A Study on flow boiling characteristics in a minichannel and conventional channel

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The flow boiling characteristics of minichannel and conventional have been evaluated for the various mass flux and heat flux. The impact of channels heat transfer analysis was carried out by mixture model (MM) of ANSYS Fluent by using water as a working fluid. The aim of this paper to find the better heat transfer in the channels at a different range of mass flow rates (0.020 kg/s to 0.040 kg/s) and heat fluxes (1000 W/m² to 2000W/m²). The analysis was explained with help of output parameters like vapour fraction, heat transfer coefficient, evaporative thin film thickness, temperature difference in channel wall side and film water temperature side, Nusselt number and friction factor. The validation was done with the help of the previous paper. It was observed that friction factor is calculated for various mass flow rate in channels, is lower from smaller diameter pipe but heat transfer is more for the case of bigger diameter. The minimum mass flow rate increases the wall surface temperature as well as high heat flux increase the channel wall temperature. The 4 mm conventional channel is better heat transfer rate compared to 3 mm minichannel.

Keywords: minichannel, heat transfer, mass flow rate, heat flux

1. Introduction

In recent years, the minichannel and conventional channel have been in wide use much application such as air conditioning and refrigeration, chemical industries, aerospace, electronics, desalination and distillation process etc. [1-5] The channel dimension classified and proposed by kandlikar and Grande [2].The channel diameter more than 3 mm is called conventional channels and 3mm ≥ D> 200 μm is called minichannels. The small diameters channels have more compact and less expensive designs but it has some limited application.

Flow boiling heat transfer has two mechanisms. One is nucleate boiling and the other one is forced convection with evaporation. The flow boiling mechanisms dependent on the mass flux and vapour quality. Particularly the flow boiling heat transfer coefficient depends on the heat flux, mass flux and vapour quality [6]While many researchers focused on flow boiling heat transfer in minichannel but the fundamental reasons for the flow boiling heat transfer mechanism, especially bubble elongation behavior and flow parameters characteristics has not explain between the minichannel and conventional channels[7-9].

The previous work, the three boiling model comparison done in a horizontal microchannel by Thavamani and Kumar [10]. Particular the prediction of vapour fraction and found the best model was mixture model. The estimation of vapour bubble is varying in the EM, MM, and VOF model. In the...
present work, the working fluid as a water and to determine the effect of heat flux and mass flow rate in minichannel/conventional channel. The simulation has been investigated with different mass flux (0.020 kg/m$^2$s, 0.030kg/m$^2$s, 0.040kg/m$^2$s) and various heat flux (1000 Wm$^{-2}$, 1500 Wm$^{-2}$, and 2000 Wm$^{-2}$) by using the water. The second objective is to estimate the various heat transfer characteristics such as vapour fraction, heat transfer coefficient, evaporative thin film thickness, channel film temperature-wall temperature, Nusselt number and friction factor in the channels.

2. Materials and methods

Table 1. Specimen materials detail in the CFD

| Sections(Parts) | Materials          |
|-----------------|--------------------|
| Left sidewall   | Copper             |
| Right sidewall  | Copper             |
| Inlet           | Water Liquid       |
| Outlet          | Water Vapour       |

![Figure 1. 2D Schematic diagram flow boiling in a minichannel and conventional channel](image)

The simplest geometric structure of minichannel and conventional channel shown in Figure 1. Both channel length is 300mm, the channel height is 5 mm and their different diameter is 3 mm and 4 mm. The selection of mass flow rate are 0.020kg/s, 0.030kg/s, 0.040kg/s. The heat flux is given to the left side wall and fluid flow domain vapour fraction are evaluated by different mass flow rate. The channel Length mention by L and the channel width mention by w

3. Numerical method

The numerical problem solved by the CFD software Ansys- license version 18.1. The different diameter of channel geometry created and make the mesh distribution in the computational 2D domain. The No of nodes 207046, 93031, 60025 are calculated the vapour fraction at the same operating condition. These nodes value of vapour fraction value are 0.3649, 0.3446, and 0.3318 respectively. The entire computation selected the no of nodes93031 because of their vapour fraction variation is very less. The convergence limits are $1\times10^5$ for all residuals because of time step stability. The simulation was run-up observed the periodic time variation of 0.25 second. The different mass flow rate with various heat flux values and boundary conditions are initiated in the mixture model. The model solution methods are dropped as the pressure-velocity coupling, and scheme selected as a coupled. The volume fraction set as quick and the momentum, energy are set as a second Order upwind.

