WATER COOLED MICRO-HOLE CELLULAR STRUCTURE AS A HEAT DISSIPATION MEDIA
An Experimental and Numerical Study

by

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Thermal performance of micro-hole cellular structure using water as a cooling fluid was investigated through CFD and then numerical results were validated with the experimental results. The minimum base temperature for the micro-hole cellular structure was found to be 29.7 °C and 32.3 °C numerically and experimentally, respectively, with volumetric flow rate of 0.000034 m³/s (2 Lpm) at a heating power of 345 W. Numerical values of the base temperature are in close agreement with experimental results with an error of 8.75%. Previously, the base temperatures of heat sinks using alumina nanofluid with 1% of volumetric concentration and water with volumetric flow rate of 0.000017 m³/s (1 Lpm) have been reported to be 43.9 °C and 40.5 °C, respectively.

Key words: *micro-hole cellular structure, water, base temperature, convective heat transfer*

Introduction

In our daily lives, electronic devices have become very important. These devices continuously generate heat which needs to be removed for efficient performance of these devices. A number of techniques which have been used by many researchers to increase the heat transfer rate are either by increasing the surface to volume ratio of heat sink devices or by changing the type of fluid-flowing through heat sinks. Some of the new techniques are under discussion in scientific community for effective thermal management and to maintain the base temperature of the computer processors in a safe zone.

Rafati *et al.* [1] utilized the nanofluid to cool the processor temperature and they have observed the largest temperature drop from 49.4-43.9 °C using alumina nanofluid for 1% of volumetric concentration at a flow rate of 1 Lpm when compared with the pure base fluid. Jajja *et al.* [2] has investigated five different geometries with different fin spacing using water as a coolant. It is found that the heat sink with pin spacing of 0.2 mm drops the base temperature of the microprocessor up to 40.5 °C at a heater power of 325 W.

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The heat dissipation from a desktop and a mobile processor is observed for 1 cm^2 area to be as high as 100 W and 30 W, respectively [3]. Mohammed and Abd El-Baky [4] investigated the thermal performance of air cooled mini channel heat sinks with different configurations experimentally. They found that the heat transfer to air from solid increases with increasing flow rate and base temperature. They reported the base temperature to be 55 °C at the inlet velocity of 11.1 m/s and heat generation of 160 W.

Tuckerman and Pease [5] introduced water cooled micro-channel to directly circulate the water in micro-channels which were fabricated in silicon chip. In following years, a lot of contribution has been made on direct cooling technology by micro-channels [6].

Cellular metal structures have characteristics of being ultra-light with high porosities. Recently, they have been emerged as a compact heat exchanger to dissipate high heat fluxes in small spaces [7, 8]. Cellular metallic foams are present in stochastic structure and periodic structure. Metal foam can dissipate heat five times faster than conventional pin fin array while having three times lesser weight [9-12].

The uniform distribution of the temperature over the surface along with value of base temperature play an important role in overall reliability and operating speed of the modern high speed computers. The cellular periodic structures have better ability to maintain uniform temperature over the surface than the stochastic structures (metal foams). Stochastic cellular structures can dissipates high heat in comparison periodic cellular structures but their load bearing capability is much lesser than periodic cellular structure [13].

Tian *et al.* [14] estimated the thermal efficiency of the brazed textile cellular periodic structures of forced air convection is approximately three times larger than that of cellular stochastic structure. They also noted that the surface to volume ratio provided by metal foams is higher but pressure drop of periodic textile structure is lesser than the pressure drop in metal foams. Wen *et al.* [15] performs numerical and experimental study on square and diamond cell shape cellular structures. They found square cells have nearly the same friction factor as that of diamond cells. De Stadler [16] developed a study to optimize channel geometry having void arrangement in one dimension with square and circular cross-section. Tian *et al.* [17] carried out experiments to evaluate the thermal hydraulic performance of cellular structure heat sink with vertical triangular rods and horizontal hollow tubes truss structure.

