Applied Thermal Engineering 114 (2017) 255–263

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Effect of air on condensation in a non-vacuum gravity heat pipe

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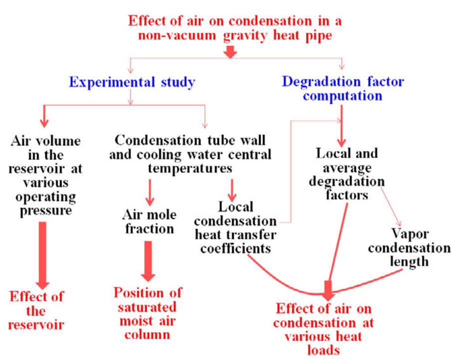
HIGHLIGHTS

- Condensation with air in a non-vacuum gravity heat pipe was investigated.
- A saturated moist air column is formed in the condensation tube downstream.
- Degradation factors are low at the condensation tube downstream at a low heat load.
- 68% of the reservoir is full of air at an operating pressure of 0.24 MPa.
- Vapor with air is 1.32 times pure vapor condensation length at present condition.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 August 2016
Revised 29 November 2016
Accepted 30 November 2016
Available online 1 December 2016

Keywords:
Condensation heat transfer
Gravity heat tube
Air
Degradation factor

ABSTRACT

An experimental and theoretical investigation was performed to show the effects of air on condensation in a non-vacuum gravity heat pipe at heat loads of 0.8–5.3 kW. Parameters involving local condensation heat transfer coefficients, air mole fractions, and air storage capacity in a reservoir mounted below the condensation tube, were calculated. A degradation factor method was applied to solve vapor condensation length. Results showed that local air mole fraction increased to over 95% in the condensation tube downstream, where a saturated moist air column was formed. The reservoir effectively alleviated the adverse effects of air on the condensation section. At an operating pressure of 0.24 MPa, 68% of the reservoir was filled with air. In the condensation tube downstream with a low heat load, air seriously affected condensation heat transfer, and the average degradation factor was only 0.26. By contrast, air slightly affected condensation heat transfer in the condensation tube upstream with a high heat load, and the average and local degradation factors were 0.7 and 0.76, respectively. Vapor condensation length with air was 1.32 times as much as pure vapor condensation length at a vapor mass flux of 1.8 g/s and an operating pressure of 0.36 MPa.

1. Introduction

Heat pipes have been applied in different applications, such as air conditioning systems, aerospace, industrial waste heat recovery, and renewable energy [1–5]. Heat pipes are highly efficient heat transfer devices in which phase change occurs repeatedly. They offer high thermal conductivity and can efficiently transport large amounts of heat over long distances. A heat pipe is composed of three sections: the evaporator section at one end, where heat is absorbed and fluid is vaporized; the condensation section at the other end, where vapor is condensed and heat is rejected; and the adiabatic section in between, where the vapor and liquid phases of fluid flow in opposite directions through the tube. Heat pipes can be classified as tubular, variable conductance, thermal diodes, pulsating, loop, and micro heat pipes. Recent studies have

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.209
1359-4311/

Nomenclature

c_a	air mole concentration, mol L^{-1}
$c_{p,c}$	constant pressure specific heat, J kg^{-1} K^{-1}
D_1	inner diameter of the condensation tube, m
D_o	external diameter of the condensation tube, m
D_{v-a}	diffusion coefficient between air and vapor, m^2 s^{-1}
f	degradation factor
$\bar{f}$	average degradation factor
G	mass flux, kg s^{-1}
h_{fg}	latent heat, kJ kg^{-1}
h_c	convective heat transfer coefficients of the cooling water, W m^{-2} K^{-1}
h_e	local experimental condensation heat transfer coefficients, W m^{-2} K^{-1}
$\overline{h_e}$	average experimental condensation heat transfer coefficients, W m^{-2} K^{-1}
h_m	mass transfer coefficients, m s^{-1}
h_{Nu}	local condensation heat transfer coefficients of the Nüsselt theory, W m^{-2} K^{-1}
$\overline{h_{Nu}}$	average condensation heat transfer coefficients of the Nüsselt theory, W m^{-2} K^{-1}
L	tube length, m
L_1	vapor condensation length, m
L_2	length of the saturated moist air column, m
M	molecular weight, kg mol^{-1}
m	condensation rate, kg m^{-2} s^{-1}
n_a	air mole fraction, mol
n_v	vapor mole fraction, mol
p	pressure, MPa
Q	heating power, W
q	heat flux per unit tube length, W m^{-2}
R	gas constant, J kg^{-1} K^{-1}
Re_v	Reynolds number = $\rho_v u D_1/\mu_v$
r	tube radius, m
Sc	Schmidt number = $\mu_v/\rho_v D_{v-a}$
Sh	Sherwood number = $h_m D_1/D_{v-a}$
T	thermodynamics temperature, K
ΔT	vapor superheated degree
u	velocity, m s^{-1}
V	volume, m^3
VR	ratio of gas volume to overall volume in the reservoir
V_a	volume of gas phase space in the reservoir, m^3
V_g	volume of air in the non-vacuum gravity heat pipe, m^3
x	mole fraction
z	tube axis

