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Thermal Hydraulics Simulation of Fuel Sub-Assembly for 1200 MWe Nuclear Power Reactor

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ABSTRACT
This study illustrates the turbulent flow simulation of coolant water through the three sub-channels of a fuel sub-assembly at a pressure around 16 MPa. The geometry details of the fuel rods, coolant sub-channels and operating parameters are similar to those of Rooppur Nuclear Power Reactor under construction in Bangladesh. The fuel sub-assembly is modeled using seven fuel rods where k-ε turbulence model is used for turbulent flow simulation. The effect of turbulent flow on temperature, velocity, pressure drop, friction factor and Nusselt number in interior, edge and corner sub-channels have been discussed for various axial locations (z =0–45Dh). Thermal hydraulic properties of the coolant water are studied for safety analyses such as: i) Hot spot in coolant channel and ii) Departure from Nucleate Boiling (DNB

Keywords: Subchannel, k-ε, Turbulent Flow, Nusselt number, DNB

1. Introduction

Nuclear Reactor is used to generate thermal energy in a nuclear power plant. The thermal energy is generated from nuclear fission in fuel rods and it is transferred to a liquid coolant that flows through the space between the fuel rods. For a pressurized water reactor (PWR) turbulent flow of water is required which causes convective heat transfer from fuel rods to coolant. Turbulent flow properties have a major influence on thermal hydraulics of the coolant. Thermal hydraulics needs to be studied for reactor to operate within safety limits. Numerical investigations of turbulent flow in fuel sub-assembly have been carried out previously.

Rehme [1] described the turbulent nature in rod bundle sub-channels and natural mixing betweeninter-connected sub-channels. He concluded macroscopic flow pulsations between sub-channels are the main reason behind high mixing rates between them rather than secondary flow. Rehme [2] also had an experimental of turbulent flow through sub-channels of a rectangular core with four fuel rods. Jian et al. [3] modeled a simple analytical model for prediction of friction factor f, and nusselt number Nu, for fully developed turbulent flow in square and hexagonal channel. Bottcher [4] investigated a CFD model of complete reactor vessel of 1000 MWe reactor. But due to computational constraints detailed sub-channel study is not done. H. Ganjiani [5] et al. did 3-D CFD analysis of turbulent flow around 3 fuel rods with spacer grids for 1200 MWe pressurized water reactor. Saxena [6] carried out a numerical simulation of Sodium flow in wire-wrapped Sub-assembly of Sodium cooled Fast Reactor (SFR) by RANS, LES and DNS approach. Mohammad Mizanur Rahman et al. [7] carried out a thermal hydraulic and safety analyses of 3 MW TRIGA MARK-II reactor by COOLOD-N2 and PARET codes. It was concluded that the thermal hydraulic models through the hot channel fuel center-line temperature in steady-state condition are validated within error margins. S. S. Mirafzal et al [9] examined the steady state and transient parameters of VVER-1000 fuel assembly using Drift-Flux Model. Ajoy et al [10] studied the thermal-hydraulic behaviour in the subchannels of High performance Light Water Reactor (HPLWR) fuel assembly. It is seen in the study the temperature rise in the corner channel is faster than other subchannels. It also concluded that the wire-wraped spacer provide less pressure drop and good mixing than spacer grid. The fuel clad surface temperature also remain within limits by wire-wrapped spacers.

So it's seen that numerical study of sub-channels fuel sub-assembly has been carried out with great importance. In our study *k-ε* turbulence model is used. The model computes four variables to determine the turbulence nature of the flow field. Turbulent kinetic energy (k), turbulence dissipation rate (ε) and turbulent eddy viscosity (μ_t) and production of turbulent kinetic energy (P_k). Turbulent kinetic energy is the measure of the energy of the fluctuations in the flow field. When turbulent occurs large eddies form which then dissipate as they break up into smaller eddies. The rate of dissipation of turbulence is measured by μ_t. Also turbulent eddy viscosity adds up to internal fluid friction when turbulent transfer of energy and momentum happens by forming and breaking of eddies. In this study these characteristics along axial flow in three subchannels (interior, edge and corner) and its effect on the flow structure has been studied. The objectives of this study are as follows:

1) To determine turbulent properties and its effect on velocity, temperature and nature of convective heat transfer in the subchannels of the fuel subassembly.
2) Study of velocity and temperature distribution profiles

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3) Analysis of the variations of pressure drops, friction factor along the axial length of the sub-assembly
4) Examining local Nusselt number and finding the minimum length for attaining a fully developed Nusselt number in the sub-channels

5) Probability of Departure from Nucleate Boiling (DNB) and finding the location of maximum temperature of coolant.

