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A New Correlation for the Onset of Nucleate Boiling Heat Flux under an Impinging Planar Water Jet

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Abstract **-** A new comprehensive correlation is presented to predict the onset of nucleate boiling heat flux in the stagnation region of a planar jet impingement boiling on a hot flat surface. The rate of heat transfer is calculated using a similarity solution approach and the effect of the main parameters of water jet, i.e. jet sub-cooling and jet velocity on the heat flux is of investigated. Then the heat flux is correlated for the wide range of both impinging velocity and liquid jet temperature, by using the least square fitting method. A comparison of the obtained results of the correlation is made with a pervious published model in a special case and good agreement is reported.

Keywords**:** Onset of nucleate boiling, Jet impingement boiling, Stagnation flow, Least square method

1. Introduction

Jet impingement boiling (JIB) is an effective technique for cooling applications such as cooling of hot rolling steel strip, coplanar computer chips and power electronics due to extracting a high heat flux concentrated at stagnation region and its neighbourhood. Hence, it has been under numerous studies in few last years, e.g., [1-7]. A review study of the jet impingement boiling has been carried out by Wolf et al. [8]. They collected and compared various existing literature correlations of boiling curve from steady-state measurements. Following, Wolf et al. [9] presented a correlation of $q'' = F\left(\Delta T_{sat}\right)$ for the fully developed boiling regime obtained from a least square fitting over fully developed boiling experimental data. Their expression correlated all the data to within +32%. Hauksson [10] experimentally investigated the rate of heat transfer during water jet impingement on a hot steel plate. He used superposition model based on chen's [11] correlation and correlated suppression factor by fitting the model to his experimental data. Recently some works have been done in jet impingement boiling area, experimentally [12-14], and some have reviewed recent progress in this field [15, 16].

One of the most important parameters in JIB is prediction of the onset of nucleate boiling (ONB) point which marks the transition from the single-phase forced convection region to partial nucleate boiling (PDB) region. The information on the conditions required for ONB and then predict heat flux at this point would be helpful in the design of two-phase flow heat transfer derives such as cooling equipment.

Hsu [17] established an expression for the onset of nucleate boiling by making a relation between the superheat and the incipience heat flux, udder the uniform heat flux condition. Miyasaka and Inada [18] experimentally studied boiling heat flux under an impinging planar water jet at the stagnation and formulated a correlation for the onset of nucleate boiling heat flux for a fixed water jet temperature $T_f = 15^{\circ}C$. Kandlikar et al. [19] numerically obtained the stagnation point temperature around the bubble which indicated the minimum temperature in the ONB.

The existing correlations for ONB are failed to predict the wall superheat at ONB and hence to calculate the wall heat flux at ONB, explicitly, in most cases. Some other existing correlations e.g., [18] are limited to a special temperature, special configuration of jet or valid just for a small range of the variables such as jet velocity and temperature.

In this study, a comprehensive correlation for predicting the onset of nucleate boiling heat flux in the stagnation region of a planar jet impingement boiling on a hot flat surface is presented. The equation is correlated by least square fitting method on data obtained from a model based on combination of Hus' equation and Newton's law of cooling with a similarity solution approach.

2. Model Problem

The details of the nozzle configuration, impinging jet configuration and the velocity field of a planar free jet impinging on a flat plate is illustrated in Fig. 1.

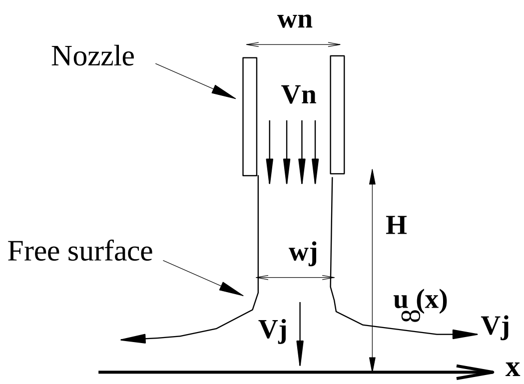

Fig. 1: Nozzle configuration and velocity field of a planar free surface jet [6].

Depending on the surface temperature, different heat transfer regimes are observed. When the surface temperature; T_s below the required temperature for initial vapor bubble nucleation, i.e. $T_s \prec T_{sonb}$, single-phase convection regime occurs. The moment T_s is well above the saturation temperature of the liquid, initial isolated vapor bubbles starts to nucleate and grow on the surface. The temperature of this point is shown as T_{onb} (onset of nucleate boiling) in Fig.2. Partial nucleate boiling regime begins from this point. If the surface temperature increases more, the boiling regime transits from partial to fully developed nucleate boiling. The variation of surface heat flux (q'') against wall superheat (ΔT_{sat}) (boiling curve) is depicted in Fig. 2.

