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Thermal efficiency of protective cladding layers in liquid sodium-cooled heat sinks with sharp corners

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ABSTRACT

Na-cooled rectangular and pentagonal minichannel heat sinks with corrosion-resistant cladded layers are investigated in this work. The pentagonal heat sink has a length scale of *a* = 13 mm and, a hydraulic diameter of 14.9 mm with a vertex angle of θ = 60 degrees. The rectangular minichannel has a height of 14 mm, an aspect ratio of 0.635 and a hydraulic diameter of 17.1 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). Four thickness values of 0.5mm, 1 mm, 2 mm, and 4.5 mm with a thermal conductivity range of 4-17 *W/mK* are numerically studied for cladding layers.

1 INTRODUCTION

Liquid metal-cooled miniature heat sinks can handle high heat dissipation rates and tolerate extreme working temperatures due to the 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 the thermal-hydraulic performance of water-cooled copper minichannel heat sinks [3,4]. Tikadar et al. [5] investigated the effect of secondary flow on the thermal-hydraulic performance of counter-flow rectangular minichannel heat sinks. The secondary flow was generated by two interconnectors between two contour flow streams. Reported numerical results for interconnected minichannel heat sinks showed a 48.37 % reduction in pressure drop and a maximum of 42% enhancement in thermal-hydraulic performance of inter-connected counterflow minichannel heat sinks in comparison with an identical conventional counter-flow minichannel heat sink.

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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 the miniature heat sink by affecting local wall temperature and heat flux distributions. Laminar flow and heat transfer of NaK in microchannel heat sinks of different aspect ratios were investigated by Pourghasemi et al. [2]. Obtained average Nusselt numbers were observed to reduce as the microchannel aspect ratio increased. Muhammad et al. [6] performed numerical simulations to study laminar flow and heat transfer for liquid metals of GaIn, GaSn, EGaIn, EGaInSn within a miniature heat sink with a width of 1 mm, a height of 4 mm and a length of 40 mm. Reported results showed that EGaIn led 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 the most 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 corrosion-resistant 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 pentagonal and rectangular copper-based miniature heat sinks while thin layers of SS-316, Inconel 718 and RHEA are cladded on the heat sink walls. Local and average Nusselt numbers are calculated to study the effect of cladding layer on the thermal performance of investigated miniature heat sinks. Turbulent flows of Na are investigated at the Reynolds number of 5000.

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 [7].

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

The following numerical procedure is implemented in the performed numerical simulations in this work to capture the conjugate heat transfer phenomenon within a miniature heat sink. First, at the fluid-solid interface within the 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 the heat is transferred from the cladding layer to the Na flow.

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 the liquid coolant specific heat capacity in (*J/kgK)*, ρ is the coolant density in *(kg/m³.)*

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

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 the whole heat sink, Nu_{ave}, is calculated by taking the integral of the 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 water and liquid metal-cooled heat sinks have been verified by authors in their previous work [2,8].

3 RESULTS

3.1 Na flows and heat transfer within minichannel heat sinks

Turbulent flows and heat transfer of Na within pentagonal and rectangular copper-based minichannel heat sinks are studied in this section. The pentagonal heat sink has a length scale of *a* = 13 mm and a hydraulic diameter of 14.9 mm with a vertex angle of θ = 60 degrees as shown schematically in Figure 1. The investigated rectangular minichannel has a height of 14 mm, an aspect ratio of 0.635 and a hydraulic diameter of 17.1 mm.

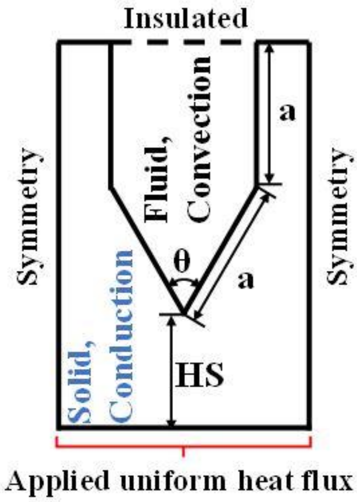

Figure 1: Schematic of the investigated miniature heat sink with a pentagonal cross-section

Four thin layers of stainless steel (SS-316), Inconel 718 and RHEA with four thickness values of 0.5mm, 1 mm, 2 mm and 4.5 mm are considered as the cladding layer at the pentagonal minichannel walls. The SST *k-ω* model with a turbulent Prandtl number of 4.11 is used to numerically model the Na turbulent flow at a Reynolds number of 5,000. The thermal conductivity for RHEA is considered as 5 *W/mK* in this work while it is assumed 10 *W/mK* and 17 *W/mK* for Inconel 718 and SS-316, respectively. The SST *k-ω* 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].

