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Intermittent Flow Pattern on Two Phase Flow Boiling with Horizontal Microchannel

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Abstract: Industrial equipment products had been developed for a small and compact design. Cooling system is also developed to mini heat exchanger with microchannel as main component. The main study is to find the characteristic of flow pattern and heat transfer effect in microchannel. The experiment has been done with visual apparatus that placed after outlet of test section with inner diameter 0.5 mm. The working fluids used is a natural refrigerant (propane) that operated on a vary parameter of experiment condition i.e. saturation temperature, mass flux and heat flux. Mapping of flow pattern used Wang's Map. The result experiment reported intermittent flow pattern occurred along operated experiment. Heat transfer showed increasing value on initial occurred two phase. The observation to visual data has reported as additional of experiment analysis.

Keywords: microchannel; natural refrigerants; intermittent flow

1. Introduction

Industrial equipment products had been developed for a small and compact design. Cooling system is also developed into mini heat exchanger using microchannel as a main component. Convective heat transfer typically exhibits a lower heat transfer coefficient than that of boiling, and coolant temperature rises rapidly⁷⁾.

Mechanism of two-phase heat transfer consist of some criterion: the first is nucleate boiling heat transfer mechanism dominates the heat transfer mechanism. This mechanism proposed by Bao et al⁶⁾, which explained the result of his experiment in investigation on coefficient of heat transfer in a smooth channel for refrigerant R-11 and HCFC 123. Heat transfer coefficient as a strong function of pressure and heat flux, while the effect of mass vapor quality and mass flux is very low. Another author, Anwar et al³⁾ have found the same of heat transfer mechanism. Anwar et al³⁾ explained heat transfer was insignificant contribution of convective but strongly influenced by the applied heat flux.

The second mechanism is both of nucleate boiling and convective boiling dominate on coefficient of heat transfer. McNeil et al²⁰⁾ have conducted an experiment with the range of mass flux was 200 – 600 kg/m².s and heat flux was 5 – 80 kW/m². The result of experiment reported that two-phase convection and nucleate boiling are occurring simultaneously. Lin et al¹⁹⁾ have an experiment with refrigerant R 141b in small tubes. Lin et al¹⁹⁾ reported that

local heat transfer are strongly effected by heat flux and mass vapor quality, but weakly effected by mass flux. Their experiment showed that both convective and nucleate boiling take place in small tube.

The third mechanism of heat transfer dominate by convective boiling. Qu et al²⁴⁾ have the conclusion of their researched that the boiling with forced convection was the dominant mechanism in microchannel saturated region. The study was carried out with deionized water over mass flux range 135 – 402 kg/m².s and outlet pressure 1.17 bar. Boye et al⁸⁾ had done the research with microchannel diameter 1.5 mm with water as working fluids and reported that heat transfer was increased, caused by convective mechanism. Mortada et al²¹⁾ studied with hydraulic diameter of 1.1 mm. The parameter of experiment used are mass flux, heat flux and mass vapor quality 0 – 1. In the boiling region, convective boiling was defined as the dominant.

The fourth mechanism of heat transfer dominate by a thin film mechanism. Huh et al¹³⁾ observed the water flow boiling in microchannel with rectangular tube ($D_h = 103.5$ and $133 \mu\text{m}$). Annular flow pattern was showed on the experiment. This clarified that the major heat transfer mechanism was a thin film evaporation between the vapor core and the heated surface. In et al¹⁴⁾ reported that high convective heat transfer of microchannel two phase flow enables nucleate boiling to be suppressed even in area with low mass vapor quality. There were found two

mechanism of heat transfer on their experiment. Thin liquid film evaporation was dominant on heat transfer mechanism with working fluids of R123, however the contrary case with R134a, that dominant heat transfer mechanism is the nucleate boiling.

Syahrul et al²⁶⁾ studied about optimization of two-phase flow system with numerically through a parametric study. The research is to investigate minimization of entropy generation from three refrigerant using genetic algorithm. Two-phase flow application in terms of air conditioning and refrigeration system has been developed continued. Even that, the study of performance and impact of environment has been conducted, one of research was done by Pal et al²³⁾

The developing of flow pattern map has done by Wang et al³⁰⁾ with modified Baker⁴⁾ map. Wang et al³⁰⁾ studied flow pattern of two phase flow boiling with R-22, R-134a, and R-147C in a smooth tube with 6.5 mm diameter. The report of the study was the refrigerant physical properties such as viscosity, density and surface tension have significant effect on the two phase flow pattern. Vertical flow pattern map was obtained by Hewitt et al¹²⁾ with studying of air-water on low pressure and steam-water on high pressure. Taitel et al²⁷⁾ developed flow pattern map that consist of bubble, intermittent, stratified, wavy, and annular flow.

