# COBEM2019-1264
# INFRARED THERMOGRAPHY APPLIED TO BOILING INVESTIGATIONS: A STATE-OF-THE-ART REVIEW

**Bianca Godoy Biancardi**
**Gherhardt Ribatski**
Heat Transfer Research Group, São Carlos School of Engineering, EESC-USP, 400 Trab. São Carlense Ave., São Carlos – SP – Brazil, 13566-590
bianca.biancardi@usp.br*;* ribatski@sc.usp.br

*Abstract. The present work presents a critical review of the literature concerning Infrared Thermography applied to the investigation of the boiling phenomena. The infrared thermography presents the following advantages over the traditional methods of temperature measurement: (i) fast time response; (ii) high accuracy; (iii) does not affect the temperature field (non-intrusive) under analyses, (iv) provides local and superficial temperature distribution. However, to achieve reliable data measurements using this technique several aspects concerning the test section design should be carefully evaluated. Several sources of measurement errors, especially regarding optical issues of the composing materials must be correctly addressed. Therefore, different approaches were adopted in literature to the test section design, calibration of the IR camera and data regression procedure. These different approaches are analyzed and their advantages and restrictions are discussed.*

*Keywords: infrared thermography, flow boiling, pool boiling, heat transfer, temperature measurements*

## 1. INTRODUCTION

New cooling strategies are a current demand in several industrial applications due to the need of dissipate extremely high heat fluxes. The technological development in different sectors such as telecommunications, micro-electronic components, microreactors, micro fuel cells systems and advanced heat sinks is associated to the miniaturization not only of the components but also of the overall system, implying on even higher heat fluxes. Generally, this trend focuses also on improving the system efficiency, decreasing the material costs and reducing the number of components. In this context, the traditional method based on forced-air convection is facing its operational limits and technologies based on phase-change processes are emerging as a promising solution to dissipate the demanded heat fluxes.

Among the proposed technologies, flow boiling in small diameter channels presents as advantages high heat transfer coefficient, low temperature gradients along the flow path, self-heat transfer enhancement and low refrigerant inventory. In order to make the use of this technology feasible, studies are being performed focusing on the evaluation of the heat transfer coefficient, pressure drop and critical heat flux and on a better understanding of the heat transfer mechanisms. Typically, the boiling process is investigated based on measurements of the temperature of the heated surface using the following techniques: (i) equidistant single-point sensors integrated near to the bottom surface of the heat sinks; and (ii) embedded thermocouples within the channel wall. Such strategies only provide the local and time-averaged temperatures due to the combined thermal inertia of the sensor and the channel wall. In fact, to a better understanding of the boiling mechanism and to engineer the surface, the two-phase flow topology and the transient temperature field along the channel are necessary. Among the techniques capable to provide such results infrared (IR) thermography has being considered the most effective since reflects the changeability of the dynamic process both locally and over time for all boiling modes (Korniliou et al. 2019).

Infrared thermography presents advantages over the aforementioned methods because it provides the measurement of the time-dependent 3D temperature distribution on the heater surface as well as local temperature, local heat flux distribution and global flow visualization, allowing non-intrusive investigations of the hydrodynamic and thermal characteristics with high spatial and temporal resolutions.

High-speed IR thermography may allow a direct comprehension of the relationship between the heat transfer on the surface and the hydrodynamics of bubble nucleation, growth and motions. So far, this technique have been first employed to pool boiling investigations (Golobic et al., 2009, Schweizer and Stephan, 2009, Golobic et al., 2012, Theofanous et al., 2002, Gerardi et al., 2010, Jung and Kim, 2014, Tetreault-Friend, 2014, Bucci et al. 2016, Golobic et al. 2019), then, to flow boiling inside macro channels (Kim et al., 2012, Yoo et al., 2015), to heat sinks based on flow boiling in microchannels (Hetsroni et al., 2003, Hetsroni et al., 2011, Xu et al., 2005, Thome et al., 2013a, Thome et al., 2013b, Krebs et al., 2010) and most recently to flow boiling inside single microchannels (Schmidt et al. 2000, Barber et

al. 2009, Diaz et al. 2006, Liu and Pan, 2016, Sefiane et al. 2019). However, despite of the large number of studies, as above mentioned, and the advantages of using IR thermography there are several aspects of boiling mechanism still unclear, some of them associated to the difficulties into implement such technique under confined conditions. Moreover, when using this technique several sources of measurement errors are present, especially related to the optical issues of the involved materials (heating surface, lens, mirrors and IR image capturing window) and the calibration of the measurement system. Accurate measurements are possible only if the optical access to the heated surface is available for the wavelengths emitted by the surface. Moreover, the wavelength of the radiation emitted by the surface and the range of wavelength measured by the camera must coincide. The properties of the materials such as absorptivity, emissivity and reflectivity for the range of wavelengths involved in the experiments are also sources of errors if not correctly addressed. The test fluid and channel geometry may also affect the quality of the measurements Different measurements strategies are adopted depending on the boiling mechanism under investigation (pool or flow boiling). In addition, to estimate accurately the temperature of the target object from the thermal images obtained by the IR camera, proper calibration of the optical measuring system is required.

In this context, the present work presents a state-of-art review concerning the applications of IR thermography on boiling investigations. Different approaches concerning test section materials (heater and substrate) and calibration methods described in literature are compared and critically discussed.

## 2. OVERVIEW

As result of the advancements of infrared thermometry, researchers have developed different apparatus to measure time-dependent local temperature and heat fluxes on boiling surfaces (Hetsroni et al., 2003, Hetsroni et al., 2011, Xu et al., 2005, Golobic et al., 2009, Schweizer and Stephan, 2009, Golobic et al., 2012; Theofanous et al., 2002, Krebs et al., 2010, Fischer et al., 2012, Thome et al., 2013, Gerardi et al., 2010, Jung and Kim, 2014, Phillips, 2014, Tetreault-Friend, 2014, Yoo et al., 2015, Kim et al., 2012, Bucci et al., 2016, Sefiane et al., 2019).

The experimental strategies adopted until now considered the heater wall design as the preponderant aspect to assure the quality of the IR temperature measurements. According to literature, in general four different heater wall configurations were proposed and implemented. Those different approaches are described here segregated according to the combined heater and substrate materials detailing the temperature measurement strategies. The studies are segregated according to the characteristics of the composition of the test sections as follows: (i) a heating channel coated by an IR-opaque material, (ii) a thin metal foil as a heater, (iii) a heat sink made of a metal heater coupled with a metal substrate, and (iv) a heating film deposited on an IR-transparent substrate.

