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Non-equilibrium approach in simulations of the R744 flow through the motive nozzle of the two-phase ejector

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ABSTRACT

The ejector technology for R744 systems was continuously improved over the last two decades in the area of control and design processes. The latter should be related with a significant interest on modelling approaches including numerical simulations. However, some limitations of the existing approaches are still present, while the application range of the ejectors is still increasing regarding mobile and domestic applications. Namely, a quality of the flow prediction in the transcritical two-phase ejector varies depending on the operating conditions and correlated phenomena. The accurate and time efficient computational approach including the operating range of low condensing pressures is presented with the aim of more effective ejector design. The mixture approach developed on the basis of the Homogeneous Equilibrium Model is described regarding prediction of the motive and suction mass flow rate which are crucial for proper control procedures of the ejector-based refrigeration cycle. Additional equation for the vapour quality transport and re-formulated property definitions are utilised for proper control of the evaporation process in the motive nozzle of the ejector. Coefficients in source terms of the quality equation were mapped regarding high accuracy of the motive mass flow rate prediction. Hence, the calibration procedure of the coefficients, resulting in an approximation function as well as mapping of the suction nozzle accuracy regarding turbulence modelling and cavitation phenomena are introduced in this study. Finally, a comparison with the baseline homogeneous equilibrium model is given on the basis of the mass flow rate prediction and field parameters.

Keywords: Carbon Dioxide, Transcritical Ejector, Phase change modelling, Expansion modelling

1. INTRODUCTION

Currently ratified by the (European Commission 2018), the Kigali Amendment has been enforced since the first day of 2019, making the phase-in of natural refrigerants an even more global initiative. Analysis of possible alternative refrigerants with low Global Warming Potential (GWP) concluded that natural refrigerants, such as R744, can overcome HFC and HFO (hydrofluoroolefin) mixtures (Mota-Babiloni et al. 2015; Purohit, Gullo, and Dasgupta 2017). Furthermore, the development of ejector technology has become an increasingly substantial part of the state-of-the-art R744 refrigeration. Elbel and Lawrence (Elbel and Lawrence 2016), in a comprehensive review of ejector technology in vapour-compression refrigeration systems, confirmed that cutting-edge refrigeration is strongly connected with highly efficient ejectors. Analysis of the current achievements and future perspectives in the ejector technology was presented in the work of (Besagni 2019). That study contains a comprehensive review of current and possible ejector implementations. Both aforementioned reviews described design tools as an important area of research and further development of the ejector technology dedicated for refrigeration based on the natural working fluids.

The crucial data for the ejector-based refrigeration unit design is contained in the mass flow rates required and delivered by the ejector motive and suction port respectively. Hence, the accuracy of the data prediction for the given ejector shape is a point of interest as well. Advanced tools from the scope of computational fluid dynamics were described in the literature regarding its accuracy in a proper area of the operating conditions which influence the phenomenon scope occurring in the ejector ducts. In the region of the motive pressures from 50 bar to 70 bar metastability effects increased influence on the computation accuracy. Current

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development of the numerical models dedicated for the R744 ejector simulations were briefly described in the last work focused on the non-equilibrium approach (Bodys et al. 2020). The path from the examples of the effective 1-D (Banasiak, Hafner, and Andresen 2012) and advanced 3-D models (Giacomelli, Banasiak, and Hafner 2018; Giacomelli, Mazzelli, and Milazzo 2018; Lucas and Koehler 2012; Palacz et al. 2016; Yazdani, Alahyari, and Radcliff 2012) was described regarding models features and its consequences in the mass flow rate prediction accuracy. Moreover, the authors developed model on the basis of the previously formulated homogeneous equilibrium model (HEM) approach (Smolka et al. 2013). However, the model was extended by the additional transport equation of the vapour quality with a source term responsible for a boiling phase-change during an expansion process in convergent-divergent motive nozzle (HNB). The model was validated including 150 operating points obtained from the R744 test rig located at SINTEF/NTNU laboratory in Trondheim, Norway. Resulted high accuracy of the motive nozzle mass flow rate were obtained where over 90 % of the points was predicted with the relative error lower than 10 %.

