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ORIGINAL ARTICLE

Heat and mass transfer through spiral tubes in absorber of absorption heat pump system for waste heat recovery

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Received 15 November 2016; accepted 10 March 2017

KEYWORDS
Absorption heat pump;
A single spiral tube;
Heat and mass transfer;
Lithium bromide/ water;
Film heat transfer coefficient;
Mass transfer coefficient;
Waste heat recovery

Abstract Heat and mass transfer of a LiBr/water absorption heat pump system (AHP) was experimentally studied during working a heating-up mode. The examination was performed for a single spiral tube, which was simulated for heat transfer tubes in an absorber. The inside and outside of the tube were subjected to a film flow of the absorption liquid and exposed to the atmosphere, respectively. The maximum temperature of the absorption liquid was observed not at the entrance but in the region a little downward from the entrance in the tube. The steam absorption rate and/or heat generation rate in the liquid film are not constant along the tube. Hence the average convective heat transfer coefficient between the liquid film flowing down and the inside wall of the tube was determined based on a logarithmic mean temperature difference between the tube surface temperature and the film temperature at the maximum temperature location and the bottom. The film heat and mass transfer coefficients rose with increasing Reynolds number of the liquid film stream. The coefficients showed opposite trend to the empirical correlation reported for laminar film flow on a straight smooth tube in a refrigeration mode in the past work. The fact can be caused due to a turbulent promotion effect of the liquid in a spiral tube.

1. Introduction

Absorption heat pump (AHP) is known as a representative heat-deriving type of refrigerator, and has been already led to commercialization. However, the AHP system recovering

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Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

http://dx.doi.org/10.1016/j.jppr.2017.05.004
2212-540X

Please cite this article as: Yoshinori Itaya, et al., Heat and mass transfer through spiral tubes in absorber of absorption heat pump system for waste heat recovery, Propulsion and Power Research (2017), http://dx.doi.org/10.1016/j.jppr.2017.05.004

Nomenclature

A	surface area (unit: m^2)
D_f	diffusivity (unit: m^2/s)
d	diameter (unit: m)
G	mass flow rate of solution (unit: kg/s)
g	acceleration of gravity (unit: m/s^2)
h_f	film heat transfer coefficient (unit: $W/(m^2 \cdot K)$)
h_a	heat transfer coefficient outside tube (unit: $W/(m^2 \cdot K)$)
k	thermal conductivity (unit: $W/(m \cdot K)$)
L_f	characteristic length given by Eq. (12) (unit: m)
$\dot{m}$	vapor absorption rate (unit: kg/s)
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate or enthalpy transfer rate (unit: W)
Q_e	latent heat of evaporation per unit time (unit: W)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (unit: K)
$\Delta T_{\ln}$	logarithmic mean temperature difference (unit: K)
U	overall heat transfer coefficient (unit: $W/(m^2 \cdot K)$)

Greek letters

β_c	mass heat transfer coefficient (unit: m/s)
Γ	parameter defined by Eq. (9) (unit: $kg/(s \cdot m)$)
μ_f	viscosity (unit: $Pa \cdot s$)
ρ_f	density of solution (unit: kg-solution/m^3)
ξ	concentration of solution (unit: kg/kg-solution)
$\bar{\xi}$	average concentration (unit: kg/kg-solution)
$\Delta\xi_{\ln}$	logarithmic mean concentration difference (unit: kg/kg-solution)

Subscripts

1–7	location in Figures 1 and 2
f	solution
i	inlet of tube
in	inside of tube
o	outlet of tube
out	outside of tube
sat	saturation condition
w	wall of tube

exhausted heat has not widely spread over industrial application at the present time because the system is complicated. If an innovative AHP is developed to recover exhaust heat at a low temperature level up to 80–90 °C and to work in the both modes of refrigeration and heating up over 100 °C with a sufficient efficiency, it will contribute greatly to energy conservation as well as heat demand for various purposes like drying, washing, chemicals can be compensated from exhaust heat without consuming little fuel. AHP in a heating-up mode was evaluated analytically in the past [1,2]. Recently some attempts have been done experimentally to develop AHP for an alternative boiler utilizing exhaust heat at 90 °C level [3–5]. Kawakami et al. [6], Nakaso et al. [7] and Nakagawa et al. [8] studied a heat pump system to generate steam over 150 °C from the heat source of hot water exhausted in a level as low as 80 °C in a bench-scale setup. Their system consisted of dehumidifier, LiBr/water AHP and zeolite/water adsorption heat pump. High temperature steam yields by evaporation during adsorption of water supplied at 80 °C directly into the zeolite bed in the adsorption heat pump. Zeolite is regenerated by dry hot air over 120 °C passing through the bed. The hot air is generated by heat exchange of dry air in absorber of AHP working in a heating-up mode after dehumidification. Performance of the AHP in this system has been reported by Marumo et al. [9] that air can be successfully heated up to 130 °C in the absorber from hot water at 80 °C and the coefficient of performance (COP) based on the pump power for flowing fluids was beyond 25 when the enthalpy of a LiBr solution at absorber exit was recovered simultaneously as steam. They employed a bundle of spiral tubes made of copper in the absorber in this AHP. The solution absorbs water vapor from evaporator on a film flowing down along the inside wall of the tubes and the temperature of the solution rises while air is heated during flowing around the tubes in the bundle. Heat exchange takes place between the solution and air through the wall of the tubes. Then the pattern of the temperature profiles of the liquid and air in the absorber is supposed to be different from conventional heat exchangers. The maximum temperature of the solution or the hot fluid side may lie not at the inlet of the tubes but appear at a location downward from the inlet because heat generation occurs inside the tubes due to vapor absorption into the solution. This fact means that the concept of logarithmic mean temperature difference could not be always adopted appropriately for estimation of heat exchange rate as done in conventional ones. However, such a heat transfer mechanism in the absorber has not been sufficiently known and the concept of the average temperature difference

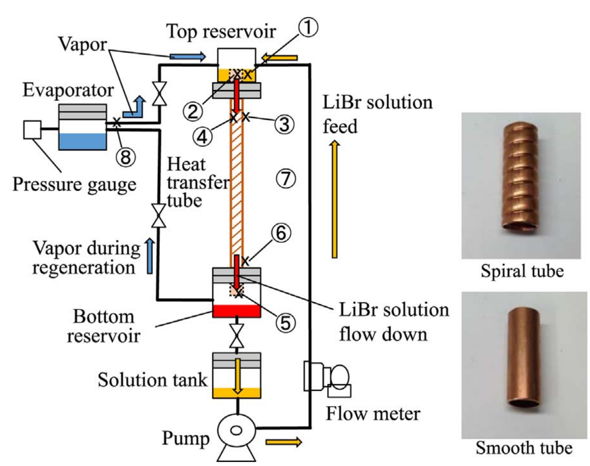

Figure 1 Experimental setup for examination of heat transfer of a single tube in absorber and heat transfer tubes tested.

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