Experimental Thermal and Fluid Science 72 (2016) 161–170

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Effect of non-condensable gas on the start-up of a gravity loop thermosyphon with gas–liquid separator

Jian Huang [a], Li Wang [a,b,*], Jianbiao Shen [a], Chuanping Liu [a]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Beijing Engineering Research Center of Energy Saving and Environmental Protection, Beijing 100083, China

ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 13 November 2015
Accepted 16 November 2015
Available online 23 November 2015

Keywords:
Non-condensable gas
Start-up
NCG-vapor blocks zone
Pressure peak curve

ABSTRACT

This study experimentally investigated the influence of non-condensable gas (NCG) on the start-up time of gravity loop thermosyphon (GLT) developed for regenerative building heating exchangers. A gas–liquid separator was added to the end of the condensate line in the GLT. Given characteristics of the NCG that accumulated in the gas–liquid separator, and the NCG is prevented from circulating in the loop, thereby effectively lowering the effect of NCG on heat exchange. The presence of NCG not only influenced the local condensation heat transfer of the condenser but also affected the start-up of the loop thermosyphon. Results of the experimental investigation revealed that the presence of NCG increased the start-up time of GLT. A higher NCG level corresponds to, a longer start-up time. In particular, the start-up time was 2.8 times more than that in the evacuation when amount of NCG was 30% in volume. The NCG–vapor blocks zone hinders the vapor transmission from the evaporator to the condenser in the vapor line between the evaporator and condenser, further causing a rapid increase in system pressure during start-up. Moreover, obvious pressure peak curve phenomena occurred in a number of conditions, such as heat load was greater than or equal 2.0 kW and amount of NCG was less than or equal 30% in volume.

1. Introduction

Separate-type loop thermosyphons (LTs) are applied to heat exchangers in waste heat recovery systems in the industry. This type of LTs present many advantages, such as separated heat and cold loads, free of tube cores and auxiliary equipment, high heat exchange efficiency, and low maintenance [1,2]. However, many experiments [3–5] have demonstrated that small amounts of non-condensable gas (NCG) can adversely affect condensation heat transfer and lower heat exchange efficiency. A conventional way to overcome these drawbacks is evacuated before being used. Evacuation requires high energy consumptions for medium- and large-scale thermosyphon heat exchangers. In addition, NCG is easily produced in evacuated systems as a result of the leakage of atmospheric gases, the dissolving of gases or impurities in the working fluid, as well as chemical reactions between the working fluid and the material of the container walls during long-term contact [6,7]. Liu [8] and Dube et al. [9] found that the accumulation of NCG at the end of the condenser region can lower the effect of NCG on condensation heat transfer. The same situation occurs in the loop heat pipe (LHP). Experiments [10,11] showed that NCG mainly accumulated inside the compensation chamber, which increased the overall pressure in the LHP thus the steady-state operating temperature. Motivated by this finding, Wang et al. [12,13] designed a set of non-vacuum LT exchanger devices that can be applied to regenerative building heating. The exchanger device transformed the off-peak electricity into heat energy, stored the heat, and removed the heat through non-vacuum LT exchanger devices. A gas–liquid separator was added at the end of the condenser to accumulate the NCG, thereby preventing the NCG from circulating in the loop and effectively lowering the effect of NCG effect on the heat exchange. A subsequent study [14] concluded that the condenser tube length of the non-vacuum loop heat tube was 1.39 times that of pure vapor condensation. The use of a non-vacuum LT heat exchanger can greatly reduce equipment investment and maintenance costs.

The presence of NCG not only influences the local condensation heat transfer of the condenser but also affects the start-up of thermosyphons [15,16] and loop heat pipes [17]. Ong and Haider-E-Alalhi [15] demonstrated that in the process where the two-phase closed thermosyphons starts at environmental temperature and then enters dynamic equilibrium working conditions,

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* Corresponding author at: School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China.
E-mail address: liwang@me.ustb.edu.cn (L. Wang).

http://dx.doi.org/10.1016/j.expthermflusci.2015.11.007
0894-1777/

Nomenclature

GLT	gravity loop heat pipes
NCG	non-condensable gas
PTFE	polytetrafluoroethylene
j	flux of condensation, kg m^{-2} s^{-1}
P_a	partial pressure of noncondensable gas, N m^{-2}
P_{atm}	atmospheric pressure, N m^{-2}
$P_{\text{dynamic equilibrium}}$	dynamic equilibrium pressure of the GLT, MPa
P_f	pressure in liquid space, N m^{-2}
P_g	pressure in vapor space, N m^{-2}
P_{max}	maximum pressure during the start-up process, MPa
P_{sp}	pressure in gas–liquid separator, MPa
P_{tot}	system total pressure vapor, MPa
P_v	partial pressure of vapor, N m^{-2}
P_*	vacuum degree, MPa
Q_e	evaporator heat loads, W
q_c	flow of cool water, L/min
R	pipe radius, m
t	start-up time, s
T_f	bulk liquid temperature, °C
T_g	vapor temperature, °C
T_{ve}	vapor temperature of evaporator, °C
T_{vc}	vapor temperature of condenser, °C
$T_{wi1}-T_{wi9}$	vapor line wall temperature, °C
$T_{wv1}-T_{wv3}$	condenser tube wall temperature, °C
V_{GLT}	volume of GLT, mL
V_{NCG}	volume of NCG, mL
α	volume fraction of NCG, %

NCG inhibits the vapor condensation heat transfer and forms a diffusion resistance in the tubes. Consequently, the vapor's mass transfer rate was decreased, thereby increasing the working pressure, slowing down the increase in the condenser's temperature, and ultimately causing hysteresis during the start-up process. The excessive levels of NGC in the oscillation and micro LT could even prevent them from starting-up and performing normally [5,10]. Therefore, the start-up process of LT with NCG should be examined. This study investigates the effects of NCG on the start-up of gravity loop thermosyphon (GLT) with a gas–liquid separator.

