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Numerical Study On Convective Heat Transfer Of Liquid Sodium (Na) In Refractory High Entropy Alloy (RHEAs)-Based Miniature Heat

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ABSTRACT

3-D numerical simulations are performed to investigate liquid sodium (Na) turbulent flows and heat transfer within a copper minichannel heat sink with width of 48 mm, height of 14 mm and hydraulic diameter of 21.7 mm. Stainless steel (SS-316), RHEAs and Inconel claddings with different thicknesses are applied to the minichannel walls to protect copper walls from the corrosive liquid sodium (Na). Three thickness values of 1 mm, 2 mm and 4 mm with thermal conductivity range of 5-17 W/mK are numerically studied for cladding layers while the average Nusselt numbers are compared together to find the optimum cladding thickness.

1 INTRODUCTION

Liquid metal cooled miniature heat sinks can handle high heat dissipation rates and tolerate extreme working temperatures due to large boiling points of liquid metals. Miniature heat sinks can be utilized for different applications from microelectronic cooling to fission batteries [1,2]. A typical straight miniature heat sink consists of several parallel channels fabricated on top of a base solid block. Miniature heat sinks are often in direct contact with hot surfaces to remove heat. Therefore, dissipated heat first diffuses within the base solid block and eventually is transferred to the coolant flowing within channels of the heat sink. This is a conjugate heat transfer phenomenon with temperature and heat flux continuity boundary conditions at the solid fluid interfaces at the heat sink channel walls. Local wall temperature and heat flux distributions along the channel walls of a heat sink determine the local heat transfer rates and Nusselt number values. Flow and heat transfer of conventional coolants such as water and air have been extensively studied in the literature so far. Experiments and numerical simulations were performed to investigate thermal-hydraulic performance of water-cooled copper minichannel heat sinks [3,4]. Ghasemi et al. [5] performed both numerical and experimental investigations to study water flow within aluminium circular minichannel heat sinks. The investigated heat sinks consisted of 4 channels with length of 60 mm and hydraulic diameter range of 4 mm-8 mm. Reported experimental and numerical results suggested that the minichannel with smallest hydraulic diameter of 4 mm had highest convective heat transfer coefficients for a given volume flow rate. On the other hand, at a given volume flow rate, the minichannel with smallest hydraulic diameter of 4 mm resulted in highest pressure drop and corresponding highest pumping power. Tikadar et al. [6] investigated the effect of secondary flow on the thermal-hydraulic performance of counter-flow rectangular minichannel heat sinks. Secondary flow was generated by two inter-connectors between two contour flow streams. Reported numerical results for interconnected minichannel heat sinks showed 48.37 % reduction in pressure drop and maximum of 42% enhancement in thermal-hydraulic performance of inter-connected counter flow minichannel heat sinks in comparison with an identical conventional counter-flow minichannel heat sink. Saeed and Kim [7] performed experimental and numerical simulations to study the effect of Al_2O_3-water nanofluid on the thermal performance of rectangular minichannel heat sinks. Maximum of 31.1% enhancement in the convective heat transfer coefficient was observed using Al2O3-water nanofluid as the coolant in comparison with pure water.

Besides water and other conventional coolants such as air and ethanol, liquid metals with high thermal conductivity values and high boiling temperatures are efficient coolants for applications involving elevated working temperatures. Low Prandtl numbers of liquid metals result in relatively small flow Peclet numbers within miniature heat sinks. Heat conduction can play a significant role in low Peclet number flows in miniature heat sink by affecting local wall temperature and heat flux distributions. Laminar flow and heat transfer of NaK in microchannel heat sinks with different aspect ratios was investigated by Pourghasemi et al. [2, 10, 11]. Obtained average Nusselt numbers was observed to reduce as the microchannel aspect ratio increased. Muhammad et al. [8] performed numerical simulations to study laminar flow and heat transfer for liquid metals of GaIn, GaSn, EGaIn, EGaInSn within a miniature heat sink with width of 1 mm, height of 4 mm and length of 40 mm. Reported results showed that EGaIn leaded to the lowest pressure loss while EGaInSn required the highest pumping power. The GaIn was observed to produce the highest heat transfer rate among all the investigated liquid metals.

