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Capillary Flow of Liquid Metal Occurring in Micro-channel Heat Exchanger Fabrication

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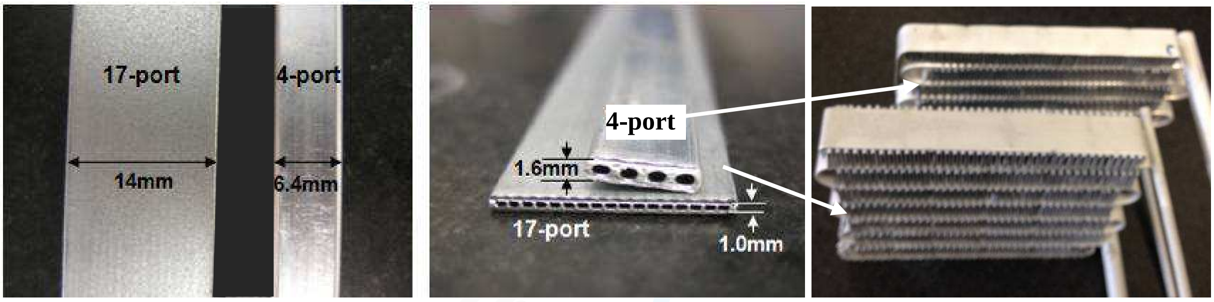
ABSTRACT

Aluminum micro-channel coils are extensively used in automotive air conditioning systems, owing to the usage of multi-port micro-channel tubes and effective fin design for the air-side heat transfer enhancement. The superior thermal performance and compact structure are attracting new applications of aluminum micro-channel heat exchangers in HVAC&R industries. The increased market demands on micro-channel heat exchangers require better understanding and subsequent good control of the manufacturing process. For example, fabrication of the micro-channel coils involves brazing of multi-port tubes with header manifolds and other components. Since capillary flow of molten filler metal is involved in a typical brazing process, there is a possibility of the liquid metal flowing into the micro-channels driven by surface tension force and subsequently blocking the refrigerant passages. This phenomenon can be overlooked during the manufacturing process due to the difficulty in identifying channel blockage using non-destructive testing methods. Undesired consequences, such as a depletion of the filler metal needed for brazing and non-uniform distribution of refrigerant flow during heat exchanger operation may occur. Current trends of reducing multi-port tube diameters and refrigerant charge lead to even smaller micro-channel port dimensions. Therefore, a good control of the manufacturing process becomes more critical. In this paper, the phenomena closely related to liquid filler metal flowing through micro-channels driven by surface tension force are studied. A hot stage microscopy system and a transparent lab furnace are used to experimentally visualize the capillary flow of molten filler metal through the micro-channels. Influences of manufacturing conditions, such as heat exchanger geometry, brazing parameters, filler metal and substrate materials on flow behavior are examined. Theoretical models for liquid metal flowing through capillary channels are also discussed. The overall goals are to better understand the capillary flow phenomena occurring during the fabrication of micro-channel heat exchangers, and to explore the potentials of control and/or utilization of the liquid metal flow characteristics in various manufacturing applications.

1. INTRODUCTION

Aluminum and its alloys are light weight, highly thermally conductive and have fairly good corrosion resistance (Hatch, 1984). These properties combined with the relatively low cost make aluminum alloys suitable materials for compact heat exchangers. Aluminum heat exchangers have been widely used in automotive as well as aerospace industries. For example, micro-channel coils are considered state-of-the-art for automotive condensers due to the superior heat transfer performance. The extended applications of aluminum heat exchangers, especially micro-channel coils in HVAC&R systems are ongoing and follow the current market trend (Nordlien *et al.*, 2011). Significant performance improvements by using micro-channel condensers in residential air conditioning systems have been demonstrated experimentally (Park and Hrnjak, 2002). Regardless of the relatively low cost of aluminum alloys, continuous efforts are devoted to further optimize heat exchanger components, such as extruded tubes and fins. Examples of extruded micro-channel tubes with various tube wall thickness and port diameters are illustrated in Figure 1. The advantages of the thickness reduction of micro-channel tubes include, among other advantages, material cost savings and reduction of refrigerant charge. However, related issues in heat exchanger manufacturing processes using brazing technology are sometimes overlooked. For example, the potential of micro-channel port blockage by liquid filler metal during brazing becomes more prominent as the size of micro-channels decreases.



