THERMAL AND CFD SIMULATION OF LAMINAR PULSATING FLUID FLOW IN MICRO TUBE

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ABSTRACT

To understand the thermal and hydrodynamic behaviour of single phase pulsating laminar fluid flow in a microtube with constant flux boundary condition and the cross-section of the solid insulated, a two-dimensional numerical analysis is carried out. The inlet velocity to the tube is the combination of a fixed component of velocity and fluctuating component of velocity which sinusoidally varies with time, thus causing pulsating fluid flow. Water is the working fluid, entering the microtube at a temperature of 300 K and Prandtl number Pr=7, with a velocity fluctuating with time sinusoidally, resulting a pulsating fluid flow in micro tube. To study the effect of axial wall conduction microtube, solid to fluid conductivity ratio is taken in a very wide range (k_{sf} = 0.340 – 7205) and average flow Reynolds number of 150. Effect of pulsating frequency on heat transfer is found to be very small. It is found that by increasing the pulsating frequency, heat transfer raises for minimum thermal conductive microtube wall material (or k_{sf}), but the heat transfer rate reduces in cases where the materials with high thermal conductivity are used. Literature review shows that, the pulsating flow either increases or decreases or shows no effect on heat transfer. For a particular pulsating frequency (Wo), with very low k_{sf} the time averaged relative Nusselt number remains [$Nu_r(z)$] almost constant which is less than the corresponding steady state Nusselt number and that leads to lower the overall Nusselt number (Nu). For a particular pulsation frequency (Wo), the overall Nusselt number is maximum at moderate values of k_{sf}. From the observations, it has been confirmed that for a specified pulsating frequency, keeping parameters like flow Reynolds number, microtube thickness to inner radius ratio (δ_{sf}) constant, an optimum value of k_{sf} exist where the overall Nusselt number attains its maximum value.

Keywords: Microtube; Axial wall conduction; Pulsating flow; Pulsating frequency; Relative Nusselt number.

LITERATURE REVIEW

Several researchers have given their significant contribution in the field of pulsating fluid flow for thermal and hydrodynamic analysis; hence the study of pulsating fluid flow isn't new one. Richardson and Tyler [1] performed experiments to study pulsating fluid flow's hydrodynamic behaviour and found that the fluid flow velocity is maximum near the pipe wall rather than at its centreline, which was theoretically verified later by Uchida [2], who analytically achieved pulsating fluid flow velocity profile in a tube, by which he assumed fluid flow parallel to the tube axis and he again confirmed the result obtained by Richardson and

Tyler. Rao and Havemann [3] have given one major significant on pulsating flow thermal behaviour, stating that the pulsation alters the thickness of the boundary layer every time, which results in changes of heat transfer rates because of changes encountered in thermal resistance. Perlmutter and Siegel [4] considered the laminar and pulsating fluid flow in between parallel plates subjected to uniform wall heat flux and uniform wall temperature conditions separately and analysed the effect of frequency of pulsating flow on heat transfer and found that Nusselt number exhibits periodic fluctuations in axial direction under isothermal wall condition. Javdani et al. [5] studied the effect of pulsating fluid flow on heat transfer in circular duct analytically, and gave a statement that velocity fluctuations effect the temperature distribution and divides it into steady and harmonic temperature field. Cho and Hyun [6] studied laminar-boundary layer equation for various frequencies of pulsating fluid flow numerically and concluded that, deviations in the value of Nusselt number from the steady flow value are very less. Maranzana et al. [7] conducted both numerical and analytical investigations in order to visualize the effects of axial wall heat conduction in micro channels, and they concluded that the effect of axial wall conduction in microchannels is negligible if M<0.015 and it can't be neglected if M>0.015, by assuming that the temperature difference in axial direction between the inlet and outlet of the solid wall and fluid domain was same, which was practically wrong. To overcome the limitations of Maranzana et al. [7], Zhang et al. [8] considered the temperature difference between inlet and outlet of the solid wall and fluid domains and found that axial wall heat conduction depends on many parameters including geometric conditions. The effect of steady as well as pulsating fluid flow in microchannel heat sinks were investigated experimentally by Persoons et al. [9].