Hung *et al.* [18] estimated the thermal performance of porous micro-channel heat sinks with different configurations and noticed that thermal performance increases using porous configuration when compared with non-porous micro-channel. Dixit and Gosh [19] performed experimental study to calculate the thermal and hydraulic performance for straight, offset and diamond mini-channel heat sinks and found the pressure drop for a diamond mini-channel have been estimated to be higher as compared to offset mini-channel. Xie *et al.* [20] performed numerical calculations on a mini channel heat sink with bottom size of 20×20 mm using water as a coolant. They have found that the optimized structure was able to dissipate heat flux of 350 W/cm^2 at a pumping power of 0.314 W.

Pin fin array now gets an old technique which can be replaced by cellular materials. More recently, cellular metallic foams belong to cellular stochastic structure category, are now being used as a compact heat exchanger. Basically the surface to volume ratio provided by metal foams are higher but when it comes to pressure drop, periodic cellular structure offers less pressure drop compare to metal foams. One more benefit of using periodic cellular structure is that, they provide a uniform temperature distribution over the surface. Prismatic structures with micro-holes belong to cellular periodic structures category are also not been explicitly addressed. Therefore, there is a need for investigation fill this gap. The focus of this research is using periodic cellular materials having 2-D void arrangement particularly one with square cross-section and other with circular cross-section which is not seen in literature so far to the best of author knowledge. In this research, thermal performance of water cooled micro-hole cellular structure is addressed. This structure provides a minimum pressure loss and higher heat transfer. We performed CFD calculations to assess the thermal management and then these numerical results are validated with experimental results.

Numerical analysis

We used the CFD approach to stimulate the conjugate heat transfer problem. We analysed the micro-hole cellular structure using commercial CFD software package ANSYS 16.0. We used ANSYS design modeler for modeling, ANSYS meshing for CFD meshing and ANSYS fluent as a CFD solver. To examine thermal and flow characteristics in numerical study, following assumptions were taken out:

- the flow is incompressible, turbulent, 3-D and in steady-state,
- fluid thermal properties are considered constant throughout the flow, and
- there is no heat generation inside the structure and no viscous heating.

Governing equations on the basis of previous assumptions are as follows for conservation of mass, momentum, energy, turbulence kinetic energy, and turbulence dissipation rate:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \tag{1}$$

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_j}+\frac{\partial}{\partial x_i}\left[\left(\mu+\mu_t\right)\frac{\partial \mu_j}{\partial x_i}\right]+\frac{\partial}{\partial x_i}\left[\left(\mu+\mu_t\right)\frac{\partial \mu_i}{\partial x_j}\right],\quad j=1,2,3 \tag{2}$$

$$\frac{\partial}{\partial x_i}\left(\rho u_i T\right)=\frac{\partial}{\partial x_i}\left[\left(\frac{\lambda}{c_p}+\frac{\mu_t}{\sigma_T}\right)\frac{\partial T}{\partial x_i}\right] \tag{3}$$

$$\frac{\partial}{\partial x_i}\left(\rho k u_i\right)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k-\rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_i}\left(\rho \varepsilon u_i\right)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+\frac{\varepsilon}{k}\left(c_1 G_k-c_2\rho\varepsilon\right) \tag{5}$$

where k, ε, and G_k represent turbulence kinetic energy, turbulence dissipation rate, and generation of turbulence kinetic energy. We calculated the heat dissipation through micro-hole cellular structure using water as a cooling fluid. The inlet velocity entering in the cellular structure is as:

$$z=0,\quad u=0,\quad v=0,\quad w=U_{\text{in}}$$

Whereas inside the solid region, the velocity is considered to be zero everywhere:

$$z=L,\quad u=0,\quad v=0,\quad w=0$$

Heat flux is supplied at the bottom of the structure as:

$$y=0,\quad -\lambda\frac{\partial T}{\partial y}=q$$

Top surface of the structure is considered to be adiabatic:

$$y = H, \quad \frac{\partial T}{\partial y} = 0$$

The right and left surfaces of the structure are considered to be adiabatic:

$$x = 0, \quad \frac{\partial T}{\partial x} = 0$$

The following boundary conditions are used for solution in ANSYS:
- heat flux of 8.16 W/cm^2 at the bottom surface to produce 345 W of heat,
- flow inlet velocity,
- pressure outlet at 0 gauge pressure, and
- water is coming in at a constant temperature of 22 °C

Mesh independent study

Mesh is considered to be independent when the temperature difference (maximum base temperature and inlet temperature) shows no more than 1% of deviation. Four cases were examined: Case1, Case 2, Case 3, and Case 4 with 1247232, 2165738, 3044843, and 4194409 number of elements, respectively. Results obtained by Case 3 and Case 4 were very close to each other. The percentage relative temperature difference deviation calculated for Case 3 and Case 4 was around 0.6%, so the numbers of elements for Case 3 were selected for the whole study. Temperature difference for the four cases with respect to number of elements is shown in fig. 1.