Kattan et al¹⁵⁾ proposed flow pattern map from a modification of Steiner²⁵⁾ map. The two phase flow pattern map is drawn in coordinates of mass flux versus mass vapor quality. The two phase flow pattern map has been verified for 702 experimental point from five refrigerant tested. Thome et al²⁹⁾ proposed flow pattern map that practical option and easier implementation. Wojtan et al³¹⁾ continually new developed flow pattern map that have been integrated into Kattan et al¹⁵⁾ and Thome et al²⁹⁾. The flow pattern map does not require any iterative calculations and easily used for identification of flow regime in the model of boiling heat transfer.

Ali et al¹⁾ was conducted experiment with visualization flow pattern using high speed camera in microchannel. The horizontal test section was a tube with internal diameter of 781 μm and heated length of 191 mm. The working fluids used was R 134a. Flow pattern map in microchannel has observed in bubbly (including isolated, confined, and elongated bubble), slug, and annular (including wavy, semi, and annular flow).

Ali et al²⁾ was plotting the two phase flow pattern map with concerning superficial velocity of both gas and liquid. The experiments showed the increased velocity of gas results in a transition of flow regimes, viz. bubbly, slug, slug annular, annular and mist in the flow pattern map. The mist flow was only observed for the lowest mass flow. The frequency of bubble was observed since both the mass and the heat flux increased. The fusion rate was caused an increased bubble frequency.

Nasrfard et al²²⁾ observed flow pattern regime of intermittent flow in a horizontal smooth tube. The result

of observation has been compared with some flow pattern maps of El Hajal et al¹⁰⁾, Kim et al¹⁷⁾, Tandon et al²⁸⁾, Cavallini et al⁹⁾. The new correlation has been developed for condensation heat transfer prediction in intermittent flow.

The data experiment result single and two phase heat transfer condition along operational experiment. The main study is to find characteristic of two phase flow pattern and heat transfer effect in microchannel. The flow pattern map that used to this experiment by Wang's map and the focus of experiment analysis on two phase heat transfer.

2. Methodology

2.1 Experimental set up

The experimental study has been conducted in a refrigeration laboratory for observation of heat transfer with microchannel under condition of two phase flow boiling. Figure 1 showed the schematic experimental apparatus. The main test section is a 0.5 mm diameter SS 316 stainless-steel pipe with length of 0.5 meters. An electrical heater is used for refrigerant heating on the main test section.

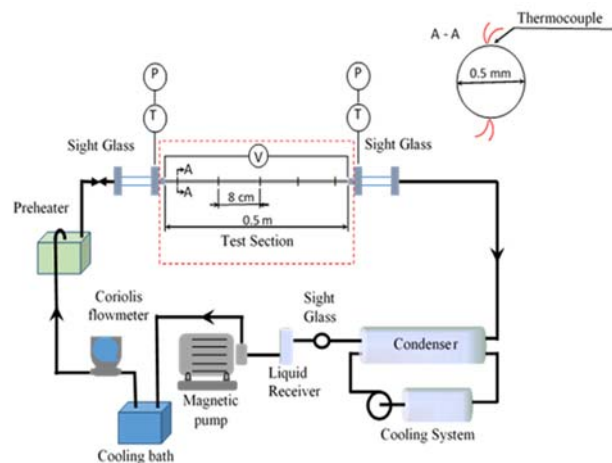


Fig. 1: Experimental apparatus

The Working Fluid of propane enters the test section as liquid in the inlet and came out from the test section as a liquid-vapor mixture flow. The thermocouples type of K was located at some points on the surface of the main test section. Five sections of thermocouples along the test section were installed with distance of 8 mm between each thermocouple sections. On each section two thermocouples at the top and bottom of the tube outer surface were attached. The immersed thermocouples were placed at inlet and outlet points of the main tube in order to find the inlet and outlet temperature difference. The heat (q) transferred to the working fluid was calculated with the following equation:

$$q = \dot{m} C_p \Delta T \quad (1)$$

The pressure transmitters were also placed at inlet and

outlet of the main tube to find a pressure difference of working fluid. After heating on the test section, the working fluid that came out from the main tube will then flow in the condenser, for condensation, that connected to a the cooling system. The condensed working fluid in the liquid phase was then moved and circulated using a magnetic pump. The cooling bath was installed next to the magnetic pump in order to maintain the working fluid in low temperature to keep the liquid phase.