(a) micro-channel tubes (b) tube cross sections (c) serpentine condensers

Figure 1: Micro-channel tubes for aluminum heat exchangers

The flow behavior of molten filler metal during metal and/or non-metal joining processes (soldering, brazing and welding) is directly related to the final qualities of the joined products. However, both experimental and theoretical studies on this subject are very difficult to accomplish due to many reasons, such as: (1) general high temperature conditions associated with liquid metals; (2) vacuum or protecting atmospheres often required in brazing processes; (3) usage of flux for oxide removal. In this paper, the focus is directed to the study of capillary flow of liquid metal occurring in micro-channel heat exchanger fabrication. Examples of brazed heat exchangers with blocked refrigerant pass by re-solidified filler metal are first illustrated. The dynamic behaviors of liquid filler metal (in this case eutectic Al-Si alloy) through micro-channels driven by surface tension force are of particular inertest due to its importance in developing novel heat exchanger designs with intricate geometries. Subsequent liquid solid interface reaction and micro-channel blockage upon solidification are illustrated. The utilization of experimental techniques such as heating stage microscopy and transparent glass furnace enables real-time observation of the capillary flow behavior of liquid metal involved in the brazing process; therefore, brazing is no longer a “black box” operation. The knowledge gained by such experimental visualization techniques can provide useful guidance on both design and fabrication of new generation micro-channel heat exchangers.

2. EXPERIMENTAL FACILITIES

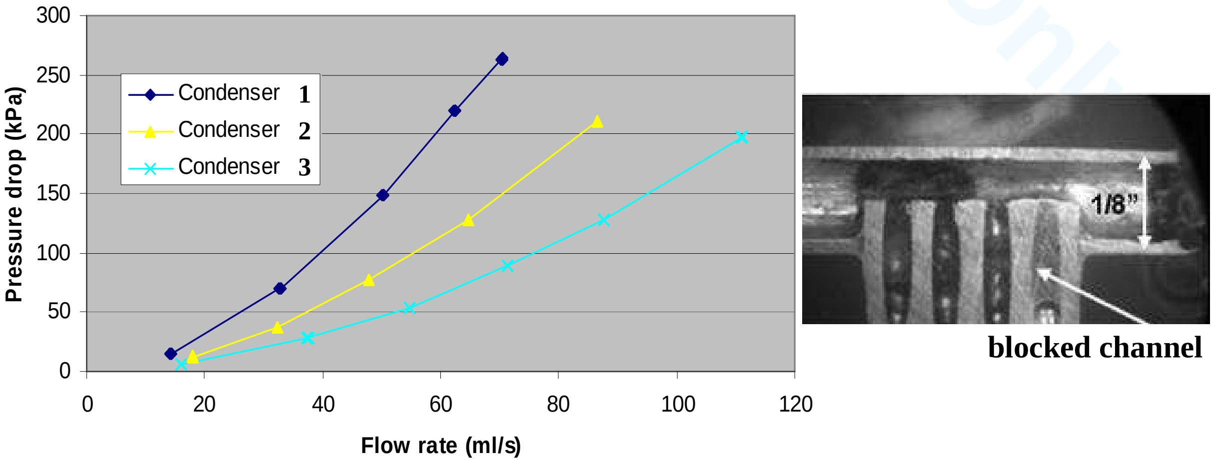
Controlled atmosphere brazing (CAB) is currently the most common manufacturing method for compact aluminum heat exchangers. The process features a protected gas atmosphere (N_2) and application of Nocolok® (Nocolok® is a registered trademark of Solvay Fluor GmbH, Germany) flux (potassium fluoro-aluminate) for the purpose of oxide removal (Garcia *et al.*, 2010). This process offers many advantages such as low investment and less post-brazing treatment since the flux is non-corrosive under normal conditions. Experimental studies presented in this paper involve a number of lab research furnaces: (1) A batch type furnace containing a retort in the heating chamber is used for brazing prototype aluminum parts such as micro-channel heat exchangers. Both heating profile and furnace atmosphere are well controlled to mimic typical industrial brazing conditions. (2) An in-house developed transparent glass furnace is used for the visualization of the brazing process in real time. Radiation heating is provided from multiple sides to the samples to maintain as uniform temperature distribution as possible. The inert atmosphere was obtained by continuous purging with pure N_2. Both automatic and manual control modes are available for brazing tests.