2. Geometry and Mesh

The fuel sub-assembly modeled here contains seven fuel rods where actually there are 163 fuel assemblies each having 312 fuel rods in the reactor core. The computational domain developed for the study contains only 10% of the actual fuel rod length and effect of spacer grids is neglected. The model was created in SolidWorks 2013. The geometrical parameters of the model is shown in the table below:

Table 1: Geometry of the computational domain

Parameter	Value	Unit
D_p	9.1	mm
P	12.75	mm
L	37.5	cm
N_{rings}	1	-
N_{pin}	7	-
a	20.95	mm

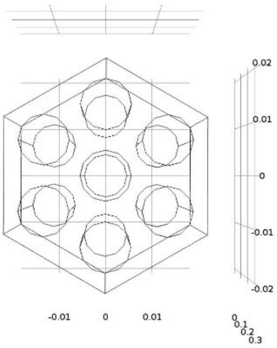


Fig. 1. (a) Computational domain of the fuel sub-assembly

Hydraulic diameter of the fuel sub assembly is defined as Eq. (1)

$$D_h = 4A_f / P_W \tag{1}$$

Where A_f is coolant flow area of the sub assembly and P_w is wetted perimeter by the flow in traverse direction. The hydraulic diameter found here is 8.4099 mm. There are three sub channels:

(1) Interior sub-channel
(2) Edge sub-channel
(3) Corner sub-channel

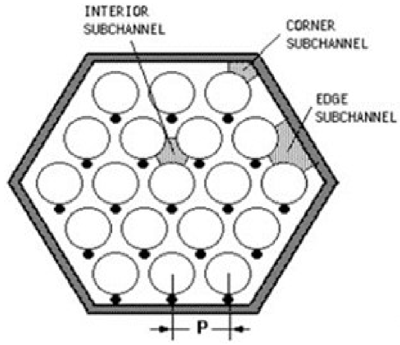
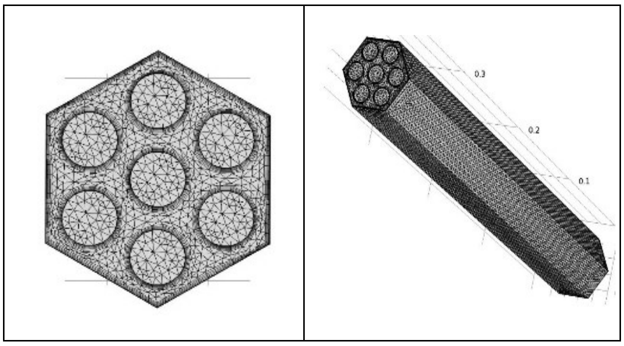


Fig. 2. Sub-channels of the fuel sub-assembly

Completed mesh contains 599119 domain elements including 331929 tetrahedral domains and 267190 prism domains. Figures of meshing domains are given below:



(a) (b)

Fig. 3. a) and b) Meshing of the of the computational domain

3. Governing Equation

The equations for the fluid flow and heat transfer in the sub-channels used in the study are as follows:

Momentum equation:

$$\rho\,(\boldsymbol{u}\,.\,\nabla)\boldsymbol{u} = \nabla.\,[-p\boldsymbol{I} + (\mu+\mu_t)\,(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^{T}) - \tfrac{2}{3}(\mu + \mu_t)(\nabla.\,u)I - \tfrac{2}{3}\rho k\boldsymbol{I}\,] + F \tag{2}$$

Continuity equation:

$$\nabla.\,(\rho\boldsymbol{u}) = 0 \tag{3}$$

Heat transfer in fluids:

$$\rho C_{P}u\,.\,\nabla T = \nabla.\,(K\nabla T) + Q + Q_{vh} + W_p \tag{4}$$

Transport equations: The standard k-ϵ model equations:

For turbulent kinetic energy :

$$\rho(u\,.\,\nabla)k = \nabla.\,[(\mu + \mu_t/\sigma_k)\,\nabla k] + P_k - \rho\,\varepsilon \tag{5}$$

