International Journal of Multiphase Flow 83 (2016) 115–127

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow

# A mechanistic IR calibration technique for boiling heat transfer investigations

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ARTICLE INFO

*Article history:*
Received 4 December 2015
Revised 1 March 2016
Accepted 12 March 2016
Available online 23 March 2016

*Keywords:*
Infrared thermometry calibration
Coupled conduction/radiation inverse problem
Boiling heat transfer

ABSTRACT

This paper presents a new calibration technique to improve the accuracy of infrared thermometry in boiling heat transfer investigations.

The technique is suitable for heaters consisting of a thin, infrared (IR) opaque conductive film coated on one side of a flat and IR semi-transparent substrate. The conductive film is in contact with the liquid and acts as the boiling surface. The IR camera sees the boiling surface through the substrate. If the substrate is not completely transparent, the radiation emitted by the IR opaque film is partially absorbed and contaminated by the radiation emitted by the substrate itself. Therefore, the correlation between the IR radiation measured by the IR camera and the temperature of the boiling surface (IR opaque film) is not unique, but depends on the temperature distribution in the substrate.

To solve this issue, we developed a model that solves the coupled conduction/radiation inverse problem in the heater. The problem is inverse because the boundary condition for the conduction problem (the boiling surface temperature) is not known. The IR camera measures the combined radiation emitted by the boiling surface, emitted by the substrate and also the reflection of the background radiation; from that information one has to reconstruct the boiling surface temperature.

The technique is unique in that it takes into account the spectral dependence of optical properties in the optical materials. For this reason, it is particularly suitable for heaters where the optical properties of the conductive film and the substrate materials depend on the wavelength of the IR radiation.

Using this technique, we can measure with improved accuracy the time-dependent 3D temperature distribution in the heater, as well as local temperature and local heat flux distributions on the boiling surface. The validation of the technique was carried out using transient conduction experiments. Then, the technique was applied to transient pool boiling experiments to prove its feasibility and show the potential applications.



## Introduction

A significant improvement in the understanding of boiling heat transfer phenomena has been possible in the last decade thanks to the rapid development of infrared thermometry diagnostics to measure time-dependent local temperatures and heat fluxes on the boiling surface (Golobic et al., 2009; Schweizer and Stephan, 2009; Golobic et al., 2012; Theofanous et al., 2002; Theofanous et al., 2002; Fischer et al., 2012; Stephan et al., 2013; Gerardi et al., 2010; Duan et al., 2012; Jung and Kim, 2014; Phillips, 2014; Tetreault-Friend, 2014; Yoo et al., 2015; Kim et al., 2012).

An important aspect for a successful implementation of IR thermometry in boiling heat transfer investigations is the heater design. Thin metal foils have been used in several investigations (Golobic et al., 2009; Schweizer and Stephan, 2009; Golobic et al., 2012); however, they have limited heat storage and low thermal capacity compared to most actual engineering applications. Another heater design (Theofanous et al., 2002; Theofanous et al., 2002; Fischer et al., 2012; Stephan et al., 2013; Gerardi et al., 2010; Duan et al., 2012; Jung and Kim, 2014; Phillips, 2014; Tetreault-Friend, 2014; Yoo et al., 2015) consists of an IR opaque, thin solid film made of an electrically conductive material, coated on an IR transparent substrate of appreciable thermal capacity (see Fig. 1).

In this heater design, the conductive film is in contact with water and acts as the boiling surface. It is connected to an electric power source and generates the thermal power required to boil the liquid by Joule heating. It is thin enough (typically a few tenths of a micron) to have a negligible temperature drop through its thickness as well as a negligible thermal capacity. Therefore, the local temperature at the interface between the conductive film and the substrate practically coincides with the local temperature at the

