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Technical Note

Forced convective heat transfer with impinging slot jets of meso-scale

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Abstract

Measurements were made to investigate the localized heat transfer behavior of submerged slot jets. The experiments were performed with kerosene jets impinging on a vertical constant-heat-flux surface from a meso-scale slot nozzle 125 μm in width with $Re = 600$–1200 and nozzle-to-plate spacing $Z/B = 2$–20. Heat transfer coefficients at the stagnation line were measured and correlated as a function of jet Reynolds numbers and Prandtl numbers. Lateral distributions of local heat transfer coefficients were also determined and correlated. Non-monotonic variations and unusual behavior of local heat transfers were observed and attributed to the possible transition from a laminar to a turbulent flow. This transition takes place within an extremely short distance of 400–500 μm.

Keywords: Slot jet impingement; Meso-scale; Heat transfer

1. Introduction

With increasing heat flux in electronic packages, slot liquid jet impingement becomes more important in the application of electronic cooling technology. Experimental investigations of heat transfers under slot liquid jets have been reviewed by Webb and Ma [1]. Except for two studies, water was employed as the working fluid [2–5]. In those two studies, the fluids used were PAO (dielectric liquid) by Gu et al. [6] and FC-72 (dielectric liquid) by Wadsworth and Mudawar [7]. Most of the investigations focused on the cases in which the free-jet flow at the nozzle exit was fully turbulent. Some reports [2,5–7] were presented concerning impinging jets in an initially laminar regime. We noted that nearly all the experimental studies [2–4,6] in the published literature were related to free-surface planar liquid jets, except for the work undertaken in Purdue University [5,7]. However, the two reports concerning the submerged slot jets both provided experimental results only for the average heat transfer. Partial compensation for the lack of information on submerged slot liquid jets may be obtained by extending the experimental and numerical results of slot air jets [8–11]. Nevertheless, as the Prandtl number of liquid may be several orders of magnitude higher than that of gas, the extrapolation of air jet knowledge to the cases of liquid jets should be reviewed with a caution on the foundational research. The key issue is the degree to which jet impingement heat transfer depends on the Prandtl number of working fluid. A

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Nomenclature

A	area of heated surface	Re	$u \cdot 2B/\nu$, Reynolds number
B	slot width of nozzle	u	mean fluid velocity at nozzle exit
C_p	specific heat at constant pressure	x	lateral distance from stagnation point
h	local heat transfer coefficient	Z	nozzle-to-plate spacing
H	height of slot duct		
k	thermal conductivity of fluid	*Greek symbols*	
L	length of potential core	μ	dynamic viscosity
L_1	streamwise length of slot duct	ν	kinematic viscosity
Nu	$h \cdot 2B/k$, local Nusselt number		
Pr	$C_p \cdot \mu/k$, Prandtl number	*Subscript*	
q	heat flux	0	stagnation point

numerical simulation of Prandtl number-dependence was performed by Shi et al. [12]. But the results were confined only to the turbulent flow of slot jet impingement. Effects of the Prandtl number on heat transfers were investigated for circular jets by Ma and coworkers [13] and Lin and Garimella [14], respectively. However, similar studies for laminar slot jets have not yet been published in detail. More experimental studies are required to investigate the influence of the Prandtl numbers and Reynolds numbers on the heat transfer behavior of slot jet impingement.

Furthermore, in the light of increasing applications of microelectronic technology to industries, more attention is directed to micro/meso-scale heat transfers. Very limited information is available for slot jets of meso-scale [15,16], so more work is needed before focusing on heat transfer enhancement with micro-scale jet impingement. The purpose of this work is to provide detailed experimental data for both the study of heat transfer in slot jet impingement and the application of micro-scale technology to heat transfer enhancement.

2. Experimental apparatus and method

The experimental apparatus and procedures in this study are the same as those described in Ref. [17]. Only a detailed description of the jet nozzle assembly is given here. The slot nozzle employed in the present experiments was made of Plexiglas. The configuration of the nozzle is shown in Fig. 1. The rectangular duct of the slot has a streamwise length of 35 mm (L_1), a width of 125 μm (B), and a height of 12 mm (H). The large aspect ratio between height and width eliminates the end effect at the nozzle and leads to a situation of truly two-dimensional planar jets. Great efforts were made to control the parallelism of the upper and lower walls of the slot. The shape and size of the nozzle were each precisely measured with a toolmaker's microscope of 0.001 mm resolution. Also, the slot was reconstructed several times until good quality was obtained. Kerosene was used as a working fluid in experiments with a mean Prandtl number of 29. The uncertainties of the experimental results were within ±6.18% for the Reynolds numbers, ±3.46% for the Prandtl numbers and ±5.19% for the Nusselt numbers. Fully developed laminar flow was kept at the exit of the nozzle, thereby ensuring the correlation as reported in Ref. [18].

