2016

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A Study of Microchannel Heat Exchanger Performance Associated with the Manufacturing Process

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ABSTRACT

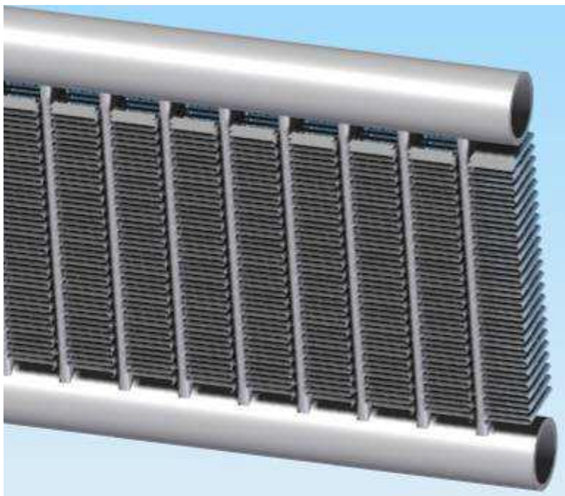
The increased demand for aluminum microchannel condensers in the HVAC&R industry imposes new challenges on the design and manufacturing processes. An aluminum microchannel heat exchanger typically contains three major components: headers, microchannel tubes and multi-louvered fins. The parts are assembled and joined together by a brazing process. To ensure high thermal performance of the brazed product, microchannel heat exchanger designers must carefully consider manufacturing issues related to the brazing process during the design stage. For example, in addition to proper sizing of the header manifolds, it is essential to determine the optimal insertion length of the microchannel tube into the header during the header/tube assembly process. An oversized header diameter not only reduces heat exchanger compactness, but also leads to increased refrigerant charge. It further increases header wall thickness requirements due to increased hoop stress. Too short of an insertion length of the microchannel tube increases the risk of overflow of liquid filler metal into the microchannels during brazing and blockage of the refrigerant passages. On the other hand, small diameter header tubes and long insertion lengths of microchannel tube may contribute to a significant increase of refrigerant side pressure drop. This paper provides both experimental and analytical studies on the influences of header geometry and microchannel tube insertion length on the heat exchanger performance, such as refrigerant side pressure drop. Samples with various header/tube assembly design parameters are prepared and brazed using controlled atmosphere brazing (CAB) technology. Brazed samples are tested in a pressure drop measurement facility. Theoretical modeling of the brazed microchannel heat exchanger is performed and compared with the experimental results. This study provides important guidance and insights with respect to the design of microchannel heat exchangers under consideration of manufacturing issues.

Keywords: HVAC & R heat exchangers, microchannel, header, brazing

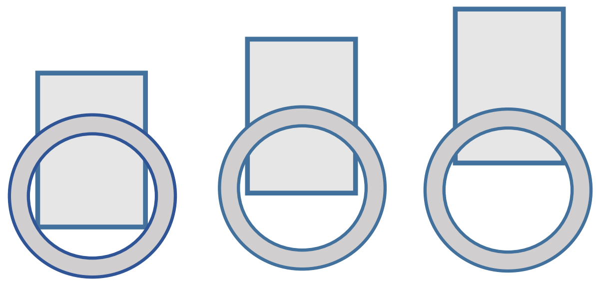
1. INTRODUCTION

Aluminum microchannel heat exchangers have demonstrated indisputable advantages such as high thermal performance and significant weight reduction compared to conventional heat transfer coils. The development of extruded microchannel tubes for refrigerant passage has significantly improved thermal performance of the heat exchangers. Controlled atmosphere brazing (CAB) of aluminum is the state-of-the-art technology for manufacturing of compact aluminum heat exchangers (Swidersky, 2009). The use of a continuous furnace with controlled nitrogen atmosphere ensures high production rate and brazing quality.