Tikekar et al. [10], by conducting experiment on pulsating fluid flow in microchannel, basically measured the pressure drop with time, across the microchannel by varying flow rate, and frequency of oscillations. From literature review, it is clear that some researchers mainly focused on hydrodynamics of pulsatile flow and many studies on the effect of pulsation on heat transfer do exist in literature, they provide contradictory results. All the existing and recent studies related to effect of axial wall conduction in microchannel systems considered steady flow of coolant. Secondly, no studies exist in open literature, dealing with the conjugate heat transfer in pulsating flow microchannel, but some researchers either considered only pressure drop or neglected conjugate heat transfer in microchannel pulsating fluid flow.

THERORETICAL BACKGROUND

Mass conservation equation:

$$\int_{CV} \frac{\partial \rho}{\partial t}\, dV = \sum_i (\rho_i A_i V_i)_{in} - \sum_i (\rho_i A_i V_i)_{out}$$

Continuity equation:

$$\frac{\partial \rho}{\partial x} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}\Big(\int_{CV} \boldsymbol{V}\, \rho dV\Big) + \sum_i (m_i \boldsymbol{V}_i)_{out} - \sum_i (m_i \boldsymbol{V}_i)_{in} = \sum \boldsymbol{F}$$

Navier-Stokes momentum equation:

$$\rho(\boldsymbol{U}.\boldsymbol{\nabla})\boldsymbol{U} = \rho\boldsymbol{g} - \nabla\boldsymbol{p} + \mu * \nabla^2\boldsymbol{U}$$

Euler's equation for inviscid flow:

$$\rho\frac{d\boldsymbol{V}}{dt} = \rho\boldsymbol{g} - \nabla\boldsymbol{p}$$

Energy conservation equation:

$$\Big(\frac{dE}{dt}\Big)_{system} = Q - W$$

Hagen– Poiseuille flow:

Velocity distribution function u(r),

$$u(r) = \frac{R^2}{4\mu}\Big(-\frac{dp}{dx}\Big)[1 - \frac{r^2}{R^2}]$$

$$U_{Avg} = \frac{R^2}{8\mu}(-\frac{dp}{dx})$$

$$u(r) = 2U_{Avg}[1 - \frac{r^2}{R^2}]$$

Pressure drop in laminar pipe flow,

$$\Delta p = p_1 - p_2 = \frac{8\mu L U_{Avg}}{R^2}$$

Friction head loss,

$$h_L = \frac{\Delta p_L}{\rho g} = f\frac{L}{D}\frac{U_{Avg}{}^2}{2g}$$

Darcy-Weisbach friction factor,

$$f = \frac{8\tau_w}{\rho U_{Avg}{}^2}$$

Average Nusselt number for laminar flow in circular pipe (q_s = constant),

$$Nu = \frac{hD}{K} = \frac{48}{11} \approx 4.364$$

Average Nusselt number for laminar flow in circular pipe (T_s = constant),

$$Nu = \frac{hD}{K} = 3.66$$

Dittus-Boelter correlation for fully turbulent flow (T_s = constant),

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

NUMERICAL SIMULATION

A microtube with dimensions of length (L), inner radius (δ_f) and tube wall thickness (Φ) is taken into account as shown. Water is the working fluid, entering the microtube at a temperature of 300 K and Prandtl number Pr=7, with a velocity fluctuating with time sinusoidally, resulting a pulsating fluid flow in micro tube. The inlet velocity (U_{in}) ,comprises of a fixed component (U_{av}) and fluctuating component ($U_{av} \cdot A \cdot \sin(\omega t)$) which function of time. A computational domain in two-dimension is considered as shown in Fig. 1(b), because of axi-symmetry. This helps in reducing computational time. In the computational model, the length (L), inner radius (δ_f), thickness (δ_s) of the microtube are kept constant at 0.2 mm, 0.2 mm, and 60 mm respectively. A typical pulsating fluid is as shown below, where the phase angles in degree(°) at different points on the curve are shown.

