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Na And NaK Laminar And Turbulent Flows And Heat Transfer Within Rectangular Minichannel Heat Sinks

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ABSTRACT

3-D numerical simulations are performed to study conjugate heat transfer of Na and NaK laminar and turbulent flows within rectangular minichannel heat sink with hydraulic diameters of less than 5 mm. Nusselt numbers and pressure drop values within steel minichannel heat sinks of different aspect ratios are obtained through numerical simulations at Reynolds number range of 600-20000. The Effects of minichannel geometrical properties such as aspect ratio and hydraulic diameter on pressure drop and heat transfer are investigated in detail. General correlations for friction factor and Nusselt numbers are proposed for minichannel heat sinks with hydraulic diameters less than 5 mm.

1 INTRODUCTION

Miniature heat sinks have been widely used for heat management of compact microelectronic packages in two recent decades. These small-scale heat sinks operate with minimum amount of coolant while they are durable with long service life. However, the liquid coolant flow regime within these small-scale heat sinks is usually restricted to laminar due to large pumping power required to reach turbulent flow at higher Reynolds numbers. Surface area to volume ratio is large in micro-scale heat sinks and this leads to higher friction and higher pressure drops. On the other hand, minichannel heat sinks provide relatively large area to volume ratio that enables them to handle high heat dissipation rates. Moreover, minichannel heat sinks have larger hydraulic diameters than microchannel heat sinks leading to less pressure drop. Therefore, it is feasible to have turbulent flow regime within minichannel heat sinks with much higher local heat transfer rates than in laminar flow. Many published research works are available in the literature on Na and NaK flows and heat transfer within big macro-scale devices [1–5]. However, a few works have been reported in the open literature so far on liquid metals heat transfer within mini-scale heat exchangers of hydraulic diameters less than 5 mm. Zhang et al. [6] conducted experiments to study GaInSn flow and heat transfer within a copper minichannel heat sink. The investigated minichannel had a height of 5 mm, width of 1 mm and length of 34 mm. GaInSn was used as the working fluid with inlet temperature of 29 ^oC while the applied heat flux to the heat sink was 300 W/cm^2. The flow Reynolds number covered the range of 1250 to 3750. Reported experimental values of Nusselt numbers for the laminar flow

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was a weak function of Reynolds number while they were 50% lower than the theoretical fully developed laminar Nusselt numbers. Pourghasemi et al. [7-9] studied laminar NaK flows and heat transfer in different miniature heat sinks. Obtained results showed that the Nusselt numbers decreased as the microchannel aspect ratio increased. Luo and Liu [10] conducted experiments to investigate heat transfer of GaInSn within compact and miniaturized heat sinks with a hydraulic diameter range of 0.91 to 2.87 mm for microelectronics cooling applications. Obtained Nusselt numbers were observed to increase with increased Peclet number for laminar flow. A new correlation was proposed to estimate Nusselt number as a function of Peclet number.

Minichannel heat sinks can be utilized in applications where "space" and "weight" are two main constraints while "usual" size channels cannot be used. Turbulent forced-convection of liquid coolants can be generated in mini-channels heat sinks while it is not feasible to have turbulent flows of liquid coolants within micro-channel heat sinks due to relatively required high pumping power and sealing issue. Therefore, the main purpose of this research work is to study laminar and turbulent flows and heat transfer of Na and NaK in rectangular mini-scale heat sinks of hydraulic diameter less than 5 mm. Nusselt numbers and pressure drop values within steel minichannel heat sinks are obtained through 3-D numerical simulations at Reynolds number range of 600-20000. Effects of minichannel geometrical properties such as aspect ratio and hydraulic diameter on pressure drop and heat transfer are investigated in detail. General correlations for friction factor and Nusselt numbers are proposed for minichannel heat sinks with hydraulic diameters less than 5 mm.

2 NUMERICAL APPROACH

The Ansys Fluent CFD solver is used to numerically solve the continuity, the momentum and the energy equations with mass flow inlet and pressure outlet boundary conditions. The governing equations are discretized using a finite volume method on a collocated grid scheme. Discretized equations are solved using a quasi-steady coupled solver scheme while a second-order upwind interpolation scheme is applied to convection terms. All thermophysical properties used in these computational analyses were applied from the reported experimental values as a function of temperature [11].All the performed numerical simulations in this work have been done for steady-state condition.

