Kielce, 28th of May 2021

Prof. dr hab. inż. Magdalena Piasecka
Faculty of Mechatronics and Mechanical Engineering
Kielce University of Technology, Poland
tel.: (+48) (-41) 3424320
email: tmpmj@tu.kielce.pl

OPINION

of the doctoral thesis by Karolina Wojtasik
titled: *Boiling of water at low pressure: the role of subcooling and thermophysical properties on the bubble dynamics and heat transfer*

written:
at the Faculty of Mechanical and Power Engineering,
Wrocław University of Science and Technology (Poland)
and
Institut National Des Sciences Appliquées, Laboratoire Cethil (France)
under supervision of:
Bartosz Zajączkowski, Prof. of WUST and Tomasz Hałon, Ph.D. (Poland)
Jocelyn Bonjour, Prof. and Romuald Rulliere, Ph.D. (France)

1. THE FORMAL BASIS

This opinion was commissioned dr hab. inż. Robert Król, Assoc. Prof., Head of Scientific Discipline Council of Environmental, Mining and Power Engineering of Wrocław University of Science and Technology according to the decision of Board for this Discipline. It was formulated in a formal letter RDND08/11/2021 dated 16th of March, 2021.

2. GENERAL CHARACTERISTICS OF THE WORK WITH COMMENTS

The doctoral thesis was supervised jointly by two scientific institutions: Polish (Wrocław University of Technology in Science) and French (Institut National Des Sciences Appliquées, Laboratoire Cethil). It was partly financed by French Government (a scholarship granted by French Government to the Author of this doctoral thesis).

The doctoral dissertation was written on 136 pages (A4 size) in English. The dissertation is structurally divided into five main chapters followed by *Acknowledgements, Abstract, Content, List of Figures, List of Tables* and *Nomenclature*. The titles of the main chapters are as follows: *Literature review* (1), *Experimental set-up and method* (2), *Bubble dynamics with a novel heat flux sensor* (3), *Boiling on a rough surface* (4), and *Preliminary studies of the process of evaporation at low pressure* (5). The summary of the work is presented in *Conclusion and perspectives* section. As a complement to the doctoral thesis, two appendices are embedded (A – *Characterization of the heated surface* and B – *PDF graphs for various operating parameters*). The bibliography is the last part of the work. 96 figures, 11 tables, and 138 cited bibliography publications were included in the doctoral dissertation.

3. THE IMPORTANCE OF THE TOPIC

Nowadays, there is a growing interest in heat transfer from elements which generate large amounts of heat. The demand for cooling efficiency entails seeking even better cooling technologies that will prevent device components from temperature overshoot, and in such solutions environmentally-friendly fluids should be applied. A promising solution, especially for cooling and air-conditioning systems and limiting of operating temperatures, has a significant effect on both durability of the devices and safety of their users. Owing to the change of state which accompanies boiling, it is possible to obtain a heat flux as large as possible at a small temperature difference between the heated surface and the saturated liquid. In turn, pool boiling helps to achieve the heat transfer efficiency, which results in higher values of the heat transfer coefficient.

Many researchers examined pool boiling of water at atmospheric pressure, often on a modified heated surface (with cavities, fins, recesses, tunnels, etc.), and the results of these experiments can be found in numerous papers. The results obtained at low pressure differ in comparison to the ones achieved at atmospheric pressure which are rarely discussed in literature but are important for the proper functioning of cooling. Short review of the relevant literature on pool boiling heat transfer presented in the doctoral dissertation indicates that there is a lack of knowledge concerning the phenomenon of water evaporation at low pressure.

In my opinion, the subject of the Ph.D. dissertation corresponds to global trends in the field of analysis of the issues covering pool boiling heat transfer. At present, the trend toward the use of change of state in heat transfer processes is the driving force behind increasingly improving cooling technologies designed to prevent exceeding operating temperatures. The results can be applied to the construction of devices for heating, cooling, thermostabilization and thermoregulation applications.

The work focused on experimental studies of the processes of boiling and evaporation occurring at low pressure. This issue for water in sub-atmospheric conditions, is still insufficiently studied.

4. SCOPE, GOALS, HYPOTHESES, STRUCTURE OF THE DISSERTATION

As the main goal of Ph.D. dissertation, the experimental study of the processes of boiling and evaporation occurring at low pressure is indicated. The present manuscript aims at extending the knowledge concerning fundamental aspects of pool boiling (with respect to bubble dynamics and heat transfer) and liquid evaporation at low pressure. For that purpose, several experimental studies were carried out. The boiling process was investigated for a polished surface with a single nucleation site and for a rough surface with multiple cavities.

Scientific hypotheses of the doctoral dissertation by Karolina Wojtasik were proposed as follows:

I. The change in the thermophysical properties of water near the triple point has a significant impact on the dynamics of the phase transformation process.