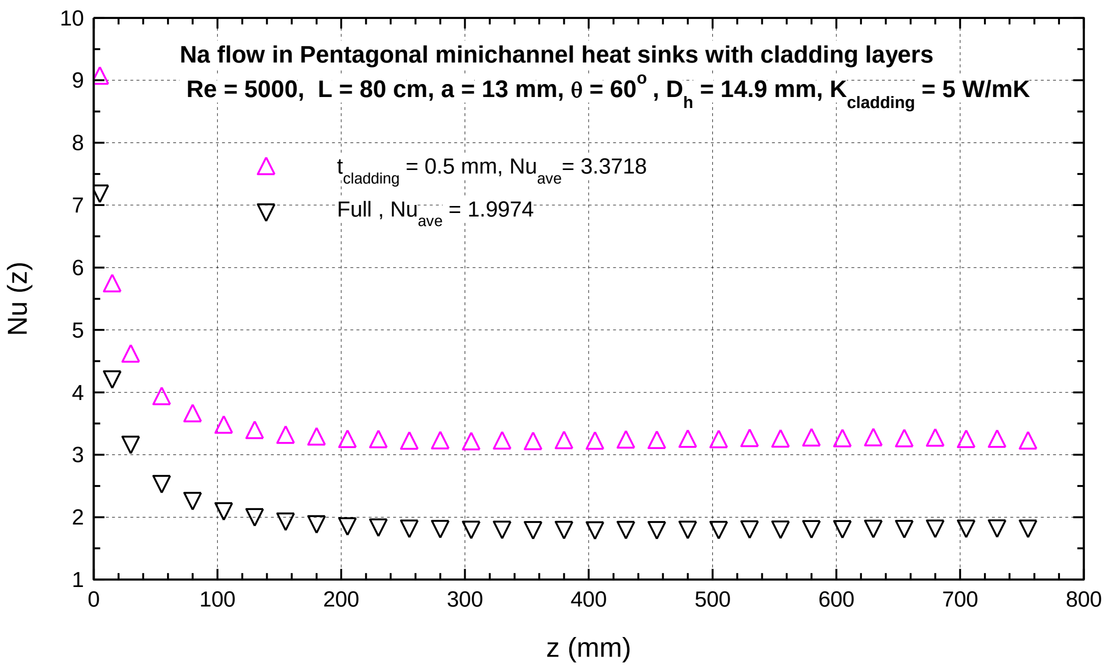

Figure 2: Local Nusselt numbers for Na flow at a Reynolds number of 5,000 within a pentagonal minichannel with a 0.5 mm thick RHEA cladding layer.

Figures 2 illustrate the obtained results for local and average Nusselt numbers in the pentagonal heat sink with a 0.5 mm thick cladding layer of thermal conductivity of 5 *W/mK*. As it can be inferred, the copper-based cladded miniature heat sink (composite case) has much higher local and average Nusselt numbers than an identical heat sink made totally out of cladding layer substrate (full clad case). The average Nusselt number for the investigated cladded pentagonal heat sink is around 3.37 while the full clad miniature heat sink has an average Nusselt number of around 2.

Cladding layer thermal efficiency, f_{clad}, is defined in Equation (7). The cladding layer thermal efficiency is obtained using the ratio of average Nusselt numbers between a cladded copper-based miniature heat sink (composite case) and an identical heat sink made totally out of the cladding layer material (full clad case).

$$f_{clad} = \left[\frac{Nu_{Composite}}{Nu_{Full\ clad}} - 1\right] \times 100 \tag{7}$$

Figure 3 presents the obtained results of cladding layer thermal efficiency in the investigated pentagonal miniature heat sink at a Reynolds number of 5000. Cladding layer thickness varies from 0.5 mm to 4.5 mm while its thermal conductivity covers a range of 4 *W/mK* – 17 *W/mK*. Reported Results suggested that a 0.5 mm thick cladding layer with thermal conductivity of 5 W/mK resulted in the highest thermal efficiency of 95 %. In other words, a cladded copper-based pentagonal miniature heat sink (composite case) with a 0.5 mm thick RHEA protective layer has 95 % higher thermal efficiency than an identical pentagonal heat sink made totally out of RHEA.

