
ABSTRACT

The effect of surface roughness on nucleate boiling heat transfer is analytically explored over a wide range of roughness values in water and Fluorinert FC-77, two fluids with different thermal properties and wetting characteristics. The test surfaces ranged from a polished surface of $0.045\mu\text{m}$ to $10.5\mu\text{m}$. Different trends were observed in the heat transfer coefficient, percentage of vapour and Vapour generated time with respect to surface roughness between the two fluids on the same set of surfaces. For FC-77, the percentage of vapour developed was increased continually with increasing roughness. For water, on the other hand, surfaces of intermediate roughness and maximum roughness displayed similar values of percentage of vapour. While the roughest surface showed maximum percentage of vapour. The heat transfer coefficients and percentage of vapour developed were more strongly influenced by FC-77 than with water. At a very least vapour generated time of 0.4sec FC-77 developed maximum percentage of vapour than with water.

KEYWORDS: Nucleate boiling heat transfer, heat transfer coefficient, surface roughness, percentage of vapour, vapour generated time.

INTRODUCTION

Nucleate boiling heat transfer is affected by several physical parameters such as surface geometry, finish, cleanliness and orientation, type of liquid and its wettability, surface material and its thickness, and gravity. Several studies have found that aging of the heat surface can also affect the nucleate boiling thermal performance. The effect of the heating surface micro structure on nucleate boiling heat transfer has called the attention of the scientific community as early as the thirties, when the first pioneering studies were being carried out. The need to understand the effect of the surface condition was apparent in the early models of nucleate boiling and boiling inception. This is reasonable since the rate of heat transfer is closely related to the bubble population. Thus raising information related to the activation mechanism of the heating surface cavities seems a reasonable first step in understanding the nucleate boiling phenomenon. However, despite being exhaustively studied, the relation between active cavities and the surface micro structure is one of the key unsolved issues in the prediction of nucleate boiling heat transfer. The increased understanding of the role of surface condition as also led to commercially available enhanced surfaces for improved boiling performance. Many of these boiling enhancements are designed to create re-entrant-type cavities structures which are more difficult for the liquid to fully wet than simple cavity shapes and, based on the analysis of Griffith and Wallis are believed to serve as more stable nucleation sites. Therefore, these enhanced surface geometries typically lead to better boiling performance compared with roughened surfaces produced by conventional machining processes. Chowdhury and Winter suggested that rougher surfaces would yield higher nucleate pool boiling heat transfer coefficient if a consistent method of surface preparation is used, but the results from other investigators have not shown such a trend. The results from the polished surfaces indicated that roughening the surfaces only improved the boiling performance up to a certain point. Due to the importance of accurately accounting for the influence of surface roughness when correlating nucleate boiling data and given the wide variety of conclusions that have been reached in previous investigations, further research is warranted. The goal of the present work is to provide additional insights into the role of surface roughness on nucleate pool boiling with an analytical exploration using two fluids with widely differing thermal properties and wetting characteristics: water and FC-77, perfluorinated dielectric fluid. Widely used nucleate pool boiling correlations are evaluated by

using ANSYS Fluent. In particular, the capability of correlations to account for the effect of surface roughness is of prime interest in this study.

MULTI PHASE EQUATIONS OF NUCLEATE BOILING HEAT TRANSFER

In ANSYS Fluent, Eulerian models are available for analysis. All of the multiphase models are governed by the following conservation equations for continuity, momentum and energy. For conservation of mass, or continuity of phase q ,

$$\frac{\partial}{\partial t}(\nu_{f,q}\rho_q) + \nabla \cdot (\nu_{f,q}\rho_q \vec{v}_q) - \sum_{p=1}^n (\dot{m}_{p,q} - \dot{m}_{q,p}) + S_q$$

where the subscripts p and q denote individual phases, ν_f is the volume fraction, ρ is the density, \vec{v} is the velocity vector and $\dot{m}_{p,q}$ is the mass transfer from phase p to phase q and vice versa for $\dot{m}_{q,p}$. S_q is a source term for mass and by default is zero. For conservation of momentum of phase q ,

$$\begin{aligned} \frac{\partial}{\partial t}(\nu_f \rho \vec{v})_q + \nabla \cdot (\nu_f \rho \vec{v} \cdot \vec{v})_q = & -\nu_{f,q} \nabla p + \nabla \cdot \tau_q + \nu_{f,q} \rho_q \vec{g} + \sum_{p=1}^n (\vec{R}_{p,q} + \dot{m}_{p,q} \vec{v}_{p,q} - \dot{m}_{q,p} \vec{v}_{q,p}) \\ & + (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{wl,q} + \vec{F}_{vm,q} + \vec{F}_{td,q}) \end{aligned}$$

