

Flow boiling of HFE-7100 over graphene coated sintered porous copper surfaces in a minichannel

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ABSTRACT

High power dense electronic devices demand efficient heat removal and thermal management. Phase change heat transfer with the application of graphene coating offers superior heat dissipation. In this study, the effects of sintered copper powders and monolayer graphene coating on flow boiling of HFE-7100 were investigated for a minichannel. Bare copper surface and surfaces with additional sintered layers of thicknesses of 0.5 mm, 1.0 mm, and 2.0 mm were compared in terms of flow boiling heat transfer. Additionally, graphene coatings were applied to each surface, and the effects of graphene coating on flow boiling heat transfer were assessed at atmospheric pressure. The experiments were conducted at different heating fluxes and two different mass fluxes (120 kg/m²s and 180 kg/m²s) for each surface. Novec HFE-7100, a dielectric fluid having a high potential for the use in electronics cooling applications, was used as the working fluid in flow boiling experiments. The results indicated that the sintered layer improved the flow boiling heat transfer performance. The sintered layer thickness of 0.5 mm offered the best heat transfer performance with an enhancement up to 145 % relative to the bare surface at high heat fluxes. It was also observed that graphene coatings further enhanced the heat transfer performance of the sintered surfaces up to 34 %. When 0.5 mm sinter thickness and graphene coating were combined, the maximum heat transfer enhancement was recorded as 227 % compared to the bare surface. In the light of high-speed camera images, flow boiling characteristics and effects of graphene coating on flow patterns were displayed. Accordingly, the graphene coating increased the nucleation site density, improved the stability of bubble formation and led to HTC enhancement for the sintered surfaces.

1. Introduction

Due to the advances in microelectronics, the integration of high-power electronic miniature devices into very compact and lightweight designs has become vital. The efficiency and performance of micro electronic devices are often limited by their inability to effectively dissipate heat [1]. In this regard, phase change heat transfer has proven to be highly advantageous for applications involving high thermal loads and tight packaging constraints [2]. By making use of flow boiling, cooling systems occupying minimal space and efficiently dissipating

heat can be designed and developed for achieving high heat flux cooling [3–5].

The performance of phase change heat transfer depends on various parameters such as the type of working fluid [6], material of heat transfer surfaces [7], surface roughness [8,9], mass flow rate [10], fluid velocity [11], system pressure [12–14], and channel dimensions [15–17].

Common methods for increasing the heat dissipation from a surface involve the alteration of the surface roughness [18] and wettability characteristics of the surface [19]. By changing the wettability of the

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surface, the heat transfer characteristics could be altered depending on the ability of emerging bubbles to remove heat from the surface [20]. The major aim regarding heat dissipation via boiling heat transfer is to increase the number of nucleation sites on the surface, to enable bubbles to depart without any delay and to avoid the formation of a permanent vapor film layer [21–23]. The modification of the surface wettability affects the size of bubbles and their tendency to depart from the surface [24,25]. A delay in the formation of a vapor film layer on a modified surface could result in the postponement of the Critical Heat Flux (CHF) condition [26].

Micro-fabrication techniques have been employed to modify surface wettability by creating precisely defined hydrophobic and hydrophilic patterns, resulting in notable improvements in both the HTC and CHF values [27,28]. Although these techniques are effective in enhancing heat transfer performance, their scalability remains limited. Furthermore, the high costs associated with micro-fabrication methods still pose significant challenges to their practical implementation in real-world applications [29].

In addition to micro-fabrication methods, another approach to alter surface characteristics is coating the surface with a porous structure. This allows for changing the surface wettability and for effectively increasing the nucleation site density through porous structures. Sarwar et al. [30] coated tube surfaces with Al_2O_3 to create microporous surfaces and conducted flow boiling experiments using water. Their findings showed that the coated surfaces exhibited an enhancement in CHF compared to smooth tubes. Wong and Leong [31] fabricated three-dimensional porous metallic structures using an additive manufacturing technique and performed flow boiling experiments with FC-72 as the coolant. Their results indicated that porous substrates achieved superior flow boiling heat transfer performance compared to plain surfaces, attributed to the increased nucleation site density and enhanced flow mixing. Lin et al. [32] conducted experiments on a surface treated with the Electroless Plating method, which resulted in micro-pores with sizes ranging from 1 to 5 μm . The experiments were conducted at different mass flow rates on this micro-porous surface. It was highlighted that the super-hydrophobic surface with such micro-porosity provided a significantly high nucleation site density. When comparing the copper sample with a porous surface to a plain surface sample, the porous surface offered a 74.8 % improvement in boiling heat transfer. The cited studies demonstrate that introducing a porous structure on a surface enhances heat transfer performance by increasing nucleation site density. However, the increased nucleation site density also raises the risk of dry-out formation, as the formation of numerous small bubbles can coalesce into larger bubbles, potentially covering the surface and disrupting heat transfer. Li et al. [33] conducted experiments on micro-porous structured copper surfaces and reported that the porous structures significantly increased nucleation site density. However, at lower mass fluxes, the intense nucleation process led to the formation of elongated bubbles, which initiated dry-out and contributed to an increased pressure drop across the channel.

Regarding graphene coatings, Kim et al. [34], conducted experiments on graphene-coated porous surfaces and demonstrated that the application of graphene coating enhanced the HTC by promoting the early onset of nucleate boiling. In a study conducted by Sadaghiani et al. [35], it was demonstrated that coating the surface with a certain thickness of graphene significantly influenced the vapor column formation and improved the heat transfer performance in pool boiling experiments. Sia et al. [36] showed that using the graphene nano-structured surfaces facilitate bubble detachment process and suppress the formation of dry spot compared to the non-graphene coated surfaces. It was shown that the application of graphene coating over the porous structures, could connect the surface pores with a highly conductive graphene network, thereby enhancing the nucleation site density, decrease bubble departure diameter and improve growth of the bubble and consequently improving the heat transfer performance. The

Table 1

Summary of test samples.

Sample No	Sample Name	Sintered Layer Thickness	Surface Condition
#S1	Bare	0 mm	Bare copper
#S2	Cu_0.5mm	0.5 mm	Sintered
#S3	Cu_1.0mm	1.0 mm	Sintered
#S4	Cu_2.0mm	2.0 mm	Sintered
#S5	Bare_Gr	0 mm	Graphene coated
#S6	Gr_0.5mm	0.5 mm	Sintered + Graphene coated
#S7	Gr_1.0mm	1.0 mm	Sintered + Graphene coated
#S8	Gr_2.0mm	2.0 mm	Sintered + Graphene coated

mentioned studies show that the heat transfer performance on modified porous surfaces could be further increased with graphene coatings.

Some studies reported that by coating the metallic porous layer on the surface with graphene, graphene could act as an oxidation barrier, which could preserve the heat transfer performance of the surface even after extended use [37,38]. The ability of graphene coatings to adhere firmly to the surface and to prevent surface oxidation makes them a promising method for real-life applications [39]. In a recent study, Ahmadi et al. [40] performed experiments on graphene-coated sintered copper surfaces at sub-atmospheric pressures, using a sinter layer thickness of 0.5 mm and reported that the graphene coating significantly improved boiling heat transfer under sub-atmospheric conditions, where larger bubble diameters and an increased risk of dry-out formation are more pronounced.

The abovementioned literature review reveals that a significant portion of studies on graphene-coated porous surfaces have focused on pool boiling. While pool boiling is an effective heat removal mechanism, it is not practical for systems with packaging constraints or those subject to motion. Additionally, most surface modification studies have not explored the sintering process, despite its advantages as a scalable, robust, and reliable surface modification technique. Although studies on both pool boiling and flow boiling exist in the literature, only a limited number have investigated the effects of graphene coatings. Research on graphene coatings is even more scarce for flow boiling and sintered surfaces, as well as for next generation working fluids.

Given the potential of graphene coatings to enhance flow boiling heat transfer, further research in this area is essential. However, there is a lack of studies on flow boiling over graphene-coated sintered porous surfaces. This study investigates the flow boiling behavior of HFE-7100 on graphene-coated sintered porous copper surfaces under atmospheric conditions, demonstrating a configuration that is suitable for practical, robust and reliable real-life applications.

2. Experimental setup

2.1. Surface preparation and characterization

A total of 8 different surface types were prepared, and flow boiling experiments were conducted. Among these surfaces, one surface was the bare copper surface, and three surfaces were sintered surfaces. For each of the prepared surfaces, two types were prepared: one with graphene coating and one without coating. The details about test surface samples are shown on Table 1.