In this study, the aforementioned HNB model was utilised for the analysis of the ejectors operating in the other installation than used for the calibration and validation process. The analysis of a visualisation ejector and a bypass ejector installed in the R744 laboratory refrigeration unit in the Silesian University of Technology (Gliwice, Poland) were conducted for the low motive pressures using the HNB model. Hence, the accuracy of the model was validated on the basis of two independent test rigs. Resulting accuracy and the flow analysis were presented with special concern on the effective design tools prepared for the utilisation in R744 refrigeration.

2. MATHEMATICAL MODEL AND RESULTED ACCURACY REGIONS

Detailed description of the mathematical model was presented in the study denoted to the model development (Bodys et al. 2020). The approach of a real fluid compressible flow and homogeneous equilibrium presented by Smolka et al. (Smolka et al. 2013) was extended by additional equation of the vapour quality based on the source term related with the boiling phenomena. The mathematical basis of the model will be presented in more detail during the conference as well. The model was introduced to the in-house developed code in the form of computing platform called *ejectorPL*. The platform was utilised in a calibration of the model where 150 operating points and two ejector geometries were involved. The graphical representation of the motive conditions from 50 bar to 70 bar of the aforementioned operating points were presented in Fig. 1 for the smaller (a) and larger nozzle (b). Moreover, the conditions of the suction nozzle and outlet port were indicated for low pressure lift (approximately 4 bar) and high pressure lift (approximately 8 bar).

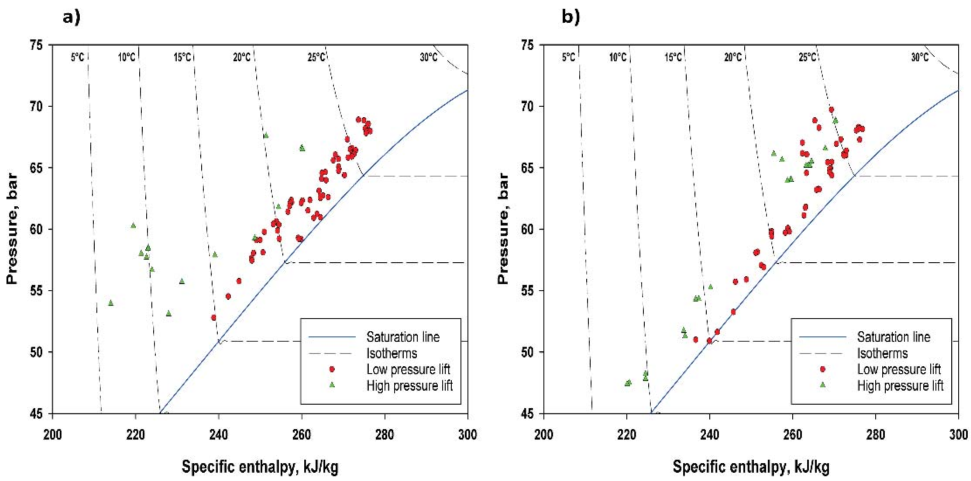

Figure 1: Operating conditions of the motive nozzle inlet utilised for the HNB calibration on the basis of smaller (a) and larger (b) motive nozzle throat (Bodys et al. 2020).

These points were used for the calibration of the coefficients in the boiling source and then for the development of the universal approximation function which utilized absolute pressure and specific enthalpy at the inlet of the motive nozzle. Resulting accuracy dispersion for both nozzles were presented in Fig. 2. In general, over 80% of the motive nozzle mass flow rates were predicted with the relative error below 10%.