Configurations based on a heating channel coated by an IR-opaque material (i) enable the measurement of either outer or inner wall temperature depending on where the IR-opaque material is deposited. To capture the local inner wall temperature, the IR-opaque material is contacting the fluid and is deposited on the internal surface of the channel. Moreover, the heating channel has to be made of a transparent/semitransparent material that, commonly, is also electrically conductive. In this way, the channel is connected to a power source and the thermal power required to boil the liquid inside the channel (or a vessel) is supplied through Joule effect. Under this condition, the IR-opaque coating emits infrared radiation at the temperature of the inner wall and it shields the IR radiation emitted by the fluid. This configuration allows that the radiation from the opaque material hit the lens, and the sensors of the camera, and if the measurement systems is properly calibrated, accurate measurements of temperature are achieved. Materials as silicon and germanium are normally used for the channel. Besides being semiconductors (doped types), these materials are IR-transparent at typical wavelength occurring in most of the boiling investigations. About the IR-opaque material, it usually is a black paint applied to the surface of interest.

The limitation of the above-mentioned arrangement is related to the geometry of the channel. As the objective of most research is to obtain the inside wall temperature distribution, the IR-opaque coat has to be applied to the inner surface. Thus, considering circular channels for instance, the channel diameter should allow the application of the coating throughout its overall length. So, for microchannels, this approach is suitable only if MEMS manufacturing processes are employed. However, as far as the present author knows, this method was not used until now for circular microchannels.

Regarding the use of metal foils as heaters (ii), investigations using this technique were conducted focusing on different applications. Among them, there are investigations primarily for pool boiling (Theofanous et al., 2002, Golobic et al., 2009, Golobic et al. 2012, Kunkelmann et al. 2012, Golobic et al., 2019), and also considering variable gravitational conditions to investigate nucleate boiling in pool boiling experiments (Schweizer and Stephan, 2009). Despite of being a reasonable method to capture transient wall temperature fields induced by nucleate boiling mechanism, covering relatively large heated areas, its implementation presents as problem the weak structure provided by the thin foil. Moreover, due to its reduced thickness, thin foil presents low heat storage capacity compared to real applications and, consequently, the results obtained through this technique can be biased by such a characteristic.

Most of studies that investigates boiling on a metal substrate coupled to a metal heater using IR thermometry (iii) are associate to applications involving thermal management of electronic components. In these studies, the test sections are generally heat sinks made of silicon containing parallel microchannels. The heaters are coupled to the bottom of the

heat sink and, commonly, the heaters are made of aluminum (Thome et al., 2013a, Thome et al., 2013b), chromium (Krebs et al., 2010), and platinum (Xu et al., 2005, Xu et al., 2006). The temperature measurements are usually performed with the IR camera having as its filming target the backside of the heat sink with the goal of mapping the surface temperature distribution of the heat sink external wall.

Referring to the configurations based on a heating film deposited on an IR-transparent substrate (iv), they were employed for pool boiling (Gerardi et al., 2010, Jung and Kim, 2014, Tetreault-Friend et al. 2014, Bucci et al. 2016) and flow boiling (Phillips, 2014, Yoo et al., 2015, Sefiane et al., 2019) investigations. The heater design consists of a thin, IR-opaque film made of electrically conductive material, coating an IR transparent substrate of relatively high thermal capacity. The conductive film contacting the test fluid acts as the boiling surface and is connected to a power source that provides the thermal power to boil the fluid by Joule effect along it. The conductive film should be thin enough to present a negligible temperature drop along its thickness as well as negligible thermal capacity (Bucci et al. 2016). On the other hand, the film should be thick enough to be opaque to infrared radiation at the wavelengths verified on the surface submitted to the boiling process. It is important to highlight that besides the function of blocking the infrared radiation emitted by the fluid, when using this configuration, the distribution of the temperature along the film practically coincides with that occurring along the surface contacting the boiling fluid. The film material can be either opaque or transparent to the visible light. Theofanous et al. (2002), Fischer et al. (2012) and Stephan et al. (2013) used visible light opaque materials as titanium and chromium. However, the most popular visible light transparent material is Indium Tin Oxide (ITO). The only caution involving the use of this material refers to its deposition process on the substrate. There are many deposition processes as Plasma Chemical Vapor Deposition (PECVD), Sputtering, etc., but each of them deliveries different properties of the material as resistivity, power capability and wettability.

In the method described above, the substrate material should present a transparency as high as possible to IR radiation at the wavelengths of interest. In addition, the substrate material should not reflect, and absorb radiation and therefore does not "contaminate" the radiation emitted by the conductive film with its own radiation. An interesting material to be used as substrate material is calcium fluoride (CaF2) because its absorptivity is negligible at the wavelengths of interest (3-5 µm for water boiling) and also presents a reasonably flat and low reflectivity spectrum. However, it is a fragile material, thus in boiling experiments with water for instance, it might easily fail due to thermal stresses (Bucci et al., 2016). In view of this, the most used material as substrate is Sapphire. This material presents a large thermal diffusivity (6.7 mm²/s compared to 3.8 mm²/s of stainless steel) and a very large mechanical strength. However, unlike the calcium fluoride, sapphire partially absorbs radiation and therefore, contaminates the radiation emitted by the boiling surface. Thus, the use of this material requires a very careful calibration procedure of the infrared camera, considering the substrate absorptivity and reflectivity.

In view of the approaches described above, it is well known that to design a test section for boiling investigations using infrared thermometry, many aspects should be considered, as composing materials, manufacturing processes, geometry, the experimental conditions and also the calibration method. Accordingly, the next section describes the principal studies found in literature concerning boiling investigations using infrared thermography technique, highlighting the objective of each study, the analyses carried out, the test section design as well as the associated challenges, and the respective calibration procedures adopted by the authors.

## 3. LITERATURE REVIEW

### 3.1. A HEATING CHANNEL COATED WITH IR-OPAQUE MATERIAL

The investigations found in literature using a heating channel lined with IR-opaque material of high emissivity were initially applied to the study of flow boiling in mini and micro-channels. However, most of the experiments were supported by infrared thermography measurements of the channel outer wall temperature, with exception of Kim et al. (2012). These authors investigated the temperature distribution on the inner wall of a conventional channel using this approach. Schmidt et al. (2000) examined heat transfer characteristics during flow boiling in a circular microchannel made of nickel-based alloy 2.4816- and 1.5-mm ID and 3.0 mm OD. The flow direction was upwards using deionized water as working fluid. The heat flux on the wall of the test section was maintained by a direct electric heating. The axial distribution of the external wall temperature was measured using infrared thermography. The internal wall temperatures and the local heat transfer coefficient were calculable assuming steady-state conditions. The authors painted the outer wall of the test section with a black lacquer (emissivity of 0.94) to ensure the high sensitivity to the temperature field of the IR measurements.

