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Thesis Review Report

Author of the thesis: Pawel Jakończuk

Title of the thesis: Investigations of an ejector refrigeration system with flashing in the motive nozzle

Submitted to: Faculty of Mechanical Engineering, Bialystok University of Technology, Bialystok, Poland

1) Aim of the work and scientific novelty

Cooling and heat pump systems play a very important role in modern society, independently whether developing or developed regions of the world are considered. Long-term sustainability of these technologies, at their current market development stage, is questionable and therefore their (electrical) energy consumption and environmental impact are critical issues to achieve targets established e.g. by the EU. This directly puts the pressure on the scientific community to find more efficient and environmentally friendly cooling solutions. Additionally, about 2/3 of the energy used by the industrial sector is in the form heat and, according to the literature, about 1/3 of it is lost to the environment. The exploitation of the industrial waste heat recovery potential will be essential for meeting the challenging carbon targets and achieving circular economy. It is estimated that the industrial waste heat recovery market will be as big as 30000 million euros in Europe by 2030.

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The topics addressed in the submitted thesis aligns well with this aforementioned context. Refrigeration systems and heat pumps integrating ejectors are in a strong expansion stage. Meanwhile, there is a need for the improvement of their energy efficiency and prove their liable operation, in particular when using new low-GWP working fluids and a low-grade heat source. The development of accurate and low-computational cost mathematical models will play an important role for component design and optimisation. The submitted thesis focuses on the analysis of the flashing type flow in the primary nozzle of (supersonic) ejectors. The primary objective of the work was to assess the performance of ejector refrigeration systems using low-grade heat sources and environmentally friendly working fluids. The work involved both experimental and numerical approaches. The main goal was achieved through identifying 4 specific objectives:

- Theoretical assessment of an ejector refrigeration system with two-phase ejector and zeotropic mixture working fluid;
- Development and validation of a 1D Homogeneous Equilibrium Model (HEM) and 0D Henry-Fauske (HF) model to simulate the fluid flow inside ejector primary nozzles;
- Development of an experimental test rig for testing ejector cooling cycles under controlled operating conditions;
- Execution of different sets of experiments using different ejectors and working fluids for model validation and performance testing.

According to the reviewer's opinion, the scientific novelty of the work performed is adequate. Pioneering contributions are explicitly stated several times throughout the thesis (e.g. on page 6), although not always fully agreed by the reviewer. Novelties include numerical methodology, working fluid type and experimental conditions.

2) General evaluation of the dissertation

The thesis presented by Mr Jakończuk is a **monography type** dissertation. The main body has about **160 pages**, excluding appendices, which can be considered adequate for this type of documents. It consists of **11 chapters** including a short introductory chapter (Chapter 1); a chapter focusing on different aspects of the ejector refrigeration cycle (Chapter 2); a very short literature review organized around a table (Chapter 3) and the

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presentation of the thesis objectives (Chapter 4). The author's own work and the main results are presented in Chapters 5-10, including both modelling and experimental activities. The author summarizes the major conclusions of the work and presents his suggestions for future research within the studied field in Chapter 11. The organization of the thesis also includes a number of appendices, lists of illustrations and abstract. By reading the document, it is clear that the candidate has performed a **large amount of work, both experimental and modelling**. The relative compactness of the dissertation is a positive aspect for the reader who is mostly interested in the results, but it could also be considered as a negative aspect for the readers who would like to have a more complete image of the background of the work. The followed methodology in some of the chapters (e.g. Chapter 10) is not clearly explained, which a shortcoming and it makes very difficult to reproduce results by the reader, if needed.

The **thesis is written in** minimally acceptable English for a non-native **English** speaker. The choice of the language is a positive aspect, since the scientific achievements of the candidate will have a larger visibility and impact. Nevertheless, the English language of the submitted document could be considerably improved for better clarity. Here and there, there are errors that interfere with the understanding of the contents. A number of suggestions are given by the reviewer to improve the quality of the English, as comments, in a reviewed version of the thesis sent separately to this document.