Copper powders with sizes ranging from 70 to 100 μm (Fig. 1) were applied to the bare copper surface using the sintering method at high temperatures (850–900 $^{\circ}\text{C}$). To obtain the samples with different thicknesses, copper powders were separately sintered onto a 1 mm thick bare copper surface with sintered layer thicknesses of 0.5 mm, 1 mm, and 2 mm during the process (Fig. 1).

Afterwards, both bare copper and sintered samples were coated with monolayer graphene using the Chemical Vapor Deposition (CVD)

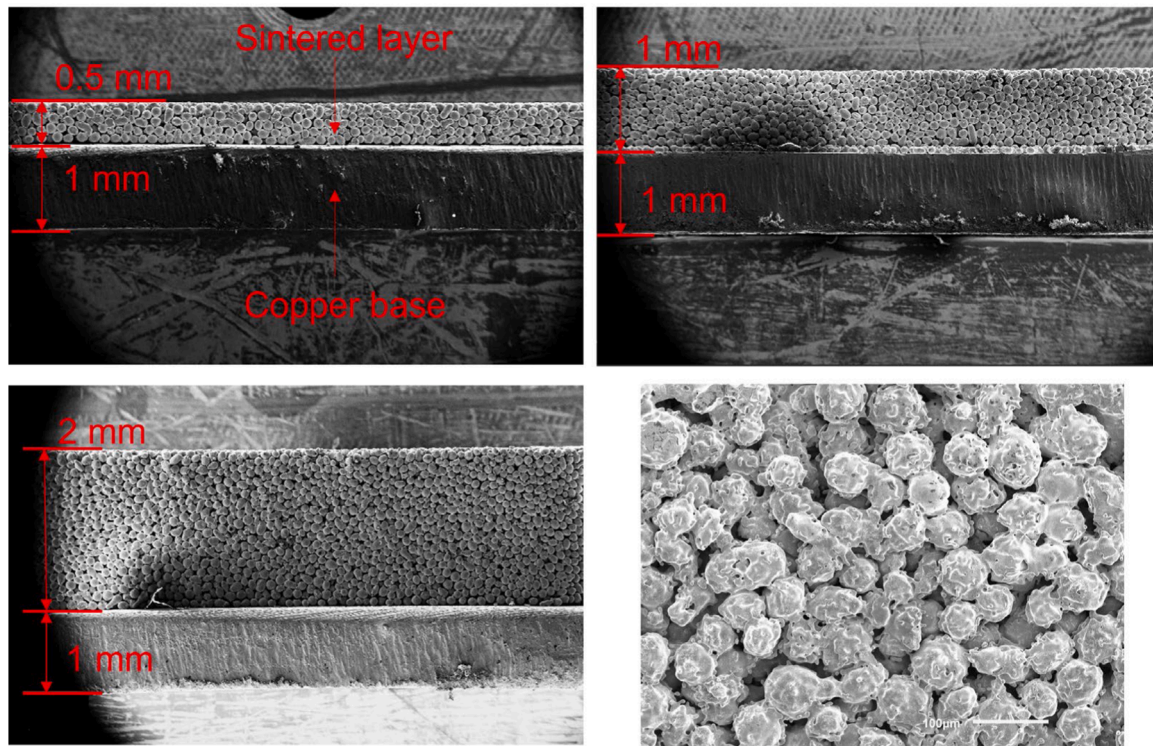


Fig. 1. SEM images of sintered samples: a) 0.5 mm sinter thickness, b) 1 mm sinter thickness, c) 2 mm sinter thickness, d) Top view of SEM image of graphene coated sinter particles of 1 mm sinter thickness sample.

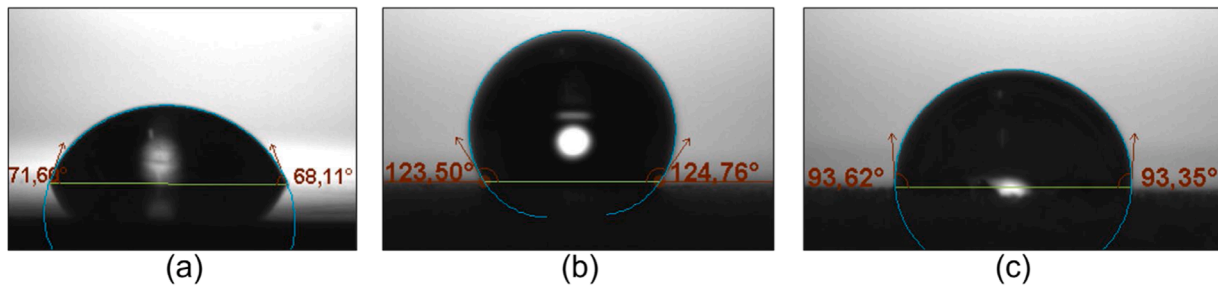


Fig. 2. Contact angle measurements: a) Bare copper, b) Non-treated sintered copper, c) Graphene coated sintered copper.

method [41]. During the graphene coating process, the copper samples were placed in a tubular furnace and annealed at 1000 °C for 40 min under the flow of 500 sccm Ar (Argon) and 70 sccm H₂ (Hydrogen). Then, 65 sccm of CH₄ (Methane) was introduced into the furnace for graphene growth. To achieve full coverage on the surfaces, the graphene growth phase was continued for 40 min. This process is a well-developed method, was previously applied to similar samples and was capable of growing monolayer graphene on the surface with minimal errors. The details for the graphene coating and characterization can be found in previous studies [39,40].

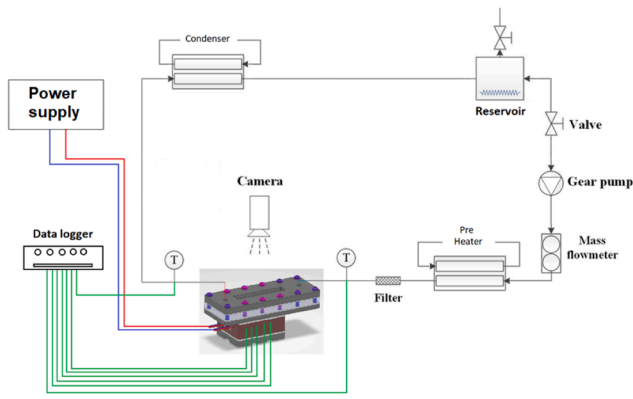
To observe how the sintered copper powders and graphene coating affect the wettability of the surfaces, contact angle measurements were performed. A ThetaLite Tensiometer (Dyne Technology) was used to measure the contact angles of 5-microliter water droplets placed on the surfaces. As shown in Fig. 2, the contact angles were measured as 70° for bare copper, 124° for non-treated sintered copper, and 93° for graphene-coated sintered copper.

2.2. Experimental setup and test procedure

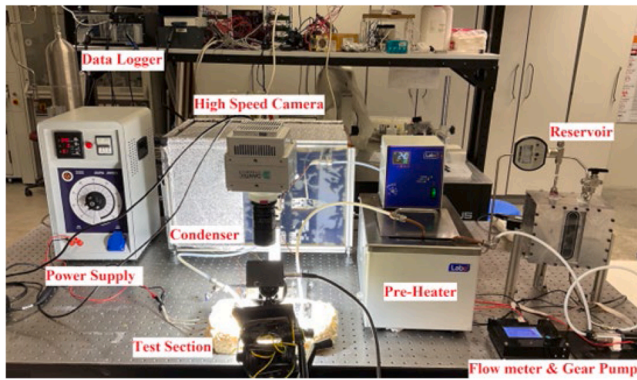
For the flow boiling experiments, a closed-loop test setup was

prepared as shown in Fig. 3. The test setup consists of a reservoir, an RPM-controlled high-precision micro annular gear pump, a flow meter, a preheater, a micro filter, an inlet temperature sensor, the test section, an outlet temperature sensor, and a condenser. Additionally, a data logger was used to record the temperature data collected during the experiments, and a high-speed camera was employed for flow visualization.

The test section and its details are shown in Fig. 4. Within the test section, two cartridge-type heaters were placed inside a copper heating block to form the heat source. Five thermocouples which were positioned 1 mm below the surface and extended along the surface were distributed along the surface. To reduce the thermal resistance, the test specimens were attached to the heating block using a thin layer of thermal paste (Arctic MX-6). A PTFE (Teflon) clamp was placed over the test specimen to ensure a good adhesion between the test specimen and heating block during flow boiling experiments. Additionally, a steel plate was positioned on top of the clamp to direct the flow, and a transparent plexiglass plate was placed on top of the steel plate to provide flow boiling images during the experiments. All components including the upper and lower steel plates and bolts were sandwiched together and tightened using bolts. Silicon gaskets were used in between



(a)



(b)

Fig. 3. Experimental test setup for flow boiling experiments a) Schematics, b) Real image.

interfaces to prevent leakage. Finally, the entire test section was

insulated with Polyurethane foam to reduce heat losses. The dimensions of the test sections used in the experiments were 50 mm x 15 mm, and the channel height was kept constant at 2 mm for all the sections.