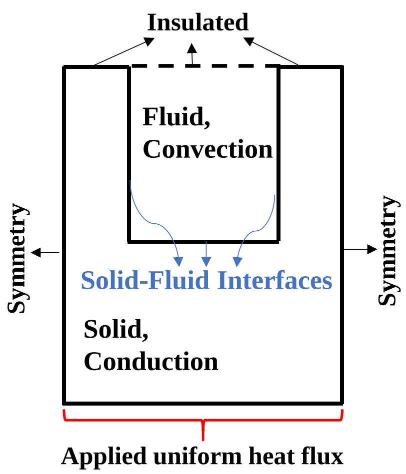

Figure 1: Conjugate heat transfer at the solid-fluid interfaces in a small-scale heat sink

Figure 1 illustrates the schematic of modelled miniature heat sink and applied boundary conditions in the present work. The following numerical procedure is implemented in the performed numerical simulations in this work to capture conjugate heat transfer phenomenon within a miniature heat sink. First, at the fluid-solid interface within miniature hat sink, the continuity of heat flux and temperature are imposed using Equation (1).

$$T_f = T_s; \qquad k_f \nabla T_f = k_s \nabla \mathrm{T}_s \tag{1}$$

When the solution for a performed steady state numerical simulation is converged, the following procedure is used to calculate the local and average Nusselt numbers. At any location z, along the modelled heat sink, the average fluid bulk temperature $T_b(z)$, average wall temperature $T_w(z)$, and average wall heat flux, $q_w(z)$ are calculated through Equations (2)-(4). C_p, represents liquid coolant specific heat capacity in *(J/kgK)*, ρ is the coolant density in *(kg/m^3.)*

$$T_b(z) = \frac{\int \rho u C_p T_f dA}{\int \rho u C_p dA} \tag{2}$$

$$T_w(z) = \frac{\{\oint T_w(x,y,z) ds\}_{walls}}{\{\oint ds\}_{walls}} \tag{3}$$

$$q_w(z) = \frac{\{\oint q_w(x,y,z) ds\}_{walls}}{\{\oint ds\}_{walls}} \tag{4}$$

The average local Nusselt number at any location z, along the minichannel is then calculated through Equation (5).

$$Nu(z) = \frac{q_w(z)\, D_h}{k_b(z)\, [T_w(z) - T_b(z)]} \tag{5}$$

where, D_h is the heat sink hydraulic diameter in *(m)* and $k_b(z)$ is the fluid thermal conductivity in *(W/mK)*. that is evaluated at the local fluid bulk temperature $T_b(z)$ The average Nusselt number for whole heat sink, Nu_{ave}, is calculated by taking the integral of local Nusselt number over the heat sink length of L, using Eq. (6).

$$Nu_{ave} = \frac{\int_0^L Nu(z) dz}{L} \tag{6}$$

The accuracy of the discussed numerical procedure (Eqs. (1) to (6)) to investigate convective heat transfer of liquid metals in miniature heat sinks has been verified in the previous published work by the same authors [7]

3. RESULTS

3.1 Na and NaK Flows and Heat Transfer Within Minichannel Heat Sinks

Turbulent and laminar flows and heat transfer of Na and NaK within several minichannel heat sinks of different hydraulic diameters and aspect ratios are investigated in this section. The aspect ratio of a minichannel (α) in this study represents the ratio between minichannel width and its height. Investigated hydraulic diameters and aspect ratios cover the range of 0.33 mm to 2.33 mm and 0.143 to 1, respectively. 15 inflation layers with growth rate of 1.2- and first-layer thickness of 1 µm have been applied to the minichannel walls in order to capture properly the temperature and velocity gradients during the simulations. Total number of mesh elements in the implemented mesh grid configuration, is 7.1 millions. The implemented SST *K*-ω turbulent model as well as the described mesh grid configuration was proven to accurately predict heat transfer rate and pressure drop within liquid-metal cooled miniature heat sinks [7]