For more detailed observations of liquid metal wetting and spreading phenomena during brazing, a high temperature heating stage (Unitron HHS-3) microscopy system is also used in this experimental study. A mini-heater coil (Kanthal wire) embedded in a ceramic holder (13 mm inner diameter) is installed in a stainless steel chamber. The heater provides radiation heating to small scale samples. A quartz window on top of the stage provides an access for visualization using a microscope, to which a digital video camera is attached to record the processes such as flux and filler metal melting, spreading and solidification during brazing. The heater can provide maximum temperatures above 1000 °C. A protected chamber atmosphere is achieved by continuous purging of inert gas or connecting the chamber to a vacuum system. The heating stage body is water cooled during the heating operation.

3. ISSUES RELATED TO FABRICATION OF MICRO-CHANNEL HEAT EXCHANGERS

Serpentine type micro-channel condensers designed for a mini-cooling system are illustrated in Figure 1(c). In this design, extruded tubes are bonded with multi-louvered fins and header tubes using the CAB batch type furnace. A few prototype condensers are brazed under normal brazing conditions. The header tube inner diameter could be as small as 3.2 mm because of the low refrigerant charge requirement of the system. Due to the fact that both the extruded micro-channel tubes and header tubes are not pre-coated with a thin clad layer of Al-Si alloy, additional filler metal form must be supplied at the joining locations during brazing. Eutectic Al-Si wire is used as filler metal in this example.

After brazing, pressure drop testes using N_2 gas flowing through the heat exchanger tubes were performed to check possible leaks at brazed joints. Although leaks were rarely identified from these brazed condenser prototypes, it has been noticed that some heat exchangers show unusual high pressure drop between the N_2 inlet and outlet. Selected test results are presented in Figure 2(a). Condensers 1 to 3 are brazed with the same materials (4-port tubes as illustrated in Figure1(b)) and have identical dimensions. The variation of N_2 pressure drop indicates that a certain level of micro-channel blockage by brazing filler metal may have occurred. One of the condensers (#2) was cut and polished at the header location to reveal the cross section of the header and micro-channel tube joint as shown in Figure 2(b). It is apparent that at least one of the extruded channels was blocked by the re-solidified filler metal. Therefore, only 75% of the refrigerant passage is available during system operation. The direct consequence of such manufacturing defects will be substantially higher pressure drop on the refrigerant side and non-satisfactory distribution of the refrigerant fluid.



(a) pressure drop vs. N_2 flow rate (b) cross section of blocked channel

Figure 2: Testing of prototype micro-channel condensers

The mathematic model for predicting the pressure drop ΔP of the N_2 gas flow through the micro-channel tube can be presented as follows:

$$\frac{\Delta P}{L_s} = \frac{f}{d} \cdot \frac{1}{2} \rho_{N_2} u^2 \qquad (1)$$

$$\dot{V} = u \cdot A_{port} \cdot N_{port} \qquad (2)$$

In Equations (1) and (2), L_s is the total length of the micro-channel tube of a serpentine condenser, d and A_{port} are the diameter and cross section area of a micro-channel port, respectively. N_{port} is the number of un-blocked ports in each condenser. ρ_{N2} is the density of N_2 gas, u is the average gas velocity, $\dot{V}$ is the total volume flow rate of N_2

through the condenser tube. f is the friction factor. Based on the equations (1) and (2), the following equation can be derived for the condenser prototypes with identical geometries:

