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A review on nucleate boiling enhancement

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ABSTRACT

In modern engine design, to reach a more compact and optimized cooling system, exploiting nucleate boiling in thermally critical regions is required. Several studies have attempted to enhance the nucleate boiling heat transfer. This paper reviews the most important issues (i.e. surface roughness, composition of the liquid, electric field, vibration, orientation of the heated surface, surfactant addition, pressure and velocity) and their effects on nucleate boiling heat transfer.

Introduction

Heat transfer plays an important role in the conceptual and detail design of reciprocating engines and has considerable influence over their operational performance and durability. During the engine performance, the walls are subjected to thermal loading in addition to the mechanical stresses. Normally the most important thermally critical regions of the engine such as the valves bridge are of major importance. The common approach to reduce wall temperature is high flow velocities in area of high heat flux and using higher rates of convective heat transfer.

An alternative to this philosophy is to exploit the large increases in heat transfer coefficient that are possible when controlled nucleate boiling begins to occur, but the progression to transition and even film boiling needs to be carefully avoided. Boiling based cooling systems were first described by Harison in 1926. Nucleate boiling has the advantages of (i) it requires less cooling pump power and (ii) it removes a lot of more heat from hotter surfaces than cooler ones. This offers the potential to achieve a more uniform temperature distribution throughout the engine structure.

The occurrence of nucleation boiling in engine acts as an unintentional safety zone for protecting components from excess temperature when the coolant flow velocity is too low to provide the required convective heat transfer. Several researches have been carried out to enhance nucleate boiling heat transfer but the most important issues are described here.

Surface roughness

To describe the surface roughness three parameters are determined: maximum peak height, R_p, maximum valley depth, R_v, and arithmetic average roughness, R_a. R_a, given in μm, is mostly recognized as the surface roughness. It is generally accepted that only those surface elements can act as active nucleation sites, which are not completely filled with liquid after bubble departure. Therefore, an increase in the average roughness may lead to an increase in the nucleate boiling heat transfer if the higher roughness is associated with additional active nucleation sites. Breitschädel (2008) carried out experiments for automotive cooling conditions, varying the roughness of Aluminum surface between $R_a = 2\ \mu m$ ("smooth"), $R_a = 45.7\ \mu m$ ("standard"), and $R_a = 130\ \mu m$ ("rough") [1].

Fig. 1 Surface roughness profile 1

As seen from the Fig. 2, measured after different operation times, both the smooth and rough surfaces exhibits almost the same heat transfer and the heat transfer curves are approximately coincident. The considerable concentration of large cavities on the very rough surface does evidently not provide additional active nucleation centers compared to the smooth surface.

As illustrated in Fig. 2 the onset of nucleate boiling for smooth (after 16 hours) and rough (after 30 hours) surfaces appear at a lower surface temperature than the corresponding values in 360 hours and 300 hours respectively. This reduction in boiling heat transfer attributes to the *Aging* phenomenon which may strongly affect the long-term activity of the nucleation sites on the heated surface. It can have many causes, such as continuous flooding of cavities, depositions on the surface, corrosion and/or mechanical erosion of the surface material, chemical reactions in the liquid phase, etc..

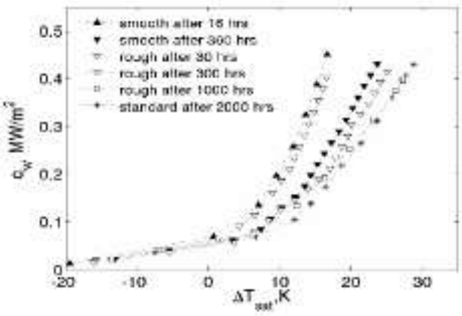

Fig. 2 Flow boiling curves for varying surface roughness after different operation times; bulk liquid velocity $u_b = 0.476\ m/s$; 50/50 Vol% ethylene glycol/water; pressure p=1.5 bar (from Breitschädel 2008)

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Campbell et al. [10] also attempted to quantify the effects of cooling passage surface roughness on the nucleate boiling regime. Tests have been conducted using aluminum test pieces with surface finishes described as smooth, intermediate and as-cast. It has been found that the as-cast surface increases the heat flux in the nucleate boiling region over that of the smooth and intermediate surfaces.