Figure 2 represents the obtained friction factors for turbulent and laminar flows of Na and NaK within different minichannels. Friction factors are calculated using the obtained results of pressure drops from numerical simulations. The Darcy friction factors presented in Figure 2, have been calculated using equation (7):

$$f = \frac{2\Delta P\ D_h}{\rho L V^2} \tag{7}$$

Where, ΔP is the pressure drop along the minichannel heat sins, L is the length of the minichannel heat sink, V is the average velocity of the coolant obtained from coolant mass flow rate. ρ is the coolant density and D_h is the minichannel hydraulic diameter. It can be sen from Figure 2 that in the laminar flow regime, the friction factors can be estimated using f = $(34.4/\mathrm{Rein})^{0.798}$. This correlation falls within $\pm$10 % of obtained numerical results. Moreover, in the turbulent flow regime, the friction factors can be calculated using f = $0.502/(\mathrm{Rein})^{0.298}$.

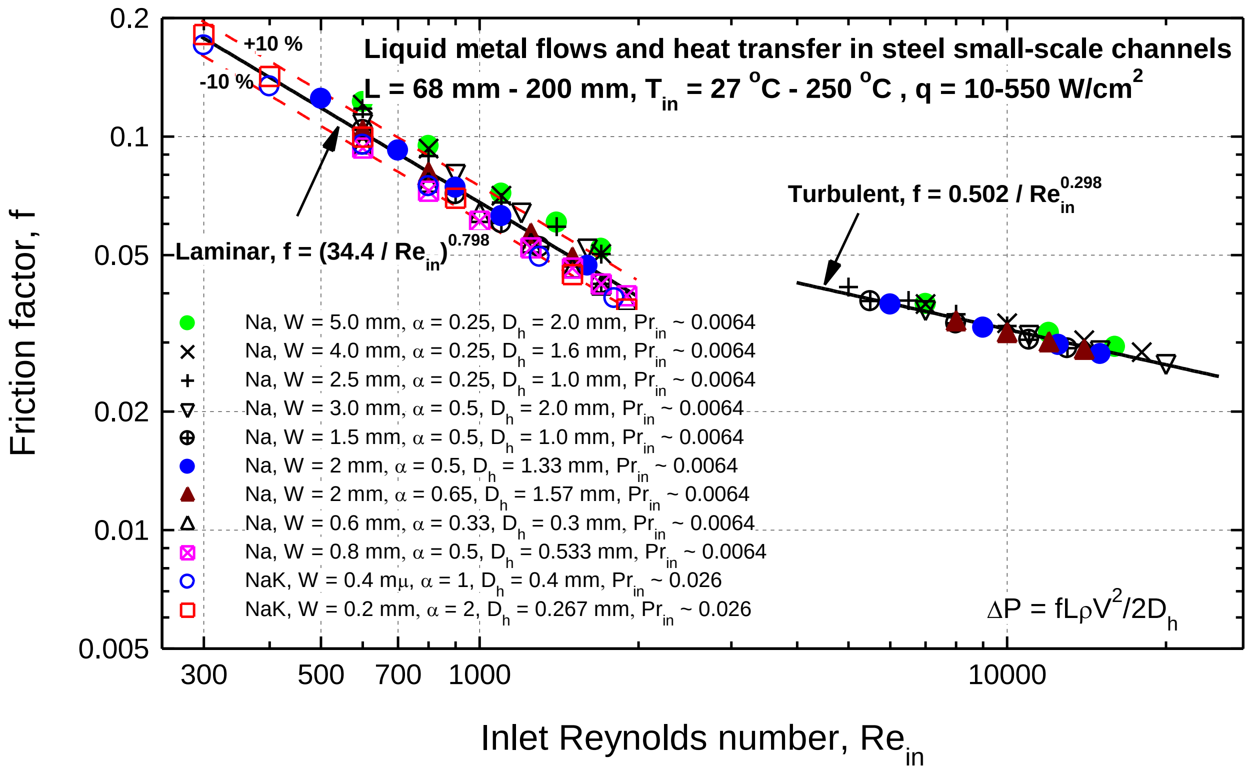

Figure 2: Friction factors for laminar and turbulent flows of Na and NaK within minichannel heat sinks