$$\Delta P \sim \frac{\dot{V}^2}{N_{port}^2} \tag{3}$$

According to Equation (3), the N_2 gas flow pressure drop through a condenser tube has a linear relationship with the square of the volume flow rate. When the micro-channel blockage occurs, a 25% reduction of the refrigerant flow passage leads to around 1.8 times increase on the pressure drop of the gas flow, a 50% of reduction of the flow passage leads to 4 times increase on the gas flow pressure drop. The experimental data presented in Figure 2(a) is represented as a ΔP vs. $\rho\dot{V}^2$ plot in Figure 3 to compare with the predictions by Equation (3). For all tested condensers, a linear relation between the pressure drop and square of flow rate is confirmed. At the same flow rate, N_2 gas pressure drop through condenser 1 and condenser 2 are approximately 3.5 times and 1.7 times of the pressure drop through condenser 3. Therefore, it can be estimated from the pressure drop test results that condenser 1 has probably 2 ports blocked by the re-solidified filler metal and condenser 2 has 1 port blocked.

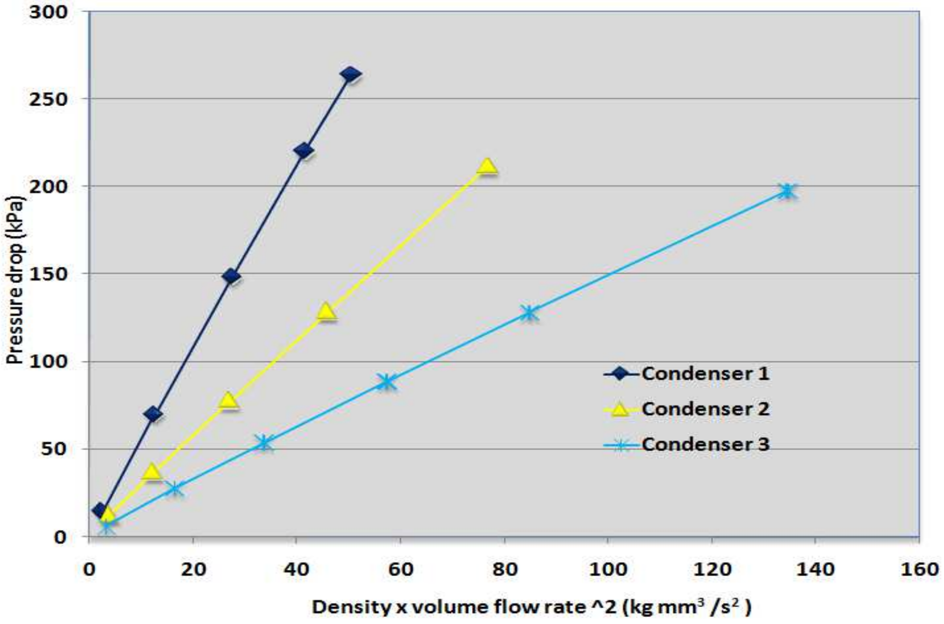
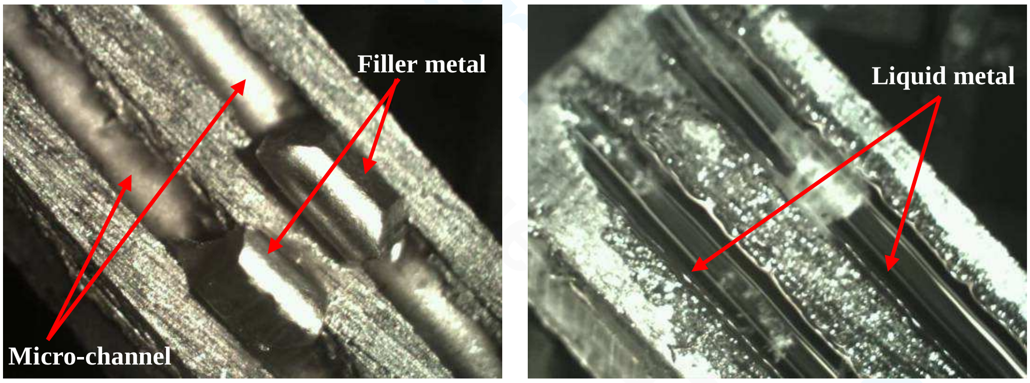