Liquid metals such as Na are corrosive and react with most of commonly used high thermal conductivity solid materials used to fabricate small-scale heat sinks such as copper. To address this problem, we propose to add a thin layer of corrosive resistance material to the walls of copper-based miniature heat sinks. Therefore, the purpose of this research is to develop a reliable numerical model to investigate fluid flow and heat transfer of Na within copper-based miniature heat sinks while thin layers of SS-316, Inconel 718 and RHEA is cladded on the heat sink walls. Local and average Nusselt numbers are calculated to study the effect of cladding layer presence on the thermal-hydraulic performance of investigated miniature heat sinks. Turbulent flows of Na are investigated at the Reynolds number of 10000.

2 NUMERICAL APPROACH

The 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 the 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 [9].

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

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 the following boundary conditions, Eq (1). The interface is at the miniature channel walls where heat in transferred from the cladding layer to the Na flow (see Figure 1). Figure 1 illustrates the schematic of modelled miniature heat sink and applied boundary conditions in the present work.

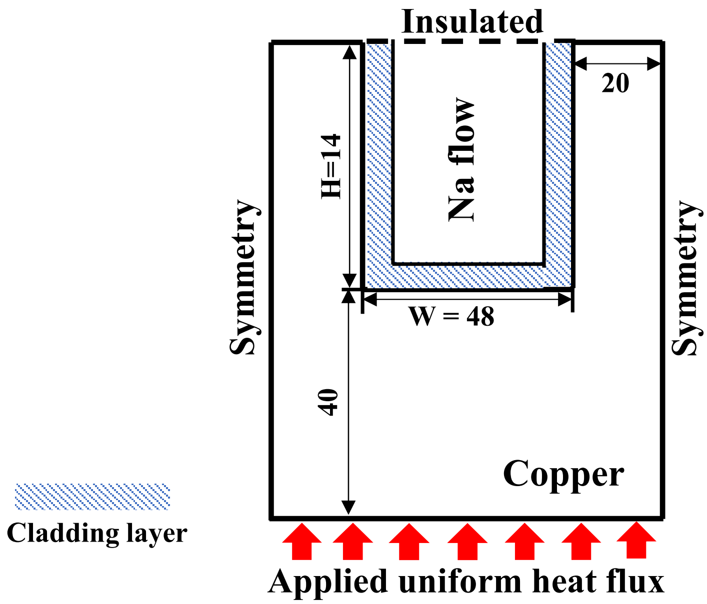

Figure 1: Schematic of a Na-cooled miniature heat sink with a cladding layer. (All dimensions are in mm)

When the solution for a performed steady state numerical simulation is converged, the following procedure is then used to calculate the local and average Nusselt numbers within the modelled miniature heat sink.

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

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

x, y, and z define spatial variables while z is along the heat sink. 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}*.)*

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

The average local Nusselt number at any location z, along the heat sink 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 and reliability of the discussed numerical procedure (Eqs. (1) to (6))to investigate conjugate heat transfer within liquid-metal cooled heat sinks has been verified by authors in their previous work [2]

3 RESULTS

3.1 Na flows and heat transfer within minichannel heat sinks

Turbulent flows and heat transfer of Na within a cladded copper-based minichannel heat are investigated in this section. The copper-based minichannel heat sink has width of 48 mm, height of 14 mm, length of 800 mm and hydraulic diameter of 21.7 mm. Aspect ratio of the minichannel is defined as the ratio between minichannel height and its width (α=H/W, See Fig. 1) which is ~0.29 for the investigated minichannel. Three thin layers of stainless steel (SS-316), Inconel 718 and RHEA with thickness of 1 mm, 2 mm and 4 mm are considered as the cladding layer at the minichannel walls (See Figure 1). The effect of cladding layers on the heat transfer within the described minichannel heat sink is modelled using shell conduction concept. Shell conduction concept is usually used to model heat transfer through thin metal sheets in numerical simulations without adding thin metal sheets into the modelled geometry that can reduce computational cost. Figures 2 and 4 illustrate the obtained results for local Nusselt numbers of SS-316, RHEA and Inconel 718 cladding layers of thickness 2 mm. The thermal conductivity for RHEA is considered as 5 *W/mK* while it is assumed 10 *W/mK* and 17 *W/mK* for Inconel 718 and SS-316, respectively. The liquid sodium (Na) flow Reynolds number is 10,000. SST K-W model with turbulent Prandtl number of 4.11 is used to numerically model the turbulent flow at Reynolds number of 10,000. The SST K-W model was shown by authors to accurately capture temperature and velocity gradients for liquid metals turbulent flows and heat transfer within miniature heat sinks [2].