Novec HFE-7100 was used as the working fluid in the experiments due to its excellent dielectric properties and suitability for electronics cooling, where water may present electrical safety risks. Additionally, its boiling point of 61 °C makes it ideal for phase change cooling applications with electronic components operating at maximum temperatures of 80–90 °C. To examine the effect of flow rate, experiments were performed at two mass fluxes (120 kg/m²s and 180 kg/m²s), representative of the moderate to high flow rates commonly observed in electronic cooling applications. During the experiments, the inlet temperature was maintained at 51 °C (corresponding to subcooling level of 10 °C) with the assistance of a pre-heater. The heating power was adjusted using an DC power supply, and the experiments were performed at different heat input levels for each surface and mass flow rate. All the temperature measurements were made under steady-state conditions at five different locations across the surface. To ensure the reproducibility of the results, all the tests were repeated for three times, and the average of the results was used for data reduction. Thermophysical properties of HFE-7100

Table 3
Applied Voltage and Currents.

Heat Flux (W.cm ⁻²)	Voltage (V)	Current (A)
1.9	40	0.40
2.5	45	0.46
3.0	50	0.50
3.8	55	0.58
4.6	60	0.64
5.3	65	0.68
6.4	70	0.76
7.2	75	0.80
8.3	80	0.86
9.4	85	0.92
10.6	90	0.98
11.9	95	1.04
13.2	100	1.10

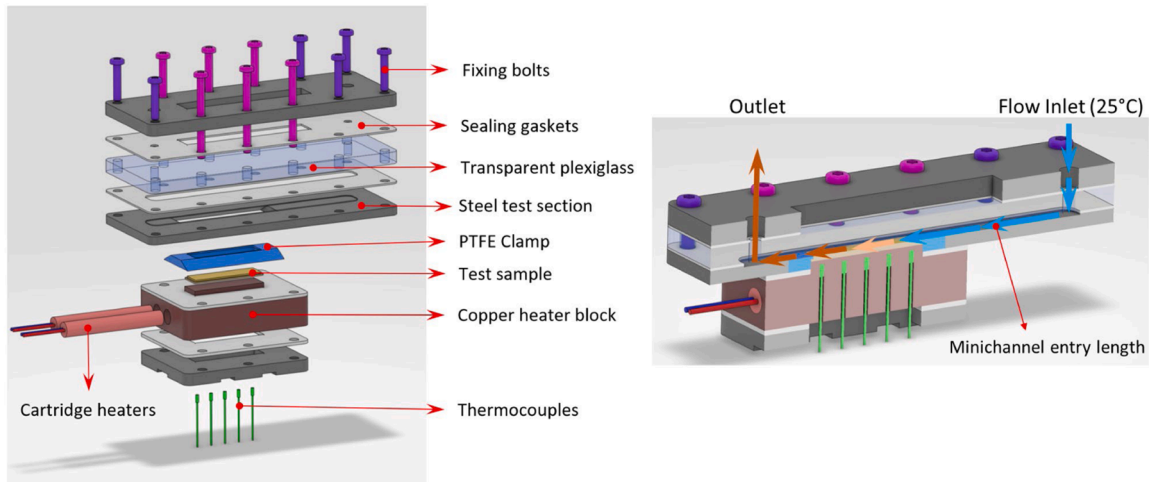


Fig. 4. Detailed presentation of the test section.

Table 2
Thermophysical properties of HFE-7100 at atmospheric pressure.

Working liquid	Density (Kg.m ⁻³)	Dynamic viscosity (Pa.s)	Specific heat (J.kg ⁻¹ .K ⁻¹)	Boiling temperature (°C)	Surface tension x 10 ³ (N.m ⁻¹)	Vapor pressure (MPa)	Latent heat (kJ.kg ⁻¹)
HFE-7100	1515	5.8 × 10 ⁻⁴	1172	61	13.6	78.7 × 10 ⁻³	127

and Applied voltage and current values shown on Table 2. and Table.3 respectively.

2.3. Data reduction and uncertainty

During the experiments, the obtained voltage, current, and temperature data were processed to obtain the heat transfer coefficient. The mass flux G was determined using the following expression:

$$G = \frac{\dot{m}}{A_c} \quad (1)$$

Here, $\dot{m}$ is the mass flow rate (kg/s), and A_c is the cross-sectional area of the mini channel (m^2). Furthermore, the recorded voltage and current values during the experiments were utilized to calculate the applied power as follows:

$$P = V.I \quad (2)$$

The applied power (P) is given in Watts (W) and was determined using the measured voltage (V) and current (I) values. Taking the heat losses into account, the heat flux applied to the surface can be obtained as:

$$q'' = \frac{P - \dot{Q}_{loss}}{A_s} \quad (3)$$

where $\dot{Q}_{loss}$ is the heat loss, and A_s is the area of the heated surface. The calculation of $\dot{Q}_{loss}$ was based on single-phase flow heat transfer. For this, single-phase Novec HFE-7100 was introduced into the test section, and the inlet and outlet temperatures were measured. With the known mass flow rate and specific heat of the working fluid, the heat loss can be determined using the following formula:

$$\dot{Q}_{loss} = P - \dot{m}c_p(T_{out} - T_{in}) \quad (4)$$

With the use of the curve fitting technique, the heat losses could be estimated at different electrical powers. Subsequently, the heat transfer coefficient (HTC) was found using the following expression:

$$h = \frac{q''}{(T_w - T_f)} \quad (5)$$

To calculate the surface temperature (T_w) in degrees Celsius ($^{\circ}C$), the temperature measured at the j th location of the thermocouple and heat flux were utilized:

$$T_{wj} = T_j - q'' \left(\frac{L_{Cu_b}}{K_{Cu_b}} + R_p + \frac{L_{Cu_s}}{K_{Cu_s}} \right) \quad (6)$$

In this context, T_{wj} represents the surface temperature of the substrate at the j th location ($j = 1-5$), and T_j corresponds to the temperature reading from the j th thermocouple location. Additionally, L_{Cu_b} and L_{Cu_s} refer to the thickness of Copper Block (thickness between the thermocouple and surface) and Copper sample, respectively, whereas K_{Cu_b} and K_{Cu_s} are their thermal conductivities. Furthermore, R_p is the thermal resistance of the applied thermal paste which was used between test surface and heater block.

During subcooled boiling experiments, the single phase fluid temperature was determined using the energy balance. The saturation temperature was assumed to remain constant along the channel. At a constant heat flux applied to the system, the fluid temperature could be calculated as:

$$T_{f,x} = T_i + \frac{q'' \cdot A_x}{\dot{m}C_p} \quad T_{f,x} < T_{sat} \quad (7)$$

$T_{f,x} = T_{sat}$ Saturated Boiling

In this equation, T_i is the inlet temperature and C_p is the specific heat capacity of the fluid. Additionally, A_x is the heated area starting from the

Table 4
Uncertainty in major parameters.

Parameter	Uncertainty
Voltage	± 1 V
Current	± 0.01 A
Temperature	± 0.1 $^{\circ}C$
Mass flow rate	± 2 %
Height of the channel	± 0.01 mm
Width of channel	± 0.01 mm
Heat transfer coefficient	± 5 %

inlet to the point of interest.

The uncertainties in voltage and current measurements were determined based on the specifications provided in the datasheet of the embedded multimeter (MSC-7203) in the power supply, as well as the variations observed during the experiments to account for potential changes caused by the increased temperature of the heating elements. For temperature measurements, thermocouples were validated prior to use, and the input values of the data logger were corrected to ensure accuracy. The uncertainty in mass flow rate was quantified by validating the flow meter against known flow rates under varying pressure conditions. Additionally, the dimensions of the channels were measured using a CMM after machining to confirm that the tolerances met the desired specifications.

By applying the uncertainty analysis proposed by Coleman and Steele [42], the average uncertainty in the heat transfer coefficient (HTC) was determined and listed in Table 4 along with uncertainties in other parameters.

High-speed video recordings of the boiling process were captured using a Phantom VEO-710 L camera with a full pixel resolution of 1920×1080 at a frame rate of 3200 fps. The resulting images were post-processed using MATLAB image processing scripts, where the grayscale pixels were reclassified to black and white. To accurately define the bubble boundaries, the darkest pixels, corresponding to the shades of bubbles on the surface, were first ignored. Then, a range for the bubble boundaries, which appeared darker than the fluid and vapor phases, was defined. Finally, the pixels within these boundaries were excluded, assuming them to be vapor inside the bubbles. This reclassification enhanced the clarity of the vapor-liquid boundaries and made the bubble edges more distinct.