II. The influence of hydrostatic pressure cannot be ignored in the experimental analysis and model studies of the boiling process in sub-atmospheric conditions.

In the first part, named *Introduction*, background of knowledge concerning dissertation subjects, problem statements such as scientific theses, main objectives, and an overview of each chapter are presented and significance of the study is underlined.

The first chapter titled *Literature review*, presents the fundamentals of heat transfer theory and state-of-the-art overview of theoretical issues relevant to the main subject of the thesis. General background concerning pool boiling process is divided into two sections: pool boiling on a flat surface and influence of low pressure on the boiling process. The first one introduces fundamental information related to the boiling process at atmospheric conditions, the other describes the influence of low pressure on the boiling behaviour.

In Chapter 2, titled *Experimental set-up and method*, the descriptions of the set-up used for conducting the experiments are provided. Test facilities, research procedures and data analysis are discussed. The data analysis and processing techniques cover parallax correction factor and image processing issues. This chapter is divided into three sections. In Section 2.1, the test section - a vacuum-tight vessel with its essential part – i.e., a heat flux sensor placed on the heated surface is described. Furthermore, the data acquisition system is presented. The next section (Section 2.2) presents the experimental procedures. The last section of Chapter 2 involves description of the data analysis and processing techniques concerning visualization of bubbles.

The main topic of the next chapter - Chapter 3, titled *Bubble dynamics with a novel heat flux sensor*, is the experimental study of water pool boiling which was conducted at low vapor pressure and on a mirror-polished surface with an artificial cavity. It focuses on the analysis of the bubble dynamics. The analysis is based on the results of experiments in which the method for heat flux determination with the help of the proposed sensor was used. The heat flux measurement is carried out in seven concentric zones. The study involves bubble foot evolution and estimation of the low-pressure bubble types. Chapter 3 is divided into five subsections. In Section 3.1, the measurement techniques applied to study the boiling phenomenon according to the literature are presented. In Section 3.2, experimental procedures and operating conditions are described. The experimental analysis of the bubble foot motion during its increase and decrease with respect to the local values of heat flux is discussed in Section 3.3. The classification of low-pressure bubble types based on thermal measurements and high-speed camera recordings is proposed in Section 3.4. In Section 3.5, the determination of the time evolution of bubble foot diameter for a defined bubble is explained.

In Chapter 4, titled *Boiling on a rough surface*, the experimental study of subatmospheric pool boiling on a rough surface with multiple nucleation sites is discussed. Chapter 4 is divided into six subsections. Section 4.1 presents the operating conditions and the experimental procedures. The research background covers experiments conducted for different values of pressure, at several values of heat flux, whereas three selected liquid levels in the tested vessel are set. In Section 4.2, experiments on pool boiling on a rough surface are conducted. During the experiments high-speed video images are collected. Four low-pressure boiling regimes, namely: the convection or small popping bubbles regime, the isolated bubble regime, the intermittent boiling regime and the fully developed boiling regime, are distinguished and characterized with the aid of statistical analysis. Section 4.3 focuses on the characterization of each regime. The influence of the liquid level and the applied heat flux on the boiling regime is featured in Section 4.4. In Section 4.5, a dimensionless boiling regime map for subatmospheric pressure is proposed on the base of own results. The map is presented as the modified Jakob number in function of the ratio of vapour pressure to the static pressure. It was stated that there is an optimal liquid level for which the bubble size and detachment frequency give the highest value of heat transfer coefficient. One of the tested liquid levels is indicated as optimal. The analysis of the time evolution of heat flux is performed statistically based on probability density functions (PDFs). The analyses of boiling regimes and heat transfer coefficient were based on the data collected, while two various roughnesses of the heated surface were used in the conducted experiments. This topic focused on the heat transfer coefficient. The boiling regime map dependent on the investigated surfaces is described in Section 4.6. No significant differences between regimes for each tested surface were noted. It is worth mentioning that low values of the average heat transfer coefficient were obtained, similar to those achieved during single phase convection.

Chapter 5, titled *Preliminary studies of the process of evaporation at low pressure,* concerns the evaporation of a drop and a thin liquid layer on a hot horizontal surface. This chapter is divided into five sections. Section 5.1 focuses on the literature review of liquid evaporation on a horizontal surface. The further part of Chapter 5 describes the experimental studies of drop and liquid layer evaporation at low pressure: in Section 5.2 the operating conditions and experimental procedures are characterized, Section 5.3 focuses on the thermal effects involved in the droplet evaporation, and in the last section - Section 5.4, the evaporation process of thin layer of liquid is discussed.

The content of the dissertation was summarized in the chapter titled *Conclusion and perspectives.* This chapter also briefly discussed the achieved results and recapitulated the novel solutions, as well as presented the perspectives and remarks for future work.

Two appendices complete the dissertation. They include specific details relating to the main topics. In Appendix A, the details of investigated heated surfaces were characterized. Appendix B shows PDF graphs for various operating parameters (PDF graphs based on the experimental data for pressure 2.4 kPa were presented and discussed in Chapter 4).

