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Energy and exergy analyses on the off-design performance of an absorption heat transformer

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ABSTRACT

Absorption heat transformers (AHTs) have great potential in utilization of low-level heat sources, such as industrial waste heat. However, the operation of an AHT is limited by heat sources, customer load, and cooling water. However, such conditions may change in practical applications. Thus, research on the off-design performance of an AHT is important and necessary. In this paper, mathematical models for the cycle and components of a vertical falling film AHT operating with water/lithium bromide solution were developed. The coefficient of performance, output heat capacity, and exergy efficiency were used to evaluate the performance of the AHT. Furthermore, the exergy loss distribution diagrams under off-design conditions were carried out, and the exergy loss ratio was decomposed into several factors to determine why exergy loss ratio varies under off-design conditions. Finally, exergy loss ratio in the solution heat exchanger plays an important role under off-design conditions, which is analyzed thoroughly. A kind of effective adjustment is studied and proven to be effective in improving the performance of the AHT. The present work provides a tool for thoroughly understanding the mechanism of performance change in the AHT under off-design conditions.

1. Introduction

The demand for energy is sharply increasing with economic development. According to the BP Statistical Review of World Energy [1], global energy consumption has increased by 5.6% in 2010, the strongest growth since 1973. On the other hand, the emergence of the energy and environmental crises indicated that energy resources should be utilized more efficiently. Huge amounts of industrial waste heat at temperatures between 70 and 100 °C are wasted daily.

Absorption heat transformers (AHTs) have received considerable attention in terms of the utilization of industrial waste heat and numerous other kinds of low-level heat resources, such as solar energy and geothermal heat, because of its specific capability to increase the temperature of heat sources from a low to a high and more useful level.

Energy analysis is important in studying AHT. Siqueiros et al. [2,3] studied the increase in the coefficient of performance (COP) of heat transformers in water purification systems with and without increasing heat source temperature. Horuz and Kurt [4,5] developed a computer code to study the effect of different parameters on the performance of the single- and double-stage AHT systems and concluded that a lower condenser temperature and higher evaporator and generator temperatures may result in higher COP and absorber heat capacity.

Exergy analysis is very effective in studying AHTs. Based on exergy analysis, exergy utilization may be derived and the location of the occurrence of exergy loss occurred can be identified. Gomri [6,7] conducted an exergy analysis for a seawater desalination system integrated into a solar heat transformer operating with lithium bromide/water, as well as a comparative study between single- and double-effect AHT systems used for seawater desalination. The results showed that the energy and exergy efficiencies of the double-effect AHT were higher than that of the single-effect AHT. Enthalpy , external, and exergy COPs, as well as exergy destruction or irreversibility in the system and its components, along with improvement potential were calculated by Rivera et al. [8,9] against the gross temperature lift and the primary operating temperatures of an experimental single-stage AHT operating with a lithium bromide/water mixture. The energy level (A) presents the quality of energy well, and the difference in energy levels between energy donor and acceptor results in the exergy loss during the energy process. Ishida and Ji [10] used the concept of energy levels and energy-utilization diagrams to analyze a single-stage AHT. The

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Nomenclature

c_p	the heat capacity of the liquid (kJ/kg)
d	diameter or equivalent diameter of the tube (m)
D	the mass diffusion coefficient of water in water/lithium bromide solution (m^2/s)
f	friction factor
g	gravitational acceleration (m/s^2)
hg	heat of absorption, or generation (kJ/kg)
ID	inner diameter
OD	outer diameter
k	heat transfer coefficient ($kw/m^2/k$)
m	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
r	vaporization heat of water (kJ/kg)
Re	Reynolds number
SHX	solution heat exchanger
u	velocity of the fluid in the flow direction (m/s)
v	velocity in the y direction (m/s)
X	mass concentration of the LiBr/water solution (%)

Subscripts

A	absorber
c	at Re = 2100
C	condenser
E	evaporator
G	generator
h	heat carrier (hot water, cooling water, heating water, or solution in the solution heat exchanger)
f	film
l	laminar regime
s	saturated
t	turbulent regime
w	wall

Greek symbols

μ	viscosity of the liquid film (pa s)
ν	kinematic viscosity (m^2/s)
λ	thermal conductivity of the liquid film (W/k/m)
δ	thickness of the film (m)
ρ	density of the liquid film (kg/m^3)
Γ	solution spray density (kg/m/s)

results showed that the exergy loss in the premixing process in an absorber is significantly large. To reduce this loss, a multiple-compartment absorber in close-to-equilibrium operation was proposed to generate high temperatures for useful heat.

