IOP Conf. Series: Materials Science and Engineering **88** (2015) 012027 doi:10.1088/1757-899X/88/1/012027

A Study of the Heat Transfer Coefficient of a Mini Channel Evaporator with R-134a as Refrigerant

E B Dollera[1], E P Villanueva[2]
[1]College of Engineering, Xavier University-Ateneo de Cagayan, Cagayan de Oro City, Philippines
E-mail: edollera@xu.edu.ph

[2]College of Engineering
Iligan Institute of Technology, Mindanao State University
Iligan City, Philippines
E-mail: ep_villanueva@yahoo.com

Abstract. The present study is to evaluate the heat transfer coefficient of the mini-channel copper blocks used as evaporator with R-134a as the refrigerant. Experiments were conducted using three evaporator specimens of different channel hydraulic diameters (1.0mm, 2.0mm, 3.0mm). The total length for each channel is 640 mm. The dimension of each is 100mm.x50mm.x20mm. and the outside surfaces were machined to have fins. They were connected to a standard vapour compression refrigeration system. During each run of the experiment, the copper block evaporator was placed inside a small wind tunnel where controlled flow of air from a forced draft fan was introduced for the cooling process. The experimental set-up used data acquisition software and computer-aided simulation software was used to simulate the pressure drop and temperature profiles of the evaporator during the experimental run. The results were then compared with the Shah correlation. The Shah correlation over predicted and under predicted the values as compared with the experimental results for all of the three diameters and high variation for D_h=1.0mm. This indicates that the Shah correlation at small diameters is not the appropriate equation for predicting the heat transfer coefficient. The trend of the heat transfer coefficient is increasing as the size of the diameter increases.

1. Introduction

Vapour compression refrigeration system is the most widely used refrigeration system today. One of the main components of a vapour compression system is the evaporator. It is a type of heat exchanger which absorbs heat and rejects it through another component, the condenser. The heat rejected in the condenser consists of heat absorbed by the evaporator and the heat from the energy input in the compressor. The compressor is the heart of the vapour compression refrigeration system, discharges hot, high-pressure refrigerant gas into the condenser, which rejects heat from the gas to some cooler environment or heat sink. The high pressure, high temperature, superheated refrigerant from the compressor, condenses and passes through a capillary tube acting as an expansion valve. The refrigerant used in this study is R-134a.

The application of mini channel technology is increasingly used to achieve high heat transfer rates with compact heat exchangers. Boiling and evaporization of R-134a inside small hydraulic diameter tube and channels find many applications in compact heat exchangers for cooling electronic gadgets

[1] To whom any correspondence should be addressed.

and other refrigeration systems. The adoption of minichannel also promotes the reduction of the refrigerant charged, which is beneficial to mass and energy conservation. Minichannel phase change may differ from the conventional channels due to differences in the relative influence of gravity, shear stress and surface tension. As dimensions of electronic components reduce at mini scale, it is necessary for us to use a cooling system which can apply to the same scale. Fluid flow inside mini channel is one of the efficient candidates for small scale cooling. According to Kandlikar, mini channels are classified based on the hydraulic diameter (D_h) of 200μm to 3 mm. There has not been any comprehensive study to determine the limits of macro channel correlations to smaller data[1]. There is a need for such a study and this paper attempts to fulfill this need to some extent.

In this study, three mini channel evaporators of hydraulic diameters 1.0 mm, 2.0 mm and 3.0 mm, with each mini channel length of 640 mm. were designed, fabricated and tested. They were experimentally tested in an experimental rig. Data were recorded and stored using data acquisition system and with the use of a Lab View Software. Heat transfer coefficients were calculated using thermodynamics principles and compared with Shah Correlations. Solid Works software was used to simulate the thermodynamic parameters involved in this study.

2. Theoretical Considerations

2.1 Refrigeration Vapor Cycle

The evaporator is a heat exchanger that absorbs heat from the refrigeration system. The evaporator receives low pressure R-134a from the pressure reducing device, absorbs heat from its environment and delivers it to the compressor as a superheated gas. From the compressor, R-134a rejects heat in the condenser and enters back to the pressure reducing device. The reduced pressure in the expansion device enables the evaporator to absorb heat from the environment at a lower and cooler temperature. Evaporators are equipment that allows two-phase flow in the system which makes them difficult to calculate the exact coefficient of heat transfer. It is normal for a conventional evaporator to experience two boiling regimes, nucleate boiling and convective boiling.