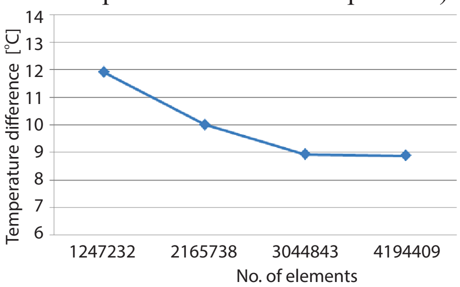

Figure 1. Mesh independent study

Data reduction

We adopt following procedure for data reduction.

Heat removed by the water circulating in the micro-hole cellular structure can be calculated from eq. (6) by applying conservation principle with one inlet and one outlet and assuming negligible changes in kinetic and potential energies as:

$$\dot{Q} = \dot{m}c_p(T_o - T_i) \tag{6}$$

Porosity of the cellular structure can be calculated from eq. (7):

$$\varepsilon = 1 - \left(\frac{V}{V_b}\right) \tag{7}$$

Blockage ratio and open area ratio of the cellular structure can be calculated:

$$R_{\mathrm{BR}} = \frac{A_b}{A_t} \tag{8}$$

$$R_{\mathrm{OPEN}} = (1 - R_{\mathrm{BR}}) \tag{9}$$

Pressure loss coefficient can be calculated:

$$K_{\mathrm{cell}} = \left(\frac{1 - R_{\mathrm{OPEN}}}{R_{\mathrm{OPEN}}}\right)^2 \tag{10}$$

Surface area density of the cellular structure can be calculated:

$$\alpha_{\mathrm{sf}} = \frac{A_{\mathrm{s}}}{V} \tag{11}$$

Log of mean temperature difference can be calculated:

$$LMTD = \frac{(T_b - T_i) - (T_b - T_o)}{\ln\left[\dfrac{(T_b - T_i)}{(T_b - T_o)}\right]} \tag{12}$$

Thermal resistance can be calculated:

$$R_{\mathrm{th}} = \frac{LMTD}{\dot{Q}} \tag{13}$$

Micro-hole cellular structure

We have enlisted the dimensions of cellular structure in the tab. 1. Water enters and leaves through the faces along –ve z-axis and +ve z-axis, respectively, so these faces are open while all the other four faces of the cellular structure are closed. Cellular structure has square void arrangement along z-axis. Make 3×3 mm square through bores with wall thickness of 1 mm on the face along the z-axis. Micro-holes of 1.5 mm diameter are on the face along y-axis. The base area of micro-hole cellular structure is of 65 × 65 mm. Micro-hole cellular structure is shown in fig. 2.

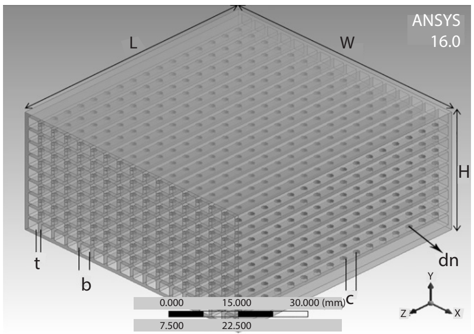

Figure 2. Micro-hole cellular structure

Table 1. Micro-hole cellular structure geometric properties

b [mm]	t [mm]	d_h [mm]	c [mm]	H [mm]	L [mm]	W [mm]	α_{sf} [m^{-1}]	ε	R_{BR}	R_{OPEN}	K_{cell}
3	1	1.5	4	49	65	65	1770	0.57	0.46	0.54	0.72

