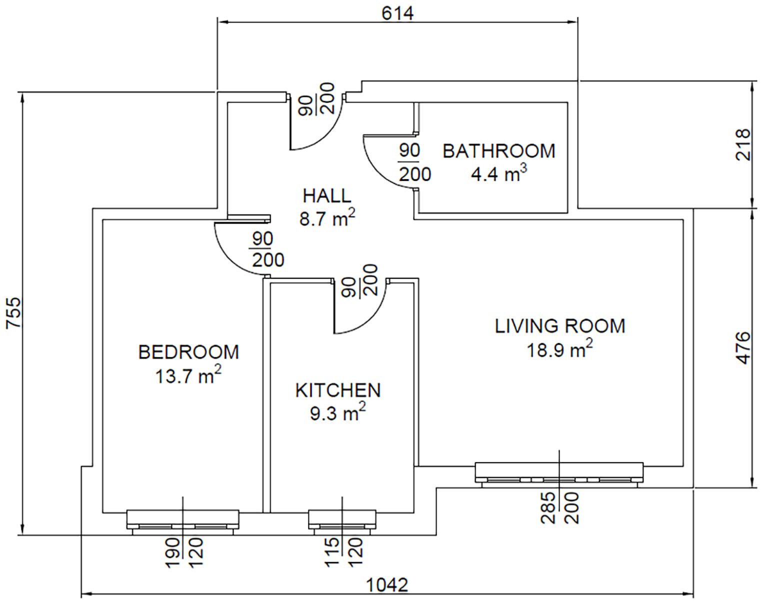

Figure 1. Building plan

Table 1. Heating load values of the model flat

Room type	Heating load [W]
Hall	467
Living room	884
Bathroom	477
Kitchen	433
Bedroom	736

from mechanical ventilation as the heat source for the heat pump (Fig. 2).

The mechanical ventilation recuperator model was implemented in Matlab and Simulink software using the iThermlib library. The performed summations showed that at a constant outdoor air temperature of -20 °C, the supply air temperature will be around 14 °C. A supply air temperature of -20 °C, according to the EN 12831 standard [5], represents the design temperature of the building and the most unfavourable operating condition for the device. The increase in supply air temperature to the design temperature of 20 °C must be provided by the compressor heat pump

MICROCHANNEL HEAT EXCHANGER

The standard design of a microchannel heat exchanger used in refrigeration systems is illustrated in Figure 3. A microchannel heat exchanger consists of parallel beams containing channels through which the refrigerant flows. Fins are

