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Białystok, 07.01.2022

Review of doctoral dissertation
M.Eng. Anas F. A. Elbarghthi
Ejector-boosted Transcritical CO2 Refrigeration System

The review was prepared on the request of Prof. Dr. Ing Petr Lenfeld, the Dean on Faculty of Mechanical Engineering, Technical Universitat in Liberec according to letter TUL-515164/2112. Supervisor of the dissertation is Prof. Ing. Vaclav Dvorak, Ph.D from Department of Applied Mechanics, TUL.

I. Brief contents of dissertation

The dissertation was written in English and is 107 pages long. It contains of following parts: **unnumbered** (at the beginning) – Author Declaration, Abstract (in English), Preface, Table of Contents, List of Tables, List of Figures, List of Abbreviations and Acronyms; and at the end of the thesis: Bibliography, coursework and Examinations, List of Publications, Author Curriculum Vitae and Appendix 1, **numbered**: Introduction (chapter 1), Literature review (chapter 2), Theory and data analysis (chapter 3), Experimental method (chapter 4), Results and discussion (chapter 5), Conclusions and future works (chapter 6).

Detailed contents of chapters is as follows:

Introduction. In this chapter the general context of the thesis is given. Candidate briefly describes CO2 transcritical refrigeration system based on ejector technology, describes advantages of CO2 as a working fluid and pointed out the development and increase application of CO2 refrigeration systems on the commercial market. Objectives of the thesis are defined. Structure of the thesis with brief description of each chapter is also presented.

Chapter 2 focuses on the background of CO2 transcritical technology, especially with ejector applied as an expansion device. A short review of the historical development of ejector refrigeration is presented. General description of commercial CO2 systems, with special attention to CO2 two-phase ejector technology is also given. Candidate describes in detail the properties of carbon dioxide as refrigerant and presents previous and current research of ejector supported transcritical refrigeration systems.

Chapter 3 describes the theoretical background of ejectors. Working principle of ejector, details of operation of ejector refrigeration systems are presented. Candidate introduces the performance parameters of the system, such as mass entrainment ratio, compression, coefficient of performance and ejector efficiency. Details of energy and exergy analysis are presented in this chapter.

Chapter 4 gives a detailed description of the CO2 transcritical cooling test facility, which was used for the experimental work. System components, monitoring and controlling system is well described. Experimental procedure and uncertainty analysis is presented.

Chapter 5 is the most important chapter in the thesis. It presents the obtained results which are analyzed and discussed in detail. Author have shown the stability of the ejector transcritical cooling system, investigated the relation between basic performance parameters as a function of operating conditions and investigated the ejector efficiency and performed the exergy analysis. Candidate have also proposed correlations for mass flow rate of the motive fluid as well as mass entrainment ratio, which allows for calculation of the mass flow rate of entrained fluid.

Finally, **Chapter 6** summarizes the most important conclusions of the thesis and provides suggestions for future research dealing with ejector refrigeration technologies.

References list contains of 128 positions, PhD Candidate is a co-author of five scientific papers and co-author of two conference papers. The works cited are: research papers, conference papers, reports, handbooks and manuals. Selection of the reference list is suitable and adequate for PhD thesis.

Appendix contains of detailed diagram of test rig used in experimental campaign.

II. General Evaluation

- **Scope of the dissertation**

Objectives of the thesis have been defined in Chapter 1. According to Author the research presented in the thesis focuses on following principal objectives:

1. Accomplish a literature review on the CO2 refrigeration system and ejector technology.
2. Conduct a comprehensive test campaign to investigate the effect of different operation conditions on the ejector profile performance experimentally.
3. Investigate the exergy distributions in the ejector profile and their effect on the rate of work recovery.
4. Assess the potential impact of the equipped expansion ejector profile on the R744 vapor compression system operational characteristics (COP and exergy efficiency improvement, power consumption).
5. Determine the contribution of the ejector to improve the exergy destruction of the total system and each component based on the second law of thermodynamics.