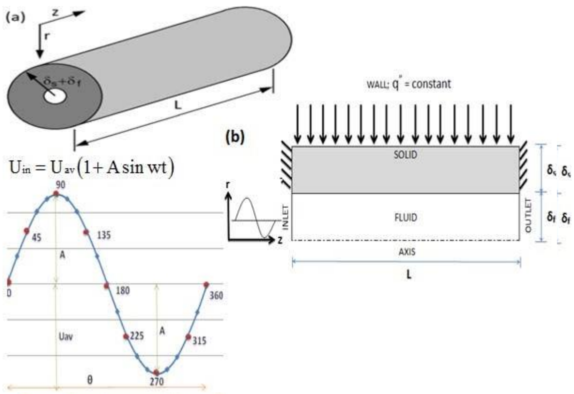

Fig: Computational domain of microtube with pulsating velocity at inlet

Assumptions made:

(1) Single phase, laminar-incompressible flow
(2) Constant thermo-physical properties of the fluid
(3) Negligible heat transfer rates of natural convection and radiation

Boundary Conditions:

(1) For solid domain, $\nabla^2 T = 0$

(2) At z=0 to z=L and r=0, $\frac{\partial U}{\partial r} = 0$

(3) At z=0 and r=0 to r=δ_f,

$$U_{in} = U_{av}(1 + A\sin\omega t);\ T_{in} = T_{atm}$$

(4) At z=L and r=0 to r=δ_f,P=0

(5) At z=0 and r=δ_f to r=$\delta_f + \delta_s$, $\frac{\partial T}{\partial z} = 0$

(6) At z=L and r=δ_f to r=$\delta_f + \delta_s$, $\frac{\partial T}{\partial z} = 0$

(7) At z=0 to z=L, r=$\delta_f + \delta_s$, q=const

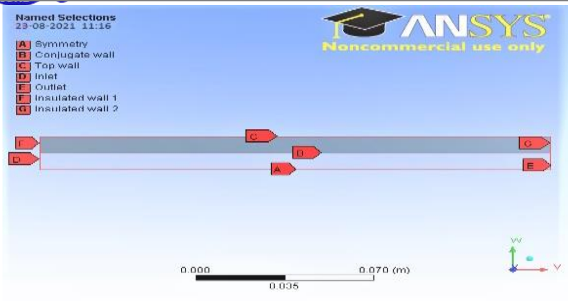

Fig: Named boundary computational domain

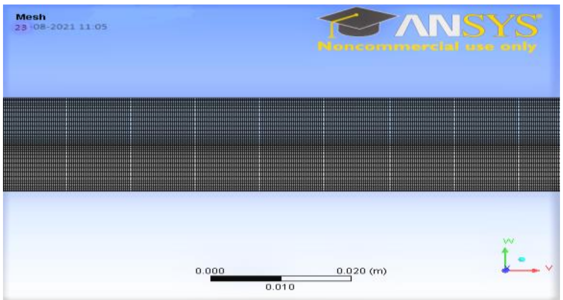

Fig: Grid structure in computational domain

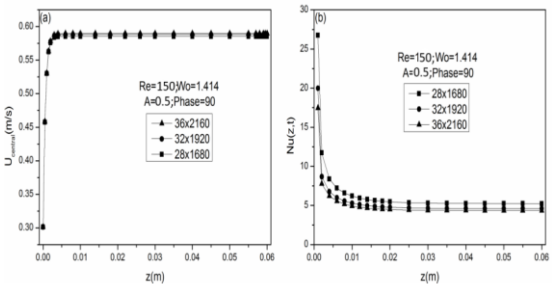

Fig: Independency test of Grid

Table: Water Thermo-Physical Properties

Property	Symbol	Value	Unit
Specific heat at constant pressure	C_p	4178	J/kg-K
Thermal conductivity	k_f	0.6084	W/m-K
Dynamic viscosity	μ	0.00089	Kg/m-s
Density	ρ	998.25	Kg/m^3

Table: Thermo-physical properties of microtube wall materials

Solid Name	ρ (Kg/m^3)	C_p (J/kg-K)	k_s (W/m-K)	k_{sf} (k_s/k_f)
Nichrome	8400	420	12	19.72
Chromium steel	7822	444	37.7	61.97
Bronze	8780	355	54	88.76
Aluminum	2719	871	202.4	332.6
Copper	8978	381	387.6	637.0
Silver	10,500	235	429	705.13

Fig: Scaled residuals monitoring

Data reduction

The parameters of interest at different phase angle of pulsation for a particular cycle are (a) local heat flux (b) local wall (c) local bulk fluid temperature. To find effect of axial wall conduction over the instantaneous local Nusselt number where conductivity ratio (k_{sf}) plays vital role, the above parameters are used.

