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Pool boiling heat transfer enhancement with segmented finned microchannels structured surface

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ABSTRACT

An experimental investigation has been carried out to investigate pool boiling heat transfer characteristics of segmented finned (SF) microchannels structured surface and compare its performance with that of uniform cross-section (UCS) microchannels structured surface and plane surface. All three surfaces have been fabricated on individual copper block with a foot print area of $10 \times 10\ mm^2$. Pool boiling experiments have been performed with these surfaces in atmospheric pressure condition using deionized water. Experiments have been performed for applied effective heat flux range of 0–200 W/cm^2. Both the structured surfaces show better heat transfer performance compared to plane surface. It has been observed that SF structured surface shows a heat transfer improvement up to a factor of 3 times the heat transfer coefficient in plane surface whereas uniform UCS structured surface shows the improvement by a factor of 2 times the heat transfer coefficient in plane surface. Thus segmented finned microchannels structured configuration shows better heat transfer performance compared to other two surfaces. The reason behind the heat transfer improvement in SF configuration might be due to more number of active nucleation sites, better rewetting phenomenon and favorable bubble growth and release mechanism.

1. Introduction

Due to simplicity and passive operation, pool boiling is used as an effective means of heat transfer in several applications such as nuclear reactor, electronic cooling, steam power plant, and process industries. Among different parameters, characteristics of heating surface largely affect the heat transfer rate in pool boiling. Surface morphology controls the nucleation site and wetting behavior which essentially control the heat transfer mechanism in pool boiling [1–3]. During last several decades extensive research works have been undertaken for exploring different techniques of surface modification for enhancing pool boiling heat transfer rate. Broadly these techniques can be classified into four main categories: surface area enhancement, surface roughness, surface wettability and separate liquid-vapor pathway [3–18].

In surface area enhancement technique plain heated surface is modified to increase the heat transfer area. Kandlikar and his group [3,4] performed pool boiling experiments by modifying the heated surface into a structured microchannels surface which enhanced the heat transfer area. They observed that in microchannels structured surface, bubbles nucleate from the bottom of the channel, slide along the wall of the channel and then grow at the top of the channels to the required size followed by departure from the top wall. Since the bubbles grow at the top of the channel, therefore most parts of the surface remain flooded with the working fluid, which is the main reason for the enhancement of critical heat flux (CHF) and heat transfer coefficient. Bubble dynamics plays an important role in heat transfer enhancement of pool boiling with structured microchannels, similar to its role in flow boiling in diverging channels and channels with pin fin [19,20]. Umesh and Raja [5] introduced square shaped fins in plain surface for heat transfer enhancement in pool boiling.

Heat transfer enhancement in pool boiling has also been reported by increasing number of nucleation sites, roughening the heating surface or by incorporating porous coatings. Creation of artificial nucleation sites decreases the temperature required for onset of nucleate boiling, which helps in generating large amount of vapor bubbles. Due to generation of large amount of vapor bubbles, the bubble departure time decreases and ultimately results in heat transfer enhancement. Benjamin and Balakrishna [6] investigated the effect of surface roughness on different materials and boiling liquids. They observed that nucleation site density depends on surface roughness, wall superheat, thermo-physical properties of the liquid. Porous coatings have also been used for enhancing heat transfer by increasing nucleation sites. Patil and

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Nomenclature

q''	heat flux (W/cm^2)
T	temperature (°C)
g	gravitational constant (m/s^2)
k	thermal conductivity (W/mK).
h	heat transfer coefficient (w/m^{2}K)
W	width of microchannels (mm)
D_h	hydraulic diameter (mm)
I	applied current (A)
V	voltage

Greek symbols

T_w	wall temperature (°C)
T_s	saturation temperature (°C)
ΔX	distance between thermocouples (mm)
δ	uncertainty

Subscripts

eff	effective
in	input
cu	copper

Kandlikar [7] used porous coatings in pool boiling experiment for increasing the nucleation sites. They found that porous coatings facilitate liquid flow through capillary pores which contribute significant increase in heat transfer performance.