- **Problem-solving procedure, the methods used and the fulfillment of the set goal**

Author of the thesis applied a proper and adequate problem-solving procedure. At first, the problem was described and defined on the basis of detail literature review, second, the detailed investigation plan and systematic test campaign were performed. Although the research plan is not presented directly in the thesis, it is essential to the conduct of comprehensive research. The testing rig used for experiments was well equipped, all necessary parameters were measured. The high-class monitoring system was used. It should be pointed out that investigations were well planned and executed. Thus, Objectives No. 1 and No.2 were met. Detail analysis of obtained results presented and discussed in Chapter 5 fulfills Objectives No.3 to No.5. The procedure applied for data processes and analysis is proper and does not raise any objections. The presented results are well discussed, conclusions are fair and supported by the results.

Conclusion: The aim of the dissertation is clearly and precisely defined. The problem-solving procedure and the methods proposed and used by the PhD candidate fully corresponds with the objective of the thesis. All defined goals were obtained, therefore, the thesis is complete.

- **Originality, relevance to the field and possible applications**

The reviewed PhD dissertation deals with the key issues for refrigeration technology and is related to the effective use of environmental safe, natural working fluids, namely carbon dioxide in transcritical cooling systems with two-phase ejector. The applied ejector is used for reduction of throttling losses, which are the inevitable companion of the throttling process. Also, the ejector operates as booster compressor, which creates an intermediate pressure. This is an opportunity to reduction of compression work required by the system, since mechanical compressor operates with lower pressure difference. In effect, the electrical power consumed by the mechanical compressor is reduced. Although the ejector is a very simple device and the refrigeration system using the ejector has a lot of advantages its application on commercial marked is limited. Ejector refrigeration systems operating with CO2 enjoy unflagging interest and their commercial application is the most advanced so far. However, a detailed research both, experimental and numerical are required in order to overcome shortcomings related to ejector technology. Research conducted within this PhD thesis perfectly fits to this requirement.

In general, the thesis provides with the valuable and original achievements. The PhD candidate examined the possibilities of using a battery of transcritical CO2 ejector in a cooling system. Author focuses mainly on system performance issues. The influence of the operation parameters, such as motive pressure and discharge pressure on the pressure lift produced by ejector, the entrainment ratio, COP of the system were investigated. It is worth nothing that the research was done under operating conditions covering subcritical and transcritical regions. Author has presented detail discussion on ejector energy and exergy efficiency. Exergy analysis was examined in detailed. The results presented in the thesis may be considered very attractive by designers and engineers, especially in terms of efficiency improvement. Therefore, these studies can be considered as original.

I found following achievements of the PhD candidate:
- development of the experiment plan;
- performance the comprehensive experimental tests in subcritical and transcritical regions;
- analysis of experimental results, including the performance characteristics;
- development of a correlations for mass flow rates;
- analysis of system performance improvement;
- analysis of exergy destruction;

It should be emphasized that the research presented and discussed in the dissertation, were carried out by the PhD candidate in cooperation with foreign recognized research center. This means that the issue of the transcritical ejector cooling cycles is of great interest. It also proves that the PhD candidate is ready to work in an international team.

Conclusion: The results presented in the dissertation are original and make a significant cognitive and application contribution in the field of applied mechanics - especially in the field of mechanical engineering.

- **Results of the dissertation and the significance of the original contribution of the dissertation author work**

The thesis undoubtedly has an application value. The scientific effect of the dissertation is to increase the knowledge base in the field of the use of CO2 transcritical ejector in refrigeration devices. The conducted experimental studies with the use of a natural refrigerant constitute an important supplement to the database containing limited experimental results. It should be emphasized that the experimental tests were carried out in a high-quality test rig in a well-recognized research center. The obtained results can be used to validate the existing models and build new computational models, especially those focused on efficiency improvement. The PhD candidate demonstrated high level of research abilities, results presentation and drawing the conclusions. I found both methodology of the experimental investigations as well as theoretical analyses as correct. Provided analysis of the obtained results is rational and contributing to the state of the art.

- **Outputs (publications, patent applications..):**

Five publications on international peer reviewed high-level journal and two papers on the international conference proceedings (both as co-author) fills the requirements for a PhD.

- **Writing quality and clarity**

The dissertation presents an original and comprehensive approach to the issue discussed here. Throughout the whole manuscript writing is clear and excellent, results are presented in clear manner, conclusions are fair and supported by results. The correct scientific and technical nomenclature is used. References and citations are clearly indicated in the text. Regardless, that the dissertation is prepared very well is not free from shortcomings that are usually inevitable. However, the formulated below remarks should be treated as suggestions that possibly may improve clarity of the presentation of the future research of the PhD candidate and do not diminish my unambiguously positive opinion of the doctoral dissertation.