Non-dimensional form of axial coordinate (z) in is defined as below

$$z^* = \frac{z}{L}$$

at the outer surface of the microtube, the heat flux applied is given by

$$\bar{q}_o = \frac{Q}{2.\pi.(\delta_f + \delta_s).L}$$

where, the total heat applied on the outer surface of the microtube is Q.

At solid-fluid interface, the ideal heat flux applied is given by

$$\bar{q} = \bar{q}_o.(\frac{\delta_f + \delta_s}{\delta_f})$$

At solid- fluid interface, the non-dimensional local heat flux is given by

$$\phi = \frac{q_z}{\bar{q}_z}$$

where q_z is the local heat flux at the solid-fluid interface along the microtube in axial direction. Along the axial direction, the time varying non-dimensional bulk fluid and microtube wall temperature are given by

$$\Theta_f = \frac{T_f - T_{fi}}{T_{fo} - T_{fi}}$$

$$\Theta_w = \frac{T_w - T_{fi}}{T_{fo} - T_{fi}}$$

where, T_f is the average bulk fluid temperature at any location z and T_w is the microtube wall temperature at the same location, T_{fo} and T_{fi} are the average bulk fluid temperature at the outlet and inlet of the microtube respectively.

The local instantaneous Nusselt number is given by

$$Nu(z,t) = \frac{h(z,t).D}{K_f}$$

where the instantaneous local heat transfer coefficient h(z,t) is given by

$$h(z,t) = \frac{q_z}{T_w - T_f}$$

The average instantaneous Nusselt number over the space is given by

$$Nu(t) = \frac{1}{L}\int_0^L Nu(z,t)\, dz$$

and the time average local Nusselt number over a one cycle is given by

$$Nu(z) = \frac{1}{t_p}\int_0^{t_p} Nu(z,t)\, dt$$

The overall Nusselt number is given by

$$Nu = \frac{1}{L.t_p}\int_0^L\int_0^{t_p} Nu(z,t)\, dt.dz$$

Relative Nusselt number is given by

$$Nu_r = \frac{Nu_t}{Nu_s}$$

where Nu_s and Nu_t are the Nusselt number corresponding to steady and transient conditions respectively.

RESULTS AND DISCUSSIONS

The average flow Reynolds number Re (based on mean velocity over a cycle) is set 150. Water is the working fluid, entering the microtube at a temperature of 300 K and Prandtl number Pr=7, with a velocity fluctuating with time sinusoidally, resulting a pulsating fluid flow in micro tube. Under steady periodic solution, entire analysis is done and following plots were observed.