The general structure of the thesis is acceptable. There are some non-conventional choices within the document, such as the abstract is placed as the last part of the thesis and the references are not numbered according to their appearance order. Since the reviewer is not familiar with the regulations and requirements of the home University, regarding thesis editing, these issues are not considered as shortcomings. The number (121) and quality of the used bibliography is satisfactory. Most references are from the past 10 years, but there are also a number of papers dating back to the last century. The reviewer found one reference that has not yet been published (submitted) and another one without the indication of the year of publication [81]. The document starts with a nomenclature section. The symbols in the nomenclature section are well organized, in alphabetical order and the units are correctly indicated. Unfortunately, the list of symbols is very incomplete, many of the variables used in the equations throughout the document are not included. After the nomenclature, the thesis is organized into numbered chapters. While some of the chapters (e.g. Chapter 5) seem to be adequately structured with sections and subsections, this logical organization of the contents is omitted in others. For example, Chapter 8 has no identified sections and subsections, only some title lines (with no numbering). It is difficult to understand how the different titles relate to each other (vertically or horizontally). The choice for this organization within the chapters the reviewer considers as a shortcoming. After the thesis body, a number of appendices are included, with data that is not directly discussed in the thesis. This is very good and considered to be a positive aspect. The use of the same numbering style for the thesis' main body and the appendices is not fortunate.

Chapter 1 is called the introduction. It is rather short, the contextualisation of the work given in a very general manner. Different research and technological problems are clearly stated and how the thesis addresses these problems are explicitly mentioned. This is a very positive aspect. By reading the document, it was not always clear whether the objectives of the work were defined here in the Introduction part or later (in Chapter 4). There were several statements regarding the importance of using waste heat source and solar energy to produce cooling. This is a positive aspect. However, these statements could have been supported by actual data, actual targets and with relevant references. This is a shortcoming. At the end of the chapter, there is a short description regarding the organisation of the thesis. It is claimed that there are two general parts, but it is not clear which chapter belongs to which part. In fact, a diagram with the different chapters and their interconnections would have helped the understanding of the organisation of the document.

Chapter 2 deals with the description of the ejector cooling cycle and working fluid types. The information included in this chapter is generally correct and focused on the work performed. The thermodynamic processes inside the ejector are correctly presented with support of mathematical equations. There are however some organisation issues and terminology issues to be mentioned. One of the apparent sections (not identified by numbers) is called "Ejector modelling – state of the art". In this section the author limits the discussion to a very specific type of ejector models only. Since there are other model types frequently used in ejector simulation, the title should refer to the specific model type reviewed in the section. Under "isobaric mixing" title, the energy and mass balance equations for the entire ejector are presented, not only for the mixing section. Regarding terminology, the author recurrently use the term "parameter" for variables and thermodynamic properties, which is a shortcoming.

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Chapter 3 is a condensed summary of the available literature regarding ejector refrigeration, as it is correctly stated in the title. The information included in this chapter is relevant and the cited works are important to the subject of the thesis. Meanwhile, Chapter 3 has only two pages and a table. The table is not discussed, it is left to the reader to interpret its contents. Tables and figures in a document should only complement and aid the reading of the text, but should not replace the need for discussion. The reviewer believes that the content of this chapter could have been easily and valuably integrated into Chapter 2.

Chapter 4 is the explicit statement of the thesis work objectives. The objectives are clearly listed here. According to the reviewer's opinion, since some of the objectives are already identified in Chapter 1 and Chapter 4 has an extension of only 2 pages, it could have been easily integrated into Chapter 1, as a separate section. Aims and objectives are presented separately. The reviewer is not sure about the underlying difference between the aims and objectives of a thesis.

