Wrocław, 06.02.2026

Dr hab. inż. Sabina Rosiek-Pawłowska, prof. uczelni
Politechnika Wrocławska
Wydział Mechaniczno-Energetyczny
Katedra Termodynamiki i Odnawialnych Źródeł Energii

REVIEW REPORT
on the PhD thesis
"COMPREHENSIVE SYSTEM AND NUMERICAL ANALYSIS OF A SMALL-SCALE EJECTOR-BASED NATURAL REFRIGERATION SYSTEM"
by Rafał Fingas (M. Eng.)

1. Formal Basis of the Review

This review was commissioned by Prof. Krzysztof Labus, Chairman of the Council of the Scientific Discipline of Environmental Engineering, Mining and Power Engineering at Silesian University of Technology via the formal notification (RIE-BD.512.1.202), dated on January 15th, 2026. The doctoral dissertation was written by Rafał Fingas (MSc Eng.) under the supervision of Prof. Giorgio Besagni from the Department of Energy at the Politecnica di Milano (Italy) and Prof. Jacek Smołka and Dr Michał Haida from the Department of Thermal Technology at the Silesian University of Technology (Poland).

2. General Characteristics of the Dissertation Contents

The doctoral dissertation is 232 pages long and contains 7 chapters. The main part is preceded by an abstract in English, Italian and Polish, followed by contents, abbreviations, final conclusions, future studies and references. The list of references comprises 150 citations.

The Introduction at the beginning of the thesis provides a solid background for further discussion. This chapter is devoted to discussing the current state of knowledge regarding thermally-driven refrigeration technologies for industrial waste heat recovery and the state of the art of ejector refrigeration systems (ERS). The PhD candidate selected these promising alternative refrigeration systems, among others, for his thesis as they offer particular advantages given their simple mechanical design and compatibility with natural refrigerants. Since ERS performance is highly dependent on the thermophysical properties of the working fluid, recent scientific knowledge concerning the application of natural refrigerants used in these types of systems was presented in detail. The PhD candidate provided numerous well-documented examples from the literature to illustrate the ERS's system efficiency and effectiveness, which was analyzed numerically and experimentally. It was pointed out that, due to their simplicity, low maintenance requirements, and their ability to use low-GWP refrigerants, these cooling systems offer an attractive sustainable solution for the industrial sector. Fixed-geometry ejectors often operate far from their design point, leading to suboptimal entrainment ratios and reduced COP. The variable geometry ejector represents a promising solution that provides increased flexibility for the ejector cycle and an overall performance improvement. The PhD thesis presented here addresses the limitations of fixed-geometry ejectors by studying the introduction of a spindle into the motive nozzle of the VGE, which enables dynamic adaptation to changing operating conditions through real-time adjustment of its nozzle area ratios, and by so doing underlining its applicability.

The Introduction section highlights the biggest challenge and gaps of knowledge related to the ejector's performance - which is accurately assessed under varying operating conditions and different climatic conditions - and points out the need to develop an optimal control system for the spindle adjustment, as this is the core mechanism for the real-time modulation of the ejector capacity, and thus one of the main research questions addressed in this study.

In my opinion, the Introduction section has been written in a very professional way. It contains multiple examples of the most important achievements in the field of thermally-driven refrigeration technology, presenting the advantages and disadvantages of using each of the technologies discussed. It underscores the PhD candidate's extensive knowledge and orientation in his field of study. To sum up this part of the dissertation, it can be stated that the PhD candidate presented the four partial goals of his doctoral dissertation in a clear fashion, three of them being related to numerical analysis and the other to the development, implementation and testing (under real laboratory conditions) of an R290 ERS equipped with VGE and driven by a real low-temperature waste-heat source.

