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**OVERVIEW**

*Report on the thesis entitled "Boiling of water at low pressure: the role of subcooling and thermophysical properties on the bubble dynamics and heat transfer" presented by **Karolina Wojtasik** for obtaining the title of Doctor at INSA-Lyon / Politechnika Wroclawska.*

The thesis manuscript presented by Karolina WOJTASIK was conducted in the context of a collaboration between the laboratories of INSA-Lyon, under the supervision of Prof. Jocelyn BONJOUR, and the Politechnika Wroclawska, under the supervision of Prof. Bartosz ZAJĄCZKOWSKI. The work describes a fundamental experimental study of boiling and evaporation physics at low pressure. Specifically, the work aims to contribute to knowledge with regard to two phase heat and mass transfer at pressures approaching the triple point, where there is a significant gap in understanding. The work has a practical trajectory towards the engineering of sorption-type refrigeration systems, which is necessary from both a technological perspective as well as an environmental one.

Despite over a century of scientific interrogation, our understanding of the boiling phenomena is very far from being complete. There is no unifying theory of boiling, nor is our basic understanding of the physics adequately resolved. It can be said that what we do know is very heavily skewed to operating pressures that predominantly involve diffusion controlled bubble dynamics, which is very different from the mechanics involved at very low pressures. Similarly, droplet evaporation has been researched extensively, and still our knowledge is far from complete. This is particularly true for sessile drop evaporation on heated substrates, where the basic mechanisms of heat transfer to the droplet base are only now being researched with rigor. Considering the above, the overarching topic of this thesis is hugely interesting and relevant to both scientists and engineers in the field of two phase heat and mass transport. In this context, Karolina WOJTASIK has performed a series of clever and logically sequenced experiments on both boiling and droplet evaporation at low pressure. Interestingly, study of the latter mode was motivated by the low effective heat transfer coefficients associated with the former mode, showing how careful fundamental measurements and analysis can inform and lead to relevant technological choices in an engineering context. Overall, the topics investigated are very open in terms of knowledge contribution and the candidate performed very careful and well thought-out experiments, with interesting and informative analysis techniques, that have indeed contributed significantly to understanding in this field.

The manuscript is 136 pages in length, is well organized and is written in very good English.

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**DETAILED CONTENTS OF THE THESIS**

*Chapter 1: Literature review*

This section of the thesis involves preparing a review of the state of current knowledge and understanding of pool boiling. It is appreciated that this is a very broad topic and it is not feasible to encompass everything we know. The candidate did a good job choosing aspects and topics of boiling that were most relevant to the present research and did so concisely and with sufficient detail to provide the reader with the basics required to follow the narrative of the ensuing discussion. Since this thesis fundamentally aims towards the effectiveness of the heat transfer at low pressure, it would have been nice to have some high-level discussion regarding the influence of pressure on the boiling heat transfer coefficient i.e. the discussion in section 1.2.4 could include some general trends in before focussing on the Ref [41] study.

*Chapter 2: Experimental setup and methods*

This chapter details the experimental apparatus and data analysis. At the heart of this work is a new concentric-ring heat flux sensor. This is a major advancement over conventional methods for measuring boiling heat flux and the candidate showed excellent scientific rigor in its implementation and use. By creating and activating an artificial nucleation site and synchronizing the multi-signal sensor with the high speed videography, the experimental facility has provided insight into the bubble dynamics and its influence on the heat transfer which is completely novel. Admittedly there is thermal mass associated with the sensor, so it is not an exact measure of the surface convective heat flux. However, real surface have thermal mass, and the sensor does detect the local rate of energy transfer (over a discrete area), which is as relevant as the surface convective heat flux. All aspects of the peripheral components of the experiment are well described as are the data reduction and experimental uncertainties. Considering that the novel heat flux sensor is a key component that separates this work from others, it would seem more complete if some further details of its design and function were detailed i.e. it would be difficult for an independent researcher to design a similar sensor with the information included. This could be included as an appendix so as not to interrupt the flow of the manuscript.

