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Effect of non-condensable gas on steady-state operation of a loop thermosyphon

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ABSTRACT

Non-condensable gas (NCG) generated inside two-phase heat transfer devices can adversely affect the thermal performance and limit the lifetime of such devices. In this work, extensive experimental investigation of the effect of NCG on the steady-state operation of an ammonia-stainless steel loop thermosyphon was conducted. In the experiments, nitrogen was injected into the loop thermosyphon as NCG, and the thermal performance of the loop thermosyphon was tested at different NCG inventories, heat loads applied to the evaporator and condenser cooling conditions, i.e. natural air cooling or circulating ethanol cooling. Experimental results reveal that NCG elevates the steady-state operating temperature of the evaporator, especially when the loop thermosyphon is operating in the low temperature range; meanwhile, the more NCG exists in the loop thermosyphon, the higher the operating temperature of the evaporator, and the lower the reservoir temperature. In addition, the existence of NCG results in the decrease of the overall thermal conductance of the loop thermosyphon, and the overall thermal conductance under the ethanol cooling condition may be even lower than that under the air cooling condition when the heat load is smaller than a certain value. Finally, the experimental results are theoretically analysed and explained.

1. Introduction

Loop thermosyphon is an effective and efficient two-phase heat transfer device that utilizes the evaporation and condensation of a working fluid to transfer heat, and the gravity to circulate the working fluid [1–4]. Without any pump or capillary action, it provides reliable and cost-saving means for transferring thermal energy in numerous engineering applications, such as in the waste heat recovery, solar water heating, geothermal system, emergency core cooling system in nuclear reactors as well as electronic cooling system [5–8].

In some cases, loop thermosyphons are expected to function well over the design life, which have to be in operation continuously for a very long time, i.e. ten years or even longer for highly reliable devices such as nuclear reactors and the high performance servers [9,10]. However, two main issues adversely affect the thermal performance of this device: the loss of working fluid due to slight leakage and the generation of non-condensable gas (NCG). NCG is the gas that cannot be condensed inside the two-phase heat transfer system and remains in the gas state during the operation. The most common NCGs are air, nitrogen, oxygen and carbon dioxide, etc. NCGs are mainly generated by the chemical reactions among the impurities, container wall, wick material and the working fluid. Impurities can be introduced into the loop during the whole manufacturing process, such as the contamination from the machining process, leftover from the cleaning process and dissolved gases in the working fluid during the charging process. Another potential gas generation mechanism is the adsorption of the wick or the container material. As a result, the NCG will release gradually inside the loop over the lifetime. In addition, air infiltration from the ambient in low pressure system may also lead to the generation of NCG due to improper brazing/welding of the joints [11–13].

As a common phenomenon, the issue of NCG in the two-phase system has been the focus of quite a few studies. Depending on the amount and distribution, NCG can cause the performance degradation or even failure of the two-phase system. For heat pipe and thermosyphon, NCG generally accumulates at the end of the

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condenser, which leads to the decrease of the heat transfer area of the condenser and ultimately reduces the heat transfer capacity [14–18]. Compared with traditional heat pipe, loop heat pipe (LHP) is more tolerable to NCG due to the presence of a compensation chamber that can accommodate most of the NCG without considerable performance degradation. However, it is worth to mention that larger amount of NCG may be generated inside the LHP than that inside traditional heat pipe, because the former one has a finer porous wick, more working fluid inventory and inner surface area as well as more complicated manufacturing process. Consequently, NCG still affects the thermal performance of LHP as its amount increases to a certain level. Experiments showed that NCG mainly accumulated inside the compensation chamber, which increased the overall pressure in the loop thus the steady-state operating temperature [12,13,19]. Furthermore, because the partial pressure produced by the NCG increases the system pressure as well as the saturation temperature during the startup, it results in a longer startup time for a given heat load. In particular, it may fail to startup at a very small heat load [20].

So far, the investigation of the effects of NCG on the loop thermosyphon performance is obviously inadequate and seldom reported. Similar to other two-phase systems, the operating temperature of the loop thermosyphon is dependent on the saturation pressure of the working fluid in the evaporator. The existence of NCG would increase the local pressure as well as the saturation temperature of the working fluid in the evaporator due to the effect of its partial pressure. Because the circulation of the working fluid in the loop thermosyphon is a very complex thermodynamic process, the change of the evaporator temperature will result in the variations of the temperature, pressure and liquid/vapour distribution of the other components, and eventually affect the overall thermal performance of the loop thermosyphon [10]. Note that, although a small amount of non-condensable gas may shut down the operation of a heat pipe, particularly at low pressure, sometimes its presence can also be utilized to help control the system temperature in a positive manner. Especially in a closed thermosyphon, during the operation, the non-condensable gas is swept along with vapour flow, and since it does not condense, it will accumulate at the end of the condenser. So with the increase of the operating temperature, the vapour pressure of the working fluid increases, thus compressing the non-condensable gas into a smaller volume and providing a greater active condenser area. The converse operation is similar. With proper design, the gas-controlled heat pipe becomes a constant-temperature variable conductance device [21].