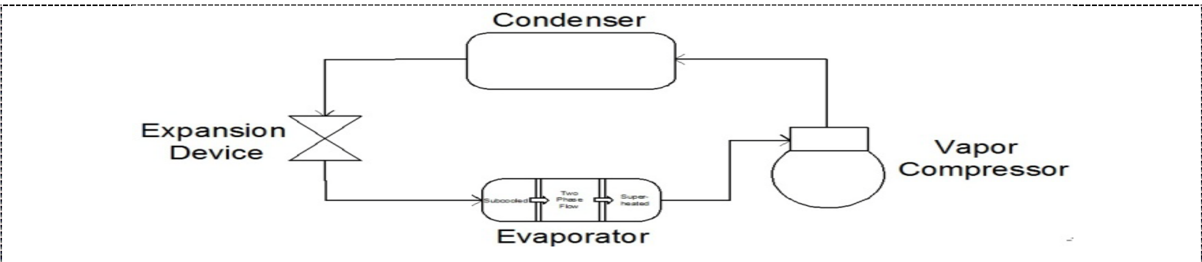

Figure 1. Schematic diagram of vapour compression refrigeration system

There are two ways in which flow boiling in small diameter channels are expected to be implemented. They are, two-phase entry after a throttle valve and sub-cooled liquid entry into the channel[2]. Because of the requirement of the liquid flow meter being used, this study belongs to the sub-cooled liquid entry into the channel. Sub-cooled liquid entry is an attractive option, because of higher heat transfer coefficients associated with sub-cooled flow boiling[2].

2.2 Two-Phase Flow Heat Transfer Coefficient, H_{TP}

From Newton's law of cooling,

$$Q = H_{TP,Exp}\,(A_i)(T_{si} - T_w) = m_r(h_{out} - h_{in}) \tag{1}$$

where Q=heat absorbed by R134a,kJ/s, $H_{TP,Exp}$ =experimental heat transfer coefficient,kW/m^2-K, A_i=inside channel surface area,m^2, T_{si} = inside saturation temperature of R134a,K, T_w=channel wall temperature,K, m_r=mass flow rate of R-134a,kg/s, h_{in}=enthalpy of R134a at mini-channel inlet,kJ/kg, h_{out}=enthalpy of R134a at mini-channel outlet,kJ/kg

From equation 1, the experimental heat transfer coefficient, $H_{TP,Exp}$, is calculated as,

$$H_{TP,Exp} = m_r\,(h_{out} - h_{in})/[\pi D_h L(x)(T_{si} - T_w)] \tag{2}$$

where D_h =hydraulic diameter,m, L = total length of the mini channel,m, and x=mini-channel length ratio.

In this study, Shah correlation [3,4] is used to determine the two-phase heat transfer coefficient. Shah correlation is the only two-phase flow correlation that approximates a decreasing experimental heat transfer coefficients as the length ratio of the mini-channel increases. The Shah correlation, $H_{TP,Shah}$, is expressed as,

$$\Psi = \frac{H_{TP,Shah}}{h_{LO}} \tag{3}$$

where Ψ =two-phase multiplier for Shah correlation, Ψ_{nb} =nucleate boiling multiplier, Ψ_{cb}=convective boiling multiplier, and $h_{LO=}$heat transfer coefficient for liquid-phase only and calculated using Dittus-Boelter[5] correlation,

$$h_{LO} = 0.023\left(\frac{k_l}{D_h}\right)\left(\frac{G(1-x)D_h}{\mu_l}\right)^{0.8}(P_r)^{0.4} \tag{4}$$

where k_l =liquid phase thermal conductivity,W/m-K, G=mass flux,kg/s-m^2, μ_l=liquid phase kinematic viscosity,kg/s-m, P_r =Prandtl number.

For nucleate boiling,

$$\Psi_{nb} = \frac{H_{TP,Shah}}{h_{LO}} \tag{5}$$

Solving for the boiling number, B_o,

$$B_o = \frac{q''}{(G)(h_{LV})} \tag{6}$$

where q''= heat flux, kW/m^2 and h_{LV} =latent heat of vaporization, kJ/kg,

For $B_o \leq 0.3 \times 10^{-4}$,

$$\Psi_{nb} = 1 + 46\,B_o^{0.5} \tag{7}$$

For $B_o < 0.0011$, Froud number, F_r can be calculated as,

$$F_{rl} = 15.4\,B_o^{0.5} \tag{8}$$

Solving for the convection number, C_o,

$$C_o = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{9}$$

where ρ_G=the gas density of R134a,kg/m^3, and ρ_L=the liquid density of R134a,kg/m^3.