It is well known that a brazing process involves the capillary flow of liquid filler metal on the surfaces of various heat exchanger components. To ensure high thermal performance of the brazed product, manufacturing issues related to the brazing process should be carefully considered during the heat exchanger designing process. A typical aluminum microchannel heat exchanger has three major components: header, multiport microchannel tube and louvered fin, as illustrated in Figure 1(a). These components are joined together by brazing. The brazing results not only influence the mechanical strength and the integrity of the final product, but also significantly impact the thermal performance of the heat exchangers. For example, the design of the header/ microchannel tube assembly is essential for brazed heat exchanger quality. An oversized header diameter not only reduces heat exchanger compactness, but also leads to increased refrigerant charge. It further increases header wall thickness requirements due to increased hoop stress. As illustrated in Figure. 1(b), the preferred header diameter should be relatively small to take advantage of charge minimization and compactness of the microchannel heat exchanger. The header should also provide sufficient space for microchannel tube insertion. The insertion length of the microchannel tube is an important design parameter that can significantly influence the heat exchanger performance. Too long of an insertion length of the microchannel tube may contribute to a significant increase of refrigerant side pressure drop. Too short of an insertion length can cause incomplete braze or blockage of microchannel by overflowing of liquid filler metal.



(a)



(b)

Figure 1 : (a) Microchannel heat exchanger assembly; (b) illustration of various microchannel tube insertion lengths into the header.

In this paper, both experimental and analytical studies are presented to illustrate the influences of header/tube assembly design on the heat exchanger performance, such as the refrigerant side pressure drop. Prototype heat exchangers with various microchannel tube insertion lengths are prepared and brazed using CAB technology. Brazed heat exchangers are tested in a pressure drop measurement facility using compressed nitrogen gas in place of the working fluid. Theoretical modeling of the pressure drop through microchannel tubes at different mass flow rate**s** is performed and compared with the experimental results.

2. MATERIALS AND EXPERIMENTS

2.1 Prototype heat exchanger fabrication

In this study, prototype heat exchangers with various header/tube assemblies (as illustrated in Figure.1(b)) are fabricated using the controlled atmosphere brazing technology. The aluminum alloy used for the header is commercially available AA6063 that contains Mg as the major alloy element. Microchannel tubes and louvered fins are usually made of AA3xxx series alloy that contain Mn as the major alloy element. Filler metal AA4047 (Al-12wt%Si) in a wire form is preplaced at the header/tube joint location. Nocolok flux (Solvay Fluro, 2013) is used in brazing to assist wetting of the molten filler metal on the substrate surfaces.

Three prototype heat exchangers are brazed in a controlled atmosphere aluminum brazing furnace under identical conditions. The inert gas atmosphere is maintained by a continuous flow of high purity nitrogen gas through the furnace chamber. Figure 2 illustrates the brazed prototypes. A schematic on the left side of each prototype shows the insertion length of the microchannel in the header. The inner diameter of the header is 20 mm, the width of microchannel tube is 18mm. The length of microchannel tube is 150 mm. Each prototype heat exchanger has two microchannel tubes for parallel flow of refrigerant. The brazed samples were leak checked and good joint integrities were confirmed.

(b)

Figure 2: Brazed microchannel heat exchanger prototypes (a) front view of the heat exchangers; (b) side view of the heat exchangers

As illustrated in Figure 2, the design parameters for all three heat exchangers are the same except for the insertion length of microchannel tubes in the headers. The designations of the heat exchangers and the characteristic tube insertion lengths are as follows: (1) HX #1 with insertion length of 10 mm; (2) HX #2 with insertion length of 14 mm; (3) HX #3 with insertion length of 18 mm. HX #1 has the minimum tube insertion length needed for a complete seal between the tube and the header. HX #3 has the maximum tube insertion length possible due to the tube end hitting the header inner wall.