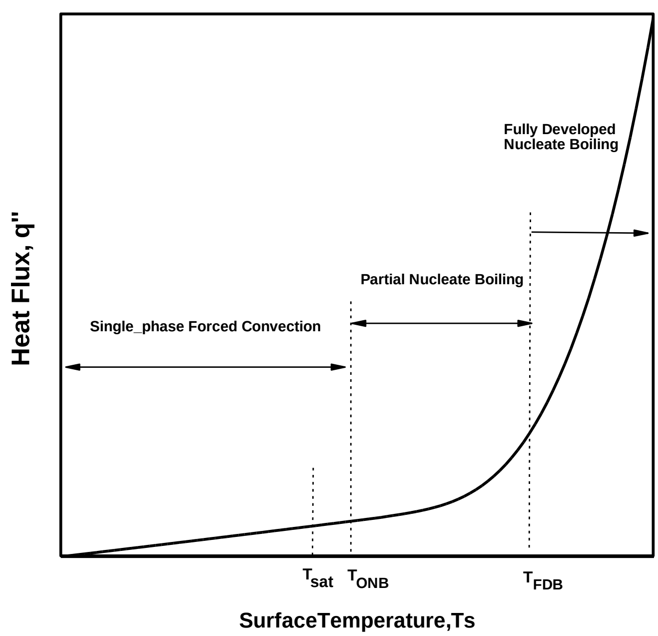

Fig. 2: Schematic of the boiling curves: solid line denotes the flow boiling; dashed line denotes the pool boiling curve.

3. Onset of Nucleate Boiling

Most researchers have used Hsu's model to estimate $\left(\Delta T_{sat}\right)_{onb}$. For uniform surface heat flux, Hsu [17] presented the the following expression between the superheat temperature and the heat flux at the onset of nucleate boiling:

$$\left(\Delta T_{sat}\right)_{onb} = \left(\frac{8\sigma q''_{onb} T_{sat}}{h_{fg} k_f \rho_g}\right)^{\frac{1}{2}} \quad (1)$$

In this equation, ΔT_{onb} is a function of q''_{onb} and some physical properties of flow phases. But, q''_{onb} itself is unknown explicitly. Moreover, this equation was drived for saturation pool boiling that does not reflect the flow boiling effects such as sub-cooling and flow velocity, what are important in the JIB problem. Newton's law of cooling is proposed to apply at the point of incipience to obtain an explicit equation to estimate ΔT_{onb} as following [6]:

$$q''_{onb} = h\left(T_{onb} - T_f\right) = h\left(\left(\Delta T_{sat}\right)_{onb} + \Delta T_{sub}\right) \quad (2)$$

The ONB heat flux; q''_{onb} obtained from Eq. (1) can be replaced in Eq. (2). So, the unknown parameter wall superheat temperature may be estimated explicitly as a function of known parameter ΔT_{sub} as:

$$\left(\Delta T_{sat}\right)_{onb} = \frac{1 + \left(1 + 4\lambda \Delta T_{sub}\right)^{\frac{1}{2}}}{2\lambda} \quad (3)$$

Where

$$\lambda = \frac{k_f h_{fg}}{8\sigma v_g T_{sat} h} \quad (4)$$

All parameters here are thermo-physical properties which are considered as known parameters, except the heat transfer coefficient; h . In the previous work [6], the heat transfer coefficient was analytically calculated by similarity solution as:

$$h = -\frac{K \left.\frac{\partial T}{\partial y}\right|_{y=0}}{\Delta T_f} = -\rho c_p \Pr^{-1} \sqrt{C\nu}\,\theta'(0) \quad (5)$$

Where the dimensionless temperature profile $\theta(\eta)$ and similarity variable η are introduced as [20]:

$$\theta(\eta) = \frac{T - T_f}{T_s - T_f}, \quad \eta = \sqrt{\frac{C}{\nu}}\, y \quad (6)$$

Substituting Eqs. (3) and (5) into Eq. (2) yields the following expression for the heat flux at onset of nucleate boiling as an explicit function of the surface temperature, liquid jet and thermo-physical properties:

$$q''_{onb} = -\rho c_p \Pr^{-1} \sqrt{C\nu}\,\theta'(0) \left(\frac{1 + \left(1 + 4\lambda \Delta T_{sub}\right)^{\frac{1}{2}}}{2\lambda} + \Delta T_{sub} \right) \tag{7}$$

4. Two-stage Least Square Method

As it was shown in the previous section, with having a fixed nozzle configuration (nozzle width and nozzle to plate distance), incipient boiling characteristics (onset of nucleate boiling temperature Eq. (3) and heat flux Eq. (7)) are affected by the two parameters; jet velocity and sub-cooling. The sub-cooling itself is a function of liquid jet temperature and jet velocity. So, the onset of nucleate boiling temperature and heat flux are functions of jet velocity and liquid jet temperature as well.