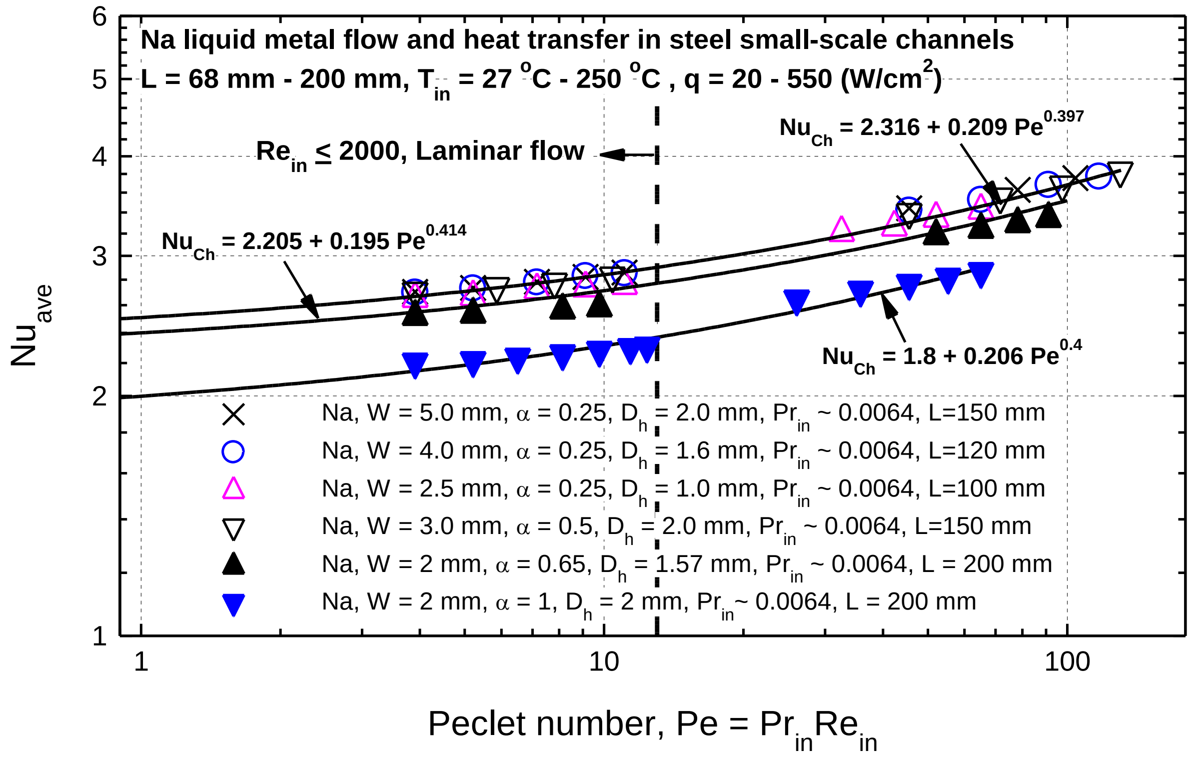

Figure 3: Average Nusselt numbers for laminar and turbulent flows of Na and NaK within minichannel heat sinks

Figure 3 illustrates the obtained average Nusselt numbers within minichannels of different aspect ratios and hydraulic diameters. As it can be inferred from Figure 3, for the same aspect ratio, the obtained average Nusselt numbers are independent of the minichannel hydraulic diameter. However, the average Nusselt number changes by changing the minichannel aspect ratio. Minichannel length, hydraulic diameter and aspect ratio are used in Figure 4, to propose a general dimensionless correlation to estimate average Nusselt numbers of Na laminar and turbulent flows within minichannel heat sinks of different geometrical parameters.