2.2 Pressure drop test

An experimental facility as illustrated in Figure 3 was set up to perform the heat exchanger refrigerant side pressure drop tests. Nitrogen gas was used in place of the refrigerant to flow through the heat exchanger. Pressure difference between the inlet header and the outlet header was measured at various mass flow rates. The nitrogen gas was supplied from a compressed nitrogen cylinder. In addition to the pressure drop and the mass flow rate, other measured experimental parameters include the nitrogen pressure and the temperature at the heat exchanger inlet, as illustrated in Figure 3. A data acquisition system was used to record the measured parameters.

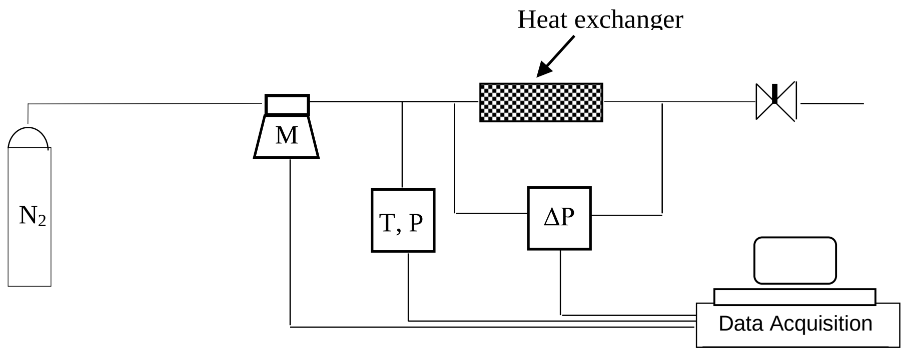


Figure 3: Schematic of pressure drop test set-up

2.3 Visualization of brazing process

Additional brazing experiments were performed using a lab furnace to visualize and understand the liquid filler metal wetting behavior during the heat exchanger brazing process. The lab furnace system is equipped with a transparent chamber which allows in-situ monitoring of the complete brazing process. The system provides radiative heating and a controlled inert gas atmosphere for a typical CAB aluminum brazing process. Brazing heating and cooling cycles are controlled by computer using an in-house developed software. Heating zone atmosphere is monitored by continuously sending sample gas to a dew point sensor. The transparent furnace chamber and a schematic of the brazing sample set up are illustrated in Figure. 4. The joining process of header and tube by liquid metal was recorded using a high resolution video camera.

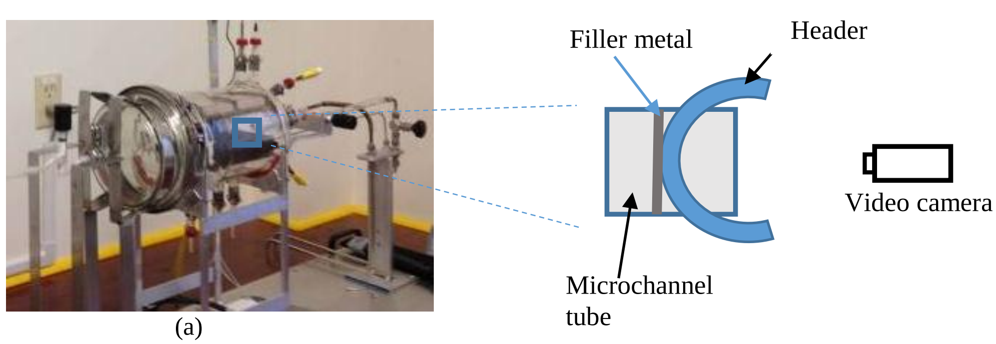


Figure 4: lab furnace system for visualization: (a) transparent furnace; (b) schematic of brazing sample assembly

