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Simulation and experimental studies of R134a flow condensation characteristics in a pump-assisted separate heat pipe

Didi Zhang, Gang Li, Yuqing Liu, Xiaoliang Tian *

Institute of Energy Engineering, School of Electromechanical Engineering, Qingdao University, China

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ABSTRACT

We combine experimental research and numerical simulations to investigate the complex and unknown flow condensation heat transfer process in a pump-assisted separate heat pipe (PASHP) employing R134a. The Chen model and Müller-Steinhagen-Heck model coincide with the experimental pressure drop and heat transfer, respectively, after comparing three correlations of the pressure drop and four correlations of the heat transfer. After analysing the establishment and selection of a model to simulate the flow condensation characteristics in a PASHP, we conclude that the turbulence model, multiphase flow model, and heat and mass transfer model can be described using the SST k-ω model, VOF model, and Lee model, respectively. The phase transformation factor $r = 3000$, the simulation results and the Chen correlation are all consistent. The pressure drop and heat transfer coefficient increases with increasing mass flow and vapour quality. The simulation results of the pressure drop and heat transfer coefficient are compared with those of the Chen and Muller-Steinhagen-Heck correlations, respectively, showing satisfactory agreement between the simulated and the calculated values. This research provides a theoretical reference for the selection of the pump, design of the heat exchanger, optimization of the system and study of two-phase flow.

1. Introduction

Heat pipes (HPs) are high-performance two-phase passive thermal transfer devices with effective thermal conductivities that are orders of magnitude higher than those of similarly dimensioned solid materials [1]. HPs are becoming increasingly popular as passive heat transfer technologies because of their high efficiency and low energy consumption. The application fields of HPs are vast [2] and include communication base stations [3], charging processes in space stations, solar systems, nanoparticles [4], the thermosyphon Rankine cycle [5], nuclear reactors, power generation [6]. The advantages of using HPs in heat exchange applications include multiple redundancies (because each HP operates independently, the unit is not vulnerable to a single HP failure), low fouling, ease of cleaning and maintenance, isothermal operation (no hot or cold spots), a low working pressure drop and high scalability and configurability [7].

Xu et al. [8] conducted visual experiments on the direct contact condensation of a stable steam jet in a tube and analysed the condensation characteristics. Zhang et al. [9] presented a comprehensive review of the correlations for flow condensation heat transfer in horizontal channels and proposed an associated analytical method to evaluate this mode of heat transfer. Szijártó et al. [10] analysed the condensation characteristics of a closed inclined pipe through simulations. Wong et al. [11] performed visual experiments to analyse the flow condensation characteristics of capillary tubes using working fluids of water and methanol.

The pump-assisted separate heat pipe (PASHP) transports energy with low consumption and high density, can enable energy transmission over long distances, and has shown great promise in high efficiency and energy conservation. Shao et al. [12] conducted an experimental investigation of the two-phase flow boiling of R134a in PASHPs and concluded that the experimental results satisfactorily aligned with the correlation employed; a new heat transfer coefficient correlation was developed, with most of the estimated values lying within an error band of ±10% of the experimental data. Guo et al. [13] conducted an experiment to investigate the effect of a PASHP on energy consumption and dehumidifying enhancements in an air conditioning system and found augmenting the system with a PASHP can significantly reduce the energy consumption and improve the dehumidifying capacity. Thus, the condensation of gas-liquid two-phase flow in HPs has been the focus of recent research; however, we cannot draw a unified conclusion due to the subject's complexity.

* Corresponding author.
E-mail address: txl6666@163.com (X. Tian).