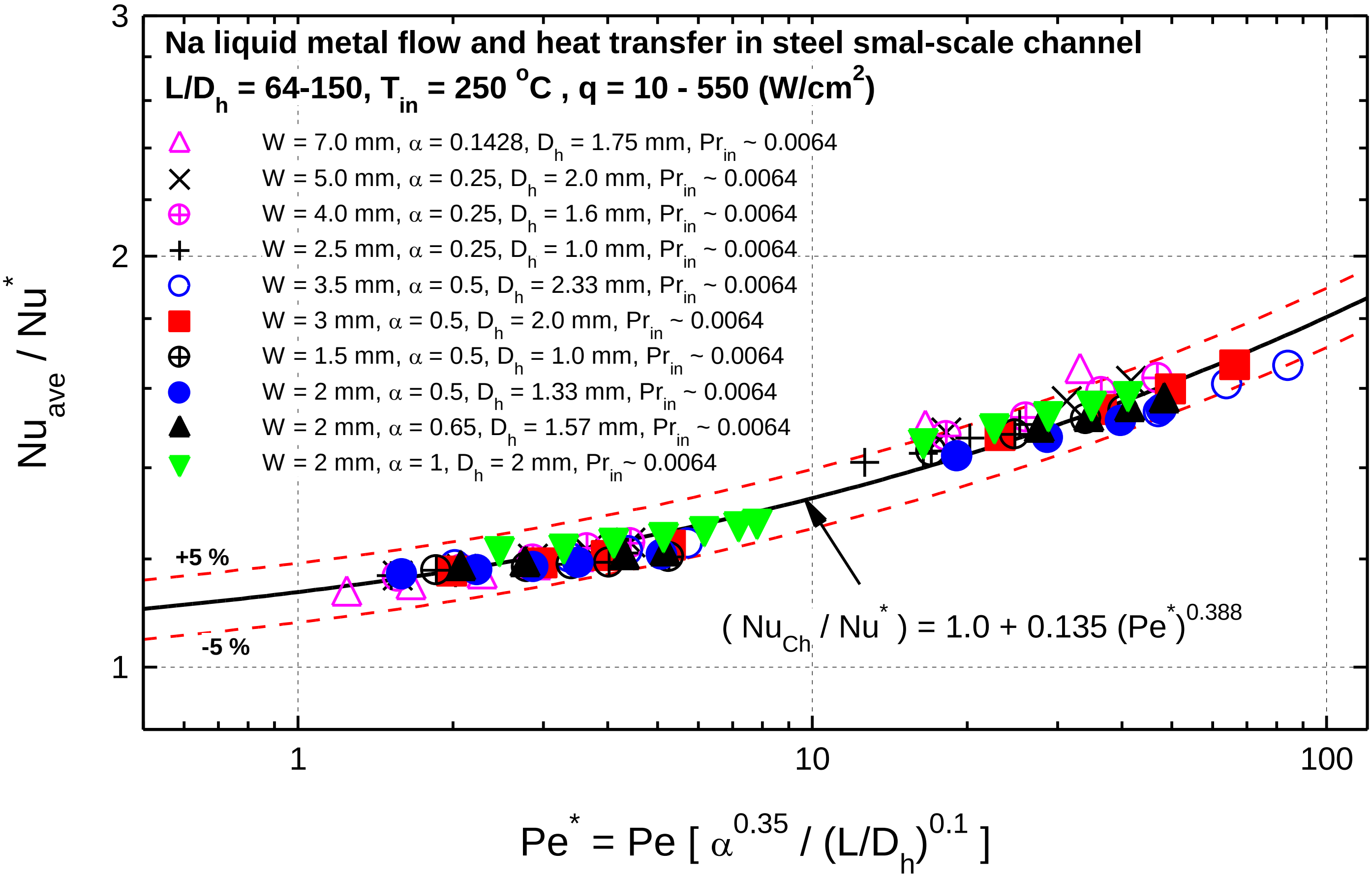

Figure 4: The general dimensionless corelation to estimate average Nusselt numbers for laminar and turbulent flows of Na within minichannel of different aspect ratios, length, and hydraulic diameters.

Figure 4 presents the obtained dimensionless correlation to predict liquid sodium Nusselt numbers within rectangular minichannel heat sinks of different hydraulic diameters and aspect ratios. The presented correlation falls within $\pm$ 5 % of the numerical data. *Pe* in the Figure 4, represents the Peclet number defining flow Reynolds number times the coolant Prandtl number. Nu^* represents the average Nusselt number within a minichannel when the Peclet number approaches a very small number (see figure 3). Value of Nu* for a minichannel with specific hydraulic dimeter, length and aspect ratio can be obtained from Figure 5.