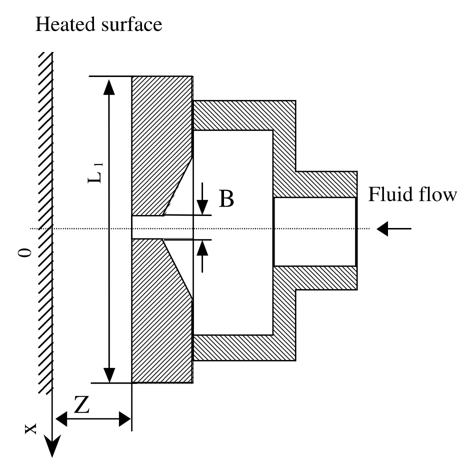

Fig. 1. Slot jet nozzle assembly.

3. Results and discussion

3.1. Stagnation heat transfer

Experimental results of stagnation heat transfer with the variation of the Reynolds number are exhibited in Fig. 2, in which comparisons of several empirical correlations of stagnation heat transfer from the work of Qin [15] and Ma et al. [16] are also plotted. In their works,

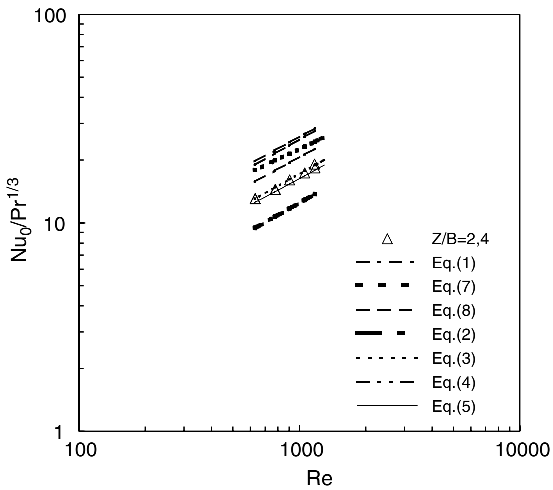

Fig. 2. Correlations of stagnation Nusselt number with Reynolds number.

local heat transfer coefficients were measured and correlated for both FC-72 and transformer oil in submerged slot jets impingement. The following correlation was recommended by Qin [15] for the stagnation heat transfer of FC-72 in a slot width of 210 μm

$$Nu_0 = 0.383Re^{0.577}Pr^{1/3} \tag{1}$$

where $Re = 1800–10{,}000$ and $Pr = 11–12$.

Also, the stagnation heat transfer data were correlated for the transformer oil submerged slot jets of 91 μm, 146 μm and 234 μm in width with $Re = 55–407$ and $Pr = 200–270$ [16]. The correlations are as following:

$$Nu_0 = 0.203Re^{0.596}Pr^{1/3} \quad \text{for } B = 91\ \mu\text{m} \tag{2}$$

$$Nu_0 = 0.28Re^{0.596}Pr^{1/3} \quad \text{for } B = 146\ \mu\text{m} \tag{3}$$

$$Nu_0 = 0.408Re^{0.596}Pr^{1/3} \quad \text{for } B = 234\ \mu\text{m} \tag{4}$$

A good correlation between the Nusselt number, the Reynolds number and the Prandtl number can be obtained for stagnation heat transfer in the present experiment

$$Nu_0 = 0.313Re^{0.573}Pr^{1/3} \tag{5}$$

where based on the previous research by Ma and coworkers [13] for the working fluid of high Prandtl number, an exponential 1/3 for the Prandtl number is adopted. The dependence of the Reynolds number on the Nusselt number is determined by an exponential value of 0.573 which is almost same as those shown in Eqs. (1)–(4). The exponential value 0.573, which is a little higher than the value of 0.5 proposed by laminar flow theory, indicates that there is formation of laminar flow at the stagnation zone and turbulent disturbance for an initially laminar jet. As shown in Fig. 2, good agreements within a deviation of ±4.5% between the present data and Eq. (3) can be observed.