Effect on base temperature

The temperature distribution of base of micro-hole cellular structure at different flow rates is shown in figs. 2-4. The maximum base temperature noticed for micro-hole cellular structure numerically are 30.9 °C, 30.2 °C, and 29.7 °C at the flow rate of 0.000017 m^3/s (1 Lpm), 0.000025 m^3/s (1.5 Lpm), and 0.000034 m^3/s (2 Lpm), respectively. Water enters the micro-hole cellular structure along +z-axis. Continuous heat flux heats up the base of micro-hole cellular structure, which is dissipated by the flowing water through it. The temperature contour of micro-hole cellular structure shows minimum temperature (mostly green regime) at the entrance as cool water enters. As the water reaches to the exit of micro-hole cellular structure, the water gains heat so high temperature (mostly red regime) can

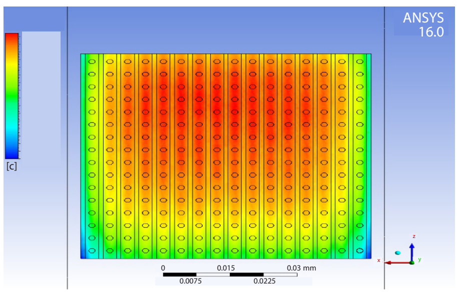

Figure 3. Bottom face temperature distribution at 0.000017 m^3/s (1 Lpm)

be noticed. The inlet face is directly facing the cool water that is the reason temperature is low at inlet as compare to the outlet. It can also be seen that temperature is low where there are solid strips and temperature is high where there is water passage. This shows that heat is dissipating quickly through the solid strips which later on dissipate to the flowing water, while red regime can be noticed between each two consecutive solid strips indicating slow process of heat dissipation comparatively.

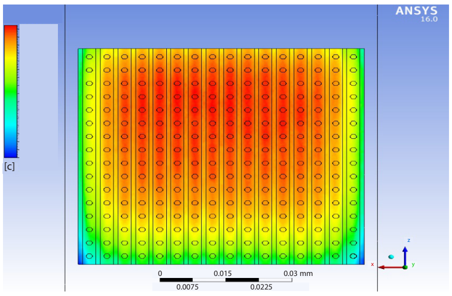

Figure 4. Bottom face temperature distribution at 0.000025 m³/s (1.5 Lpm)

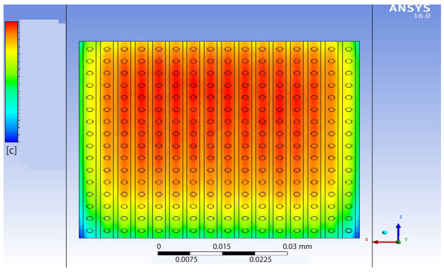

Figure 5. Bottom face temperature distribution at 0.000034 m³/s (2 Lpm)

Figure 6. Fabricated micro-hole cellular structure

Experimental set-ap

After numerical study, micro-hole cellular structure is experimentally evaluated and the obtained results are compared with CFD results. The micro-hole cellular structure is manufactured on the wire cut electrical discharge machining and is shown in the fig. 6.

Test loop

A constant heat flux of 8.16 W/cm^2 is supplied by the cylindrical copper block comprising of two surface heaters connected by AC source. A constant voltage of 220 V and current of 1.57 A is supplied to maintain the constant heat generation of 345 W. Cellular structure is mounted on the top of the copper heating cylinder. Copper block is placed for the uniform temperature distribution between copper heating cylinder and cellular structure. Thermal paste is used to ensure the impeccable contact between:

– the cellular structure and copper block and
– copper block and copper heating cylinder.

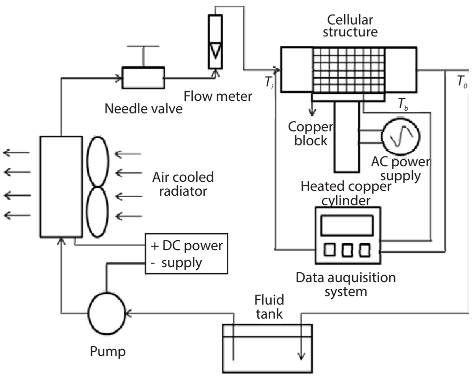

Figure 7. Schematic of experiment set-up

Flow rate is measured by flow meter and controlled by needle valve (full scale accuracy ±5%). The DC pump is used to maintain the flow rate throughout the loop. Distilled water is used in fluid reservoir. The *K*-type thermocouples (5TC-SE-MT-32-1N) are used for temperature measurement of fluid and base of cellular structure. A slotted way is made on the surface of copper block. A fine wire *K*-type thermocouple is placed in the slotted way to measure the base temperature of cellular structure; the position of base temperature can be seen from fig. 7. Temperatures are measured by five-channel thermo couple and voltage, Micro SD Data Acquisition DAQ. The 240 mm liquid cooler computer radiator is used to cool the hot water coming out from the heated cellular structure. Cellular structure is place in between the acrylic duct and is sealed by high temperature silicon. Schematic of experimental set-up is shown in the fig. 7.