In the next part of the dissertation, Mr. Fingas presented and discussed the results of his research. This part is divided into six chapters:

Chapter 2 presents the design of the controllable R290 variable-geometry ejector. Highly interesting results were obtained as a result of fruitful cooperation with an international group from Politecnica di Milano, which specializes in Sustainable Energy System Analysis and Modelling (Prof. Fabio Inzoli and Prof. Giorgio Besagni). As a result of this cooperation, under the cotutelle agreement established between the Silesian University of Technology and Politecnica di Milano, a number of very interesting numerical analyses and experimental results were obtained covering both the analyses using CFD simulations, carried out on the spindle-based VGE of Prof. Besagni's group, and then the choice of R290 as its working fluid and the subsequent experimental research conducted at Silesian University of Technology to evaluate the performance of the manufactured VGE when using R290 as the working fluid, assessing the modulating influence of the spindle positioning on the ejector capacity in real time, which is a scope of the next chapter.

Chapter 3 presents the experimental setup, methodology and analysis of the R290 variable-geometry ejector with a controllable spindle, in which the PhD candidate defines the measurement system, instrumental, and testing procedure used in this study. The existing literature of the PhD supervisors was fruitfully sourced to select the methods and experimental test rig used in this study. The effective and controlled experimental study of this VGE was conducted on a separate test rig connected to the heat-pump system, ensuring the operating condition for the manufactured ejector, which amounts to a significant experimental challenge given the constraints imposed by the laboratory-scale test facility designed for high-pressure natural refrigerant applications, which was not tailored to an ERS but rather configured as a flexible platform for standalone ejector testing (compared to the original one designed and reported in the CFD analysis of Prof. Besagni's group). The experimental results presented in this chapter confirm that the spindle significantly influences the mass entrainment characteristics of the ejector. Higher spindle values increased the mass entrainment ratios under identical motive pressure conditions, demonstrating effective capacity control through changes to the motive nozzle area ratio. The ability to adjust the effective throat area using the spindle enables performance optimization under varying pressure-lift conditions, thus allowing the ejector to keep operating closer to its design point. This confirms the VGE's potential as a dynamic and efficient component within refrigeration systems operating under variable thermal loads. It was undoubtedly an ambitious research task to take on, and it can be said that obtaining positive results required not only experimental proficiency but, above all, the ability to analyze the ejector's capacity control capability, which entailed a detailed investigation of the experimentally determined ejector performance curves and an analysis of the static pressure distribution through the ejector. This careful work has provided insights into the internal flow dynamics and shockwave behavior as influenced by the spindle position.

Chapter 4 presents the development of the CFD-based reduced-order models (ROM) of the R290 VGE. The ROMs were developed using the POD technique combined with RBF interpolation based on the data generated by the CFD model alone. A pure numerical approach based on advanced HEM modeling of the VGE was adopted for the reduced-order modeling, ensuring ejector operation within the desired ejector operating range. In this chapter, the PhD candidate pointed out that the ROMs were completed with a novel, more universal framework based on ejector performance parameters that had different sets of inputs and outputs. In this PhD thesis, two distinct reduced-order modeling approaches were analyzed. The first model utilized a conventional approach concerning the typical thermodynamic variables as inputs, namely the pressure and specific enthalpy at the ejector inlet nozzles, and the pressure at the diffuser outlet. As an output, the ROM predicted the motive and suction mass flow rates for the given operating point within the ejector's operational range. In the second approach, the Universal Low-Pressure Fluids VGE ROM (ULF-VGE ROM) was based on a general concept designed to improve the ejector modeling flexibility and transferability across different refrigerants that have similar thermophysical properties, mainly in terms of their pressure-wise operation in the subcritical refrigeration system. To provide high ROM accuracy based on the CFD results, a model calibration was conducted to determine the required resolution of the CFD points map for the specified operating envelopes at each ejector port, confirming that high-resolution CFD input data is essential for accurate ROM performance, especially for capturing the suction mass flow and the entrainment behavior. In this chapter, the PhD candidate also presented the resulting operational envelope of the developed ROMs and their implementation into the Dymola software, allowing a very fast model to be obtained for dynamic simulations.