Figure 3: Pressure drop vs. square of volume flow rate

4. SURFACE TENSION DRIVEN FLOW THROUGH MICRO-CHANNELS

4.1 Wettability test using heating stage microscopy

The observation of micro-channel blockage makes it necessary to further study the flow behavior of liquid filler metal through the extruded tubes under typical CAB brazing conditions. It is speculated that the interior surface of the micro-channel features a different surface morphology than the regular aluminum alloy sheet surface due to the extrusion process. Studies have shown that variations of substrate surface morphology can significantly affect the wetting properties of the molten filler metals (Yost *et.al.*, 1995; Zhao and Sekulic, 2009) during brazing and soldering processes. Therefore, a heating stage microscopy test was arranged to test the wettability of an eutectic Al-Si alloy (AA4047) on the inner surface of a 4-port extruded tube. A small sample (approximately 10 mm x 5 mm) of the micro-channel tube was ground using SiC paper until the interior of the channel was accessible. Two pieces of eutectic Al-Si alloy (cut from a 0.75 mm diameter wire) were placed on the open channels as shown in Figure 4(a). Nocolok® flux was applied on the sample surfaces to assist oxide removal during the wetting test. The sample was heated in the heating stage chamber by radiation to a brazing temperature above the filler metal melting point (577 °C). Continuous flow of pure N_2 was supplied to maintain an inert atmosphere inside the heating chamber. Figures 4(a) & (b) present still images (extracted from the video captured by a digital camera attached to the microscope) before and after the melting of the filler metal. Good wetting of liquid filler metal on the channel wall is clearly demonstrated. Upon melting, the eutectic liquid Al-Si alloy spreads extensively to the ends of the channels driven by capillary force and eventually distributed uniformly along the channel walls as illustrated in Figure 4(b). This test confirms that the extrusion process does not have a negative effect on the surface morphology as far as the liquid metal wettability is concerned.

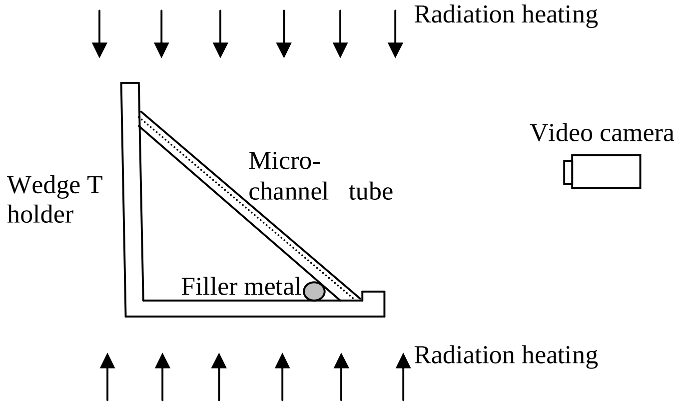


(a) solid filler metal sitting on micro-channel (b) molten filler spreading inside micro-channel

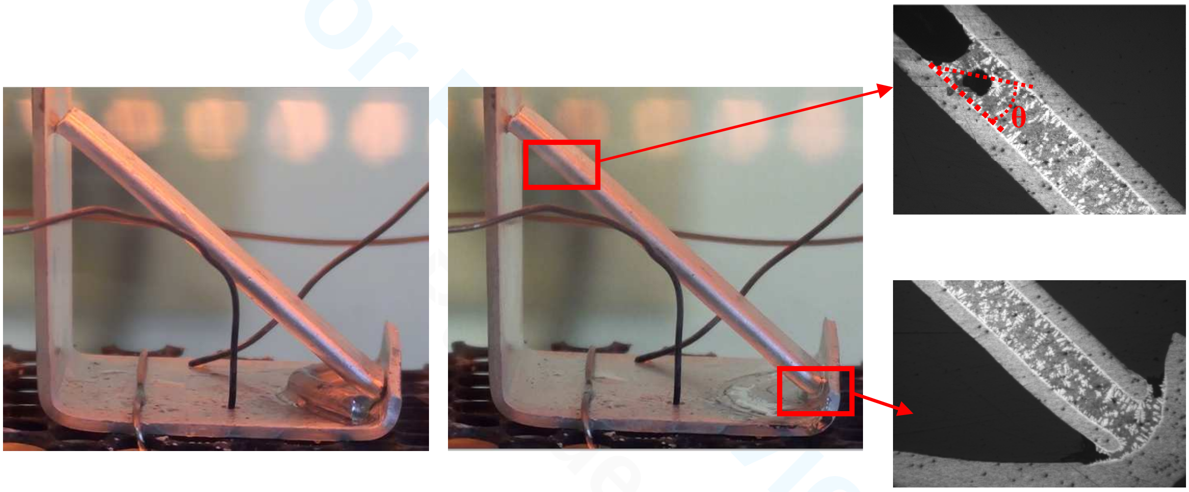
Figure 4: Wetting test of eutectic Al-Si filler on micro-channel surfaces