Uncertainty analysis

The uncertainty in the experimental data is estimated by the method developed by Kline and McClintock [21]. This method incorporates the estimated uncertainties in the experimental measurement of heat transfer rate. The uncertainty in the heat transfer rate is found as 4.8%. The uncertainty related with the temperature measurements is estimated as ±0.1 °C.

Results and discussions

Effect of pressure drop with flow rate

Effect of pressure drop with volumetric flow rate is given in fig. 8. It is observed that pressure drop increases as volumetric flow rate increases. Minimum pressure drop is noticed as 300 Pa while largest pressure drop as 1050 Pa at the volumetric flow rate of 0.000017 m^3/s (1 Lpm) and 0.000034 m^3/s (2 Lpm), respectively. More pressure drop requires more pumping power to maintain the desire volumetric flow rate. Pressure drop depends upon the pressure loss coefficient which is calculated as 0.72. The structure discussed in this study shows the minimum pressure loss coefficient at the given open area ratio which can be validated from the result reported by Tian *et al.* [14].

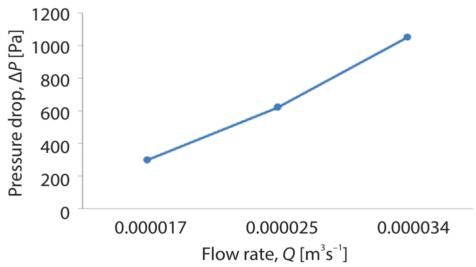

Figure 8. Variation of pressure drop with volumetric flow rate

Effect of base temperature with flow rate

Variation of base temperature with volumetric flow rate is shown in fig. 9. Base temperature tends to decrease with the volumetric flow rate. Minimum base temperature calculated numerically and experimentally is 29.7 °C and 32.3 °C at 0.000034 m^3/s (2 Lpm) of volumetric flow rate at the heating generation of 345 W. The experimental data is in good agreement with the numerical prediction as it shows 8.75% error calculated between the base temperatures computed numerically and experimentally. It is than compared with the base temperature noted for rectangular mini-channel at 11.1 m/s with 160 W heat generation was 55 °C by Mohammed and El-Baky [4]. Base temperature noted by using water at 0.000017 m^3/s (1 Lpm) with 0.2 mm fin spacing was 40.5 °C by Jajja *et al.* [2] while Base temperature noted using alumina nanofluid for 1% of volumetric concentration at 0.000017 m^3/s (1 Lpm) was 43.9 °C. Similar trend of base temperature with volumetric flow rate is reported by Rafati *et al.* [1].

