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The two-phase closed tubular cryogenic thermosyphon

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ABSTRACT

The heat transfer characteristics of a two-phase closed tubular cryogenic thermosyphon filled with nitrogen fluid have been investigated. The thermosyphon consists of a 1.1 cm inside diameter, 5 m long copper tube coated with a few layers of the high-vacuum superinsulation and enclosed into a vacuum jacket. A free-boiling liquid nitrogen pool has been used as a cooling machine. The system is compact, free from mechanical vibrations, and can provide thermal stabilization of remotely located devices in the temperature range of 80–120 K with the heat transfer limit up to 100 W.

1. Introduction

A two-phase closed tubular thermosyphon is a high-performance heat transfer device that can be used to transfer a large amount of heat at a high rate [1]. The thermosyphon or gravity-assisted heat pipe consists of three basic sections as shown in Fig. 1: a cooling section (condenser) located above a heating section (evaporator) and a passive adiabatic section connecting the two active sections. A condenser is a part of the thermosyphon of length L_c used to deposit the heat energy Q into a cooling machine operating in good thermal contact with this section. The condensate generated inside the condenser falls down due to gravity through the adiabatic section into the evaporator, where the liquid is boiling and absorbing the heat Q. The generated here vapor rises into the condenser, returning the heat to the cooling machine, condensing to the liquid, then, the heat transfer cycle repeats. Since the operation of the thermosyphon relies upon the gravitational force, the evaporator must be located below the condenser.

There are discussed a few working fluids that can be used in cryogenic thermosyphons (Table 1). At this study, we have used a simple cryogenic cooling machine in which the condenser is immersed in liquid nitrogen that freely boils at atmospheric pressure providing the temperature of the condenser at the fixed temperature: $T_b = 77.36$ K. Nitrogen is a cheap cooling agent, which is available in large amounts and can provide safe operations. As seen from Table 1, the nitrogen-based cooling machine can operate in the temperature range between 63.15 K and 126.2 K and pump out the heat from the evaporator with the latent heat of vaporization LHV = 199 kJ/kg.

2. Experimental apparatus

The schematic drawing of the experimental setup is shown in Fig. 2a. The setup consists of a test stand, a liquid nitrogen reservoir and a working fluid charging system.

The test stand includes a cryogenic thermosyphon connected to a cooled device or cold head (a steel ingot of 4 kg mass) installed with an adjustable heater and resistance thermometer. The adiabatic section of the thermosyphon is made of 5 m long copper pipe with 11 mm inside diameter wrapped in multiple layers of vacuum superinsulation and enclosed into a vacuumed bellow hose of 68 mm inside diameter. The evaporator is constructed as a well of 11 mm in diameter and 7 cm in length inside a copper pad of $8 \times 8 \times 2$ cm^3 dimensions attached to the cold head pictured when disassembled in Fig. 2b. The condenser is a stainless steel closed pipe with 11 mm inside diameter and L_C = 30 cm length installed onto the bottom lid of the custom made liquid nitrogen reservoir via $1\frac{1}{3}''$ CF flange. The liquid nitrogen boiling at atmospheric pressure works as a heat sink for the thermosyphon. The vacuum jacket surrounding the reservoir and the thermosyphon is pumped out with a turbo-molecular pump.

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Nomenclature

A	cross section (mm^2)
D	diameter (mm)
FR	filling ratio (%)
HTL	heat transfer limit (W)
k	thermal conductivity (W/(m K))
L	length (m)
L_A	length of the adiabatic section operating at T_A temperature (m)
L_C	length of the cooling section operating at T_C temperature (m)
L_H	length of the heat absorbing section operating at T_H temperature (m)
L_P	Length of the section filled with a liquid (m)
LHV	Latent heat of vaporization (kJ/kg)
Q	Heat energy (J)
R	Total thermal resistance (K/W)
T	Temperature (K)
T_b	Temperature of the boiling point (K)
$T_{c.p.}$	Temperature of the critical point (K)
$T_{t.p.}$	Temperature of the triple point (K)
W	Power (W)

