THESIS EVALUATION FORM

PhD Candidate Name:

Rafał Fingas

Title of the Thesis

COMPREHENSIVE SYSTEM AND NUMERICAL ANALYSIS OF A SMALL-SCALE EJECTOR-BASED NATURAL REFRIGERATION SYSTEM

Thesis Evaluator

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General Comments (please write a short comment <u>on the thesis work</u>. Please justify the Overall Assessment given below)

The Thesis investigates the performance of a variable-geometry ejector (VGE) refrigeration system using propane as a natural refrigerant.

The Thesis is well written and well structured, the objectives are clearly defined at the beginning of the document and recalled at the start of each section, the methods are adequately described, and the conclusions are supported by the obtained outcomes.

The analysis of the studied system is comprehensive, ranging from fundamental flow physics to real-world system operation, encompassing both CFD simulations, numerical modeling, and experimental tests.

In particular, detailed CFD simulations of the VGE are implemented to investigate the internal flow structure of the ejector in terms of pressure distributions, choking behavior, and mixing phenomena. This in-depth analysis is not purely descriptive: the results are used to build performance maps, which are then exploited to develop two different reduced-order models (ROMs), aimed at simulating the performance of the whole refrigeration system under dynamic boundary conditions, resulting in an engineering-relevant tool.

The system adaptability to variable ambient temperatures and load conditions is investigated quite exhaustively, by considering both three different climatic zones and three different real industrial waste heat profiles, highlighting the conditions where the proposed system outperforms traditional fixed geometry ejectors the most, as well as the room for improvement. In addition, the possibility of extending one of the developed ROMs to VGE refrigeration systems with different natural refrigerants and blends is demonstrated, and a comparative analysis of the system performance as a function of the adopted refrigerant is conducted.

Unfortunately, the boundary conditions imposed by the experimental facility prevented the experimental outcomes from being effectively employed for the subsequent numerical analysis, but the reported study demonstrates a solid understanding of both measurement techniques and uncertainty analysis.

To sum up, the Thesis provides a valuable contribution to understanding the behavior of a variable-geometry ejector refrigeration system under dynamically variable conditions and to further promote its use in real applications.

Some requests for clarification and some suggestions for improvement are reported in the last section of the present document.

Overall Assessment. Please suggest a possible outcome of the evaluation among the choices:

☐ PhD thesis not ready to be defended. Major revisions needed: please list and explain them in the form of last page.

☑ PhD awardable. ☑ Minor revisions suggested: please list and explain them in the form of last page;

☐ PhD awardable *cum laude* (top 10%)

Evaluation Table 1 of 2 (Please tick the appropriate box: 4 – Excellent, 3 – Very Good, 2 – Good, 1 – Fair, 0 – Poor, N/A, Not Applicable). Please add a short comment if the evaluation is Fair or Poor

Scientific soundness and significance	Ex=4	VGood=3	Good=2	Fair=1	Poor=0	NotApp	Comment
Wide relevance/interest of the research theme		✔					
Objectives well defined and scientifically supported	✔						
Adequacy of the methodological approach	✔						
Quality of the experimental setup			✔				
Novelty of the approach		✔					
Contribution to knowledge in the field	✔						
Quality of the results		✔					
Interest for applications	✔						
Discussion and conclusions valid and properly supported		✔					

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Evaluation Table 2 of 2 (Please tick the appropriate box: 4 – Excellent, 3 – Very Good, 2 – Good, 1 – Fair, 0 – Poor, Not App: Not Applicable). Please add a short comment if the evaluation is Fair or Poor

Written Document	Ex =4	VGood =3	Good =2	Fair= 1	Poor= 0	NotA pp	Comment
Quality of the Abstract (is it exhaustive?)		✔					
Document organization. Suitable balance of the component parts of the thesis	✔						
Adequacy of the references	✔						
Clarity		✔					
Communication effectiveness	✔						
Properly supported discussion and conclusions		✔					

In case revisions are either required (major) or simply suggested (minor), please list and explain them below.

Some suggestions for minor revisions are as follows.

Section 1.7 could be named "Content" since it describes the content of each chapter.

Sections 2.1: A motivation for the chosen geometry of the VGE is missing. The candidate should discuss why such specific lengths and angles, taken from previous works, are selected. Please also focus on the reasons behind a short constant-area section and the presence of another 11 mm constant-area section.