For horizontal tubes with $F_r \leq 0.04$,

$$N = 0.38\,Fr_l^{-0.3}C_o \tag{10}$$

So that,

$$\Psi_{cb} = \frac{1.8}{N^{0.8}} \tag{11}$$

and use the result of equation (7) or equation (11) into equation (3) whichever is higher.

3. Description of the Experimental Work

An experimental rig was constructed to house all the refrigeration components and instrumentation sensors. A fabricated mini channel evaporator was used in the experimental test set-up by tapping a 1/8 hp vapour compressor. The dimension of the mini channel is 100 mm *x* 50 mm *x* 20mm copper block. Fins were also fabricated on each face of the copper block and each face contains 24 fins with width of 2 mm, length of 50 mm and thickness of 5 mm.

The refrigerant passes through the mini channel with hydraulic diameter varied from 1mm, 2mm and 3mm. Leak tests were done to ensure that there will be constant flow of refrigerant in the system.

During the experiments, refrigerant flow rate was controlled using a by-pass valve from the main evaporator. The refrigerant mass flow rate was measured at the inlet of the mini channel evaporator. The two temperature sensors and two pressure transducers were mounted on the refrigerant-side at the inlet and outlet of the mini channel. One temperature sensor was also installed at the middle of the mini channel.

An insulated wind tunnel was fabricated and a forced draft fan was installed to guarantee sufficient supply of air across the mini channel. Two temperature sensors were mounted on the wind tunnel, one at the inlet and one at the outlet of the tunnel. The air velocity over the mini channel was measured using hotwire anemometer.

The temperature sensors, flow meter and pressure transducers were connected to the data logger. The data logger was interfaced with the computer. Lab VIEW software had been used to operate the data logger and to store the data in the computer. The data logger was set to scan the data from the flowmeter, temperature sensors and pressure transducers at an interval of 30 seconds.