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Nomenclature

Cp	specific heat capacity, J·kg^{-1}·K^{-1}
d_i	inner diameter, m
d_o	tube outside diameter, m
G	mass flux, kg· m^{-2}· s^{-1}
g	gravitational acceleration, m· s^{-2}
k	thermal conductivity, W·m^{-1}·K^{-1}
H	heat transfer coefficient, W·m^{-2}·K^{-1}
h_{lv}	enthalpy of vapourization, J·kg^{-1}
h_f	frictional drag, Pa
L	length, m
P	pressure, Pa
P_r	Prandtl number
Q_h	heating capacity, W
Q_c	condensing capacity, W
q	heat flux, W·m^{-2}
r	phase transformation factor
T	temperature, K
t	time, s
v	velocity, m· s^{-1}
Re	Reynolds number
x	vapour quality

Greek symbol

α	void fraction values
λ	on-way loss factor
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
ρ	density, kg·m^{-3}
σ	surface tension, N/m

Subscripts

f	flow
in	inlet
l	liquid phase
lo	only liquid
out	outlet
sub	sub-cooling
tp	two phase
v	vapour phase
vo	only vapour
wi	inside wall
wo	outside wall

Therefore, we must explore the mechanism further, particularly because there are few previous studies of the flow condensation characteristics of PASHPs.

The objective of the present experimental study is to explore the condensation characteristics of the PASHP, including the flow regime and the heat transfer and pressure drop characteristics, to compare the various correlations from the literature and to obtain the correlations of heat transfer and pressure drop. The model selection for the simulation is analysed, and it is concluded that the suitable turbulence model, multiphase flow model and heat transfer model flow simulation are optimal for the PASHP. The condensation process consists of simulating various mass flows in the pipe and analysing the simulation results of the flow pattern, pressure drop and heat transfer characteristics. Then, the predictions of the pressure drop model and heat transfer model are compared with the results from the literature. Finally, the condensation process under various mass flows is simulated, and the flow regime and the heat transfer and pressure drop characteristics are analysed. Then, the simulated heat transfer and pressure drop are compared with the calculated heat transfer and pressure drop, using the developed correlation.

2. Experiment

2.1. Experimental configuration and method

Fig. 1 shows a simplified schematic diagram of the experimental facility used to test the pressure drop of the condensing section of the PASHP under the various test conditions described in Table 1. The test arrangement consists of a pump, mass flow meter, evaporation section, test-condenser, differential pressure meter, thermostatic water tank, observation section, high-frequency camera, sub-cooler, and reservoir. The pump is a magnetic gear pump positioned after the reservoir. A portion of the liquid coming from the pump flows into the reservoir though a bypass valve and air-cooled sub-cooler, and the remaining liquid flows into the evaporator, which is electrically heated when it passes through the flow meter. The test-condenser, which is a double-pipe heat exchanger positioned after the evaporator, is cooled by water from the thermostatic water tank. The double-pipe heat exchanger has a 1 m effective length and is prepared from a smooth copper tube, with a 52 and 54 mm inner and outer diameter of the outside tube, respectively, and a 10 and 12 mm inner and outer diameter of the inside tube, respectively. The working fluid then flows into the reservoir though a transparent tube and sub-cooler.

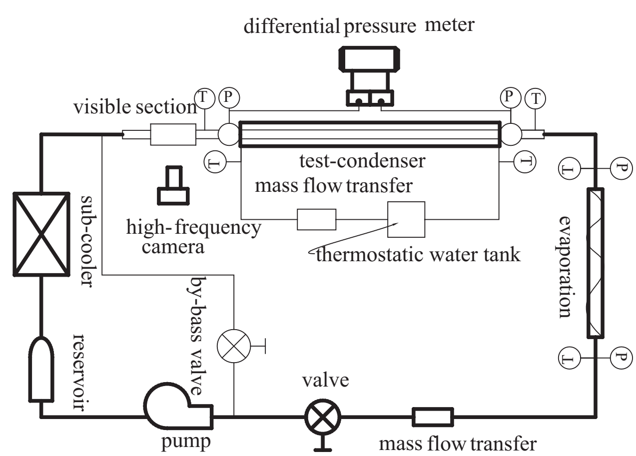

Fig. 1. A schematic diagram of the experimental apparatus.

Table 1
Uncertainties of the measured quantities.

Parameter	Uncertainty
Pipe diameter	±1 μm
Length	±1 mm
Temperature	±0.1 K
Pressure	±0.1%fs (fs = 2 MPa)
Pressure drop	±0.075%fs (fs = 1000 Pa, fs = 8000 Pa)
Mass flow rate	±1.0%
Energy meter	±0.5%
Heat flux	±3.68%
Vapour quality	±4.98%