Szabolcs Varga

Invited Lecturer/Coordinating researcher

Faculty of Engineering of the University of Porto/

Institute of Science and Innovation in Mechanical and Industrial Engineering, Porto

Rua Dr Roberto Frias,

4200-465 Porto

Portugal

Thesis Review Report

Author of the thesis: Mikołaj Mastrowski

Title of the thesis: The development of the application for components selection to the ejector refrigeration systems, driven by low-grade waste heat from industrial processes, based on the mathematical model and the experiments on the prototype refrigeration aggregates

Submitted to: Silesian University of Technology, Gliwice, Poland under the specific discipline: Environmental Engineering, Mining and Energy.

1) Aim of the work and scientific novelty

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. Therefore, 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. There are several waste heat recovery options available, including direct use, heat-to-electricity, heat upgrading and heat-to-cold solutions.

The submitted thesis aligns well with this aforementioned context. The industrial waste heat recovery potentials and available technological options are clearly identified in Section 1.1 of the Thesis. The work performed focuses on the development low-temperature waste heat driven ejector cooling cycles for industrial cooling. The main objective of the work is identified as the development of a mathematical design tool that can be used for the selection of system components and optimise their configuration for a particular cooling application. Four specific objectives are identified in the document such as the formulation of a mathematical system model, experimental testing of two ejector cooling cycle prototypes of different capacities for waste heat utilization, mathematical model validation and the (experimental) comparison of two new generation HFO working fluids in one of the prototypes.

The scientific novelties of the thesis are explicitly identified in Section 1.3 under four bullet points. The contents of these bullet point in general terms are correct. One of the novelties mentioned there is the development and experimental validation of the design tool for industrial scale ejector cooling systems. The novelty of this component is clear, as the results were published in a highly ranked scientific periodical. Other novelties of the work performed are identified as the development of the first demonstrators of this kind and the application of new generation working fluids in real ejector cooling prototypes. The reviewer agrees completely with the innovative nature of the tested systems, although it would have been more fortunate if the candidate explicitly mentioned his personal contribution to these innovations (they are indirectly included in the Preface of the thesis). Finally, the last novelty mentioned in the thesis is associated with the empirical ejector "component efficiencies" in association to the new generation working fluids applied. It is common practice when developing simplified ejector models to include empirical constants in the mathematical description of the ejector flow in order to account for the deviations of the idealised case from the real one. Different authors identify different efficiencies. It would have been more fortunate if the candidate identified more clearly in what sense his application of the empirical efficiency constants was innovative.

2) General evaluation of the dissertation

The thesis presented by Mr Mastrowski is a monography type of dissertation. The main body has about 130 pages, which can be considered as adequate for this type of document. It consists of 6 chapters including a short introductory chapter (Chapter 1); two chapters focusing on the prototype description, instrumentation and the different testes configurations (Chapter 2 and 3); one chapter describing the author's modelling approach to the problem (Chapter 4). The main results are presented in Chapter 5, focusing on the validation of the developed design tool, operating characteristics of the prototypes and performance analysis (Chapter 5). The author summarizes the work and presents the major conclusions in Chapter 6. The extent of the dissertation is a positive aspect for the reader who is interested in the specifics of the work elaborated, but it could also be considered as insufficient for the readers who would like to have a more complete image ejector types, applications and all types of existing mathematical models to simulate ejector flow.

The thesis is written in English by a non-native English speaker. Therefore, generally speaking, the language of the written text can be considered as acceptable. However, it could be improved for better clarity. Occasionally, understanding of the contents of the dissertation is negatively affected by the less careful choice of the presentation. A relatively large number of suggestions are given by the reviewer to improve the quality of the English text, as comments, in a reviewed version of the thesis which is sent separately from the present review report.

