EVAPORATIVE HEAT TRANSFER OF CO_2 IN A GROOVED MULTI-CHANNEL MICRO-TUBE

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ABSTRACT

Recent studies on evaporation of carbon dioxide in micro-channels reported that the heat transfer coefficient decreased drastically with increasing quality. To improve the evaporating heat transfer characteristics a grooved multi-channel micro-tube was suggested in this study, and the evaporating heat transfer characteristics have been experimentally investigated. The multi-channel aluminum tube, which is directly heated by the electricity, has 8 channels with a diameter of 0.8mm and a length of 1.1m. Each channel has eight micro-grooves with the width of 0.2mm and depth of 0.1mm. The heat transfer coefficients were measured in the range of heat fluxes from 12 to 18 kW/m^2; mass fluxes 400 – 800 kg/m^2s; evaporative temperature 5℃; and qualities from zero to superheated state. The measured values were compared with those in the plain multi-channel micro-tubes with the same diameter. The heat transfer coefficient was found to be increased at low qualities $(x < 0.4)$. At high qualities, the sudden drop of the HTC due to the dry-out phenomena was not improved. In the evaporation process of CO_2, the grooves applied to microchannels have a noticeable effect only in low quality regions.

INTRODUCTION

Recently, the natural refrigerant carbon dioxide has been spotlighted as a possible vapour compression working fluid. Carbon dioxide has many advantages as a refrigerant such as environmentally benign, safe, low cost, high volumetric capacity, and good transport characteristics. Because of high working pressure, CO_2 is suitable for micro channel tubes, and a number of researches have been carried out to find the heat transfer characteristics in the micro channel evaporators.

Petterson [1] investigated carbon dioxide evaporative heat transfer in a multi-channel micro tube and observed the flow vaporization of CO_2. Study of flow pattern was performed in separate test rig, using a 0.98mm heated glass tube. In this paper, the heat transfer and pressure drop measurements were performed at varing vapor fraction for temperatures from 0℃ to 25℃, mass flux 190-570 kg/m^2s, and heat flux 5-20 kW/m^2s.

He summarized that heat transfer was significantly influenced by dryout, particularly at high mass flux and high temperature. And he observed increasing entrainment at higher mass flux and dominance of annular flow.

Yun. et al.[2] researched on flow boiling heat transfer coefficient of CO_2 in stainless steel tube with inner diameters of 0.98 - 2.0mm. The HTC is measured at mass fluxes in the range from 500 to 3750 kg/m^2s; heat fluxes from 7 to 48 kW/m^2; evaporative temperature 0, 5 and 10℃. They concluded that the effect of heat flux on HTC before critical vapour quality is very strong at all mass fluxes. The influence of mass flux on the heat transfer coefficient before critical quality is only significant when the mass flux is less than 500kg/m^2s.

In a study of the authors [3], it was also found that the HTC dropped rapidly if the quality is higher than 0.4~0.5. In order to enhance the HTC, grooved surface have been successfully applied to conventional tubes and refrigerants [4,5].

Therefore, the application of grooves to the micro-channel tubes came to the authors' mind to improve the evaporation HTC of CO_2.

The effect of the grooved heat transfer surface for CO_2 in conventional tube has been seldom investigated. Moreover, that in the micro-tubes has never been investigated. In this study, therefore, experiments have been conducted to evaluate the possibility of the application of grooves to multi-channel micro-tubes.

NOMENCLATURE

A	[m^2]	Cross section area
D	[mm]	Diameter
G	[kg/m^{2}s]	Mass flux
h	[W/m^{2}K]	Heat transfer coefficient
I	[A]	Current
k	[kW/mK]	Thermal conductivity
ℓ	[m]	Distance from the inlet
L	[m]	Length of test tube
P	[MPa]	Pressure
$\triangle P$	[kPa]	Pressure drop between inlet and exit
$\ddot{q}$	[kW/m^2]	Heat flux