4.2 Capillary rise of molten filler metal in micro-channel tubes

When a liquid flows spontaneously inside a small tube against gravity due to the surface tension action, the phenomena is often called “capillary rise” (De Gennes *et al*., 2004). To illustrate the important role of capillary force on controlling the flow of molten liquid flow during a brazing process, especially when micro-channel tubes are involved, the following experiment using a transparent brazing furnace is arranged. The side view of basic sample set-up is illustrated in Figure 5(a). A 4-port extruded tube (~30 mm length) was held in a tilted position by a wedge T-shaped aluminum holder. A piece of eutectic Al-Si filler wire (~2 mm diameter) was placed on the holder substrate near the bottom end of the micro-channel tube. All sample parts were cleaned and fluxed before exposing them to a heating process that mimics a typical CAB brazing cycle for aluminum heat exchangers. The filler metal starts to melt as the temperature exceeds its melting point (~577 ^{o}C) as illustrated in 5(b). The liquid metal quickly flows into the micro-channels when it is in contact with the micro-channel ports. The imbibition of the majority of liquid Al-Si into the channels is completed in a matter of seconds. As illustrated in Figure 5(c), only a thin layer of residue remains on the Al plate where the filler metal was originally positioned. The cross section images of the brazed sample at selected locations are also presented in Figure 5(c). It is found that the liquid metal travels almost the entire length of the channel, regardless the influence of the gravity. Higher capillary rise is expected when more liquid filler metal is available or the micro-channel diameter becomes smaller.



(a) experimental sample set-up



(b) onset of filler melting

(c) capillary rise of molten filler metal

Figure 5: Capillary rise of liquid filler metal through micro-channel tube

For capillary driven flow through a cylindrical tube, studies show that the dynamic behavior of flow is determined by various factors including surface tension, inertial forces, viscous dissipation as well as gravity forces (Fries and Dreyer, 2008). In the case of molten liquid flow during a brazing process, the situation is more complicated, because many other factors may also be influential. For example, the substrate dissolution, and/or chemical reaction at the liquid solid interface should be considered in modeling of the liquid metal flow behavior. Equations (4) and (5) have been developed by Washburn and other researchers to model the flow through a capillary tube when inertial force is neglected (Washburn, 1921; Fries and Dreyer, 2008):

$$t = \frac{2\mu}{\sigma R Cos\theta} x^2 \qquad \text{(gravity force neglected)} \qquad (4)$$

And

$$t = -\frac{8\mu}{\rho g R^2} x - \frac{16\sigma\mu Cos\theta}{\rho^2 g^2 R^3} \ln\left(1 - \frac{\rho g R}{2\sigma Cos\theta} x\right) \qquad \text{(gravity influence considered)} \qquad (5)$$

In the above equations, t is the time variable during the flow of liquid, x is the flowing distance along the capillary tube, and θ is the contact angle between liquid and solid at the triple line location. An illustration of θ is presented in Figure 5(c), assuming solidification of liquid filler does not significantly change the contact angle. σ and μ are the surface tension and viscous properties of the liquid, respectively. Based on these models, it is estimated for a typical molten liquid metal flowing in a micro-channel tube, that the flow distance may reach 10 mm in less than 0.1 second. However it must be pointed out that these models only apply based on following assumptions: (1) the influence of the liquid-solid interface reaction can be neglected; (2) the existence of liquid flux on molten filler metal surface does not affect liquid metal flow behavior; (3) oxide layer on both filler and base metal are completely removed during brazing; (4) an infinite amount of bulk liquid is available at the capillary tube entrance, i.e. the bulk liquid surface has a zero curvature at the source location. In fact, all these assumptions are very difficult if not impossible to realize in a practical brazing process.

