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Experimental investigation of the new approach for controlling the ejector-based R290 heat pump system utilizing two-phase ejector and thermoelectric subcooling module.

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1. Introduction

The global energy landscape is going through a transition forced by the growing need for sustainable and eco-friendly energy alternatives. The concerns over climate change and the harmful environmental impact of conventional energy sources, like coal-based boilers, have encouraged scientists to develop zero-emission systems. Heat pump systems have emerged as a significant player in this transition, specifically in the context of household heating sources. Such systems can harness natural energy sources with zero emissions. In recent years, following the ban on harmful hydrofluoroolefins (HFO) refrigerants [1] and the announcement of the European Union's energy policy [2], a very strong focus has been placed on the development of modern heat pump systems that will allow a cheap and environmentally beneficial transition to electrification of domestic heating. One of the main goals is to improve the efficiency of systems utilizing natural refrigerants, which are whose impact on the environment is negligible, so that they could be as competitive as the broadly used synthetic refrigerant heat pumps that were used extensively back in the day. Fixed-type ejectors represent a viable approach to enhancing the performance of refrigeration systems since they play an integral role in the heat pump systems' operational mechanism by recovering part of the expansion losses. These fluid-dynamic components work by utilizing high-pressure fluid to entrain and mix with low-pressure fluid. The fluid introduced to the motive nozzle expands and accelerates to supersonic speed. Consequently, thanks to the phenomena connected with supersonic flow, the motive and suction nozzle streams are thoroughly mixed and accelerated in a mixer of constant cross-section owing to the generated supersonic shockwaves. This results in the pressure at the ejectors' outlet exceeding that at the suction nozzle port.

Fixed-type ejectors offer reliability and simplicity due to their lack of moving parts, yet their efficiency is challenging to maintain due to the absence of control mechanisms. They have been successfully introduced to the refrigeration cycles showing efficiency improvement over the typical vapour compression systems. Roman and Hernandez [3] examined the theoretical behavior of an ejector cooling system utilizing a variety of working fluids such as propane (R290), butane (R600), isobutane (R600a), R152a, and R134a. Their study indicated that the system operating on R290 was distinguished by superior performance and efficiency. Moreover, the experimental analysis by Butrymowicz et al. [4] suggested that isobutane ejector systems could be effective competitors against absorption systems, provided the motive heat source's temperature is maintained below 80°C. However, these analyses primarily consider fixed-type ejectors, which are noted to lose efficiency under off-design conditions. Different approaches for controlling the capacity of the ejector were investigated in the literature, such as multi-ejector concept, variable-geometry ejector with needle, or vortex control generation. The multi-ejector concept was formulated by Hafner et al. [5] for medium- and large-capacity applications (e.g. supermarkets, reversible heat pumping equipment) utilizing the carbon dioxide (R744). It contains a combination of a few ejectors of with fixed geometry and different size. It allows for using different number of ejectors adjusting the R744 transcritical refrigeration system capacity for current cooling needs and maximizing their efficiencies, which contributes to the COP and exergy efficiency improvement by up to 7% and 13.7, as reported by Haida et al. [6].

The approach of needle-based ejector brought by Elbel and Hrnjak [7] was thoroughly examined numerically by Besagni et al. [8] for performance comparison of fourth generation and natural refrigerants (R1233zd(E), R1234yf, R1234ze(E), R290, R1270, and R600a) to synthetic commonly used refrigerants (R134a, R245fa, R152a) focusing on the possibility to control the capacity as well as the mass entrainment ratio when different fluids are concerned. The authors performed multi-scale analysis devoted to both local and global scale effect of the needle-based ejector and were able to control the ejector capacity. By changing the position of the needle inside motive nozzle the efficiency of ejector-based system can be increased for operating condition by an average of +5%. Zhu and Elbel [9] proposed a solution of vortex-based capacity control for the ejector, in which an adjustable vortex at its inlet is generated to control the nozzle restrictiveness (and thus the ejector capacity) without varying the nozzle geometry dimensions. The authors stated that the mass flow rate can be decreased by 36%, which directly contributes to the capacity decrease.

So far, no thermal control of the ejector’s capacity has been introduced and tested, hence the aim of this work was to propose the thermoelectric subcooling method for capacity control of the ejectors. The thermoelectric modules (TEMs) implemented between the working fluid heat exchanger (propane) and the auxiliary loop heat exchanger (glycol loop) according to the preliminary CFD study can reduce the motive nozzle mass flow rate of the ejector and improve the COP of the system by increasing the heating capacity of the heat pump system, in which the ejector with thermoelectric subcooler will be installed and tested experimentally. Such a solution has been widely investigated for the CO_2 vapour compression cycle [10]. Additionally, the subcooling of the liquid line is crucial for the ejector stable operation, which thanks to such a solution can be provided within a short period of time after the start of the device and facilitate precise control of the degree of undercooling even for variable environmental conditions.