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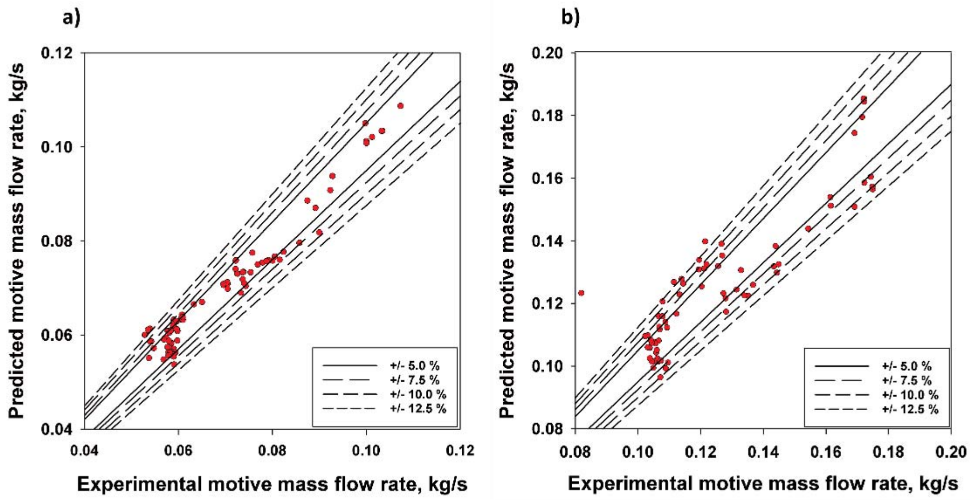

Figure 2: Accuracy dispersion of the HNB approach for the smaller (a) and larger (b) motive nozzle throat (Bodys et al. 2020).

3. EFFECTIVE AND VALIDATED NUMERICAL TOOL USED FOR THE EJECTOR PERFORMANCE ASSESSMENT.

Regarding the high accuracy of the model and low computational cost on the level of 40 minutes, the model was used for the analysis of the ejectors installed in the laboratory test rig in Gliwice, Poland. Additional description of the test rig features, measurement equipment as well as its accuracy will be presented during the conference. Especially, the motive nozzle mass flow rate was crucial from the point of view of the compressor size. The ejectors goal is different however its motive nozzles are similar hence it could be served by the same compressor. Namely, the construction of the first ejector was designed in order to visualise the flow through the mixing section and diffuser. The visualisation ejector was presented in Fig. 3 with the picture of the visualisation layout. Regarding the best authors knowledge, it is the first reported in the literature R744 ejector with circular cross-section manufactured using transparent mixing and diffuser section for the visualisation purposes. The second ejector was devoted for the analysis of prototype bypass duct of the suction nozzle. The experimental analysis of the bypass ejector using R744 as a working fluid was not yet reported in the literature. Regarding the operating conditions of the bypass ejector where chocking phenomenon is provoked by the high motive and low suction pressures, the HNB computations where not used. However, the HNB model was utilised for the analysis of the off-design conditions of the transparent ejector. The computational analysis was based on the experimental data delivered from the test rig which will be described during the conference. Furthermore, more detailed discussion based on the experimental tests on both ejector constructions will be provided during the conference as well.

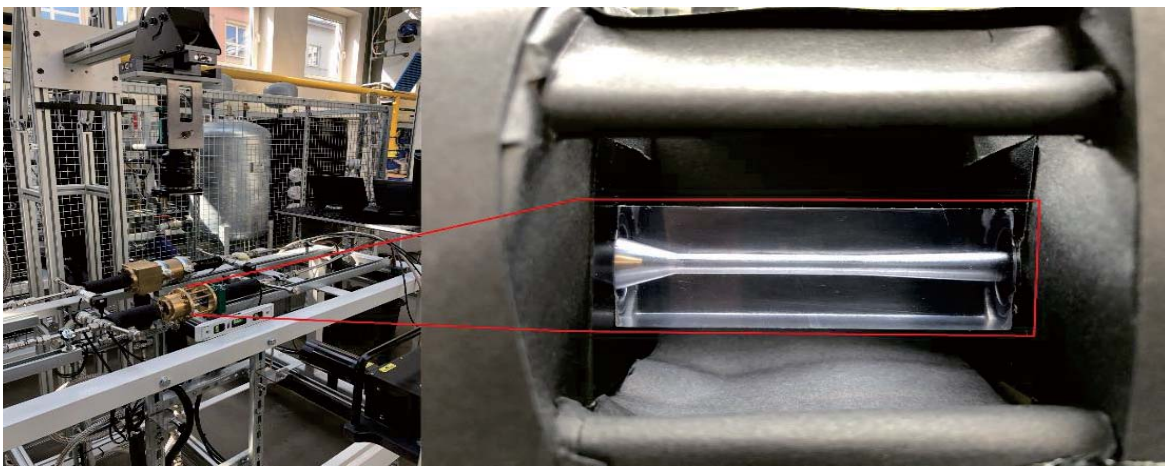

Figure 3: Photography of the R744 visualisation ejector at the laboratory test rig (on the left) and zoomed view of the transparent section including suction nozzle, mixing section and the diffuser.

