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Investigation of R123 Pool Boiling Performance of Anodic Aluminum Oxide Membrane based Nano Porous Heater Assembly

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1. Introduction

As technology advanced with reducing system scale, the required heat removal capability per unit volume or area increased. The boiling heat transfer has been applied to the high energy density industries including nuclear power plants, high-performance electronics cooling, water desalination, refrigeration [1]. The upper limit and efficiency of the boiling heat transfer rate are closely related to the system's safety and economics. Therefore, an investigation of boiling heat transfer enhancement has been conducted for decades by various researchers.

Conventionally, boiling heat transfer performance is measured by a two-parameter called critical heat flux (CHF) and heat transfer coefficient (HTC). The CHF is the upper limit of the heat transfer rate of boiling heat transfer and characterized by burn-out heating surface or loss of system integrity due to the formation of an insulating vapor blanket. The HTC is defined as a ratio between applied heat flux level and corresponding wall superheat of the system and represents the efficiency of boiling heat transfer. The boiling heat transfer research had been focused on the enhancement of both CHF and HTC for increased system safety margin and economics.

As an advancement of surface technology, micro/nanoscale surface modification got a lot of attention in the boiling heat transfer research field [2]-[5]. The surface wettability change and formation of micro/nano porous structure via surface modification show enhanced boiling heat transfer performance. Increased surface wettability facilitates the liquid rewetting process during the bubble ebullition cycle and shows enhanced CHF performance. The micro/nano porous surface shows enhanced CHF and HTC via additional capillary-induced liquid flow and increased nucleation site density.

Despite the active boiling research works with various micro/nanoscale modified surfaces, boiling heat transfer research with nano-porous membrane surfaces is remains the initial stage. The novel concept of boiling configuration called thin-film boiling was proposed by Wang and Chen [6]. The thin film boiling utilizes the nano porous anodic aluminum oxide (AAO) membrane as the heater material. The liquid transported through the submicron scale pores via pressure difference and form the liquid puddles on the AAO membrane surfaces. The boiling takes place inside the thin liquid puddles and shows unprecedently high CHF enhancement (~12,000 kW/m2). However, the exact mechanism of the thin film boiling enhancement mechanism on nano porous membrane is still ambiguous. A precise analysis of thin-film boiling mechanism analysis with a high-resolution visualization technique is needed.

The current study covers the fabrication of nano porous membrane heater and performance validation of the as-fabricated nano porous heater under R-123 refrigerant pool boiling conditions. The fabricated nano porous heater assembly will be utilized for the thin-film boiling visualization study.

2. Experimental Setup

2.1 Nano Porous Heater Fabrication

The ~60 μm thick commercial anodic aluminum oxide (AAO) membrane with a nominal pore size of ~200 nm was selected as the base substrate for the nano porous heater assembly in the current study.

The ~50 nm thick platinum (Pt) layer was sputtered on AAO membrane with the DC-sputtering method. The sputtered Pt layer served as both the heating element and resistance-temperature detector. The ~200 nm thick gold (Au) layer was sputtered on the Pt layer to serve as a contact pad for the electric connection. The ~10 nm thick chrome layer was sputtered between AAO/Pt and Pt/Au layer as adhesive. The active heating area of fabricated AAO membrane based nano porous heater is 7.1 mm x 7.1mm. The schematics of nano porous heater assembly can be found in fig. 1.

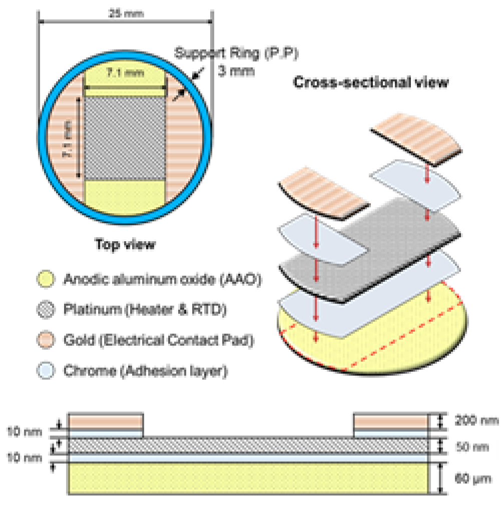

Fig. 1. Schematics of AAO membrane based nano porous heater assembly in current study.

