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REVIEW
of the doctoral dissertation of M.Sc. Eng. Rafał Fingas
"Comprehensive system and numerical analysis of a small-scale ejector-based natural refrigeration system"

1. Basis for preparing the review

The basis for preparing this review of the doctoral dissertation by M.Sc. Eng. Rafał Fingas is Resolution No. 265/2025 of the Discipline Council dated 18 December 2025. The Resolution states that, pursuant to Article 190(2) of the Act of 20 July 2018 – Law on Higher Education and Science (consolidated text: Journal of Laws 2024, item 1571, as amended) and Resolution No. 43/2023 of the Senate of the Silesian University of Technology in Gliwice dated 25 September 2023, the Discipline Council of Environmental Engineering, Mining and Energy of the Silesian University of Technology appointed me as a member of the doctoral committee.

2. Introduction

The author's motivation for undertaking this work was the growing global demand for cooling, driven by urbanisation, digitalisation, and climate change, which creates increasing pressure to deploy refrigeration technologies with a lower environmental impact. The author notes that the transition to natural refrigerants is further reinforced by regulations limiting the use of substances with high global warming potential, which, in practice, forces the search for solutions that combine high efficiency with low emissions and compliance with regulatory trends. In this context, the author directs the dissertation towards the development and assessment of a refrigeration system using natural refrigerants and waste heat as a realistic alternative to conventional vapour-compression systems. Accordingly, the dissertation focuses on thermally driven refrigeration technologies that utilise waste heat and can support the decarbonisation of the cooling sector. The author emphasises that ejector-based refrigeration systems are a promising solution due to their simplicity, low maintenance requirements, and compatibility with waste heat; however, their deployment is limited by high sensitivity to varying boundary conditions. In particular, fixed-geometry ejectors often operate far from the design point under varying heat source and ambient temperatures, which reduces the mass entrainment ratio and the coefficient of performance (COP). The author indicates that variable geometry ejectors may mitigate this drawback through continuous adaptation of the nozzle geometry,

yet a research gap remains regarding reliable performance assessment under realistically varying conditions and the development of effective spindle control.

The dissertation is primarily computational and model-based. The author's conclusions are founded on a combination of advanced Computational Fluid Dynamics (CFD) simulations, reduced-order modelling, and dynamic system-level analysis. In line with the stated objectives, the author performs dynamic simulations of an ejector-based refrigeration system using the natural refrigerant R290, employing real waste-heat temperature profiles and weather data (different climatic zones). The ejector behaviour is represented by reduced-order models derived from CFD results, suitable for integration into system simulations and for constructing the control logic. At the same time, the work includes an experimental campaign for a spindle-based variable geometry ejector using R290 and an analysis of the applicability of the proposed approach to other natural refrigerants and mixtures. Therefore, the dissertation should be regarded as timely and relevant to the development of environmentally friendly refrigeration technologies and the practical utilisation of low-grade waste heat.

3. Scope of the dissertation

The doctoral dissertation by Rafał Fingas entitled "Comprehensive System and Numerical Analysis of a Small-Scale Ejector-Based Natural Refrigeration System" was prepared within the Joint Doctorate Programme (Gliwice–Milan, 2025). The dissertation was developed under the supervision of Prof. Giorgio Besagni and Prof. Jacek Smołka, with Michał Haida PhD, serving as co-supervisor. The dissertation comprises 233 pages. The introductory part contains acknowledgements and a preface describing the joint doctoral (cotutelle) framework between the Silesian University of Technology and Politecnico di Milano, as well as abstracts in several language versions, including "Abstract" and "Streszczenie". The dissertation also includes a list of symbols and abbreviations ("List of symbols / Abbreviations"), which organises the notation used in the subsequent chapters.

The core content of the dissertation is divided into eight chapters. In Chapter 1 ("Introduction"), the author presents the background of thermally driven refrigeration technologies, reviews absorption, adsorption and ejector-based solutions, and then discusses natural refrigerants (including ammonia, CO_2 and hydrocarbons) in the context of waste-heat utilisation. The chapter concludes with the motivation, objectives, and scope of the work.

The author formulates four partial objectives:

1) Development of an ejector-based refrigeration system using R290 and a variable geometry ejector, utilising a real low-temperature waste-heat source and weather temperature data to perform analyses under realistic operating conditions.

