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Horizontal distribution of two-phase refrigerant in parallel flat mini-channels

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ABSTRACT

A literature survey revealed that no prior investigation has been conducted on the horizontal distribution of a two-phase refrigerant in mini-channel tubes, which may be of importance for the cooling of heat-generating objects. In this study, we investigated R-134a distribution into four flat tubes inside a horizontal plane. In order to simulate the battery of an electric vehicle, a 600-W power supply was used during our tests. Tests were conducted with mass fluxes ranging from 280 to 480 $kg\,m^{-2}s^{-1}$ and an inlet quality of 0.2. The effects of inlet port orientation and heat exchanger inclination on flow distribution were investigated. Results indicated that the effects of heat exchanger inclination on flow distribution were more prevalent than those of inlet port orientation. However, these effects are weakened as mass flux increases. Flow distribution deteriorated as the inclination of the heat exchanger increased. Header pressure drop constituted a significant portion of heat exchanger pressure drop and became more pronounced as mass flux increased.

1. Introduction

Flat mini-channel tubes made of aluminum are widely used in air-cooled heat exchangers due to their potential to reduce air-side pressure drop when compared to round tubes. These tubes are typically combined with louver fins, brazed in a furnace, to form a brazed aluminum heat exchanger. In a brazed aluminum heat exchanger, a number of tubes are grouped into a pass by using a header to reduce excessive pressure drop. The typical hydraulic diameter of a flat tube is 1–2 mm. Another potential application area of the flat mini-channel tube is the cooling of heat-generating objects, such as the battery of an electric vehicle [1]. Flat tubes may be attached to the top of the battery and may remove heat through evaporation of refrigerant flowing in the tubes. A conceptual sketch of such a heat exchanger is presented in Fig. 1. The tubes are located in a horizontal plane with a header. In this case, it is important to distribute the two-phase refrigerant (particularly the liquid) evenly into each tube. Otherwise, the thermal performance decreases significantly.

A literature survey revealed that most of the studies on two-phase refrigerant distribution in a header-branch configuration have been conducted using a vertical plane with a brazed aluminum heat exchanger application in mind. Webb and Chung [2], Hrnjak [3], Lee [4], and Ahmad et al. [5] have provided recent reviews on this subject. Watanabe et al. [6] investigated the flow distribution of a round header (20 mm I.D.) with four round tubes (6 mm I.D.) in an upward flow configuration using R-11. Mass flux (based on the header cross sectional area) was varied from 40 to 120 $kg\,m^{-2}s^{-1}$ and inlet quality was varied up to 0.4. The flow distribution was highly dependent on mass flux and inlet quality. Vist and Pettersen [7] tested a round header (8 mm and 16 mm I.D.) with ten round tubes (4 mm I.D.) using R-134a. Mass flux was varied from 12 to 21 $kg\,m^{-2}s^{-1}$ and inlet quality was varied up to 0.5. For a downward flow configuration, most of the liquid flowed through the front portion of the header. For an upward configuration, most of the liquid flowed through the rear portion of the header. Koyama et al. [8] investigated the effects of tube protrusion depth for a horizontal round header (9 mm I.D.) with six vertical flat tubes using R-134a. Mass flux was fixed at 130 $kg\,m^{-2}s^{-1}$ and inlet quality was varied up to 0.4. Tests were conducted for a downward configuration. Protrusion depth was systematically varied and the optimal configuration was found to be that with the two front tubes protruding to the center of the header and remaining four tubes flush-mounted. Better liquid distribution was obtained at lower vapor qualities. Kim et al. [9] and Kim and Byun [10] investigated the effects of flow inlet direction for a round header (17 mm I.D.) with ten flat tubes (D_h = 1.32 mm) using R-134a. For downward flow, normal and vertical inlets yielded approximately similar liquid distributions, although slightly better results were obtained with a normal inlet at high mass fluxes or high inlet qualities. For upward flow, the vertical inlet yielded the best flow distribution.