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4. NUMERICAL ASSESSMENT OF THE EJECTOR DEDICATED TO THE VISUALISATION STUDY

The extension of the HNB approach was introduced in a form of a cavitation modelling. The phase change related with this phenomenon was based on the approach presented by (Singhal et al. 2002). Hence, additional source term R_{cav} was implemented to the transport equation of the vapour mass fraction. This term was presented in equation (1):

$$R_{cav} = C_e \frac{\sqrt{k}}{\sigma} \rho_l \rho_v \left[\frac{2}{3}\frac{P_v - P}{\rho_l}\right]^{\frac{1}{2}} (1 - f_v) \quad (1)$$

In similar to the source term correlated with the boiling phase change, the cavitation source term requires empirical assessment of the coefficient C_e which directly indicates the intensity of the vapour phase generation rate. Analysis within 10 operating points with the motive pressure between 60 bar and 70 bar was based on the experimental tests at the laboratory R744 refrigeration unit located in Gliwice, Poland. The obtained data allowed for the assessment of the aforementioned formulation presented by (Singhal et al. 2002). Namely, the coefficient value of 2 and 4 was investigated since its influence is visible regarding the motive nozzle mass flow rate. The motive nozzle prediction accuracy of the simulations based on the HNB approach and with additional cavitation source terms is presented in Fig. 4. First of all, the HNB over predicted motive nozzle mass flow rate from 7% to 12%. Introduced cavitation phenomena was related with intensified evaporation during the expansion process. Hence, the motive nozzle mass flow rate was reduced. Average reduction of the motive nozzle mass flow rate between neglected and introduced cavitation phase change was on the level of 3 percentage points. Therefore, this modification had the minor effects on the motive nozzle mass flow rate.

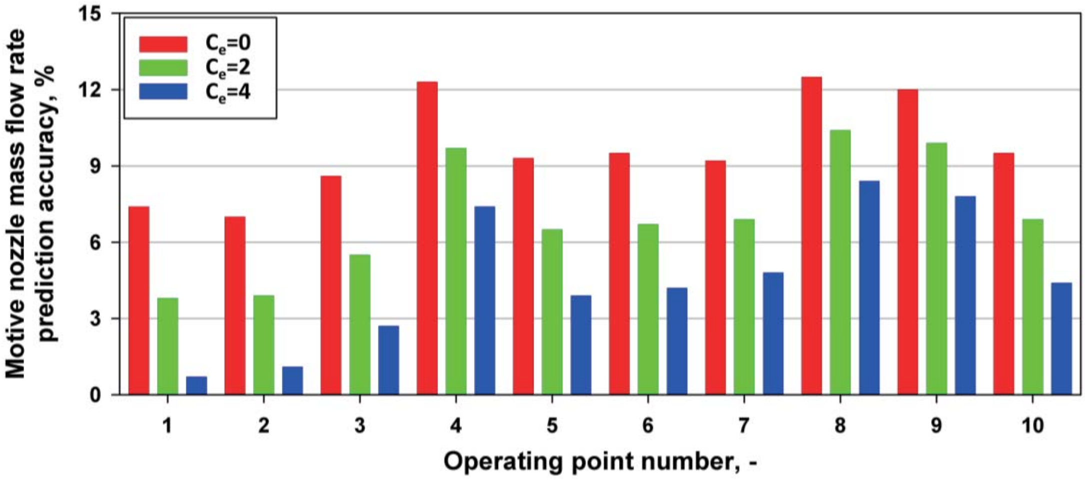

Figure 4: Motive nozzle mass flow rate prediction accuracy for baseline HNB approach (green bars) and with a cavitation phenomenon correlated with the coefficient value equal to 2 (green bars) and 4 (blue bars).