where τ_q is the stress-strain tensor, g is the gravitational acceleration, R_{pq} is an interaction force between phase p and q , F_q is a body force, F_{lift} , is a lift force, F_{wl} , is a wall lubrication force, F_{vm} is a virtual mass force, and F_{td} , is a turbulent dispersion force. Depending on the boundary conditions and flow regime, several of the external forces may not be included during the iterative calculations. To ensure conservation of momentum is properly closed, the interaction force, R_{pq} , which depends on friction, pressure and cohesion among others, is constrained with the following conditions

$$\vec{R}_{p,q} = -\vec{R}_{q,p} \text{ and } \vec{R}_{q,q} = 0$$

For conservation of energy of phase q ,

$$\begin{aligned} \frac{\partial}{\partial t}(\nu_{f,q}\rho_q h_q) + \nabla \cdot (\nu_{f,q}\rho_q \vec{u}_q h_q) = & \nu_{f,q} \frac{\partial p_q}{\partial t} + \tau_{q,i} \nabla u_{q,i} - \nabla \cdot \vec{q}_q + S_q \\ & + \sum_{p=1}^n (Q_{p,q} + \dot{m}_{p,q} h_{p,q} - \dot{m}_{q,p} h_{q,p}) \end{aligned}$$

where h_q is the specific enthalpy of phase q , q_q is the heat flux, S_q is a source term for enthalpy (chemical reaction, radiation, etc), Q_{pq} is the intensity of heat exchange between phases and h_{pq} is the inter phase enthalpy. To ensure conservation of energy is properly closed, the inter phase heat exchange, Q_{pq} , is constrained with the following conditions

$$Q_{p,q} = -Q_{q,p} \text{ and } Q_{q,q} = 0$$

This model divides the total wall heat flux into three components: Convective heat flux, quenching heat flux, and evaporative heat flux. The wall heat flux is written in the following form

$$\dot{q}_w = \dot{q}_C + \dot{q}_Q + \dot{q}_E$$

where q_C is the convective heat flux, q_Q is the quenching heat flux, and q_E is the evaporative heat flux. The surface of the heated is divided into two subsections, one being the fractional area A_b , which is covered by nucleating bubbles, and the other being $(1-A_b)$, which is covered by fluid. The convective heat flux is expressed in the following form

$$\dot{q}_C = h_C(T_w - T_l)(1 - A_b)$$

where h_C is the single phase heat transfer coefficient as calculated by Fluent, T_w is the wall surface temperature, and T_l is the liquid temperature. The quenching heat flux, which models the cyclic averaged transient energy transfer

resulting from liquid filling the region near the wall immediately after bubble detachment, is expressed in the following form

$$\dot{q}_Q = \frac{2k_l}{\sqrt{\pi\alpha_l t}} (T_w - T_l)$$

where k_l is the thermal conductivity of the liquid, t is the periodic time of bubble generation and departure, $\alpha_l = k_l / \rho_l C_{pl}$ is the thermal diffusivity, and again T_w and T_l are the wall and liquid temperatures respectively. The evaporative heat flux is expressed in the following form:

$$\dot{q}_E = V_d N_w \rho_v h_{lv} f$$

where V_d is the volume of bubble based on the bubble departure diameter, N_w is the active nucleate site density, ρ_v is the vapour density, h_{lv} is the latent heat of evaporation, and f is the bubble departure frequency. In order to close the above equations, the following parameters need to be defined Fractional area of influence, frequency of bubble departure, nucleation site density, and bubble departure frequency. The fractional area of influence as proposed by Del Valle and Kenning is expressed in the following form

$$A_b = K \frac{N_w \pi D_w^2}{4}$$

where D_w is the bubble departure diameter, and K is an empirical constant usually set to 4, however it has been found that this value is not universal and may vary between 1.8 and 5. The following relation for this constant has been implemented

$$K = 4.8 e^{-\left(\frac{Ja_{sub}}{30}\right)}$$

and Ja_{sub} is the sub cooled Jacob number defined as

$$Ja_{sub} = \frac{\rho_l C_{pl} \Delta T_{sub}}{\rho_v h_{lv}}$$

where $\Delta T_{sub} = T_{sat} - T_l$. In order to avoid numerical instabilities due to unbound empirical correlation for nucleation site density, the area of influence was restricted in Fluent in the following way