A new comprehensive correlation for onset of nucleate boiling heat flux q''_{onb} by least square fitting method on data obtained from the present model; Eq. (7) is presented in this section. This new correlation is considered as a function of both liquid jet temperature and jet velocity. The best fitting curve to q''_{onb} data as a function of v_n, is a power function of jet velocity v_n as following:

$$q''_{onb} = aV_n{}^b \tag{8}$$

Where a and b coefficients are functions of liquid temperature, T_f. So, the fitting should be done in two stages. First a fitting to find q''_{onb} - v_n curve in an arbitrary T_f. Then a fitting to find a and b as functions for different amounts of T_f (polynomial function). By least square fitting method on data in the wide range of velocities $0.8 \le V_n \le 8$, and $1 \le T_f \le 99$, the polynomial functions of a and b is obtained as the following:

$$a = \sum_{i=0}^{3} a_i T_f{}^i \tag{9}$$

$$b = \sum_{i=0}^{11} b_i T_f{}^i \tag{10}$$

All the results are presented for H=15 mm, w_n =10 mm in order to compare with data of Ref. [18]. The constant coefficients a_i and b_i are presented in the tables 1 and 2.

Table 1: The constant coefficients a_i in Eq. (9).

a_0	a_1	a_2	a_3
1.3797	-0.0106	-3.8096e-5	7.7694e-8

Table 2: The constant coefficients b_i in Eq. (10)

b_0	b1	b2	b3	b4	b5
0.6012	0.0045	- 1.1968e-3	1.6497e-4	-1.2521e-5	5.8011e-7

5. Results and Discussion

In the present problem problem, the variation of thermo-physical properties with temperature has been considered by by evaluating them at the film temperature defined by $(T_s + T_f)/2$. The correlation equations for the thermo-physical properties of water and other coolants in gas and liquid states are presented as a function of temperature in VDI-Heat Atlas Atlas [21].

Variation of ΔT_{onb} as a function of v_n for different amounts of T_f is shown in Fig. 3. As it can be seen, increasing jet velocity results in a delay in the onset of nucleate boiling. So, ΔT_{onb} increases. Because, once jet velocity increase the thermal boundary layer becomes thinner and temperature gradient within it is not sufficient to allow bubble to be formed and thus nucleation is delayed. The same result is depicted for variation of ΔT_{onb} with respect to T_f .

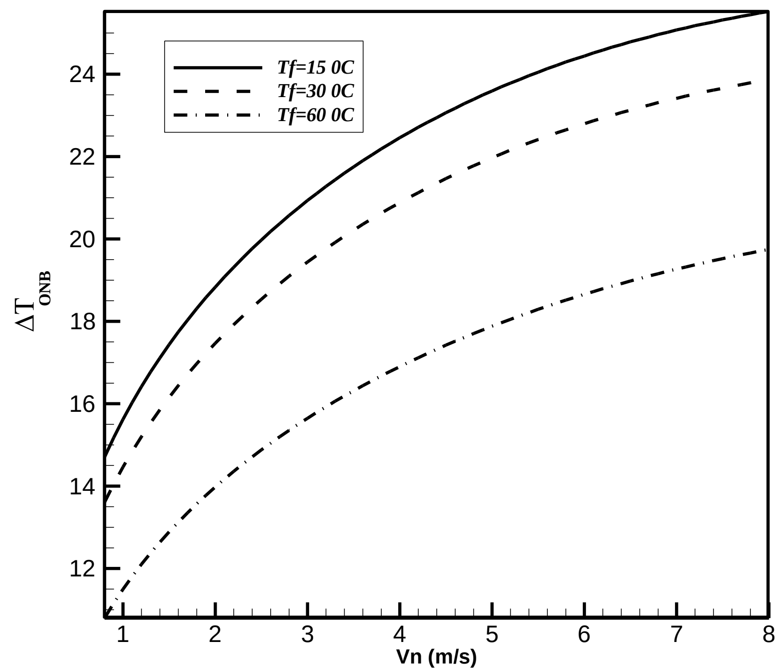

Fig. 3: Effect of degree of liquid jet temperature (T_f) on the T_{onb} as a function of v_n .