Despite of certain below mention imperfections present in the submitted thesis, which consist of many well treated original measurement and analysis, the thesis provides high-level of scientific research.

Major remarks (in the order of appearance)

1. Abstract and later in the text: Author uses the term "ejector profile" e.g. " investigate (...) the impact of the ejector profile on the system performance. It was not explain what kind of profile was used or to which profile it was referring? Usually, "profile" is used to geometric parameters, e.g. suction chamber or mixing chamber shape. Clarification of this issue would help the reader understand the Author's intention.
2. The Author uses the term "dead state". It was first introduced in *List of subscripts*, and is used throughout the text. It would be better if this term was clarified, what does it mean? Is it stagnation state?;
3. Section 3.3, p.42: It is written that "At the critical mode operation, both motive and suction nozzle flows are choked. The mass entrainment ratio reaches the maximum and remains constant with a further decrease in the range of the ejector discharge flow pressure" This explanation is not precise. Double-chocked operation of the ejector is both, for deceasing and also increasing the discharge flow pressure, as long as discharge pressure is lower than critical pressure value.
4. Section 4.1, p.49: Author claims that investigated ejector characterizes the smallest profile produced by the manufacturer. Figure 4.4 on p.54 shows the sketch of multi-ejector block and photo of tested ejector, however, in my opinion detailed schematic diagram of ejector geometry would clarify the ejector view.

5. Section 4.1, p.49: The test facility is well described, however, it is not clear what was the contribution of the PhD Candidate in testing-stand design, build or modification. Author should emphasized this issue.
6. Section 4.2.2, p.54: The test rig was equipped with multi-ejector pack contains of six parallel ejectors. However, only one was investigated within this PhD thesis. Is that mean that other ejectors were inactive? If no, is it possible to assess the influence of other ejectors operation on the tested one? If yes, what kind of changes in flow were observed, e.g. mass flow rate through entire system will be reduced and also velocity will be lower. In my opinion the issue should be discussed in more detail.
7. Section 5.1, p.62. Referring to the results shown in Fig. 5.3 authors claims that the ejector recorded the highest efficiency of 0.369 at P_{MN} = 90 bar and T_{MN} = 25 °C. How this temperature was found? This figure shows the ejector efficiency for different pressure, however, the temperatures are not differentiated.
8. The same paragraph: Author summarizes results shown in the Fig. 5.3 "the points characterized by efficiency greater than 0.30 are recorded at a substantial P_{lift} from 2.4 to 8.2 bar". This is almost entire range on the horizontal axis. It should be pointed out by the Author, that for given motive pressure, the ejector was fed by liquid with different temperature, as shown in Fig. 5.1a. Therefore, Author should clarify how to select the operating points with the highest efficiency among the presented results.
9. For ejector technology, especially for those operating as supersonic ejectors the speed of sound and shock waves are crucial, fundamental, physical phenomena. They are responsible for chocking flow and pressure increase inside ejector. However, Author did not discussed these issues in the thesis.

Minor and editorial remarks

1. List of variables: I suggest to use legal SI units for pressure, Pa or MPa instead bar.
2. Section 2.4, p.26: HCFCs was wrongly identified as hydrochlorocarbons instead hydrochlorofluorocarbons.
3. Description of system components shown in fig.2.12 is hard to read.
4. Section 3.3, p.46: parameter u used in eqs. (3-9)-(3.11) is not defined.
5. Equation (4-1) was used to estimate two different parameters. For this reason I suggest to present this equation as two separate equations or at least to use different constant notations.
6. Founded editorial mistakes and typos: e.g. missing space (p.29); "ration" instead "ratio" (p.64).

III. Concluding remarks

The present thesis highlight very interesting results obtained in the framework of a consistent experimental and theoretical studies and well-designed objectives.
Despite of certain above mention imperfections present in the submitted thesis, which consist of many well treated original measurement and analysis, the candidate M.Eng. Anas F. A. Elbarghthi convinced the reviewer about his ability for serious and creative scientific work. The present thesis fulfill all criteria for a PhD dissertation. **Overall evaluation: POSITIVE. The thesis is recommended to be accepted, admitted to defense and candidate to be awarded by the PhD scientific degree.**

doc. Ing. Tomáš Hyhlík, Ph.D.
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Review of the dissertation thesis

Author: **M.Eng.Anas F.A. Elbarghthi**

Thesis title: **Ejector-boosted Transcritical CO_2 Refrigeration System**

The assessed dissertation has 106 pages. It contains 8 tables, 43 pictures, a list of 128 cited sources and a list of 7 author's publications.

