CHAPTER 4
Experimental setup & procedure

An experimental setup has been developed to carry out pool boiling experiments on nano-textured surfaces. In this chapter, an effort has been made to describe details of the experimental setup, procedure, uncertainty analysis, and validation of experimental setup.

4.1. Description of pool boiling apparatus

To perform the pool boiling experiments, an experimental facility has been developed in the laboratory to perform the pool boiling experiments. The schematic diagram of the experimental setup is shown in Fig. 4.1. The pool boiling setup primarily consists of a boiling chamber, a copper block test section, an auxiliary heater, a data acquisition system (NI PXIe-1071), two voltage variacs (Dimmerstat), a condenser unit, and a supporting stand. The boiling chamber is made of aluminium sheet, having dimensions of 220 x 220 x 210 mm, which has approximately 10 litre of capacity. To visualize the boiling phenomenon, two glass windows (120 x 120 mm) have been fitted to the wall of the boiling chamber facing each other. One window is used for eye/camera visualization, while the other is used to provide adequate light through it. A valve is fitted near the bottom of the boiling chamber to drain out the liquid as per the requirement. The boiling chamber has a circular hole of 70 mm at the centre of the bottom face, through which the upper portion of the heating block is exposed to the chamber's liquid. A silicon gasket is used to make the leak-proof joint between the copper heating block and the boiling chamber. Since test samples need to be replaced by other samples to conduct experiments on different surfaces. Therefore, test samples are fixed on the copper heating block (Top surface) with the help of a soft solder (alloy of lead and tin in the ratio of 60:40).

The soft solder (k = 50 W/m-K) provides the least thermal resistance between the heating block and test sample due to better contact and relatively higher thermal conductivity. Test samples are held in a sample holder with a screw and O-ring arrangement. The sample holder is made of PTFE Teflon formed into a disc shape (Fig. 4.2) with an external diameter of 80 mm and a thickness of 6 mm.

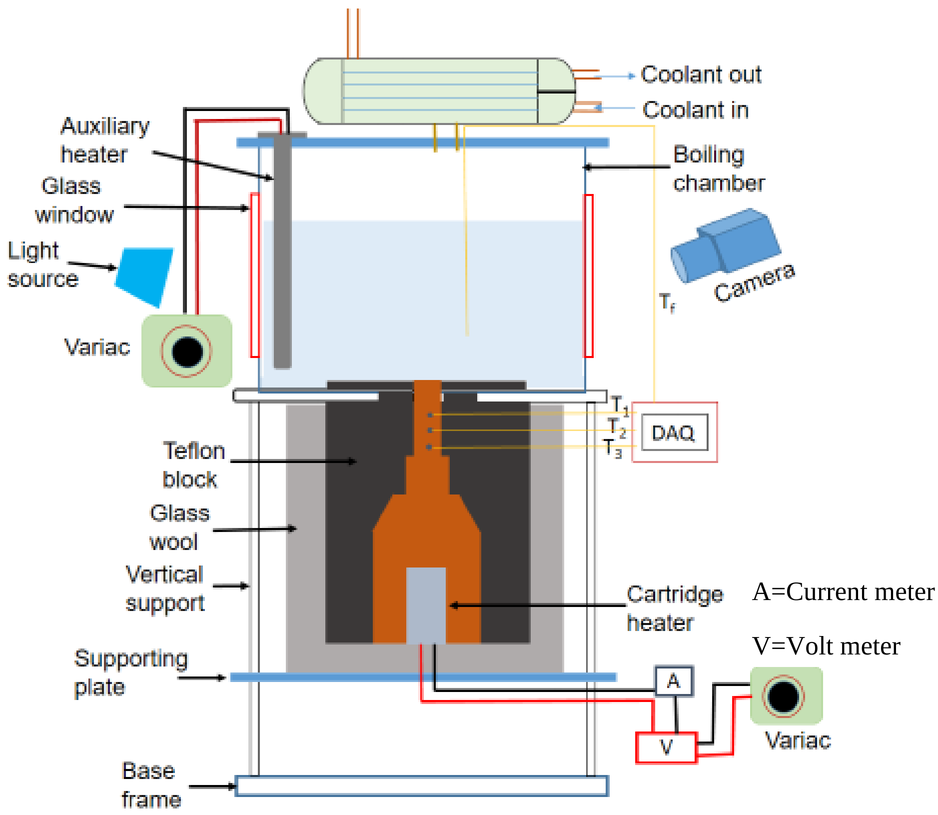

Fig. 4.1. Schematic diagram of pool boiling experimental setup (not to scale).

