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DIPARTIMENTO DI ENERGIA

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Professor Jacek Smolka,
Institute of Thermal Technology, Silesian University of Technology,
Gliwice, Poland

Ref.: "*PhD Dissertation of Jakub Bodys - Non-equilibrium two-phase model of transcritical CO2 flow for ejector design in state-of-the-art refrigeration systems.*"

Attached to this letter, the evaluation of the PhD Dissertation of Jakub Bodys "*Non-equilibrium two-phase model of transcritical CO2 flow for ejector design in state-of-the-art refrigeration systems*" is provided.

Based on the comments and observations, I recommend that the candidate be admitted to the defense of his thesis to obtain the PhD title at *SUT*.

Also, based on the quality of the work, taking into account the present-day state-of-the-art, the achieved results, I recommend a **distinction** for this thesis work.

Best Regards,

Dr. Giorgio Besagni, Ph.D
Assistant Professor at Politecnico di Milano
Department of Energy
Via Lambruschini 4, 20156 Milano, Italy
e-mail: giorgio.besagni@polimi.it

Firmato digitalmente da:GIORGIO BESAGNI
Organizzazione: POLITECNICO DI MILANO/80057930150

Annex. Evaluation of PhD Dissertation of Jakub Bodys - Non-equilibrium two-phase model of transcritical CO2 flow for ejector design in state-of-the-art refrigeration systems

The PhD dissertation presented by Jakub Bodys concerns a coupled experimental numerical study of R744 ejectors, and it is composed of 4 monothematic papers. In particular, the thesis is divided into two main parts/topics (i) a numerical investigation and (ii) an experimental investigation of an ejector prototype. In turn, the two parts are structured into sub-sections, building on the contents of 4 monothematic papers.

The general goal of the dissertation is to contribute to the existing discussion on multi-scale ejector performance analysis, encompassing the local scale (provided by numerical tools), to understand and clarify the behaviour at the component scale (supported by experimental methods). Such knowledge is needed to set up an ad-hoc control systems to extend the operation range of ejector-based systems; indeed, an ejector is a fluid-dynamic controlled device, and a change in the local scale affects the performance at the component scale. The proposed thesis has different specific goals within this general framework, as clearly listed and discussed in Section 1.5.1 and Section 1.5.2: all listed goals have been achieved, and the limitations of the present dissertation have been listed.

First, on the numerical side, the thesis aims to improve previously developed numerical models for R744 ejectors, including additional physics within existing modeling approach to extend their range of applicability (the candidate proposed the *HNB* modelling approach as an extension of the previously developed modelling methods). The different phases of numerical model development have been discussed, presented, commented, and its limitations have been discussed. Also, the novel modelling approach has been validated and compared with experimental data, strengthening the quality of the dissertation itself. It is worth mentioning that the numerical results are discussed with different connections between the numerical modelling settings and assumptions and the local fluid dynamics and the local scale (e.g., the phase change process happening more or less instantaneously and relationships with *HEM* assumptions). These considerations are very much appreciated.

Second, the proposed thesis contributes to the existing discussion on the ejector control-systems by proposing a bypass ejector (bypass located into the diffuser) with two suction zones based on numerical and experimental investigations. The proposed idea is original, interesting and valuable: such a control system is less studied in the literature, where most of the studies focused on needle-based, moving nozzle systems or other bypass strategies bypass. To this end, a coupled numerical/experimental approach is used. The former supports the ejector's design, and the latter clarifies ejector performances experimentally. The study of an ad-hoc prototype is valuable, and the prototype building and structure has been discussed.

Based on the comments and observations, I recommend that the candidate be admitted to the defense of his thesis to obtain the PhD title at *SUT*.

Also, based on the quality of the work, taking into account the present-day state-of-the-art, the achieved results, I recommend a **distinction** for this thesis work.

In the following, a list of detailed comments is provided to improve the work's quality.

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1. In *paper#1*[1], the candidate discussed including a source term for "*boiling*" in an additional transport equation; then, the candidate developed a calibration map (simulating experimental tested conditions) for the tuning coefficient within the source term. The calibration procedure was obtained using a fixed turbulence model (*k-ε based model*). Subsequently, in *paper#2*[2], the candidate discussed the inclusion of a second source term for "*cavitation*" along with the previously obtained formulation for the "*boiling*" effect. In this phase, the candidate performed a sensitivity study on the calibration coefficient within the "*cavitation*" source term for different turbulence models. Thus, the calibration procedures were performed one after another; however, the outcomes for the "*boiling*" effects were obtained for a precise turbulence model, where no screening of turbulence effects. This aspect needs to be discussed in more detail, considering that the primary/secondary flow interactions are of primary importance in ejector performance prediction (this is also related to *remark#4*).