2) Development of two reduced-order models for the variable geometry ejector based on CFD results, including an approach enabling calculations for other refrigerants or their blends with similar thermophysical properties.

3) Assessment of the waste-heat recovery potential of the ejector-based refrigeration system using real waste-heat temperature profiles, and analysis of system operation in different climatic zones under varying environmental and load conditions.

4) Investigation of the feasibility of adapting the variable geometry ejector design developed for R290 to other natural refrigerant blends, including identification of performance trade-offs and key design considerations for a multi-refrigerant ejector.

Chapter 2 ("Design of Variable Geometry Ejector") concerns the design of the variable geometry ejector, covering the geometry, spindle control, and a description of the manufactured device.

Chapter 3 presents the experimental rig and measurement methodology for the variable geometry ejector using R290 (propane), including the measurement procedures, operating range, and results related to capacity control and static pressure profile analysis. The author reports experimental results within the following operating ranges: the motive nozzle inlet pressure was maintained between 15.8 and 20.2 bar at 80–105°C; the suction nozzle inlet pressure ranged from 2.2 to 5.4 bar at 22–36°C; and the diffuser outlet pressure ranged from 2.3 to 6.0 bar (48–78°C). Eight spindle positions (SP0–SP7) were tested. In the static pressure profile measurements, the outlet pressure was controlled within 5–6 bar while the suction pressure was varied to change the "pressure lift".

Chapter 4 is the key part of the dissertation, as it develops reduced-order models for the variable geometry ejector intended for fast dynamic simulations of the entire ejector-based refrigeration system. The input dataset for the reduced-order models was generated exclusively from CFD simulations (without using experimental measurements in the dataset). The CFD calculations were performed in ANSYS Fluent; the author relies on a previously developed and tested homogeneous equilibrium model (HEM) approach and cites its prior literature validations. The operating envelope of boundary conditions for the CFD simulations is defined, and the numerical meshes for the analysed spindle positions are taken from Besagni et al. Two reduced-order model formulations are presented using the POD-RBF method. The first, "classical" model uses pressures and specific enthalpies at the motive and suction nozzle inlets and the outlet pressure as inputs, and returns the motive and suction mass flow rates. The second, a generalised formulation, aims to enhance transferability to other fluids with similar properties by using pressure ratios and inlet temperatures as inputs and returning the mass entrainment ratio. The author also reports a sensitivity analysis with respect to the resolution of CFD-based maps and indicates that only high-resolution input data provide the required accuracy (relative errors below 1%). The chapter ends with an implementation of the reduced-order models in Dymola via external functions, enabling very fast system simulations without the computational burden typical of CFD.

Chapter 5 describes the development and application of a dynamic model of the ejector-based refrigeration system in Dymola/Modelica for the refrigerant R290, where the key component (the variable geometry ejector) is represented using the reduced-order models from Chapter 4. The author describes the system structure (generator, condenser, evaporator, piping and control) and the adopted correlations and library components for heat transfer and pressure losses, and then defines a base scenario in which the main time-varying forcing is the ambient temperature, influencing condensation conditions and thereby ejector operation. Solver settings are provided (including a 0.1 s time step) together with a practical note on the computational cost of a 24-hour simulation.

A central element of Chapter 5 is the spindle control logic: at each time step, the algorithm selects the spindle position (SP0–SP7) by searching across a set of reduced-order models to obtain the most favourable operation (in practice, maximising suction entrainment). The author then performs a 24-hour dynamic analysis for real ambient temperature profiles for three locations (Gliwice, Milan, Trondheim) and compares the variable geometry ejector case against fixed-geometry ejector variants. The conclusion is clear: the advantage of the variable geometry ejector increases with the variability of external conditions, since geometry control keeps the ejector closer to design operation; the author reports substantial increases of the daily-averaged COP (up to about 52%) and improvements in cooling effect depending on the climate.

