International Journal of Heat and Mass Transfer 53 (2010) 3414–3428

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Performance of naphthalene thermosyphons with non-condensable gases – Theoretical study and comparison with data

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ARTICLE INFO

Article history:
Received 17 July 2009
Received in revised form 20 February 2010
Accepted 20 February 2010
Available online 22 April 2010

Keywords:
Thermosyphons
Naphthalene thermosyphons
High temperature heat exchangers
Non-condensable gases (NGC)

ABSTRACT

Naphthalene thermosyphons are efficient heat transfer devices that operate within 250 and 400 °C. There is a lack of literature about naphthalene thermosyphons, especially with the presence of non-condensable gases (NCG). Thermal circuit resistance models, considering or not NCG, are developed. NCG–vapor flat front hypothesis is adopted. Condensation and evaporation heat transfer coefficients are obtained from literature correlations. Thermal resistance data provided from naphthalene thermosyphon charged with argon, is obtained using especial experimental setup. Two combinations of correlations provided good comparison with data, for thermosyphons with and without NCG. These models are successfully applied for heat exchanger design.

1. Introduction

Two-phase thermosyphons are high conductance thermal devices, which can present different geometries and sizes, being very suitable for applications in compact and efficient heat exchangers. Actually, the industry interest in such devices is increasing, as they are reliable, robust and safe and demands low maintenance.

Basically, a thermosyphon is a hollow evacuated tube, partially filled with working fluid. Heat is delivered to the thermosyphon in the bottom of the tube, the evaporator. The liquid in contact with the heat evaporates and the resulting vapor, due to the pressure gradients, flows to the top of the tube. In this region, the condenser, heat is removed and the vapor condensates. The resulting liquid returns to the evaporator by means of gravity. Thermosyphons and heat pipes are very similar devices; in heat pipes the liquid is returned to the evaporator by means of the capillary forces provided by a wick usually located close to the tube wall.

The heat Pipe Laboratory of the Federal University of Santa Catarina, Brazil (Labtucal/UFSC) has, over the past 15 years, developed several heat pipe and thermosyphon technology thermal equipment, for different industrial or electronic cooling applications. The research and development work includes: modeling and tests of special heat pipes or thermosyphons; testing of small scale equipment prototypes; design and fabrication of very small devices, for electronic thermal control of earth and satellite equipment [1–3]; design of large equipment, such as heating systems for industrial ovens [4,5] or asphalt storage tanks [6]; fabrication and test of cryogenic heat pipes, for cooling satellites sensors [7,8]; and high temperature thermosyphons [9].

Many of these equipment works at moderate temperature levels (between 0 and 250 °C). Water has been used as the working fluid. However, new industrial applications demands for higher operating temperature levels, ranging between 200 and 400 °C, where water is not appropriated. Actually, the water vapor pressure for temperatures above 250 °C, is very high, and, to guarantee the mechanical integrity of water thermosyphons operating at high temperatures, the case walls must be thick, increasing the equipment weight and cost. On the other hand, for very high temperature levels (above 600 °C), liquid metals, such as mercury and sodium are used, as reported in the literature [10,11]. For intermediate temperatures, between 300 and 600 °C, organic working fluids and, among them, naphthalene, has being considered as a suitable fluid [12–14] and has been applied in many heat exchangers in China. Although used naphthalene is hardly mentioned in classical books [15–18]. Naphthalene can chemically react with the case metal, generating non-condensable gases (NCG), which accumulate on the extreme condenser regions, reducing the heat transfer capacity of the thermosyphon. Not many theoretical and experimental works deal with the thermal performance of naphthalene thermosyphons, especially those concerning the presence of NCG.

Heat pipe or thermosyphon heat exchangers have been designed, tested and are operating in many countries around the world [14,19,20]. A software for the thermal design of these equip-

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doi:10.1016/j.ijheatmasstransfer.2010.03.041

Nomenclature

A	tube cross section area (m^2)
d	diameter (m)
h	coefficient of heat transfer ($W/m^2\,K$)
H	condenser length (m)
K	thermal conductivity (W/m K)
l	length (m)
N	number of moles
P	pressure (Pa)
R	thermal resistance (°C/W)
$\mathfrak{R}$	ideal gas constant
T	temperature (°C, K)

