Review opinion

of the PhD thesis, entitled

Analysis of the low-boiling working fluid expansion processes in the volumetric expander operating in the ORC system

written by

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General comments

The organic Rankine Cycle (ORC) modifies the Clausius-Rankine cycle of the steam power plant by employing organic working fluid or low-boiling working fluid instead of water. However, the ORC technology is getting well-known in several applications, it still includes potential for further development, particularly in case of utilising intermittent and fluctuating heat sources.

The thesis work is dealing with the related challenging questions on the efficiency of various ORC systems as: impact of the low-boiling working fluid expansion process under different operating conditions; influence of different working fluids; advantages of using volumetric expanders, especially operating under two-phase conditions.

Beside the theoretical analysis and modelling work, in some cases experimental validation and AI prediction tools were also used.

Comments to the formalities of the Thesis

The Thesis work consists of 119 pages and including six chapters, list of References, and an appendix of Thermal properties and classification of working fluids.

The general structure of the thesis works is appropriate, the entire text is edited and written in a reasonably good professional English. However, there left some grammatical mistakes in the text.

The author cited 143 references in the Thesis work. The list of the 11 own journal publications, where the candidate is the first author in 10 cases, and his contribution is dominating. It is very beneficial during the evaluation of the thesis, that there are several direct citations of these publication in the text when it is required to understand, what is his own work performed and results achieved. So, the publications strongly support to prove the scientific results and outcome of the work.

Comments to the content of the Thesis

The one-page Abstract part is clear, comprehensive and provides an easy understanding what the thesis work is dealing with and what about the new findings. The only thing is that I have found a bit general the keywords.

It is rather strange for me the positioning of the Contents section in the text body, especially the case that Abstracts, Declaration and Acknowledgements parts are in front of the Contents itself, where they are listed.

The dissertation chapters systematically structured by a hypothesis, followed by a discussion, and finally presenting the main contributions and statements.

As a main outcome of the dissertation, the new scientific results were formulated in 7 thesis statements.

The Chapter 1 gives the introduction to the topic of the Thesis work including outlines the background and motivation, the current state of the art and aims and the objectives of the research to be carried out.

The only thing what I missed in this Section is a more detailed discussion about the Solar-ORC cycle that can use solar collector as a heat source equipment through a heat boiler. So, solar thermal is one of many heat sources that can support an ORC system in a simple way. Additionally, today it is a fact, that renewable energy sources including solar are the key to overcome reducing usage of fossil fuel. *I would like to have your further comments on this issue.*

The Chapter 2 describes the methodology of thermodynamic modelling simulation possibility of the low-boiling expansion process under subcritical operating conditions.

Special attention was devoted to the efficiency comparison of the different ORC systems influenced by different types of working fluid is described.

In Fig. 2.1 it is shown brief historical aspect of working fluids as an alternative to water used in various applications. Upon the 4th generation typical working fluids and key issue of "global warming", *could you estimate what kinds of new approaches do we expect in the coming decade.*

Fig. 2.6 shows the flow chart of modelling and simulation for selected ORC systems under subcritical conditions which was coded in Matlab. *The question is that have you defined a new Matlab "block" specifically for ORC studies. If yes, how were about the input/output variables and parameters. Can you provide a block scheme of that? Additional question is, have you performed any measurements in order to validate the model developed?*

Chapter 3 describes the theoretical analysis of the low-boiling expansion process influencing the efficiency of the different ORC configurations.

Additionally, comparison has been performed between subcritical and transcritical operating conditions along with the influences caused by the different types of working fluids.

The results what you have got via modelling seem to be reliable. *However, similarly to the Chapter 2, the same question could be asked again, that have you make any measurements for validation of your model?*

Chapter 4 deals with the experimental study of a volumetric expander used in an ORC system operating under two-phase conditions and describing several components.

Since the wet isentropic efficiency itself is affected by several variables of the working fluid (temperature, vapor quality, pressure, etc). *I just wonder, how its accuracy affecting by the measurement uncertainty?*

This chapter also discusses the application possibility of artificial intelligence techniques combining by experimental methods for predicting the isentropic efficiency of two-phase expanders. The technical description of the experimental test-stand system is detailed properly.

Another question is that what was the reason to use specifically the deep neural networks (DNNs) for AI modelling?

Did you consider making a sensitivity analysis to optimise the number of hidden layers and the number of neurons applied in the DNNs model?

In Chapter 5, different applications of ORC systems employing a two-phase volumetric expander are studied, paying attention on thermodynamic issues.

Brief description of fluctuating and intermittent heat sources was shown along with the general thermodynamic systems. Additionally, a case study of a typical district heating system was performed.

The Chapter 6 gives a comprehensive summary of the thesis work pointed out the key findings and emphasizing their significance, and possible impacts on the field of thermal power generation. Additionally, some directions for future research on this topic were suggested.

Comments to the Thesis statements

The dissertation includes the new scientific results, e.g. 7 Thesis statements, which are located at the end of the appropriate chapters.

