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Microscale phase separation condensers with varied cross sections of each fluid phase: Heat transfer enhancement and pressure drop reduction

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ABSTRACT

Micro-condenser using the phase separation concept was investigated in this paper. Lined pin fin arrays generate liquid passages and vapor passages alternatively in chip width direction. The decreased Gibbs free energy with gas–liquid interface advancing pin fin throat location is the mechanism to induce liquid flow from vapor passages to liquid passages. The decreased energy dissipation due to decreased interfacial area between the two phases accounts for pressure drop reduction. Three micro-condensers were investigated: microchannel condenser (SWM), parallel phase separation condenser (PPS with constant cross sections of fluid passages) and conical phase separation condenser (CPS with varied cross sections of fluid passages). Micro-condensers had identical project condensation surface of 25.0 mm by 3.0 mm. The etched depth was 75 μm. Water-vapor was the working fluid. Compared with SWM, phase separation condensers increased mass flow rate by 15% at similar pressure drops. PPS condenser enhances heat transfer at moderate or smaller cooling intensity, but deteriorates heat transfer at large condensed liquid flow rate, at which over liquid expansion occurs to flood all pin fin side walls. CPS condenser self-adapts variations of flow rates of the two phases to stabilize vapor–liquid interface near pin fin membrane. Pin fin side walls facing vapor passage are covered by thin liquid film to eliminate over liquid expansion. CPS condenser enhances heat transfer over entire operating parameter ranges, increasing condensation heat transfer coefficients by 74% maximally while pressure drops are decreased. CPS condenser has the best performance among the three condensers.

1. Introduction

Chen et al. [1] published first paper of phase separation tube for large size condensers in 2012. The tube cross section is divided into a core region and a near wall region, which are interfaced by a membrane separator. Condensed liquid is captured by the membrane separator and flows in the core region. Vapor is resisted by the separator to flow in the near wall region. Thus, condenser tube wall is covered by ultra-thin liquid film to enhance heat transfer.

Mesh screen with micro-pores was the separator material [1]. The phase separation effect was verified using a horizontal air-water flow system. The tube had an inner diameter of 13.08 mm and a length of 2.5 m. A 9.32 mm diameter mesh cylinder, acting as the membrane separator, was suspended in the tube. Mesh pore size was ~100 μm. Experiments showed that at small liquid content of the two-phase mixture, all liquids are collected by mesh cylinder and flow inside, air flows in the near wall region, which is called the full separation mode. At large liquid content of the two-phase mixture, mesh cylinder collects part of liquid, but the tube surface area covered by gas is significantly increased, which is called the partial separation mode.

Subsequently, experiments were performed on phase separation tube [2,3]. The separation effect is also effective for vertically positioned tube [4]. The liquid film thickness can be decreased to 1/6–1/3 of that in a bare tube without inserting a membrane separator [5]. Xie et al. [6] reported condensation heat transfer in a horizontal tube with a 14.81 mm diameter and a 1200 mm length, by suspending a membrane separator, which was formed by packaging two layers of mesh screen surfaces [7]. Measurements showed that phase separation condenser tube can have condensation heat transfer coefficients of more than two times of those in a bare tube, maximally. Meanwhile, the total thermal resistance was decreased by 45.6%, maximally.

Here, the phase separation tube for large size condensers is extended to micro-condensers, having wide applications in