Similar approach was also adopted by Diaz et al. 2006 and Boye et al. (2007). These authors performed flow boiling experiments with water in rectangular and circular mini/microchannels, respectively. In both studies, the fluid flowed upwards and the test section was made of nickel alloy Inconel 600 and was directly heated through Joule effect. Both studies used a special thin black lacquer layer of high emissivity to coat the outer wall. The authors mentioned that since the exact heat conductivity resistance of the lacquer was not available, the calibration was referred to the metallic outer wall temperature, which could be calculated under inner adiabatic conditions. Diaz et al. (2006) used 1D solution of the steady-state heat conduction problem in radial direction with constant heat generation to calculate the inner wall

temperatures. The authors mentioned that the influence of the axial heat conduction was found to be negligible under the given conditions. They verified also that the analysis of the experimental uncertainties of the wall temperature, fluid pressure, and electrical voltage led to averaged errors in the heat transfer coefficient (HTC) up to 30 %. That high value was found to be caused mainly by the uncertainties of the wall temperatures measurements. Based on such a result, the authors highlighted that very high measurement accuracy are necessary to obtain experimental results for the HTC under flow boiling conditions in minichannels.

Barber et al. (2009) investigated flow boiling and its associated instabilities inside a rectangular microchannel made of borosilicate glass using high-speed filming along with IR thermometry. The heating method was electrical resistance via an external metallic deposit, tantalum (Ta), on the exterior wall of the microchannels. Barber et al. (2009) mentioned that Tantalum is both, transparent and conductive, hence enabling simultaneous uniform heating and visualization of the flow inside the microchannel. Also, they highlighted that borosilicate is an opaque material to IR radiation. The authors reported that the camera was not in situ calibrated because its system provides automatic transmission correction of temperature based on the atmospheric temperature, relative humidity and input distance from the object.

The method of temperature measurement abovementioned can present uncertainties related to the impossibility of measuring directly by the camera the surface temperature of the inner wall contacting the fluid. Thus, the time-varying inner wall temperature due to the boiling is hard to capture with this approach in microchannels, unless the wall thickness is extremally thin, or if a very careful calibration method is used, taking into account the heat transient axial conduction and also the optical properties of the involved materials. The uncertainties of the temperature measurements propagate and infer errors in the determination of relevant parameters in the boiling investigations, such as HTC. In this way, this approach should not be used if is not possible to apply the black paint on the inside wall of the microchannel.

Another application for this approach was used by Kim et al. (2012) for a single conventional n-type silicon tube 6 mm ID x 8 mm OD x 120 mm long using high-speed IR thermography. The authors measured the heat transfer and liquid film thickness distributions over a relatively large region of the two-phase flow. They used as test section a multilayer wall consisting of a silicon substrate onto which a polyimide tape was attached. In addition, a thin opaque black paint layer was deposited on the top of the polyimide tape. The polyimide was used as an insulator to amplify the temperature variations and to provide a robust signal to the IR camera, otherwise the high conductivity of the silicon would damp out temperature variations due to conduction through the substrate, reducing the magnitude of temperature differences and the spatial resolution. The black paint was used to ensure an opaque coating contacting the fluid. A schematic of the channel wall composition is depicted in Fig. 1a.
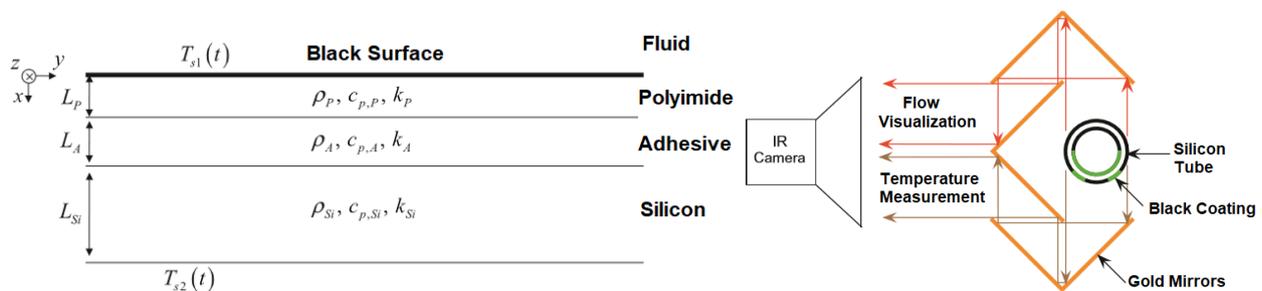


Figure 1- (a) System schematic for the conduction problem. (b) Test section
(Source: Kim et al. 2012)

In the above-mentioned study the reflectivity and absorptivity of wall materials and interfaces were experimentally evaluated using the IR camera and a blackbody as reference. In addition, the emissivity of the black surface was experimentally determined. The mirror arrangement displayed in Fig. 1b allowed simultaneous visualization of the flow along with measurements of the temperature distributions on the internal and external surfaces of the channel wall. FC-72 was used as the working fluid and gravitational effects on flow boiling, and liquid film thickness were evaluated by performing experiments under microgravity conditions. The authors developed a theoretical model for the calibration of the IR camera measurements that takes into account the gradient temperature within the polyimide and the silicon substrate, as well as the optical properties of the composing material. 1D heat conduction was assumed for the silicon substrate, the adhesive and the polyimide tape in order to stablish the temperature gradient through these layers, adopting as boundary conditions the temperature of the black paints Ts1 and Ts2 (see Fig. 1a). Therefore, the estimative of the blackbody surface temperature takes into account the emissions from the black surface and the layers of materials composing the wall (which depended on the temperature profile within them), and the reflection from the surroundings. In this way, as both the temperature distribution within silicon and tape, and the temperature of the black surface were unknown, the authors solved the coupled conduction and radiation problem according to the following algorithm:

(1)  An arbitrary temperature profile (t=0) within the multilayer was assumed;

(2) It was computed the energy emitted by the silicon that reached the interface Silicon-Ambient, and also the energy emitted by the tape that reached the interface Tape-Silicon from the temperature profile assumed above. Then, based on the total radiation reaching the camera, the energy emitted by the black surface was calculated, and hence its temperature;

(3) Once the temperature of the black paint was determined, a new temperature profile along the layers was obtained;

(4) The steps 2 and 3 were repeated for each successive time step.