Subscripts

0	initial condition
adiab	adiabatic
c	cross section
cond	condensation
eff	effective
env	environment
evap	evaporator
ext	external
f	fluid
int	internal
max	maximum
NCG	non-condensable gas
pc	cooling system wall
pool	pool
v	vapor
w	wall
water	water

ment was developed by Borges et al. [21], which takes into account the thermal resistances associated with the evaporation and condensation phenomena that happens inside the thermosyphon and the convection heat transfer that happens outside the evaporator and condenser section of the device. The coefficients of heat transfer used to estimate the thermosyphon internal evaporation and condensation resistances are obtained from literature correlations, which are based on experimental data, usually developed for working fluids such as water, alcohols, ammonia, etc. For the determination of outside thermosyphon convection heat transfer, literature correlations for cross flow tube bundle arrays [22] are applied. Actually, the thermal resistances associated with the external heat transfer mechanisms are usually much larger than the internal resistances. Therefore, the geometry and the number of thermosyphons are much more dependent on the capacity of the thermosyphon tube bundle to absorb and reject heat in the evaporator and condenser regions then the capacity of the tubes to transfer this heat. In these softwares, the overall internal thermosyphon resistance is estimated using the analogy between electrical and thermal circuit [23] models. These models present very good results for water, methanol, acetone and other well known working fluids. But almost no comparison of traditional models with moderate–high temperature working fluids, such as naphthalene, is found in the literature.

The influence of NCG in the thermal performance of thermosyphons is very important information to be considered for the design of heat exchangers. NCG results from deficiencies in the fabrication process (low vacuum inside the tube before charging, gasses or impurities dissolved in the working fluid, etc.) or due to the chemical reaction of the working fluid and case material.

Several theoretical models for the prediction of heat transfer behavior of heat pipes and thermosyphons can be found in the literature. Some of them take into account the presence of NCG. The level of complexity of these models varies from simple (electric analogy) to sophisticated two dimensional models, which considerers the presence of a non-flat vapor–NCG front in the condenser, usually solved using numerical methods. Obviously the complex models describe the physical phenomena with greater precision than the simple ones, but they are far more computational time consuming, being in many applications unsuitable for implementation in heat exchanger design softwares.

The main objective of the present paper is to study theoretical and experimentally the thermal performance of naphthalene thermosyphons, operating in several temperature levels, without and with the presence of NCG. Data obtained from an especial experimental apparatus, able to control simultaneously the heat power input and the thermosyphon temperature, are compared with the present model. The thermal behavior of this experimental apparatus is also modeled. Therefore, the present paper addresses the question of whether literature models developed for and compared with conventional working fluids can also be applied to naphthalene thermosyphons, with or without NCG. For the present study, a simple 1D model, based on the electric/thermal analogy, applicable to heat exchanger design softwares, is developed for the prediction of the thermal behavior of naphthalene thermosyphons.

2. Literature review

2.1. Thermosyphon modeling

The electrical and thermal analogy model has been widely applied for steady state conditions [18,23,24] in thermosyphons. Many papers in the literature study the condensation and evaporation processes inside thermosyphon condensers and evaporators. Most of the condensers theoretical works are based on the Nusselt classical model for vapor condensation over a vertical wall [25]. Two different regions are observed in the evaporator: the thin film and the pool. For the film region, models based on Nusselt evaporation, similar to those used for the condenser, were developed [26]. For the pool region, pool boiling evaporation theory is applied [25]. The models are compared with data and, as a result, model based correlations were obtained, which are used for the prediction of the coefficients of heat transfer for the evaporation and condensation inside the thermosyphon. Most of the experimental data used for correlations are based on water, but working fluids such as alcohols, ammonia and acetone were also tested. These models and correlations were implemented in the software developed for the design of heat exchangers [20,21], which has been used successfully for water thermosyphon equipment.

Although the condenser region plug effect of NCG in heat pipes and thermosyphons are similar, the condensation heat transfer phenomena are quite different for both devices, so that models developed for heat pipes cannot be directly applied for thermosyphons. The presence of NCG inside heat pipes was investigated along the years, mainly for the study of the thermal behavior of variable conductance heat pipes, which are usually applied for the thermal control of spacecrafts and satellites [15–18].

Edwards and Marcus (1972) [27] developed a 1D model for the prediction of the heat transfer in heat pipes with NCG. They observed that, in steady state conditions, there is a smooth decrease