3. Results and discussion

3.1. Single phase validation

To ensure the proper operation and reliability of the experimental setup, single phase heat transfer tests were conducted on the bare copper sample. Initially, the heat flux was applied, and the temperatures were measured at the inlet and outlet of the test section. Simultaneously, the temperatures at various locations on the surface were also measured. Using the obtained temperatures at the inlet and outlet, the heat transfer rate was calculated as: $\dot{Q} = \dot{m}c_p(T_{out} - T_{in})$. Subsequently, the average heat transfer coefficient was determined as:

$$h = \frac{\dot{Q}}{A(T_{wall} - T_f)} \quad (8)$$

where the T_f and T_{wall} are the average temperatures of the fluid and surface, respectively. With the known heat transfer coefficient (h), Nusselt number (Nu) was calculated using the formula $Nu = hD_H/k$, where D_H is the hydraulic diameter of the channel, and k is the thermal conductivity of the fluid. The obtained Nusselt numbers were then compared with the correlations provided by Shah and London [43]:

$$Nu = 1.953 (Re.Pr.D_H/L)^{1/3} \quad \text{where } (Re.Pr.D_H/L) \geq 33.3 \quad (9)$$

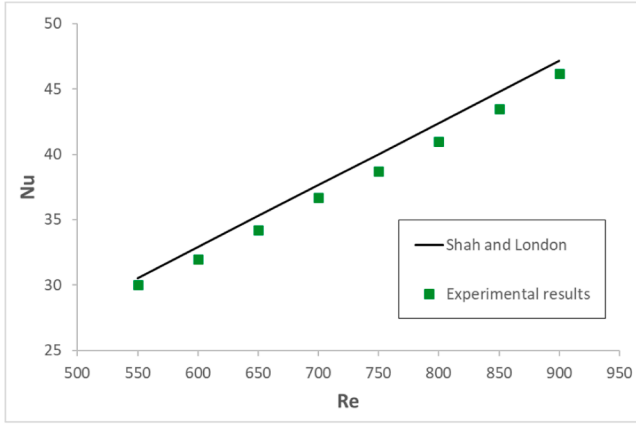


Fig. 5. Comparison between experimental results and predictions of the correlation of Shah and London [43].

$$Nu = 4.364 + 0.0722 (Re.Pr.D_H / L) \quad \text{where } (Re.Pr.D_H / L) < 33.3 \quad (10)$$

The comparison of the results with the predictions of the correlation of Shah and London [43] is depicted in Fig. 5. As can be observed, the obtained experimental results are in a satisfactory agreement with a 5 % average deviation from the predictions of the correlation provided by Shah and London [43].

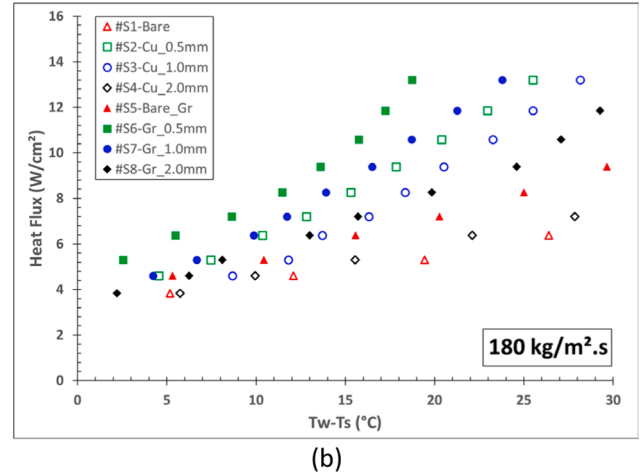
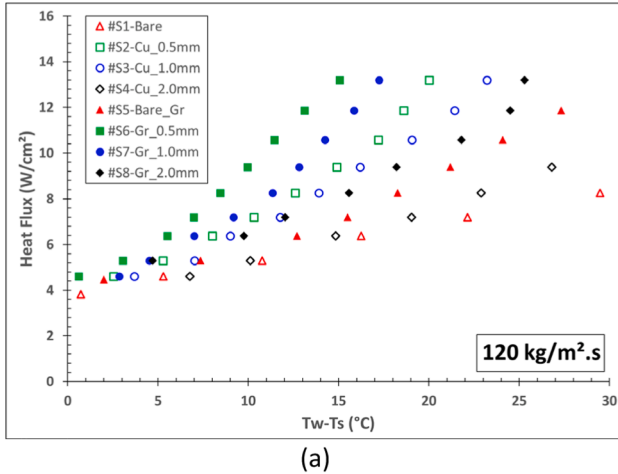


Fig. 6. Boiling curves for the (a) mass flux of 120 kg/m².s and (b) mass flux of 180 kg/m².s.

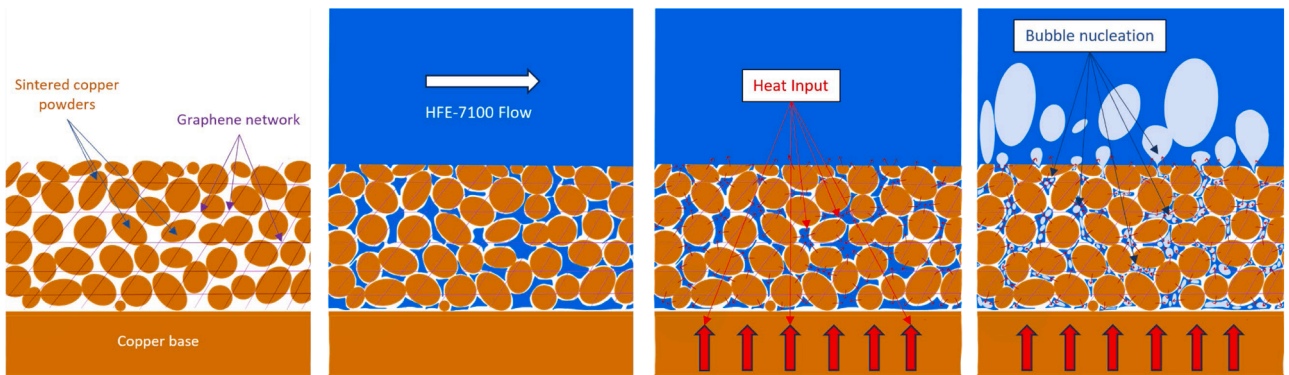


Fig. 7. Bubble nucleation and growth inside copper pores under flow boiling condition.

3.2. Boiling curves

Fig. 6 presents the boiling curve. Among the non-graphene coated surfaces (#S1–#S4), the sample with a 0.5 mm sintered layer (#S2) exhibits a smaller increase in surface temperature as the applied heat flux increases, compared to the other samples. Specifically, at a heat flux of 9.4 W/cm², the surface temperature of #S2 is 11.9 °C lower than that of the thickest sintered layer (#S4). This superior performance can be attributed to the reduced thermal resistance and enhanced heat transfer efficiency of the thinner sintered layer, which likely promotes more effective bubble formation and detachment.

The surface with a 0.5 mm sintered layer and graphene coating (#S6) demonstrates the best overall performance, achieving a surface temperature reduction of 4.9 °C compared to the non-coated counterpart (#S2) at a heat flux of 13.2 W/cm². This improvement is likely due to the better bubble formation and departure effect of the graphene coating, which facilitate better heat dissipation and nucleation site activity.

The results also reveal that thicker sintered layers introduce greater thermal resistance, leading to higher surface temperatures at equivalent heat fluxes. This trend suggests that optimizing the sinter layer thickness is critical for balancing mechanical strength and thermal performance. These findings are particularly relevant for practical applications, such as cooling systems in electronic devices or high-performance thermal management systems, where minimizing thermal resistance is essential for efficient operation.