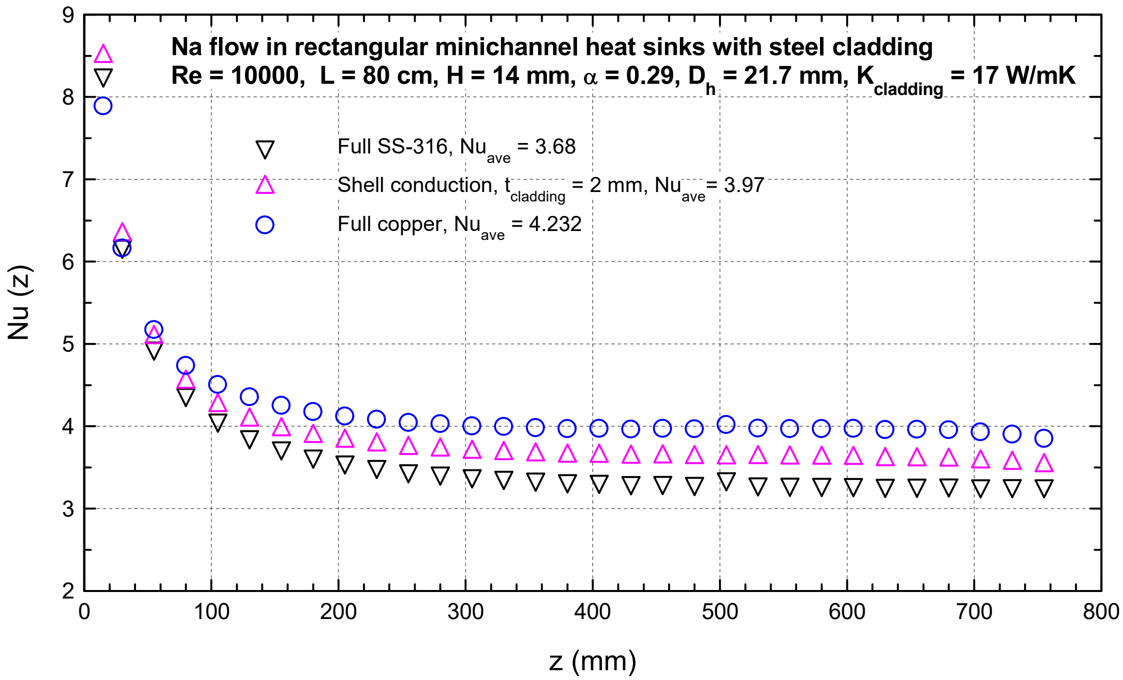

Figure 2: Local Nusselt numbers for Na flow at Reynolds number of 10,000 within a minichannel with 2 mm of SS-316 cladding layer

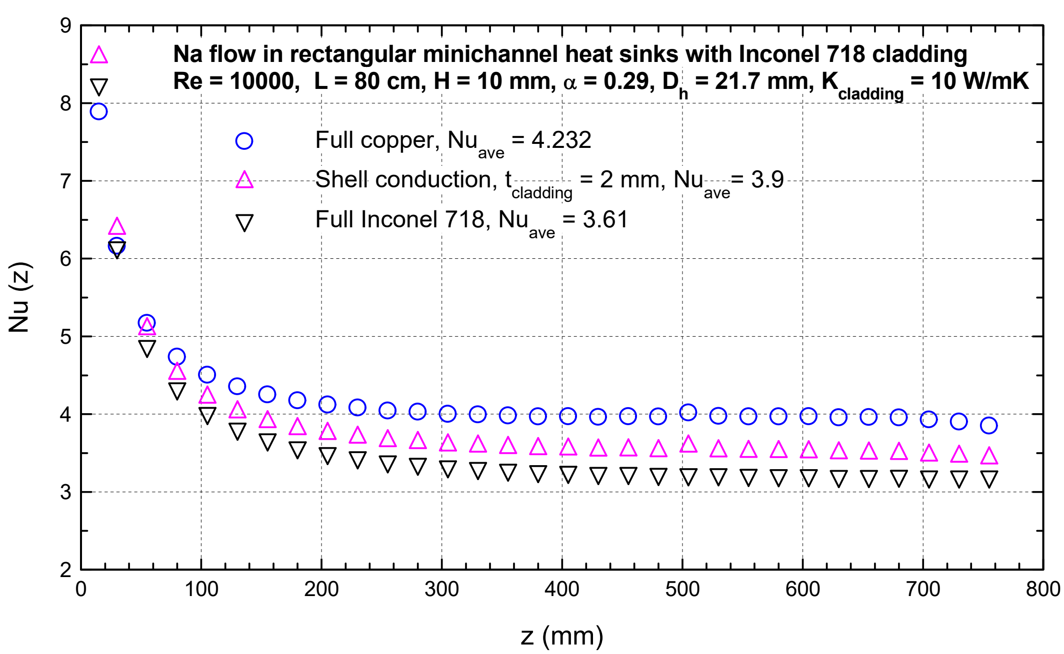

Figure 3: Local Nusselt numbers for Na flow at Reynolds number of 10,000 within a minichannel with 2 mm of Inconel 718 cladding layer