Greek letters

λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
δ_l	thickness of condensate, m
δ_g	thickness of gas film layer, m
μ	dynamic viscosity, Pa s

Subscript

a	air
ax	axial direction
av	average
c	cooling water
i	the ith coordinate point at z axis
$i+1$	the $(i+1)$th coordinate point at z axis
in	inlet
l	condensate
s	saturation
v	vapor
w	wall
0	initial state

focused on loop and tubular heat pipes [1]. Loop heat pipes can be operated against gravity and exhibit maximum heat transport capability [2]. Lightweight materials are used for miniature loop heat pipes to achieve high performance [3]. Tubular horizontal heat pipes have been applied to air conditioning systems in the tropics to increase cooling and power-saving capabilities [4]. Tubular heat pipes have the highest operating temperature among different heat pipes, thereby providing viable optimization and integration for renewable energy systems [1,5]. A gravity heat pipe is a gravity-assisted tubular wickless heat pipe that plays an important role in the large-scale heating industry.

Non-condensable gas (NCG) is one of the main factors that affect heat pipe performance and lifetime. NCG has two sources: (1) residual air after the heat pipe is evacuated and (2) hydrogen generated by the chemical reaction between the pipe material and the working fluid. Several researchers [6–10] have studied the effects of NCG on loop heat pipes. The majority of the NCG is located in the vapor region and the reservoir of loop heat pipes [6–8], which lead to highly elevated pressure. Therefore, NCG affects the start-up performance of loop heat pipes. Higher NCG content in the loop heat pipe results in higher temperature overshoot and liquid superheat, as well as longer startup time. Large heat load contributes to better startup performance in the presence of NCG. Huang et al. [8] proposed that gas-vapor blocks the zone between vapor and NCG in the condenser. This zone inhibits the vapor from flowing toward the condenser and prevents NCG from diffusing toward the evaporator. Prado-Montes et al. [9] found that 3.34 g of additional NCG stops the operation of loop heat pipes at low heat load between 50 and 100 W. The part of the NCG may accumulate in the primary wick lore, which leads to a local rupture of the liquid bridge through the wick, and dry-out, which leads to the inoperability of loop heat pipes. Moreover, NCG induces the oscillatory behavior of a loop heat pipe at low heat load. The addition of 0.5–1% mass fraction of ethanol forms the Marangoni effect on the surface of the condensate film of gravity loop thermosyphon in the presence of massive NCG [10]. Other studies [11–14] focused on the effects of NCG on tubular heat pipes. The effect of NCG on the transient response of wicked tubular heat pipes has been considered [11]. NCG is mixed with the vapor at startup, separated from vapor, and pushed to the condenser's end as the vapor pressure increases. Therefore, the presence of NCG slows the cooling rate of a wicked tubular heat pipe once it occupies much of the cooled region. NCG results in a large temperature gradient near the condenser's end and reduces the effective thermal conductance in radically rotating tubular heat pipes [12]. Moreover, NCG affects the condensation section of a separate-type heat pipe [13]. The sophisticated physical models were carried out to model condensation heat transfer in tubular heat pipes [14]. NCG should be removed via evacuation because it degrades condensation heat transfer in the heat pipe system. However, evacuation in a gravity heat pipe system that involves many tubes increases equipment investment costs and maintenance inconvenience. The adoption of a non-vacuum gravity heat pipe can save a lot of evacuation expenses and bring a large energy saving effect in the large-scale