2. As a follow-up to the previous remark, I feel that the two source terms included might be "*blended*" to have a unique formulation, where one of the effects depends on the other, depending on the local flow properties. This would also help distinguish regions where cavitation (e.g., related to pressure difference) and boiling (e.g., related to thermal difference) prevail. Such a procedure might be also beneficial in the case of a couple calibration procedure (below concern).

3. It is stated that the calibration procedure of the "*boiling*" source term was conducted in the region below 70 bar. It might be better explained why a calibration procedure encompassing conditions above 70 bar is not conducted; this might help obtain a more general and comprehensive modelling approach.

4. Before discusisng the concern, a brief introduction is needed. In general, the performance of ejectors can be easily explained considering that the ejector operation relies on two concurrent physical phenomena: (i) the low-pressure fluid entrainment process caused by the primary flow expansion and (ii) the compression effect, provided by the diffuser, which raises the secondary flow pressure. These two effects are contrasting, and an improvement of the former would deteriorate the latter. For this reason, the performance of an ejector needs to be provided considering both the entrainment ratio in on-design operation and the critical pressure (or providing the ejector operating curves). Coming to the core of the thesis, in papers#3[3] and #4[4], when discussing the bypass ejector, it is stated that the double bypass affects the pressure recovery and proposed and more uniform pressure within the ejector. Such a control system is more beneficial, especially at lower pressure lifts. It is also discussed that using such a control system helps obtain a more uniform efficiency of the ejector in its operating range.

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[1] Bodys, J., Smolka, J., Palacz, M., Haida, M., & Banasiak, K. (2020). Non-equilibrium approach for the simulation of CO2 expansion in two-phase ejector driven by subcritical motive pressure. International Journal of Refrigeration, 114, 32-46.
[2] Bodys, J., Smolka, J., Palacz, M., Haida, M., Banasiak, K., & Nowak, A. J. (2022). Effect of turbulence models and cavitation intensity on the motive and suction nozzle mass flow rate prediction during a non-equilibrium expansion process in the CO2 ejector. Applied Thermal Engineering, 201, 117743.
[3] Bodys, J., Smolka, J., Banasiak, K., Palacz, M., Haida, M., & Nowak, A. J. (2018). Performance improvement of the R744 two-phase ejector with an implemented suction nozzle bypass. International Journal of Refrigeration, 90, 216-228.
[4] Bodys, J., Smolka, J., Banasiak, K., Palacz, M., Haida, M., & Nowak, A. J. (2018). Performance improvement of the R744 two-phase ejector with an implemented suction nozzle bypass. International Journal of Refrigeration, 90, 216-228.

When discussing the effect of the proposed control system, the candidate need also to comment on the changes in the ejector operating curve (and on the changes in the entrainment ratio and the critical points). This is of particular importance as the entrainment ratio is constant in ejectors (without such a bypass) when operating in on-design mode (double-checked condition). As the proposed ejector seems to overcome this limitation, it would be beneficial to present the changes in the ejector operating curves.

5. The structure of the jet flowing outside the primary nozzle is known to affect the ejector performance. For example, in some studies, a more over-expanded jet increased the entrainment ratio and reduced the critical pressure (and vice-versa). The candidate might elaborate on the changes of the primary flow jet and the related changes at the entrainment ratio and critical point reported in the previous point. In Papers#3 and #4, some details are given, but a more detailed discussion should be devoted and not only limited to the dimensions of the shock train patter but also to the jet structure itself. Such considerations need to be coupled with the comments at Remark#4.

6. Based on the outcomes given at remarks#4 and #5, the candidate might also elaborate on the combined use of a suction chamber bypass with other control systems (e.g., needle-control systems or moving nozzles or primary flow bypass).

7. It is mentioned that a turbulence intensity of 10 % is used as boundary conditions. As such a value may seem higher than the previous literature (e.g., 5% for the primary and secondary or 5 % for the primary and 2 % for the secondary), what is the influence of such a value on the numerical outcomes?