Surface wettability plays a major role in bubbles formation and their release mechanism in pool boiling. During last several years several research works have reported the modification of surface wettability by applying hydrophilic, hydrophobic or nanowires coatings on the surface. Wu et al. [8] experimentally investigated nucleate boiling and CHF of water and FC-72 on hydrophilic coating of TiO_2 on the heating surface. The TiO_2 coated surface had high affinity towards water and the surface remained flooded with the liquid. They observed 50.4% and 38.2% increase in CHF for water and FC-72 respectively. Similar experiment and observation was reported by Takata et al. [9]. Several works [10–12] have reported the combined effect of hydrophilic and hydrophobic surfaces on nucleate boiling. Zupančič et al. [12] performed pool boiling experiment with a mixed patterned surface having micron size hydrophobic patches on a hydrophilic surface. They observed significant increase in heat transfer coefficient. Incorporation of nanowires at proper thermal conditions changes both topological and chemical properties of the surface due to oxidation of chemicals on the surface which affects the wettability of the surface. Yao et al. [13,14] fabricated nanowires in heating surface by etching process which showed better heat transfer performance due to enhancement in surface wettability. Presence of nanowires in microchannels increased the overall heat transfer coefficient. The combination of nanowires and structured microchannel in pool boiling surface increases the surface wettability rendering the surface more hydrophilic, thus improving its CHF limit as compared to structured microchannels surface without nanowires. Inclusion of micro/nano structures in a heating surface increases both heat transfer coefficient and CHF limit due to (i) high surface roughness (ii) low thermal resistance because of thin layers of coating. The heating surface also experiences low thermal stress as it doesn't allow the heat to be accumulated on the surface. As soon as the heat is generated it gets removed from the surface, due to which the temperature difference between the surface and surroundings is very less resulting in low thermal stress, and better durability [15–17].

During pool boiling, uninterrupted liquid supply and removal of vapor bubbles from the nucleating region facilitate heat transfer mechanism and increase the CHF. Jaikumar and Kandlikar [18] modified a heating surface by incorporating separate channels for nucleating bubbles and separate feeder channels for liquid supply. They observed significant increase in heat transfer coefficient and CHF limit. The advantage of such surface is that continuous liquid supply to nucleate sites is possible which enhances the heat transfer performance.

Enhanced surface area for heat transfer, uninterrupted liquid supply to nucleate cites and favorable bubble departure mechanisms are key factors for enhancement of heat transfer coefficient and critical heat flux in pool boiling.

In present work a new configuration of microchannels structured surface is introduced in pool boiling to enhance heat transfer area and also to facilitate rewetting of heating surface. The heating surface is modified to a segmented finned microchannels structured surface. In this configuration both primary and secondary channels are fabricated on the heating surface to facilitate the coolant liquid supply to nucleating sites. Our group has already extensively investigated the performance of segmented finned microchannels in flow boiling and observed the better performance compared to uniform and diverging microchannels [21–24]. The objective of the present work is to investigate the performance of segmented finned microchannels structured surface in pool boiling heat transfer. The performance of segmented finned microchannel structured (SF) surface has been compared with the uniform cross-section microchannels structured (UCS) and plain surface. Further present results have been compared with the available experimental results of pool boiling with structured surfaces.

2. Experimental setup

2.1. Components of the experimental setup

An experimental setup has been developed for performing pool boiling experiment. The schematic view of the experimental setup has been shown in Fig. 1. Main components of the setup are: boiling vessel, test module, thermocouples, AC power source, high speed camera and high speed data acquisition system. A cylindrical vessel made of borosilicate glass with diameter 150 mm and height 300 mm has been used to store liquid pool. Pool boiling experiment was performed with deionized water. The test module housing the heating surface has been fitted into the boiling vessel from the bottom side and heating surface was kept in horizontal position during experimentation. The boiling chamber was covered by a lid with a small hole at the center of the lid. Thus the chamber is partially open to the ambient for vapor venting. Similar types of chamber for pool boiling experiments have been reported in the literature [14,25].

A silicone rubber band heater of 600 W was used as an auxiliary heater to maintain the saturation temperature of water in the reservoir. Temperature of heating surface and water were measured using five numbers of K- type thermocouples. Three thermocouples T_1 T_2 and T_3 have been used to measure heating surface temperature whereas two thermocouples T_4 and T_5 have been used