Section 2.2: An explanation could be provided about why 7 mm is the last spindle position at which the ejector can entrain the secondary stream. Please check Equation 2.1: the AR is defined as the ratio between the effective throat area and the constant exit area of the nozzle, but it increases when the effective area decreases.

Section 3: The procedures and results of an experimental campaign are extensively reported, but the Thesis title refers to the numerical analysis only, probably because the experimental outcomes were not used as input datasets to create the ROMs. Are future experimental tests planned in conditions similar to those of the numerical analysis? A compressor is used to produce high pressure gas to be sent to the ejector motive nozzle inlet, but it is not included in the schematic diagram of the test rig of Figure 3.1: please explain the disposition of the different elements of the setup. The spindle positions analyzed range from SP0 to SP7, for a total of 8 configurations. However, Figure 3.5 shows 9 markers, and SP7 (where no measurable suction flow was observed) is listed as 8 mm instead: please, clarify. From SP0 to SP4, the ejector operates in a single-choking regime: what is the effect on the device efficiency?

Section 4: The ranges of the boundary conditions for the numerical simulations are given in Table 4.1, but please also define the steps selected for each parameter to obtain 275 968 cases. The grid independence of the results should be deepened; two cycles of mesh refinement were applied, but how is it demonstrated that grid convergence was achieved? Was the CFD model validated against literature results of similar VGEs? The computation time for CFD simulations (30-45 minutes) should be accompanied by the technical characteristics of the used PC. In Section 4.1.4, four representative spindle positions are selected; behavior of SP7 is strongly different from that of SP0-4: which is the limit SP at which flow reversal and ejector malfunction begin? In Figure 4.7 the relative error reaches -50%, but in the text it is reported as -100%. In Section 4.6, three ROM variants should be two.

Section 5: Please clarify the parameters for the auxiliary fluid (Therminol 59) in the generator: in Section 5.1 page 127, the second fluid in the brazed plate heat exchanger model is considered an incompressible liquid, but at the beginning of Section 5.1 the waste heat source has a superheat level, and it has a fixed temperature of 90 °C, while thereafter the waste heat source fixed temperature is 95 °C. At page 123 and in Figure 5.1 the temperature difference between the inlet and outlet of the auxiliary loop is 4 K, whereas at page 132 the controller maintains a fixed **temperature differential between the generator's inlet and outlet of 15 K. In the condenser and evaporator, is copper** selected as the material also for the fins? In the typical day selected, Trondheim has the lowest maximum ambient temperature, so the evaporator capacity is higher than that in the other two cities (Figure 5.7 vs 5.5-5.6), but wouldn't the Trondheim building need a lower cooling capacity than the Milan and Gliwice buildings? This would inhibit the exploitation of the higher evaporator potential of the VGE in Trondheim, ultimately leading to COP values lower than those of Table 5.7 in real applications. Could you estimate the COP decrease if a city with higher summer temperatures, above 30 °C, is selected? Figure 5.8: is there an additional bar (Milan, SP0) not present in the text? In 5.4-Conclusions, in Trondheim the VGE adjusts to a more favorable geometry during midday peaks (from SP7 to SP6), but in Figure 5.7 the COP decreases in such a situation.

Section 6: An inverse relationship is observed between the COP and the ambient temperature, whereas a source-temperature decrease results in a slight COP drop: can we conclude that, between the two independent variables, the fluctuations in ambient temperature generally have a stronger effect on a VGE COP value than the fluctuations in the waste heat source temperature? When discussing the results, presenting also the source temperature (waste heat) within the plots of Figures 6.4-6.21 would help follow your comments.

Section 7: Which was the criterion for the selection of the representative operating point used to check the compatibility of other refrigerants with the ULF-VGE ROM limits? In the second line after Equation 7.6, a reference could be missing. In Figure 7.4, why do the blue indicators (SP0) often fall above the red ones (SP1)? At the end of page 210, the 40% R290/55% R1270/5% R600a mixture, achieving an average COP of 0.47, seems not to perform better, as declared, than pure R290 (COP = 0.49).

In future developments, will the VGE system be tested in a real application? Could you estimate the energy and economic savings of the studied system compared to traditional vapor-compression chillers?