To the best of our knowledge, the existing studies of the effect of NCG on the two-phase systems are mostly conducted when operating around ambient temperature or even higher temperature range, and the effect of NCG on the loop thermosyphon when operating in the low temperature range i.e. around 0 °C or even below has never been experimentally studied. Sarno et al. employed a loop thermosyphon for the thermal management of the avionics of an in-flight entertainment system [22]. Dube et al. experimentally investigated the effects of non-condensable gases on the performance of loop thermosyphon heat exchangers, and suggested that NCG reservoir should be installed in the highest points of the loop thermosyphon, in the entrance or exit of the condenser. This would help the NCG to accumulate in the reservoir when the loop thermosyphon is in operation [23].

For traditional working fluids such as ammonia and R134a, its saturation pressure drops rapidly as the saturation temperature decreases. However, the partial pressure produced by the NCG drops very slowly with the decrease of the temperature for a given volume and amount. Under this condition, the ratio of the partial pressure produced by the NCG to the system saturation pressure will become much larger when operating at low temperature range than that at ambient temperature range. In other words, the effect of NCG on the operation of the loop thermosyphon may be more salient when it is operating at low temperature range.

In our previous paper [24], the effect of non-condensable gas on the startup of a loop thermosyphon has been experimentally investigated in detail, and some important conclusions have been drawn. The objective of this study is to experimentally investigate the effect of NCG on the steady-state operation of the loop thermosyphon when it is operating at both ambient and low temperature range. By injecting nitrogen into the loop as the NCG, the temperature variations of the specified points along the loop at steady-state operation with different NCG inventories, heat loads applied to the evaporator and condenser cooling conditions are studied. Furthermore, the effect of NCG on the overall thermal conductance are investigated and analysed. The experimental results are theoretically analysed and explained, which contributes to a better understanding of the physical mechanism of the effect of NCG and can guide the design of the loop thermosyphon to minimize or control the effect of NCG.

2. Experimental system

2.1. Experimental setup

Fig. 1 shows the schematic of the loop thermosyphon in the experiment. It was an ammonia-stainless steel type. Ammonia was selected as the working fluid due to its excellent thermo-physical properties and compatibility with stainless steel [11]. The loop thermosyphon has four evaporators suitable to multiple heat source applications, and each evaporator has an aluminium plate fin. The vapour and liquid transport lines as well as the condenser line were all stainless steel smooth-walled tubes. The basic parameters of the loop thermosyphon are presented in Table 1, where o.d. and i.d. represent the outer and inner diameters respectively.

Heat load was applied to the evaporator through thin-film electric resistance heaters attached to the outer surface of the plate fins. The heat load can be adjusted by altering the output voltage of the DC power in the range of 0–150 W, and the maximum uncertainty of the heat load is around ±5%. The condenser line with plate fin was mounted inside an aluminium radiant panel, and the condenser was cooled by two means, i.e. natural air cooling or circulating ethanol cooling to realize that the loop thermosyphon operate at different temperature ranges. Under the air cooling condition, the heat was rejected to the room-temperature atmosphere through the radiant panel by means of natural convection and radiation, as shown in Fig. 2; and under the ethanol cooling condition, the condenser was cooled by the circulating ethanol with constant temperature (−20 °C) in two cold plates located on one side of the radiant panel along the condenser line, as detailed in Fig. 3. Heat loss to the ambient can be safely neglected as sponge thermal insulation materials were employed to reduce the heat transfer between the loop thermosyphon components and the ambient.

Twenty eight type T thermocouples (TCs) were attached tightly to the component surfaces to monitor the temperature profile along the loop thermosyphon, as illustrated in Fig. 1. Thermal grease was used to reduce the thermal contact resistance, and industrial adhesive tape was employed to fix the thermocouples. To inhibit the effect of the heater and cooler in the surface temperature measurement, the thermocouples on the evaporator and condenser were all attached at the walls that are apart from the heaters and the coolers as far as possible, as shown in Figs. 1 and 3. The maximum measurement errors of the thermocouples is ±0.5 °C, and the temperature data from the thermocouples was