As for a multi-pass configuration, Byun and Kim [11] investigated

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Nomenclature

c_p	specific heat, J kg^{-1}K^{-1}
d	tube inner diameter, m
D	header diameter, m
f	friction factor
Fr	Froude number
G	mass flux, kg m^{-2}s^{-1}
GFR	gas flow ratio
h	enthalpy, J kg^{-1}
L	length, m
LFR	liquid flow ratio
$\dot{m}$	mass flow rate, kg s^{-1}
N	number of channels
P	pressure, Pa
P_c	critical pressure, Pa
R	function of a measured variable
Q	supplied heat, W
Re	Reynolds number
T	temperature, K
v	specific volume, m^3 kg^{-1}
w	parameter uncertainty
We	Weber number
x	quality or measured variable

Greek notations

α	void fraction
ΔP	pressure drop, Pa
μ	viscosity, kg m^{-1} s^{-1}
Φ^2	two-phase multiplier
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

a	acceleration
c	critical
ch	channel
cont	contraction
deg	degree
exp	expansion
f	friction factor or friction
ft	flat tube
g	gas or gravitation
go	all gas
H	header or homogeneous
head	header
i	inlet or i_{th}
in	inlet
l	liquid
lg	latent heat
lo	all liquid
meas	measured
minor	minor
o	outlet
out	outlet
p	preheater
r	refrigerant
rt	round tube
sat	saturation
tr	transition
w	cooling water

the refrigerant distribution in a two-pass evaporator with a vertical intermediate header for the upward flow of R-410A. Through flow visualization, they determined that the two-phase jets, which exited the first pass, hit the backside of the vertical intermediate header and were deflected upward, forming a thin liquid film. In the second pass, liquid was continuously sucked into the tubes, and became thinner as it traveled upstream. More liquid was supplied to the upstream channels as mass flux increased. Zou and Hrnjak [12] also investigated the refrigerant distribution in a two-pass evaporator with a vertical intermediate header for the upward flow of R-134a. Two different flow patterns (churn and separated) were identified in the intermediate header, with a churn flow yielding a better distribution due to the more homogeneous nature of the flow. Better flow distributions were obtained at high mass fluxes and low inlet qualities. Byun and Kim [13] extended the study to a two-row four-pass configuration.

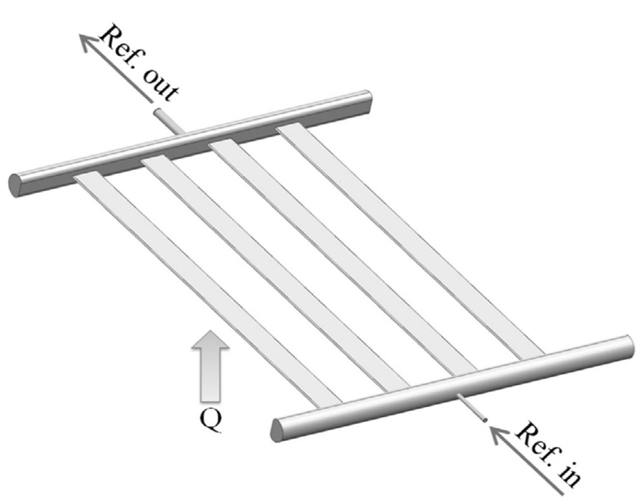

Fig. 1. Schematic drawing of the mini-channel heat exchanger considered in this study.

The literature survey reveals only one prior investigation on two-phase distribution of mini-channel tubes in a horizontal plane, which may be of importance for the cooling of heat-generating objects. Hirota et al. [14] investigated two-phase nitrogen-water distribution into five horizontal mini-channel tubes. One thing to note is that their header was a flat rectangular channel having the same height with the branching tube. Results showed that more liquid flowed into the nearest and the furthest downstream tubes. In this study, we investigate R-134a distribution into four mini-channel tubes inside a horizontal plane (Fig. 1). The tubes were heated using plate heaters to simulate a real car battery. The inlet quality was 0.2 and the mass flux (based on a header cross-sectional area of 344 mm^2) was varied from 280 kg m^{-2} s^{-1} to 480 kg m^{-2} s^{-1}. The corresponding mass flow rate varied from 35 kg h^{-1} to 60 kg h^{-1}. A D-type header was used with flat tubes protruding 4.0 mm into the header. The flat tubes had a 0.8 mm hydraulic diameter and a 12.0 mm^2 cross-sectional area (Fig. 2). The effects of inlet port orientation and heat exchanger inclination on flow distribution were investigated. The heat exchanger may be inclined based on the movements of the vehicle.

2. Experiments

The same apparatus used by Kim et al. [9] and Kim and Byun [10] was used in this study. One may consult those papers for additional details. A schematic diagram of the experimental apparatus is presented in Fig. 3. A detailed diagram of the test section is presented in Fig. 4. The test section consists of two D-type headers, which are 56 cm apart,