Applied Thermal Engineering 102 (2016) 513–519

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

The impact of filling level resolved: Capillary-assisted evaporation of water for adsorption heat pumps

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HIGHLIGHTS

- Novel experimental setup to study continuously varying filling levels is presented.
- Heat transfer coefficients are experimentally determined.
- Influencing factors on transfer coefficients for coated finned tubes are analyzed.
- Macro-/microscopic structures (fins/coatings) and their combination are compared.
- Heat transfer coefficient is increased 11-fold by combining fins and coatings.

ARTICLE INFO

Article history:
Received 15 January 2016
Accepted 12 March 2016
Available online 21 March 2016

Keywords:
Film evaporation
Filling level
Capillary action
Water
Adsorption chiller
Adsorption heat pump

ABSTRACT

Evaporation of water at low pressures is usually limited by low heat transfer coefficients. Poor heat transfer can severely restrict the performance of cooling devices such as adsorption heat pumps and chillers. The heat transfer can be enhanced by using structures such as fins and porous coatings. These structures provide capillary action to wet the heat exchanger tubes surface with a thin water film leading to high heat transfer coefficients. Hence, the evaporation performance strongly depends on the thickness of the thin water film and consequently on the filling level of the heat exchanger. In this work, the evaporation performance is investigated systematically for horizontal copper tubes with macroscopic fin structures, microporous coatings and the combination of both structures. In particular, an experimental setup is introduced to study continuously varying filling levels. The influence of evaporation temperature and heat flow on the heat transfer coefficient is studied. The heat transfer is found to depend strongly on the filling level and the temperature, whereas the heat flow has no significant influence at the studied measurement conditions. It is shown that the heat transfer is directly proportional to the tube surface wetted by capillary action. The evaporation performance of thermally-coated tubes can reach heat transfer coefficients similar to falling film evaporators. Thus, the presented tube structures allow for improved evaporator designs for future adsorption heat pumps using water as refrigerant.

1. Introduction

Adsorption-based energy systems can provide efficient heating and cooling by using low temperature solar or waste heat sources [1,2]. Possible applications include adsorption-based storage [3], heat pumps [4] and chillers [5]. Besides improving efficiency, current research aims at increasing the specific cooling power (SCP). To achieve high SCP values, compact and light components with good heat transfer characteristics are crucial. Next to the adsorber itself the second most important component for high SCP values is the evaporator [6].

The evaporator determines the vapor pressure in the adsorption process. The pressure level in the evaporator directly affects the kinetics and the maximum loading of the adsorption process. Thus, poor evaporators can drastically limit the performance of adsorption-based energy systems [7,8].

Evaporation is particularly challenging for water, the most commonly used refrigerant in adsorption chillers [9,10]: At common evaporation temperatures of 5–10 °C water vapor pressures are very low and therefore the favorable mechanism of nucleate boiling requires high wall superheat of up to 20 K [11–14]. To avoid the efficiency losses due to large temperature differences, nucleate boiling can usually not be exploited. Instead, natural convection determines the heat transfer resulting in low heat transfer

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http://dx.doi.org/10.1016/j.applthermaleng.2016.03.052

Nomenclature

A	tube reference surface (m^2)
A_f	tube reference surface depending on the filling level (m^2)
c	heat capacity (J/(kg K))
C	constant (–)
d_i	inner tube diameter (mm)
d_o	outer tube diameter (mm)
f	filling level in the evaporator (–)
h_i	inner heat transfer coefficient (W/(m^2 K))
h_o	outer heat transfer coefficient (W/(m^2 K))
H_f	fin height (mm)
L	tube length (m)
$\dot{m}$	mass flow (kg/s)
p	pressure (mbar)
Pr	Prandtl number (–)
$\dot{Q}$	heat flow (W)
Re	Reynolds number (–)
T_{in}	evaporator water circuit inlet temperature (°C)
T_{out}	evaporator water circuit outlet temperature (°C)
T_s	steam temperature (°C)
U	overall heat transfer coefficient (W/(m^2 K))
U_f	overall heat transfer coefficient considering A_f as reference surface (W/(m^2 K))
$\dot{V}$	evaporator water circuit volume flow (m^3/s)
γ	angle (rad)
δ_f	fin thickness (mm)
$\Delta_{vap}h$	enthalpy of vaporization (W/kg)
Δ_f	fin distance (mm)
$\Delta_{ln}T$	logarithmic mean temperature difference (K)
η_{bulk}	dynamic viscosity at the mean temperature of the fluid (kg m/s)
η_{wall}	dynamic viscosity of the fluid at the wall (kg m/s)
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
$\sigma_{\Delta T_i}$	uncertainty of the measured temperature differences (K)
σ_U	uncertainty of the overall heat transfer coefficient (W/(m^2 K))
$\sigma_{\dot{V}}$	uncertainty of the volume flow (m^3/s)