The result obtained from the presented correlation, Eq. (8) in different liquid jet temperatures is presented in Fig. 4. The onset of nucleate boiling is strongly affected by forced convection. By increasing jet velocity, the temperature of the onset of nucleate boiling is shifted to higher wall superheat temperatures (Fig. 3) and the heat flux also increases (Fig. 4). The subcooling also has a strong influence on the heat flux q''_{onb} . As it can be seen, increasing the degree of sub-cooling temperature in a fixed jet velocity, results in a significant increase in q''_{onb} .

To validate the correlation, a compression with Miyasaka's correlation has been done. Miyasaka and Inada [18] presented a correlation of q''_{onb} as a function of only v_n , for a fixed liquid jet temperature T_f =15 0c as:

$$q''_{onb} = 1.4 V_n^{0.56} \tag{11}$$

An error analysis showed that presented correlation has an average relative error 5% from Eq. (11) with maximum relative error 12%. As seen, a good agreement is depicted between result of Eq. (8) and Miyasaka's correlation, Eq.

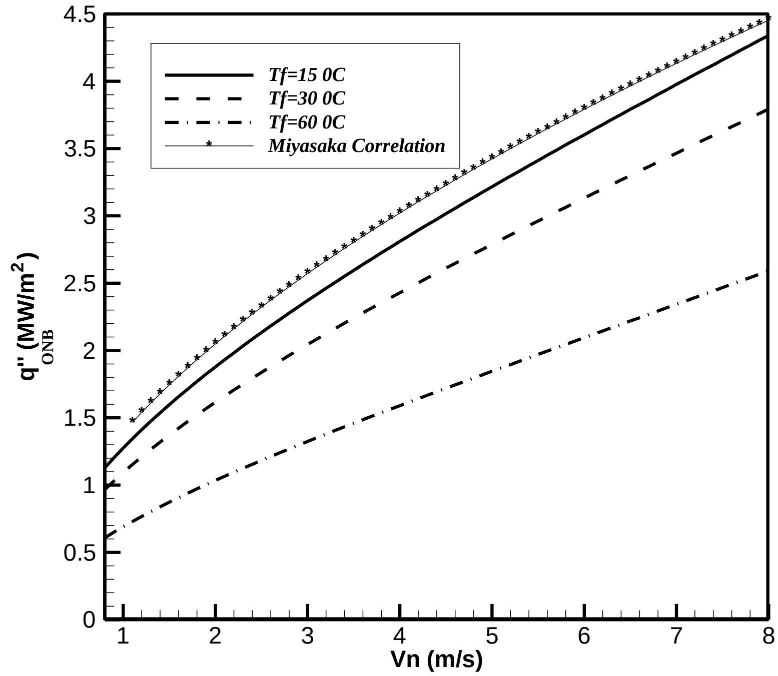

Fig. 4: Effect of degree of liquid jet temperature T_f on the q_{onb} as a function of v_n .

6. Conclusions

An analysis of the incipience of nucleate boiling in jet impingement boiling problem is carried out. Modelling of the problem of jet impingement boiling is a significant challenge. Prediction of onset of nucleate boiling as a key parameter in flow boiling problems is also challenging. Most correlations in this regard in the literature have limitations. A comprehensive new correlation to predict incipient boiling components (onset of nucleate boiling temperature, ΔT_{onb} and heat flux, q''_{onb}) is presented as a function of both impinging velocity and sub-cooling temperature, for the first time. This correlation predicts an increase of heat flux in onset of nucleate boiling monotonically by increasing the jet velocity and degree of sub-cooling.

Nomenclature

Symbol Definition

h heat transfer coefficient (W/m^2°C)
h_{fg} latent heat of vaporization (J/kg)
H nozzle to plate distance (m)
k thermal conductivity (W/m °C)
p pressure (N/m^2)
Pr Prandtl number
q'' heat flux (W/ m^2)
T Temperature (°C or K)
ΔT temperature difference (°C or K)
V jet velocity (m/s)
w_j jet width at impingement (m)
w_n nozzle width (m)

Greek symbols

ν molecular kinematic diffusivity (m^2/s)
μ dynamic viscosity $(kg/m.s)$
ρ density (kg/m^3)
σ surface tension (N/m)
λ parameter defined in Eq. (4)

Subscripts

fc forced convection
f fluid (liquid)
g gas (vapor)
j jet related value
n nozzle related value
nb nucleate pool boiling
onb onset of nucleate boiling
s surface
sat saturation
sub sub-cooled
sup superheat
0 reference related value

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