Composition of the liquid

Boiling of mixtures is considerably more complex than that of pure fluids. With a pure fluid, liquid simply evaporates at the liquid-vapor interface to become a vapor. When two fluids are present, with different boiling pressures, the more volatile component will evaporate at the liquid-vapor interface into a vapor bubble of the more volatile component. This causes the liquid-vapor interface to become depleted in the more volatile component, and requires that for further evaporation, molecules of the more volatile component have to diffuse through the bulk liquid to reach the interface and evaporate. This is a less efficient process than with a pure liquid, and consequently the heat transfer rate is reduced compared to that of boiling of the boiling of the more volatile component alone. This is supported by test results in Robinson experiments [2] for different coolants shown in Fig. 3, where boiling heat transfer coefficients measured with pure water were considerably larger than those measured with 50-50 water antifreeze mixture, which in turn were considerably larger than those measured with pure antifreeze.

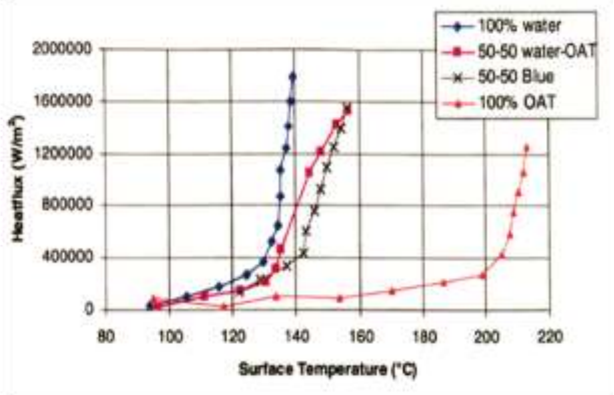


Fig. 3. Effect of coolant type at 0.25 m/s, 2 bar Absolute pressure

Electric field

In order to investigate the effects of an electric field on the nucleate boiling heat transfer enhancement including bubble dynamics behavior, Y.C. Kweon et al. have performed some basic experiments under saturated pool boiling [3]. For this purpose, the boiling curve, onset of nucleate boiling and critical heat flux are measured.

In recent years, the importance of Electrohydrodynamics (EHD) enhancement of heat transfer on the boiling process has been widely recognized. A number of experimental and analytical efforts have been devoted to obtain more information about EHD effects (Jones, 1978; Yabe and Maki, 1988; Kawahira et al., 1990 Ogata et al., 1992; Seyed Yagoobi et al., 1996).

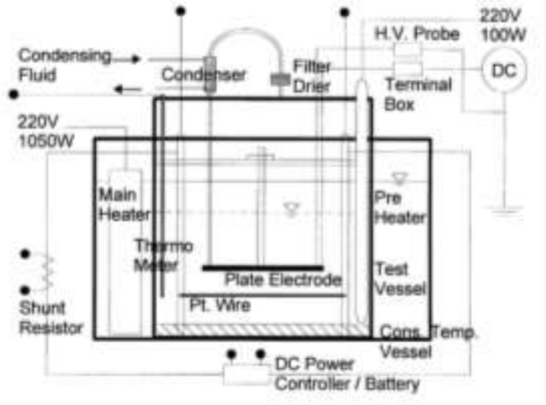


Fig. 4. Schematic diagram of EHD pool boiling apparatus

Some major effects of an electric field on boiling include the increase of maximum heat flux and bubble frequency and the decrease of bubble size. In particular, these effects are more remarkable when the electric field is strong and nonuniform due to the mutual interactions between a bulk liquid, vapor bubbles and an electric field. It has been found from these studies that more bubbles of small size depart at the heated surface by a non-uniform electric field and these bubbles enhance the heat transfer.