Chapter 5 presents the development of the dynamic numerical model of the R290 ERS equipped with the reduced-order VGE model, using a highly accurate ejector modeling approach, which enables the system performance to be evaluated under varying ambient temperature conditions taken from historical data. To evaluate the performance of the proposed VGE-based refrigeration system under varying ambient conditions, a dynamic object-oriented model of the ERS was developed using Dymola simulation software, based on Modelica modeling language, which is suitable for the simulation of complex engineering systems. Therefore, the chapter presents the system layout built in Dymola software, describes the mathematical formulation of all the system components, the selected solver and its settings, the ejector control and the simulated ERS conditions, representing its operation in three different climatic zones. The VGE-based ERS showed the greatest benefits in hot climates with high daily temperature variability, where spindle control provides continuous on-design operation.

Chapter 6 analyzes the R290 ERS performance under variable ambient temperature conditions and using different waste-heat sources. To assess the performance and control response of the R290 ERS in realistic operating scenarios, source temperature inputs were derived from actual waste-heat data from three different industrial sites: a mine, a forge, and a bearings factory. The results provide an insight into the system operation in different environmental and industrial scenarios, focused on evaluating the best application for the proposed R290 ERS system. The results reveal that the system's efficiency is highly sensitive to both ambient temperature and source stability. ERS operation in cooler climates presented higher COP and reduced generator heat input, while stable waste-heat sources enhanced overall control effectiveness and energy performance in all cases.

Chapter 7 evaluates the ERS system's application using alternative natural refrigerants (and selected blends) using the generalized approach for ROM. It describes the screening of other refrigerants similar to R290 under selected reference operating conditions. The results revealed that an ERS with R1270 utilizing R290 VGE delivered up to a 21% higher cooling capacity and 10% COP improvement compared to a system utilizing R290, while other R290-based blends showed comparable or lower performance, indicating a need to expand the ROM operational envelope or re-design the ejector for other refrigerants.

Chapter 8. The Conclusions section - where the main conclusions obtained from the conducted research were clearly presented. The main achievement was the development of a generalized ULF-VGE ROM, using the pressure ratios and inlet temperatures as inputs in order to return the VGE characteristic expressed in the mass entrainment ratio. The R290 VGE model can potentially be extended to other refrigerants that have similar characteristics studies without needing to remodel the ejector's geometry. Recommendation for further research – this section lays out how future research could be conducted combining the FGE-based multi-ejector modules with a VGE, providing smooth and fast modulation. This could be particularly beneficial for industrial sites that have distinct thermal dynamics, where the combination of two ejector types might provide a stable cooling capacity decoupled from the variable heat source. Hence, the scaling-up of the small-scale ejector-based natural refrigeration system is clearly possible, especially if the proposed ERS concept is enhanced by integrating state-of-the-art heat exchangers to utilize waste heat, thus reducing temperature differences and exergy losses in the generator loop, while increasing the system's overall COP.

Regarding the part of the PhD thesis devoted to the results and discussion, it can be stated that the PhD candidate carried out a number of experiments and numerical analyses to develop a new approach that accurately assesses the R290 VGE performance by considering the dynamic nature of real waste-heat and ambient-temperature characteristics in different climatic zones as well as the application of alternative natural refrigerants - leading to a maximization of the VGE-based ERS's potential and greater industry attention. The stated goal was achieved although the results revealed that the R290 VGE ROM operational envelope defined in this PhD thesis could only be used with refrigerants that have very similar characteristics, therefore the ULF-VGE ROM operational envelope needs to be extended to cover a much wider range of ejector geometry pressure ratios than that presented in this PhD thesis. On the other hand, this might be a good reason to continue the particular research line.

On the whole, the Results and Discussion section of this PhD thesis is very well written and contains high-quality illustrative figures and tables. Furthermore, all the results have been interpreted in a careful and justified manner.