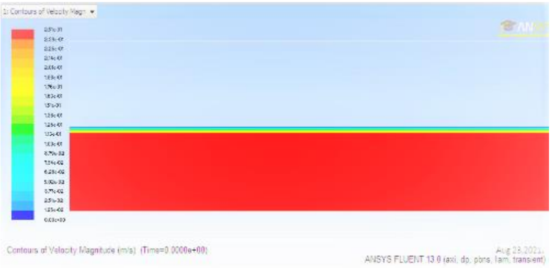

Fig: Contours of velocity magnitude before calculation in entrance region

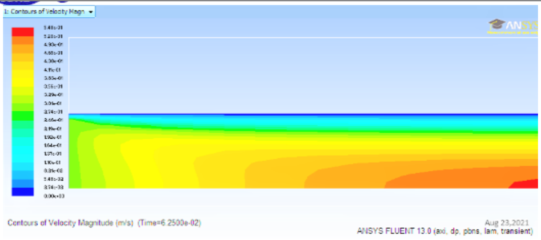

Fig: Contours of velocity magnitude at phase angle 45° in entrance region

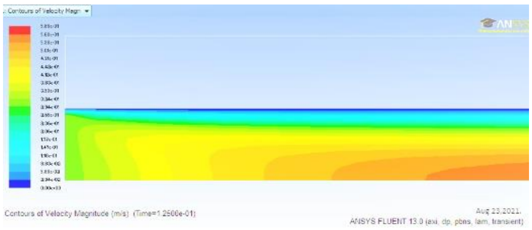

Fig: Contours of velocity magnitude at phase angle 90° in entrance region

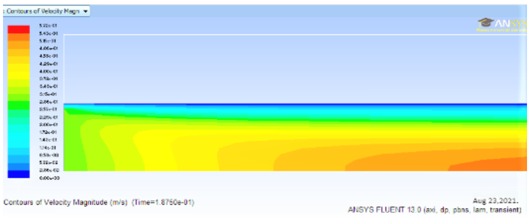

Fig: Contours of velocity magnitude at phase angle 135° in entrance region

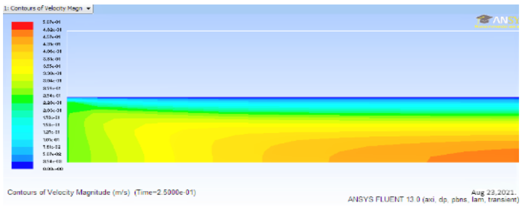

Fig: Contours of velocity magnitude at phase angle 180° in entrance region

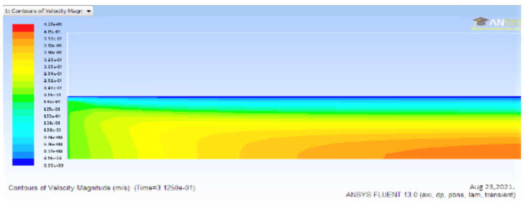

Fig: Contours of velocity magnitude at phase angle 225° in entrance region

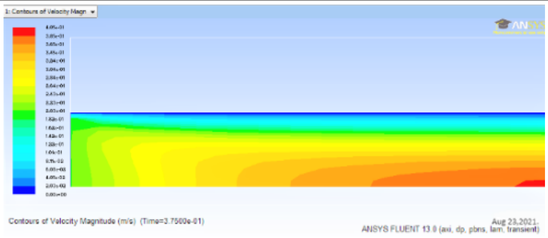

Fig: Contours of velocity magnitude at phase angle 270° in entrance region

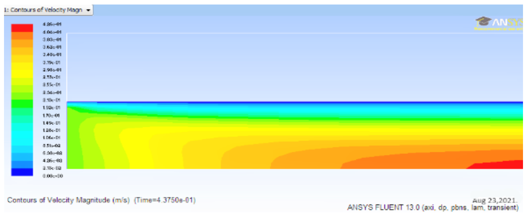

Fig: Contours of velocity magnitude at phase angle 315° in entrance region

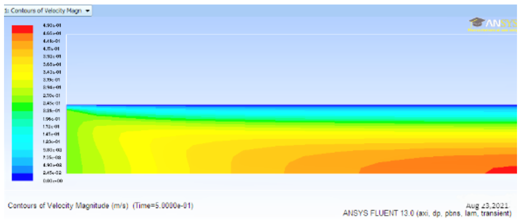

Fig: Contours of velocity magnitude at phase angle 360° in entrance region

It has been found that over a cycle, the hydrodynamic entry length changes continuously. Thermal behaviour may also get affected, as the hydrodynamic boundary layer changes continuously over a cycle, by such pulsating flow. For lower solid-fluid thermal conductivity ratio, the mean fluid bulk temperature linearly increases in the flow direction from micro tube inlet to outlet, where the temperature of the wall linearly varies only in fully developed region according to convention theory of heat transfer.

For higher solid-fluid thermal conductivity ratio, the conventional temperature variation is not exactly followed, which indicates that there is heat transfer to upstream from downstream in the micro tube wall, because of axial wall conduction in opposite to flow direction. The bulk fluid temperature decreases and wall temperature increases with the phase angle change from 0° to 90°. The increment rate of wall temperature of tube is higher than that of the bulk mean fluid temperature. For very low thermal conducting materials, the increment in wall temperature is more. Again, by increasing phase angle further to 270°, the wall temperature decreases and the bulk fluid temperature increases, compared to that of phase angle 0°.

In axial fluid flow direction, the local instantaneous Nusselt number in fully developed region is lowest for minimum solid to fluid conductivity ratio and at any location, irrespective of phase angle, Nusselt number increases first and then slightly decreases and increases again. Space averaged Nusselt number in axial flow direction, shows negligible change from phase angle 0° to 180°, but enhancement in space averaged Nusselt number can be noticed in phase angle range of 180° to 360° and the following plots for Nusselt number were obtained from all thermal analysis made on pulsating laminar fluid flow.