5. ASSESSMENT OF DISSERTATION

5.1. General remarks

The subject of the doctoral dissertation corresponds to global trends in the field of boiling heat transfer. The results can be applied to the construction of devices for heating, cooling, thermostabilization, and thermoregulation applications. It is worth mentioning that pool boiling of water at low pressure is still insufficiently studied. To sum up, the subject of the dissertation is scientifically important and up-to-date.

Generally, the doctoral dissertation meets the conditions of art. 13 of the Law on scientific degrees and titles as well as on degrees and titles in the area of art dated on the 14th of March 2003. Below I present my opinion towards the most important aspects of the dissertation by Ms. Karolina Wojtasik:

- The aims of the research have been clearly defined for the study under consideration.
- The Author formulates two verifiable hypotheses. According to the state-of-the-art, they were relevant and of practical importance.

- The hypotheses have been verified by the results of extensive experimental studies and theoretical analyses in detail explained in the dissertation.
- The main achievements of the research are supported by peer-reviewed journals and conference papers co-authored by the Author of the dissertation.
- The appropriate research methods and techniques (i.e., methodology of experiments, mathematical models and calculations) were used to prove the hypotheses. The Author showed a detailed investigation of the topic and the ability to interpret the results and develop conclusions.
- The discussion of the literature and state-of-the-art analysis are well prepared. The number of references is reasonable (138) for a Ph.D. dissertation, and their selection is suitable both for the background theoretical knowledge and for the literature review concerning the discussed field.
- The dissertation is well structured and comprehensible and is prepared with proper enough editing skills. The text is written concisely, clearly, and in almost error-free English with the proper scientific terminology in the field.
- Most of the figures are carefully prepared and clearly annotated.
- The obtained results were discussed, analyzed and interpreted in detail, conclusions were formulated and remarks for future works were provided.

5.2. Critical remarks and comments

Considering the high standard of the dissertation in all its aspects, a few minor critical remarks are to be pointed out as follows:

- Nomenclature section: the unit of sensitivity of the sensor ("*s*") looks as unproperly, there is no explanation concerning "*u*", see Eq. (2.3).
- It was stated that the sensitivity of the heat flux measurement was estimated during the calibration process conducted by the manufacturer of the sensor, but this information is too general and a certification document should be provided.
- More detailed information about wall temperature measurements (by thermocouples connected to the data acquisition station) should be added.
- Images shown in Figure 5.13 are not sufficiently clear, it is difficult to observe the subsequent phases of splashing of liquid on the heated surface.
- The uncertainty of the heat transfer coefficient should be added and discussed.
- The name of the Jakob number is sometimes given unproperly (as "Jacob") in the work.

- What was the reason to assume the selected liquid levels (2 cm, 15 cm, and 28 cm) for investigation?
- Due to my experience with using enhanced heated surfaces, I cannot understand the statement of the Author who claims that it was not possible to easily obtain a higher difference in the surface roughness of the tested surface. Microstructured surfaces can be produced by means of active and passive methods. There is a lot of passive methods using chemical, thermal, mechanical, or combined mechanical and thermal processes which can modify the properties and structure of a surface. For example, the spark erosion process in electromachining can be applied. In my research, cavities in the 0.10 mm thick alloy plate surface were made by electromachining, using an electric etcher and branding pen. Finally, the depth of the cavity craters in the modified surface was usually below several μm and the layer of melted metal of the plate and an electrode material, a few μm high, accumulated around the cavities. Such a method is my proposition to apply in the described experimental research.

6. CONCLUSION

Summarizing, the doctoral thesis by Karolina Wojtasik is interesting, innovative, and original methodologically. This work proves her original contribution to pool boiling heat transfer. The doctoral dissertation has proved the candidate's ability to plan, initiate and execute scientific investigations. **In my opinion, the doctoral dissertation by Karolina Wojtasik fully complies with Polish and international standards for Ph.D. dissertations. The thesis remains in accordance with the scope of the scientific discipline: environmental engineering, mining and energy. It meets the conditions of art. 13 of the Law on scientific degrees and titles as well as on degrees and titles in the area of art dated on the 14th of March 2003** (Dziennik Ustaw - Official Journal of Laws of 2003, No. 65, item 595) with later amendments. Specifically, it is clear that Ms Karolina Wojtasik has presented original solutions to a selected scientific problem. She has demonstrated general theoretical knowledge in the field of environmental engineering, mining and energy (in particular – the field of energy). She clearly has the ability to independently conduct scientific research. The research methodologies have been described in detail, which follows the good practice of science reproducibility and replicability. In conclusion of the assessment, I strongly recommend this dissertation to be subjected to public defense. Furthermore, **I propose this doctoral thesis to be distinguished.**

Magdalena Piasecka