For dissipation:

$$\rho(u\,.\,\nabla)\,\varepsilon = \nabla.\,[(\mu + \mu_t/\sigma_e)\ \nabla\varepsilon] + C_{e1}\,\frac{\varepsilon}{k}P_k - C_{e2}\,\rho\frac{\varepsilon^2}{k} \quad (6)$$

Here, Turbulent Eddy viscosity

$$\mu_t = \rho\, C_\mu\, (k^2/\varepsilon) \quad (7)$$

production of turbulent kinetic energy:

$$P_k = \mu_t[\nabla u : (\nabla u + (\nabla u)^T)\,] - 2/3\,\rho k\,\nabla.u \quad (8)$$

Where values of constants in the k-ε turbulence model are $C_\mu = 0.09$, $C_{e1} = 1.44$, $C_{e2} = 1.92$, $\sigma_k = 1.0$ and $\sigma_e = 1.3$

Relative pressure drop :

$$P_r = (P - P_{in})/\,P \quad (9)$$

Friction factor:

$$f = 2D_h\,\Delta P\,/\,(\rho\, L\, v^2) \quad (10)$$

Reynolds Number,

$$Re = \rho u D_h\,/\,\mu \quad (11)$$

Nusselt number : The Dittus-Boetlter equation-

$$Nu = 0.023Re^{0.8}\,Pr^{0.4} \quad (12)$$

4. Boundary Condition

The Boundary conditions for flow field and thermal field are as follows:

Thermal Insulation:

$$-n.(-K\nabla T) = 0 \quad (13)$$

At solid boundary surface the fluid will have zero velocity relative to the boundary

$$u = 0 \quad (14)$$

Inlet:

$$u = -u_0.n \quad (15)$$

Outlet:

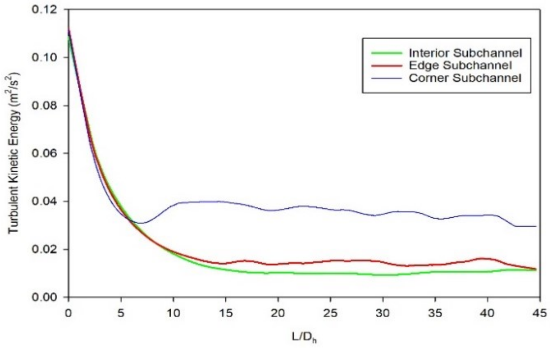
$$[\rho\boldsymbol{I} + \mu + \mu_t\,(\nabla u + (\nabla u)^T - 2/3\ \mu(\nabla.u)I\,].n = -p_0 n \quad (16)$$

Also, uniform heat flux of 278 KW/m^2 has been set at the fuel rod walls. For $Re = 3.55\times10^5$, the inlet velocity and temperature are 5.66 ms^{-1} and 570° K respectively. The outlet pressure has been fixed to 16.06 MPa. The fluid flows upward inside the sub-channels of the fuel rod assembly.

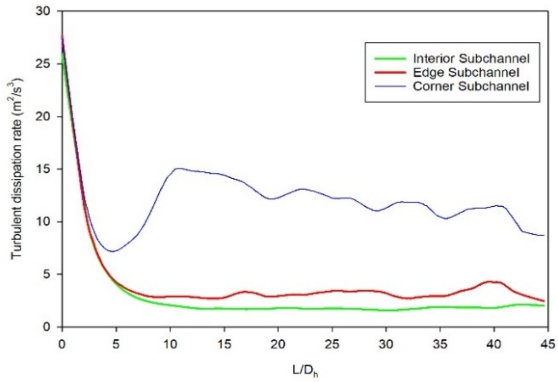
5. Result and Discussion

5.1 Turbulent Properties Distribution

Due high Reynolds number the coolant water flowing axially is turbulent. Turbulent characteristics like turbulent kinetic energy, turbulence dissipation rate and turbulent eddy viscosity play a major role in the flow structure and temperature of the fluid. From Figure 1 it is seen that all the properties are more dominant in corner subchannel than interior and edge subchannel. Velocity fluctuations and formation of eddies in corner subchannel influence its flow characteristics and dissipation of turbulence affects its fluid's temperature and convective cooling which will be discussed in the later sections.