3. Substantive value of the dissertation

The topic addressed in this PhD thesis has an international dimension and is an opportunity for both the academic and private sectors to stand out in terms of technological development. The main objectives are to underpin the scientific understanding for energy-efficient thermally-driven, ejector-based refrigeration systems to satisfy the growing global demand. These systems offer an especially promising solution for waste-heat recovery, help combat climate change, safeguard the environment and, above all, make industrial systems more sustainable. One of the main goals was to present the tools necessary to advance ejector technology and to scale it up from small to medium-sized industrial applications. Accomplishing this will also lead to new investment in refrigeration technology by utilizing low-temperature waste heat as a driving source that enables thermally-driven cycles to replace or supplement electrically powered vapor compression. Such an approach reduces primary energy consumption and refrigeration leakages, problems that exacerbate climate change. Waste heat is typically referred to as a by-product of industrial processes and is often discharged unused into the environment despite containing valuable thermal energy. Thus, climate friendly waste-heat-driven cooling solutions are extremely important when considering economical and technical conditions, and are of particular interest to the business and academic sectors. The research activity led to a small-scale ERS equipped with spindle-based VGE being developed, tested and modeled. This system was driven by ultra-low-grade waste heat and operated using the natural refrigerant R290. The novelty of this approach was that it adjusted the motive nozzle area ratios in real time via spindle displacement. This allowed near-optimal ejector entrainment ratios to be maintained, thus increasing the operating condition range. This adjustment represented the core mechanism for real-time modulation of the ejector capacity, demonstrating its suitability for dynamic energy systems such a waste-heat recovery or variable-load refrigeration cycles.

This PhD thesis presents the experimental campaign that focused on assessing the controllable R290 spindle-based ejector, developing the CFD-backed ROMs to enable accurate dynamic simulation, assessing ERS performance under varying ambient conditions and waste-heat temperatures, and analyzing the potential application of the R290 VGE ROM using alternative natural refrigerants and their blends.

The scientific approach presented here is very impressive in terms of analyzing the CFD-based ROMs of the R290 VGE models developed using the POD-RBF technique. It included an approach that enables the rapid and accurate reproduction of ejector behavior. A generalized ULF-VGE ROM was developed using pressure ratios and inlet temperature as inputs in order to return the VGE characteristics expressed in the mass entrainment ratio. By combining this generalized model with a mathematical nozzle, it can be applied to alternative refrigerants that have similar thermodynamic characteristics, thus potentially extending the R290 VGE modeling to other studies using fluids similar to R290, without the need to remodel the geometry.

In general, the PhD candidate appreciated the value of collaborating with scientists from both universities. As a result of this collaboration, it was possible to manufacture, test and model the controllable spindle-based ejector, which could adjust to the fluctuating ambient temperatures and load conditions described in this dissertation. The numerical analysis of a small-scale ejector-based natural refrigeration system within a climate change scenario is a timely research topic. Employing advanced CFD modeling to characterize the ejector behavior across varying operating regimes and using suitable reduced-order models that can be integrated into dynamic system-level simulations, significantly increases the value of this doctoral thesis, extending its scope to VGE control system development. This has definite engineering value and represents an advance in the field of interest.

4. General and specific comments

After reading this PhD doctoral thesis, I have several questions and observations that I would like the PhD candidate to comment on:

1. The layout of the work, and its division into chapters and subchapters appears to be correct. Nonetheless, the proportions of the individual parts have not been maintained, in particular in the case of the Introduction section (50 pages) compared to other chapters (Chapter 2: 16 pages, Chapter 3: 29 pages, Chapter 4: 39 pages, Chapter 5: 33 pages, Chapter 6: 36 pages, Chapter 7: 17 pages, and Chapter 8: 5 pages).
2. On page 49, the PhD candidate indicated four partial goals, however he did not formulate his own research hypotheses, the formulation of which would certainly have an impact on the final value of the scientific work presented in this dissertation. I would like to ask the PhD candidate to comment on this important remark. If there was an initial hypothesis, I would also like to know if the PhD candidate was able to validate/prove it.
3. In my opinion, discussion regarding the originality of this PhD thesis based on criticism of other state-of-the-art studies is indispensable. I would therefore ask the PhD candidate to clarify this.
4. The reviewed dissertation was not prepared in a "classic way", meaning it does not follow a "classic" PhD thesis structure, which would include an introduction, an existing literature section, the methodology, the experimental section, and the results and discussion. I admit it was difficult to follow the subsequent PhD candidate's steps in some places because there was no methodology chapter. For this reason, I would like to ask the candidate to provide a PhD methodology flowchart.