Flow rate was measure using a coriolis flow meter. A preheater was placed before the main tube to adjust the working fluid temperature in order to unsure the working fluid in liquid phase when enter the test section. Two sight glasses was placed before and after the main tube for visualization of working fluid flow pattern.

The calculating of measurement uncertainty of thermocouple has been done by mean deviation method. Table 1 below showed the experimental data uncertainty. The uncertainty of the heat received from heater and coefficient of heat transfer was found using partial differential model. The formula used for calculation was written as follow:

$$\delta q = C_p \Delta T \delta \dot{m} + \dot{m} \Delta T \delta C_p + \dot{m} C_p \delta \Delta T \quad (2)$$

$$\delta h = \frac{1}{A} \delta \dot{q} - \frac{\dot{q}}{A^2} \delta T_{wall} + \frac{\dot{q}}{A^2} \delta T_{sat} \quad (3)$$

With $A = T_{wall} - T_{sat}$.

Table 1. Uncertainty of experiment

	Uncertainty
Average temperature	± 0.42 °C
Heat received from heater	± 0.05 Watt
Average heat transfer coefficient	± 3.0 W/m ² .°C

The parameters of experiment in this study were including mass flux, heat flux, and temperature of saturation. Table 2 showed the range of measured and calculated data of mass vapor quality, void fraction and Z sub-cooled. Parameter of experiment and calculated result in this study showed on Table 2.

Table 2. Parameter of experiment and calculated result

Parameter of experiment	Value
Heat flux (kW/m ²)	5.28 – 7.66
Saturation temperature (°C)	31.96 – 33.14
Mass flux (kg/m ² .s)	681 – 776
Mass quality (-)	Up to 0.15
Void fraction (-)	Up to 0.77
Z sub-cooled (m)	Up to 0.19

2.2 Data Reduction

Experimental tube diameter is classified as microchannel by Kew et al¹⁶⁾ when the Co number is more than 0.5. The regime of flow during the test section consist of single liquid and two phase flow. The length of between the inlet and the zero vapor quality is defined as Z sub-cooled. The two phase flow occurred nearly the length of Z sub-cooled. The equation of Z sub-cooled is written as follow:

$$Z_{sc} = L \frac{i_f - i_{fi}}{\Delta i} \quad (4)$$

The equation to calculate the outlet mass quality is written as follow:

$$x_o = \frac{\Delta i + i_{fi} - i_f}{i_{fg}} \quad (5)$$

The equation to develop flow pattern map of Wang et al³⁰⁾ consist of function of G , λ and x in axis ordinate and x , ψ' and λ in abscissa axis. Wang et al³⁰⁾ has modified two correction property from Baker⁴⁾, where Hashizume¹¹⁾ has reviewed the surface tension for correction. Both of the two property are written as follow:

$$\lambda = \left(\frac{\rho_g \rho_l}{\rho_a \rho_w} \right)^{1/2} \quad (6)$$

$$\psi' = \left(\frac{\sigma_w}{\sigma} \right)^{1/4} \left(\left(\frac{\mu_l}{\mu_w} \right) \left(\frac{\rho_w}{\rho_l} \right)^2 \right)^{1/3} \quad (7)$$

The equation to obtain the local coefficient of heat transfer of the present experimental study is written as follow:

$$h = \frac{\dot{q}}{T_{wall} - T_{sat}} \quad (8)$$

3. Result and Discussion

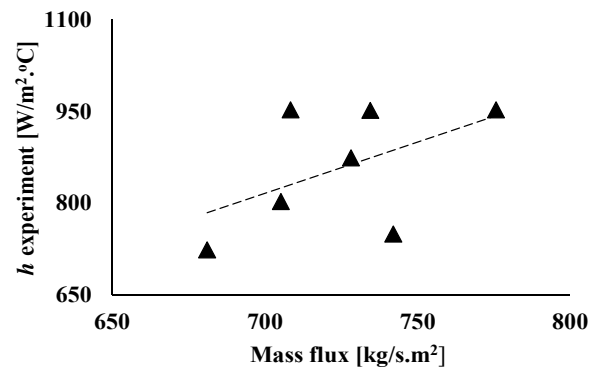


Fig. 2: Mass flux effect on coefficient of heat transfer experiment with $\dot{q} = 5.28 - 7.66$ (kW/m²)

Figure 2 shows the experimental results, viz. the effect of mass flux on coefficient of heat transfer. It explained

that the effect of mass flux and mass vapor quality on coefficient of heat transfer and also mapping flow pattern of the experimental data with Wang et al³⁰⁾ map.