On the other hand, the modification of the evaporation process introduced noticeable changes to the thermodynamic properties along the motive nozzle divergent part. The vapour quality from the operating point characterised by the motive pressure of 60 bar was presented in Fig. 5 for the baseline HNB simulation and for the cavitation cases. In order to improve clarity of the comparison, range of the contours was limited to 0.2 and 0.25 for HEM with HNB comparison and cases with cavitation respectively. The instantaneous evaporation of the HEM approach comparing to the HNB is visible along the divergent part of the motive nozzle. The difference in vapour quality of approximately 0.18 is visible at the motive nozzle outlet cross-section This difference has its consequence in the under prediction the motive nozzle mass flow rate for HEM by approximately 26 %. Next, the utilised cavitation model was successfully verified since the regions of the highest cavitation-based evaporation was expected in the near-wall cells. In the Fig. 5 the intensified cavitation results in higher level of the vapour quality around the motive nozzle walls where the level of vapour quality equal to 0.1 was marked and described. Hence, the intensified cavitation resulted in higher vapour quality level closer to the motive nozzle throat.

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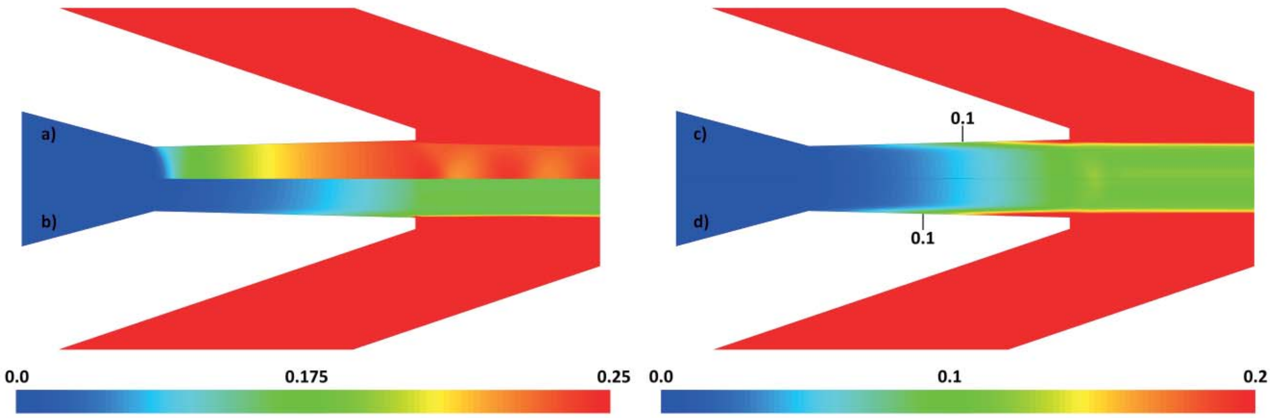

Figure 5: Vapour quality distribution in the motive nozzle obtained from the HEM (a), HNB with no cavitation (b) and HNB with cavitation related with coefficient C_e equal to 2 (c) and 4 (d).

5. CONCLUSIONS

The HNB model was calibrated using wide range and large number of operating points obtained from the experimental test rig equipped in the multi-ejector module. In this study additional and independent validation procedure of the model was provided utilising ejector of different shape and capacity. Moreover, the experimental data was delivered from the laboratory test rig characterised by different layout and cooling capacity. It is worth to mentioned that test rig was dedicated to the ejector investigations. In a result, previously obtained approximation function for the phase-change intensity was successfully utilised for the visualisation ejector during off-design conditions. The resulting accuracy proved the high potential of the developed approach regarding motive nozzle mass flow rate prediction.

The same approach based on the additional equation of the vapour mass quality was extended by the cavitation term source proposed by Singhal (Singhal et al. 2002). Successful verification of the implemented sub-model was based on the cavitation phase-change in the expected regions – namely in the near-wall regions characterised by higher turbulence intensity. Furthermore, intensity of the cavitation could be effectively regulated and finally adjusted using proper coefficients in order to meet experimental data in form of mass flow rate or visualisation pictures. In latter scenario, application of the most proper turbulence model for the advanced CFD design tools would be equipped in the validation source.

Hence, further work will be focused on the mixing phenomena and suction stream assessment regarding the cavitation and turbulence models selection for the optimum accuracy and time cost required for the developed computational tool.

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