4. Governing Equations

Generally, laminar flow occurs in micro-channel because of their dimensions is very small. The Reynolds’s number value much smaller than $2.3\times10^3$. Reynolds’s number selection depend on the research work. Reynolds’s number selection ranges depend on the mass flow rate. It laminar flow Reynolds number value lesser than $5\times10^5$ in the mini channels. The fluid flow characteristics assumptions are considered in the CFD analysis. The assumptions are following
➢ The fluid is incompressible and steady state condition.
➢ The gravity effect is negligible

The fluid flow described by the governing differential equation. Navier-Stokes equation are

\[ \rho \frac{du}{dt} = -\rho u \nabla u + \mu \nabla^2 u - \nabla P + F \]  
- (1)

\[ \frac{d\rho}{dt} + \nabla \cdot \rho u = 0 \]  
- (2)

Table 2. Computational simulation: Thermo-physical properties of working fluid

| Parameters                              | Value          | Unit  |
|-----------------------------------------|----------------|-------|
| Inlet mass flow rate (m<sub>i</sub>)    | 0.020, 0.030, 0.040 | Kgs<sup>-1</sup> |
| Channel length (L)                      | 300            | mm    |
| Fluid density (\(\rho\))               | 1000           | Kg m<sup>-3</sup> |
| Inlet fluid temperature (T<sub>i</sub>) | 25             | °C    |
| Heat flux (q')                          | 1000, 1500, 2000 | W m<sup>2</sup> |
| Processing time                         | 25             | s     |
| Latent heat of vaporization (h<sub>fg</sub>) | 2256         | kJ kg<sup>-1</sup> |
| Thermal conductivity (K<sub>t</sub>)     | 0.60           | W m<sup>-1</sup>K<sup>-1</sup> |
| Enthalpy (h<sub>i</sub>)                | 2259           | kJkg<sup>-1</sup> |
| Specific heat C<sub>ps</sub>             | 381            | Jkg<sup>-1</sup>K<sup>-1</sup> |
| Thermal conductivity K<sub>t</sub>       | 388            | Wm<sup>-1</sup>K<sup>-1</sup> |
| Density \(\rho_s\)                      | 8978           | Kg m<sup>-3</sup> |
| Dynamic viscosity (\(\mu\))             | 8.90 \times 10^{-4} | Nsm<sup>-2</sup> |
| Operation temperature (K)               | 300            | K     |

5. Boundary conditions

Fluid analysis software solves governing equation based on the FEM. Mixture model considered as best represent a model. It is referencing from the published paper [10]. The 2D fluid domain have the Left side wall, right sidewall. The left sidewall attached on solid domain. The various heat flux ranges selected from 1000W/m<sup>2</sup> to 2000W/m<sup>2</sup>. The data selection from the global solar radiant exposure over in India at January 1.543 kW/m<sup>2</sup>. The left side wall attached to the solid domain. The mass flow rate selected from 0.020kg/s to 0.040kg/s in rectangular minichannel because of thin liquid film heat transfer occurs the mass flow rate of 50 kg/s [11]. The grid independence test are conducted in the rectangular channel at the different number of nodes with the same operating condition. The entire computation was run with number no nodes 93031. Finally, no-slip boundary conditions considered in fluid wall side.

6. Validation

The mixture model is the best simulation model for prediction of vapour fraction and reported in the published paper [10]. The validation result is shown in figure 2. The mini and conventional channel has excellent heat removal capabilities in some application. When the selection of working fluid as water, the flow rate selected as lower. The ranges of mass flux selected from 1 kg m<sup>-2</sup>s to a maximum of 50 kg m<sup>-2</sup>s [11].
7. Simulation Results and discussion

The vapour phase contour profiles are taken by different mass flow with heat flux and taken from the converged solution files. The vapour fraction will be evaluated with reaching the time second of 0.25. The following different contour profiles are shown the vapour fraction. The vapour fraction related to different mass flux and heat flux by different diameter of channel. It is shown in Figure 3 and Figure 4.

7.1 Effect of vapour fraction for the constant mass flow rate of 0.040 kgs⁻¹ with different heat flux in the minichannel and conventional channel

After simulation time step, the 3 mm and 4 mm diameter of the channel vapour phase contour profiles are taken from the mixture boiling model. The vapour fraction estimated a constant mass flow rate and the different heat flux in the channels. The heat flux increases the evaporation rate also increases in the channel, as a result the vapour fraction increases gradually inside the channel. The vapour fraction contour profile is shown in Table 3 and Figure 3. Bubble elongated size or vapour fraction depend on the channel height, hydraulic diameter and fluid velocity. The fluid flow velocity depends on the surface of the channel because the fluid velocity affect by the channel friction factor. The friction factor very high in the 4 mm of the minichannel, therefore the lifting of the vapour bubble very less and formation of the vapour fraction also very less.