The proposed calibration technique and its algorithm were validated based on experiments performed using the apparatus shown in Fig. 2a. The apparatus consists of a silicon wafer heated through a thin film heater. Then, polyamide tape with a thin black coating on its upper surface was deposited onto the top of the silicon wafer and a small piece of a polyimide tape with black paint was attached to the bottom to measure the bottom temperature. Since, the black surface was not transparent to IR, the temperatures could be directly obtained based on the energy captured by the IR with the help of mirrors. To validate those values, the calculated temperature of the upper surface was compared with the temperature obtained by the energy captured by the camera when the top of the wafer was cooled through an air jet. Figure 2b shows the result obtained for the calculated temperature using the regression procedure, and the corresponding value directly measured using the camera.
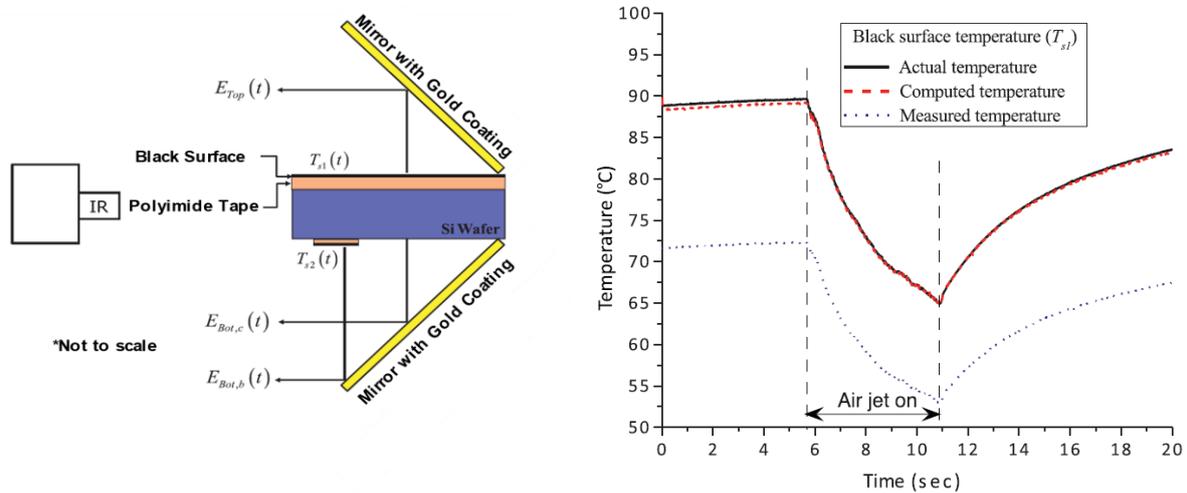


Figure 2- (a) Experimental setup for validation of the calibration procedure. (b) Comparison of the top temperature, determined by the algorithm (computed), and the corresponding measured value. (Source: Kim et al. 2012)

### 3.2. A HEAT SINK MADE OF A METAL HEATER COUPLED WITH A METAL SUBSTRATE

This approach was mainly applied to studies concerning thermal management of electronic components with the test section consisting of heat sinks based on microchannels. Hetsroni et al. (2002) were pioneers in using infrared thermography to investigate the boiling mechanism in microchannels based heat sinks. They conducted experiments in a silicon substrate with 21 parallel triangular microchannels etched on its surface. An electrical heater consisting of a thin film deposited on the bottom of the silicon substrate was used as heat source. The upper part of the microchannels was covered with a Pyrex glass serving as thermal insulator and a transparent cover, allowing the observation of the boiling phenomena. They used a 760 Thermal Imaging Radiometer to characterize the temperature field on the electrical heater. Then, the 2D heat diffusion equation was solved to obtain the temperature field along the wall as shown in Fig. 3 (a). Heat fluxes through the planes normal to the y axes at y=0 and y=a were assumed as negligible due to the symmetry. A uniform heat flux was adopted on the base of the heat sink. The region contacting the Pyrex was assumed as adiabatic. The problem was solved numerically and one of the images displaying the results is presented in Fig. 3 (b).

Xu et al. (2005) also studied flow boiling heat transfer in a silicon heat sink composed by 10 etched triangular microchannels. A Pyrex glass was attached on the top of the microchannels allowing flow visualizations. A thin platinum film was deposited on the backside of the silicon wafer and was used as heating source by supplying AC power directly to its surface. A thin black lacquer with emissivity of 0.94 was painted on the heater surface in order to amplify its emission. Then, the temperature field on the backside of the silicon chip surface was obtained through an IR image system, focusing on an effective heated area of 15 x 4.2 mm². The authors were able of capturing the effects of flow pattern transitions on the temperature distributions along the back surface of the silicon chip.
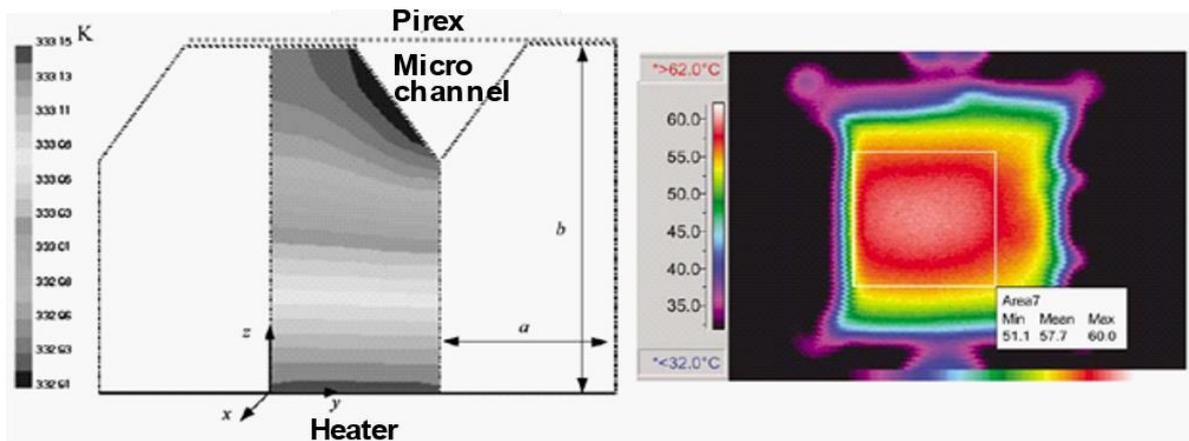
Figure 3- (a) Temperature distribution within the silicon wall (b) Infrared image of the heater (Source: Hetsroni et al. 2002)