A schematic diagram of the Y.C. Kweon EHD pool boiling apparatus is shown in Fig. 4. The boiling vessel is insulated and made of tempered glass to facilitate visual observations. The condenser located above the boiling vessel is provided for condensing the vapor generated in the vessel. A thin wire is selected in order to produce a large gradient of the electric field at the surface of the wire. It generates the strong nonuniform electric field.

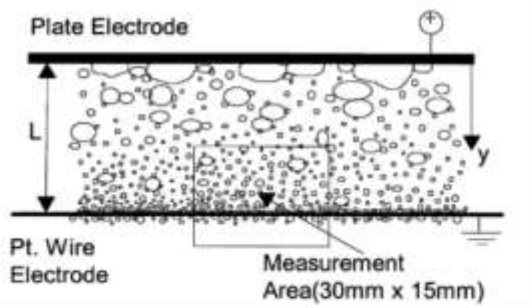


Fig. 5. Cross section of the plate-wire electrode for nucleate pool boiling

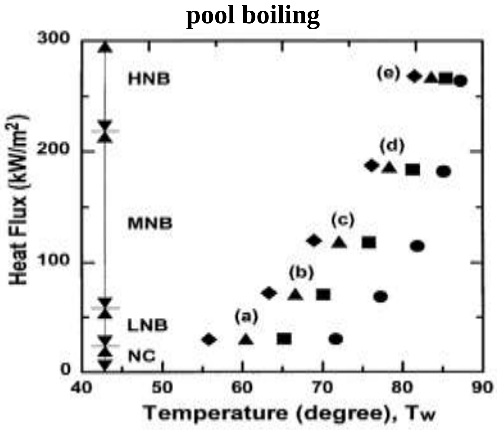


Fig. 6. EHD pool boiling curves of a wire in a non-uniform dc field: (a) 29 kW/m^2; (b) 69 kW/m^2; (c) 115 kW/m^2; (d) 183 kW/m^2; (e) 265 kW/m^2 (●: 0kV, ■: 5 kV, ▲: 10 kV, ♦: 15 kV)

Fig. 6 shows the pool boiling curves under 5, 10 and 15 kV dc voltages, compared with that under zero field case. With increasing the applied voltage, the boiling curves are shifted to lower wire temperature and the increase of heat flux isremarkable. When the wire temperature is about $75°C$, the heat flux at 15 kV dc voltage increases about 3.5 times greater than that at zero field case. The effects of an electric filed on the departure behaviors of bubbles in a pool are conceptually shown in Fig. 7. The figure describes that the imposing nonuniform electric field can change bubble dynamics. Although the increase of CHF is caused by both, the electro-convection effect and the EHD boiling effect due to bubble behaviors, the EHD boiling effect by bubble behaviors become more important as the applied voltage increases.

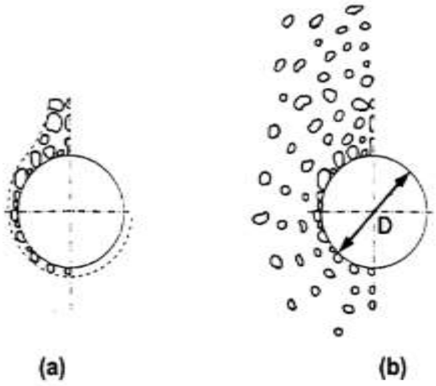


Fig. 7. Dynamic departure behavior of bubbles around a wire (a) zero field, (b) electric field

Vibrations

In order to assess the effect of vibration on boiling heat transfer, some experiments were conducted by Robinson in Bath university [2]. As shown in figure the rectangular duct was excited to vibrate vertically by a shaker. A signal generator was the source of the sinusoidal excitation signal with manually adjusted frequency and amplitude. To avoid any failure in the pipe work, the inlet and outlet pipes were chosen of flexible rubber hoses. Three vibration frequencies were chosen for test corresponding to low (1000 rev/min), mid speed (2250 rev/min) and high speed (5500 rev/min), with two amplitudes at each frequency corresponding to low and high load.