As shown in Fig. 6, the effect of mass flux appears limited within the studied range (120–180 kg/m².s). This is likely due to the interplay between mass flux, subcooling, and bubble dynamics. At higher mass flux,

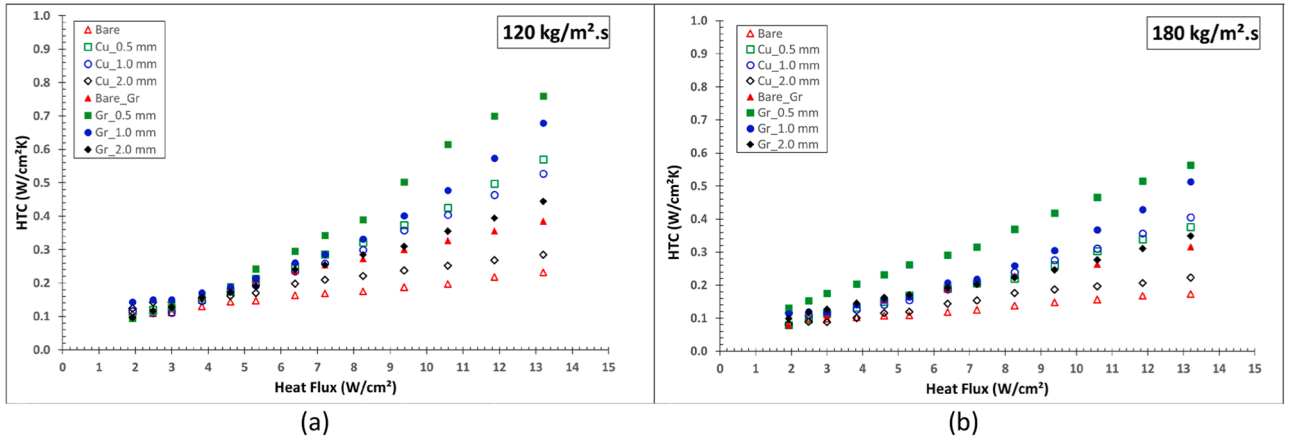


Fig. 8. Heat transfer coefficients (HTC) for (a) mass flux of 120 kg/m²s, (b) mass flux of 180 kg/m²s.

the subcooled liquid promotes local condensation at bubble tops, reducing the bubble size and prolonging detachment. Furthermore, for the wetting liquid HFE-7100, higher mass flux can suppress bubble growth and delay detachment from the surface, collectively contributing to the observed trend. It should be noted that the selected mass flux range (120–180 kg/m²s) offers a balance among enhanced nucleate boiling, liquid replenishment, avoidance of boiling instabilities, and high performance under operating conditions.

As illustrated in Fig. 7, the combination of the porous structure of the surface with a highly conductive graphene coating leads to enhanced heat transfer, bubble formation and boiling performance. Highly conductive graphene coating between pores improves the formation of vertical vapor columns and results in more effective heat transfer between surface and coolant which is particularly dominant in nucleate boiling.

Considering the significant impact of liquid superheat on bubble nucleation within nucleate boiling region, the graphene coating serves as a conductive network, which facilitates the rise of the liquid temperature to the necessary temperature to initiate nucleation. The duration for the liquid to achieve this superheated state is called the waiting period. The presence of the graphene network decreases the waiting period, resulting in improved conduction heat transfer across the porous medium and consequently leading to enhanced flow boiling heat

transfer.

3.3. Heat transfer performance

Fig. 8 shows the heat transfer coefficient profiles. Among the non-graphene-coated surfaces (#S1–#S4), the HTC values for #S2 and #S3 are higher compared to those of #S1 and #S4, with #S2 exhibiting the highest HTC across the applied heat flux range. On the other hand, the sintered surface with the thickest layer (#S4) shows only a slight improvement in HTC relative to the bare surface (#S1), indicating that increasing the sintered layer thickness further does not significantly enhance heat transfer. This behavior suggests that excessive thickness may introduce additional thermal resistance and hinder effective heat dissipation.

The enhanced heat transfer performance compared to the bare copper surface can be attributed to several key factors inherent to the porous structure. First, the sintered layer significantly increases the density of active nucleation sites, facilitating earlier bubble formation and more efficient boiling inception. Second, the porous network promotes capillary wicking, which ensures continuous liquid replenishment at the heated surface. Third, the porous structure increases the effective heat transfer surface area, enhancing the overall heat transfer coefficient. Finally, the structured surface influences bubble departure

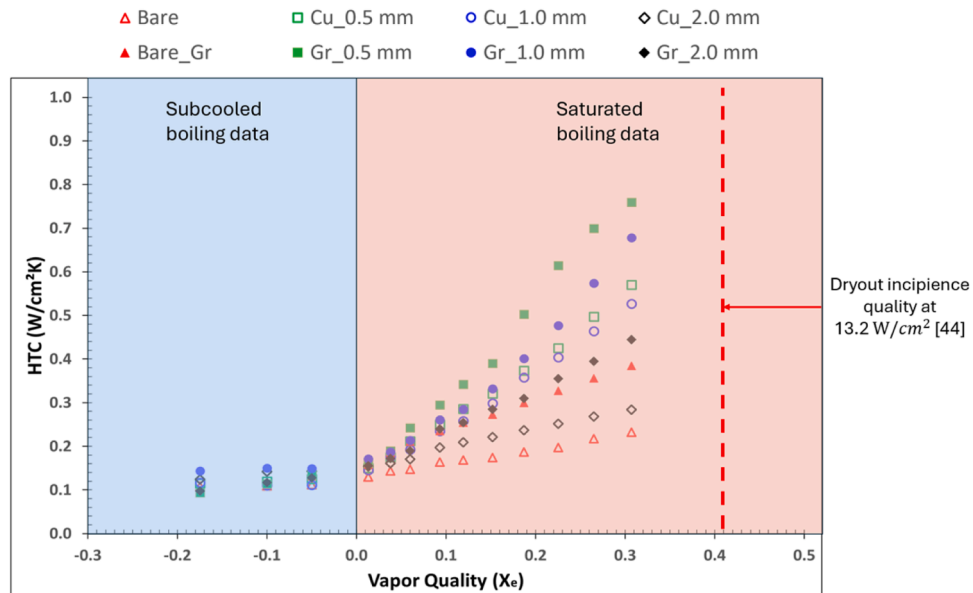


Fig. 9. Variation of heat transfer coefficients (HTC) of different surfaces for mass flux of 120 kg/m²s with respect to the exit vapor quality (X_e).

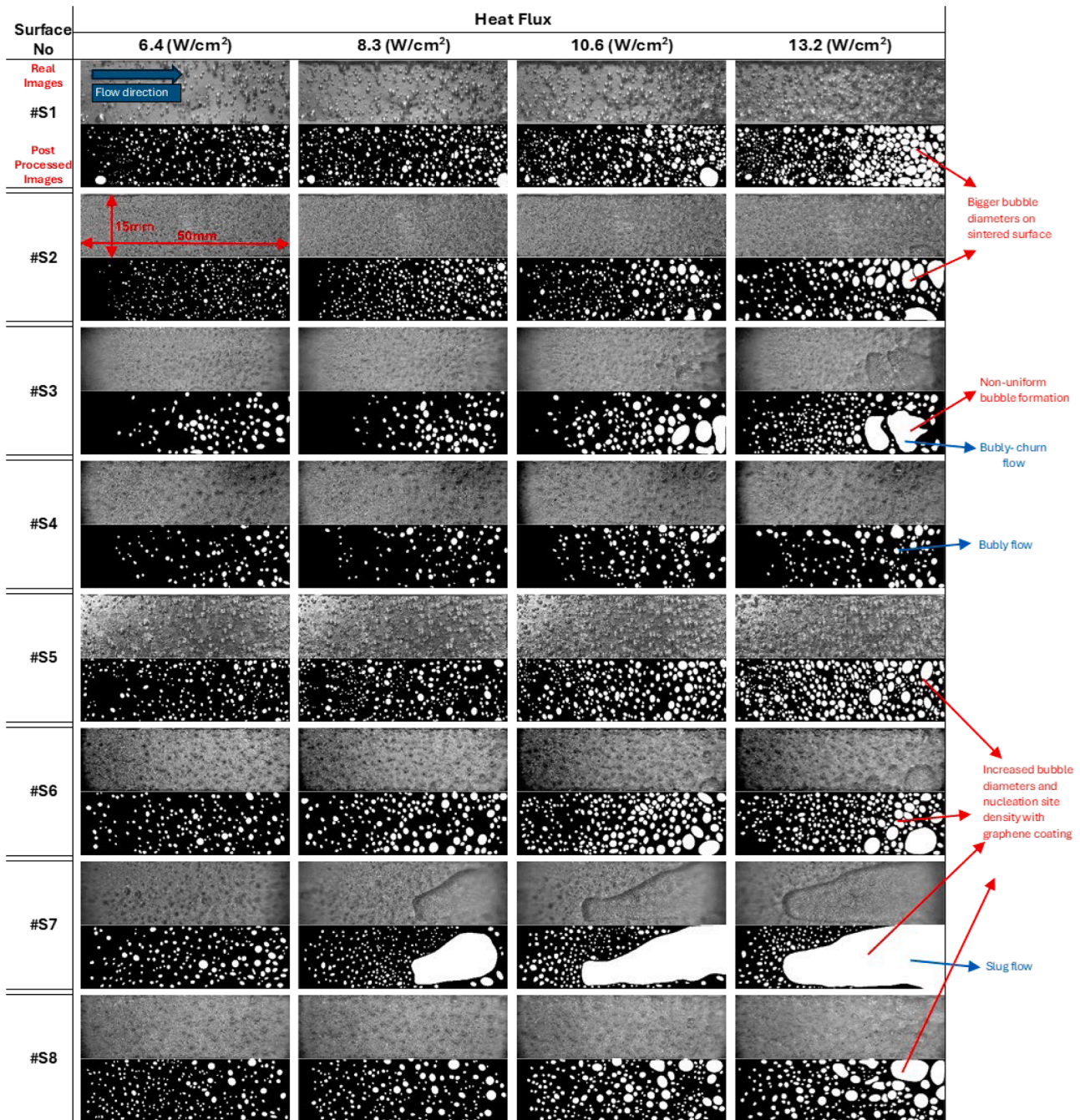


Fig. 10. Flow visualisation images on different samples for the mass flux of 120 kg/m²s.