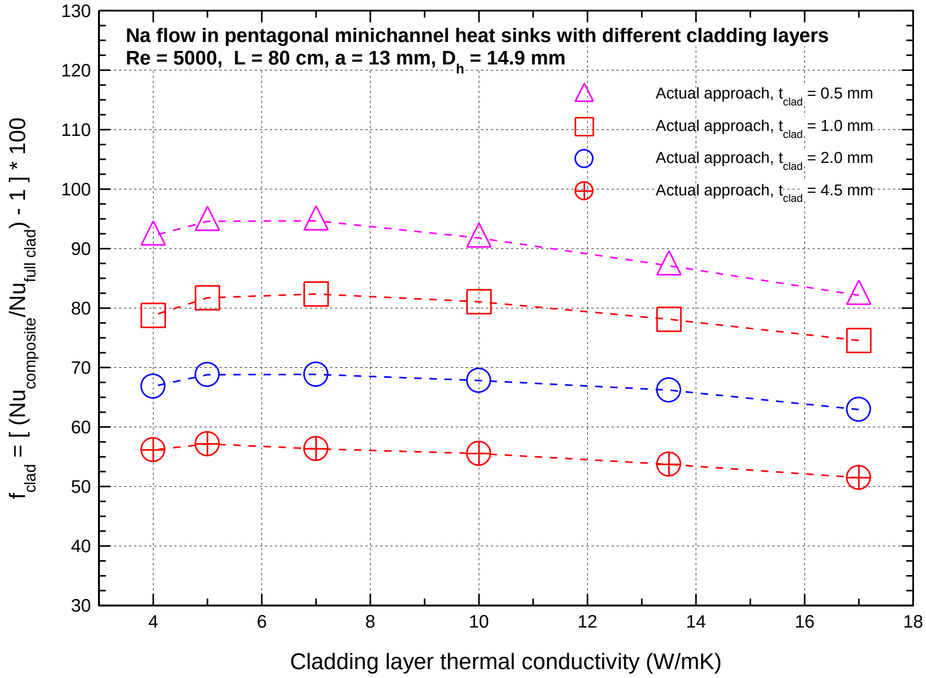

Figure 3: Cladding layer thermal efficiency in the investigated pentagonal minichannel heat sink.

Fugure 4 presents the obtained results for cladding layer thermal efficiency in the investigated rectangular copper-based minichannel heat sink. The highest thermal effcicency of the investigated rectangular heat sink is around 15% for a 0.5 mm thick cladding layer with thermal conductivity of 7 W/mK. Inconel 718 and RHEA are more expensive than copper and therefore the concept of a copper-based cladded minichannel heat sink proposed and investigated in this research can reduce the total operational cost of miniature heat sinks designed for extreme working conditions.