Subscripts

Cu	copper
vap	vaporization
f	fin
i	inner
in	inlet
o	outer
out	outlet
s	steam
w	water

Abbreviations

CP	coated plain
CF	coated finned
max	maximum
SCP	specific cooling power
UP	uncoated plain
UF	uncoated finned

coefficients. As a consequence, evaporation requires large surfaces, reducing the SCP of the cooling device.

To enhance the heat transfer, several researchers proposed macroscopic structures such as fins [15] and microscopic structures such as coatings [16]. Finned tubes are already used in adsorption heat pumps [17]. These structured surfaces provide capillary action generating a thin water film on the evaporator surface, which increases the evaporation performance. For fin structures, this effect can be investigated analytically [18,19], whereas for porous coatings mainly experimental investigations have been performed [16,20]. Xia et al. [15] and Schnabel et al. [21] showed for discrete filling levels that both kinds of structures can lead to significant improvement of the evaporation process.

In this work, macroscopic and microscopic structures for heat transfer surfaces are systematically investigated. A promising thermal coating is presented which greatly improves the heat transfer. Preliminary data has been shown in a conference presentation [22]. We resolve in detail the performance of coated finned tubes as a function of the filling level of the evaporator. A key contribution of this work is the introduction of a novel experimental setup to resolve the impact of the filling level continuously. The measurements with continuously resolved filling level show that the heat transfer coefficient increases strongly with lower filling level. The optimal filling level is precisely identified and allows exploiting the full potential of the structured heat exchangers in adsorption chillers. We further analyze the active heat transfer area and the impact of evaporation temperature and of heat flow on the heat transfer coefficient. The measurements show that the heat transfer coefficient depends on the temperature whereas the heat flow has no significant influence.

In Section 2 we present the investigated heat exchangers and the novel experimental setup. In Sections 3 and 4, we compare different structures and provide a detailed analysis of the most promising heat exchanger. In Section 5, the results are summarized and conclusions are presented.

2. Materials and methods

2.1. Investigated heat exchangers tubes

Four heat exchanger tubes made of copper are investigated in this study (Fig. 1). As reference for the investigated microscopic and macroscopic structures, an ordinary uncoated plain (UP) tube

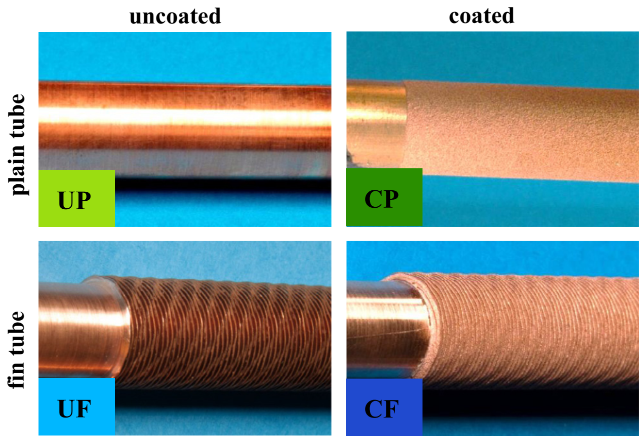

Fig. 1. Photos of the investigated tubes: the uncoated plain tube (UP) and uncoated finned tube (UF) on the left and the coated plain tube (CP) and coated finned tube (CF) on the right.