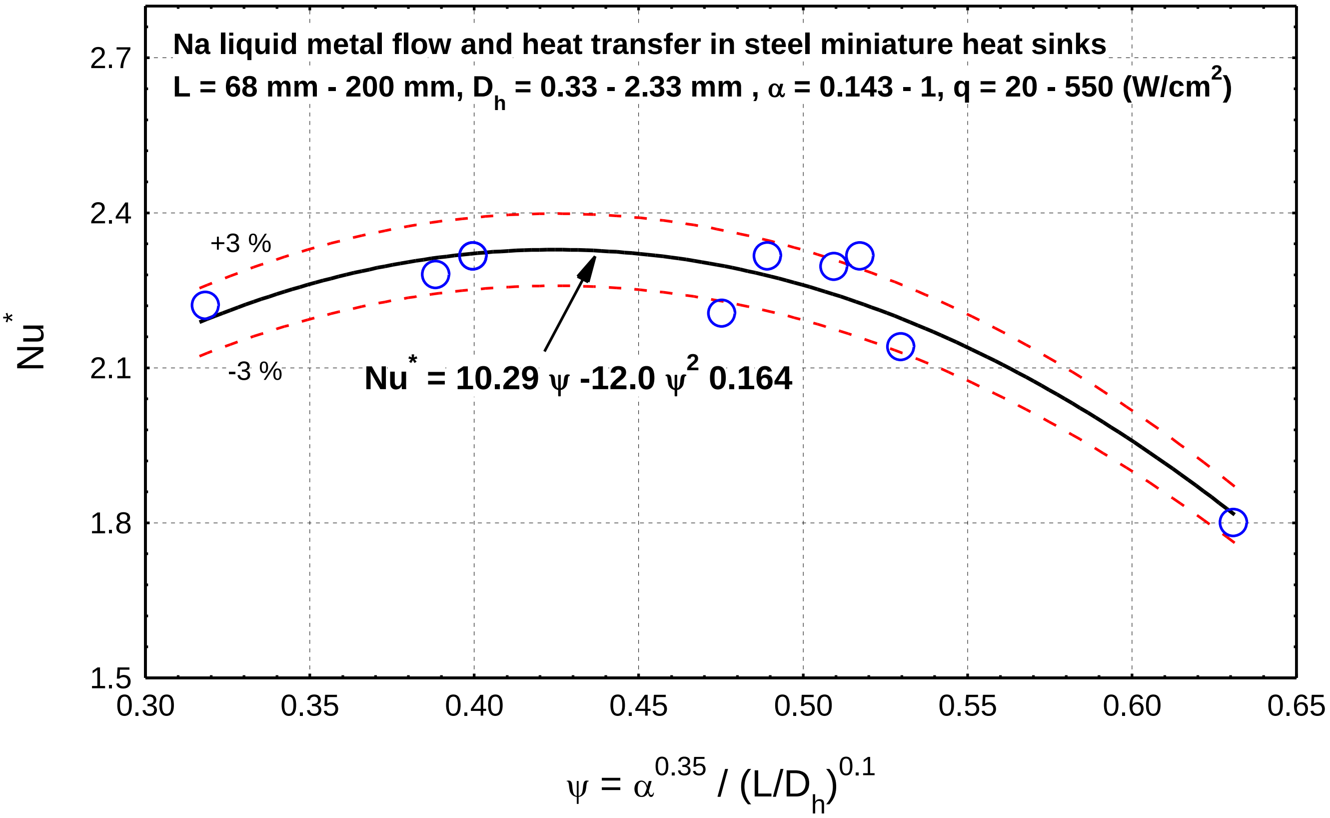

Figure 5: Nu* as a function of minichannel heat sink geometrical parameters for laminar and turbulent flows of Na.

3 CONCLUSION

Laminar and turbulent flows and heat transfer of Na and NaK within minichannel heat sinks of different aspect ratios and hydraulic diameters have been investigated in this research. The performed numerical simulations cover the aspect ratios in the range of 0.143-1 and hydraulic diameters in the range of 0.33 mm to 2.33 mm. General correlations have been proposed to obtain the friction factors and average Nusselt numbers for Na and NaK flows within investigated minichannel heat sinks. The presented correlations provide a useful tool for engineers to design and optimize Na cooled minichannel heat sinks for different cooling applications.

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