Krebs et al. (2010) investigated flow boiling in a branching microchannel silicon heat sink (see Fig. 4) using infrared thermography. The heat sink consisted of a bottom channel silicon wafer and a top silicon cover wafer. Three 0.5-µm-thick Nichrome ring heaters, electrically isolated from each other, were etched to the backside of the channel wafer in order to provide uniform heat flux to the channels. A thin (~2-3 µm) layer of gold was deposited on the bottom of the top silicon wafer. This layer was used for bonding the silicon wafers and providing an IR-opaque top channel wall, from which the temperature was measured through the IR camera. In order to reduce reflectance and increase transmittance, a Si3N4 anti-reflective coating was deposited on the IR viewing-side of the heat sink. All the system was proper calibrated to ensure reliable temperature measurements. The authors used a proper calibration test section composed with a copper cylinder that was heated on its bottom. The heat sink was attached to the top of the copper cylinder and the system was proper insulated. There were six thermocouples located at different radial positions at a depth of 1.6 mm below the heat sink bottom surface. The camera was positioned on the top of the heat sink. Calibration was performed without flow inside the microchannels (natural convection was considered an unimportant factor). The temperature of the thermocouples as well as the one measured by the camera were recorded and the temperature provided by the thermocouples were used as reference temperature in the calibration plots at each equivalent pixel location of the surface.



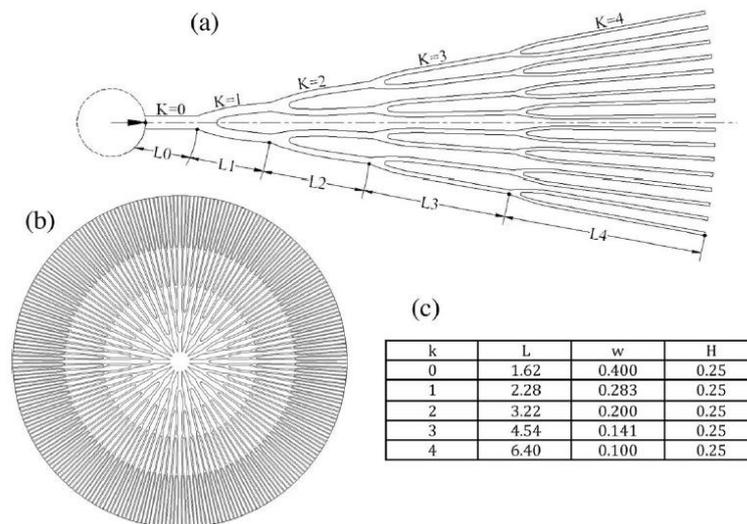| k | L | w | H |
|---|---|---|---|
| 0 | 1.62 | 0.400 | 0.25 |
| 1 | 2.28 | 0.283 | 0.25 |
| 2 | 3.22 | 0.200 | 0.25 |
| 3 | 4.54 | 0.141 | 0.25 |
| 4 | 6.40 | 0.100 | 0.25 |

Figure 4- Heat sink geometry. (a) single three depicting the branching nature of the channels. (b) entire heat sink from the center. (c) heat sink channel dimensions (Source: Krebs et al. 2010)

Szczukiewicz et al. (2013a) evaluated experimentally different micro-evaporators made of silicon with 67 microchannels and 100 x 100 µm² of cross-section area and determined the time-averaged heat transfer coefficients using infrared thermography for temperature measurement. The test section was made of a 380 µm-thick double-side polished silicon wafer bonded to a transparent Pyrex cover. Two independents serpentine micro-heaters, made of aluminum, were sputtered onto the backside of the micro-evaporator. Also, 50 µm-wide 4-wire aluminum resistance

temperature detectors (RTDs) were placed onto the back side in between the heater coils. The total length of the microchannels was 10000 µm while the heated length was 9765 µm. A high-emissivity black matt tape made of PVC was placed onto the backside of the micro-evaporator to improve the accuracy of the temperature measurements. A schematic of the test section is presented in Fig. 5. The IR camera was positioned in the backside of the heat sink. The authors mentioned that the total base heat flux splitted into two, and it was the sum of the heat transferred to the silicon substrate and to the black matt tape (see Fig. 5). The heat flux to the tape is balanced by the heat emission by radiation from the surface covered with the matt black tape. The heat emission by radiation by the surface with the black matt tape was evaluated according to the Stefan-Boltzmann law for a blackbody exposed to a known ambient temperature and was found negligible. The base temperature (Tb) was calculated according to the Fourier law with the temperature measured by the camera as reference, and the conductivity of the tape experimentally measured. They found that the temperature drop through the tape is one order of magnitude lower than the IR temperature measurement accuracy, and then this temperature gradient was considered negligible. Therefore, the temperature of the footprint was calculated according to Fourier Law based on the IR temperature measurement, the conductivity of the silicon wafer, including its change as the temperature drops across the microevaporator wall, and the heat flux provided by the heater.
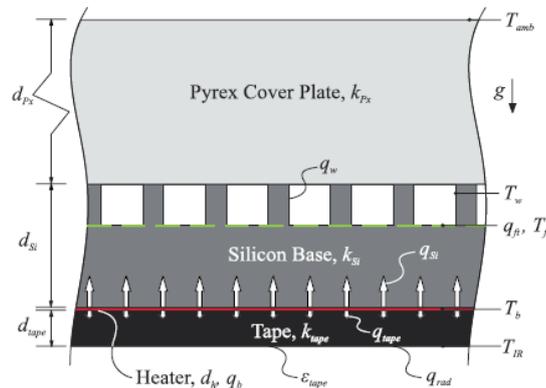


Figure 5- Sectional view of the micro-evaporator (Source: Szczukiewicz et al. 2013)