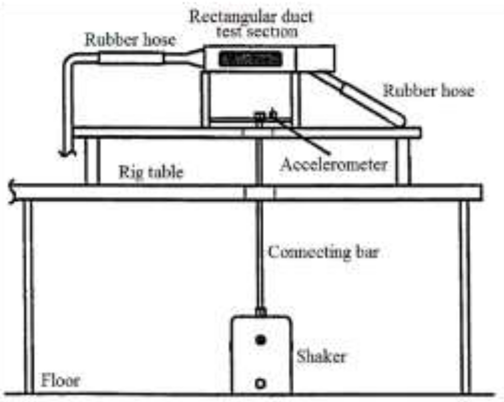
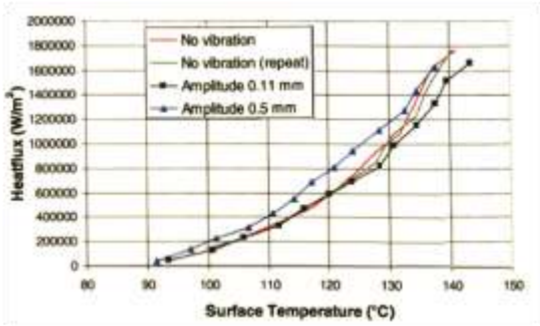
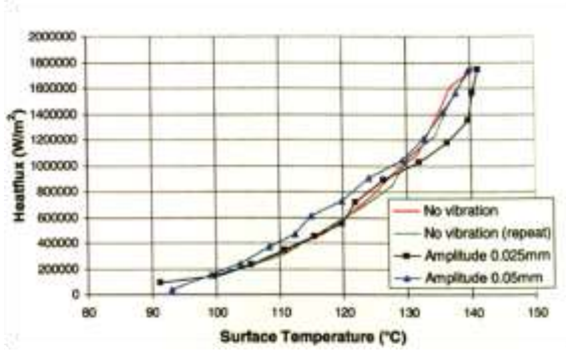


Fig. 8. Experiment rig to assess vibration effect on boiling heat transfer

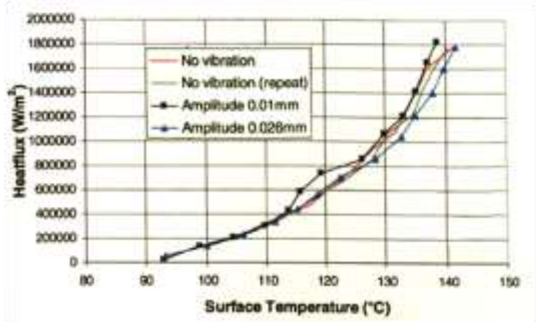
The results of test section on the heat transfer are illustrated in Fig. for three different excitation frequencies.



(a)



(b)



(c)

Fig. 9. Effect of vibration at 1 m/s, 1 bar Absolute pressure for 3 different excitation frequencies, (a) 33 Hz; (b) 75 Hz; (c) 183.2 Hz

Orientation of the heated surface

Since nucleate boiling by nature involves the motion of a low-density vapor phase in a high-density liquid carrier phase, the dynamics in the thermal boundary layer maybe strongly influenced by the buoyancy forces, especially at low flow rates of the bulk liquid. In such a case the orientation of the superheated surface relative to the direction of gravitational acceleration is of major importance. This aspect is mostly ignored by the nucleate boiling models though. The modeling within the BDL model is based on the bubble dynamics occurring on a surface plate heated from the bottom. Steiner et al. [4] assessed the quality of BDL predictions when the heated surface is oriented differently (Fig. 10). Their main results were:

- The boiling heat transfer on a vertical heated surface (orientation $90°$ with gravity vector) is well predicted by BDL.
- The boiling heat transfer on a horizontal surface heated from the top (orientation $180°$ with gravity vector) is well predicted until the transition to film boiling regime occurs.