The schematic diagram of the copper heating block with sample holder arrangement is shown in Fig.4.3. To generate heat, a cylindrical cartridge heater with a power rating of 600 W/230V is tight-fitted inside the copper block from the bottom end and supported by a ceramic block with a thickness of 50 mm.

Fig. 4.2. Sample holder made of PTFE Teflon (pictorial view).

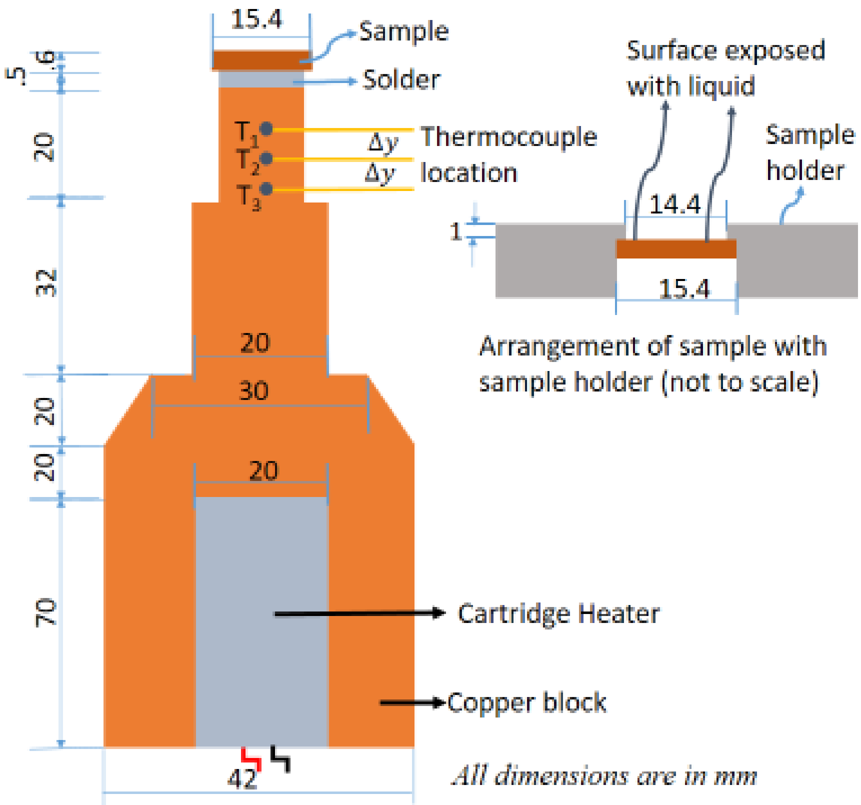

Fig. 4.3. Schematic diagram of copper heating block with cartridge heater and sample holder arrangement.

Fig. 4.4. Image of cartridge heater.

Fig. 4.5. Image of K-type thermocouple (wire diameter 0.3 mm).

The copper block was converted into a desired shape (Fig 4.3) from a uniform cylindrical rod of diameter 42 mm and length 175 mm. Bottom portion of the copper block has a diameter of 42 mm, and it was reduced to 14.4 mm at the top in various steps. The heating block arrangement is placed vertically on a supporting plate. It has two layers of insulation to minimize heat losses in the radial direction. The first layer of insulation (adjacent to the heater) was provided using PTFE Teflon of thickness 50 mm, whereas the second layer of insulation was provided using ceramic wool of thickness 100 mm. In order to calculate the heat flux, temperatures at three different locations in the copper heating block were measured with the help of K-type thermocouples. Thermocouples were inserted at the centre of the copper heating block and connected to a NI data logger. A pictorial view of K-type thermocouple is shown in Fig. 4.5. The location of thermocouple T_1 is 8 mm below the top surface, T_2 is 5 mm from T_1, and T_3 is 5 mm below T_2 as indicated in Fig. 4.3.

