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Heat and mass transfer enhancement for falling film absorption with coated distribution tubes at high temperature

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ABSTRACT

This paper experimentally studied the characteristics of the vertically falling film absorption outside a brass tube with different circumferential coating patterns at high temperature. The effects of spraying liquid density and inlet temperature of solution on heat and mass transfer are investigated. The results show that the heat transfer coefficient of falling film absorption increases with the increase in the spraying liquid density of solution; the mass transfer coefficient of falling film absorption increases initially, and then decreases with the increase in spraying liquid density of solution. The heat and mass transfer coefficients of falling film absorption increase with the increase in the inlet temperature of LiBr solution and the operation temperature. With the same spraying liquid density and the inlet temperature of LiBr solution, the overall heat transfer coefficient of the circumferential coated division tube is higher than that of the bare brass tube; however, the mass transfer coefficient of the circumferentially coated division tube is lower than that of the bare brass tube.

1. Introduction

The continued rising of energy demand and global warming is remarkably attracting the attention of governments and academic communities around the world. Energy efficiency, reducing energy consumption per unit output has become the focus of world's energy strategy. The absorption heat transformer (AHT) mainly driven by waste heat source for low grade energy reuse after ascending temperature is an energy conservation and environmental protection technology and has a broad market and application prospect [1–6]. However, practical industrial applications of AHT are limited in the past few decades because the operating temperature is usually less than 150 °C. In industry, particularly in oil-refinery and steel plants, there is a large amount of waste heat at high temperature even more than 200 °C. Therefore, the most important aspect for AHT at present is to explore techniques for operating at higher temperature range, which could upgrade the waste heat at higher temperature for industrial applications directly. Chen et al. [7] experimentally investigated the corrosion of stainless steel in LiBr solution at 150–200 °C and prepared a Fe/Cr dropped SiO_2 thin film to improve the anticorrosion characteristic of SUS304 stainless steel at higher temperature [8]. Hao et al. [9] installed a prototype of 5 kW high temperature absorption heat transformer operating with water/lithium bromide mixture. The experimental system is operated at the temperature of 150–205 °C, the gross temperature lift of the system is over 40 °C. The corrosion phenomenon is insignificant due to the usage of surface anti-corrosion technology [7,8]. The experimental results show that the COP and Q_a increase with the increase of the evaporating temperature, and increase firstly and then decrease with increasing the absorbing temperature and the generating temperature, and decrease with the increase of GTL.

Absorber is the most important component in absorption system and its characteristics significantly influence the whole system efficiency. Heat and mass transfer modes of absorption can be mainly classified into two types: the falling film mode and the bubble mode. Falling film absorption has been widely used due to its high heat transfer rate and small temperature difference. Surfactant agent and novel configuration tube are commonly used to enhance the performance of falling film absorption process. Yang and Jou [10,11] carried out numerical simulation on the falling film flow in porous medium for the enhancement of absorption process. Miller and Blanco [12] experimentally studied the falling film absorption with different kinds of enhanced tubes, including pin-fin tube, grooved tube, helix tube and petal tube. The heat and mass transfer coefficients of the falling film absorption are enhanced considerably. The pin-fin tube with 6.4 mm pitch increases the mass absorbed by about 225% over a smooth tube and a grooved tube is the second best performance with 175% enhancement over a smooth tube. Yin et al. [13] experimentally studied the falling-film absorption for water-lithium bromide systems on the vertical enhancement tubes. They found that the existence of low-ribs, fins and the leaning channels intensifies the Marangoni

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Nomenclature

A	heat transfer area (m^2)
a	heat transfer coefficient ($W\,tm^{-2}\,K^{-1}$)
b	thickness of tube (m)
c_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
d	diameter (m)
h	enthalpy ($kJ\,kg^{-1}$)
K	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
K_m	mass transfer coefficient ($m\,s^{-1}$)
m	mass flow rate ($kg\,s^{-1}$)
p	vapor pressure (Pa)
Δq	mass flow rate of absorption vapor ($kg\,s^{-1}$)
Q	heat capacity (kW)
R	gas constant ($J\,mol^{-1}\,K^{-1}$)
Re	Reynolds number
T	temperature (°C)
ΔT_m	logarithm mean temperature difference (°C)
u	velocity ($m\,s^{-1}$)
x	concentration (wt% LiBr)

Greek symbols

Γ	mass flow rate per unit of wetted perimeter ($kg\,tm^{-1}\,s^{-1}$)
μ	viscosity of the solution (Pa s)
ρ	density ($kg\,m^{-3}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)