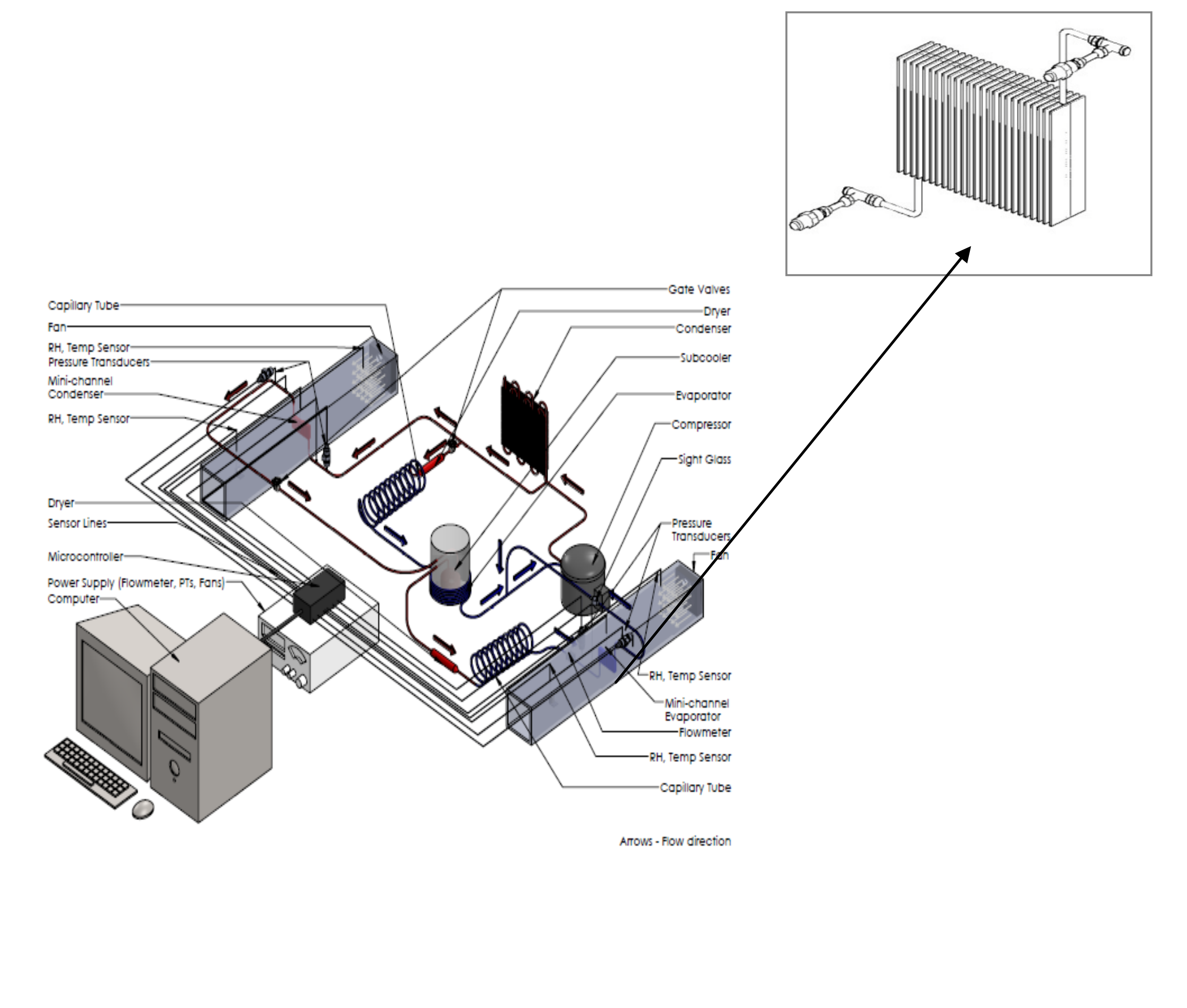

Figure 2. Experimental set-up.

4. Data Analysis and Evaluation of Heat Exchanger Performance

The results related to the heat transfer coefficient and pressure drop were obtained from the readings of three thermocouples, two pressure transducers, a flow meter and an anemometer, installed in the test section. The heat absorbed in the evaporator is calculated by the relation,

$$Q = m_r\,(h_{out} - h_{in}) \tag{12}$$

where m_r is the refrigerant mass flow rate obtained directly from the flow meter, h_{in} is the enthalpy entering to the mini channel evaporator corresponding to a measured pressure and temperature, and h_{out} is the enthalpy leaving the evaporator corresponding to a measured pressure and temperature conditions.

The average values of experimental heat transfer coefficient were calculated based on the average inside surface temperature of the mini channel,

$$Q = h_{TP,Exp}(A_i)(T_{sat} - T_{si}) \tag{13}$$

5. Results and Discussion

The heat exchangers in Figure 3 show the view of the interior part and Figure 4 shows the finned exterior surface of the mini channel evaporator. These mini channels were fabricated and joined together through oxy-acetylene welding. These heat exchangers were capable of operating at maximum pressure of 10 bars.

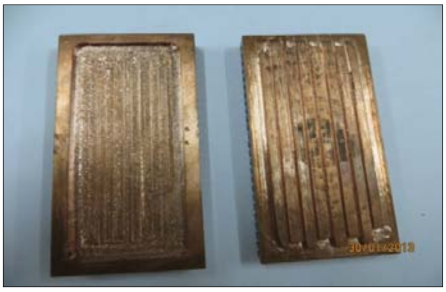

Figure 3. Interior part of mini-channel.

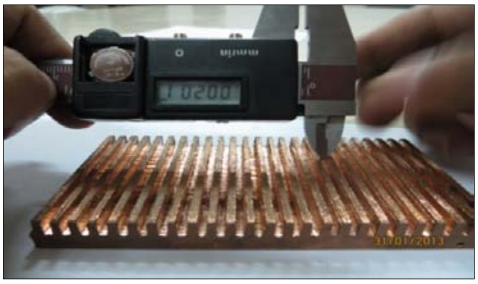

Figure 4. Exterior Part of mini-channel.

Figure.5, shows the variations of the experimental heat transfer coefficient and the Shah correlation with the length ratio. Shah correlation over predicted the heat transfer coefficient for the D_h = 1.0mm in most part of the total length of the mini channel but approximates each other values near the inlet and outlet of the mini channel.

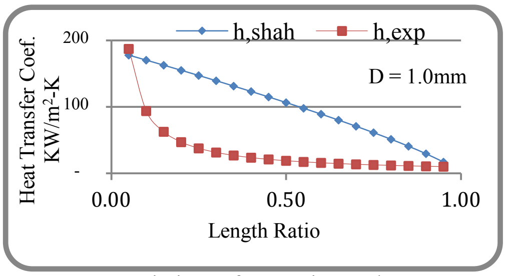

Figure 5. Variation of Experimental Heat Transfer Coefficient & Shah Correlation for 1mm.