The temperatures T_1, T_2, T_3, and liquid temperature (T_f) were measured with the help of a data acquisition system (National Instrument PXIe-1071, Fig 4.6) and temperature module (NI TB-4353). A 1-D model has been created in lab view for monitoring and recording the temperature in real-time. The temperature distribution within the copper heating block at different heat fluxes is shown in Fig. 4.7.

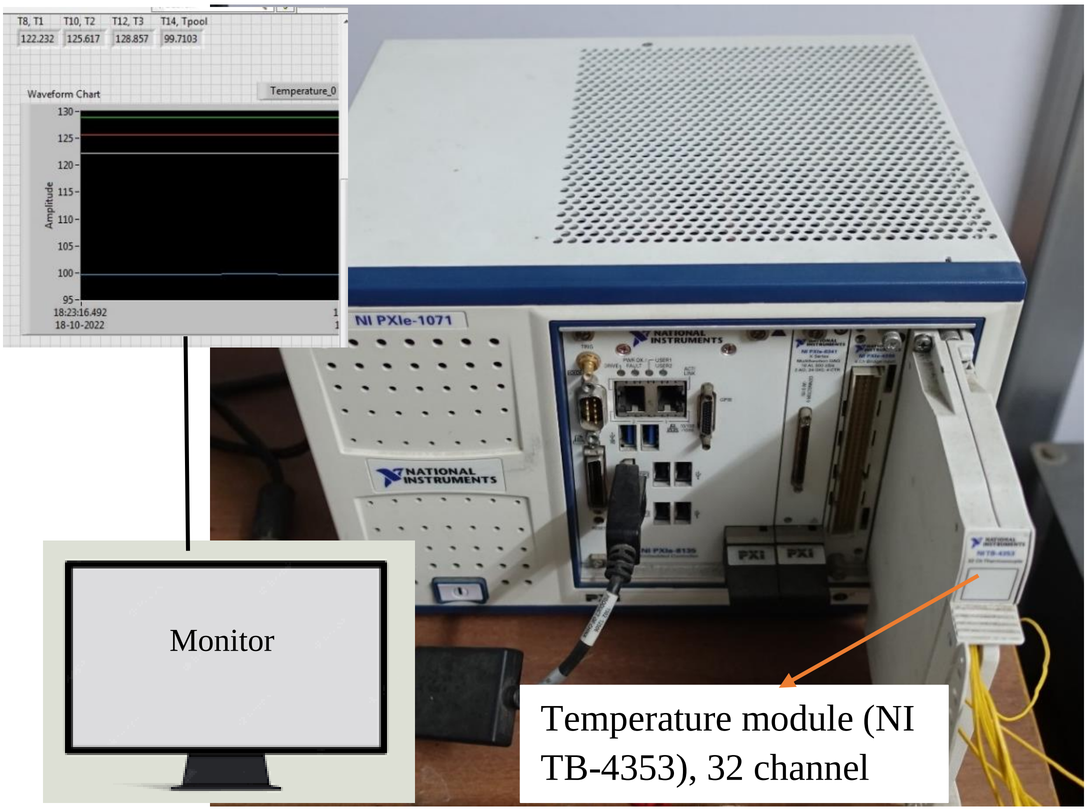

Fig. 4.6. Data acquisition system for temperature measurements (NI PXIe-1071).