The general view of the experimental setup is shown in Fig. 3. The charging system is equipped with manually or/and electronically operated valves and on-line controllable pressure/vacuum and gauges to provide operations up to eight thermosyphons simultaneously for variety applications. The working nitrogen fluid is stored in a standard high pressure liquid nitrogen tank. The thermosyphon can be filled with a precisely measured amount of nitrogen. The filling ratio has been calculated taking in account the amount of the loaded nitrogen and geometry of the thermosyphon:

$$FR = \frac{L_P}{L_H + L_C + L_A} \cdot 100\% \tag{1}$$

The most experimental data have been measured at $FR = 6.5\%$ that is quite close to the minimum value providing operations in a steady mode. During the test the difference in vertical positions of the condenser section and the evaporation section was fixed at 2 m (Fig. 3).

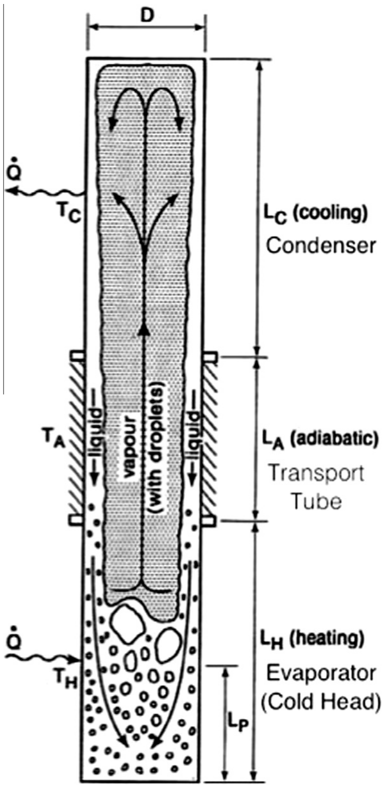

Fig. 1. The operating principle of a two-phase closed tubular thermosyphon (heat pipe) [1].

3. Experimental data and discussion

At the beginning of each test, the thermosyphon has been evacuated at room temperature. Then, a cooling power has been applied to the condenser and the thermosyphon began to be charged with nitrogen fluid. In Fig. 4 there is shown a dependence of the temperature of the cold head on time at different heat load conditions at two filling ratios. The cooling rate 0.6 K/min has been measured at $FR = 3.2\%$. The cooling rate 3 K/min has been observed at the filling ratio of $FR = 6.5\%$ used at the following test. After the lowest temperature (80 K) of the cold head has been achieved, the electric power was applied via an electrical heater (15 Ohm, 200 W resistor) installed on the cold head as shown in Fig. 2b. The temperature has been raised with the artificial heat load increased. The steady states have been observed at 20, 40, 60, and 80 W heat loads as shown in Fig. 4. After achieving 120 K at the 80 W applied power, the heater has been switched off and the temperature of the cold head has been stabilized again at ≈80 K after 1 h of operation. At the head load of 100 W and more, the thermosyphon can not operate at steady mode and the temperature is rapidly rising. This may be described as a dry-out limitation when the evaporator is totally losing the liquid similar to what has been observed by Park et al. [2]. From this test we have concluded that the heat transfer limit for our thermosyphon is $HTL \approx 100$ W.

The dependence of the temperature of the cold head versus applied heat loads is shown in Fig. 5. The highest temperature of the cold head 120 K has been achieved with 80 W artificial heat loads; the lowest temperature of 80 K has been observed if only the natural head load due to imperfections of vacuum thermoinsulation W_0 affected the temperature of the cold head. Fitting the experimental data with linear function $T(K)$, from Fig. 5 we can

Table 1
Properties of working fluids for cryogenic thermosyphons.

Fluid	$T_{c.p.}$, K	T_b, K	$T_{t.p.}$, K	LHV, kJ/kg
He	5.25	4.22	2.1768	21
Ne	44.45	27.104	24.556	86.3
N_2	126.2	77.36	63.15	199
O_2	154.58	90.19	54.8	213
CF_4	227.5	145.2	89.4	135.95
Ar	150.85	87.302	83.81	162.3
Kr	209.35	119.93	115.78	107.5
Xe	289.74	165.05	161.4	96.3