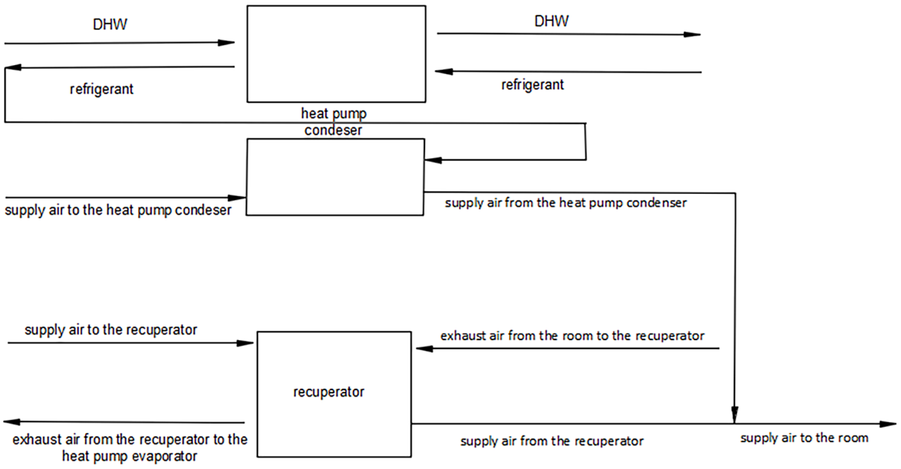

Figure 2. Hybrid heat pump model

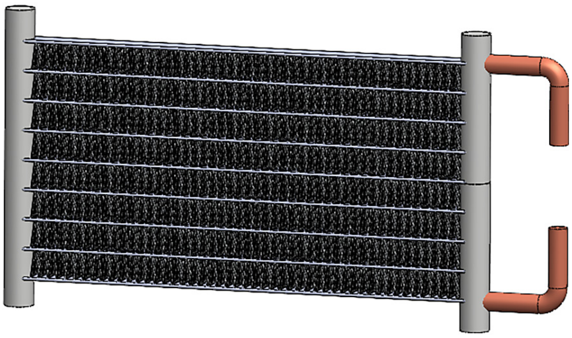

Figure 3. Microchannel beam heat exchanger

positioned between the beams of the exchanger to increase the heat transfer surface area. The exchanger is exposed to an air stream, which acts as the energy carrier. The main operating parameters of microchannel heat exchangers include the shape and dimensions of the microchannels, the length and shape of the refrigerant paths, and the thickness and spacing of the fins.

When selecting the heat transfer surface area of a microchannel heat exchanger, it is essential to determine its heat transfer coefficient. This is a complex and intricate process due to factors such as the complex geometry of microchannels. The cross-sections of microchannels are small, ranging from hundreds of micrometers to a few millimetres, which results in different fluid dynamics compared to plate heat exchangers. Additionally, microchannel heat exchangers consist of numerous parallel microchannels, which increases the complexity of the analysis due to the possibility of uneven flow distribution in individual microchannels. Modelling the flow and heat transfer in a microchannel heat exchanger requires advanced computational tools, such as CFD (computational fluid dynamics) [31]. It is a tool commonly used in fluid flow modeling, including cases where modeling of air flow is required [33–35]. Microchannel heat exchangers commonly used in refrigeration systems do not fit within the pipes of mechanical ventilation systems due to their dimensions. Therefore, it is necessary to develop a new design for microchannel heat exchangers, both in terms of the positioning of the exchanger beams relative to each other and the shape of the microchannels. Due to these reasons and the complex geometry of microchannels, the simulation studies were conducted on a simplified model of a 1-metre-long microchannel heat exchanger, consisting of a single fin and two beams with microchannels placed parallel on both sides of the fin. The sample was 22 mm high and 18 mm width. Each beam contained two coil runs with nine microchannels of various cross-sectional shapes. wide (Fig. 4, Table 2).

Simulation studies were conducted using SolidWorks software, utilising the Flow Simulation library, which employs CFD tools to analyse fluid flow and heat transfer. The simulations were carried out in two steps. In the first step, the flow analysis of the refrigerant was performed for different microchannel cross-sectional shapes (Table 2, Fig. 5) with an air volume flow rate of 1 m^3/h and a refrigerant mass flow rate of 0.005 kg/s. For the simulation studies, the most commonly encountered cross-sectional shapes of microchannels

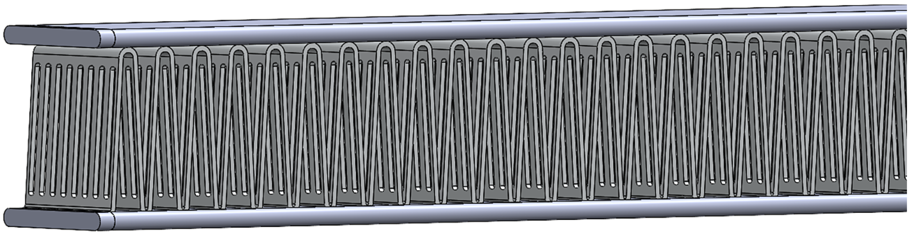

Figure 4. Modelled heat exchanger

Table 2. Design parameters of the tested microchannel beam heat exchanger

Parameter	Value
Model length [m]	1
Coil width [mm]	18
Coil height [mm]	2
Distance between coils [mm]	18
Shapes of the cross-section of the microchannel	Square, circle, triangle, hexagon, square with fluted sides, circle with fluted sides, triangle with fluted sides, hexagon with fluted sides, ellipse, horizontal rectangle, vertical rectangle, ”L” shape