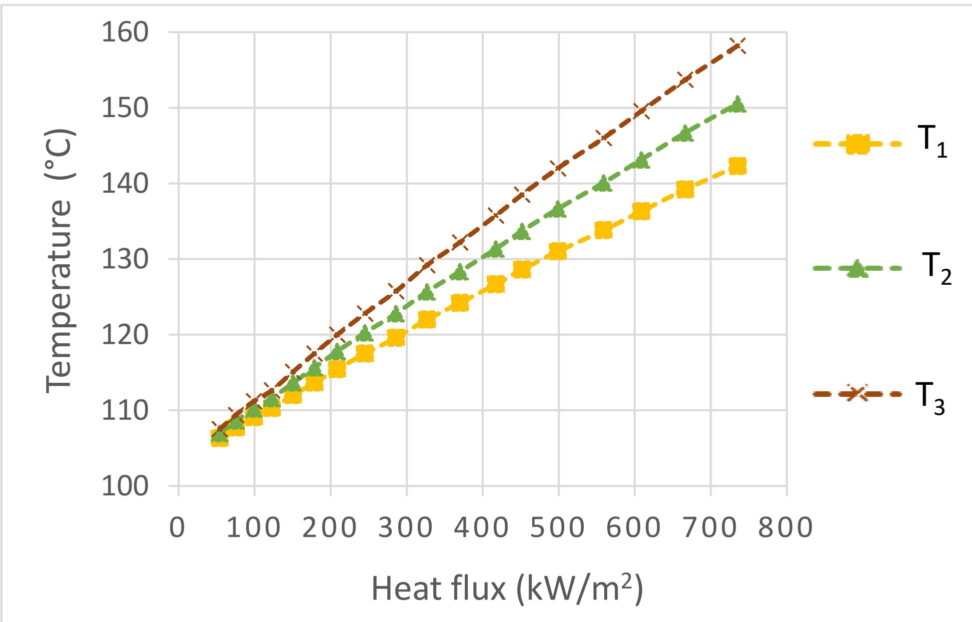

Fig. 4.7. Temperature distribution within copper heating block.

Two voltage variac has used to supply and control power to the auxiliary heater, and copper heating block. An auxiliary heater of 750 W /230 V (Fig. 4.8) was placed into the working fluid from the top cover of the test chamber, which is used to preheat and maintain the water at nearly saturation temperature with the help of an autotransformer.

Fig. 4.8. Pictorial view of an auxiliary heater (750W/230V).

A small condenser is installed horizontally at the top of the boiling chamber to condense the water vapour and return it to the chamber, ensuring that the water level remains constant throughout the experiment. The whole setup is kept on a stand, which has mainly four vertically threaded rods of 12 mm, base and top frame. The vertical rod is fixed to the base and top frames. To support the copper heating block, a 4 mm thick mild steel plate is used between the top frame and the base frame, which can slide up or down and be temporarily placed at a particular location with the vertical rod. Details specifications of various elements/devices are given in Table 4.1. A pictorial view of the developed pool boiling experimental facility is shown in Fig. 4.9.

4.2. Experimental procedure

Experiments were performed with Milli-Q water near the saturation temperature under atmospheric conditions. The boiling chamber was filled with water of a volume of about ¾ of its capacity. Before the actual experiment, water in the boiling chamber was boiled for one hour to degas the non-condensable gases present in the water.