dynamics, leading to more frequent bubble detachment and reduced bubble coalescence. These combined mechanisms outweigh the added thermal resistance from the sintered layer, ultimately resulting in a better boiling heat transfer performance. It is also worth noting that there exists an optimal sintered layer thickness, beyond which the benefits may diminish due to excessive thermal resistance or bubble entrapment. In the case of the 2 mm sintered layer shown in Fig. 6, the combination of these enhancement mechanisms still provides better performance than the bare copper surface.

The HTC profiles of the graphene-coated sintered surfaces (#S5–#S8) are also shown in Fig. 8. Consistent with the trend observed in the non-coated surfaces, the surface with a 0.5 mm sintered layer (#S6) delivers the highest HTC among the coated surfaces. The addition of graphene coating leads to a notable enhancement in heat transfer,

evident from the onset of boiling. This enhancement can be attributed to the graphene coating's superior thermal conductivity between pores and its ability to promote nucleation site density, resulting in more efficient heat transfer mechanisms.

The comparison between coated and uncoated surfaces reveals that graphene coating significantly enhances HTC values, particularly for optimized sintered layer thicknesses. These findings emphasize the critical role of layer thickness and surface modification in maximizing heat transfer performance. Such improvements have potential implications for applications requiring efficient thermal management, such as electronics cooling or high-power density systems.

When comparing the HTC results for mass fluxes of 120 kg/m²s and 180 kg/m²s, the effect of mass flux is minimal at lower heat fluxes. At higher heat fluxes, the lower mass flux (120 kg/m²s) performs better,

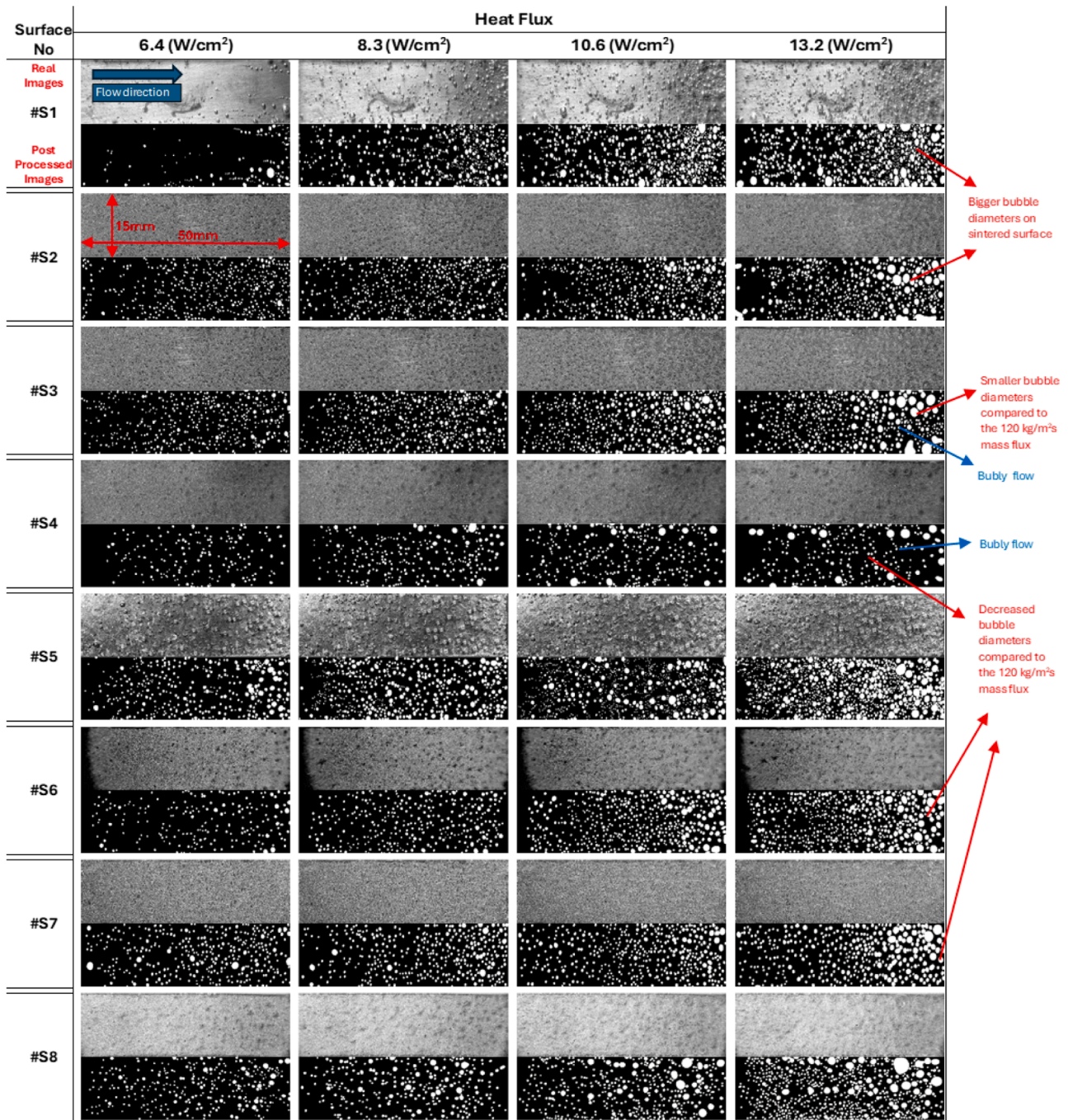


Fig. 11. Flow visualisation images on different samples for the mass flux of 180 kg/m²s.

likely due to the dominance of nucleate boiling. When comparing the HTC results for mass fluxes of 120 kg/m²s and 180 kg/m²s, the effect of mass flux is minor at lower heat fluxes. At higher heat fluxes, the lower mass flux case (120 kg/m²s) performs better, likely due to the dominance of nucleate boiling. For the graphene-coated surface, the coating enhances the nucleation site density at lower mass flux, further improving boiling heat transfer by promoting smaller bubble formation and earlier nucleation. For uncoated sintered surfaces, larger bubbles observed at the lower mass flux reflect longer residence time and more developed nucleate boiling, which also enhances heat transfer.

Fig. 9. shows the heat transfer coefficient profiles with exit vapor quality (X_e) for tested heat fluxes for mass flux of 120 kg/m²s. The variation of heat transfer coefficients with exit vapor quality reveals that the heat transfer coefficient generally increases as vapor quality rises,

both in the subcooled and boiling regions. This increase is particularly more significant for graphene-coated surfaces. Kim and Mudawar [44] developed a correlation to predict the dryout incipience quality by synthesizing data from various studies with different boundary conditions. To give an idea about how close the experimental conditions are to the permanent dryout condition, the dryout incipience quality, as estimated from the correlation, is also presented in Fig. 9.

3.4. Flow visualisation

Flow patterns were recorded using a high-speed camera during the experiments and are shown in Fig. 10 and Fig. 11 at different heat fluxes for all the surfaces and the mass fluxes of 120 kg/m²s and 180 kg/m²s. Real images captured from the high speed camera recordings are post

processed to increase the resolution and shown one under the other with the real images. It can be observed that graphene coating increases the nucleation site density on all the surfaces. The graphene coating accelerates the formation of bubbles between the sinter particles, which triggers bubble generation over a larger region. It can be observed that the bubble diameters on graphene-coated surfaces are larger compared to those on non treated surfaces. Graphene accelerates the vertical vapor column formation, leading to the creation of larger bubbles on the surface. In summary, enhanced bubble formation from multiple locations at low/medium heat flux values contributes to the heat transfer performance. At high heat flux values ($>10 \text{ W/cm}^2$), it can be seen that the bubbles forming on graphene-coated surfaces are more regular and uniform. This suggests that the graphene network within the sinter layer distributes the thermal load evenly across the entire surface and disperses the nucleation sites more uniformly. On graphene-coated surfaces, during flow boiling, dry spot regions are repeatedly rewetted with liquid at frequent intervals. At high heat fluxes, a comparison of bubble diameters on bare copper and sintered surfaces underscores the impact of reduced wettability. On sintered copper surfaces, reduced wettability weakens liquid-solid adhesion, limiting the lateral spread of the bubble base and promoting greater vertical growth. Consequently, bubbles grow to larger diameters and remain attached to the surface longer until buoyancy and drag forces overcome the weakened adhesion. The combination of this effect and the increased nucleation site density enhances the overall heat transfer performance of the sintered surfaces.