For the purpose of studying kinetics of molten Al-Si alloy flow in the capillary micro-channel tube, a similar glass furnace experiment is performed. In this case, the 4-port extruded tube was ground until the inner wall of the channels is visible, i.e. the capillary channels are open to the atmosphere in this experiment. The same sample treatment procedure and brazing conditions are applied. An effort has been made to track the front location of the liquid flow based on the captured video. The results of non-dimensional flow distance (i.e. ratio between flow length

x and total channel length L) vs. time for two selected channels are presented in Figure 6. These two channels present the examples where the fastest (channel 1) and slowest flow (channel 2) occurred. The measurement of flow length uncertainty can be larger than 10% at some locations because of the difficulties in determining exact liquid front locations due to the reflective lighting effects from liquid metal, and existences of flux and liquid metal precursors. Figure 7 illustrates a series of still images taken from the captured video. Visual examination of the open micro-channel tube has revealed that the channel depth varies from one channel to another due to the imprecise control of the grinding process. Such alteration of the channel geometry leads to the differences of flowing speed observed in different channels. It is speculated that non-uniformity of channel depth also exists along the flow direction in each single channel. The transient flow behavior such as a hesitation of the advancing liquid front or a sudden acceleration at some locations (Figure 6), may be indications of such channel geometry non-uniformities. An apparent substrate (the micro-channel tube wall) dissolution has been observed after metallurgical cutting and polishing of the brazed sample at the bottom end of the micro-channel tube, as shown in Figure 7(d), where the tube is in contact with liquid metal for the longest time during brazing. Such interaction between liquid and solid substrate leads to the consequences such as: (1) reduction of the tube wall thickness; (2) change of filler metal composition (i.e. more Al dissolved in to the filler metal) and liquid properties.

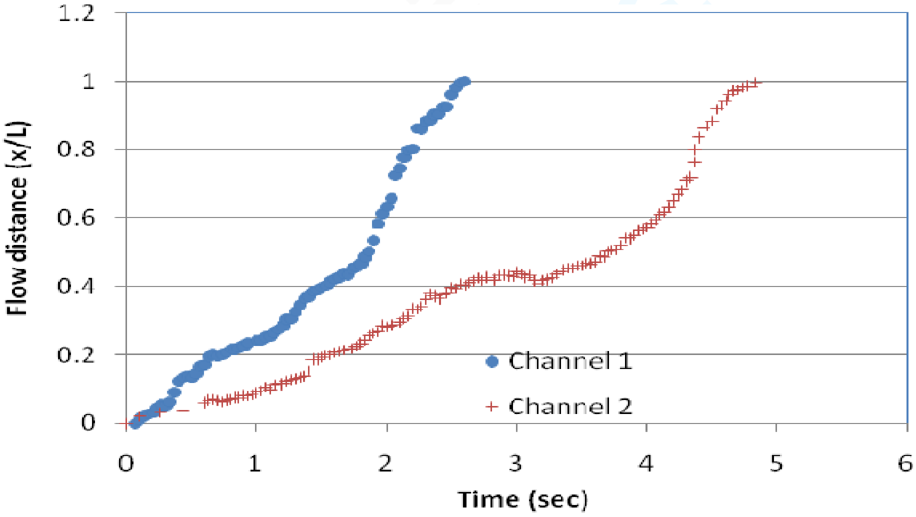
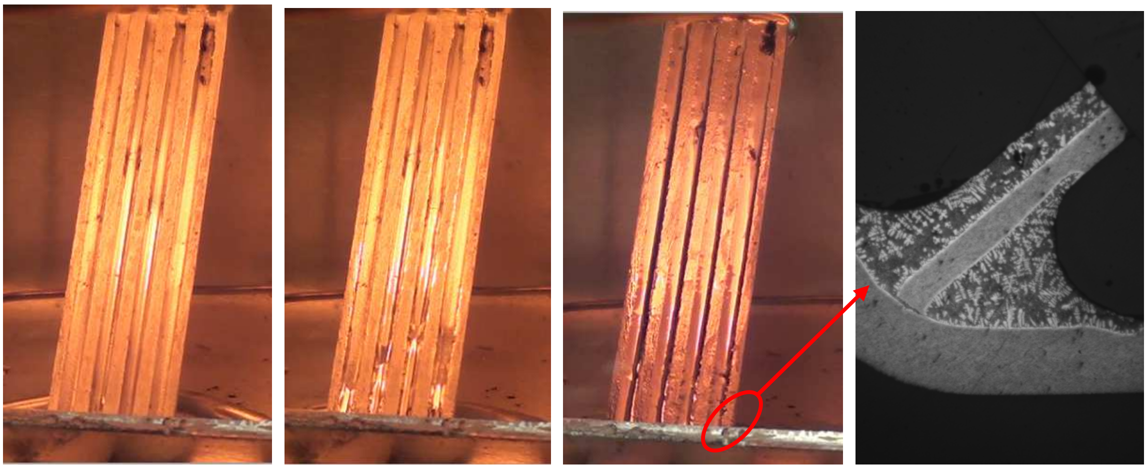