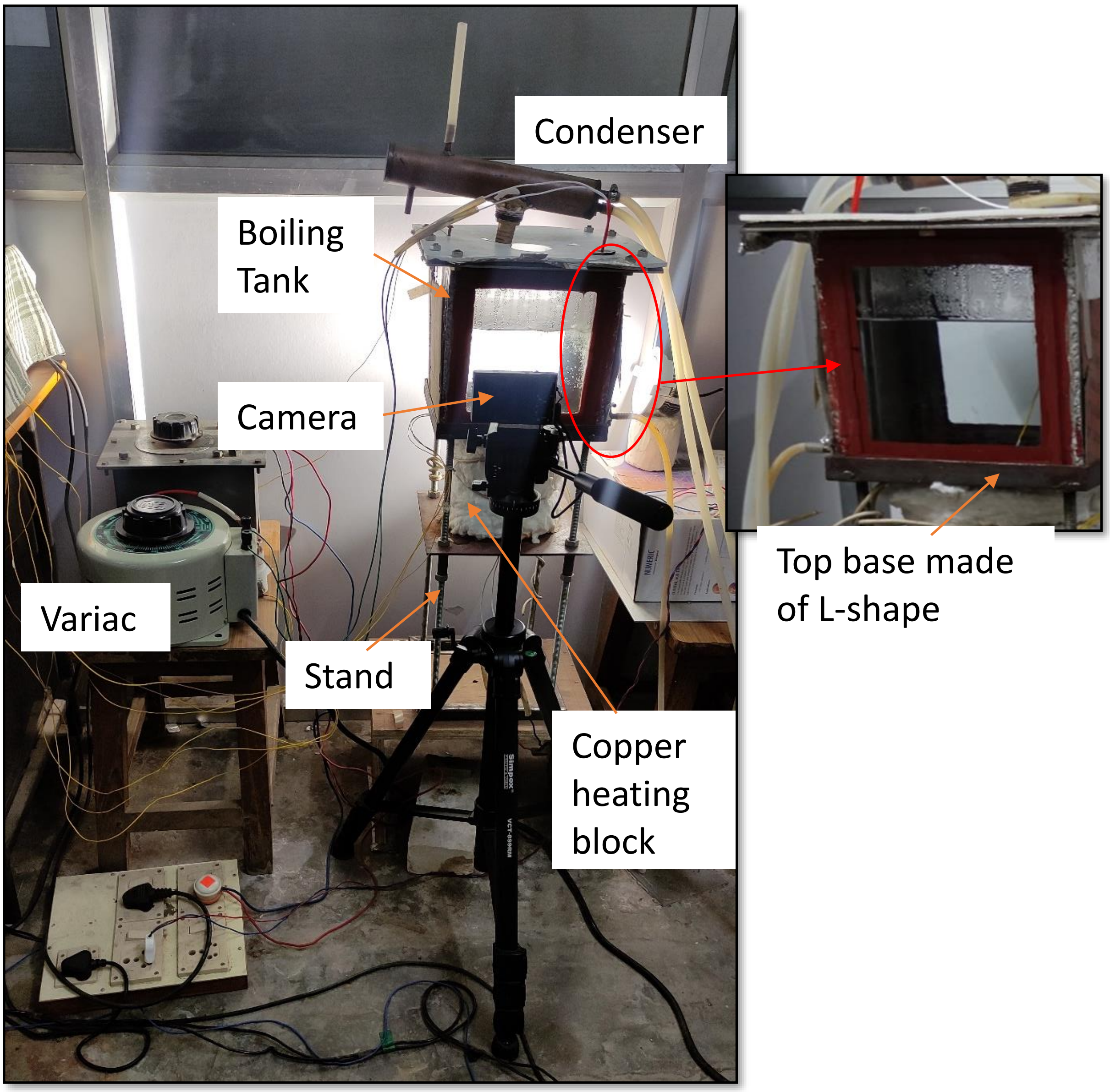

Fig. 4.9. Pool boiling test facility (Pictorial view)

Then copper heating block power supply is switch on to heat the sample. The temperature reading was only recorded, when heating block temperature reached to the nearly saturation temperature of water. In the existing setup the copper heating block temperature reaches to the nearly saturation temperature on and after 28 volt of power supply by voltage variac. Below the 28V of power supply copper heating block temperature (T_1) does not attaint the saturation temperature of the water, therefore wall superheat will be negative which is not in our interest.

Table 4.1. Specifications of various Devices/Elements of experimental setup

Sl. No.	Device/Element	Specifications
1	Auxiliary heater Type : Cartridge heater	Sheath material : SS316 Power : 750W @230V Length : 225mm, Diameter : 20mm Hot Zone (Bottom) : 100mm Cold Zone (Top) : 125mm
2	Copper block heating element Type : Cartridge heater	Sheath material : SS316 Power : 600W @230V Length : 70mm, Diameter : 20mm
3	Voltage Variac	Type : 15D-1P Max Load: 15A (4.05 kVA) Input : 240V, 50/60Hz Output : 0-270V
4	Data acquisition system (National Instruments)	Model : PXIe-1071 Input : 100-240V/AC Frequency : 50/60Hz Current : 4-2 A
5	Thermocouple	K-type Wire Diameter : 0.3mm Max. Temperature Sense : 600° C