3. RESULTS AND ANALYSIS

3.1 Pressure drop of refrigerant side gas flow

In general, the major contributions to the refrigerant side pressure drop through a microchannel heat exchanger are: (1) header loss ΔP_{header}; an d, (2) pressure drop through the microchannel tubes ΔP_{tube} . The mathematic model for predicting the pressure drop ΔP can be presented as follows:

$$\Delta P = \Delta P_{header} + \Delta P_{tube} \quad (1)$$

$$\frac{\Delta P_{tube}}{L} = \frac{f}{d} \cdot \frac{G^2}{2\rho} \quad (2)$$

$$G = \frac{\dot{m}}{A_{port} \cdot N_{port}} \quad (3)$$

In Equations (2) and (3), L is the length of the micro-channel tube, d and $Aport$ are the hydraulic diameter and the cross section area of a micro-channel port, respectively. $Nport$ is the number of open microchannel ports in each heat exchanger. ρ is the density of the N_2 gas, $\dot{m}$ is the N_2 gas mass flow rate, G is the N_2 mass flux in each microchannel , f is the friction factor, which is a function of Re number ($Re = G \cdot d/\mu$) according to the correlations as follows:

$$\text{Re} < 2300 \qquad f = 64/Re$$
$$2300 < \text{Re} < 20000 \qquad f = 0.316 \cdot Re^{-0.25}$$
$$\text{Re} > 20000 \qquad f = 0.184 \cdot Re^{-0.2}$$

Although the actual microchannel has a square shape in this study, the correlations for circular tube are used for simplification purpose.

The experimental and analytical results of the pressure drop of N_2 gas flow through the prototype heat exchangers are presented in Figure 5. The solid lines are the experimental results obtained from the testing facility illustrated in Figure. 3. The dashed lines are predicted results for the pressure drop through microchannel tubes ΔP_{tube}. More details related to the predictions are provided in Section 3.2.