The topicality of the dissertation thesis

It is clear that ejector – boosted transcritical CO2 refrigeration system can be more powerful compared to the refrigeration system without an ejector as documented by the author in the review. I understand the dissertation thesis as the step on the path to developing an efficient transcritical refrigeration system.

Achievement of set objectives

The author formulates five objectives of the thesis. The first objective is a literature review of the CO_2 refrigeration system and ejector technology and is documented in chapter 2. The second objective is to perform the test campaign to investigate ejector performance. The results of measurements are in chapter five. The third and fifth objective is to analyze the studied problem from the point of view of exergy. Exergetic analysis is presented in chapter 3 and results are in chapter 5. The fourth objective is to show the positive impact of the ejector on transcritical refrigeration systems with CO_2. It is documented in chapter five.

Suitability of the used methods of solution

In my opinion, the solution methods were chosen and used correctly. In solving individual parts of the dissertation, the PhD student used theoretical and experimental methods and analyzed the obtained results. The focus of the dissertation thesis is on the analysis of experimental results.

Contribution of the dissertation

From my point of view, it is possible to find a few contributions in the dissertation. One of the contributions is a theoretical analysis of the studied problem. The main contribution is a precise analysis of measured data.

Formal level of dissertation

From a formal point of view, the work is at a high level. It would be appropriate to cite your publications more. I do not consider it appropriate to use the nabla and delta symbols for consumed and produced exergy. Their meaning is from my point of view connected with something different from mathematics.

Comments on the publications of the dissertation author

There is a list of the author's publications at the end of the dissertation. These are mostly journal papers. The list contains three published journal publications and two conference papers. There are also two publications under review.

Notes on the dissertation

It is obvious from the dissertation thesis that the author likes percentage comparisons. When using percentage comparisons at thesis, it is often not obvious at first glance what values the author compares. It would often be useful to use parameter values when comparing or to add percentages to the graphs.

Questions and remarks

1) The experiment was performed on the test facility installed at the Norwegian University of Science and Technology. Did you modify the test facility somehow? What do you see as your main personal contribution in terms of experimental measurement?
2) I think that throttling loss is wrongly visualized in figure 2.10 and figure 5.11. Express the rate of dissipated energy connected with throttling and try to visualize it (use entropy).
3) Equation (3-7) is not an equation for specific exergy. What is the right meaning of this equation?
4) How the parameters a, b, c and d in the equation (5-2) are determined? It seems to be incorrect to call the values based on equation (5-2) predicted values. It looks that parameters a, b, c and d are based on the fit of experimental data.
5) Are the parameters of the parallel system in chapter 5 based on measurement?

I recommend the dissertation thesis for the defense.

In Prague on 26.1.2022

doc. Ing. Tomáš Hyhlík, Ph.D.

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External examiner report

PhD candidate: M.Eng. Anas F. A. Elbarghthi

Thesis title: Ejector-boosted Transcritical CO_2 Refrigeration System

SCOPE AND TOPIC OF THE DISSERTATION

The presented dissertation of **M.Eng. Anas F. A. Elbarghthi** deals with current issues of the use of natural refrigerants in industrial refrigeration systems where the refrigerants ammonia (R717), propane (R290) and carbon dioxide (R744) appear to be the most promising. However, the use of each of these refrigerants carries with certain pitfalls associated with its properties.

In case of the carbon dioxide its main disadvantage is the low critical temperature of 30.98 °C at a relatively high pressure of 73.77 bar. The low critical temperature means that the refrigeration system is not able to achieve condensation of the refrigerant vapor and the system is thus operated in transcritical mode, at least for a certain part of the year. In order to achieve the required cooling efficiency of the device the high compression of refrigerant vapor is required which entails increased costs for compression work.

Many research groups around the world are working to address this issue, looking for ways to reduce compression work and increase cooling system efficiency. Using an ejector in a refrigeration circuit is one promising way to achieve this. It is an active area of international research with significant scientific and technological challenges for use in practical applications.

