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Nucleate boiling heat transfer in a helium natural circulation loop coupled with a cryocooler

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ABSTRACT

A gravity based U-shape natural circulation loop coupled with a cryocooler is proposed to serve as a self-sustaining thermal link at the temperature of liquid helium. Experiments are performed with a constant helium mass inside the system by keeping the loop closed. This thermal link is mainly composed of a condenser/phase separator cooled by the second stage of a 1.5 W-class cryocooler at 4.2 K. Connected to the condenser, a 23 cm high testing tube is heated along its entire length. Liquid helium flows through this tube to the condenser and is recondensed there. Helium in both normal and supercritical regions is encountered in the experiment and the boiling curve is obtained with the heat flux being controlled. The different boiling regimes and hysteresis during the recovery process are observed and analyzed. Heat transfer coefficient is determined in the nucleate boiling regime and compared with existing correlations. The correlation proposed by Kandlikar reproduces the heat transfer coefficient within 30% error in the regime of two-phase nucleate boiling.

1. Introduction

For various applications in heat exchanger, energy conversion and cooling system, natural circulation loops have been proven to be a simple but efficient device for transferring heat [1]. The operation principle is that the flow is driven by density gradients caused by thermal effects while additional pumping mechanism is not required. The loops can be heated from below or on the side, and cooled from above. Several investigations have been focused on the performance of natural circulation loops [1–3], including heat transfer process in the regimes of single phase convection [4,5] and two-phase boiling [6,7]. A variety of working fluids have also been studied, such as water [8], carbon dioxide [5], hydrocarbon fuel [9] and those working at low temperatures: R-133 [10], R-134a [11], nitrogen [12,13] and helium [14]. In the superconductor technology domains, natural circulation loops working with cryogens are more and more employed nowadays. The cooling systems of large superconducting magnets for high energy physics particle detection are generally based on natural circulation loops [15], such as the Compact Muon Solenoid (CMS) at CERN (European Organization for Nuclear Research) [16] and Reactions with Relativistic Radioactive Beams (R3B) at GSI (Helmholtz Centre for Heavy Ion Research) [17,18]. Considering the important heat load (several hundreds of Watts) that these large magnets receive, the cooling system is normally open where the helium vapor is recovered outside the magnet by a liquefaction facility. The liquefaction facility recondenses the produced vapor and ensures a constant liquid level in the loop by feeding a reservoir to compensate the loss of mass due to evaporation.

For smaller cryo-magnetic systems subjected to heat loads in the order of a few Watts, another cooling scheme can be used. It is proposed here to employ a small natural circulation loop coupled with a condenser as a self-sustaining cooling system. The condenser on top of the loop is mounted below the second-stage cold head of a cryocooler at liquid helium temperature. It serves as the liquefaction facility inside the system with the maximum cooling capacity of 1.5 W at 4.2 K, and eliminates the need of additional setup and cryogen transport from outside to the loop. Few studies on helium heat transfer have been performed in a single tube [19,20], parallel tubes [21] and U-shape circulation loop in large dimension [22]. Flow in the U-shape loop is conveniently caused by the weight imbalance between the two branches. As part of the loop is heated, the local fluid becomes lighter and rises while fluid in other part of the loop flows down. When the heat load is high enough, boiling appears and two-phase flow is generated in the loop, which can greatly improve the heat transfer. Based on previous studies for large systems [12,22], such circulation loops are effective for cooling down magnets. For smaller systems and heat loads, the proposed self-sustaining loop can be used as cooling device even when the systems are distant from liquefying facility.

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Nomenclature

A	cross-sectional area
Bo	Boling number: q/GL_h
Co	Convection number: $(1/x-1)^{0.8}(\rho_v/\rho_l)^{0.5}$
C_p	heat capacity
D	diameter of the loop
g	gravitational acceleration
G	mass flux
h	heat transfer coefficient
H	enthalpy
k	thermal conductivity
L_h	latent heat of vaporization
m	mass flow rate
M	molecular weight
P	pressure
Pr	Prandtl number
q	heat flux
Re	Reynolds number
T	temperature
x	vapor quality
X_{tt}	Martinelli parameter: $(1/x-1)^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}$
z	location on the testing tube