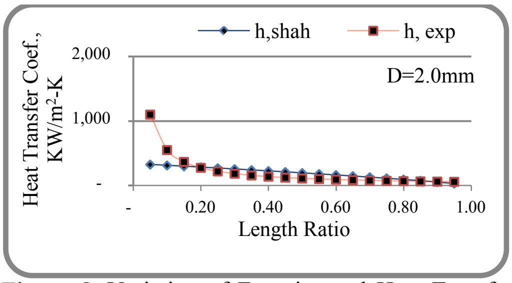

Figure 6. Variation of Experimental Heat Transfer Coefficient & Shah Correlation for 2mm.

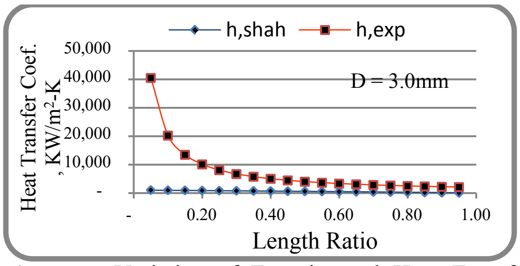

Figure 7. Variation of Experimental Heat Transfer Coefficient & Shah Correlation for 3 mm.

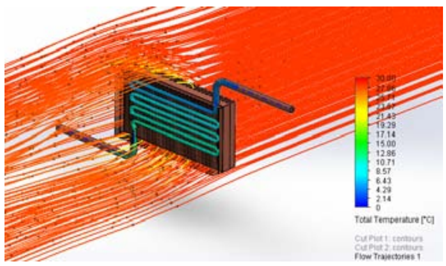

Figure 8. Temperature Profile for 1mm.

Figure 6 shows the variation of the experimental heat transfer coefficient and the Shah correlation with the length ratio. Shah correlation over predicted the heat transfer coefficient for the D_h=2.0mm in some parts of the total length and under predicted in some parts of the mini channel length. Greater variation of the heat transfer coefficients at the inlet is attributed to the sub-cooled liquid condition. Figure 7, shows Shah correlation under predicted the heat transfer coefficient for the D_h=3.0mm in all parts of the length ratio from 0.05 to 0.95.The greater variation occurs below 0.50. Figure 5, Figure 6 and Figure 7, show that the experimental heat transfer coefficient and the Shah correlation increase as the hydraulic diameter of the mini-channel increases. These two methods in calculating the heat transfer coefficient conformed each other as to the magnitude of the heat transfer coefficient.

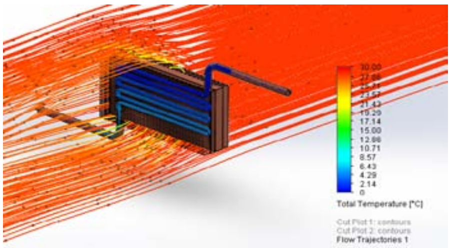

Figure 9. Temperature Profile for 2mm.

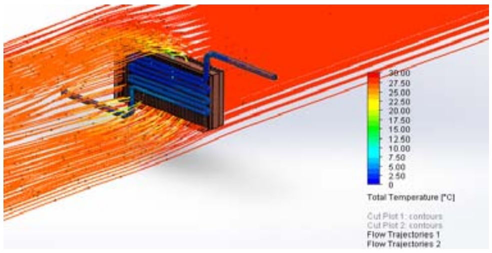

Figure 10. Temperature Profile for 3mm.

Figures 8, 9 and 10, show the temperature profile inside the mini channel. The refrigerant R-134a enters the mini-channel at a sub-cooled liquid condition, represented by the blue color. The temperature at the outlet condition is represented with the red color signifying the superheated condition at the mini-channel outlet.

6. Conclusions and Recommendations

Based on the data obtained in this study, the following conclusions are drawn. The experimental heat transfer coefficient for D_h=1.0mm has the lowest value and D_h=3.0mm has the highest value for the three tested mini channel evaporator. Shah correlation over predicted the values for D_h=1.0mm and under predicted the values for D_h=3.0mm. This variation is caused by the difference of mass flux introduced to the system. Shah correlation approximates the experimental values for 2.0mm near the centre of the length of mini channel.The experimental heat transfer coefficient and the Shah correlation increases as the hydraulic diameter increases. The simulated temperature profile of R-134a approximates the experimental values obtained using temperature sensors. Sub-cooled condition of R-134a results a higher experimental heat transfer coefficient and decreases as the temperature of R-134a increases inside the mini-channel evaporator.

It is recommended that further study will be done by using constant mass flow rate as basis for comparison and to further study the behavior of the mini channel with hydraulic diameter of 0.5mm, 1.5mm and 2.5mm.

7. References

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