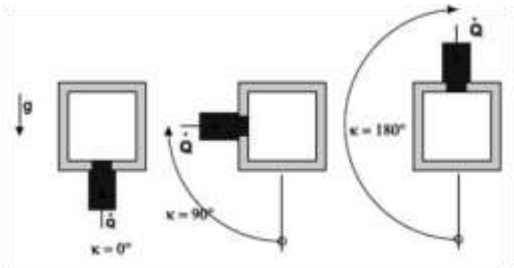


Fig.10. Orientation of heated plate

Irrespective to orientation of heated surface, the measuring point of heat flux is also important. Fig. 11 shows the experimental rig which Robinson [2] used to evaluate the heat transfer coefficient in different points of the heated surface.

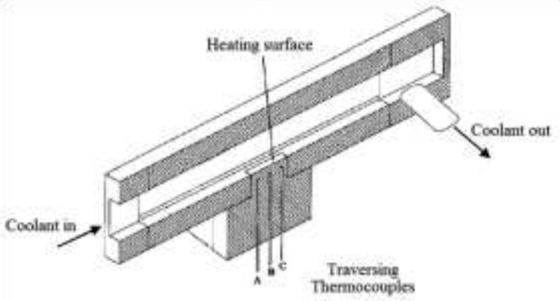


Fig. 11. Cutaway diagram of the Robinson rig duct and the traversing thermocouples position

Traversing thermocouples were placed in three different points of the heated surface to measure the flow temperature and subsequently the wall heat flux values.

	Distance from edge of duct inlet (mm)	x/D_h
Thermocouple A	86	6.988
Thermocouple B	101	8.206
Thermocouple C	116	9.425

Table 1. Positions of measurement thermocouples, and their x/D_h ratios

A comparison of the average ratio of experimentally measured heat transfer coefficients (HTC) at positions A, B and C is tabulated in table 2.

	HTC A:B ratio	HTC A:C ratio	HTC B:C ratio
Experimental data	1.13	1.13	0.99

Table 2. Experimental heat transfer coefficient ratios for different thermocouple positions

The majority of the difference in heat transfer coefficient measured at A, B and C is due to the different entrance factors, with other contributions arising from small differences in the fluid properties resulting from surface temperature differences A, B and C.

Surfactant addition

Nucleate pool boiling enhancement by means of surfactant additives has generated a lot of interests for many years. It is most desirable that employing surfactant additives in liquids can develop and mature into an enhancement technique for boiling heat transfer. Many investigators have studied the surfactants effect on nucleate boiling heat transfer since 1939.

Addition of the surfactant to water in low concentrations, causes no significant change in saturation temperature and other physical properties, except for surface tension, which is greatly reduced. In fact, surface tension has been consistently subjected to studying for its relationship to boiling heat transfer in the past. The nucleate boiling heat transfer coefficient, h, is related to the equilibrium surface tension, σ, of the aqueous surfactant solution by the following equation

$$h \propto \sigma^n$$

The values of constant n ranges from 0 to -3.3. Surface tension is a theoretically important variable for boiling. The rate of nucleus formation is proportional to $e^{-\sigma^3}$. Thus, small decreases in σ should cause large increases in the number of nuclei. Wuu-Tsann Wu et al. studied nucleate pool boiling enhancement experimentally by means of surfactant additives [5].

The water soluble surfactants used in his work are Sodium Dodecyl Sulfate (SDS) with 95% and 99% purity grades and Polyoxyethylated t-octylphenol (Trixon X-11). SDS is an anionic surfactant, while Triton X-100 is a non-ionic one.

The pool boiling apparatus used by Wuu-Tsann Wu et al. is shown in Fig. 12. An electric heating element is constructed of a seamless stainless steel tube (5.3 mm o.d., 4.8 mm i.d., and 100 mm long). Both ends of heating elements are welded to copper tubes. The junction of the chromel/alumel thermocouple was placed at the center of the heating element. Heat conduction in the axial direction could be neglected since the heating element was sufficiently thin and long. The thermocouples actually measured an average temperature of inner tube wall. The heat flux released from the heating element to the surrounding liquid was controlled by adjusting the current supplied by a rectifier. The outer tube surface temperature could be computed from the inner tube surface temperature and the heat flux values.