Subscripts

i	inside
o	outside
s	LiBr solution
1	inlet
2	outlet

effect and increases the surface area of tubes. Fujita [4] experimentally studied the characteristics for a falling film absorber with smooth tubes which was twined with metal wire in the same distance. The results showed that the wavy liquid film caused by the tube patterns is attributed to the higher heat and mass transfer performance. The flow characteristic of liquid film on the circumferentially coated division tube demonstrated that the thickness and wave amplitude of falling liquid film increase with the increase in the spraying liquid density [15,16]. And the liquid film flows through a bare region and then is retained and accumulated at the boundary of the coated and uncoated regions due to the different wettability and a thicker, uneven liquid ring is observed at the boundary.

In the present work, the experiments of falling film absorption at the high temperature are conducted on the outside vertical tube surfaces using bare brass tubes and circumferentially coated division tubes. The effects of the spraying liquid densities and the inlet temperatures of LiBr solution on the performance of heat and mass transfer are presented. The enhancement mechanism of falling film absorption process is discussed by comparing the heat and mass transfer coefficients between the circumferentially coated division tube and the bare brass tube.

2. Experimental set-up

The schematic diagram of the experimental set-up used in the present study is shown in Fig. 1. It consists of two principle components, namely, absorber and generator, and has the instrumentations for temperatures, concentrations and flow rate measurement. The main components of the experiment system are made of 304 stainless steels in order to avoid corrosion. The generator works as a boiling pool and a 10 kW electrical heater is immersed in the solution at the bottom of the generator. The absorber consists of a 160 mm outer diameter stainless steel tube and a test tube with 19 mm outer diameter. LiBr solution flows in the annular space and the oil flowed inside the test tube. All test tubes are 1500 mm long with 19 mm outer diameter and 14 mm inner diameter. A solution distributor is mounted right above the tube banks in the absorber.

The fluorocarbon coating layers of polytetrafluoroethylene (PTFE) [14] are used in the present study for preparing the hydrophobic surface and the length of the coating layer is 10 mm. The Contact angle is measured using the OCAH200 contact angle measurement system (Dataphysics Corp., Germany) with an uncertainty of 0.1° to determine the surface wettability. The static contact angles and the advancing contact angles of water on PTFE coating layers are 110° and 128°, respectively. The coating thickness is measured by the BYKO-test 7500 coating thickness measurement gauge (BYK Corp., Germany) with the uncertainty of ±2% + 1 μm. The coating thickness is about 30 μm. Details of preparation method of the coated division tubes are referenced to the report by Zhou [14] and Wang et al. [15,16]. The bare brass tube and two types coated tubes are shown in Fig. 2.

The weak LiBr solution in the generator is heated to boil and the refrigerant (water) in the solution is vaporized. After then, the strong LiBr solution at the bottom of the generator is pumped to the absorber by the strong solution pump. From the solution distributor, the strong LiBr solution falls downward along the outside surface of the vertical tube as liquid film pattern, while the oil is circulating inside the tube as coolant to remove the absorption heat. The water vapor is absorbed into the strong LiBr solution film. Finally, the weak LiBr solution that leaves at the exit of the absorber goes to the generator.

The vacuum pump is used to achieve the vacuum requirement and remove the non-absorbable gases from the system. A quantity of LiBr solution at 55 wt% and predetermined quantity of oil is charged in the generator and the oil tank. Then the electrical heater in the generator is turned on to increase the LiBr solution temperature which is adjusted by a voltage regulator. The flow-rate of water vapor entering the absorber is controlled by a motor-operated adjusting valve. To circulate the strong LiBr solution into the absorber, the strong solution pump is started. The oil pump is also turned on to circulate the oil through the absorber. At last, the weak solution pump is started to pump the weak solution into the generator. The flow rate of LiBr solution was controlled by a magnetic coupling gear pump. The system achieves a steady state when the variations of the measured parameters are less than ±0.3% for at least 30 min [6]. The measured pressure, temperature and flow rates at steady conditions are recorded.

The solution flows rate is measured with two metallic conduit float flow meters with an accuracy of ±1.5% of full scale. A metallic conduit float flow meter with a read accuracy of ±2.5% of full scale is used to measure the oil flow rate. The temperatures of LiBr solution, oil and water vapor are measured by Pt100 platinum resistance thermometers with an accuracy of ±0.1 °C. The pressure in the absorber is measured using a digital pressure gauge with an