In single-phase flow, HTC generally increases with mass flux due to enhanced convective heat transfer. However, in flow boiling, while an increase in the mass flux can enhance convective heat transfer, under the specific experimental conditions of our study, it actually leads to a deterioration in HTC. This counterintuitive behavior can be attributed to several factors. One possible explanation is the inlet subcooling. As the mass flux increases, the subcooled liquid can cause local condensation at the tops of bubbles, leading to a reduction in bubble diameter. This is evident in Fig. 10 and Fig. 11, which show that bubble sizes are larger at lower mass flux in the low heat flux region. This shrinkage of bubbles can prolong bubble detachment and reduce the effective heat transfer coefficient. Another contributing factor could be bubble suppression. Since HFE-7100 is a wetting liquid, an increase in the mass flux can suppress bubble growth and delay detachment from the superheated surface. It is important to note that these trends are observed specifically for the two tested mass fluxes (120 and $180 \text{ kg/m}^2\text{s}$). The enhancement or deterioration behavior may shift outside of this range, and further investigation is needed to fully characterize the broader trend.

4. Conclusion

This study investigates the effect of copper sintered layers and graphene coating on flow boiling in a minichannel using the working fluid Novec HFE-7100, whose saturated temperature is 61°C at atmospheric pressure. Heat fluxes up to 13.2 W/cm^2 could be obtained for surface temperatures below 80°C at low mass fluxes ($<200 \text{ kg/m}^2\text{s}$). The key findings obtained from the conducted study are summarized as follows:

- Sintering copper powder with dimensions of $70\text{--}100 \mu\text{m}$ onto the copper surface improved boiling heat transfer. The sintered layer thickness of 0.5 mm led to the best performance. At the heat flux of 13.2 W/cm^2 , 0.50 mm sintered layer (#S2) lead to 145 % enhancement compared to the bare copper surfaces(#S1). Increasing the sinter layer thickness negatively affected boiling heat transfer.
- Graphene coating improved heat transfer for all the surfaces. Maximum heat transfer enhancement (at a heat flux of 13.2 W/cm^2) was recorded as 227 % compared to bare copper (#S1).
- Graphene coating increased the nucleation site density and promoted bubble formation. Bubbles forming on graphene-coated surfaces were more spherical and evenly distributed across the surface. The film layer forming on graphene-coated surfaces detached from

the surface and was continuously replenished by the liquid flow, preventing the formation of dry spots. This phenomenon could be observed at high heat flux values ($>10 \text{ W/cm}^2$).

This study demonstrates the potential of graphene coatings on porous structures to enhance flow boiling heat transfer. The method employed is applicable to a wide range of thermal applications involving both flow boiling and porous structures. Since most electronic components have an operating temperature limit around 80°C – 100°C , combining 0.5 mm sintered surfaces with graphene coatings ensures reliable surface temperatures even at a heat flux of 13.2 W/cm^2 . Future research could explore surfaces with varying particle sizes and thinner sintered layers ($0.2\text{--}0.3 \text{ mm}$) to further expand the scope and applicability of these findings.

CRediT authorship contribution statement

Tayfun Güler: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation. **Vahid Ebrahimipour Ahmadi:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ilker Alagozoglul:** Validation, Resources, Methodology, Investigation, Formal analysis. **Saifa Amin:** Visualization, Resources, Methodology, Formal analysis. **Ahmet Muhtar Apak:** Resources, Methodology, Investigation, Conceptualization. **Alper Apak:** Resources, Methodology, Formal analysis, Conceptualization. **Murat Parlak:** Writing – review & editing, Resources, Project administration, Investigation, Conceptualization. **Umur Tastan:** Resources, Project administration, Methodology, Investigation, Conceptualization. **Ismet Inonu Kaya:** Writing – review & editing, Software, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Ali Sadaghiani:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Koşar:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] J. Lee, I. Mudawar, Low-temperature two-phase microchannel cooling for high-heat-flux thermal management of defense electronics, *IEEE Trans. Compon. Packag. Technol.* 32 (2009) 453–465, <https://doi.org/10.1109/TCAPT.2008.2005783>.
- [2] B. Parizad Benam, A.K. Sadaghiani, V. Yağcı, M. Parlak, K. Sefiane, A. Koşar, Review on high heat flux flow boiling of refrigerants and water for electronics cooling, *Int. J. Heat Mass Transf.* 180 (2021), <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121787>.
- [3] L. Cheng, G. Xia, Fundamental issues, mechanisms and models of flow boiling heat transfer in microscale channels, *Int. J. Heat Mass Transf.* 108 (2017) 97–127, <https://doi.org/10.1016/j.ijheatmasstransfer.2016.12.003>.
- [4] A.K. Sadaghiani, N.S. Saadi, S.S. Parapari, T. Karabacak, M. Keskinöz, A. Koşar, Boiling heat transfer performance enhancement using micro and nano structured surfaces for high heat flux electronics cooling systems, *Appl. Therm. Eng.* 127 (2017) 484–498, <https://doi.org/10.1016/j.applthermaleng.2017.08.018>.