2. System layout

The thermoelectric subcooler with TEMs was designed for the ejector-based R290 heat pump system designed for hot water production in domestic application. The system equipped with two brazed-plate heat exchangers, reciprocating Frascold compressor, liquid separator handling additional pressure level in the system and throttling valve for pressure lift parameter controlled was additionally equipped with microchannel heat exchanger with thermoelectric modules. The thermoelectric subcooler was installed upstream the two-phase ejector motive nozzle and the heat rejected from the system was used for preheating the water coming back to the auxiliary loop glycol tank. The schematic diagram of the ejector-based system with thermoelectric subcooler is presented in Fig. 1.

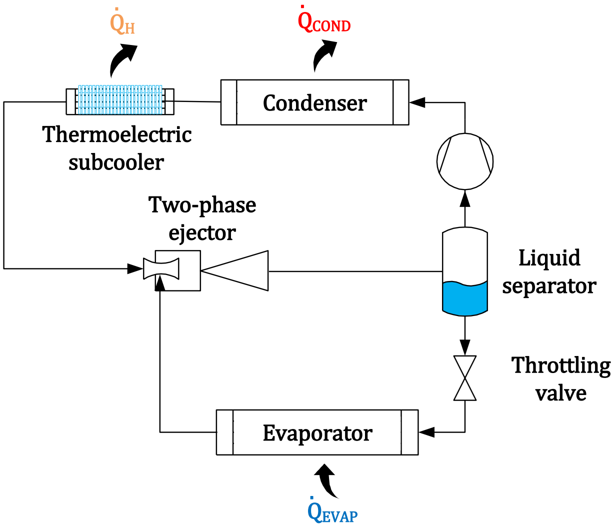

Fig. 1. Schematic diagram of the R290 ejector-based heat pump system with thermoelectric subcooler.

All the subcooler parts were made of aluminium and the total assembly consist of the microchannel R290 heat exchanger, two cold plates for glycol flow and 12 TEMs manufactured by Laird Thermal Solutions with a nominal heatiing capacity of 95.4 W at 25.0 °C of each. This solution allowed for manufacturing the compact size device providing high heat flux rate. All the parts were fixed tight by means of the fixer bolts attached to the external fixer plates. The subcooler assembly is presented in Fig. 2.

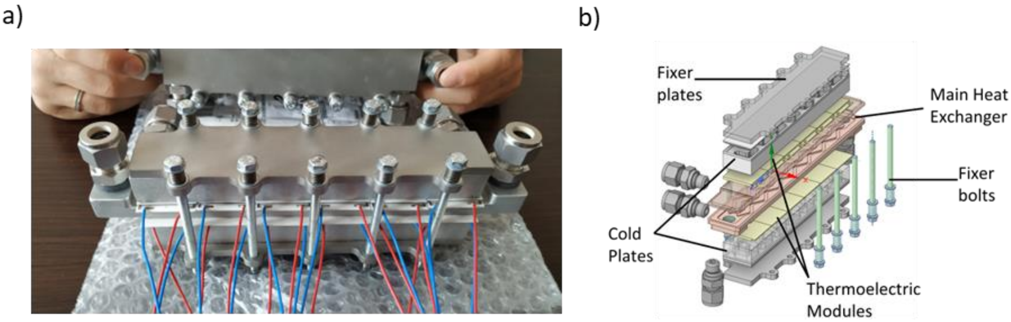

Fig. 2. The thermoelectric subcooler assembly: a) fully assembled device and b) assembly view in the 3D designing tool.

3. Preliminary results

The thermoelectric subcooler was designed using the Ansys Fluent CFD software coupled with the electrical calculations of the thermoelectric modules. In the on-design conditions the thermoelectric subcooler can bring the heating effect of 100 W for the warm climate zone and 125 W for the moderate climate zone, by supplying the modules with 6 V and 9 V, respectively, which allows to maintain high COP of the thermoelectric modules in the range of 5.5 and 3.5 for warm and cold climate zones. The graphical representation of the possible heating effect in the heat pump system producing the hot water at temperature of 35°C is presented in the Fig. 3.