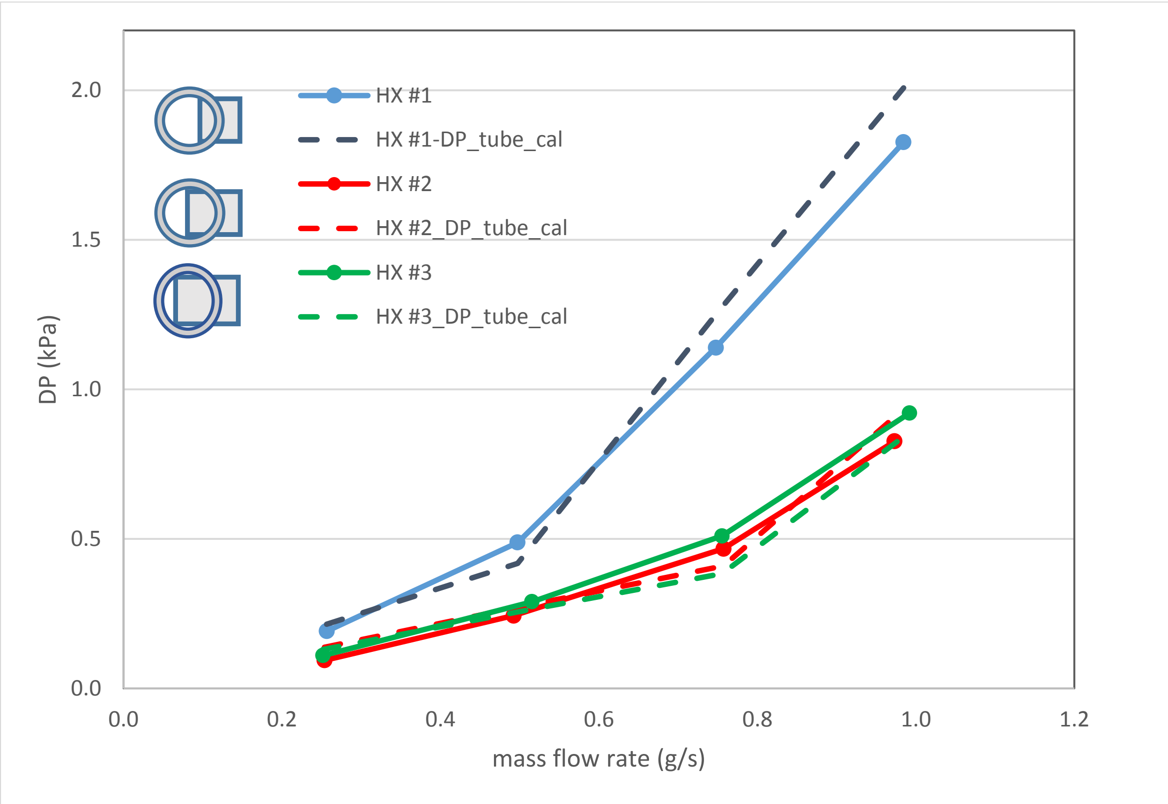


Figure 5 : Increased pressure drop for the same nitrogen mass flow rate in HX1 indicates clogged channels and quantifies potential effects in real operation

As expected, the HX#3 shows slightly higher pressure drop than the HX#2 at the same N_2 gas mass flow rate, most likely due to the maximum tube insertion length in the header which leads to a higher pressure loss ΔP_{header}. On the other hand, the total pressure drop of the gas flow through the HX#1 is significantly higher than the HX#2&3 even though the minimum insertion tube length is used in this heat exchanger. According to equations (2) and (3), the tube pressure drop ΔP_{tube} increases as the N_2 gas mass flux G increases. The increase of G at the same total mass flow rate is a direct consequence of the reduction of the microchannel port number. Such results indicate that a high percentage of the microchannel ports in HX#1 have been blocked by the filler metal during brazing. The phenomenon of microchannel blockage by brazing filler metal has been discussed in a previous study (Zhao, et.al, 2012). The fact that the ends of microchannel tubes are in close contact with the header/tube joining location imposes a high risk of liquid filler metal flowing into the microchannel by capillary action.

3.2 Visual inspection of the heat exchanger head/tube assemblies

After completion of the pressure drop tests, three heat exchanger prototypes were inspected by cutting open the headers to reveal the ports of microchannel tubes. The appearances of the microchannel ports are presented in Figure 6. As predicted, a serious problem of ports blockage by brazing filler metal in HX#1 is clearly illustrated. In one of the two microchannel tubes, only 1/3 of the ports appear unblocked. For HX#2 and HX#3, no apparent port blockage can be visually identified. However, a more careful inspection by inserting a thin gauge wire in each channel reveals that two ports in HX#2 were blocked. After the thorough inspection, it is concluded that: for HX#1, 15 out of 38 microchannel ports are blocked; for HX#2, 2 out 38 microchannel ports are blocked; for HX#3, all 38 ports are open. With the known amount of open microchannel ports, i.e., N_{port} =23, 36 and 38 for HX#1,#2 and #3, respectively, the pressure drop of N_2 gas flow through the microchannel tube ΔP_{tube} can be calculated using Equations (2) and (3). The calculated results are presented as dashed lines in Figure 5. In general, the trends of predicted pressure drops of gas flow through the microchannel tubes show good correlation with the experimental results. The fact that the predicted HX#2 tube pressure drop is slightly higher than the HX#3, opposite to the observation from the experimental data, indicates that the pressure drop contributed by the header ΔP_{header} is not negligible, especially when the insertion length of the microchannel tube is sufficiently long, such as in the HX#3.