Chapter 5 proposes a methodology and discusses the results of technological solutions to increase the heat removal from available (waste) heat sources for the ejector cooling cycle. This is very interesting and relevant for the reduction of exergy destruction. Two approaches are considered, both studied through mathematical modelling and simulation. Generally speaking, the results are interesting and new, which is a positive aspect. The English of the written text could be improved for better understanding. There are also some editing errors, e.g. two paragraphs on page 51 are repeated. The solution algorithm to the models is clearly presented and the model equations are given. Although it is not always clear why some of the formulas are numbered and why some others are not. The estimation of the temperature glide (page 55) could be better explained, it is not clear how the saturation temperature is a function of a temperature (t_5). A very important outcome of the analysis is the demonstration of the benefit of using zeotropic mixtures in ejector cycles. Four mixtures were studied, which is a very positive aspect of the work. The choice for the specific mixtures (fluids and their mass fractions) and how some relevant properties were estimated (e.g. speed of sound) are not given. This is a shortcoming. The ejector cycle performance results are shown in a set of figures as a function of the generator temperature. The presentation of the figures help interpretation. On page 61, it is stated that the COP for 0°C evaporator temperature is higher then for 6°C. This requires verification. On page 64, there is a statement where the author relates entrainment ratio

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and temperature glide. This is not obvious from the presented data. Figure numbering could be also revised on this page. There are some incorrect terms used on page 69, e.g. "compression temperature" and "The zeotropic cycle allows for conserving even more energy", since energy is always conserved.

Chapter 6 introduces the experimental test rig that was constructed and used by the author for data collection. The collection of a large amount of experimental data is a very positive aspect of the thesis. According to the reviewer, the title of the chapter could be more auto-explicative. The test rig components are well described with the instrumentation, except for TR in Figure 6.1, which should be the refrigerant tank (T) in the component list. The information in this chapter is very complete, but the way it is presented (through listings and tables) makes it difficult to read. While in previous chapters, temperature is presented by "t", here symbol "T" is used.

Chapter 7 deals with the validation of the 1D HEM model with experimental data, for the primary nozzle flow, in terms of predicted mass flow rate. Validation of mathematical model with experimental data is a positive aspect of the work. The governing and closure equations for the flow variables are presented. It is claimed that the governing equations were modified, but it is not clear in what sense. It is also not explained in the text, how the governing differential equations were integrated. Many of the variables here are not included in the nomenclature (although most of them explained locally). Equations 7.8 and 7.9 seem to be the same, only rearranged. It is claimed that Equation 7.10 is the (only) speed of sound model for HEM. The reviewer believes that this is not the only model available, but this is an option. Some of the statements would require some additional reasoning, e.g "Due to this simplification w, h, x, ρ and $aHEM$ are functions of only pressure", since properties should depend always on the independent ones (except along the saturation line). The comparison of the calculated mass flow rate to the experimental ones is a correct validation procedure. Nevertheless, looking at Figure 7.2. it seems that the output of the model is the geometry of the nozzle for critical flow and the flow rate is input. During validation, the flow rate was output. These could have been better explained in the text. There are 29 experimental points, which is excellent. However, it seems that there are two real sets with inlet pressures about 2 and 2.3 MPa. Within each set, the observed experimental flow rate variation is due the experimental uncertainty (things that could not be controlled). This is not reflected on the calculated flow rate. This is expected, but the author should have addressed this issue. The model underestimated the primary

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flow rate, which was correctly discussed. At the end of the chapter, it is concluded that this underestimation was due to non-equilibrium effects. According to the reviewer's opinion, this statement is not supported by the presented data nor supported by reference works. This is a shortcoming.

Chapter 8 discusses the Henry-Fauske model and its validation with experimental data for three different working fluids and three different ejectors. This is a very important contribution and the results are extremely valuable for the scientific community working in the ejector field. The most important shortcoming of the chapter is the lack of vertical and horizontal organization of the text into logical sections and subsections. It is not always clear how the different sections (identified by titles only) relate to each other. As a consequence, it is not always clear whether the data presented refer to simulation or experimental results (e.g. Figure 8.4). It requires special attention and unnecessary effort from the reader. The model equations are clearly shown. The only comment that could be made is that the ideal gas assumption in the model should be stated. Also, in Equation 8.16, the use of the equal sign is no adequate, because it is a finite difference approximation. The experimental data is summarised in Table 8.1 and 8.2. This latter is not referred in the text, such as figures 8.2 and 8.3. The reviewer misses the presentation of the experimental procedure. It is not explained how the "measured" inlet vapour quality was determined. If not mistaken, only temperature and pressure were measure at the inlet, but these properties are not independent in two phase state. This could have been better explained. In Figure 8.8, the model flux density seems to be independent of the quality at the nozzle inlet while the measured data seem to decrease with the quality. This could have been discussed. In the summary of Chapter 8, it is stated that "This investigation contributes to designing efficient ejector-based refrigeration systems..." but this contribution is not clearly addressed in the discussion.