The work itself is rather complete. It demonstrates excellent knowledge of the candidate regarding ejector operation and modelling, heat exchanger and data analysis. Mr Mastrowski has performed both numerical modelling work and experimental validation work using adequate methodology, which is very good. The general structure of the thesis is adequate, nevertheless there are some non-conventional choices within the document. For example, the abstract is placed as the last part of the thesis. The reviewer has also some comments regarding the document edition. The equations in the text are preceded by ".", which is not common, normally ":" is used. The are several compound figures (e.g. Fig.5.3) in the document. Normally the components of these type of figures are identified as a), b), etc. In the nomenclature, some of the variables (e.g. MER) are identified as abbreviations, but in fact they are symbols. The Roman symbols are in apparent alphabetical order, but the non-dimensional groups (e.g. Re) seem to be out of place. There are several internal titles used in the text (e.g. on page 88). They seem to be (sub)sections, but they are not numbered and therefore they are not in the table of contents. Since the reviewer is not familiar with the regulations and requirements of the home University, regarding thesis editing, these remarks could be omitted. Some additional editing remarks are included in the attached thesis with comments. The author has used about 100 references, most of which were published over the last 10 years. This can be considered sufficient, but not exhaustive. The references indicated are relevant to the work performed.

Within the introductory chapter (Chapter 1), the background of the work is presented. It is relevant, but the term "context" would have been more descriptive, since the waste heat context is presented. The inclusion of some figures or diagrams, where the candidate identifies the waste heat classes that are relevant for cold generation, would have been valuable. The reviewer thinks that suitable energy technologies should be demand driven. It is therefore more relevant what the industrial cooling context is and then how we could satisfy it from waste heat. It was not addressed in the background section. The background is followed by a short literature review section, where the ejector cycle and ejector operation are explained. Point 2 is identified in the text as the suction nozzle with reference to Fig1.1, although it does not show any nozzles. The ejector flow description is referring to an idealisation of the real one. It should be explicitly stated. It is not always clear if the cited works were experimental or purely numerical studies. A table with summarizing the cited publications would have helped the interpretation. In section 1.2.4, only the so called 0D or 1D approaches are discussed for ejector modelling. It is a limitation, therefore it should be stated in the section title. The motivations and objectives are clearly identified at the end of Chapter 1, therefore it is a very positive aspect. English could be improved.

Chapter 2 gives a short overview of the prototype systems. The two prototypes are named after their heat source usage and not after their rated cooling capacity, which is unconventional for cooling equipment. The term high-temperature cooling is introduced, but it is not clearly explained for what industrial processes are needed these cooling temperature levels. It is stated that the ejectors (key component) in the prototypes were designed by MARANI company. What were the design conditions for each of these ejectors? How were they designed? This information is not indicated in the thesis. The author has developed a design tool but the correct dimensions of the installed ejectors were not verified with the model.

Chapter 3 focuses on the test rigs, applied instrumentation and their various configurations. It would have been advantageous to state here what was the author's own specific contribution to the development of the control and monitoring system and to the development of the various configurations of the prototypes. The chapter is well structured, and an experimental uncertainty analysis is given, which is very positive. The information given is almost complete, but some questions remain. Was there any particular reason why the pressure at the suction inlet of the 200 kW unit was not measured? What was the capacity of the condensate tank? Section 3.2 discusses the experimental sets that were performed. According the reviewer, this section could have been a bit better organized, with a table to summarize the 5 sets of experiments. This is also true for Section 3.4, where table or diagram with the different system modifications would have helped interpretation. More comments are included in the commented thesis.