Vertical falling film AHTs have been studied and successfully applied in industrial processes, thereby generating a large number of economic and social benefits. Inoue et al. [11] reported that the simplification of a unit and the improvement of heat transfer performance can be realized using a tube-side falling film design, wherein the temperature of the output heat can reach 200 °C. Ma et al. [12] reported test results for the first industrial-scale AHT equipment in China in terms of recovering the water heat released from a mixture of steam and organic vapor at 98 °C in the coacervation section of a synthetic rubber plant. The recovered heat was used to heat water from 95 to 110 °C. The results showed that the mean COP was 0.47, that a gross temperature lift of 25 °C can be realized, and that the payback period was approximately 2 years.

A large number of numerical studies have been conducted to investigate the vertical falling film of a water/lithium bromide solution. Numerous assumptions and mathematical models for vertical falling films of a water/lithium bromide solution in a laminar regime were developed, and the distribution of temperature, concentration, and heat and mass transfer coefficients were obtained [13–15]. Experimental studies have been also performed to investigate vertical falling film of a water/lithium bromide solution. Matsuda et al. [16,17] studied the effect of different solution rates, column lengths, solution concentrations, and pressure on the absorption (evaporation) rate and mass and heat transfer coefficients of falling film.

Most simulation work of AHTs just focused on the parameters of the cycle. And the components of the AHT were considered as black boxes. The exergy loss distribution of an AHT in off-design conditions has been rarely studied. Furthermore, the reason for the occurrence of exergy loss distribution variation is also rarely reported.

The present paper investigates the off-design performance of a single-effect vertical falling film AHT operating with water/lithium bromide. The mathematical models are developed to simulate and calculate the heat and mass transfer process of the components of the AHT. Such simulation and calculation connect the cycle parameters with the parameters of an external medium well, such as heating source or cooling water. Moreover, the exergy loss distribution of each component under off-design conditions is studied to find the key component which primarily affects the off-design performance of AHT. In addition, we decompose the exergy loss ratio into several factors to find which factor primarily causes the variation of the exergy loss ratio under off-design conditions.

2. Description of the AHT cycle

A schematic diagram of a vertical falling film AHT is shown in Fig. 1. AHT has two cycles, namely, the solution and refrigerant cycles. First, the solution cycle is shown as the bold line in Fig. 1. The weak water/lithium bromide solution from the absorber is cooled in the solution heat exchanger by the strong water/lithium bromide solution and then throttled using a throttle valve. The solution then flows into the generator and falls on the vertical tube. The film of the solution is heated by the hot water 03 to generate vapor. The strong solution from the generator is pumped into the solution heat exchanger and then sprayed into the adiabatic absorber, where the solution absorbs vapor adiabatically for saturation. The saturated solution flows into the absorber and falls on the vertical tube. The film of the solution on the tube absorbs the vapor from the evaporator and releases heat to hot water 07. Second, the refrigerant cycle is shown as the dashed line in Fig. 1. The vapor generated from the generator is cooled by cooling water 05 and is then condensed in the condenser. Then, the liquid refrigerant is pumped into the evaporator, where it is heated by the heating water and consequently evaporates into vapor. The vapor is then absorbed in the adiabatic absorber and subsequently absorbed by the strong solution.

Unlike an absorption heat pump (AHP), the absorber and evaporator of an AHT are in the high-pressure level, whereas the generator and condenser are in the low-pressure level. This condition makes the temperature of the absorber the highest in the AHT cycle. Thus, the purpose of the AHT is to obtain heat with higher temperature. On the other hand, the purpose of an AHP is to obtain a greater amount of heat. Falling film absorbers, generators, evaporators, and condensers may provide good heat and mass transfers and produce minimal pressure loss. The advantages of the components of a vertical falling film are the generation