Very important experimental data is discussed in **Chapter 9** for two types of primary nozzle geometries. This is an important contribution, because both local variables and global performance indicators were measured and analysed. The experimental tests were carried out with the working fluid R123. This condition, according to the reviewer's opinion, leads to the major shortcoming of the title of the chapter by referring to R1336mzz(Z). The title of the chapter could have referred to R123 and after the discussion of the results, the extrapolation of the data to R1336mzz(Z) could have been made in a dedicated section within the chapter using the scientific reasoning of the author

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presented in the early part of Chapter 9. Not structuring the chapter into sections and subsection is also a shortcoming. Regarding the scientific reasoning of extrapolating the experimental result of R123 to R1336mzz(Z) could be generally correct by comparing thermodynamic properties over the expected range within the ejector flow. Nevertheless, the reviewer is missing the comparison for the viscosity and the speed of sound in particular. The experimental results are discussed in detail, which is very good, nevertheless, the methodology followed during the analysis is not always clear. There are approximation curves fitted to the experimental data in many figures (e.g. Figure 9.12), but how these curves were fitted is not explained, even though the discussion refers to behaviour of the fitted curves. This is a shortcoming. On page 132, a maximum volumetric entrainment ratio of 8 is mentioned, while on the referred figure, about 6 is shown. Which one is correct?

Chapter 10 presents the experimental research results for yet another working fluid from the HFO group, specifically for R1234ze(E). This environmentally friendly refrigerant has not been experimentally tested in two-phase ejector cooling cycle before, which is an important achievement of the author. Table 10.1 summarizes the experimental conditions. Unfortunately, there is no information given regarding the experimental procedure or the ejector used during the tests. As a consequence, for example, it is not clear if the data points in Figure 10.1 are inputs or results. The presentation of the results is based on the same logic as in Chapter 9. This helps the reader to understand the discussion, but also lead to the same shortcomings. E.g. on Figure 10.4, it is not clear how the curves were fitted to the experimental point, using what type of mathematical relationship and how the vapour quality was measured at the nozzle inlet and outlet. The observed results are compared to ejector theory, which is good, but not indicating any reference work to support statements, which is a shortcoming.

Chapter 11 focuses on the conclusions of the work and proposes some topics for future research. The main conclusions are summarised, however a large part of the text is a summary of the work, instead of focusing on the conclusions only. The main conclusions are arranged under 4 numbered bullet points and in 3 additional paragraphs. The reviewer misses how the key finding from the thesis work will potentially improve the performance of ejector cooling systems or how they will contribute to their market deployment.

3) Specific remarks, comments and questions

The reviewer has made a number of **specific remarks**, comments and suggestions for the improvement of the written thesis work. Many of the comments are related to the improvement of the English language and can be completely omitted. To address other issues and scientific questions should be considered by the candidate for the discussion or for a revision of the dissertation, if possible, depending on the regulations of the home university. A full list of these remarks, comments and questions is not provided here for easier interpretation, they are sent separately a **commented version of the thesis document** (P_Jakonczuk _revised thesis_SV.pdf).

4) Statement of approval

Szabolcs Varga hereby declares that the presented dissertation meets the requirements of the Act of 20 July 2018, the Law on Higher Education and Science (Journal of Laws of 2023, item 742, as amended).

5) Final note

The present reviewer reserves the right of nominating the candidate for distinction after the public thesis presentation

Porto, 23rd of May of 2025

Varga Szabolcs

Szabolcs Varga

Reviewer