Figure 6: Liquid metal flow distance vs. time in selected micro-channels



(a) (b) (c) (d)

Figure 7: Capillary rise of liquid filler metal through open channels: (a) onset of filler metling; (b) progress of capillary rise of liquid metal; (d) liquid metal delivered to other end of the capillary channel; (d) cross section iamge shows substrate dissolution

It is found that the liquid flow speeds in the open micro-channels as presented in Figure 6 are much lower than the estimated flow speed of capillary rise through a close tube based on Washburn's theory (Washburn, 1921). The following reasons may contribute to such discrepancy: (1) the assumption of zero curvature of the liquid source in Washburn's model does not apply to the current experiment as it is apparent from the visualization results that the bulk liquid forms a meniscus between tube and plate. The cross section image of the re-solidified joint in Figure7 (d) also confirms such observation. Therefore, the capillary pressure driving the liquid flow is expected to be smaller. (2) In the case of an open channel flow, channel geometry in addition to the port diameter, such as the cross section depth, must be included in the models for flow kinetics. A detailed study of modeling the capillary rise in the micro-channel tubes is out of the scope of this paper and will be addressed in future studies.

5. CONCLUSIONS

In this study, a series of research activities have been performed for the purpose of better understanding the capillary flow phenomena occurring during the fabrication of micro-channel heat exchangers. Potential defects of the heat exchangers due to the blockage of the extruded micro-channel tube by undesired flow of filler metal have been illustrated. The capillary flow of liquid Al-Si alloy through a micro-channel tube is experimentally studied in detail using visualization brazing facilities. Good wettability of commonly used Al-Si filler metal on extruded tube inner surface was confirmed. It has been demonstrated the surface tension driven eutectic Al-Si filler metal can flow into the refrigerant channels even against gravity. Therefore, good control on the heat exchanger design, materials selection, and brazing parameters is very important to ensure the quality of final products, especially under current trends of continuous downsizing heat exchanger components. The visualization study of kinetics of liquid metal flowing through capillary tube provides useful information and guidance on the process control. Future studies will be focused on the following aspects: (1) extended experimental studies to the wettability of various filler metal (e.g. hypoeutectic Al-Si alloy, Al-Zn alloy, composite brazing sheet) on Al heat exchanger components with different surface morphologies; (2) explore correlations between liquid filler metal behavior vs. micro-channel tube and header geometries; (3) seeking proper models to predict the capillary flow behaviors of liquid filler under given brazing conditions.

NOMENCLATURE

A	area	(m^2)
d	diameter	(m)
f	friction factor	
g	gravitational acceleration	(m/s^2)
L	tube length	(m)
N	number of port	
R	radius	(m)
t	time	(s)
u	velocity	(m/s)
$\dot{V}$	volume flow rate	(m^3/s)
x	flow distance	(m)
ρ	density	(kg/m^3)
σ	surface tension	(N/m)
μ	viscosity	(Pa s)
θ	contact angle	(radians)
ΔP	press drop	(kPa)

Subscripts

N_2	nitrogen
port	tube port
s	serpentine

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