- [5] T.G. Karayiannis, M.M. Mahmoud, Flow boiling in microchannels: fundamentals and applications, *Appl. Therm. Eng.* 115 (2017) 1372–1397, <https://doi.org/10.1016/j.applthermaleng.2016.08.063>.
- [6] U. Sajjad, I. Hussain, M. Sultan, S. Mehdi, C.C. Wang, K. Rasool, S.M. Saleh, A. Y. Elnaggar, E.E. Hussein, Determining the factors affecting the boiling heat transfer coefficient of sintered coated porous surfaces, *Sustainability* 13 (2021), <https://doi.org/10.3390/su132212631>.
- [7] H. Seo, J.H. Chu, S.Y. Kwon, I.C. Bang, Pool boiling CHF of reduced graphene oxide, graphene, and SiC-coated surfaces under highly wettable FC-72, *Int. J. Heat Mass Transf.* 82 (2015) 490–502, <https://doi.org/10.1016/j.ijheatmasstransfer.2014.11.019>.
- [8] V.Y.S. Lee, G. Henderson, A. Reip, T.G. Karayiannis, Flow boiling characteristics in plain and porous coated microchannel heat sinks, *Int. J. Heat Mass Transf.* 183 (2022), <https://doi.org/10.1016/j.ijheatmasstransfer.2021.122152>.
- [9] P. Cui, Z. Liu, Enhanced flow boiling of HFE-7100 in picosecond laser fabricated copper microchannel heat sink, *Int. J. Heat Mass Transf.* 175 (2021), <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121387>.
- [10] A. Kaya, M.R. Özdemir, A. Koşar, High mass flux flow boiling and critical heat flux in microscale, *J. Therm. Sci.* 65 (2013) 70–78, <https://doi.org/10.1016/j.jthermalsci.2012.10.021>.
- [11] B. Soleimani, M. Ziabasharhagh, The interaction of surface orientation and roughness on nanofluid sub-cooled flow boiling, *Results Eng.* 22 (2024), <https://doi.org/10.1016/j.rineng.2024.102222>.
- [12] N. Li, A. Rachel Betz, Boiling performance of graphene oxide coated copper surfaces at high pressures, *J. Heat Transfer* 139 (2017), <https://doi.org/10.1115/1.4036678>.
- [13] A. Koşar, M. Rafet Özdemir, M. Keskinöz, Pressure drop across micro-pin heat sinks under unstable boiling conditions, *Int. J. Therm. Sci.* 49 (2010) 1253–1263, <https://doi.org/10.1016/j.jthermalsci.2009.12.018>.
- [14] L. Yin, M. Sun, P. Jiang, C. Dang, L. Jia, Heat transfer coefficient and pressure drop of water flow boiling in porous open microchannels heat sink, *Appl. Therm. Eng.* 218 (2023), <https://doi.org/10.1016/j.applthermaleng.2022.119361>.
- [15] Y.K. Prajapati, M. Pathak, M. Kaleem Khan, A comparative study of flow boiling heat transfer in three different configurations of microchannels, *Int. J. Heat Mass Transf.* 85 (2015) 711–722, <https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.016>.
- [16] A. Khalili Sadaghiani, A. Koşar, Numerical and experimental investigation on the effects of diameter and length on high mass flux subcooled flow boiling in horizontal microtubes, *Int. J. Heat Mass Transf.* 92 (2016) 824–837, <https://doi.org/10.1016/j.ijheatmasstransfer.2015.09.004>.
- [17] W.-T. Yan, C. Li, W.-B. Ye, Y. Hong, S.-M. Huang, The effect of aspect ratio on hydraulic and heat transfer characteristics in a fractal microchannel, *Int. J. Fluid Mech. Res.* 47 (2020) 71–84, <https://doi.org/10.1615/InterJFluidMechRes.2019028306>.
- [18] S.G. Kandlikar, S. Joshi, S. Tian, Effect of surface roughness on heat transfer and fluid flow characteristics at low Reynolds numbers in small diameter tubes, *Heat Transf. Eng.* 24 (2003) 4–16, <https://doi.org/10.1080/01457630304069>.
- [19] B.J. Jones, S.V. Garimella, Surface roughness effects on flow boiling in microchannels, *J. Therm. Sci. Eng. Appl.* 1 (2009) 1–9, <https://doi.org/10.1115/1.4001804>.
- [20] C.C. Hsu, P.H. Chen, Surface wettability effects on critical heat flux of boiling heat transfer using nanoparticle coatings, *Int. J. Heat Mass Transf.* 55 (2012) 3713–3719, <https://doi.org/10.1016/j.ijheatmasstransfer.2012.03.003>.
- [21] A. Koşar, Y. Peles, Critical heat flux of R-123 in silicon-based microchannels, *J. Heat Transf.* 129 (2007) 844–851, <https://doi.org/10.1115/1.2712852>.
- [22] Y. Şişman, A.K. Sadaghiani, K.R. Khedir, M. Brozak, T. Karabacak, A. Koşar, Subcooled flow boiling over microstructured plates in rectangular minichannels, *Nanoscale Microscale Thermophys. Eng.* 20 (2016) 173–190, <https://doi.org/10.1080/15567265.2016.1248584>.
- [23] D. Liu, S.V. Garimella, Flow boiling heat transfer in microchannels, *J. Heat Transf.* 129 (2007) 1321–1332, <https://doi.org/10.1115/1.2754944>.
- [24] M. Shojaeian, A. Koşar, Pool boiling and flow boiling on micro- and nanostructured surfaces, *Exp. Therm. Fluid Sci.* 63 (2015) 45–73, <https://doi.org/10.1016/j.expthermflusci.2014.12.016>.
- [25] S.G. Kandlikar, Heat transfer mechanisms during flow boiling in microchannels, *J. Heat Transfer* 126 (2004) 8–16, <https://doi.org/10.1115/1.1643090>.
- [26] M. Ahmadi, S. Bigham, Gradient wick channels for enhanced flow boiling HTC and delayed CHF, *Int. J. Heat Mass Transf.* 167 (2021), <https://doi.org/10.1016/j.ijheatmasstransfer.2020.120764>.
- [27] V.E. Ahmadi, A. Aboubakri, A.K. Sadaghiani, K. Sefiane, A. Koşar, Effect of functional surfaces with gradient mixed wettability on flow boiling in a high aspect ratio microchannel, *Fluids* 5 (2020), <https://doi.org/10.3390/fluids5040239>.
- [28] A. Aboubakri, V.E. Ahmadi, S. Celik, A.K. Sadaghiani, K. Sefiane, A. Koşar, Effect of surface biphilicity on FC-72 flow boiling in a rectangular minichannel, *Front. Mech. Eng.* 7 (2021), <https://doi.org/10.3389/fmech.2021.755580>.
- [29] N.V. Upot, A. Mahvi, K. Fazle Rabbi, J. Li, A.M. Jacobi, N. Miljkovic, Scalable and resilient etched metallic micro- and nanostructured surfaces for enhanced flow boiling, *ACS Appl. Nano Mater.* 4 (2021) 6648–6658, <https://doi.org/10.1021/acsnanm.1c00524>.
- [30] M.S. Sarwar, Y.H. Jeong, S.H. Chang, Subcooled flow boiling CHF enhancement with porous surface coatings, *Int. J. Heat Mass Transf.* 50 (2007) 3649–3657, <https://doi.org/10.1016/j.ijheatmasstransfer.2006.09.011>.
- [31] K.K. Wong, K.C. Leong, Nucleate flow boiling enhancement on engineered three-dimensional porous metallic structures in FC-72, *Appl. Therm. Eng.* 159 (2019), <https://doi.org/10.1016/j.applthermaleng.2019.113846>.
- [32] Y. Lin, J. Li, J. Sun, W. Li, Y. Cao, Onset of boiling, heat transfer, and flow patterns of flow boiling on the superhydrophobic porous copper surface in a microchannel, *J. Heat Transfer* 143 (2021), <https://doi.org/10.1115/1.4051324>.
- [33] J. Li, Y. Lin, K. Zhou, W. Li, Subcooled flow boiling on micro-porous structured copper surface in a vertical mini-gap channel, *J. Therm. Sci. Eng. Appl.* 12 (2020), <https://doi.org/10.1115/1.4048372>.
- [34] J.M. Kim, S.C. Park, B.T. Kong, H.B.R. Lee, H.S. Ahn, Effect of porous graphene networks and micropillar arrays on boiling heat transfer performance, *Exp. Therm. Fluid Sci.* 93 (2018) 153–164, <https://doi.org/10.1016/j.expthermflusci.2017.12.029>.
- [35] A.K. Sadaghiani, A.R. Motezakker, S. Kasap, I.I. Kaya, A. Koşar, Foamlike 3D graphene coatings for cooling systems involving phase change, *ACS Omega* 3 (2018) 2804–2811, <https://doi.org/10.1021/acsomega.7b02040>.
- [36] G. Di Sia, M.K. Tan, G.M. Chen, Y.M. Hung, Performance enhancement of subcooled flow boiling on graphene nanostructured surfaces with tunable wettability, *Case Stud. Therm. Eng.* 27 (2021), <https://doi.org/10.1016/j.csite.2021.101283>.
- [37] A.S. Kousalya, A. Kumar, R. Paul, D. Zemlyanov, T.S. Fisher, Graphene: an effective oxidation barrier coating for liquid and two-phase cooling systems, *Corros. Sci.* 69 (2013) 5–10, <https://doi.org/10.1016/j.corsci.2012.12.014>.
- [38] A. Jaikumar, A. Rishi, A. Gupta, S.G. Kandlikar, Microscale morphology effects of copper-graphene oxide coatings on pool boiling characteristics, *J. Heat Transfer* 139 (2017), <https://doi.org/10.1115/1.4036695>.
- [39] V.E. Ahmadi, M.H. Khaksaran, A.M. Apak, A. Apak, M. Parlak, U. Tastan, I.I. Kaya, A.K. Sadaghiani, A. Koşar, Graphene-coated sintered porous copper surfaces for boiling heat transfer enhancement, *Carbon Trends* 8 (2022), <https://doi.org/10.1016/j.cartre.2022.100171>.
- [40] V.E. Ahmadi, T. Guler, S. Amin, A.M. Apak, A. Apak, M. Parlak, U. Tastan, I.I. Kaya, A. Sadaghiani, A. Koşar, Effect of graphene coating on flow boiling in a minichannel at sub-atmospheric pressures, *Int. J. Heat Mass Transf.* 229 (2024) 125762, <https://doi.org/10.1016/j.ijheatmasstransfer.2024.125762>.
- [41] X. Li, W. Cai, J. An, S. Kim, J. Nah, D. Yang, R. Piner, A. Velamakanni, I. Jung, E. Tutuc, S.K. Banerjee, L. Colombo, R.S. Ruoff, Large-area synthesis of high-quality and uniform graphene films on copper foils, *Science* 324 (1979) 1312–1314, <https://doi.org/10.1126/science.1171245>, 2009.
- [42] H.W. Coleman, W.G. Steele, *Experimentation, validation, and Uncertainty Analysis For Engineers*, John Wiley & Sons, 2018.
- [43] R.K. Shah, A.L. London, *Laminar Flow Forced Convection in Ducts: A Source Book for Compact Heat Exchanger Analytical Data*, Academic press., New Jersey, 2014.
- [44] S.M. Kim, I. Mudawar, Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – Part I. Dryout incipience quality, *Int. J. Heat Mass Transf.* 64 (2013) 1226–1238, <https://doi.org/10.1016/j.ijheatmasstransfer.2013.04.016>.