The candidate has demonstrated a clear awareness of the importance of the research topic and has provided high quality scientific building blocks that contribute to the feasibility of the technological solution. Therefore, I consider that the topic of the dissertation is up to date and of high scientific and technological importance.

GOALS AND METHODOLOGY

The aim of the dissertation is described by research objectives, which are:

1. Accomplish a literature review on the CO2 refrigeration system and ejector technology.

2. Conduct a comprehensive test campaign to investigate the effect of different operation conditions on the ejector profile performance experimentally.
3. Investigate the exergy distributions in the ejector profile and their effect on the rate of work recovery.
4. Assess the potential impact of the equipped expansion ejector profile on the R744 vapor compression system operational characteristics (COP and exergy efficiency improvement, power consumption).
5. Determine the contribution of the ejector to improve the exergy destruction of the total system and each component based on the second law of thermodynamics.

The student conducted an extensive research on the use of ejectors in refrigeration circuits using R744 refrigerant and methods for evaluating their efficiency.

He used the acquired knowledge to evaluate experimental data obtained during his internship at the NTNU/SITNEF in Trondheim. The performed evaluation and commenting of the achieved experimental results are relatively extensive and detailed.

He also used the obtained results to process a mathematical model of the ejector, which he used to evaluate the efficiency of the cooling equipment under different operating conditions and compared the values obtained with the simulated data of the system without the ejector. Part of these comparisons is also an exergetic analysis of the entire system with the determination of its critical points.

Although the presented results are thoroughly described, I lack a description of how the student arrived at them in the text of the thesis. In particular, I miss the description of the cooling circuit model, where it is not clear which parameters are calculated and which were selected (input parameters). Hence there are some unclear points e.g. how the compressor power was determined in the comparison of the two cycles.

Objective No. 3 - Investigation of the exergy distributions in the ejector profile and their effect on the rate of work recovery was not completely fulfilled, in my opinion. However, I consider this goal to be too ambitious and its fulfilment to be unrealizable on a commercially available ejector without the possibility of adding additional measuring points and knowledge of detailed geometry. Total exergetic parameters of the ejector were evaluated and used to successfully meet other objectives. Deficiencies in the fulfilment of this point do not affect the contribution of work and the fulfilment of overall goals.

The student used available and adequate means in the solution, chose suitable methods of solution, which he logically connected. The stated comments on the fulfilment of some goals do not have a significant effect on the fulfilment of the work objectives and the applicability of the achieved results.

I consider the goals of the work were met.

RESULTS OF THE DISSERTATION

The dissertation brings original results that expand knowledge in the field. I see the original benefit of the work in the evaluation of results from real measurements and the overall comparison of cooling cycles with and without ejector.

The benefit for the field is the finding of critical boundaries, from which the application of the ejector does not contribute to increasing the efficiency of the system.

I consider the work to be beneficial for the further development of the field.

ARRANGEMENT OF DISSERTATION AND ITS LINGUISTIC LEVEL

The dissertation has a good language level. The graphics page is also at a good level, but I would point out the vague separation of table and figures descriptions that merge with the surrounding text.

The arrangement into individual chapters is logical and corresponds to the problem-solving procedure.

PUBLICATION ACTIVITY

According to the attached overview and the Scopus database, the student published 4 articles in scientific journals and one conference paper in 2020 and 2021. Moreover, he is mentioned as a co-author in another conference article and another journal paper is under review. Four of these publications deal directly with the area of the dissertation, two articles are on the related field and one is completely outside the scope of the submitted dissertation.

From my point of view, this is an above-standard publication activity which corresponds to the achieved h-index h = 2 which is not common among doctoral students of mechanical engineering.

SUMMARY

The submitted dissertation deals with the current topic. The student has demonstrated the ability to study the issue and apply the acquired knowledge to the results of experiments. The knowledge gained during the dissertation is practically usable for the design of transcritical refrigeration cycles with R744 refrigerant.

I recommend candidate M.Eng. Anas F. A. Elbarghthi for the oral defence of the dissertation, to which I ask him the following questions:

1. Can you briefly describe the calculation procedure of the cooling circuit parameters used in Chapter 5? How were the compressors performance determined?
2. Can you formulate recommendations for the design of a transcritical refrigerating system with an ejector, based on the results of your dissertation?

In case of a successful defence, I recommend that the student be awarded the academic degree Ph.D.

Brno 18. 1. 2022

Ing. Jiří Hejčík, Ph.D.