Following this approach, the authors verified that the 1D heat conduction procedure did not take into account heat spreading towards the colder surrounding regions and hence they observed variations of the local heat transfer coefficients with vapor quality along the channel. In this way, in order to minimize heat-spreading effects, a 3D thermal conduction scheme following Costa-Patry (2011) was employed. Figure 6 presents (a) the temperature map at the base of the silicon substrate, (b) the control volume for heat conduction schemes, (c) the actual heat flux at the root of fins along the channel length and, (d) the local wall heat transfer coefficients obtained assuming 1D and 3D conduction schemes plotted as function of local vapor quality.
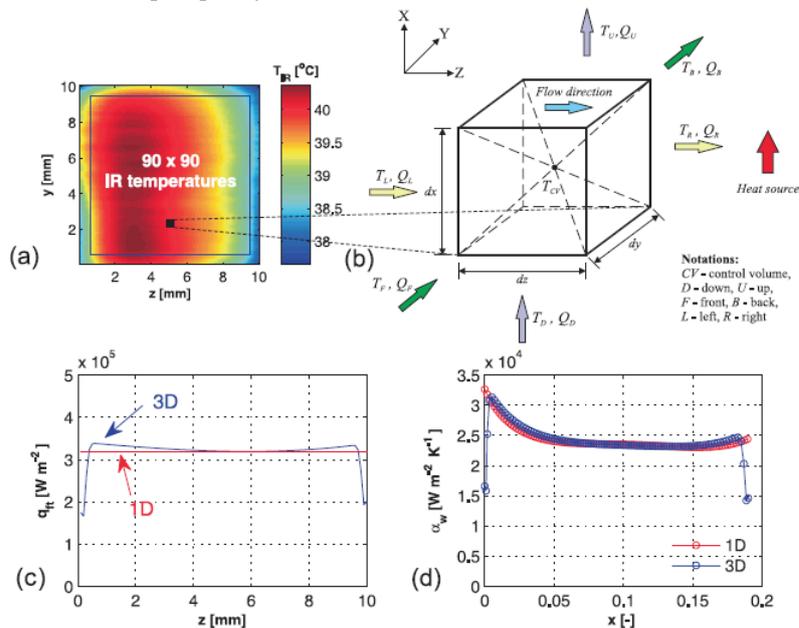


Figure 6- (a)Temperature distribution. (b) control volume for the heat conduction schemes. (c) actual heat flux. (d) local wall heat transfer obtained assuming 1D and 3D conduction schemes. (Source: Szczukiewicz et al. 2013)

## 3.3. A HEATING FILM DEPOSITED ON AN IR-TRANSPARENT SUBSTRATE

Yoo et al. (2015) performed accurate wall temperature measurement using infrared thermometry for a vertical test section composed of a single vertical conventional square channel 10 x 10 mm² with total height of 305 mm and heated length of 265 mm. Except for the heated wall, transparent acrylic walls, enclosed the channel. An ITO film exposed to the test fluid and heated through an electric current was attached to a soda-lime glass substrate. The heater wall presents the multilayer configuration depicted in Fig. 7. The sapphire wall has the purpose of trap the air and improve the thermal insulating features of the test section. On the outer surface of the sapphire window, a black lacquer was painted to provide the boundary condition for the wall temperature measurement. The IR camera to measure the temperature distribution on the heated wall was positioned in front of the sapphire window, while two high-speed video cameras were used to observe bubble motions through the acrylic walls. The authors mentioned that because of the multilayer configuration of the heater wall the total energy measured by the IR camera consisted of the energy emitted by the several layers composing the heater wall, as well as the reflection effects caused by the background. In this way, in order to estimate the amount of IR radiation emitted by the ITO film, and then, estimate correctly the inner wall temperature, the authors followed the calibration method proposed by Kim et al. (2012) above detailed. They also measured the reflectivity, transmissivity and emissivity of all involved materials using a blackbody as reference. Figure 8 shows the results obtained by the authors for the calibration. The blue curve represents the temperature of the ITO film captured directly from the camera, and the red curve is the ITO temperature captured by the camera through the substrate.
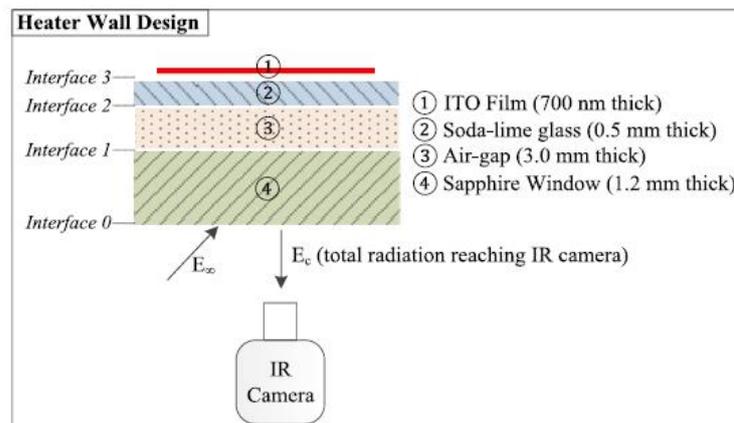


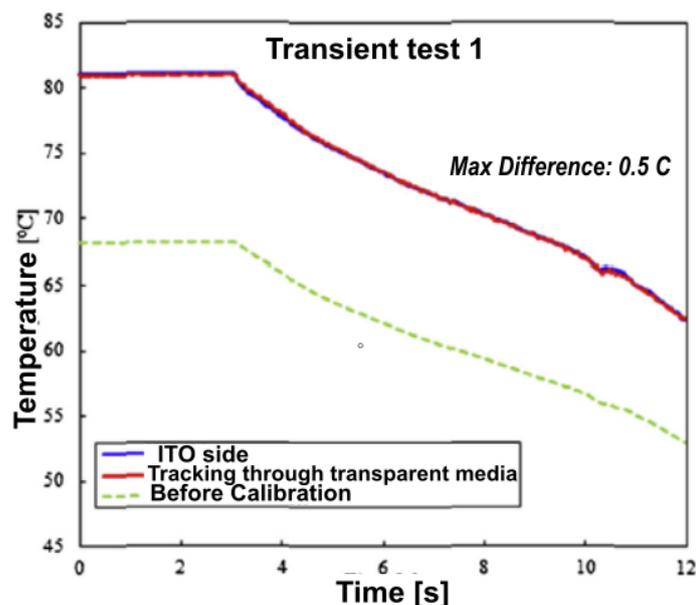Figure 7- Heater wall design (Source: Yoo et al. 2015)



Figure 8- Validation test under transient condition (Source: Yoo et al. 2015)