After the power supply to the copper heating block, there is a waiting time to reach the steady state. Once a steady state was reached data was recorded for 2 minutes, and the average value was considered for further calculations. The system is assumed to be in a steady state when temperature variation within the copper heater falls within the range of ±0.2° C in the last 4 minutes [16, 119]. The input power has been increased by a step of 4 - 6 V. In each of such cases, data were recorded after the system reached a steady state. This procedure was repeated until the copper heating block temperature T_3 reached nearly 170° C. Each experiment was conducted three times to check the repeatability and found that results were quite repeatable with slight variation under the uncertainty limits. The present study focused on medium to high flux but below the CHF point. Therefore, in most of the experiments heat flux does not reach the CHF, so the cartridge heater can be protected from thermal burnout.

4.3. Calculation of Heat flux and other performance parameters

Heat flux supplied to the boiling surface is calculated using one-dimensional Fourier's law of heat conduction (Eq. 4.1) in the axial direction. To verify the one-dimensional heat conduction, the temperature profile in the region, where the actual temperature is being measured was plotted and shown in Fig. 4.10. From Fig. 4.10, it can be assumed that the heat loss in the radial direction is insignificant because temperature profile in the axial direction is nearly linear at different heat fluxes. Hence, one-dimensional Fourier's law of heat conduction (given as Eq. 4.1), can be applied to calculate the heat flux in the axial direction.

$$q'' = -k_{Cu}\frac{dT}{dy} \tag{4.1}$$

In above expression k_{Cu} is thermal conductivity of copper rod considered constant value 387 W/m-K at around 100° C, and $\frac{dT}{dy}$ is temperature gradient, calculated using the higher order backward difference scheme given by Eq. 4. 2.

$$\frac{dT}{dy} \approx \left(\frac{3T_1 - 4T_2 + T_3}{2\Delta y}\right) + O(h^2) \tag{4.2}$$

Where, T_1, T_2, and T_3 are measured temperatures at three different locations in the copper block, and the distance between adjacent thermocouples (Δy) is 5 mm.