2.2 Pool Boiling Experimental Facility

The pool boiling experiment with the fabricated AAO membrane-based nano porous heater assembly was performed to check the validity of the fabricated nano porous heater assembly for the boiling heat transfer application. The R-123 refrigerant was selected as a working fluid in the current study due to the low boiling point. The long-term exposure of the AAO membrane to the high temperature (> 100 ºC) environment causes internal structure degradation [7]. The boiling point of the R-123 at atmospheric conditions is 27.6 ºC.

The fabricated AAO membrane-based heater assembly was attached to the PEEK holder with heat-resistant silicon adhesive. The ~1mm thick Sn foil was utilized to make an electrical connection between the power supply module and nano porous heater assembly. The Sn foil was physically pressed against the Au contact pad with a custom-made PEEK clamp with a set screw. The rubber gasket was placed between the PEEK clamp and Sn foil to minimize the thermally induced stress during the experiment. The schematics of the test section is depicted are Fig. 2.

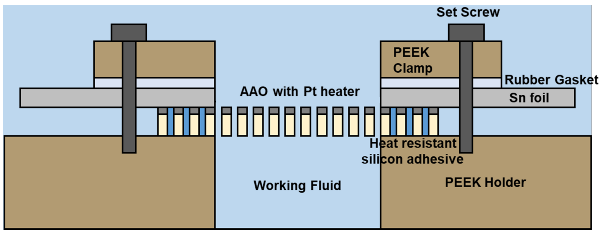

Fig. 2. Schematics of R123 pool boiling experiment test section with AAO membrane based nano porous heater.

The pool boiling experiment setup can be found in Fig. 3. The saturated R-123 pool boiling experiment was conducted at atmospheric conditions. The R-123 working fluid inside the pool was kept as a saturated state with aid of a hot plate. The working fluid level was kept constant during the experiment due to the coil condenser. The direct Joule heating method was utilized to manipulate the heat flux level during the experiment.

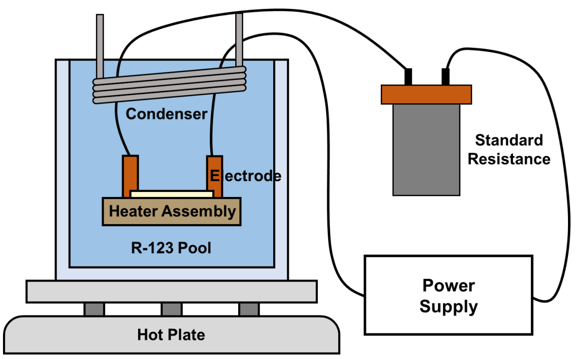

Fig. 3. Schematics of R-123 pool boiling experimental apparatus setup.

3. Results and Discussion

3.1 Resistance Temperature Detector Calibration

The resistance-temperature detector performance of the fabricated Pt deposited AAO membrane base nano porous heater was analyzed. The temperature of the Pt deposited layer can be calculated by Eqn. (1). Where T is the temperature of the nano porous heater assembly surface, T0 is baseline temperature, α is temperature coefficient of resistance, R is the resistance value of the sputtered Pt layer at T, and R0 is baseline resistance value at T0. The calibrated resistance-temperature detector performance fabricated Pt sputtered nano porous heater assembly is depicted in Fig. 4.

$$T = T_0 + \frac{1}{\alpha}\left(\frac{R}{R_0} - 1\right) \quad (1)$$

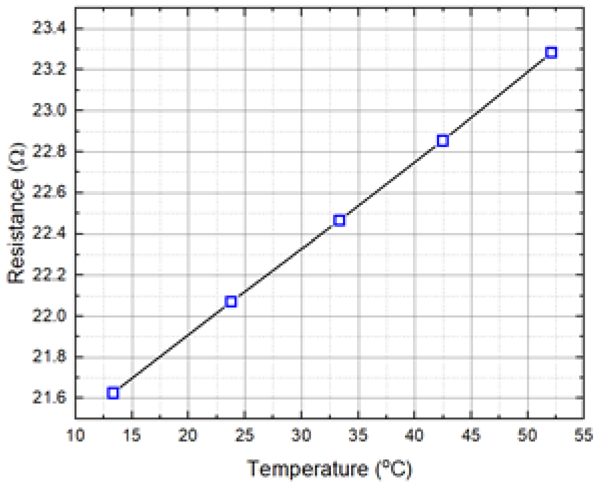

Fig. 4. RTD calibration results of 50 nm thick Pt heater on fabricated AAO membrane.