R	[Ω]	Resistance
T	[K]	Temperature
△t	[m]	Wall thickness
x	[-]	Quality

Subscripts
wi	Inner wall
wo	Outer wall
sat	Saturated state

EXPERIMENT

Experimental Apparatus

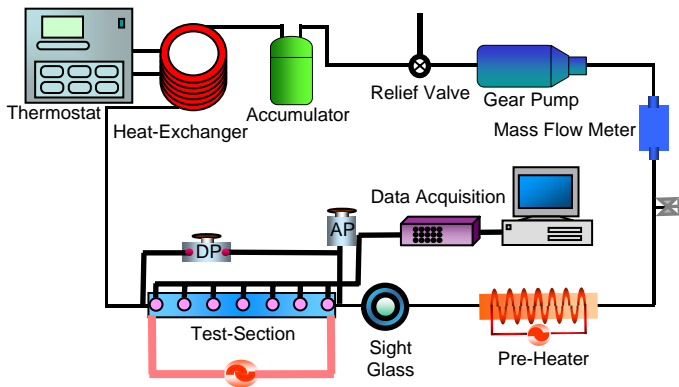The schematic diagram of experimental apparatus is shown in Figure 1.

Figure 1 Schematic diagram of experimental apparatus

The sub-cooled liquid state refrigerant is circulated by a magnetic gear pump, and the mass flow rate is measured by a coriolis mass flow meter. The inlet quality of refrigerant is controlled by a pre-heater, and the state of the refrigerant flow is conformed at sight glass. Inlet and outlet refrigerant pressure is detected by absolute and differential pressure transmitter. In the test section, liquid state carbon dioxide is heated and evaporated by the Joule heat of the tube. Experiments were performed for a smooth and a grooved micro tube. The smooth tube is an extruded aluminum tube with 6 circular channels whose diameter is 0.8mm. The grooved tube is also an extruded aluminum tube with 8 grooved channels. The groove depth is 0.1mm and the width is 0.2mm. The details of the test section are shown in Figure 2 and Figure 3. And Figure 4 shows the photo of the cross section of the grooved tube.
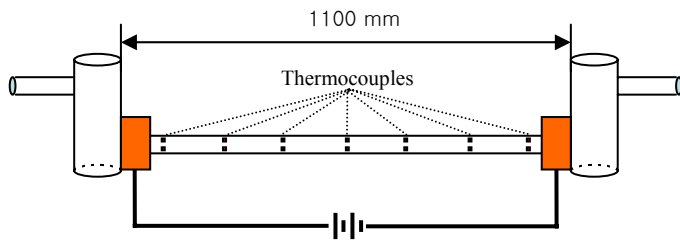

Figure 2 Schematic of the test section

Since the resistance of the aluminum microchannel tube was quite low, a high current power supply system was required. So 5V-1500A rectifier was used. To ensure the even heating of the test section, it was assembled to the jig as tightly as possible.

The entire system including the test section is well insulated from the surroundings. The thermostat is controlled to adjust the cooling capacity. The refrigerant is cooled down in the heat-exchanger and the liquid, which is separated in the accumulator, is supplied to the gear pump.
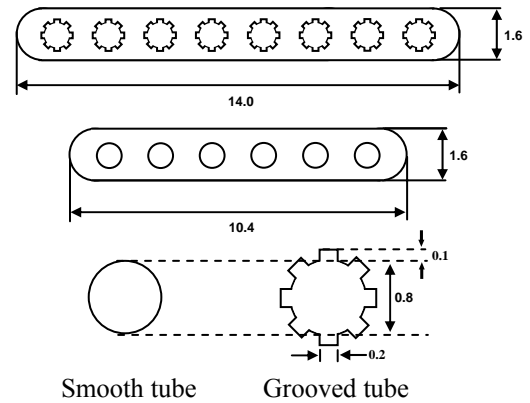

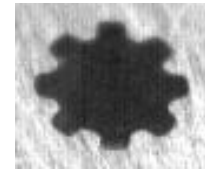**Figure 3** Cross section of the tested micro tubes