*Chapter 3: Single Bubble Dynamics and Heat Transfer*

This chapter considers single bubble events over a range of low pressure thermodynamic states, including head-induced subcooling. Importantly, the work (probably for the first time) coordinated local and time varying heat transfer measurements with low pressure bubble dynamics. The results are completely novel and provide significant new insight into low pressure boiling; in particular the synthesizing of the bubble foot motion with the heat transfer. It was very interesting to see this relationship, in particular at the scale of the ‘large’ bubbles. The categorizing of the bubble regimes with the heat transfer and the explanations provided in the context of the thermal and fluidic condition near the surface are well supported by the measurements and are the beginning of an explanation towards how changing the low pressure boiling conditions influences the heat transfer (when boiling on 'real' surfaces with multiple bubbles etc.). The presentation of time and space varying measurements is inherently challenging. Regardless, it would be nice to include some time sequenced photographs (showing the bubble dynamics) with a spatial depiction of the heat flux distribution (say a false-colour heat flux bar) beneath the photographic image. As it stands it is difficult to mentally interpolate the bubble foot and heat flux data as they are shown in time opposed to space.

*Chapter 4: Boiling on roughened surfaces*
This chapter describes boiling heat transfer on surfaces which have roughness, and thus multiple nucleation sites, that are more commensurate with real-life engineering surfaces. It is of course a natural progression from the single bubble cases, inasmuch as the knowledge gained from the single bubble events is relevant and help explain observations of the multiple (sequential or neighbouring) bubble boiling. I was very impressed with the very clever data analysis techniques used in this section and how they were coordinated in such a way as to give much more information about the boiling heat transfer process than a simple raw heat flux versus time signal. This was able to quantitively distinguish boiling regimes, which is typically purely observational. The boiling regime maps are truly impressive.

*Chapter 5. Drop & film evaporation*
The final core chapter of the thesis details work on drop evaporation. In the previous chapter, regardless of the interesting physics, the effectiveness of boiling on the heat transfer at these low pressures is limited, and the candidate correctly identifies that alternative and potentially more effective means could/should be explored for two phase heat transfer at low pressures. Spray cooling is a logical choice as it provides a potential means for higher heat transfer coefficients whilst continually replenishing liquid to the surface. The chapter begins with an overview of the literature in order to contextualize the problem apart from the previous boiling discussion. Here, many aspects of droplet evaporation are discussed, though I feel a small section should be included that specifically focusses on the mechanisms of heat transfer i.e. the heat added at the base ultimately leaves by convection and latent heat, but the heat flow is resisted and this changes from the triple line to the bulk droplet; these mechanisms should be detailed as it is more relevant to the ensuing discussion than, say, what influences the dry patterns. The chapter continues into a discussion on the results of single droplet evaporation for both a small and large droplet. Here the heat flux sensor is again used to provide spatially and temporally resolved information regarding drop evaporation. Heat transfer measurements of this type are extremely rare in the literature, which mostly has focussed on the dynamics of the droplet in order to insinuate the heat transfer. Thus, once again, leveraging the utility of this new sensor technology has

provided new insight into this research topic. Expanding the work to include preliminary results for droplet streams and films has also produced interesting conclusions which will be useful for the next candidate who will likely go deeper into this topic.

**SUMMARY**

The thesis remains in accordance with the scope of scientific discipline: environmental engineering, mining and energy. The work carried out in this investigation provides a substantial contribution to knowledge in the area of two phase heat and mass transfer at low pressures and therefore meets the conditions of article 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. It is a field of very practical interest, yet has received very little attention in the open literature. The candidate, Karolina WOJTASIK, has performed excellent experimental research and clever data analytics in such a way that new insight into the basic physics of boiling and evaporation at low pressure is provided. It is my opinion that the thesis can progress to the viva voce examination.

Warm regards,

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