The total system pressure that contains NCG is the sum of the vapor partial pressure and NCG partial pressure: $P_{tot} = P_v + P_a$. However, the vapor partial pressure in a closed LT is difficult to measure accurately. When NCG accumulates, its partial pressure increases affecting the passing through of vapor to reach the condensation film. As a result, the vapor partial pressure decreases. The vapor condensation flux on the condensation film surface is shown as Eq. (1) [18]:

$$j = \left(\frac{M}{2\pi R}\right)^{1/2}\left[\frac{p_g}{T_g^{1/2}} - \frac{p_f}{T_f^{1/2}}\right] \tag{1}$$

The first item in the square brackets on the right-hand side of the equation represents the molecular flux that enters the liquid membrane because of the moisture condensation, which depends on the vapor partial pressure and temperature on the liquid membrane. The second item in the square brackets represents the molecular flux that leaves the liquid membrane because of liquid evaporation, which depends on the pressure and temperature on the liquid membrane. Therefore, when the temperature of the surface liquid membrane equalizes, a lower vapor partial pressure leads to a lower local vapor condensation flux and temperature of the tube wall. Thus, we can study the effects of NCG on the start-up of GLT by analyzing the temperature of the vapor line wall.

2. Experimental facility and operation

The GLT experimental apparatus is shown schematically in Fig. 1(a). This device is composed of an electric evaporator, a double-pipe condenser with an annular cooling jacket, and a gas–liquid separator with a liquid indicator. All of the components as well as the vapor line and liquid line are stainless steel smooth-walled tubes. Tap water is selected as the working fluid and air is used as the NCG. The parameters of the GLT are shown in Table 1.

The evaporator is a stainless steel cylinder, with 6 thin-film electric heating rods installed at the inner bottom of the cylinder. The evaporator can produce 0–3.5 kW heat load with altering the AC power output voltage. The design of the double-pipe condenser is based on the devices proposed by Kuhn [19] and Hasanein [20]. The double-pipe condenser is made of stainless steel. Cooling water is introduced at the bottom of the outer jacket, and the vapor–NCG mixture is introduced at the top of the inner tube. The coolant is tap water, the coolant temperature is controlled to be between 15 °C and 20 °C. The vapor line is 2000 mm long and connects the evaporator and the condenser. The vapor from evaporator heats the vapor line and flows through it during the start-up process. Nine K-Type thermocouples ($T_{wi1}-T_{wi9}$) that are isometrically fixed to the external surface of the vapor line to detect the vapor temperature. Three thermocouples for measuring the wall temperature of the vapor inner line are fixed on the wall at 20, 350, and 700 mm distances from the condenser inlet. The location and number of the test points in the experiment station are shown in Fig. 1(a).

A gas–liquid separator is installed at the end of the condenser line and the top of the gas–liquid separator is 80 mm higher than the top of the evaporator. Due to the effects of gravity and the communicating vessel, the liquid level in the evaporator is consistent with that in the gas–liquid separator. But, when GLT starts it generates a pressure differential which causes a difference of the liquid level between the evaporator and gas–liquid separator. There is a liquid indicator (transparent PTFE tube) parallel connected with the gas–liquid separator, as shown in Fig. 1(a), to monitor the liquid level in the separator in the GLT start-up process. During the starting and operation of the GLT, the NCG should be collected in space of the gas–liquid separator provided, and the NCG influences over pressure distribution. Also, the liquid in gas–liquid separator prevents the NCG from circulating in the loop and effectively lowers the NCG effect on the heat transfer in evaporator.

A manifold branch is installed in the pipe line between the condensate and gas–liquid separator to pump out air and fill the water and NCG. We refer to Singh's [10] method for evacuating the air as well as for injecting a certain volume of NCG and the measured volume of liquid into the GLT, as shown in Fig. 1(b). The total GLT volume $V_{\text{GLT}} = 4562$ mL, including volume of evaporator, condenser, gas–liquid separator and all tubes. The fluid filling quantity of this experiment is 70% in total GLT volume (i.e., the fluid filling quantity is 3193.4 mL). We define the volume fraction of NCG: $\alpha = \frac{V_{\text{NCG}}}{V_{\text{GLT}}} \times 100\%$, the V_{NCG} and V_{GLT} are at room temperature (20 °C) and atmosphere in all experiments.

We use the charging station device to make a vacuum in the GLT by the four way valve (via port A and D) as shown in Fig. 1(b) after all components of GLT are nearly at room temperature, and then switch the four way valve for NCG charging (via port A and C) from air cylinder. We control the NCG content by