Chapter 6 extends the analysis from Chapter 5 by considering system operation when the cooling is driven by low-grade waste heat supplied to the generator, with its temperature varying in time according to industrial data. The author introduces real, unfiltered waste-heat temperature profiles with 1 s resolution from three industrial sites (a mine, a forge, and a bearings factory), differing in stability and fluctuation amplitude within approximately 90–101°C. Evaporator-side conditions are kept constant (including 10°C evaporation temperature and 3 K superheat) to isolate the impact of waste-heat fluctuations and ambient conditions on ejector operation and spindle control.

Nine 24-hour scenarios are defined as combinations of three climatic zones (Gliwice, Milan, Trondheim) and three waste-heat profiles; results are interpreted using instantaneous trends and daily-averaged COP and cooling capacity. The conclusions indicate that a more stable waste-heat source leads to smoother control and more predictable operation, whereas more dynamic profiles force frequent SP adjustments and cause greater performance fluctuations.

Chapter 7 addresses whether a variable geometry ejector optimised for R290 can be reasonably used with other refrigerants (and their blends) without re-designing the geometry, by employing the generalised reduced-order modelling approach from Chapter 4 that outputs the mass entrainment ratio. The author emphasises that this enables analysis of other fluids at a lower computational cost. The analysis is performed stepwise: candidate fluids are selected, a compact motive nozzle model is implemented in Dymola, and the resulting COP and cooling capacity are compared. The author indicates that, among pure fluids, only R1270 meets the screening criteria; among blends, he lists, inter alia, R436A/B/C and selected mixtures containing dimethyl ether. The verification shows agreement between the generalised and baseline reduced-order models for R290 (with small deviations around the critical region). The results show improved COP and cooling capacity for R1270 and R290–R1270 blends (for pure R1270 on the order of +10% COP and +20% cooling capacity), while adding dimethyl ether leads to decreases (for a 50/50 blend about −6% COP and −20% cooling capacity) and may cause stability issues for more restrictive settings (e.g., SP7).

The dissertation concludes with Chapter 8. In this chapter, the author summarises the work as an analysis of an ejector-based refrigeration system with a variable geometry ejector, powered by low-grade waste heat and operating with R290, combining experiments, CFD-supported reduced-order models, and dynamic simulations under variable ambient and source conditions. He notes that the experiments confirmed the feasibility of controlling entrainment via spindle position, and that static pressure profiles may support further CFD calibration. The author reiterates the development of two reduced-order model formulations and the main conclusion that a single variable geometry ejector can replace several fixed-geometry ejectors by expanding the operating range and maintaining operation closer to the design region. In the future work section, he proposes developing a hybrid reduced-order model (CFD plus experiments), implementing more continuous spindle control, extending the model operating envelope, and system-level enhancements (e.g., improved heat exchangers and cold-energy storage).

4. Critical and discussion remarks

1) In Chapter 2.3 ("Manufactured ejector"), the 3D geometry of the ejector is presented. Please specify which machines were used to manufacture the device components and how the dimensional accuracy of the machined surfaces was verified.

2) In Chapter 3, the author shows that for the spindle position SP7 the highest mass entrainment ratio (about 0.40–0.45) is achieved, but only within a very narrow operating range and with high sensitivity to changing conditions. At the same time, later in the dissertation (in the CFD/reduced-order model results) SP7 is described as a "malfunction regime", i.e. a situation in which flow reversal and a negative suction-side mass flow occur. Can the author clearly indicate the boundary conditions (motive inlet pressure p_motive, suction pressure p_suction and outlet pressure p_out) that separate the "high MER" operation at SP7 from the onset of malfunction/backflow? In other words, can a simple control boundary be defined indicating when SP7 is safe and beneficial and when it should not be used?

3) Were the CFD results compared against the experimental measurements presented in Chapter 3?

4) Is the developed reduced-order model scalable to other ejector dimensions (different diameters/lengths)?

5) What is the dissertation's thesis statement (main research thesis/hypothesis)?

6) Since the author cites a hybrid reduced-order model approach combining CFD and experimental data as a means of improving accuracy, did he consider using his own measurements (at least for validating selected operating points or for calibrating the model around the critical region), especially given the reported sensitivity of the characteristics in the on-/off-design transition region?

7) Please explain whether the system model developed in Dymola/Modelica was validated, and if so, how.