The structure of the theses is organized in a reliable way. The number of the theses are appropriate to cover the value of the new scientific results. It is beneficial that all the theses are accompanied with the own publications justifying their scientific merit.

It is rather convincing, that all the 7 thesis statements are published in significant international journals.

According to my evaluation, my itemized comments to the thesis statements are as follows:

The investigation results summarized in Thesis 1 and Thesis 2 demonstrates that, under certain conditions, increasing the temperature and pressure range of the expander does not necessarily improve cycle efficiency for ORC systems operating under subcritical conditions.

In *Thesis 1* the theoretical modelling simulation result shows that under subcritical operating conditions, the cycle efficiency of partially evaporated organic Rankine cycle (PE-ORC) is not always located between that of organic Rankine cycle (ORC) with the saturated vapor state of the working fluid at the inlet to the expander and trilateral flash cycle (TFC or trilateral ORC) in the cycle efficiency and temperature of the working fluid at the inlet to the expander (ηcycle − T2) diagram. *I accept the Thesis.*

In *Thesis 2* it is proved that increasing the operating temperature range of the low-boiling working fluid expansion process in the ORC, PE-ORC and TFC systems with various types of working fluids may improve the cycle efficiency under subcritical operating conditions. This statement is specific to certain operating temperature ranges. *I accept the Thesis.*

The Thesis 3 and Thesis 4 significantly contribute to the theoretical understanding of the operating conditions for volumetric expanders under subcritical and transcritical conditions. These theses examine the effects of increased temperature and pressure ratio ranges, as well as the vapor quality at the expander inlet.

In *Thesis 3* it is proved that under ideal operating conditions (i.e., considering isobaric evaporation, isentropic expansion, isobaric condensation, and isentropic pump process), an increased operating temperature range of the low-boiling working fluid expansion process in the ORC, PE-ORC and TFC systems enhances cycle efficiency. This approach also applies to the transcritical power cycle (TPC). *I accept the Thesis.*

In *Thesis 4* it is proved that evaluating the cycle efficiency of various transcritical power cycle (TPC) configurations with different values of vapor quality from the expander outlet, using either wet or isentropic working fluids, an equal efficiency point (EEP) can typically be identified under ideal operating conditions (i.e., considering isobaric evaporation, isentropic expansion, isobaric condensation, and isentropic pump process). *I accept the Thesis together.*

The investigation results related to Thesis 5 and Thesis 6 introduce an innovative approach by combining experimental methods with artificial intelligence techniques. Deep neural network

(DNN) or deep learning was chosen for the analysis to predict the wet isentropic efficiency of a multi-vane expander, which can be effectively used in ORC systems operating under two-phase conditions.

In *Thesis 5* it has been stated that on the low-boiling working fluid expansion process in an organic Rankine cycle system can be done under two-phase conditions with a multi-vane expander using 2,2-Dichloro-1,1,1-trifluoroethane (R123) as the working fluid. Additionally, the operational parameters of the process have been identified. *I accept the Thesis.*

In *Thesis 6* it was stated that the wet isentropic efficiency can be predicted using deep learning or deep neural networks (DNNs), which are methods within the field of artificial intelligence. Low accuracy of prediction was observed when using only the pressure ratio and vapor quality at the expander inlet as input variables of DNN for determining the wet isentropic efficiency of low-boiling working fluid expansion processes. Adding the temperature of working fluid to the expander inlet as an additional input parameter of the DNN significantly enhances the accuracy of the model. *I accept the Thesis.*

In *Thesis 7* it is shown that the incorporation of a two-phase expansion system in an organic Rankine cycle (ORC) system significantly enhances its adaptability to the application in fluctuated low- and medium-temperature heat sources (both renewable and waste heat). Such systems maintain optimal cycle efficiency across wider operational conditions compared to ORC systems with a superheater that operates under superheated conditions. In engineering sense these are valuable results, however based on the general proven methods applied in the thesis, I can't consider them as scientific ones. For that reason, *I do not accept the Thesis.*

Final conclusions:

In coincidence with my detailed review, I evaluate in a highly grade the scientific results carried out in this work, in all the aspects, as formulation of the research problem, the applied materials and methods, the research results and their presentation, the discussion and conclusions and also the clarity and the structure of the dissertation. I state furthermore that the author has got independent input into planning and completing the research, and furthermore he proved his ability to analyse scientific issues and command of the research approach.

It should be mentioned however, that in some cases of the performed calculations, measurements the suggested statements are not always provided together with their constrains and the operating conditions. It is however rather beneficial, that in the case of undetermined parts, the necessity of further research is clearly indicated.

The new scientific results are summarised in 7 theses. My acceptance considerations of them are described before.

Summarising my overall evaluation, the final clarification is, that in case of successful public defence, I *strongly suggest to award to Sindu Daniarta the PhD degree*.

September 30, 2024

Farkas

Prof. I. Farkas