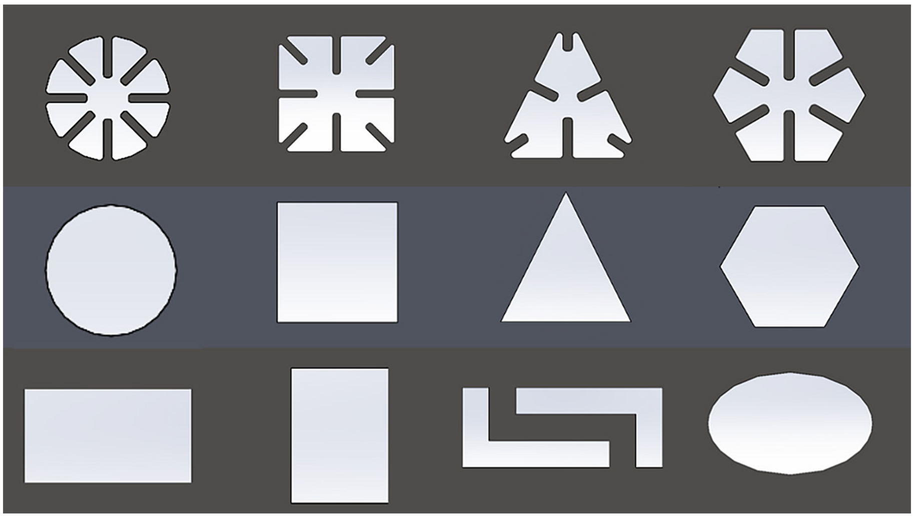

Figure 5. Shapes of the cross-section of the microchannel (from the left in the top row: circle with fluted sides, square with fluted sides, triangle with fluted sides, hexagon with fluted sides; from the left in the middle row: circle, square, triangle, hexagon; from the left in the bottom row: horizontal rectangle, vertical rectangle, "L" shape, ellipse)

were selected, such as circles, squares, and triangles, along with their corresponding cross-sectional shapes with an extended heat exchange surface (achieved by using corrugated sides of the microchannel cross-sections). The studies were also conducted for several innovative, unconventional microchannel shapes (ellipse, horizontal rectangle, vertical rectangle, 'L' shape). Then, simulation studies were carried out for selected microchannel shapes under varying operating conditions. The air volume flow rate was adjusted in increments of 10 m^3/s, and the refrigerant mass flow rate was adjusted in increments of 0.001 kg/s (Table 3).

ANALYSIS OF THE OPERATING PARAMETERS OF A MICROCHANNEL BEAM HEAT EXCHANGER FED WITH R290

The study quantified the improvement in cooling performance by analyzing the heat transfer rate values of the heat exchanger for different microchannel geometries. These indicators reveal how changes in channel shape affect heat exchange efficiency. The simulation studies included more than 500 simulations. Due to the vast amount of data, only the most significant results, according to the authors, are presented in this paper.

Effect of microchannel shape on heat exchanger output

Figure 6 shows a sample simulation of a 1-metre-long heat exchanger model with triangular cross-section channels. The tests were conducted with an R290 refrigerant inlet temperature of 40 °C, a refrigerant mass flow rate of 0.005 kg/s, an air temperature of 20 °C, and an air volume flow rate of 1 m^3/s. Under these initial operating conditions, the refrigerant outlet temperature dropped to 28.13 °C, and the outlet air temperature increased to 20.37 °C. In this case, the exchanger efficiency of the heat exchanger reached 342.28 W. Table 4 and Figure 7 present the results of the simulation