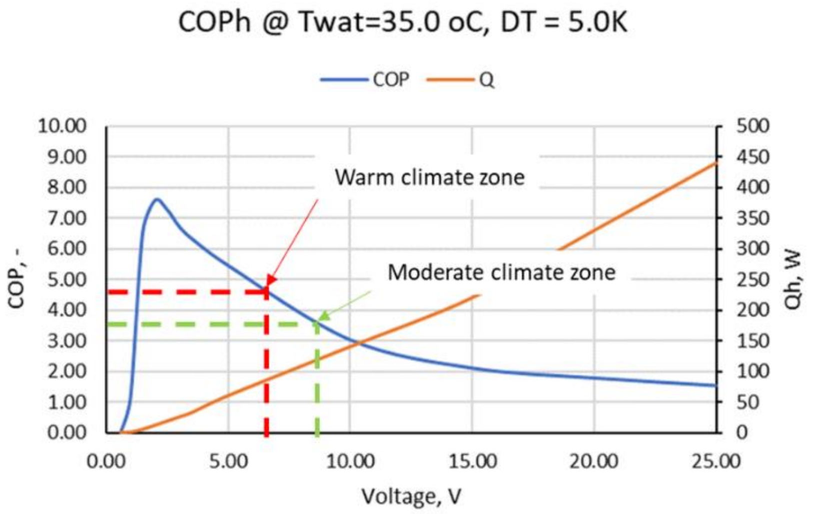

Fig. 3. Estimated heating effect of the thermoelectric subccoler installed in the R290 ejector-based heat pump for warm and moderate climate zones.

As far as the capacity control method is concerned, the possible subcooling degrees were then introduced to the CFD model of the R290 two-phase ejector to analyze the possibility of an increase of the ejector motive nozzle mass flow rate. The CFD results in terms of the mass flow rate, and two ejector performance parameters, i.e. mass entrainment ratio and ejector efficiency, exposed to the subcooling effect of the thermoelectric subcooler are presented in Fig. 4.

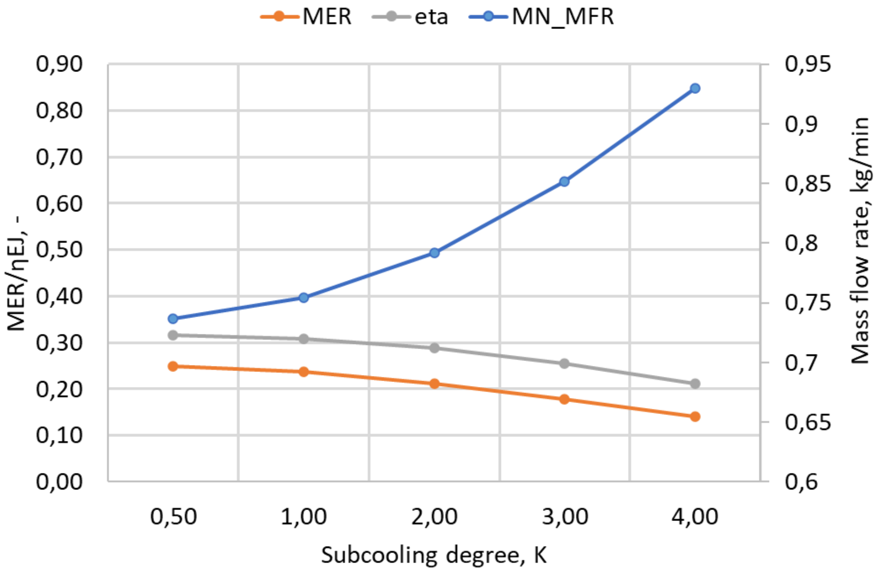

Fig. 4. The numerical simulation of the thermoelectric subcooler effect on the R290 two-phase ejector.

According to the CFD results, the mass flow rate can be increased up to 27% by subcooling the liquid by up to 4K. This also influences the ejector performance, which drops down from 0.3 to 0.2, mainly due to the drop of the mass entrainment ratio. This behaviour confirms that the subcooling of motive nozzle is connected only with the motive nozzle mass flow rate change and does not affect the ejector mixing of two streams of different pressure and temperature, and thereby the mass entrainment ratio, so its local effect only changes the condenser heating capacity. This effect is then additionally supported by the regeneration of heat in the auxiliary loop by the glycol coming from the subcooler cold plates.

4. Conclusions

The preliminary analysis showed a promising result for the thermoelectric modules capacity control method for two-phase ejector installed in the R290 heat pump for domestic application. The subcooling degree can help with adjusting the heating capacity of the system as well as improve the overall COP by recovering the heat from the subcooling for the auxiliary loop. Next step is to validate the results experimentally by installing the subcooler in the heat pump system and thoroughly test it in order to provide a control system for the capacity control and maximization of the subcooler effects on the system. In the future, other methods of manufacturing of the thermoelectric subcooling assembly will be tested, such as using the 3D printing method for manufacturing all the subcooler parts or combining the 3D printed metal parts for heat exchanger with hard and durable metal-powder-based resins for subcooler construction to study their impact on the final subcooler performance aiming to reduction of its production costs.

5. References

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