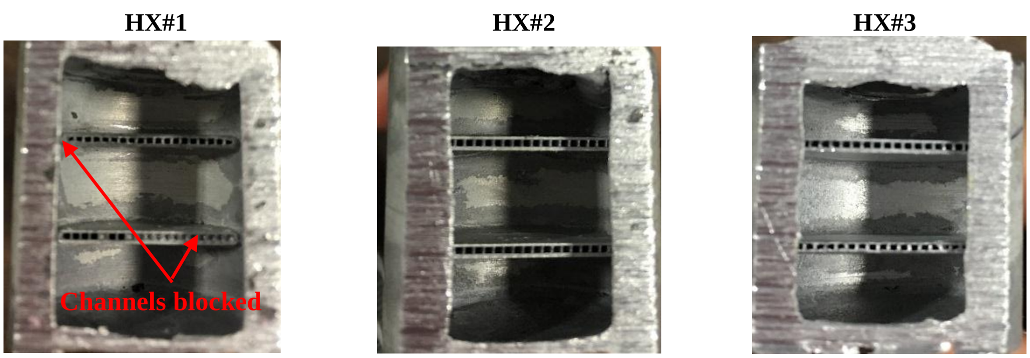


Figure 6 : Visual inspection of the microchannel ports in the headers

During the visual inspection of the inner space of the header, an interesting phenomenon was found in the HX#3 as illustrated in Figure 7. As mentioned previously, for the purpose of creating a maximum insertion length of the microchannel tube in the header of HX#3, the left and right corners of the microchannel tube ends have to hit the inner wall surface of the header. Although no filler metal was preplaced in the vicinities of the additional contact points, the spreading of liquid filler metal may be enhanced by the microgrooves on the header inner wall surface (generated during machining). An extensive spreading of eutectic Al-Si filler metal on a substrate surface with microgrooves has been reported in a previous study (Zhao, et.al, 2014). The liquid metal eventually reaches the contact point of the tube end and the header wall and forms a small joint, as clearly demonstrated in Figure. 7. Fortunately, no port blockage was identified in this particular sample. However, such an assembly does increase the risk of liquid filler metal flowing into the microchannel ports.

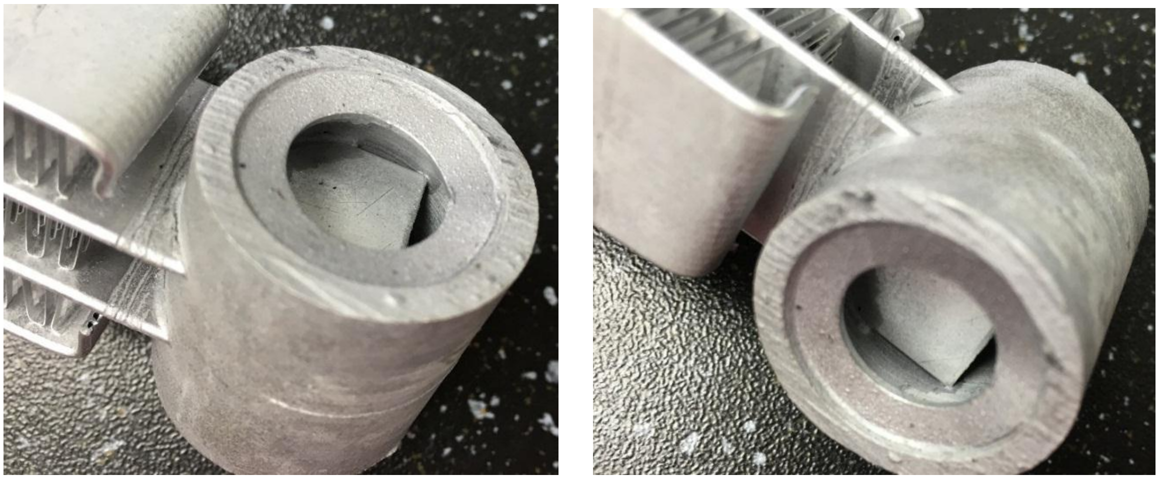
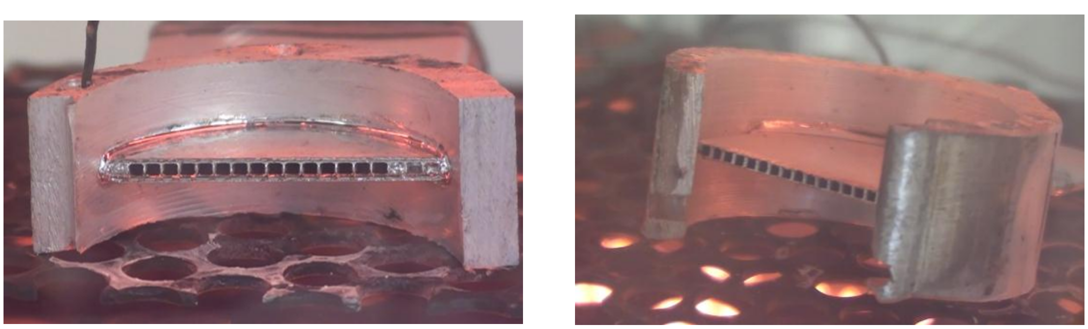