Table 3. Operating parameters of the tested microchannel beam heat exchanger

Parameter	Value	Notes
Volume flow of air [m^3/s]	$\dot{v}$ = (5 ÷ 55)	with a step of 10
Refrigerant mass flow [kg/s]	$\dot{m}$ = (0.001 ÷ 0.005)	with a step of 0.001
Refrigerant	R290	-
Refrigerant inlet temperature [°C]	40	-
AIr inlet temperature [°C]	20	-

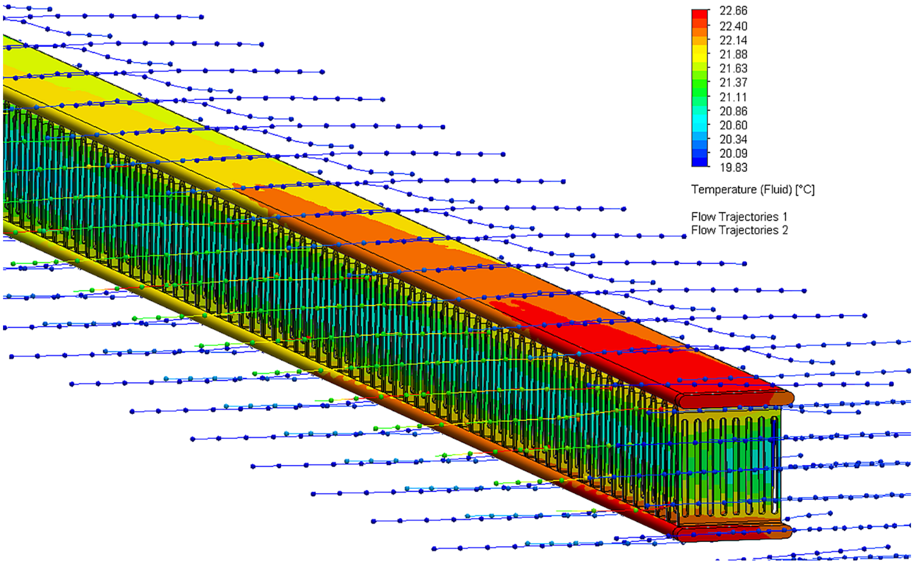

Figure 6. Sample simulation of temperature distribution on the heat exchanger model

studies. The analyses indicate that the highest exchanger efficiencies are achieved for triangular microchannel cross-sections and microchannels with fluted walls. Therefore, microchannels with these cross-sections were selected for further analysis. The "L" shaped microchannel was rejected due to excessive refrigerant flow resistance.

In the case of square cross-section channels, despite a surface area increase of 42.50%, the exchanger efficiency increased by only 9.11%. A more favourable increase in efficiency relative to the increase in heat exchange surface area occurs with hexagonal microchannels. An increase in the heat exchange surface area always leads to an increase in heat transfer rate (Fig. 8). The tests were conducted with a refrigerant mass flow rate of 0.005 kg/s and an air volume flow rate of 1 m^3/s.

Figure 9 shows the heat transfer rate values for the most commonly used microchannels with non-fluted cross-sectional shapes and microchannels with hexagonal and triangular cross-sections with fluted sides at an air volume flow rate of 55 m^3/s. The graph indicates that the efficiencies are similar in case microchannels with non-fluted cross-sectional shapes, but for most refrigerant flow rates, triangular shapes achieve higher efficiency values than microchannels with square, hexagonal, and circular shapes. Comparative analysis microchannels with non-fluted cross-sectional shapes and microchannels with fluted cross-sectional shapes shows that under the same operating conditions, the use of microchannels with hexagonal or triangular cross-sections with fluted sides significantly increases the heat transfer rate of the exchanger.