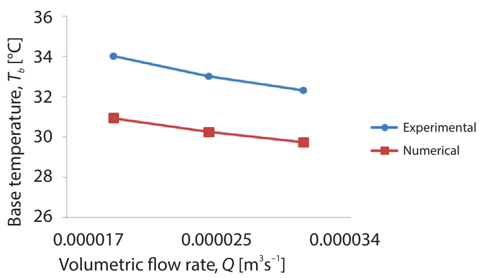

Figure 9. Variation of base temperature with volumetric flow rate

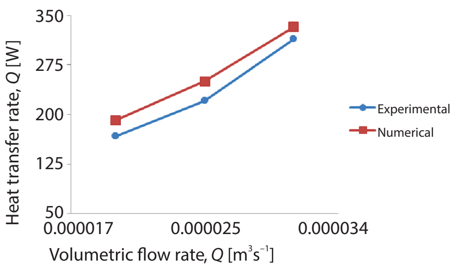

Figure 10. Variation of heat transfer rate with volumetric flow rate

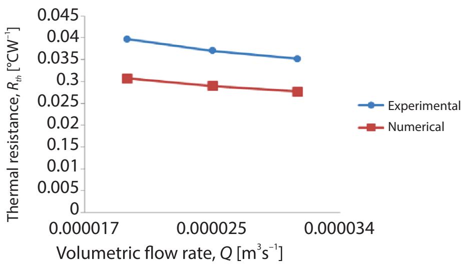

Figure 11. Variation of thermal resistance with volumetric flow rate

Effect of heat transfer rate with flow rate

Effect of heat transfer rate with volumetric flow rate is shown in fig. 10. Heat transfer rate increases with increase in volumetric flow rate. Maximum heat transfer is found numerically and experimentally at the volumetric flow rate of 0.000034 m^3/s (2 Lpm) as 332 W and 314 W, respectively while minimum heat transfer rate is found at the volumetric flow rate of 0.000017 m^3/s (1 Lpm) as 191 W and 167 W, respectively. Similar trend of heat transfer rate with volumetric flow rate is reported by Jajja *et al.* [2].

Effect of thermal resistance with flow rate

The effect of thermal resistance with volumetric flow rate is shown in fig. 11. Thermal resistance of micro-hole cellular structure decreases by increasing the volumetric flow rate of water. The maximum thermal resistance is noticed as 0.0397 °C/W at the volumetric flow rate of 0.000017 m^3/s (1 Lpm), while minimum thermal resistance is noticed as 0.0352 °C/W at the volumetric flow rate of 0.000034 m^3/s (2 Lpm). Thermal resistance is inversely related to the heat transfer rate, lower the thermal resistance higher the heat transfer will be. As by increasing the volumetric flow rate, heat transfer rate increases. That is the reason that thermal resistance decreases with increase in volumetric flow rate. A similar trend of thermal resistance is found in [20].

Conclusions

In this research work micro-hole cellular structure was investigated numerically using water and then experimentally validated. The core verdicts of this current study are:

- The minimum base temperature was recorded as 29.7 °C numerically which was then validated by experimental recorded base temperature as 32.3 °C at the volumetric flow rate of 0.000034 m^3/s (2 Lpm).
- Numerical results are validated experimentally and are in good agreement, an error of 8.75% was estimated between the base temperature computed numerically and experimentally at the heat flux 8.16 W/cm^2 (345 W of heat supplied).
- Pressure drop and heat transfer rate increases by increasing the volumetric flow rate. The minimum pressure drop was estimated at the volumetric flow rate of 0.000017 m^3/s (1 Lpm), while the maximum heat transfer was recorded at 0.000034 m^3/s (2 Lpm).
- Base temperature and thermal resistance decreases by increasing the volumetric flow rate. The minimum base temperature and thermal resistance was estimated at the volumetric flow rate of 0.000034 m^3/s (2 Lpm).

Nomenclature

A_b – frontal blocked area, [mm^2]
A_t – frontal total area, [mm^2]
A_s – surface Area, [mm^2]
b – length of square side, [mm]
c – centre to centre distance, [mm]
c_p – specific heat, [kJkg^{-1}K^{-1}]
d_h – hole diameter, mm
H – height, [mm]
K_{cell} – pressure loss coefficient
L – length, [mm]
$LMTD$ – log of mean temperature difference, [°C]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
ΔP – pressure difference, [Pa]
$\dot{Q}$ – heat transfer rate, [W]
Q – volumetric flow rate, [m^{3}s^{-1}]
q – heat flux, [Wcm^{-2}]
R_{BR} – blockage ratio
R_{OPEN} – open area ratio
R_{th} – thermal resistance, [°CW^{-1}]
T_b – base temperature, [°C]
T_i – fluid inlet temperature, [°C]
T_o – fluid outlet temperature, [°C]
t – wall thickness, [mm]
U_{in} – inlet velocity
u, v, w – velocity in x, y, and z, respectively, [ms^{-1}]
V – volume of the structure, [mm^3]
V_b – total volume of whole solid block, [mm^3]
W – width, mm

Greek symbol

α_{sf} – surface area density
ε – porosity
μ_{t} – turbulence viscosity, [kgm^{-1}s^{-1}]
λ – thermal conductivity, [Wm^{-1}°C^{-1}]

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