PH.D. THESIS

Non-equilibrium two-phase model of transcritical CO_2 flow for ejector design in state-of-the-art refrigeration systems

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Nierównowagowy dwufazowy model transkrytycznego przepływu CO_2 do projektowania strumienic w najnowszych systemach chłodniczych

Abstract

Dynamic growth of natural working fluids applied to the refrigeration and heating technology was firstly driven by the ecological aspects contained in law regulations starting from the Montreal Protocol in 1987 up to the current ratification of the European so-called F-Gas regulation. The group of natural working fluids contains such substances as water, air, ammonia, carbon dioxide (CO_2) and hydrocarbons. The CO_2 could be described as the most promising solution considering large systems where the implementation and exploitation occur near areas with personnel and customers presence. The characteristic of the CO_2 provides advantages in ecological and technical safety. Firstly, by means of the low impact on ozone layer depletion and global warming. Secondly, due to non-toxicity and non-flammability. Substantial efforts were executed in research and commercial fields regarding the last decade of development of the refrigeration and heating technology based on CO_2 as a working fluid. Namely, technical challenges correlated with the low temperature of the critical point and consequently high throttling losses were solved on the laboratory as well as on industrial scale. Key role of that solution could be assigned with the two-phase ejector that is the main topic of interest in this thesis is utilised for the expansion work recovery, reduction of the compressor power consumption as well as pump functionalities. The development path of the market could be indicated from the 2000s with the first commercial unit to 16 000 units in 2018 and 29 000 units in 2020 in Europe. Lower number of the units was reported for the North America and Japan, however similar percentage increase could be noticed in those regions as well. The growing number of units implicated new exploitation fields such as small convenient stores and mobile applications. Finally, the range of the CO_2 applications was enlarged in the meaning of the climate zones and correlated ambient temperatures and cooling loads.

In this thesis research activities could be divided into two parts: numerical simulations and experimental tests of a prototype ejector. The aforementioned enhancement of the climate zones with potential application was a part of the motivation for the development of the numerical model of the ejector operating in the mild climates. First attempts of the accurate simulation and then design possibilities of the ejector driven by subcritical motive conditions (below 73 bar and 31.1°C) were characterised by unsatisfactory under-prediction of the motive nozzle and consequently high discrepancy of the suction mass flow prediction. The numerical model developed in this thesis included additional equation devoted to the non-equilibrium phase-change in the motive nozzle. Additionally, the intensity of the boiling phase change was tuned

on the basis of the experimental mass flow rate data. The resulted relative error of the motive nozzle stream prediction was evaluated as a satisfactory. However, further development of the model were necessary for the accurate prediction of the secondary stream. This stage of the model development was described in the paper published in International Journal of Refrigeration. Further work involved coupled analysis of the cavitation influence and turbulence model selection. Additionally, the dedicated validation data was obtained from the R744 test rig located in the laboratory of Silesian University of Technology. The installation was designed for 50 kW of cooling capacity and is dedicated for the ejector tests due to additional measurement equipment. The presence of the cavitation phenomenon was predicted to occur in the mixing section where potential influence on motive and suction streams interaction was predicted. Unfortunately, this mechanism was evaluated as a negligible from the suction stream prediction point of view. On the other hand, screening of the turbulence models resulted in satisfactory accuracy with maintenance of the low-computational cost of the ejector simulation. The aforementioned reliable level of the resources required for the ejector analysis and consequently design process was one of the goals of the project. Finally, the ejector model was published in the Applied Thermal Engineering.

The second part of the thesis was focused on the new type of the ejector and development of its prototype including preliminary design as well as experimental tests. The specific feature of the prototype ejector was a bypass duct of the suction nozzle. This solution was analytically considered for ejectors with other working fluids than CO_2. The analysis provided high potential of this solution, however no experimental test were delivered. Hence, the idea of the suction nozzle bypass duct for the CO_2 ejector was numerically tested proving high increase of the suction flow rate, i.e. up to 37% compared to the standard design. The 2-D simulations evaluated an influence of the bypass duct geometry, positioning and operating conditions, particularly the pressure lift. The described study was published in the International Journal of Refrigeration. The conclusions from the preliminary analysis were utilised in the prototype ejector. The manufactured device was dedicated to the cooling capacity of approximately 50 kW. The experimental tests resulted in the performance maps, influence of the operating conditions and opening degree of the bypass duct on the prototype ejector efficiency. Additionally, simulations of the tested device delivered some insight into the flow characteristics and possible modifications of the suction chambers for further efficiency improvement. The proposed control strategy of the bypass duct opening could be easily implemented to the control and regulation systems of the state-of-the-art CO_2 units. The performance improvement at the level of 35% provided more uniform operation of the ejector along a wide range of the receiver pressure. Since the prototype utilises the same number of ports as standard ejector, there is a possibility of drop-in replacement without modifications of the installation layout. The analysis of the bypass ejector was published in the Applied Thermal Engineering with a recommendation for further development of this promising solution.