Bucci et al. (2016) applied infrared thermometry to investigate pool boiling of water. They used as the boiling surface a thin film of ITO deposited on a sapphire substrate as shown in Fig. 9a. The heating effect was obtained

through Joule effect by supplying electrical current directly to the ITO layer. As pointed out by Kim et al. (2012) and Yoo et al. (2015), the authors highlighted that the radiation measured by the IR camera is a result of the radiation emitted by the boiling surface (ITO film), the substrate (sapphire in their case) and reflected by the background. However, Bucci et al. (2016) pointed out that although for silicon substrate as in the studies of Kim et al. (2012) and Yoo et al. (2015) is suitable working with average optical properties, the same is not true for sapphire because its absorption coefficient is highly dependent on temperature and hence on the radiation wavelength as shown in Fig. 9b. Therefore, a new calibration procedure was proposed by Bucci et al. (2016) based on Kim et al. (2012) that instead of the average energy radiance, considers the spectral photon radiation. Single-phase steady state and transient conduction experiments were conducted to validate their calibration model.
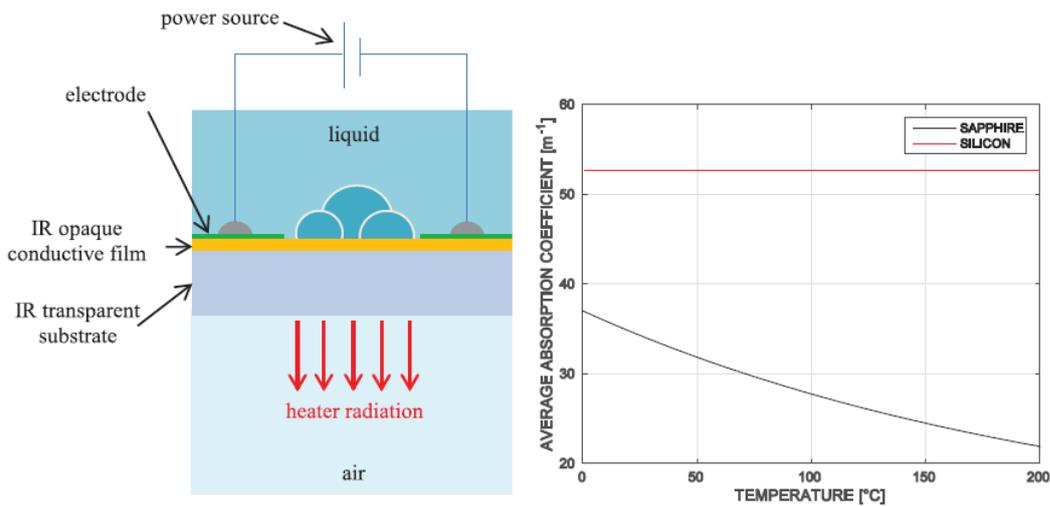


Figure 9- (a) sketch of a typical heater for IR thermometry investigation of boiling heat transfer. (b) average absorption coefficient in sapphire and silicon (Source: Bucci et al. 2016)

Recently, Korniliou et al. (2019) evaluated heat transfer coefficients during flow boiling in a rectangular microchannel using wall temperature measurements from a high-speed IR camera. The microchannel (192 μm of hydraulic diameter) was made of PDMS (polydimethylsiloxane) and was attached to a glass microscope slide following oxygen plasma activation. The rear side of the 0.17 mm thick microscope glass slide was coated with a 200 nm conductive, transparent thin film of ITO, which was deposited by magnetron sputtering and provided the heating of the fluid in the channel. A schematic of the test section is shown in Fig. 10. The effective area of the ITO/glass was 2.26 x 20 mm. The copper board shown in Fig.10 provided electrical contact with the ITO heater. A high-speed IR camera recorded, from the glass side, the spatial distribution of the wall temperature. In order to measure the emissivity of the ITO+glass sample they used a black paint (emissivity of 0.95) attached to a heated copper block. The sample was attached on the surface with the black body using a thermal adhesive tape. A silicon heater was attached to the backside of the copper block and provided the heating. A K-type thermocouple was placed on the sample in order to validate the temperature measurements obtained from the IR camera. The estimated average emissivity over the range of 38-75 °C for the ITO-coated glass sample was found to be 0.76. From the temperature field provided by the IR camera they evaluated the heat transfer coefficient for single-phase flow and flow boiling.
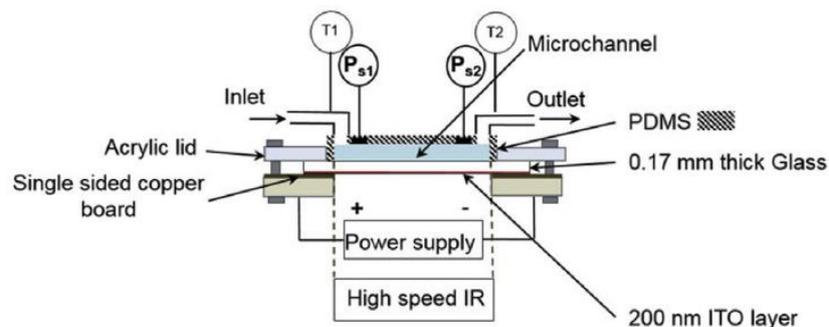


**Figure 10 -** The test section, which consisted of a microchannel with integrated pressure sensors. (Source: Korniliou et al. 2019)

## 4.  CONCLUSIONS

An extensive study of literature concerning infrared thermography applied to boiling investigation was carried out. It was concluded that extreme care should be exercised when using this non-intrusive technique to study the boiling mechanisms and aspects such as composing materials, geometry, and manufacturing processes should be taken into account during the test section design. Additional challenges are present when applying this technique to microscale conditions such as the heater material and its positioning as well as the location of a black paint coating, in order to obtain the temperature field of the surface contacting the fluid. Moreover, a proper method of calibration has to be developed to ensure accurate data.  In this way, authors have proposed different strategies in order to apply appropriately infrared thermography to boiling investigations. Those who first investigated boiling in a single microchannel through infrared thermometry used a heating channel coated with IR-opaque material as test section. These authors reported measurement errors associated to the impossibility of measuring directly the surface temperature of the inner wall contacting the fluid mainly due to the tube small dimensions, not allowing the application of a black painting on its internal surface. Thus, it is concluded that this method can be considered suitable to micro scale only if a very careful calibration procedure based on inverse heat transfer problem is used in order to correctly provide the time-varying inner wall temperature. On the other hand, a heating channel coated with IR-opaque material showed reliable temperature measurements when applied to conventional channels as performed by Kim et al. (2012) mainly due to the possibility of applying the black coating on the inner wall of the channel and also due to the calibration method developed which took account the optical properties of all composing materials. Lastly, the use of infrared thermography in configurations with a heating film deposited on an IR-transparent substrate besides providing accurate measurements for pool and flow boiling in micro and macroscale channels. The challenge of this approach is related to the difficulty of handling the infrared semi-transparent/transparent materials, such as sapphire and germanium, limiting the geometry of the test section.