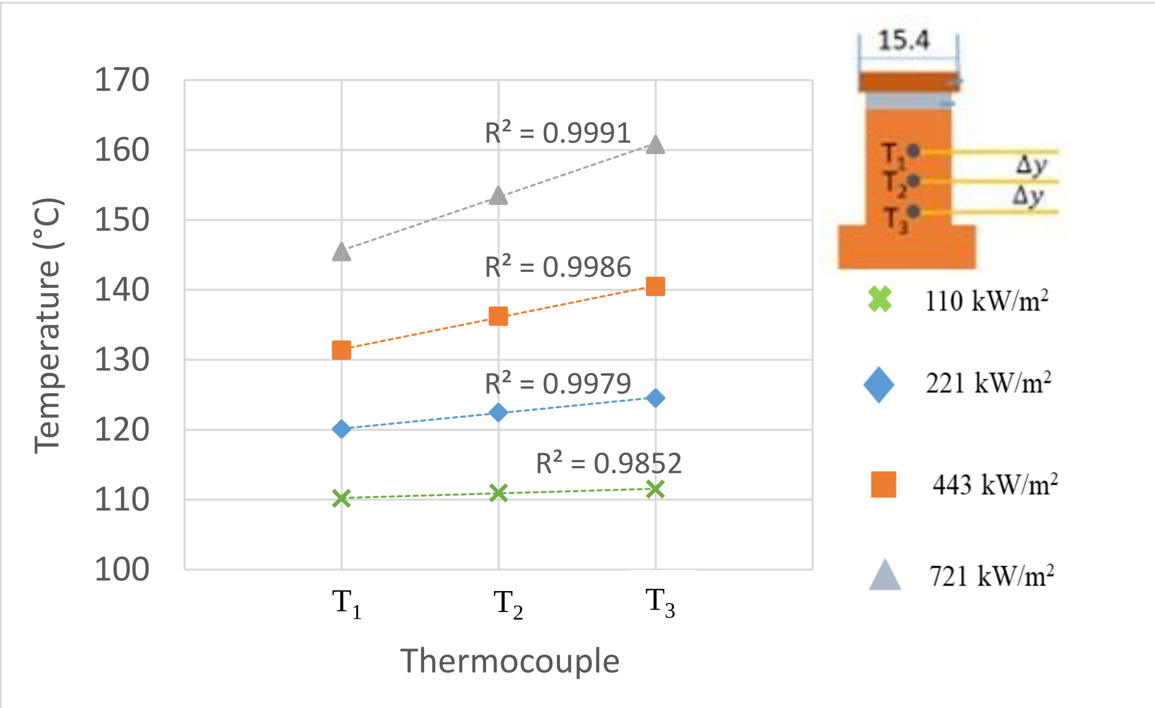

Fig. 4.10. Plot of temperature profile at different heat flux which are measured by thermocouple in copper heating block.

The wall temperature is evaluated as given in Eq. (4.3), the heat transfer coefficient (h), and wall superheat (ΔT) are evaluated as given in Eq. (4.3), Eq. (4.4), and Eq. (4.5), respectively.

$$T_w = T_1 - q^{"}\left(\frac{y}{k_{Cu}} + \frac{y_{solder}}{k_{solder}} + \frac{y_s}{k_s}\right) \tag{4.3}$$

$$h = \frac{q^{"}}{(T_w - T_f)} \tag{4.4}$$

$$\Delta T = T_w - T_{sat} \tag{4.5}$$

Where, y = 8 mm is the distance of thermocouple T_1 from the top surface of heating block, T_f =liquid temperature, y_{solder} = 0.5 mm, thickness of solder paste, and y_s= 0.6 mm, is the thickness of the sample.

4.4. Uncertainty analysis

Various instruments were used to measure the different parameters in the present experimental work. All these instruments have individual random errors of measurement, which are an unavoidable quantity in any experimental investigation [120]. The systematic errors of temperature measurements (thermocouples), distance between thermocouples, and length are given in Table 4.2.

Table 4.2. Uncertainty of measured parameters

Sl. No.	Measured parameters	Uncertainty
1	Temperature measurements (T_1, T_2, T_3, T_f,)	±0.2° C
2	Distance between thermocouple (Δy)	±0.5mm
3	Length (y)	±0.1mm
4	Contact angle (θ)	±2°

The uncertainties of other derived parameters such as heat flux, surface temperature, and heat transfer coefficient are estimated as explained in references [121, 122], which are presented below, and their respective values are listed in Table 4.3.

$$\frac{Uq''}{q''} = \left[\left(\frac{3UT_1 * k_{Cu}}{2\Delta y * q''}\right)^2 + \left(\frac{3UT_2 * k_{Cu}}{2\Delta y * q''}\right)^2 \left(\frac{UT_3 * k_{Cu}}{2\Delta y * q''}\right)^2 + \left(\frac{U\Delta y}{\Delta y}\right)^2\right]^{1/2} \tag{4.6}$$

$$UT_w = \left[(UT_1)^2 + \left(\frac{y_1}{k_{Cu}} Uq''\right)^2 + \left(\frac{q''}{k_{Cu}} Uy_1\right)^2\right]^{1/2} \tag{4.7}$$

$$U\Delta T = \left[(UT_w)^2 + (UT_f)^2\right]^{1/2} \tag{4.8}$$

$$\frac{Uh}{h} = \left[\left(\frac{UT_w}{T_w - T_f}\right)^2 + \left(\frac{UT_f}{T_w - T_f}\right)^2 + \left(\frac{Uq''}{q''}\right)^2\right]^{1/2} \tag{4.9}$$

Table 4.3. Estimated uncertainty of derived parameters

Derived parameters	**Symbols**	**Maximum Uncertainty**
Boiling surface temperature	T_W	0.50° C
Wall superheat	ΔT (T_W-T_{sat})	0.54° C
Heat flux	q''	10%
Heat transfer coefficient	h	11.04%

4. 5. Validation of experimental setup

Pool boiling experiments were initially performed on a polished copper surface (bare surface) in Milli-Q water at saturation conditions. The data obtained from experiments are plotted and compared with the most widely used Rohsenow's model [33] and experimental data reported by Das et al. [36] for polished surfaces, as shown in Fig. 4.11. Rohsenow's model depends on the fluid properties and a liquid-surface interaction coefficient (C_{sf}). The values of C_{sf} for pure water and polished copper surfaces given by various researchers fall in the range of 0.0085–0.016.