$$A_b = \min\left(1, K \frac{N_w \pi D_w^2}{4}\right)$$

The frequency of bubble departure as proposed by R. Cole is expressed in the following form:

$$f = \frac{1}{t} = \sqrt{\frac{4g(\rho_l - \rho_v)}{3\rho_l D_w}}$$

INFLUENCE OF SURFACE ROUGHNESS ON NUCLEATE BOILING

It is well known that nucleate boiling heat transfer can be well represented by an exponential relationship given by $h\alpha q^n$, where n is a function of pressure and surface characteristics. Several researches have also noted that the dependence of heat transfer coefficient at a fixed heat flux can be modelled by an exponential relation, $h\alpha R^m$, where R is some measure of the surface roughness. Putting these two relationships together yields

$$h = CR^m q^n$$

where C is a constant, surface roughness can both the magnitude of heat transfer coefficient and change the slope of its variation with heat flux since the exponent n is also dependent on roughness. with few experimentations the exponent m values are given at different heat fluxes. For water, the roughness exponent m is 0.09 at 50kW/m² and 100kW/m² and increases slightly to 0.11 at a heat flux of 300kW/m². With FC-77 greater dependence of surface roughness on the heat transfer coefficient is seen that with water, resulting in higher roughness exponents ranging from $m=0.118$ at 50 kW/m², 0.2375 at 100kW/m² and 0.7125 at a heat flux of 300kW/m². The results indicate that the surface roughness exponent is not a constant across different fluid-surface combinations. Since it is well known that the wet ability of the fluid has important consequences on the nucleation behaviour, It is reasonable to

hypothesize that m is also a function of the contact angle. Although contact angles were not measured in the current study, FC-77 is highly wetting on most metal surfaces while water is moderately wetting. Therefore, it may be proposed that highly wetting fluids are well represented by a roughness exponent $m=0.2$ while for moderately wetting fluids, $m=0.1$ is more appropriate.

MATERIAL, COOLANT AND SURFACE ROUGHNESS COMBINATIONS

S.no	Material +Fluid	R_1 (μm)	R_2 (μm)	R_3 (μm)
1	Si+Water	0.045	6.2	10.5
2	Si+FC-77	0.045	6.2	10.5

For theoretical analysis two solid and fluid combinations were taken into consideration at three heat fluxes (50, 100, 300 kW/m^2) at reduced pressures (0.046 bar for water for FC-77) for the fluid at three different roughness values with a cross section of 0.000288m^2 .

Heat transfer coefficient at different heat fluxes in kW/m^2 K

Surface roughness (μm)	At 50 kW/m^2	At 100 kW/m^2	At 300 kW/m^2
0.045	3.265	5.553	9.18
6.2	9.259	16.64	18.73
10.5	16.05	30.387	34.55

Wall super heat at different heat fluxes in K:

Surface roughness (μm)	At 50 kW/m^2	At 100 kW/m^2	At 300 kW/m^2
0.045	5.3	18.01	32.6
6.2	5.1	6	9.87
10.5	4.54	5.33	8.68