5. The Introduction section seems to lack a general scheme that might serve as an example of spindle-based R290 VGE integration in an industrial refrigeration system, such as in the food retail industry or any other sector in which low-grade waste heat is available on site. This would underscore the potential applicability of the solution analyzed. Therefore, I would like the PhD candidate to include such a scheme.
6. In Chapter 3, the PhD candidate stated that the absolute values of the suction nozzle mass flow rate obtained during the experimental campaign were substantially lower than those predicted in the CFD simulations presented by the Besagni group, and that several factors probably contributed to this discrepancy. One of them, as stated by the PhD candidate, was the pressure of the motive nozzle in the experimental setup, which was significantly lower than the one used in the numerical analysis referenced, thus directly affecting the potential for entrainment. This statement reappears throughout the PhD dissertation. However, there is no information regarding the aforementioned predicted in the CFD simulation values. I would like to ask the PhD candidate to provide information on those discrepancies here.
7. Following the experience gained by using this spindle-based VGE prototype, I would like to ask the PhD candidate to explain how the VGE design should be modified to fulfill the close-to-market solution objectives, once the most efficient ejector performance is ensured. What is the investment cost for manufacturing the small-scale ejector (like the one studied during this PhD thesis) and what would be its possible payback period, once used in real application? Secondly, considering the main future directions referred to in Chapter 8 - specifically that related to possible improvements resulting from combining the FGE-based multi-ejector modules with a VGE, which would be beneficial for industrial sites with distinct thermal dynamics, where combining two types of ejectors could provide a stable cooling capacity decoupled from the variable heat source - I would ask the PhD candidate to provide an example of the design of such multi-ejector parallel system architecture, as well as the potential energy benefits resulting from its application. What would be the computational time in Dymola software for that kind of hybrid system over a one-year operating period? Considering also the trade-offs between safety and efficiency of the finally selected R1270, I would like to ask the PhD candidate about the approximate refrigerant charge requirements and limits for that kind of industrial-scale application.
8. I would like the PhD candidate to assign the proper measurement location to each differential pressure sensor, since it is not clear from the description (starting at Page 60) nor from the information gathered in Table 3.1, where on the test rig the measurement instrument description was given, nor where the undefined DP1-DP6 abbreviations were used for differential pressure sensors.
9. On page 71, Fig.3.6 could be represented using a 2x2 grid subplot. I would add more ticks on the y axis to approximate the y axis scale to the obtained results. Moreover, I would like to ask the PhD candidate to explain why the error bar intervals marked for each represented measurement point are different. How, for example, should the last SP4 measurement point be interpreted (Fig. 3.6 c) in comparison to the previous one?
10. On page 81, the PhD candidate stated that the proposed ROM approaches based on the CFD simulation results data source, obtained using an advanced and versatile homogeneous equilibrium model, may be implemented in any kind of system equipped with the gas ejector. Therefore, I would like to ask the PhD candidate to indicate what kind of data will be necessary to apply this approach to another ejector-based system?
11. On many occasions, the PhD candidate referred to the "sustainable solution", indicating that R290 VGE was a promising solution for sustainable cooling systems, but without explaining its definition. Therefore, I would appreciate it if the PhD candidate could explain what, in his opinion, would this mean in the case of an ejector-based refrigeration system?
12. Are there scientific positions in the existing international literature that coincide with the cognitive, methodological and research scope of the doctoral dissertation?

13. On 101, subparagraph 4.2.3. the PhD candidate indicated that, for the model calibration conducted to determine the required resolution of the CFD points map for the specified operating envelopes at each ejector port, SP3 was selected, as it was an intermediate representative of the average ejector operation. Was an attempt made to analyze the SP2 and/or SP4 together with the SP3?
14. In Chapter 4, the PhD candidate stated that both ROMs were developed using the POD technique combined with RBF interpolation based on the data generated only by the CFD model. The reason given for not using the experimental data as the input dataset to develop the ROMs was the limitations inherent in the available experimental set-up, the operational range of which was not within the desired operating condition range for the dynamic analyses of the R290 VGE application in the ERS (the main system for the considered ROM application). I would like to ask the PhD candidate to indicate how he would plan this part of his thesis in the hypothetical case that the quality of the experimental data would have been of sufficient quality?
15. Please provide a list of the publication record related to the topics presented in the PhD thesis and please indicate the PhD candidate's contribution to each of the thesis goals, considering the existing literature from all three PhD supervisors.
16. Apart from the above issues, certain editorial issues were found, such as:

