INTERNATIONAL JOURNAL OF REFRIGERATION 67 (2016) 259–270

Available online at www.sciencedirect.com

ScienceDirect

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

Experimental heat transfer coefficients of pool boiling and spray evaporation of ammonia on a horizontal plain tube

José Fernández-Seara *, *Ángel A. Pardiñas*, *Rubén Diz*

Área de Máquinas y Motores Térmicos, E.T.S. de Ingenieros Industriales, University of Vigo, Campus Lagoas-Marcosende N 9, 36310 Vigo, Spain

A R T I C L E   I N F O

Article history:
Received 5 November 2015
Received in revised form 25 February 2016
Accepted 27 February 2016
Available online 4 March 2016

Keywords:
Spray evaporation
Pool boiling
Ammonia
Experimental heat transfer coefficients

A B S T R A C T

We have determined experimentally both spray evaporation and pool boiling heat transfer coefficients, using ammonia and titanium plain tubes, to compare both processes and to contribute to the existing database. In the paper we have detailed the experimental equipment used and the methodology followed. We have also exposed the data analysis process followed to obtain spray evaporation or pool boiling heat transfer coefficients from the experimental data measured and we present and discuss the results obtained.

Spray evaporation heat transfer coefficients depend on heat flux and on the refrigerant film flow rate. At the high heat flux range, spray evaporation heat transfer coefficients decrease with decreasing film flow rates, suggesting the existence of dry patches, which we confirmed visually. Spray evaporation is particularly beneficial at the low heat flux range studied. Under certain conditions of high heat flux, pool boiling outperforms spray evaporation due to the heat transfer coefficient deterioration caused by dry patches.

Coefficients expérimentaux de transfert de chaleur en ébullition libre et en évaporation par aspersion d'ammoniac sur un tube lisse horizontal

Mots clés : Évaporation par aspersion ; Ébullition libre ; Ammoniac ; Coefficients expérimentaux de transfert de chaleur

1. Introduction

Studies on climate change and ozone depletion from the 1970s and 1980s of the past century, such as those from Charney et al. (1979) or Farman et al. (1985), marked the beginning of a great concern in the scientific community about environment and energy efficiency. The measures adopted to stop and revert the situation, included in the international treaties of Montreal and Kyoto and their later revisions, concern refrigerants such as

* Corresponding author. Área de Máquinas y Motores Térmicos, E.T.S. de Ingenieros Industriales, University of Vigo, Campus Lagoas-Marcosende N 9, 36310 Vigo, Spain. Tel.: + 34 986 812605; Fax: + 34 986 811995.

E-mail address: jseara@uvigo.es (J. Fernández-Seara).

http://dx.doi.org/10.1016/j.ijrefrig.2016.02.019

Nomenclature

Roman symbols

A	area [m^2]
c_p	specific heat capacity of the liquid [J kg^{-1} K^{-1}]
d	diameter [m]
EF	enhancement factor [dimensionless]
f	Darcy–Weisbach friction factor [dimensionless]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	tube length [m]
LMTD	logarithmic mean temperature difference [K]
$\dot{m}$	mass flow rate [kg s^{-1}]
P	pressure [Pa]
Pr	Prandtl number [dimensionless]
q	heat flow [W]
R	thermal resistance [K W^{-1}]
Re	Reynolds number [dimensionless]
T	temperature [K]

Greek symbols

Δ	difference
Γ	film flow rate per side and meter of tube [kg s^{-1} m^{-1}]

Subscripts and superscripts

boiler	boiler
evap	evaporator
hw	heating water
i	inner
in	inlet
l	liquid
o	outer
out	outlet
ov	overall
pb	pool boiling
SH	superheating
sp	spray
t	tube
w	wall

CFCs, HCFCs and HFCs, widely used in refrigeration and air conditioning equipment. Natural refrigerants remain as the main alternative for these applications. According to Lorentzen (1988), ammonia, a natural refrigerant, is almost unbeatable by any other in terms of thermodynamic and transport properties. Thus, it is worthy in industrial equipment to face its drawbacks: toxicity, flammability and material compatibility. Reducing the charge is a solution to minimise their effect (Bolaji and Huan, 2013) and spray evaporators fulfil this condition.

Spray evaporators in refrigeration systems are heat exchangers with shell-and-tube structure. In contrast with flooded evaporators, in which the tube bundle is immersed in a pool of liquid refrigerant, falling film evaporators use spray nozzles or other devices to spread liquid refrigerant on the bundle. The refrigerant that remains liquid after one row of tubes falls to the next and so on. The excess of liquid refrigerant, distributed to minimise dry patch appearance, is collected at the bottom of the evaporator and returns to the distribution system.

Spray evaporators, also known as falling film evaporators, have been widely employed in petrochemical industry, desalination processes and OTEC (Ocean Thermal Energy Conversion) systems. The experience in other fields such as heat pumps and refrigeration is limited, but according to Ayub et al. (2006), the use of spray (falling film) evaporators instead of pool boiling evaporators is justified from the points of view of refrigerant charge reduction, heat transfer improvement and equipment size.

Comprehensive reviews on spray evaporation and on its comparison with pool boiling are those from Ribatski and Jacobi (2005), Fernández-Seara and Pardiñas (2014) or Abed et al. (2015). The studies from Moeykens and Pate (1994) and Roques and Thome (2007), developed with R134a on tubes of different outer geometries, compare the heat transfer performance of pool boiling and spray evaporation. The main conclusion from these works is that spray evaporation enhances heat transfer as long as there is a correct refrigerant distribution that prevents dryout. The higher the percentage of dry areas on the tube, the lower the average heat transfer coefficient on the tube, since the local heat transfer coefficients of dry areas are negligible (Habert and Thome, 2010). The number of studies on spray evaporation of ammonia in the literature is limited, and we remark those from Zeng and Chyu (1995). The authors stated that spray evaporation heat transfer coefficients in a tube bundle are up to 50% greater than under pool boiling. They also affirmed that, the lower the saturation temperature, the closer spray evaporation and pool boiling heat transfer coefficients are.

Shell-and-tube heat exchangers working with ammonia as refrigerant are normally made of carbon steel or stainless steel. However, titanium is becoming frequent when corrosion is an issue, such as for marine applications. In addition, titanium has greater resistance to erosion than steel, allows increasing the velocity of the fluid through the tubes and reducing the inner thermal resistance (Ayub, 2004). Besides, the density of titanium is half that of steel and it is possible to reduce importantly the weight of heat exchangers.

The objective of this work is to contribute to the database of spray evaporation and pool boiling heat transfer coefficients of ammonia on titanium horizontal tubes, using an experimental test rig that allows isolating the boiling process and controlling the conditions very accurately, as well as discarding the effect of oil. In this paper, we explain the experimental test rig used and the experimental procedure followed. We thoroughly describe the data analysis process to calculate the heat transfer coefficients from the experimental data, and we show and discuss the results obtained. We support some of these explanations with photographic material obtained during the experiments.