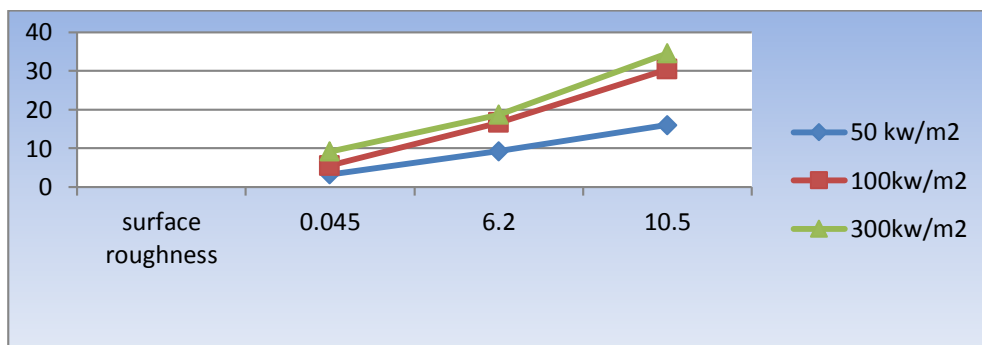


Figure 1 Heat transfer coefficient Vs Surface roughness

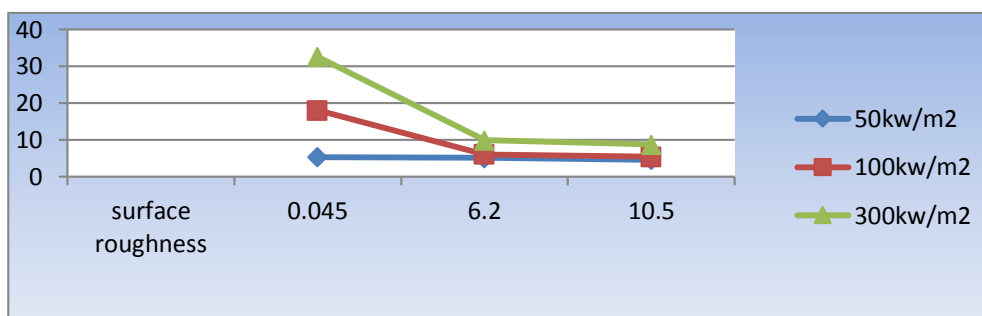
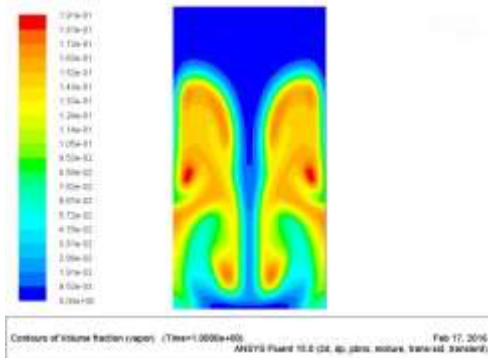


Figure 2 Wall super heat Vs Surface roughness

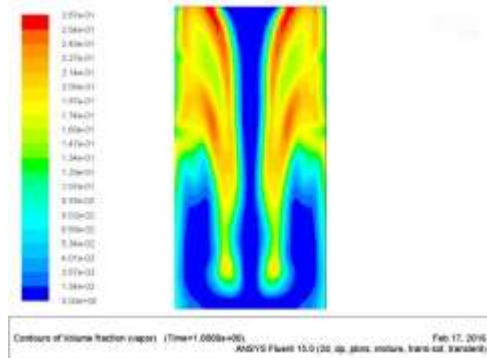
The generated graphs clearly shows that when roughness increases the heat transfer coefficient also increases and wall superheat reduces, the increase in heat transfer is the measure of heat removal rate from the silicon plate when we use water as coolant. similarly the reduction in wall superheat indicates more heat transfer whenever we increase the roughness.

RESULTS AND DISCUSSION

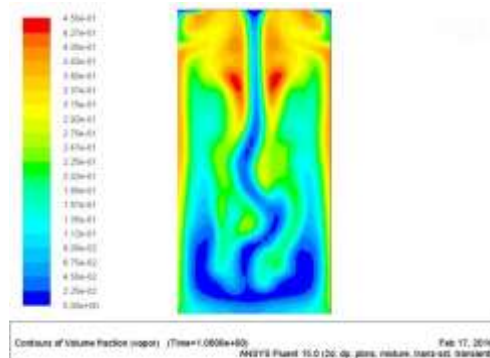
Silicon and Water combination



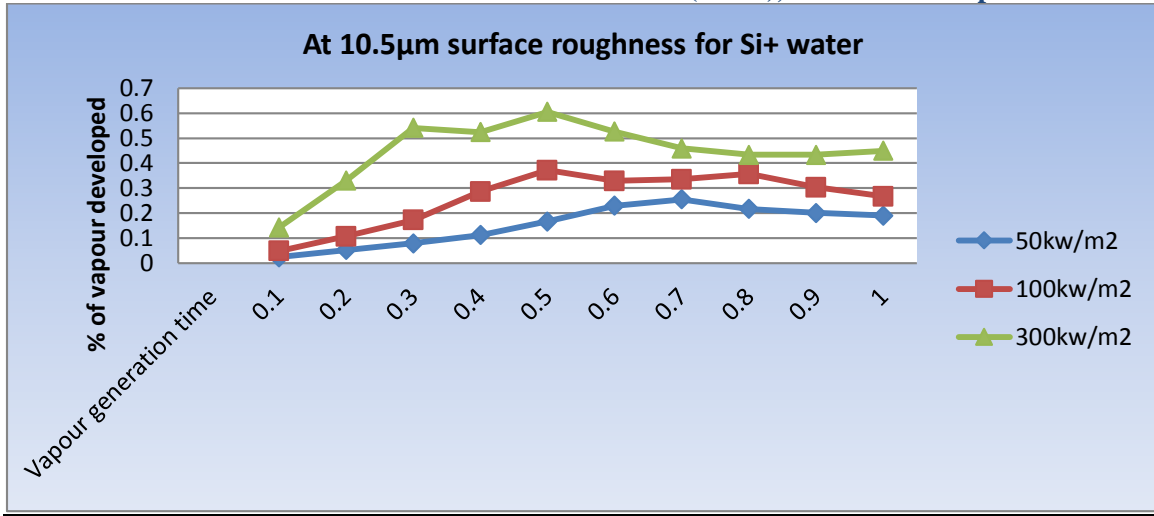
At 50Kw/m² & 10.5micro meter roughness at 1.0s