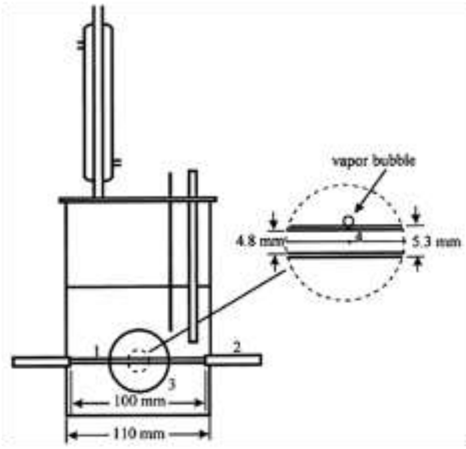


Fig.12. Pool boiling apparatus: (1) Heating element, (2) Copper tube, (3) View window, (4) Thermocouple junction

Fig. 13 shows the reproducibility of the boiling data of pure water. These data are the first, the second, and the third runs for water in a series of runs for aqueous solutions of various concentrations with three different surfactants. This shows that no serious change of surface condition of the heating element occurs when a series of experiments is carried out. Fig. 13 (b-d) shows correspondingly the boiling curves for surfactant solutions of 99% SDS, 95% SDS, and Triton X-100. The enhancement of nucleate boiling heat transfer is significant by the addition of all three surfactants but with different degree.

In general, the addition of surfactant in water makes the number of vapor bubbles much larger, the size of bubbles smaller, and the coalescence of bubbles more difficult [6,7,8].

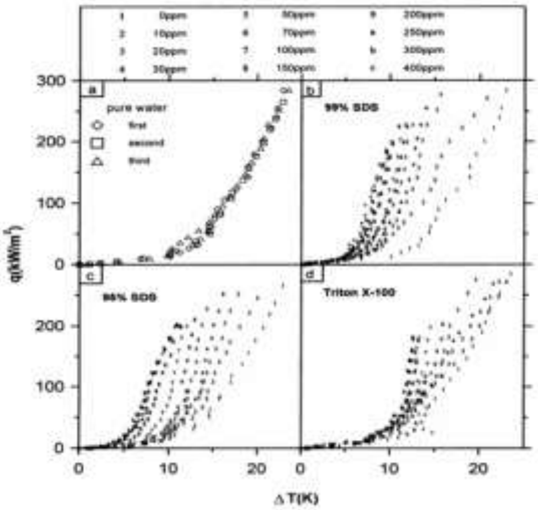


Fig.13. Boiling curves of aqueous solutions of 99% SDS, 95% SDS, and Triton X-100

Pressure and velocity

Robinson [2] conducted a research to assess the effects of pressure and velocity on boiling heat transfer in a bottom heated rectangular duct according to the IC engines operating conditions. As shown in Fig. 14, the channel is horizontal, 241 mm long and has a rectangular cross section of 16×10 mm^2. The heating surface is at the bottom of the flow channel.

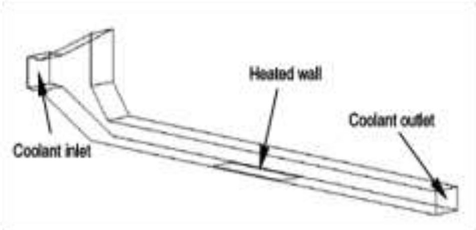


Fig. 14. Geometry of the flow channel

The liquid used in the experiment was a mixture of 50% ethylene glycol antifreeze and 50% water (by volume). Three traversing thermocouples are placed in different positions of heated surface to measure the surface temperature and the heat flux. The effects of working pressure and velocity were investigated in different operating conditions. The experimental results are illustrated in figures 15 and 16.

The most important effect of pressure on the boiling heat transfer is its close association with the saturation temperature. The saturation temperature determines the degrees of superheating ΔT_{SUP} and subcooling ΔT_{SUB}, and hence the onset of nucleate boiling, ONB.