As reported in the studies of Ma et al. [16], nozzle geometry creates a definite functional relationship between the stagnation Nusselt number and the jet Reynolds number. Stagnation heat transfer rates increase with the increase in nozzle size of the slot jet, which is consistent with the present study and the experimental results of the planar air jets reported elsewhere [9]. It was reported by Gondon and Akfirat [9] that this feature may result from a reduction of the turbulence. However, to the best of our knowledge, there is no detailed information on the turbulence intensity for slot jets at an initially laminar flow. Further research is required for the understanding of turbulence on the laminar slot jet, particularly for the slot liquid jets of meso-scale.

Present correlation concerning stagnation line heat transfer is also compared with the correlation developed for free-surface slot jets. Based on previous studies, a stagnation heat transfer correlation was recommended for free-surface planar jets with $Pr = 0.7-10$ by Vader et al. [3]

$$Nu_0 = 0.505Re^{0.5}Pr^{0.376} \tag{6}$$

This correlation has been verified with the experimental data reported by Inada et al. [2] at $Re = 940$ for low-turbulence water jets with near-uniform velocity profiles. For a large liquid Prandtl number, Eq. (6) may be modified by altering the exponential of the Prandtl number from 0.376 to 1/3

$$Nu_0 = 0.505Re^{0.5}Pr^{1/3} \tag{7}$$

The power of 1/3 was recommended for large liquid jet Prandtl numbers by Ma and coworkers [19]. The correlation curve (7) is shown in Fig. 2. The experimental data are also compared with the empirical correlation presented for water jets of 10 mm in width at $Re = 2\times10^4–9\times10^4$ by Vader et al. [3] after the same modification in the Prandtl number dependence

$$Nu_0 = 0.28Re^{0.58}Pr^{1/3} \tag{8}$$

A somewhat higher deviation is observed between the present data and Eqs. (7) and (8) as shown in Fig. 2. On considering the significant differences in fluid Prandtl number, Reynolds number and nozzle geometry between these investigations, the discrepancy between Eqs. (1)–(4), (7), (8) and the present data is acceptable.

The effect of nozzle-to-plate spacing on the heat transfer at the stagnation line is illustrated in Fig. 3, where the Nusselt number Nu_0 at the stagnation line is plotted as a function of the dimensionless separation Z/B with the Reynolds numbers ranging from 600 to 1200. It can be seen from the figure that the variations of Nu_0 with Z/B, which is not monotonic, exhibit a complex nature depending on the jet Reynolds number. Within a definite dimensionless separation Z/B, called

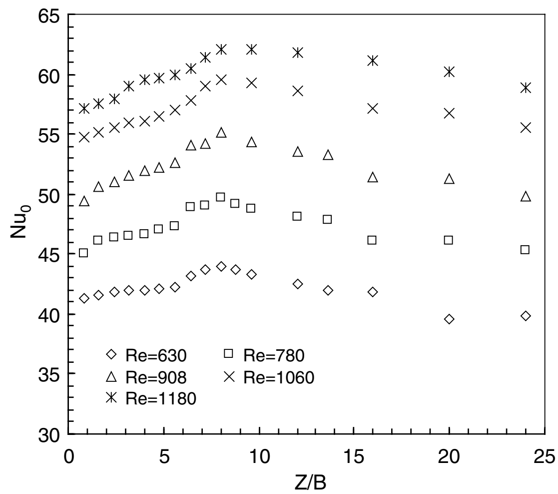

Fig. 3. Variation of stagnation Nusselt number with nozzle-to-plate spacing.

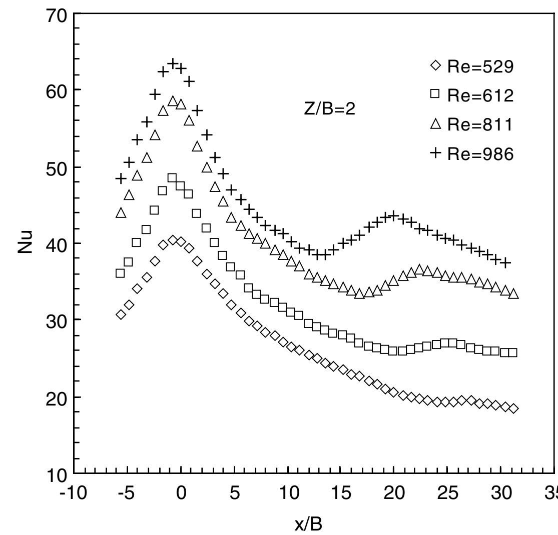

Fig. 4. Lateral variation of local heat transfer coefficient at $Z/B = 2$.

the potential core length L/B, the Nusselt number increases essentially with nozzle-to-plate spacing Z/B to a maximum. The values of L/B corresponding to a maximum Nusselt numbers are determined approximately from the experimental data to be 8 for the present work. Beyond the dimensionless spacing length, a general diminution of heat transfer coefficient is observed with increasing of separation distance. This trend is consistent with the results reported for the planar jets [9–11,15,16,20] and the circular jets [17,19,21].