8) The author uses real waste-heat temperature profiles with 1 s resolution and declares that they were used without filtering, which causes frequent SP changes and fluctuations in performance parameters. In this context, was the effect of generator-side thermal inertia and spindle actuator limitations (maximum positioning speed, delays) considered (or at least estimated), and would filtering or limiting the SP rate of change materially affect the daily-averaged COP and cooling capacity?

9) Can the author justify to what extent the screening procedure for fluids/blends (based on a single reference point 85°C/5°C/20°C and a ±10% criterion for pressure ratios) is representative of the full operating envelope of the refrigeration system? In other words, under different ambient conditions and/or different waste-heat temperature levels, does the list of "matching" fluids (e.g., R1270, R436A/B/C) remain the same, or does it change significantly?

5. Editorial remarks

1) On page 59, there is an error in the last line: the word "the" appears twice.
2) Figure 3.2 (test rig photograph) is too small. The photograph should be larger so that the reader can better understand the setup.
3) On page 50, in the description of Chapter 5, the word "representing" appears twice ("representing representing").
4) In Section 3.2.2 ("Uncertainty analysis") on page 66, there is a typo: "foollowing equation".

6. Assessment of the dissertation

In my opinion, the topic of the dissertation is timely and interesting, as it concerns refrigeration driven by the recovery of low-grade waste heat and the regulation of an ejector-based refrigeration system under unsteady operating conditions. The dissertation is comprehensive: it includes experimental studies of a variable geometry ejector, the development of reduced-order models based on CFD results, implementation of these models into dynamic system analysis in Dymola/Modelica, and evaluation of system operation under variable environmental and source conditions, as well as an analysis of other refrigerants and mixtures. I consider the following to be the main achievements of the candidate:

1) Experimental confirmation that spindle position effectively controls the mass entrainment ratio of a variable geometry ejector, and that the measured static pressure profiles can support further validation and calibration of numerical models.

2) Development of two reduced-order models based on CFD results using the POD-RBF method (a classical and a generalised formulation), including assessment of the effect of map resolution on accuracy (errors below 1%), and implementation in Dymola/Modelica enabling fast dynamic computations.

3) Development of a dynamic model of an ejector-based refrigeration system in Dymola/Modelica and demonstration of the advantage of a variable geometry ejector over a fixed-geometry ejector in a daily analysis for three climatic zones (daily-averaged COP improvement from about 0.4% to over 50%, and cooling-capacity increase from about 2% to over 21%).

4) Consideration of cases in which waste heat is the thermal driving source for cooling production, and demonstration of the influence of source stability on spindle-position selection and system performance.

5) Assessment of using the same variable geometry ejector geometry with other refrigerants and mixtures by means of the generalised reduced-order modelling approach, including a screening procedure and a quantitative evaluation of mixture composition effects (e.g., improvement for R1270 and deterioration for mixtures containing dimethyl ether).

From a formal standpoint, the dissertation is coherent and readable; the methodology and results are logically connected. The work is written carefully and clearly, with appropriately selected illustrative material.

7. Final conclusions

In conclusion, I find that the critical remarks and questions presented in this review are of a discussion nature and do not diminish the scientific value of the work, which I assess highly. The dissertation provides an original and useful solution to the problem of maintaining high efficiency of an ejector-based refrigeration system under variable conditions by employing a variable geometry ejector and its control in dynamic simulations. The author demonstrated that the proposed approach enables analysis and control of the system both under varying climatic conditions and under variable supply of low-grade waste heat, which is directly relevant to practical waste-heat-driven cooling applications. Based on the content of the dissertation, I also conclude that the candidate has a very good command of the theoretical foundations of thermodynamics and ejector flows, as well as the competence to independently perform experimental investigations and advanced numerical modelling.

I consider that the doctoral dissertation of Mr M.Sc. Eng. Rafał Fingas entitled "Comprehensive system and numerical analysis of a small-scale ejector-based natural refrigeration system" more than fulfils the requirements for doctoral dissertations as specified in Article 187(1) and (2) of the Act of 20 July 2018 – Law on Higher Education and Science (consolidated text: Journal of Laws 2024, item 1571, as amended). In view of the above, I submit a motion to the Discipline Council of Environmental Engineering, Mining and Energy of the Silesian University of Technology to admit the dissertation to public defence.

Podpisał Artur Cebula