The increased mass flux at microchannel flow result in higher coefficient of heat transfer. The result is illustrated in Figure 2. Higher mass flux in microchannel will suppress the nucleate boiling mechanism. The mass flux has a great effect on coefficient of heat transfer, viz. force convective boiling was seen as the dominant mechanism for heat transfer²⁴⁾.

Figure 3 depicts effect of mass vapor quality on coefficient of heat transfer. The experimental data has result on mass vapor quality up to 0.16. Figure 3 shows that the coefficient of heat transfer goes up at small mass vapor quality of less than 0.05.

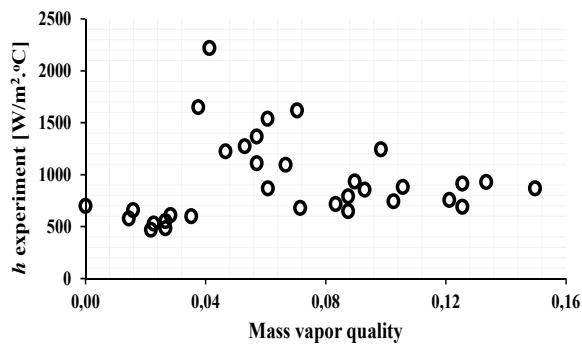


Fig. 3: The effect of mass vapor quality on heat transfer coefficient with $\dot{q} = 5.28 - 7.66$ (kW/m²) and $G = 681 - 776$ (kg/m².s)

The nucleate boiling is occurred at this small vapor quality regime with an initial growth of micro bubble. The increasing mass vapor quality in microchannel showed decrease coefficient heat transfer. This result has similarity with Lee et al¹⁸⁾ that reported heat transfer with nucleate boiling is significant at small mass vapor quality.

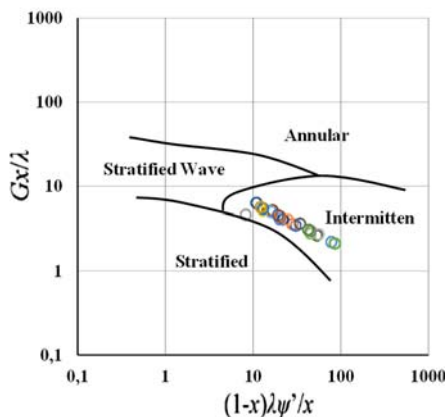


Fig. 4: Experimental data plotted on the Wang et al³⁰⁾ map with $\dot{q} = 5.28 - 7.66$ (kW/m²) and $G = 681 - 776$ (kg/m².s)

Figure 4 showed the experimental result in the intermittent region when it is mapped on Wang flow pattern map. Intermittent flow is a combination of slug flow and elongated bubble flow¹⁵⁾. The viscosity, density, and surface tension has great influence on two phase flow pattern. Figure 3 and figure 4 are same data, where arise of mass vapor quality caused intermittent flow pattern move to the left up of the map. Visual record data experiment showed similar trend with prediction flow pattern from the Wang et al³⁰⁾ map.

4. Conclusion

The study of characteristic of flow pattern and heat transfer coefficient effect in microchannel has conducted successfully. The present study shows that mass flux has a strong effect on coefficient of heat transfer. An increasing mass flux caused increasing of coefficient of heat transfer with convective heat transfer mechanism. Coefficient of heat transfer is higher at low mass vapor quality, and increasing of mass vapor quality caused coefficient of heat transfer become lower. Experimental data showed the prediction flow pattern with Wang et al³⁰⁾ is occurred on intermittent flow region.

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Nomenclature

C_p	heat specific (J/kg.°C)
G	mass flux (kg/m ² .s)
h	heat transfer coefficient (W/m ² .°C)
i_f	enthalpy of saturation liquid (kJ/kg)
i_{fi}	enthalpy of liquid inlet (kJ/kg)
i_{fg}	latent heat (kJ/kg)
L	tube length (m)
\dot{m}	flow rate (kg/s)
q	heat received (W)
\dot{q}	heat flux (W/m ²)
T_{wall}	wall temperature (°C)
T_{sat}	saturation temperature (°C)
ΔT	temperature difference (°C)
x_o	out let mass vapor quality (-)
x	mass vapor quality (-)
Z_{sc}	sub-cooled length (m)

Greek symbols

ρ_g	vapor density of refrigerant (kg/m ³)
ρ_l	liquid density of refrigerant (kg/m ³)
ρ_a	density of air (kg/m ³)

ρ_w	water density (kg/m ³)
μ_l	liquid viscosity of refrigerant (Pa.s)
μ_w	water viscosity (Pa.s)
σ	surface tension (N/m)
σ_w	water surface tension (N/m)
Δi	increasing of enthalpy (kJ/kg)

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