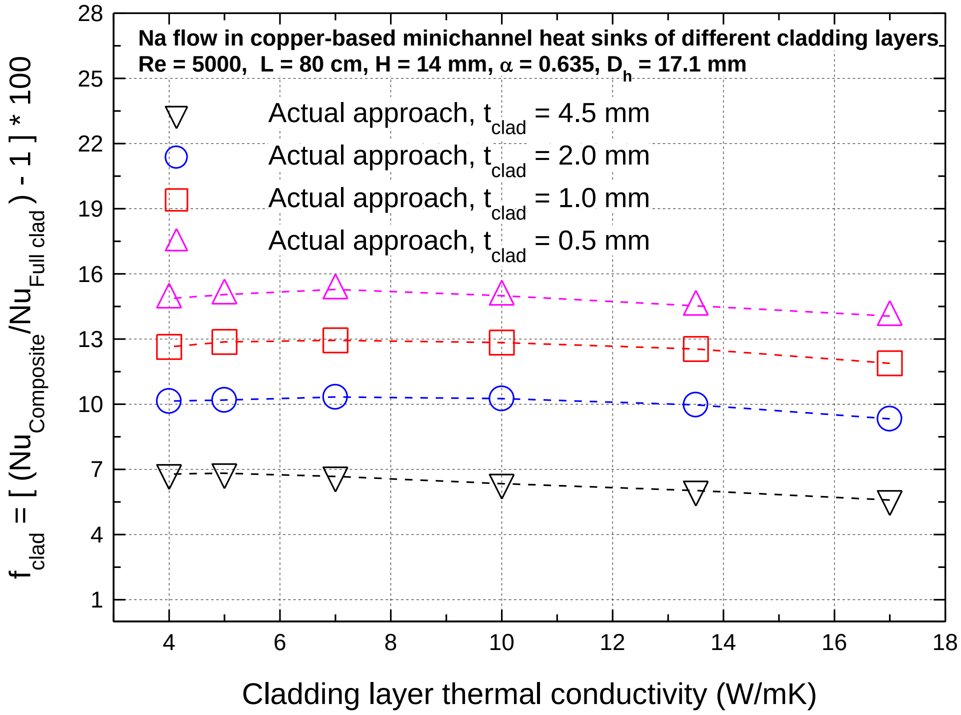

Figure 4: Cladding layer thermal efficiency in the investigated rectangular minichannel heat sink.

4 CONCLUSION

Forced convection of liquid sodium (Na) have been investigated in copper-based cladded minichannel heat sinks with pentagonal and rectangular cross sections in the present work. The pentagonal heat sink has a length scale of a = 13 mm and a hydraulic diameter of 14.9 mm with a vertex angle of θ = 60 degrees. The investigated rectangular minichannel has a height of 14 mm, an aspect ratio of 0.635 and a hydraulic diameter of 17.1 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). Four cladding thickness values of 0.5mm, 1 mm, 2 mm, and 4.5 mm with a thermal conductivity range of 4-17 W/mK are examined. The thermal conductivity range was chosen such that the cladding layer resembled SS-316, RHEA and Inconel 718. The obtained results showed that a 0.5 mm thick cladding with thermal conductivity of 5 *W/mK* provided the highest thermal efficiency. Inconel 718 and RHEA are more expensive than copper and therefore the concept of a copper-based cladded minichannel heat sink proposed and investigated in this research can reduce the total operational cost of miniature heat sinks designed for extreme working conditions.

REFERENCES

[1] G. Liang, I. Mudawar, Review of single-phase and two-phase nanofluid heat transfer in macro-channels and micro-channels, International Journal of Heat and Mass Transfer. (2019). https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.086.

[2] M. Pourghasemi, N. Fathi, S. Rodriguez, Numerical Study on Flow and Heat Transfer of Water and Liquid Metals Within Micro-Scale Heat Sinks for High Heat Dissipation Rate Applications, arXiv Preprint arXiv:2106.11752. (2021).

[3] A.F. Al-Neama, N. Kapur, J. Summers, H.M. Thompson, Thermal management of GaN HEMT devices using serpentine minichannel heat sinks, Applied Thermal Engineering. 140 (2018) 622–636. https://doi.org/10.1016/j.applthermaleng.2018.05.072.

[4] X. Cao, H. ling Liu, X. dong Shao, H. Shen, G. Xie, Thermal performance of double serpentine minichannel heat sinks: Effects of inlet-outlet arrangements and through-holes, International Journal of Heat and Mass Transfer. 153 (2020). https://doi.org/10.1016/j.ijheatmasstransfer.2020.119575.

[5] A. Tikadar, T.C. Paul, S.K. Oudah, N.M. Abdulrazzaq, A.S. Salman, J.A. Khan, Enhancing thermal-hydraulic performance of counter flow mini-channel heat sinks utilizing secondary flow: Numerical study with experimental validation, International Communications in Heat and Mass Transfer. 111 (2020). https://doi.org/10.1016/j.icheatmasstransfer.2019.104447.

[6] A. Muhammad, D. Selvakumar, A. Iranzo, Q. Sultan, J. Wu, Comparison of pressure drop and heat transfer performance for liquid metal cooled mini-channel with different coolants and heat sink materials, Journal of Thermal Analysis and Calorimetry. 141 (2020) 289–300. https://doi.org/10.1007/s10973-020-09318-2.

[7] V. Bobkov, Thermophysical properties of materials for nuclear engineering: a tutorial and collection of data international, ATOMIC ENERGY AGENCY, Vienna, 2008.

[8] M. Pourghasemi, N. Fathi, Probing the accuracy of experimental data on Nusselt numbers within miniature heat sinks, Journal of Thermal Science and Engineering Applications. 14 (2022) 111001.