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Nomenclature

A	interface area (m^2)
A_c	cross sectional area of flow passages over the entire condenser width (m^2)
$A_{c,l}$	cross sectional area of liquid passages over the entire condenser width (m^2)
$A_{c,v}$	cross sectional area of vapor passages over the entire condenser width (m^2)
A_p	channel cross sectional area (m^2)
A_s	projected surface area of a droplet (m^2)
A_t	total side wall area of pin fins (m^2)
a	ratio of all droplets surface area to the two-phase mixture volume (m^{-1})
C_d	drag coefficient of a droplet in a flowing vapor
Co	confinement number
d_d	droplet diameter (m)
d_p	channel hydraulic diameter (m)
E	energy dissipation (W)
E_{lg}	energy dissipation due to interaction between two-phases (W)
$E_{tp,w}$	energy dissipation for interaction between two-phase mixture and wall (W)
F_d	frictional force between vapor and droplet (N)
$F_{tp,w}$	frictional force between two-phase mixture and channel wall (N)
G	mass flux (kg/m^2 s)
$G_{Gibbs,c}$	constant parameter of Gibbs free energy (J)
G_{Gibbs}	Gibbs free energy (J)
H_e	etched depth (μm)
h	condensation heat transfer coefficient (W/m^2 K)
k	copper thermal conductivity (W/m K)
L	curvature radius at the initial location at t_1 (m)
L_c	channel length (m)
l_c	capillary length (m)
l_1	wetting length (μm)
m	mass flow rate (g/s)
m_c	cooling water flow rate (g/s)
N_d	number of droplets
O	initial curvature center point
O'	curvature center point at $t = t_2$
P	pressure (Pa)
$P_{e,l}$, $P_{e,v}$	exit pressures in liquid passage and vapor passage, respectively (Pa)
P_{in}	upstream pressure of micro-condenser (Pa)
P_l	pressure in liquid passage (Pa)
$P_{l,a}$	pressure in liquid passage for interface deviating from pin fin membrane (Pa)
$P_{l,c}$	pressure in liquid passage of CPS condenser with interface near pin fin (Pa)
$P_{l,i}$	pressure in liquid passage assuming vapor-liquid interface near pin fin (Pa)
$P_{l,p}$	pressure in liquid passage of PPS condenser with interface near pin fin (Pa)
P_v	pressure in vapor passage (Pa)
$P_{v,a}$	pressure in vapor passage for interface deviating from pin fin (Pa)
$P_{v,c}$	pressure in vapor passage of CPS condenser with interface near pin fin (Pa)
$P_{v,i}$	pressure in vapor passage assuming vapor-liquid interface near pin fin (Pa)
$P_{v,p}$	pressure in vapor passage of PPS condenser with interface near pin (Pa)
ΔP	pressure drop across condenser (Pa)
ΔP_{CPS}, ΔP_{PPS}	pressure difference between vapor passage and liquid passage for CPS and PPS condenser, respectively (Pa)
q	heat flux (kW/m^2)
Re	Reynolds number
r_1	radius of interface at $t = t_1$ (μm)
S_2	exposed surface area (μm^2)
T	temperature (°C)
$T_{sat,i}$	saturation temperature at each section center (°C)
$T_{w,i}$	wall temperature at the top surface of the copper block (°C)
t	time (s)
t_1	initial time before wetting (s)
t_2	time when the interface travels a distance of l_1 (s)
V	vacuum volume not occupied by solid structure (μm^3)
v	velocity (m/s)
v_m	velocity of two-phase mixture (m/s)
v_s	slip velocity between liquid and vapor (m/s)
W_n	total width at narrowed location along the flow direction (m)
x, y, z	copper height direction, chip width direction and axial flow direction (m)
z_e	exit location

Greek symbols

α	half of vertex angle of arc-shaped interface (rad)
β	volume ratio of the vapor phase to the two-phase mixture
θ	contact angle between water and silicon (rad)
η	thermal efficiency
γ	surface tension (N/m)
ρ	density (kg/m^3)
$\tau_{tp\text{-}w}$	shear stress between two-phase mixture and channel wall (N/m^2)

Subscripts

CPS	conical phase separation condenser
g, l, v, s	gas phase, liquid phase, vapor phase and solid phase, respectively
i	section number
in	condenser inlet
out	condenser outlet
PPS	parallel phase separation condenser
SWM	solid wall microchannel condenser
1, 2, 3	regions in the copper block

compact energy and power systems. For example, micro-condenser is an important component of loop heat pipe. It is also a key component of compact refrigeration or heat pump system, dissipating heat to environment for electronic cooling applications.

Wall effect is important in small channels [8]. Capillary length l_c is defined as $l_c = \sqrt{\frac{\gamma_{lg}}{g\Delta\rho}}$. For vapor-water system, l_c is ~2.5 mm. Droplet confinement number Co is $Co = l_c/d_p$. In microchannels, Co is much larger than 1.0, yielding droplet confinement effect to block channel. The scale effect makes it more difficult to remove liquid. How to remove condensed liquid is a big issue.

Table 1 lists condensation heat transfer studies published in open literature [9–22]. Physically, condensation heat transfer is related to flow patterns [9]. Liquid film condensation and dropwise condensation are two frequently encountered modes [10,19]. For film condensation, liquid film separates cold wall and vapor core to dominate heat transfer [16,17]. Many factors such as capillary number, contact angle and heat flux influence the liquid film thick-