(a)



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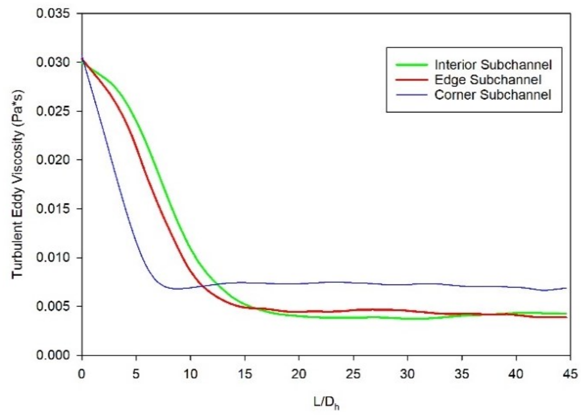


(c)

Fig. 4 (a) Turbulent kinetic energy, (b) Turbulence dissipation rate, (c) Turbulent eddy viscosity along 3 sub-channels in the axial direction

5.2 Velocity Distribution

The velocity distribution along 3 sub channel along the axial distance is shown in the Figure 5. Inlet velocity is fixed at 5.66 m/s. Up to an axial distance of $4D_h$ the velocity in all the sub channels has a sharp increase. Then the velocity along interior and edge sub channel gradually increased whereas in the corner sub channel it decreased. As seen in Figure 1 corner subchannel has more turbulent viscosity and turbulence dissipation rate. These are caused by forming of large eddies and their breaking of large eddies into smaller eddies. In these processes internal fluid friction rises here more than other subchannels and as a result flow velocity in the corner decreases.

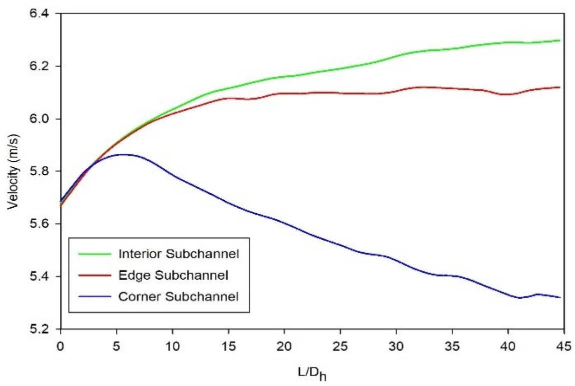


Fig. 5. Variation of velocity along 3 sub-channels in the axial direction

5.2 Temperature Distribution

The temperature distribution along 3 sub channel along the axial distance is shown in the graph where temperature of the cooling water at the inlet is fixed at 570K.Increase in temperature in the interior sub-channel is greater due to being surrounded by fuel rod walls which has uniform heat flux. From Figure 6 it is seen that in the corner subchannel fluid is adjacent to only one fuel rod and edge subchannel is adjacent to two fuel rods. But increase in temperature is more in the corner because of more dissipation of turbulent kinetic energy than the other. Here average temperature rise in the sub-channel is about 1K because the model is .001% of the whole core volume. For full reactor volume this temperature increase is about 30 K.

5.3 Local Nusselt Number Variation

Nusselt number is a function of Reynolds number according to equation no 12. Reynolds number depends on hydraulic diameter, D_h which is a varying quantity in the three subchannels. From equation 1 we found D_h of interior Subchannel to be 6mm, for edge subchannel 10 mm and for corner subchannel 4 mm. From figure 7 and 8 the difference in Reynolds number and local nusselt number is shown. In edge subchannel, greater local nusselt number suggest that the convective heat transfer is more here than other two subchannels. Also temperature gradient is seen to be less than two subchannels in figure 6. The slope in figure 7 for edge and interior subchannel comes to zero at 20 D_h which suggests that the nusselt number has reached its fully developed state. For proper heat removal the length the sub-channel must be fixed considering the minimum length for attaining a fully developed nusselt number. In the corner subchannel nusselt number reaches it peak in $5D_h$ and continuously decrease along the axial length. This suggests that the convective heat transfer in this subchannel is decreasing but from figure 9 it can be seen that the local fluid enthalpy in corner subchannel is increasing. So, for having a low nusselt number and high fluid enthalpy there is a probability of nucleate boiling (DNB) occurring at the corner sub-channel. Due to nucleate boiling a two phase flow may occur which will decrease the convective heat transfer coefficient.