The fabricated Pt sputtered nano porous heater assembly shows good lineability between temperature and resistance value. The temperature coefficient of resistance (α) is 0.001974. The wall superheat of the current R-123 pool boiling experiment was calculated with Eqn. (1) with the measured temperature coefficient of the resistance value.

3.2 R-123 Pool Boiling Experiment

The saturated R-123 pool boiling under atmospheric conditions was conducted to validate the performance of the fabricated Pt sputtered AAO membrane-based nano porous heater assembly for the boiling heat transfer application. The boiling curve data and the corresponding visualization results are depicted in Fig. 5. The measured critical heat flux (CHF) value of the fabricated nano porous heater assembly was ~251.3

kW/m2 and shows a 16% deviation with the Zuber CHF prediction model (~216.02 kW/m2) [8].

As shown in Fig. 5, the all the possible pool boiling regime was observed during the experiment. At the low heat flux regime (a), the natural convection is the dominant heat removal mode. When the applied heat flux increased up to ~25.2 kW/m^2 (b) onset of nucleate boiling was initiated and characterized by nucleation of small vapor bubbles and sharp increase of slope of boiling curve. As the applied heat flux increase (c), the nucleated bubbles start to coalescence. At CHF point (~ 251.3 kW/m^2, d), the nano porous heater surfaces are patially covered with insulating vapor blanket and wall temperature increase rapidly.

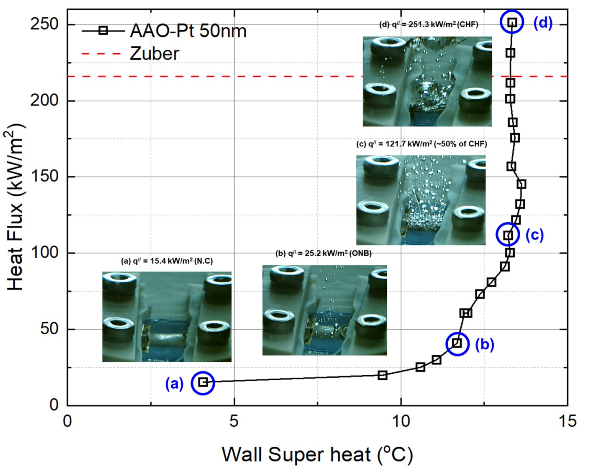

Fig. 5. R123 pool boiling curve of Pt deposited AAO membrane based nano porous heater assembly.

4. Summary and Future Work

As a preliminary study for the thin film boiling visualization experiment, fabrication of AAO membrane-based nano porous heater assembly and the pool boiling performance of the fabricated nano porous heater assembly was evaluated.

The resistance-temperature detector performance of fabricated Pt sputtered nano porous heater assembly shows good lineability with the temperature coefficient of resistance of 0.001974. The wall temperature of the Pt sputtered heater surface was successfully detected during the pool boiling experiment.

The saturated R-123 pool boiling experiment results validate the applicability of the current AAO membrane-based nano porous heater assembly for the boiling heat transfer application.

The thin film boiling visualization experiment with the high-resolution visualization technique will be conducted in near future with fabricated AAO membrane based nano porous heater. The experimental facility of thin film boiling facility was made and described in Fig. 6. The purpose of the visualization experiment is to elucidate the unprecedented high CHF enhancement mechanism of the thin-film boiling regime.

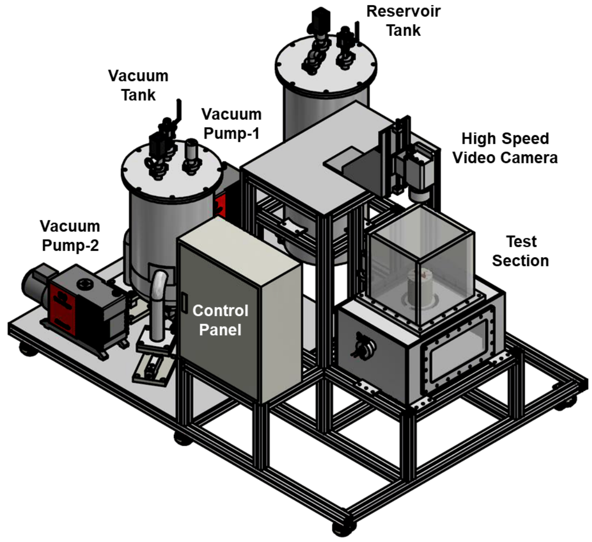

Fig. 6. Thin film boiling experimental faciltiy.

Acknowledgement

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