Table 4. Simulation results for different exchanger channel shapes

Channel shape	Heat transfer rate [W]	Heat transfer surface area [m^2]
Square	319.08	0.40
Square with fluted sides	348.15	0.57
Hexagon	324.14	0.38
Hexagon with fluted sides	349.07	0.47
Circle	324.78	0.38
Circle with fluted sides	343.46	0.51
Triangle	341.28	0.42
Triangle with fluted sides	346.42	0.49
Ellipse	317.08	0.37
Horizontal rectangle	312.07	0.38
Vertical rectangle	327.41	0.38
”L” shape	338.74	0.43

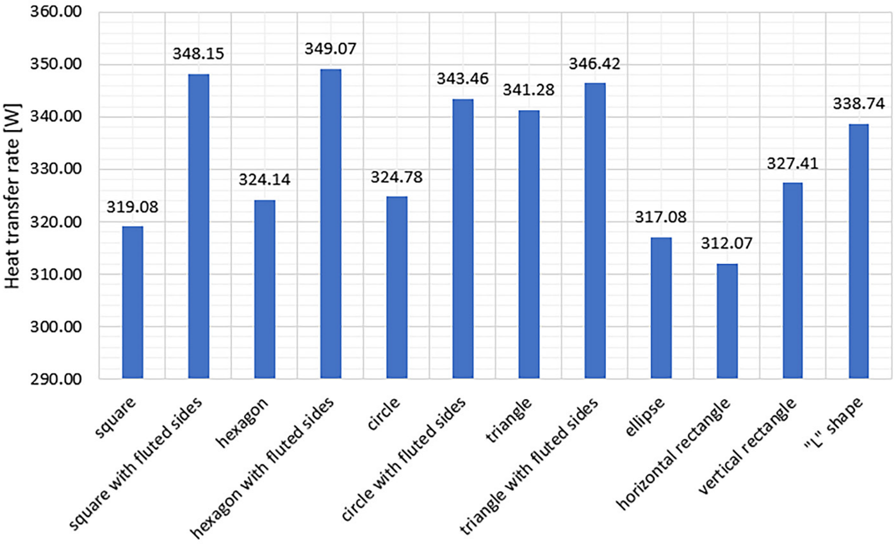

Figure 7. Comparison of heat transfer rate depending on microchannel shape

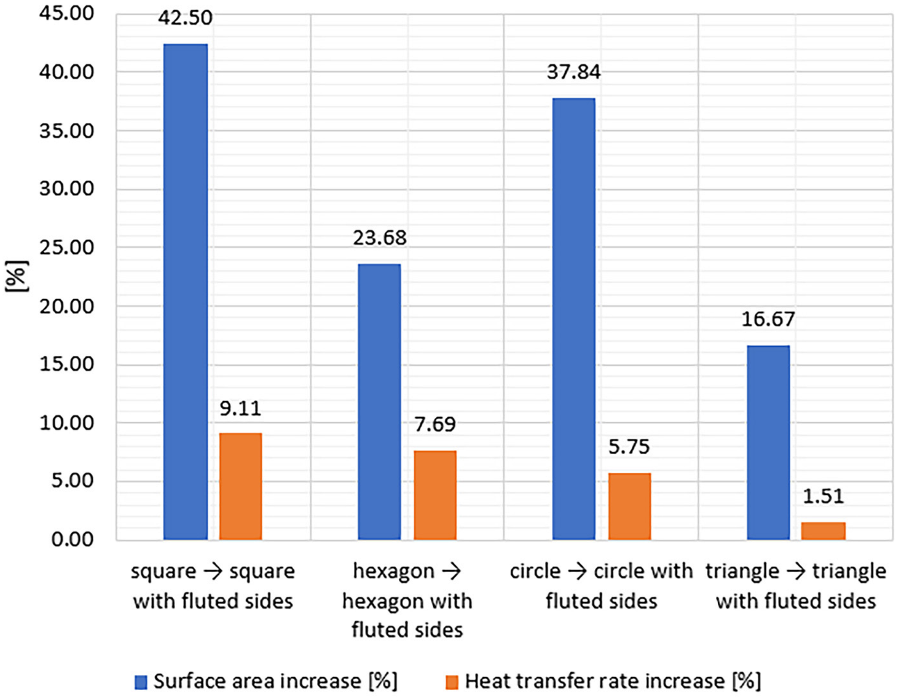

Figure 8. Increase in heat transfer rate and heat exchange surface area

Analysis of the heat transfer rate of a microchannel beam heat exchanger depending on the operating parameters