Figure 7 : Extensive spreading of liquid filler metal

The experimental results have shown that the HX#2 uses an ideal tube insertion length to provide a balance between the two known risks: (1) the pressure drop loss in the header, and (2) overflow of liquid filler metal into the microchannel. However, it has been found that even with HX#2, there are still two microchannels being blocked after brazing. The cause for such an extensive filler metal/flux flow (without the assistance of direct contact between tube ends and the header wall) is not clear. The microchannel tubes used in this study seem to have a Zn coating to improve corrosion resistance of the heat exchanger (Janssen, et. al, 2011). One hypothesis is that the Zn coating on the tube surface affects the wetting behavior of liquid filler metal. A detailed study of the influence of Zn addition in substrate surface on wetting properties of the Al-Si filler metal will be provided in a future publication.

3.3 Visualization of header/tube brazing process

Brazing tests using the transparent lab furnace were performed to closely observe the flow behavior of liquid filler metal during the brazing process. Two samples as illustrated in Figure. 4(b) were prepared. One sample has a short tube insertion length and the other has a long insertion length. The header sections were cut open for the purpose of visualization. Flux was applied on the filler metal and the substrate surfaces. The samples were brazed under typical CAB aluminum brazing conditions. Figure 8 presents two images extracted from recorded videos of the header/tube brazing processes. Figure. 8(a) shows that for the sample with a short insertion length, liquid filler metal can easily access the microchannel and block the ports upon solidification. The image presented in Figure. 8(b) illustrates the joint formation between the header and the tube without overflowing of liquid filler metal into the microchannel. In this case, no extensive spreading of the liquid filler metal on the inner tube wall surface was observed, probably due to a relatively smooth surface morphology in this particular sample. More visualized wetting tests of the liquid filler metal on header and tube surfaces will be performed in the future study.



(a) (b)

Figure 8: Visualization of header/tube brazing process for samples with (a) short tube insertion length, and (b) long tube insertion length.

4. CONCLUSIONS

In this study, the importance of considering manufacturing issue**s** during the heat exchanger design process is demonstrated. A series of aluminum microchannel heat exchangers are fabricated using the controlled atmosphere brazing technology. Various insertion lengths of the microchannel tube in the header were designed to study the influence of the insertion length on the heat exchanger refrigerant side performance. It has been found that a short tube insertion length significantly increases the risk of microchannel blockage by liquid filler metal during brazing. Two-thirds of the microchannel ports were found blocked in one of the microchannel tubes for the heat exchanger with minimum insertion length. On the other hand, the increase of tube insertion length seems to cause higher pressure drop contribution from the header, but the influence is relatively small when compared to the pressure drop increase caused by microchannel blockage. The visualization of header/tube brazing process confirms the high risk of microchannel blockage with short tube insertion length. A theoretical model was used to predict the heat exchanger refrigerant side pressure drop with the given number of open microchannels. The trends of the theoretical model show good correlation with the experimental results.

NOMENCLATURE

A	area	(m^2)
d	hydraulic diameter	(m)
f	friction factor	
G	mass flux	(kg/m^2s)
L	length	(m)
$\dot{m}$	mass flow rate	(kg/s)
N	number of ports	
Re	Reynold's number	
ρ	density	(kg/m^3)
μ	viscosity	(Pa s)
ΔP	pressure drop	(Pa)

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