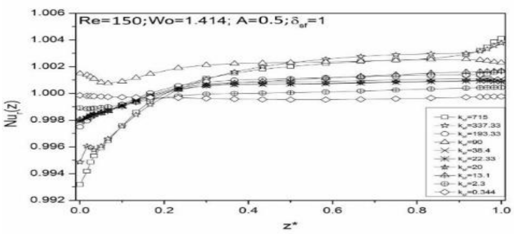

Fig: Variation of time average relative Nusselt number for all k_{sf} values

CONCLUSIONS AND FUTURE SCOPE

A numerical analysis is performed to enlighten the effect of pulsating fluid on axial wall heat conduction for the laminar flow in a microtube with constant heat flux boundary condition imposed on its outer surface. Wide range of solid to fluid conductivity ratio is taken for the analysis, while the thickness ratio (δ_{sf}), amplitude (A), and flow rate (Re) remain constant. Based on the numerical simulation, following conclusions are drawn:

(1) Because of pulsating fluid flow, maximum velocity is observed for the phase angle $90^{0,}$ while minimum is observed at phase angle 270^{0}

(2) For a particular pulsating frequency (Wo), with very low k_{sf} the time averaged relative Nusselt number remains [$Nu_r(z)$] almost constant which is less than the corresponding steady state Nusselt number and that leads to lower the overall Nusselt number (Nu). For a particular pulsation frequency (Wo), the overall Nusselt number is maximum at moderate values of $k_{sf.}$

(3) But at higher values of ksf , for a particular frequency again slight reduction in the overall Nusselt number (Nu) is observed.

(4) For a particular pulsation frequency (Wo), an optimum value of k_{sf} (moderate value of k_{sf}) exists at which maximum overall Nusselt number (Nu) is attained. The same result was observed for the steady flow in circular microtube with constant heat flux boundary condition and for steady flow in a microtube subjected to partial heating on its outer wall under constant heat flux boundary.

(5) For various phase angles over the axial length, the relative instantaneous local Nusselt number is fluctuated. More oscillations are produced at the entry region where in the developed region it is delayed while approaching the steady state Nusselt number.

(6) Empirically, the pulsation frequency (Wo) has negligible effect on heat transfer.

(7) It is found that by increasing the pulsating frequency, heat transfer raises for minimum thermal conductive microtube wall material (or

k_{sf}), but the heat transfer rate reduces in cases where the materials with high thermal conductivity are used.

(8) Literature review shows that, the pulsating flow either increases or decreases or shows no effect on heat transfer.

(9) One of the future scopes of project is thermal analysis of multi-phase flow with pulsating fluid flow because working fluid in most of the engineering applications undergoes phase change. Thermal and hydrodynamic analysis of a pulsating fluid flow can also be done for the turbulent flow with very high or low Reynolds number, apart from this. In some practical situations, tube wall may also be subjected to constant wall temperature or partially heated instead of full heating. So, these requirements will initiate further work in the above project. It is expected that, this present work will give significant idea and create a path for new future work.

SUBSCRIPTS

avg	Average value
c	Centreline
s	Solid, microtube material
f	Working fluid
fi	Fluid inlet
fo	Fluid out
in	Microtube inlet
out	Microtube outlet
*	Dimensionless quantity
s	Steady state condition
t	Transient state condition

GREEK SYMBOLS

δ_f	Microtube inner radius, mm
δ_s	Microtube wall thickness, mm
ϕ	Non-dimensional heat flux rate
μ	Dynamic viscosity of working fluid, Kg/m-s
ρ	Mass density of material, Kg/m^3
°	Degrees -phase angle indication
Θ	Non-dimension Temperature distribution
ω	Angular frequency of pulsating flow, rad/s
ν	Kinematic viscosity of fluid, m^2/s
Φ	Rayleigh dissipation function
∇	Differential operator

NOMENCLATURE

A	Pulsating flow amplitude
c_p	Constant pressure specific heat, J/Kg-K
D	Microtube inner diameter, mm
f	Pulsating flow frequency, Hz
h(z,t)	Instantaneous local heat transfer coefficient, $W/m^2 - K$
K_f	Working fluid thermal conductivity, $W/m - K$
K_s	Microtube material thermal conductivity, $W/m - K$
K_{sf}	Solid to Fluid thermal conductivity ratio
L	Microtube length, mm
L_c	Microtube characteristic length $(L_c = D)$,mm

Nu(z,t)	Instantaneous local Nusselt number
Nu(z)	Time averaged Nusselt number
Nu(t)	Space averaged Nusselt number over the tube
Nu	Overall Nusselt number

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