The analysis of the heat transfer rate of the heat exchanger depending on its operating parameters was conducted for selected microchannel shapes, for which the exchanger achieved the highest efficiency in previous analyses. Figures 10–12 show the heat transfer rate of heat exchangers depending on the cross-sectional shapes of the microchannels for different mass flows of R290.

For the lowest volumetric air flows, the heat transfer rate values of the heat exchanger do not differ significantly depending on the channel shapes. Differences become apparent only at higher air flows. At flows of 45 m^3/s and 55 m^3/s, an increase in the heat transfer rate of the heat exchanger is observed for microchannels with fluted cross-sections. The highest heat transfer

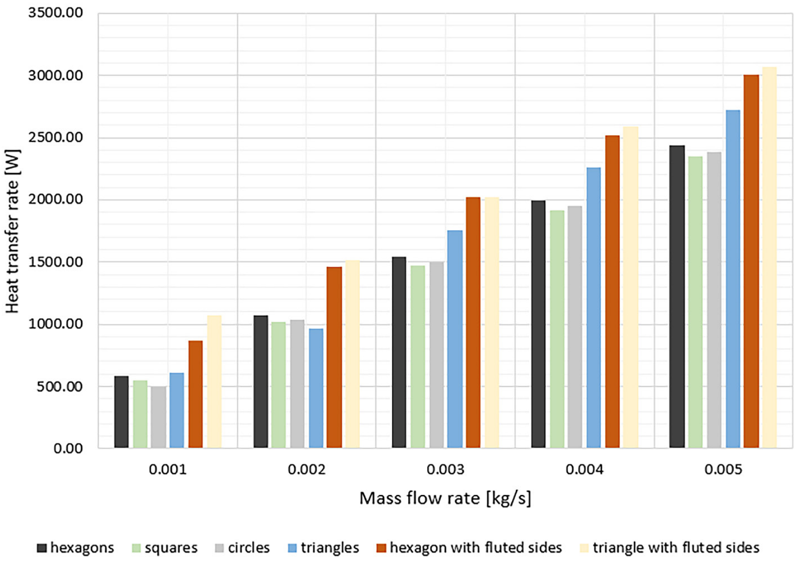

Figure 9. Heat transfer rate values at an air volume flow rate of 55 m^3/s for selected microchannel shapes