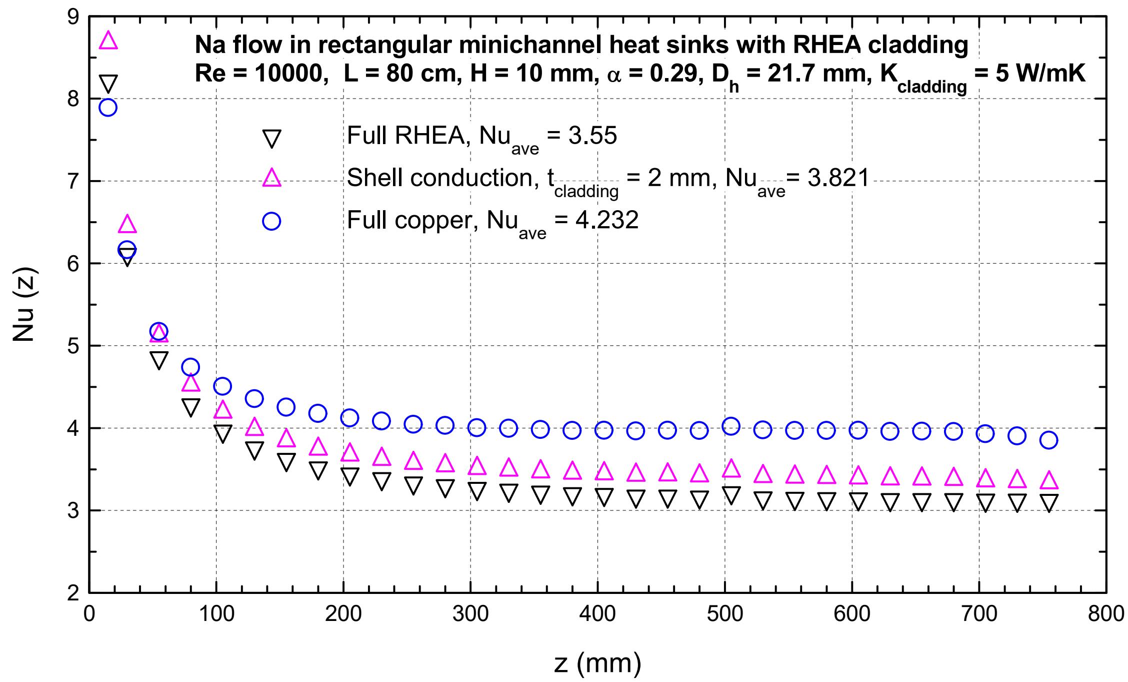

Figure 4: Local Nusselt numbers for Na flow at Reynolds number of 10,000 within a minichannel with 2 mm of RHEA cladding layer

As it can be seen from Figures 2 to 4, the full copper-based minichannel heat sink has the highest local and average Nusselt numbers. The full Inconel 718 and RHEA based minichannel heat sinks provided the lowest local and average Nusselt numbers while Nusselt numbers for cladded minichannel heat sinks fall in the middle. Table 1 shows the obtained extended results of average Nusselt numbers from the performed numerical simulations for 3 different thicknesses and thermal conductivity coefficients of cladding layers.

Table 1: Average Nusselt numbers for a copper-based minichannel heat sink with different cladding configurations

Case	Nu_{ave} (without cladding)	Nu_{ave} (copper + cladding)		
		$t_{cladding}$ = 4 mm	$t_{cladding}$ = 2 mm	$t_{cladding}$ = 1 mm
Copper, K = 400 W/mK	4.32	----	---	---
SS-316, K = 17 W/mK	3.68	3.89	3.97	4.051
Inconel 718, K = 10 W/mK	3.61	3.82	3.9	3.982
RHEA, K = 5 W/mK	3.55	3.77	3.821	3.891

As it is expected, the average Nusselt number in the cladded minichannel heat sink approaches the value for Nusselt number in full copper based minichannel heat sink as the thickness of the cladding layer is reduced from 4 mm to 1 mm (see Table 1). Figure 5 reports the enhancement in the convective heat transfer rate (cladding efficiency) in the cladded minichannel heat sink compared with full SS_316, Inconel 718 and RHEA based minichannel heat sinks.