Greek letters

σ	surface tension
μ	dynamic viscosity
ρ	density

Subscripts

e	effective
f	bulk fluid
i	inlet
l	liquid
m	averaged
nb	nucleate boiling
pool	pool boiling
r	reduced
sat	saturation
sp	single phase
sub	subcooled
t	total
tp	two-phase
v	vapor
w	wall

One of the key factors in designing and evaluating natural circulation loops is the heat transfer characteristics. Although the single phase heat transfer is better understood, two-phase boiling is a complex issue involving the interactions between convection and nucleation. Basically there are two types of two-phase heat transfer correlations that are taking account of forced convection and boiling heat transfer. Shah proposed a correlation based on the single phase forced convection heat transfer coefficient, h_l, modified by a parameter ψ to take account of the boiling effect [23]:

$$h_{tp} = \psi h_l, \tag{1}$$

where h_{tp} is the two-phase heat transfer coefficient and ψ is defined as a function of Boiling number Bo and Convection number Co (see Table 1). h_l represents the single phase liquid heat transfer coefficient calculated by the Dittus–Boelter correlation [24]:

$$h_l = 0.023\ \mathrm{Re}_l^{0.8}\mathrm{Pr}_l^{0.4}\left(\frac{k_l}{D}\right). \tag{2}$$

Later, Kandlikar [25] developed a general correlation for heat transfer in tubes. His correlation can also be written in terms of Eq. (1) while different expression of ψ has to be used depending on the values of Bo and Co, as defined in Table 1.

The other early correlation was proposed by Chen [26], by directly adding a term representing pool nucleate boiling into Eq. (1).

$$h_{tp} = Fh_l + Sh_{pool}, \tag{3}$$

where h_{pool} represents the micro-convective mechanism at the wall, i.e. the pool nucleate boiling, deducted from the Froster and Zuber's equation [27]:

$$h_{pool} = 0.00122\left(\frac{k_l^{0.79}C_{pl}^{0.45}\rho_l^{0.49}g^{0.25}}{\sigma^{0.5}\mu_l^{0.29}L_h^{0.24}\rho_v^{0.24}}\right)\Delta T^{0.24}\Delta P^{0.75}. \tag{4}$$

F and S are parameters treating the extensions of convection and nucleation. Many correlations that are developed afterward are based on Chen's correlation, i.e. separating the two mechanisms of heat transfer, for example Gungor and Winterton's correlation [28] for flow in tubes and annuli.

Besides, Kutateladze suggested a correlation for pool boiling heat transfer [29] and a power-type combination of h_l and h_{pool} for flow boiling condition, $h_{tp}^n = h_l^n + h_{pool}^n$, [30]. His pool boiling correlation has been later studied by Brentari and Smith in comparing with a variety of data for cryogenic fluids [31], including experiments conducted at different pressures with different orientations of the heater. Liu and Winterton then developed a new correlation for two-phase boiling by employing the power-type combination ($n = 2$) of the convective and pool boiling contributions [32]. The power type asymptotic correlation of Steiner and Taborek [33] was also based on Kutateladze's flow boiling correlation with $n = 3$.

In this paper, we experimentally investigate the heat transfer inside the small natural circulation loop in a close cycle with a constant mass of helium. Our experiments cover both the normal and supercritical regions of helium where the wall temperature is measured at different locations at the testing tube, i.e. the heated part of the loop. The boiling curve of normal helium is obtained with the heat load as the controlled parameter. The nucleate boiling heat transfer coefficient is calculated and compared with several existing correlations.

2. Experimental setup

The experimental apparatus is composed of a U-shape circulation loop, consisting of two vertical and one horizontal tubes, as shown in Fig. 1. The top of vertical tubes are connected to the condenser, which is mounted below the second-stage cold head of a Gifford–McMahon type cryocooler (1.5 W at 4.2 K). The testing tube is made of OFHC copper, whose thermal conductivity at 4.2 K is around 700 W/(mK). It has a total length of $z_t = 23$ cm, an outer diameter of 6 mm and inner diameter of 4 mm. The tube is wrapped with a wire heater that is connected to a power supply controlled by computer program. The rest of the loop is in stainless steel insuring that there is no longitudinal heat transfer in the testing tube. During the experiments, the whole loop and the cold head of the cryocooler are located in a cryostat insulated by an aluminum thermal shield to minimize the radiation. The cryostat is evacuated and a vacuum of 10^{-7} mbar is maintained during the