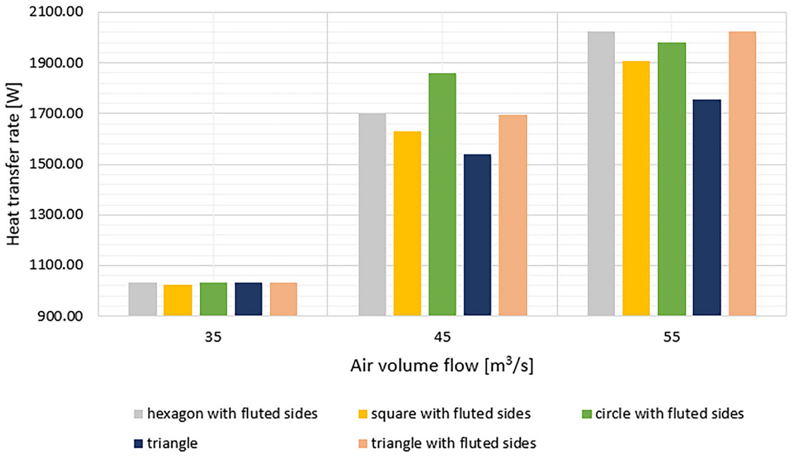

Figure 10. Heat transfer rate values for an R290 flow rate of 0.003 kg/s

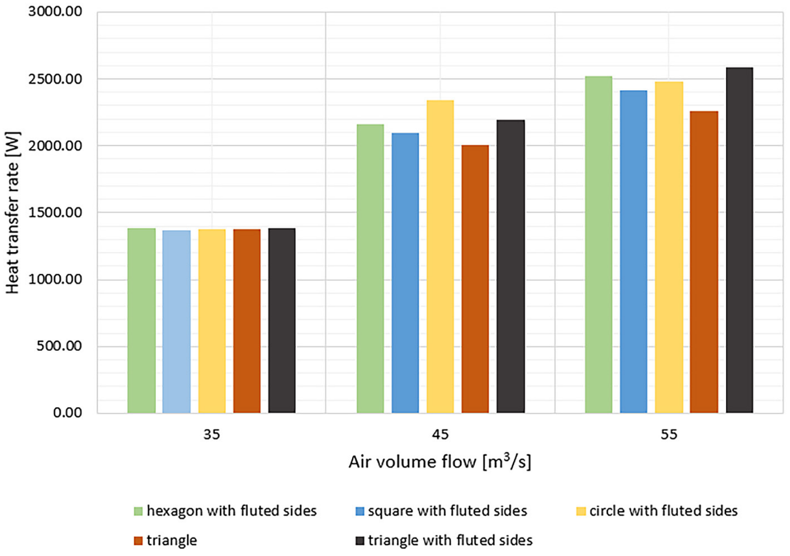

Figure 11. Heat transfer rate values for an R290 flow rate of 0.004 kg/s

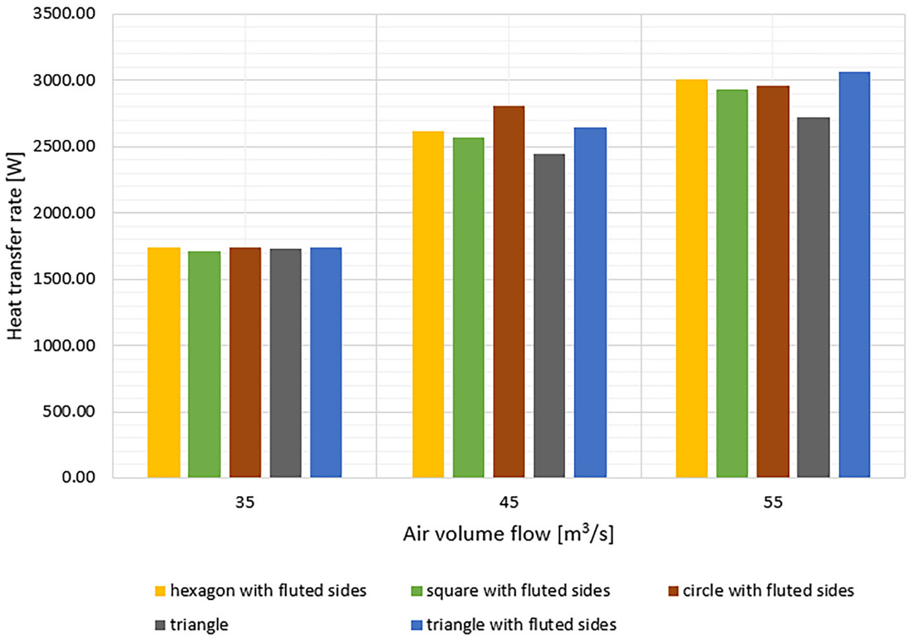

Figure 12. Heat transfer rate values for an R290 flow rate of 0.005 kg/s

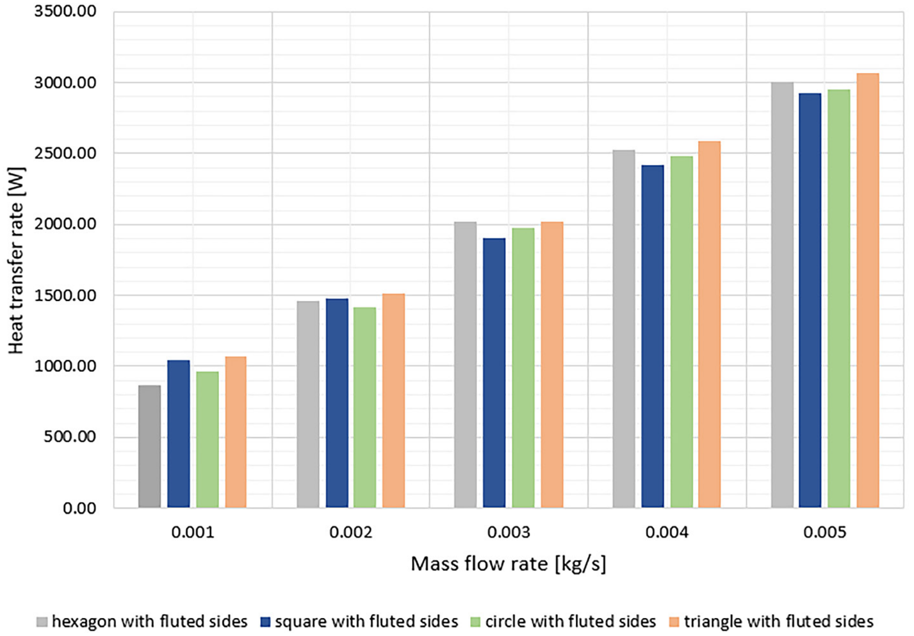

Figure 13. Heat transfer rate values at an air volume flow rate of 55 m^3/s for selected microchannel shapes

rate values are achieved with fluted triangular microchannels. Figure 13 shows the comparison of heat transfer rate values for microchannels with fluted cross-sections at a volumetric air flow rate of 55 m^3/s. The graph indicates that for the same operating conditions of the heat exchanger, the capacities are similar, but at higher refrigerant flow rates, fluted triangles and hexagons achieve higher heat transfer rate values compared to other microchannel shapes.

CONCLUSIONS

This paper presents an analysis of the performance of a microchannel heat exchanger using the natural refrigerant R290, which is a promising alternative to commonly used fluorinated refrigerants. R290 is a key solution in modern refrigeration, in the context of climate protection and ozone layer preservation, as it is characterized by a low impact on global warming and has no negative effect on the ozone layer. The analysis indicates that the design of the microchannel heat exchanger significantly impacts its cooling efficiency. The geometry and shape of the microchannels are parameters that have a substantial influence on cooling efficiency. By utilising microchannels with a regular hexagonal cross-section and fluted walls, it is possible to double the heat transfer rate of the condenser compared to commonly used microchannels with square and circular cross-sections. The use of microchannels with a regular hexagonal or triangular cross-section not only enhances the efficiency of the heat exchanger but also makes it possible to reduce its size while maintaining heat transfer rate. The developed design of the microchannel heat exchanger facilitates the reduction of the refrigerant charge in the refrigeration system. This provides potential and a basis for further research. In particular, attention should be given to the possibility of installing refrigeration units in enclosed spaces where the R290 refrigerant charge must be less than 150 grams. This would allow for the safe operation of refrigeration systems filled with a flammable refrigerant and would also influence the technological development of new refrigeration systems. Microchannel heat exchangers should undergo further studies, particularly regarding their applications in enclosed spaces, such as residential buildings, in units with a nominal heating capacity of up to 5 kWh. It is also necessary to conduct practical studies that validate the theoretical research and focus on the complexity of producing various microchannel shapes and their associated costs.

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