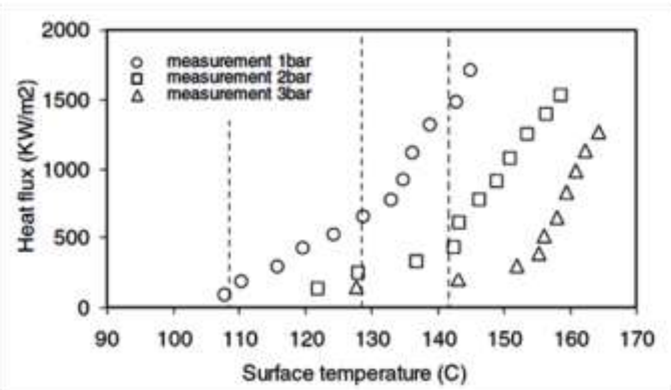


Fig.15. Heat flux versus wall temperature under different pressure at flow velocity 0.25 m/s

The saturated temperatures associated with the pressures of 1 bar, 2 bar and 3 bar are $108°C$, $128°C$ and $142°C$ respectively. As shown in Fig. 15 it is expected that before the wall temperature reaches the saturation point, the wall heat flux increases linearly, exhibiting the convective heat transfer. After the wall temperature exceeds the saturation point, the heat flux increases rapidly as the result of the onset of nucleate boiling. Increasing the working pressure also delays onset of nucleate boiling.

Robinson also examined the flow velocity effect on the boiling heat flux. Experimental results for various flow velocities at pressure of 2 bar are demonstrated in Fig. 16.

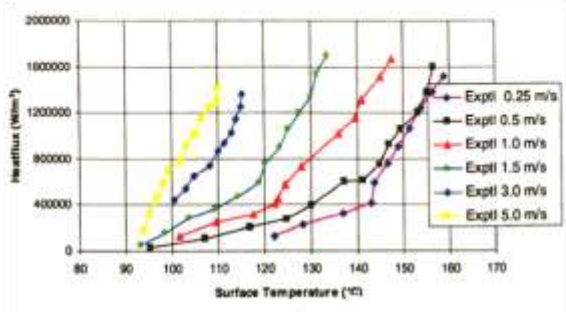


Fig. 16. Heat flux versus wall temperature under different velocity at 2 bar Absolute Pressure

The effects of velocity was examined by varying the velocity from 0.25 m/s to 5 m/s at a fixed pressure of 2 bar and a fixed inlet temperature of $90°C$. Nucleate boiling is clearly suppressed with increasing velocity, which is a well-known phenomenon in pure water. There is no sign of boiling above 1.5 m/s, as shown. Nucleate boiling usually requires some degree of superheat (excess temperature) to activate nuclei. It can be concluded that at lower flow rates, large increases in the rates of heat transfer at solid/liquid interface can be obtained in comparison with those achievable through purely convective mechanisms. Subsequently, the possibility exists of reducing bulk coolant volume and volume flow rates to achieve the same thermal conditions, resulting in less pump power and lower fuel consumption. Similar experiments are also carried out by H S Lee et al. [9].

Conclusion

Several studies have been on nucleate boiling, and the potential advantages have been shown to be greater heat flux for a specific wall temperature, lower coolant pump power, more compact cooling passages and lower cost of material and coolant. Nucleate boiling based cooling probably has greater potential than conventional convective cooling systems.

Nomenclature

C	Concentration (ppm)
dc	direct current
D_h	hydraulic diameter (mm)
h	heat transfer coefficient W/m^2K
$i.d.$	inner diameter (mm)
n	constant
$o.d.$	outer diameter (mm)
p, P	pressure (N/m^2)
q_w	wall heat flux (W/m^2)
R_a	arithmetic average roughness, μm
R_p	maximum peak height, μm
R_v	maximum valley depth, μm

x	distance from edge of duct inlet (mm)
ΔT_{sat}	saturated superheat, (K)
ΔT_{SUB}	subcooling (K)
ΔT_{SUP}	superheating (K)
σ	surface tension (N/m)

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