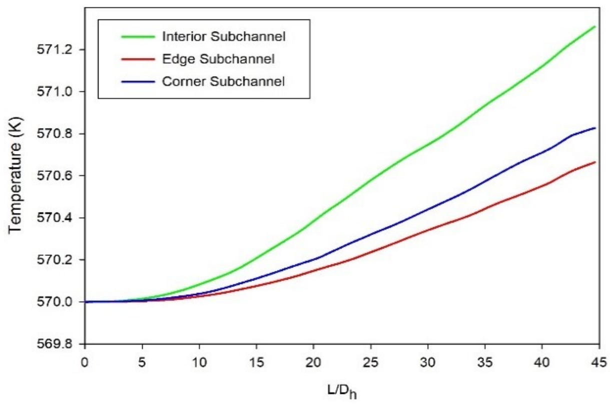


Fig. 6. Variation of temperature along 3 sub-channels in the axial direction

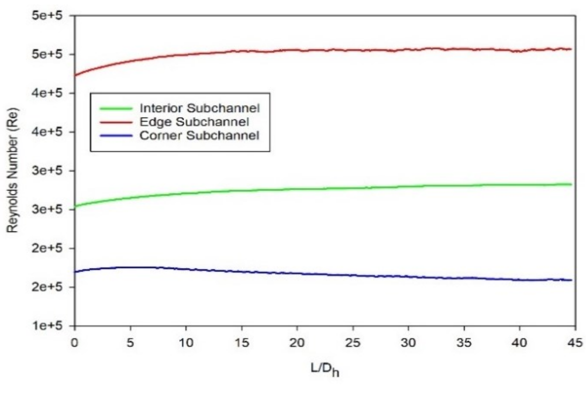


Fig. 7. Variation of Reynolds number along 3 sub-channels in the axial direction.

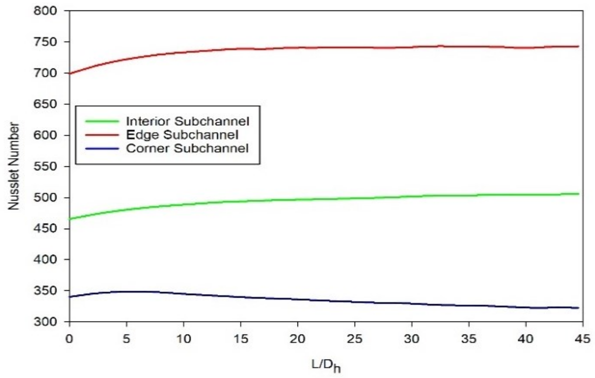


Fig. 8. Variation of local Nusselt number along 3 sub-channels in the axial direction

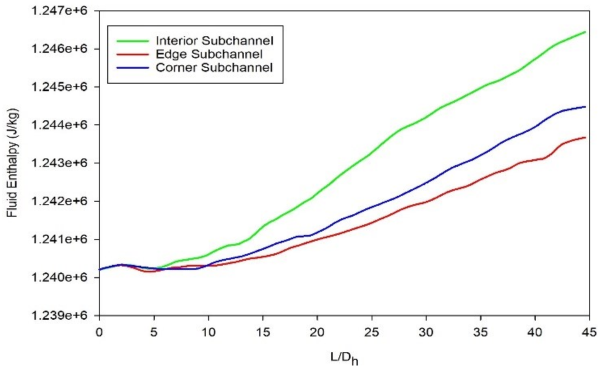
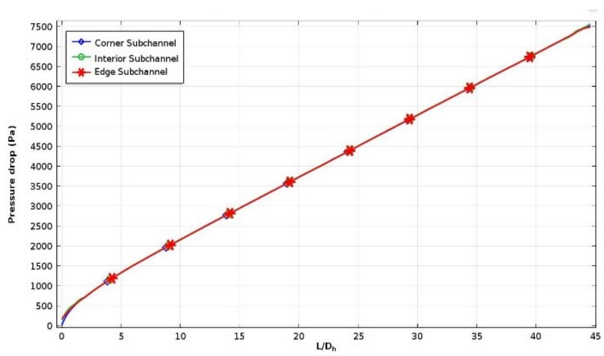


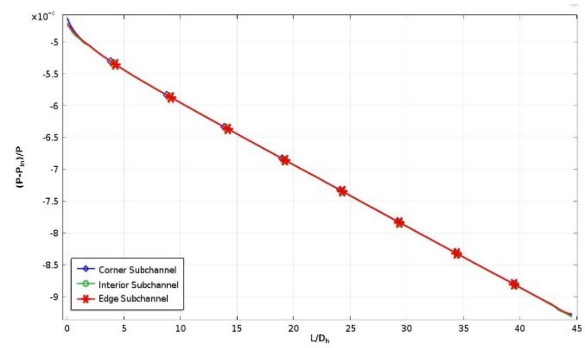
Fig. 9. Variation of Fluid Enthalpy along 3 sub-channels in the axial direction