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.03.007
0301-9322/

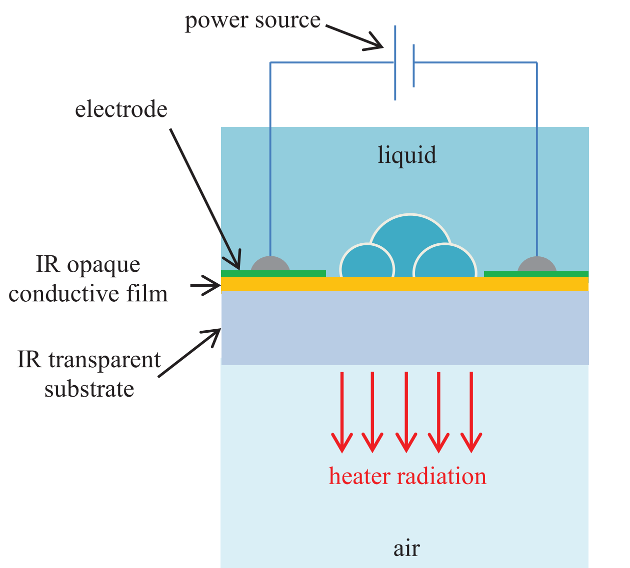


**Fig. 1.** Sketch of a typical heater for IR thermometry investigation of boiling heat transfer (not to scale).

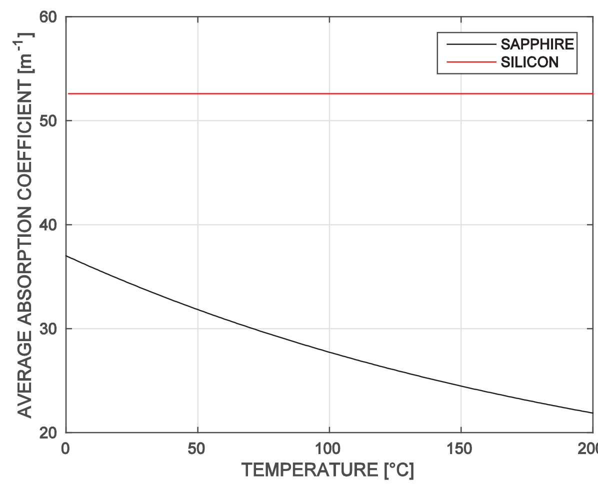


**Fig. 2.** Average absorption coefficient in sapphire and silicon.

boiling surface. On the other hand, the film is thick enough to be opaque to infrared radiation in the range of wavelengths useful for boiling investigations, typically from 3 to 5 µm. Therefore, it shields completely the IR radiation emitted by the liquid and emits IR radiation at the temperature of the boiling surface. The film material can be either opaque or transparent to visible light. Common visible light opaque materials are titanium (Theofanous et al., 2002; Theofanous et al., 2002) and chromium (Fischer et al., 2012; Stephan et al., 2013), whereas the most popular visible light transparent material is Indium Tin Oxide (ITO) (Gerardi et al., 2010; Duan et al., 2012; Jung and Kim, 2014; Phillips, 2014; Tetreault-Friend, 2014; Yoo et al., 2015).

The substrate has to be as transparent as possible to IR radiation. It should not reflect and, more importantly, should not absorb and "contaminate" with its own radiation the IR radiation emitted by the conductive film. It should be an easily machinable, strong material, capable to withstand high mechanical and thermal stresses. It should not be hygroscopic, nor soluble in water or toxic. An interesting candidate as substrate material is calcium fluoride. This material has no IR absorption in the range from 3 to 5 µm, which is the range of interest for boiling investigations of water at atmospheric or even higher pressure. Furthermore, calcium fluoride has a reasonably flat and low reflectivity spectrum. These two attributes enable the measurement of the boiling surface temperature by a simple calibration curve that can be obtained in steady-state conditions (uniform heater temperature), correlating the temperature of the conductive film (measured by a thermocouple) with the radiation measured by the IR camera (Fischer et al., 2012; Stephan et al., 2013). Unfortunately, calcium fluoride is a fragile material. It is difficult to handle and, in boiling experiments with water, it might easily fail due to thermal stresses even before the occurrence of CHF (Personal conversation with Prof. Hyungdae Kim, 2015). It is probably for this reason that the most used substrate material is sapphire, not calcium fluoride. Sapphire has a very large thermal diffusivity (6.7 mm$^2$/s compared to 3.8 mm$^2$/s of stainless steel), which reduces temperature gradients, and a very large mechanical strength, which reduces the consequences of thermal stresses. For these reasons, sapphire has been successfully used also in CHF investigations, i.e. see Tetreault-Friend (2014). However, contrary to calcium fluoride, sapphire partially absorbs and emits infrared radiation in the range between 3.5 and 5 µm, and therefore contaminates the radiation emitted by the boiling surface. The contamination is neither uniform in space nor constant in time, but depends on the local, time-dependent temperature distribution in the substrate. As such, the use of calibration curves obtained with uniform temperature distributions in steady-state conditions might result in additional experimental uncertainties on the measured local temperature and heat flux distributions. Moreover, the absorption coefficient of sapphire $\alpha_\lambda$ is highly dependent on the radiation wavelength (see Appendix A.1), and therefore calibration techniques based on average optical properties as the one developed for silicon heaters by Kim et al. (2012) and adopted by Yoo et al. (2015) are not satisfactory. To reinforce this statement, Fig. 2 shows the average absorption coefficient $\bar{\alpha}$ of Sapphire, evaluated as follows

$$\bar{\alpha} = \frac{\int_{3\ \mu m}^{5\ \mu m} \alpha_\lambda\ N_{p\lambda}(T) d\lambda}{\int_{3\ \mu m}^{5\ \mu m} N_{p\lambda}(T) d\lambda} \tag{1}$$

where $N_{p\lambda}(T)$ is the spectral photon flux emitted by a blackbody at temperature $T$ and $\alpha_\lambda$ is the spectral absorption coefficient. The average absorption coefficient of silicon is also shown for comparison, as reported by Kim et al. (2012). As can clearly be seen, the average absorption coefficient of sapphire is highly dependent on the temperature, and therefore on the wavelength, of the IR radiation. As such, a calibration model developed for sapphire substrates should take the spectral dependence of its optical properties into account.

To achieve a more accurate estimation of temperature and heat flux distributions on the boiling surface it is therefore necessary to separate spectrally the radiation emitted by the boiling surface (and partially absorbed by the substrate) from the radiation emitted by the substrate itself. To this end, we have developed a model to solve the coupled conduction/radiation inverse problem in the heater. The problem is inverse because the boundary condition for the conduction problem (the boiling surface temperature) is not known a priori. What is known is the total radiation measured by the IR camera, which combines the radiation emitted by the boiling surface (ITO in our case), the radiation emitted by the sapphire substrate and also reflection of the background radiation (at ambient temperature). With this technique we can estimate the time-dependent 3D temperature distribution in the substrate, as well as local temperature and local heat flux distributions on the boiling surface, starting from the time-dependent 2D radiation measured by the IR camera.

The technique consists of three modules: the conduction model, the radiation model, and algorithm to solve the coupled conduction/radiation inverse problem, described below in the order. Then, the validation of the model and its application to boiling heat