- A List of Figures and List of Tables would be useful.
- Page 41, Fig. 1.6. - the title for the x axis is missing. I would add the "distance along axis".
- Page 62, Fig.3.2. - I would appreciate better quality images of the experimental test rig used in the R290 VGE tests, especially the zoomed image of the tested ejector and the one illustrating the thermocouple montage.
- On page 69, the PhD candidate started to present the results of the evaluation of the ejector performance curves, analyzing the relationship between the mass entrainment ratio and the outlet pressure increase. This was performed for selected spindle positions, although only four representative spindle positions were picked out, namely SP0, SP2, SP4 and SP7. There is a lack of explanation regarding the reason for choosing those spindle positions, which is only later referred to on page 89.
- Page 50 - there is missing part in the Chapter 7 description.
- Fig.4.11, 4.12, 4.13 could be represented using a 2x2 grid subplot.
- On page 143, there is no explanation for why the fixed-ejector simulations throat diameters of SP1-SP3, for the cases of Gliwice and Milano, were chosen, nor for the diameters of SP5-SP7 in the case of Trondheim.
- Page 153, Fig. 5.8. - there was no SP0 for the Milano case.

5. Final Conclusion

To sum up the review, I would like to emphasize that the substantive value of the dissertation, despite certain shortcomings, is high. The goals set at the beginning were largely achieved, which clearly allows me to state that it meets the requirements for this type of dissertation. The candidate for the PhD degree has proven that he is an experienced specialist in the field of heat-driven ERS equipped with a variable geometry ejector, that he is capable of carrying out properly designed research using a variety of experimental and computational techniques, and that he can skillfully interpret the obtained results and approach them critically.

The author has demonstrated a deep understanding of the subject encompassing ERS equipped with centrally aligned spindle VGE, driven by ultra-low-grade waste heat and operating with the natural refrigerant R290, and of operational optimization, maximizing its performance for variable operating conditions. The PhD candidate has also demonstrated his ability to perform computational analysis, being very proficient in the use of mathematical apparatus. The author has solved a timely scientific problem, and the PhD thesis makes a significant contribution to the development of the scientific discipline covering environmental engineering, mining and power engineering. The results of the research conducted under this doctoral dissertation are of high value and may be of practical importance in terms of designing a new computational approach for R290 and other natural refrigerants (and their blends) used in ERS equipped with VGE, leading to better performance analysis. In my opinion, the dissertation has been prepared to a very high standard throughout. It is written in the correct scientific language, and the transparent graphics make it user-friendly. In terms of content, this work is an example of an ambitiously planned research task and its effective implementation. From a scientific point of view, I evaluate the work very positively. Its quality is also evidenced by the fact that some of the results have already been published in the form of an original publication. Although there is no information regarding the PhD candidate's publication record in the PhD dissertation, it is worth noting that according to ORCID platform information the candidate is a co-author of various scientific publications from the JCR list, which were published during his education at the Doctoral School of Silesian University of Technology and the Politecnica di Milano.

In conclusion, I can therefore state that the reviewed doctoral thesis by Rafał Fingas (M.Sc. Eng.), entitled '*COMPREHENSIVE SYSTEM AND NUMERICAL ANALYSIS OF A SMALL-SCALE EJECTOR-BASED NATURAL REFRIGERATION SYSTEM*' meets all statutory (referring to the Act of July 20, 2018, Law on Higher Education and Science; consolidated text: Journal of 2024 Laws, item 1571, as amended) and customary requirements for doctoral dissertations.

Consequently, I am applying to the Environmental Engineering, Mining and Power Engineering Scientific Discipline Council at the Silesian University of Technology for admission to the next stages of the doctoral procedure for awarding a doctoral degree to Mr. Rafał Fingas.

Sabina Rosiek-Pawłowska