Figure 4 Photo of the cross section of the grooved tube

28 thermocouples were attached at the tube wall to measure the wall temperature. The temperature difference between the wall and the refrigerant was quite small. Therefore, after being attached to the wall, the thermocouples were checked to have the accuracy of 0.2 K. Temperatures were measured at 7 locations; with an interval of 16 cm. (3, 19,····, 99cm from the inlet) At each measuring location, 4 thermocouples were attached on the top and bottom of the micro-channels (2 on each side).
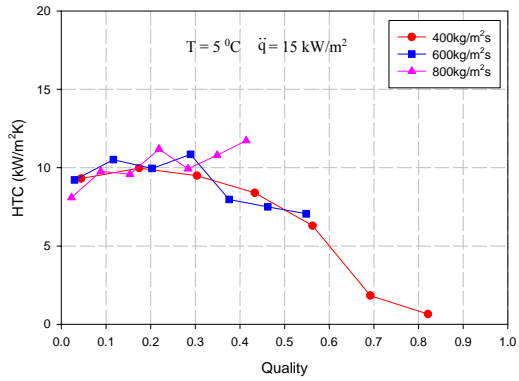
Before charging the system with refrigerant, joint between the jig and power supply, contact between the jig and test-section were checked in order to avoid partial heating at the test-section. After the system was evacuated by a vacuum pump, carbon dioxide was charged. For each case the data were collected when the system reached steady state.
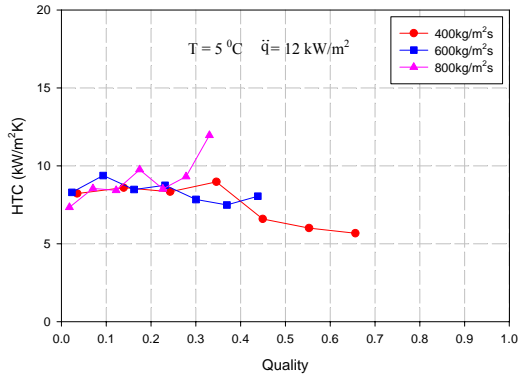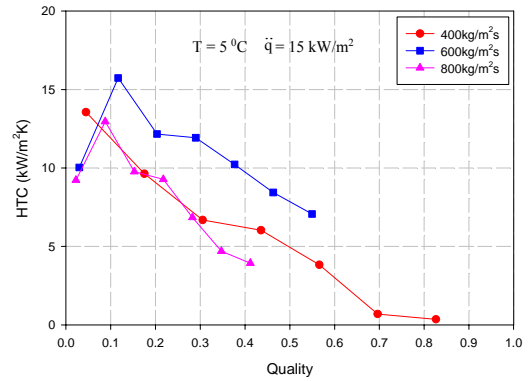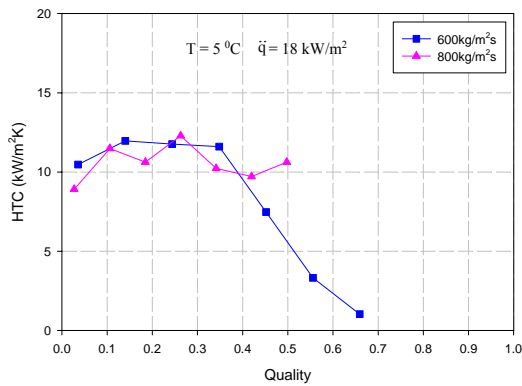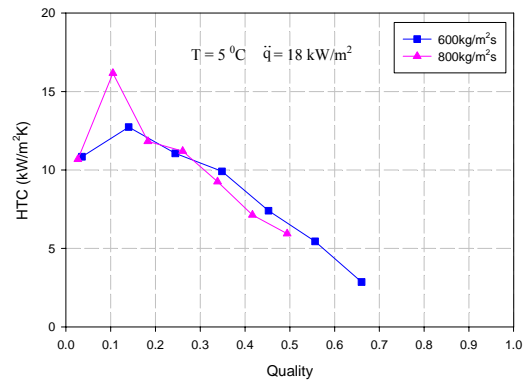
(a)
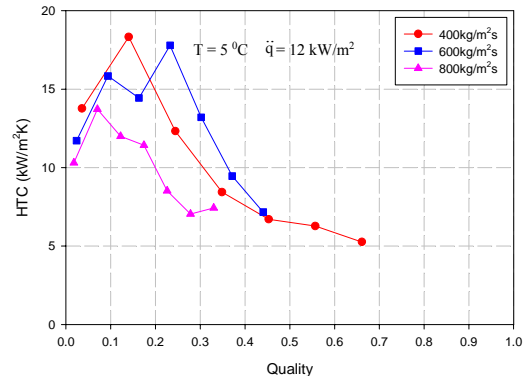
(a)

(b)

(b)

(c)

(c)