3.2. Lateral variation of local heat transfer

Lateral variations of local heat transfer were measured with the same slot nozzle. The effects of Reynolds number and nozzle-to-plate spacing were examined experimentally. The experimental results in a range of Reynolds numbers $Re = 529-986$ and nozzle-to-plate spacings $Z/B = 2-20$ are plotted in Figs. 4 and 5.

Lateral distribution of local heat transfer coefficients is exhibited in Figs. 4 and 5, in which the profiles are generally of a bell shape with a peak appearing at the stagnation line. The heat transfer coefficients decrease monotonically with increasing lateral distance from the stagnation line, which results from the thickening of the wall-jet flow boundary layer along the target surface.

In Fig. 4, it is seen that the local heat transfer coefficients increase with increasing Reynolds numbers for a nozzle-to-plate spacing. An interesting phenomenon may be found that a second peak of local heat transfer coefficients appears at some special position from the stagnation line for higher Reynolds numbers, whereas there is nothing special when nozzle-to-plate spacing Z/B exceeds 8.

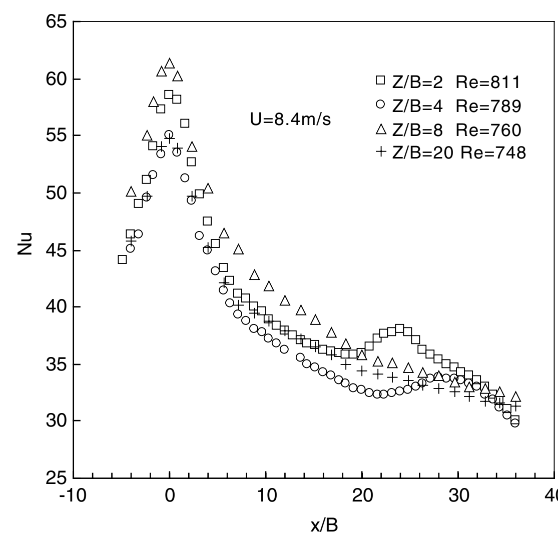

Fig. 5. Lateral distribution of Nusselt number with different Z/B at $U = 8.4$ m/s.

As illustrated in Fig. 4, the hump profiles of the curves are clearly observed at different Reynolds numbers. The local Nusselt number declines from the stagnation line to a minimum and then increases with the increase in the lateral distance to a second peak value. Beyond this peak the local heat transfer coefficient decreases again. Similar heat transfer phenomena were reported for planar air jets by Sparrow and Wong [20] and for the transformer oil slot jets by Ma et al. [16]. This effect is attributed to the free stream turbulence generated by mixing of the impingement flow with the quiescent environment or the possible transition from a laminar to a turbulent regime. The maximum and minimum of local heat transfer coefficients might be symptoms of the onset and completion, respectively, of the possible transition. From the present data, the length between the two points above is determined to be between 400 μm and 500 μm.

The influence of nozzle-to-plate spacing is illustrated in Fig. 5, in which for a jet velocity, local heat transfer profiles increase with increasing nozzle-to-plate spacing to a maximum at $Z/B = 8$, then decrease gradually. It may be well explained by the influence of the arrival velocity coupled with turbulence intensity.

4. Conclusions

Experimental study was performed to investigate the heat transfer with impinging kerosene slot jets of mesoscale ($B = 125\,\mu m$) with Reynolds numbers ranging from 600 to 1200.

1. The stagnation heat transfer coefficient with heated surface within potential core can be well correlated by Eq. (5) for the present work.
2. Local heat transfer enhancement appeared with higher Reynolds number and smaller nozzle-to-plate spacing in present experiment. Non-monotonic variations of Nusselt number with lateral distance, Reynolds number and nozzle-to-plate spacing were examined and ascribed to possible transition from laminar to turbulent regime.

Acknowledgements

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