Chapter 4 presents the mathematical formulation of the developed models. The chapter is quite complete and well structured. It starts with the statement that an iterative model was developed in the thesis. According to the reviewer's opinion, "iterative" is not a model type, but a mathematical procedure to solve (non-linear) problems using numerical methods. Most models need an iterative method to solve them. The author should clarify statement. Additionally, it is written that "The system model also includes a simulation of an…". The reviewer does not agree with this statement, since a mathematical model is a closed from mathematical representation of a system (from a certain aspect resulting from assumptions). A simulation is the process to obtain results (outputs) with the model for a set of inputs. A model does not include simulation. One can perform a simulation with a model. The term "parameter" is often incorrectly used in the thesis. E.g., on the top of page 33, the results are referred to as output parameters. It should be correctly output variables. "Parameter" is often confused in the text with "variable" or "fluid property". Some of the ejector sections that the candidate considered for his 0D ejector model are physical, some others are hypothetic. The author could have included a figure where these sections inside the ejector are identified. Some of the mathematical formulas are not "nicely" presented. For example, Eq.4.3 is the definition of the fluid specific enthalpy as a function of the pressure and entropy using "h". In Eq.4.4 the same function "h" is used for the speed of sound. The motive fluid expansion efficiency is defined in Eq.4.25, but not mentioned in the assumptions. Also, Eq4.25, as it is, seems violate the mass flow equation. The average flow velocity × the density× the cross-section area normal to the flow (0D approach) = mass flow rate (see Eq.4.27). How can mass flow be a higher value than the left-hand side (efficiency < 1)? The definition of the expansion efficiency should be more clearly done! In the Fanno flow model, do you have an ideal gas assumption? It is not clear from the text. There seems to be a typing error in Eq. 4.52. There are several empirical correlations applied for the heat transfer calculations in the heat exchangers. The validity range for these correlations could have been indicated. More comments are included in the commented thesis.

Chapter 5 is the most important results chapter in the thesis. This chapter starts with the performance assessment of the developed approach by validating the simulation results with published experimental data and experimental data collected using the existing prototypes. Validation of the model results with published data involved also the adjustment of the efficiency constants by minimising the error between the predicted and experimental data. The adjustment method is not very clearly explained. For one of the fluids, the performance of the developed model was also compared to an approach where the model efficiencies were estimated from CFD results. Later in this chapter, the model validation is also performed with data from five sets of experiments performed by the candidate using the two prototypes in different configurations. The analysis performed is very complete and thorough. The model performance is discussed in detail for different operating conditions. The ejector model constants were adjusted by minimising the error for the motive mass flow rate prediction. This approach could have been better explained. The primary mass flow rate is mostly determined by the inlet fluid properties and nozzle throat geometry. It is not obvious how e.g. the suction nozzle efficiency influences the primary mass flow rate. How would the "optimal" values of the ejector model constants be if another objective function was chosen (e.g. minimizing the error for the secondary flow rate)? The results for MER, the pressure ratio and ejector efficiency are clearly presented, but sometimes scientific reasoning is not explored. The results for the adjusted ejector model coefficients are shown in table 5.3 obtained by fitting the model results to the data for the different experimental sets. Thus, the model was validated with exactly the same sets of experimental data which was used for optimising the model. What about if the ejector model was compared to "unseen" data? In Section 5.2 the results of the heat exchanger models are discussed. Please note that in several occasions the relative error for the temperatures is indicated with units of Kelvin (see fig.5.20). The relative error is dimensionless, it should be corrected in the entire thesis.

Chapter 6 provides a summary of work and presents the main conclusions. The conclusions are generally correct based on the results. According to the reviewer's opinion, Chapter 6 could be further improved by focusing on the conclusions of the work performed in view of the defined objectives. The summary part is not very necessary, once the summary of the work is included the abstract after the reference list. The quality of Chapter 6 could be also improved by discussing what new questions of the work has opened up and specifying the future work needed to answer these questions. The few sentences included at the end of the chapter are too generic. To a certain extent, the reviewer misses the discussion of how the developed design tool can be used in the future for the improvement of the prototypes or development of new ones or contribute to the TRL upgrade of ejector cooling systems.

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 that are not in this report. A full list of these remarks, comments and questions are available in commented version of the thesis document (PhDThesis_Mastrowski_final_Commented_SV.pdf), which will be separately sent to this review report for easier interpretation. Most of the indicated issues should be considered as optional by the candidate for the revision of the submitted version of the dissertation.

4) Statement of approval

Hereby, Szabolcs Varga declares that the presented dissertation fulfils the requirements of the Law on Academic Degrees and Title and Degrees and Title in the Arts (Act of 14 March 2003) with amendments from 21 April 2017

5) Final note

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

Porto, 06th of March of 2025

Podpisał Szabolcs Varga

Reviewer