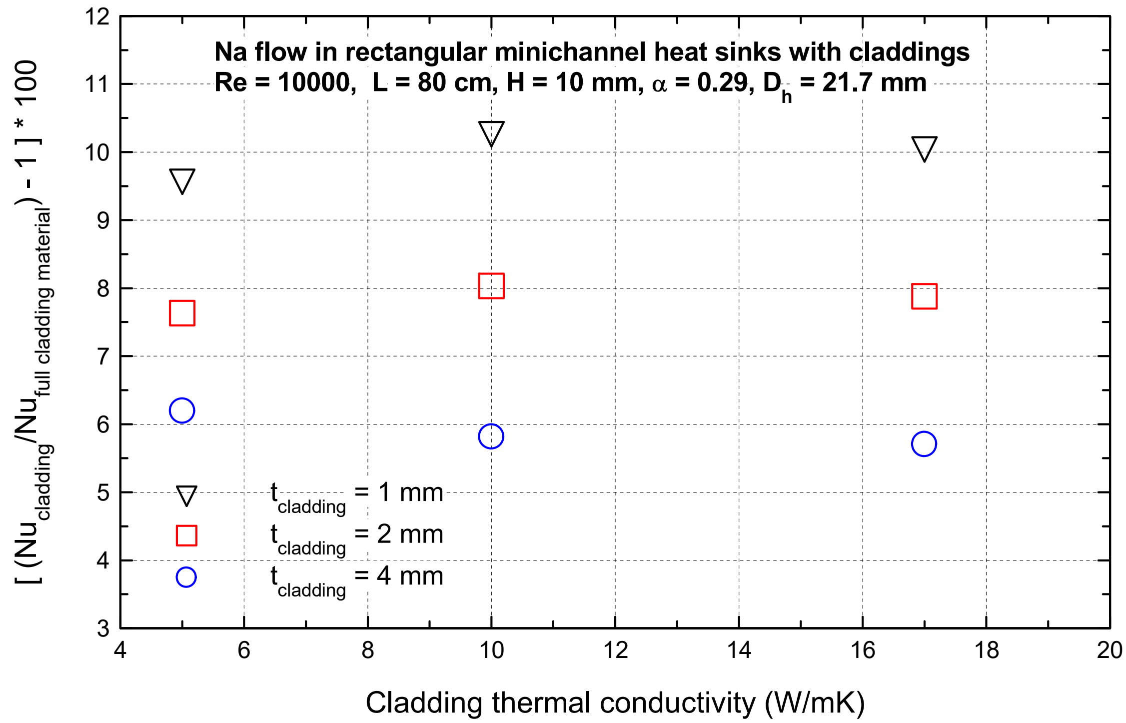

Figure 5: Cladding efficiency in the investigated minichannel heat sinks

For the investigated thicknesses of the cladding layers in the present work, Figure 5 confirms that a cladding layer of 1 mm thick with thermal conductivity of 10 W/mK results in the highest enhancement in convective heat transfer rate. The enhancement in the heat transfer rate is almost 10.5 % in comparison with a similar minichannel heat sink fabricated totally from Inconel 718 with thermal conductivity of 10 W/mK. Inconel 718 and RHEA are more expensive than the copper and therefore the concept of copper-based cladded minichannel heat sink proposed and investigated in this research can reduce total cost in real world applications of miniature heat sinks in extreme working temperatures and high heat dissipation rates.

4 CONCLUSION

Turbulent flows and heat transfer of liquid sodium (Na) within a copper-based cladded minichannel heat sinks have been investigated numerically in the present work. The investigated minichannel heat sink had the aspect ratio of 0.29, length of 800 mm and hydraulic diameter of 21.7 mm. Cladding layers with thickness range of 1 mm – 4 mm and thermal conductivity range of 5 – 17 W/mK were applied to the minichannel walls to protect the copper from corrosive liquid sodium. The thermal conductivity range was chosen such that the cladding layer resembled SS-316, RHEA and Inconel 718. The obtained results showed that the cladding layer of 1 mm thick with thermal conductivity of 10 W/mK provided the highest thermal efficiency. Inconel 718 and RHEA are more expensive than the copper and therefore the concept of copper-based cladded minichannel heat sink proposed and investigated in this research can reduce total cost in real world applications of miniature heat sinks with high working temperatures and high heat dissipation rates.

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