5.4 Pressure drop variation

Pressure at outlet is set to 16.06 MPa and average pressure at inlet is 16.07 MPa. Here the total pressure drop of 7.5 KPa. Pressure drop is higher at the inlet and gradually decreases along the axial direction in all three subchannels.The figures for pressure drop and relative pressure drop along axial length is given:



(a)



(b)

Fig. 10: (a) Pressure drop (b) Relative Pressure drop along axial direction

5.5 Variations of friction factor

Local friction factor is calculated from local velocities in different sub-channels. The variation between friction factor along the axial direction in 3 sub-channels is shown in the following graph. Friction factor is more in edge subchannel because of larger coolant flow area. Interestingly while having smaller flow area coolant subchannel's friction factor gradient along axial length is more than interior subchannel because of added turbulent viscosity in its flow area.

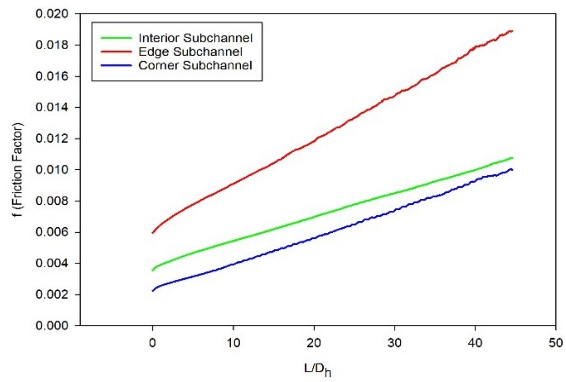


Fig. 11. Variation of friction factor along axial direction in 3 sub-channels

6. Conclusion

A three-dimensional Computational Fluid Dynamics (CFD) analysis for turbulent flow in the interior, edge and corner sub-channels of hexagonal fuel sub-assembly of a 1200 MWe nuclear power reactor is carried out. Having different geometrical shapes and boundary conditions, the effect of operational parameters in the three sub-channels varies accordingly. .The following remarks may be drawn from the study-

1) In Corner sub-channel turbulent properties like turbulent kinetic energy, turbulence dissipation rate and turbulent eddy viscosity along the axial length is significantly large than other two subchannels. The flow

velocity decreases in the corner subchannel due to this eddy viscosity.

2) For having higher Nusselt Number in in the edge subchannel region the fluid temperature is lower than that of other two subchannels. But in the corner subchannel because of the decreasing of nusselt number and increasing temperature and fluid enthalpy along its axial length probability of DNB and occurrence of hot spot in fuel rod adjacent to this subchannel is more than other two subchannels.

3) For proper heat removal from the fuel rod surface the length of the fuel sub-assembly should be such that the nusselt number should can reach its fully developed state. In this simulation the fully developed nusselt number is attained in edge and interior subchannel. The length of the fuel sub-assembly should more than taken here for computation to find fully developed nusselt number in the corner subchannel.

4) In the corner sub-channel along the direction of fluid flow slope of friction factor increase is more due added turbulent viscosity. Friction factor is greater in edge because of larger coolant flow area.

5) Relative pressure drop is almost the same for various Reynolds numbers in all the three sub-channels.

Nomenclature

A_f : Coolant flow area, m^2

a : Side of a hexagonal wall, m

C_{pu} : Heat capacity at constant pressure, $kJ \cdot kg^{-1} \cdot K^{-1}$

D_h : Hydraulic diameter, m

I : Identity matrix

K : Thermal conductivity, W/m*k

k : Turbulent kinetic energy, m^2/s^2

L : Length, m

Nu : Nusselt Number, dimensionless

P : Pressure, Pa

P_{in} : Inlet Pressure, Pa

Pr : Prandtl Number, dimensionless

P_w : Wetted Perimeter, m

Q : Heat generation, J

Q_{vh} : Heat generation due to viscous heating, J

Re : Reynolds Number, dimensionless

T : Temperature, K

u : Velocity, m/s

W_p : Work done by Pressure, J

ρ : Density, kg/m^3

μ : Viscosity, Pa*s

μ_t : Turbulent eddy viscosity, Pa*s

ε : Turbulence dissipation rate, m^2/s^3

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