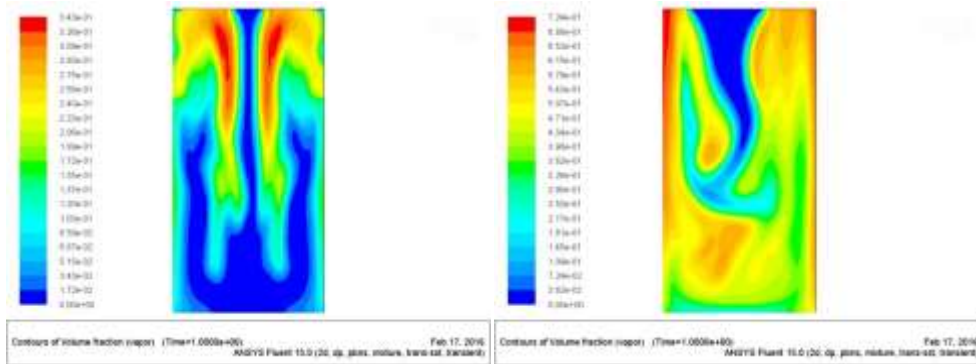
At 100Kw/m² & 10.5micro meter roughness at 1.0s



At 300 Kw/m² & 10.5 micro meter roughness at 1.0s

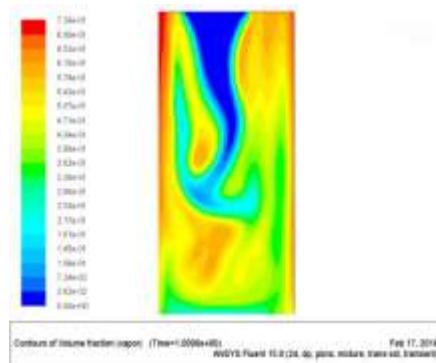


Silicon and FC-77 combination

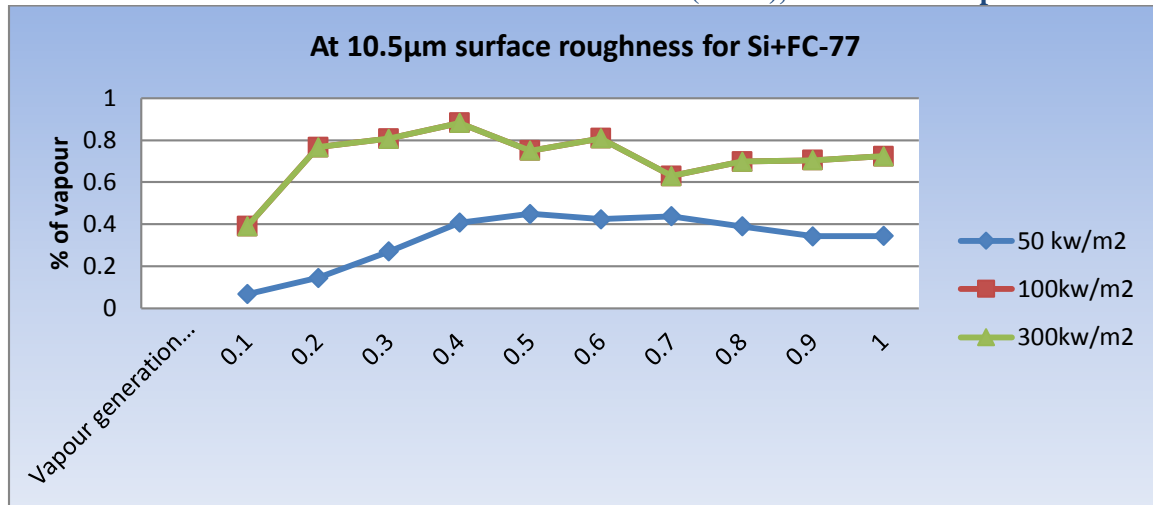


At 50Kw/m² & 10.5micro meter roughness at 1.0s

At 100Kw/m² & 10.5micro meter roughness at 1.0s



At 300Kw/m² & 10.5micro meter roughness at 1.0s



CONCLUSION

Nucleate pool boiling at reduced pressure from surfaces with a wide range of surface roughness in two fluids with different wetting characteristics was explored by using ANSYS-Fluent. For water and silicon combination, and silicon and FC-77 combination. For water, the results indicate little improvement in heat transfer coefficient and percentage of vapour for roughness beyond 6.2 μ m. On the same set of surfaces FC-77 exhibited a different trend with respect to surface roughness, at a fixed heat flux. The general trend of increasing heat transfer coefficient with surface roughness was correlated using $h\alpha R^m$. The results indicate a stronger dependence on surface roughness for FC-77 with $m=0.2$ compared with $m=0.1$ for water. The analytical results compared with each other, and FC-77 developed maximum % of vapour at maximum roughness of 10.5 μ m. The results obtained analytically proved that the % of vapour increases with surface roughness.

ACKNOWLEDGEMENTS

Prof A.Ramakrishna and Naveen are thanked for their helpful and insightful discussions.

REFERENCES

1. Jakob, M., 1936, "Heat Transfer in Evaporation and Condensation—I," Mech. Eng. Am. Soc. Mech. Eng., 58, pp. 643–660.
2. Westwater, J. W., 1958, "Boiling Heat Transfer," Am. Sci., 47, pp. 427–446.
3. Clark, H. B., Strenge, P. S., and Westwater, J. W., 1959, "Active Sites for Nucleate Boiling," Chem. Eng. Prog., Symp. Ser., 5529, pp. 103–110.
4. Bankoff, S. G., 1958, "Ebullition From Solid Surfaces in the Absence of a Pre-Existing Gaseous Phase," Trans. ASME, 79, pp. 735–740.