## 5.  ACKNOWLEDGEMENTS

## 6.  REFERENCES

Barber, J., Sefiane, K., Brutin, D., Tadrist, L., "Hydrodynamics and heat transfer during flow boiling instabilities in a single microchannel", Applied Thermal Engineering, Volume 29, Issue 7, 2009, Pages 1299-1308, ISSN 1359-4311

Bucci, M., Richenderfer, A., Su, G. Y., MacKrell, T., Boungiorno, J., "A mechanistic IR calibration technique for boiling heat transfer investigations". International Journal of Multiphase Flow, Volume 83, 2016, Pages 115-127, ISSN 0301-9322.

Costa-Patry, E., Cooling high heat flux micro-electronic systems using refrigerants in high aspect ratio multi-microchannel evaporators, Ph.D. thesis, Ecole Polytechnique Federale de Lausanne, 2011.

Diaz, M.C., Boye, H., Hapke, I., Schmidt, J., Staate, Y., Zhekov, Z., "Investigation of flow boiling in narrow channels by thermographic measurement of local wall temperatures", Microfluid Nanofluid 2 (2006) 1e11.

Fischer, S., Herbert, S., Sielaff, A., Slomski, E.M., Stephan, P., Oechsner, M., "Experimental investigation of nucleate boiling on a thermal capacitive heater under variable gravity conditions", Microgravity Sci. Tec. 24 (2012) 139e146.

Gerardi, C., Buongiorno, J., Hu, L.W., McKrell, T., "Study of bubble growth in water pool boiling through synchronized, infrared thermometry and high-speed video". Int. J. Heat. Mass Trans, 53 (2010), pp. 4185-4192.

Golobic, I., Petkovsek, J., Baselj, M., Papez, A., Kenning, D., "Experimental determination of transient wall temperature distributions close to growing vapor bubbles". Heat Mass Transf., 45 (2009), pp. 857-866.

Golobic, I., Petkovsek, J., Kenning, D.B.R., "Bubble growth and horizontal coalescence in saturated pool boiling on a titanium foil, investigated by high-speed IR thermography". Int. J. Heat. Mass Tran, 55 (2012), pp. 1385-1402.

Golobič, I., Voglar, J., Zupančič, M., Peperko, A., Birbarah, P., Miljkovic, N., "Analysis of heater-wall temperature distributions during the saturated pool boiling of water". Experimental Thermal and Fluid Science, Volume 102, 2019, Pages 205-214, ISSN 0894-1777.

Hetsroni, G., Mosyak, A., Pogrebnyak, E., Rozenblit, R., "Infrared temperature measurements in micro-channels and micro-fluid systems", International Journal of Thermal Sciences, Volume 50, Issue 6, 2011, Pages 853-868, ISSN 1290-0729.

Hetsroni, G., Mosyak, A., Segal, Z., Pogrebnyak, E., "Two-phase flow patterns in parallel micro-channels", International Journal of Multiphase Flow, Volume 29, Issue 3, 2003, Pages 341-360, ISSN 0301-9322.

Jung, S., Kim, H., "An experimental method to simultaneously measure the dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface". Int. J. Heat Mass Transf., 73 (2014), pp. 365-375.

Kim, J., Kim, T. H., Kommer, E., Dessiatoun, S., "Measurement of two-phase flow and heat transfer parameters using infrared thermometry", International Journal of Multiphase Flow, Volume 40, 2012, Pages 56-67, ISSN 0301-9322.

Krebs, D., Narayanan, V., Liburdy, J., Pence, D., "Spatially resolved wall temperature measurements during flow boiling in microchannels", Exp. Therm. Fluid Sci. 34 (4) (2010) 434–445.

Lin Liu, T., Pan, C., "Infrared thermography measurement of two-phase boiling flow heat transfer in a microchannel", Applied Thermal Engineering, Volume 94, 2016, Pages 568-578, ISSN 1359-4311.

Phillips, B., 2014. Experimental Investigation of Subcooled Flow Boiling Using Synchronized High Speed Video, Infrared Thermography, and Particle Image Velocimetry (Ph.D. Thesis). Massachusetts institute of Technology, Cambridge, MA.

Schmidt, J., Hapke, I., Boye, H., "Onset of nucleate boiling in minichannels", International Journal of Thermal Sciences, Volume 39, Issue 4, 2000, Pages 505-513, ISSN 1290-0729.

Schweizer, N., Stephan, P., "Experimental study of bubble behavior and local heat flux in pool boiling under variable gravitational conditions". Multiph. Sci. Technol., 21 (2009), pp. 329-350.

Sefiane, K., Korniliou, S., Mackenzie-Dover, C., Harmand, S., Duursma, G., Christy, J. R. E., Terry, J. G., Walton, A. J., "Local wall temperature mapping during flow boiling in a transparent microchannel", International Journal of Thermal Sciences, Volume 135, 2019, Pages 344-361, ISSN 1290-0729.

Tetreault-Friend, M., "Systematic Investigation of the Effects of Hydrophilic Porosity on Boiling Heat Transfer and Critical Heat Flux (MSc Thesis)". Massachusetts institute of Technology, Cambridge, MA (2014).

Theofanous, T. G., Tu, J.P., Dinh, A.T., Dinh, T.N., "The boiling crisis phenomenon - Part I: nucleation and nucleate boiling heat transfer". Exp. Therm. Fluid Sci., 26 (2002), pp. 775-792.

Thome, J. R., Szczukiewicz, S., Borhani, N., "Fine-resolution two-phase flow heat transfer coefficient measurements of refrigerants in multi-microchannel evaporators", International Journal of Heat and Mass Transfer, Volume 67, 2013a, Pages 913-929, ISSN 0017-9310.

Thome, J. R., Szczukiewicz, S., Borhani, N., "Two-phase heat transfer and high-speed visualization of refrigerant flows in $100 \times 100$ μm2 silicon multi-microchannels", International Journal of Refrigeration, Volume 36, Issue 2, 2013b, Pages 402-413, ISSN 0140-7007.

Xu, J., Shen, S., Gan, Y., Li, Y., Zhang, W., Su, Q., 2005. "Transient flow pattern based microscale boiling heat transfer mechanisms. J. Micromech. Microeng. 15 (6), 1344e1361.

Yoo, J., Estrada-Perez, C. E., Hassan, Y. A., "An accurate wall temperature measurement using infrared thermometry with enhanced two-phase flow visualization in a convective boiling system", International Journal of Thermal Sciences, Volume 90, 2015, Pages 248-266, ISSN 1290-0729.

## 7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.