Figure 3. Effect of vapour fraction for constant mass flow rate 0.040 kgs⁻¹ with different heat flux in the minichannel and conventional channel
Table 3: comparison of vapour fraction in the 3mm and 4 mm channel with different heat flux.

| Heat flux (W/m²) | 3 mm mini channel | 4 mm conventional channel | Contour profile |
|-----------------|-------------------|---------------------------|----------------|
| 1000            |                   |                           |                |
| 1500            |                   |                           |                |
| 2000            |                   |                           |                |

The parameters of heat transfer characteristics

7.2 Effect of vapour fraction for constant heat flux of 1500 W m²⁻² with different heat flux in the minichannel and conventional channel

The vapour fraction estimated at constant heat flux with a different mass flow rate in the channels. The vapour fraction gradually decreases with increases in mass flow rate. The vapour fraction increases in 3 mm minichannel compared to 4 mm of the conventional channel. Because convective latent heat of vaporization is more in the 3 mm of minichannel and frictional factor very less. It is shown in Figure 4 and Table 4.

![Figure 4](image)

**Figure 4.** Effect of vapour fraction for constant heat flux of 1500 W m⁻² with a different mass flow rate in the minichannel and conventional channel.

Table 4: comparison of vapour fraction in the 3mm and 4 mm channel with mass flow rate

| Mass flow rate (kg/s) | 3 mm mini channel | 4 mm conventional channel | Contour profile |
|-----------------------|-------------------|---------------------------|----------------|
| 0.020                 |                   |                           |                |
| 0.030                 |                   |                           |                |
| 0.040                 |                   |                           |                |

7.3 The parameters of heat transfer characteristics

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The compact of the minichannel and conventional channel has been widely used in the various thermal application. The different type of channel used to higher heat rejection capability with the lower flow resistance. Two different widths of the channel are estimated with their heat transfer coefficient, the temperature difference between the wall and fluid, Nusselt number and friction factor by the fluent software with license version 18.1.

The heat transfer coefficient directly professional to the thermal conductivity of water and nusselt number, indirectly professional to the hydraulic diameter. The channel heat transfer coefficient depends on the channel wall temperature, water film temperature and film layer thickness. The channel water film temperature calculated from the average of inlet and outlet of channel temperature. The channel temperature difference \((T_w-T_f)\) gradually increase and decrease of heat transfer coefficient at various mass flow rate with constant heat flux. It is shown in figure 5. Conventional channel heat transfer coefficient very high compared to 3mm minichannel heat transfer coefficient at different mass flow rate with constant heat flux because of the vapour bubble elongation very less due to frictional force. It is shown in figure 6.

![Figure 5. Effect of channel temperature difference with various mass flow rate at 1500 W m\(^{-2}\) in the minichannel and conventional channel](image)

![Figure 6. Effect of channel heat transfer coefficient with various mass flow rate at 1500 W m\(^{-2}\) in the minichannel and conventional channel](image)

The channel friction factor depends on the mass flow rate. The friction factor increases the mass flow rate decrease because a very thin film layer creates more friction on the channel surface. It is shown in figure 7. The 4 mm conventional channel has higher friction factor because of a very thin fluid layer developed inside the channel due to shear force. The 4 mm conventional channel Nusselt number increases with increase in mass flow rate because the heat transfer coefficient is very high. It is shown in figure 8. The evaporative thin film thickness was increase with lower mass flow rate due to the latent heat of vaporization. The 4 mm conventional channel developed a very thin layer of evaporative film.
thickness compared to 3 mm mini channel because of bubble formation is very less. It is showed in figure 9.

Figure 7. Effect of channel friction factor with various mass flow rate at 1500 W m\(^{-2}\) in the minichannel and conventional channel.

Figure 8. Effect of channel Nusselt number with various mass flow rate at 1500 W m\(^{-2}\) in the minichannel and conventional channel.

Figure 9. Evaporation thin film thickness with minichannel length in the minichannel and conventional channel.
8. Conclusions

This article presents numerical results of flow boiling heat transfer in minichannel and conventional channel using the water as the working fluids. It shows that both heat transfer and mass transfer affected by the various diameter of the channel. The grid-independent test conducted with different nodes, same time step. The vapour fraction evaluated and reported. The main concluding points of the numerical investigation in this study are the following.

- The mixture model is selected for numerical simulations in the minichannel and conventional channel. Each case of the minichannel and conventional channel estimated by different heat flux and mass flow rate at the same boundary conditions. The time iteration step was 0.25s
- The vapour fraction predicted and estimated in the channel. The minichannel vapour fraction was more compared to conventional channel due to physics of bubble growth inside the channel. But the heat transfer coefficient is high in the conventional channel compared to minichannel. The evaporation film thickness was measured for the elongated bubble flow at two dimensionless distance from the bubble head.

Acknowledgements

The authors are grateful for the financial support from SRMIST, School of mechanical engineering, kattankulathur-603203 for his doctoral study.

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