Figure 5 Effect of heat & mass flux on the HTC in the smooth tube

Figure 6 Effect of heat & mass flux on the HTC in the grooved tube

Table 1 Comparison between the smooth tube and grooved tube regarding HTC (x < 0.3)

Heat flux (kW/m²)		12		15		18	
Micro Channel Tube		HTC smooth MCT	HTC grooved MCT	HTC smooth MCT	HTC grooved MCT	HTC smooth MCT	HTC grooved MCT
Mass flux (kg/m²s)	400	8.39	14.81	9.63	11.59		
	600	8.73	14.95	10.13	12.46	11.40	11.55
	800	8.65	10.50	9.71	9.61	10.83	12.46

Test Condition

A series of test was performed in the smooth microchannel tube. The combination of three evaporating temperatures (0, 5, 10℃), four heat fluxes (0, 12, 15, 18 kW/m²), and four mass fluxes (400, 600, 800, 1000 kg/m²s) resulted in 36 cases for heat transfer.

Another series of test was done in the grooved microchannel tube. Experiments were conducted for various evaporation temperatures (5℃), heat fluxes (12, 15, 18 kW/m²), and mass fluxes (400, 600, 800 kg/m²s).

The calculation of heat and mass flux in the grooved microchannel is based on the smooth tube with a diameter of 0.8mm.

Data Reduction

The heat flux was calculated by the electric current and resistance of the test section.

$$\ddot{q} = \frac{I^2 R}{A}$$

The inner wall temperature was calculated from the measured outer wall temperature using the steady state heat conduction equation.

$$T_{wi} = T_{wo} - \frac{\ddot{q}\Delta t}{k}$$

The heat transfer coefficient was calculated as follows:

$$h = \frac{\ddot{q}}{T_{wi} - T_{sat}}$$

where T_{sat} was determined from the property relation of CO_2.

$$P_{sat.local} = P_{sat.in} - \Delta P \frac{\ell}{L}$$

$$T_{sat} = f(P_{sat})$$

The saturation pressure (P_{sat}) and the pressure drop (ΔP) were measured with an absolute and differential pressure transmitter respectively. The properties of carbon dioxide were calculated with REFPROP (ver. 6.01).

RESULT AND DISCUSSION

Figure 5 shows the effect of heat and mass flux on the HTC for the smooth tube. For high qualities, the HTC suddenly decreases with the quality which can be attributed to partial dry-out in the channel. At low quality regime, HTCs are increased with increasing heat flux due to the activated nucleate boiling. Regardless of mass flux, HTCs are maintained up to the quality of 0.3-0.4.

Figure 6 shows the effect of heat and mass flux on the HTC for the grooved tube. At low quality domain, HTCs are enhanced by grooved surface in almost all operating conditions. At high quality region, however, HTCs of grooved tube are also decreased similarly with the smooth tube. A peak HTC point is observed between the quality of 0.1 and 0.3 in the grooved tube.

The HTCs of quality domain lower than 0.3 were averaged and the mean HTCs in each case are shown in Table 1. At qualities lower than 0.3, the HTCs of the grooved tubes are higher than that of the smooth tubes in almost all operating conditions. Among these, in case of 12 heat flux, HTCs are significantly improved in the grooved micro-tube. The HTCs in the smooth tube are increased with the heat flux. In contrast, the HTCs in the grooved tube have a tendency to decrease with the heat flux. In comparison with the smooth tube, the mass flux greatly influences on the HTC in the grooved microchannel. The mass flux change brings about considerable HTC difference. It is thought that the increment of heat transfer area and activated nucleate boiling which are caused by grooved surface result in these phenomena. For those reasons, the system has a tendency to reach the peak HTC rapidly and high mass flux becomes relatively favorable with regard to HTC as the heat flux is increased.

CONCLUSION

In this paper, heat transfer characteristics during the carbon dioxide evaporation process have been investigated in both smooth and grooved multi-channel micro tube. Main findings in these experiments can be summarized as follows.
- In the grooved tube, the HTC was increased at the qualities lower than x = 0.3.
- The dry-out phenomena at high qualities were persistent and not removed by the grooves.
- In the grooved tube, the HTC is considerably depends on the mass flux in contrast with the smooth tube.
- At low quality regime, the HTCs are increased as the heat flux is increased for the smooth tube. But in the grooved tube, the HTCs are decreased with the heat flux.

ACKNOWLEDGEMENTS

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