5. Bankoff, S. G., 1958, "Entrapment of Gas in the Spreading of a Liquid Over a Rough Surface," AIChE J., 41, pp. 24–26.
6. Griffith, P., and Wallis, J. D., 1960, "The Role of Surface Conditions in Nucleate Boiling," Chem. Eng. Prog., Symp. Ser., 5630, pp. 49–63.
7. Hsu, Y. Y., 1962, "On the Size Range of Active Nucleation Cavities on a Heating Surface," ASME J. Heat Transfer, 84, pp. 207–216.
8. Corty, C., and Foust, A. S., 1955, "Surface Variables in Nucleate Boiling," Chem. Eng. Prog., Symp. Ser., 5117, pp. 1–12.

9. Kurihara, H. M., and Myers, J. E., 1960, "The Effects of Superheat and Surface Roughness on Boiling Coefficients," AIChE J., 61, pp. 83–91.
10. Hsu, S. T., and Schmidt, F. W., 1961, "Measured Variations in Local Surface Temperatures in Pool Boiling of Water," ASME J. Heat Transfer, 83, pp. 254–260.
11. Marto, P. J., and Rohsenow, W. M., 1966, "Effects of Surface Conditions on Nucleate Pool Boiling of Sodium," ASME J. Heat Transfer, 88, pp. 196–204.
12. Berenson, P. J., 1962, "Experiments on Pool-Boiling Heat Transfer," Int. J. Heat Mass Transfer, 5, pp. 985–999.
13. Webb, R. L., 1981, "The Evolution of Enhanced Surface Geometries for Nucleate Boiling," Heat Transfer Eng., 2, pp. 46–69.
13. Webb, R. L., 2004, "Odyssey of the Enhanced Boiling Surface," ASME J. Heat Transfer, 126, pp. 1051–1059.
15. Bier, K., Gorenflo, D., Salam, M., and Tanes, Y., 1978, "Pool Boiling Heat Transfer and Size of Active Nucleation Centers for Horizontal Plates With Different Surface Roughness," Proceedings of the Sixth International Heat Transfer Conference, Toronto, Canada, Vol. 1, pp. 151–156.
14. Chowdhury, S. K. R., and Winterton, R. H. S., 1985, "Surface Effects in Pool Boiling," Int. J. Heat Mass Transfer, 2810, pp. 1881–1889.

AUTHOR BIBLIOGRAPHY

	<p>U. Ramya Sri Student BVC Engineering college</p>
	<p>A. Rama Krishna Professor BVC Engineering college</p>