In the present study, C_{sf} value considered is 0.0152, which is also suggested by Z. Wu et al. [121], under similar conditions. From Fig. 4.11, we can say that the present experimental data shows a similar trend to the experimental value reported by Das et al. [123], and to the data obtained from Rohsenow's model [33]. The deviation in present experimental data and Das et al. [123] data may appears due to variations in sample and their surface finish condition.

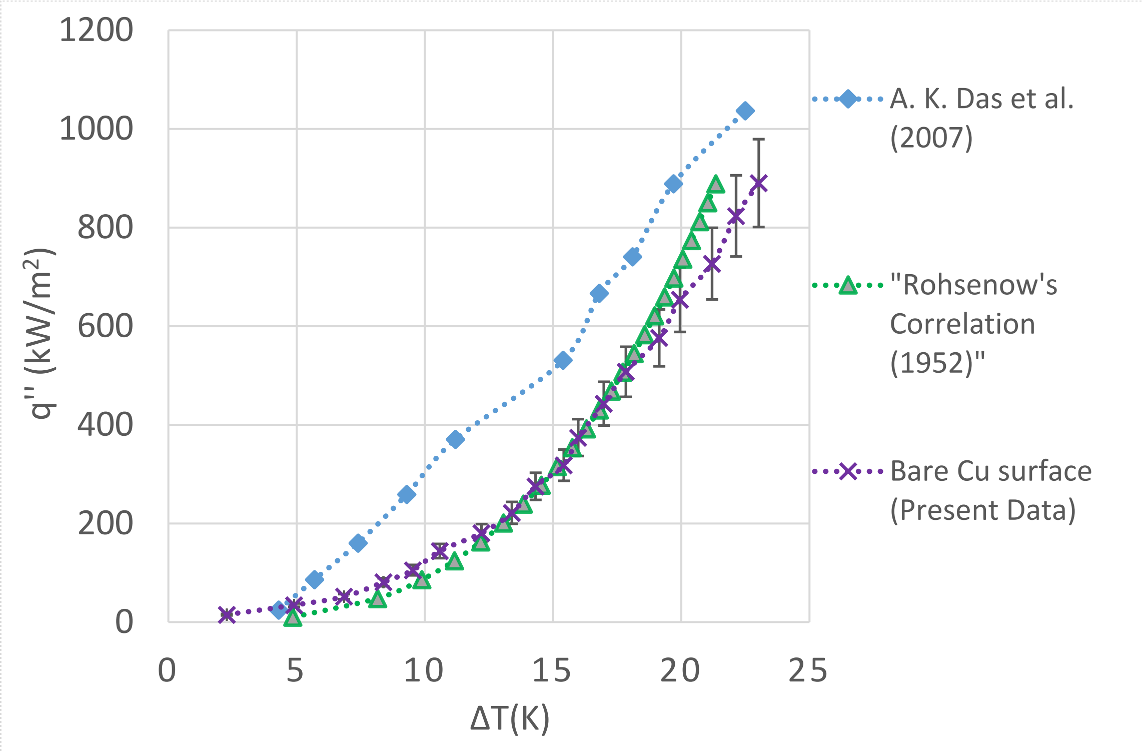

Fig. 4.11. Comparison of pool boiling data of bare surface with Rohsenow's model (1952) and experimental data [Das et al. (2007)].

A good agreement of present experimental results on polished copper (bare) surface with Rohsenow's model indicates that the developed test facility can be used for further experiments on micro/nano-textured surfaces.

4.6. Summary

This chapter described the explanation of experimental setup employed in the pool boiling study. It also described the experimental condition, experimental procedure and data analysis method. Pool boiling experiments with demineralized water on bare surface compared with Rohsenow's correlation (1952) and literature data. Further experimental uncertainty associated with measured quantity and derived quantity has discussed.

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