International Journal of Heat and Mass Transfer 127 (2018) 196–205

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Direct-coupled desorption for small capacity ammonia-water absorption systems

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ARTICLE INFO

Article history:
Received 4 April 2018
Received in revised form 21 June 2018
Accepted 24 June 2018

Keywords:
Absorption cycles
Ammonia-water desorption
Waste heat recovery
Heat and mass transfer model

ABSTRACT

An investigation of direct gas-coupled desorption for small capacity ammonia-water absorption is presented. Some applications favor or require the use of direct-coupling of the heat source for desorption; therefore, a systematic treatment of this topic is needed for the optimal design of small-capacity absorption systems. Gas-coupled desorption is accomplished through diabatic distillation, and an optimal gas side geometry is established. Gas side optimization considers pressure drop minimization as well as geometric constraints such as column diameter and number of gas tubes. A heat and mass transfer model is developed and validated with experiments. Excellent internal vapor purification is achieved and the results agree well with the heat transfer and pressure drop predictions. These results demonstrate the applicability of direct-coupled desorption to small-capacity ammonia-water absorption systems. A comparative assessment with indirect-coupled desorption components is also made.

1. Introduction

Heat sources for absorption chillers and heat pumps are often available in the form of hot gas, e.g., waste heat streams. For some systems, it is beneficial to directly couple the hot gas stream with the desorber, i.e., the component in the absorption system that utilizes heat to generate refrigerant vapor. This facilitates system size and weight reduction as well as minimization of exergy destruction. Small-capacity systems, in particular, require the development of novel and compact heat exchangers to ensure their technological and economic feasibility. Waste heat is inherently dispersed and its sources are often small-capacity systems. Engine waste heat recovery for refrigerated trucking or diesel generator exhaust utilization for space conditioning in military forward operating bases are representative examples. While waste heat recovery is a strong motivation for the development of compact and effective direct-coupled desorption components, direct-fired systems also benefit. Absorption systems that are directly driven by the combustion of a fuel such as natural gas or biofuels rely on both, radiative and convective heat transfer. The former takes place in the combustion chamber but the latter requires a relatively large heat transfer area and dictates the size and weight of the combustion-desorption assembly. Effective gas-coupled desorption concepts can be adapted to include a close-coupled combustion chamber and reduce overall system size and weight.

Studies in the literature are typically limited to steady-state simulations and focus on the thermodynamic feasibility of waste heat utilization. Cao et al. [4] provide a summary of recent and representative investigations related to waste heat recovery from shipping vessels. Talbi and Agnew [26] offer a comparative simulation study of various configurations of cooling use from an absorption system driven by diesel engine waste heat. It was found that a combination of engine cooling and space conditioning optimizes waste heat recovery and emphasizes the potential of small-capacity absorption systems.

Very few experimental studies of waste heat driven absorption systems are available in the literature. Horuz [10] coupled a commercially available 10 kW cooling capacity, natural gas fired ammonia-water absorption system to a 6 L diesel engine. Only minor modifications to the desorber were required for waste heat utilization. While the feasibility of waste heat utilization was demonstrated, the investigation showed that engine performance was reduced due to increased backpressure and additional control capability is required to respond to variation in waste heat availability. Kren [13] provides a comprehensive study of flue gas-fired absorption chillers, which includes an experimental investigation of a large-capacity water/lithium bromide system with a gas burner capacity of 315 kW. The balance between gas-side pressure drop and gas-side heat transfer coefficient is

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.118
0017-9310/

Nomenclature

A	area, m^2
AAD	absolute average deviation
AD	absolute deviation
c_P	specific heat capacity, $kJ\,kg^{-1}\,K^{-1}$
CR	circulation ratio
$LMTD$	logarithmic mean temperature difference, K
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
NPS	nominal Pipe Size
Nu	Nusselt number
P	pressure, kPa
$\dot{Q}$	heat duty, kW
R	thermal transfer resistance, $K\,W^{-1}$
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature, °C
U	overall heat transfer coefficient, $W\,K^{-1}\,m^{-2}$
UA	overall heat transfer conductance, $W\,K^{-1}$
x	ammonia concentration (mass basis)

Greek symbols

α	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
Φ	optimization parameter
Δ	difference
η	efficiency

Subscripts/superscripts

cs	concentrated solution (high ammonia concentration)
des	desorber
ds	dilute solution (low ammonia concentration)
gas	natural gas or heat source gas stream
hot	desorber dilute solution outlet state point
i	segment, state point or frame number
in	inlet
L	liquid state
opt	optimal
out	outlet
pur	purification
ref	refrigerant
total	total
V	vapor state
wall	wall
I	first-law based
II	second-law based
*	thermodynamic equilibrium

discussed and an optimization criterion is proposed as shown Eq. (1). It is suggested that geometric variation of a heat exchanger design concept will result in a local maximum of this criterion, which can guide optimal heat exchanger design.

$$\Phi = \frac{\alpha_{gas}}{\sqrt{\Delta P_{gas}}} \tag{1}$$

In the present study, a gas-coupled desorber concept for ammonia-water absorption systems is presented. The design uses diabatic distillation for small-capacity applications, i.e., cooling capacities less than 10 kW. Design considerations and parameters on the gas side and solution side are discussed. An optimization study in which pressure drop constraints and geometric considerations are evaluated to optimize gas side geometry is conducted. A heat and mass transfer model is developed for performance prediction. A prototype desorber is fabricated and performance is evaluated in an ammonia-water absorption test facility. Results show better-than-predicted component performance and validate the suitability of this design for small-capacity ammonia-water absorption applications. The application of this design for a packaged waste heat recovery chiller for military application is discussed as an example case.

2. Design Concept, considerations and conditions

The proposed design uses diabatic distillation, which is thermodynamically favorable compared to conventional ammonia-water desorption designs, including separate heat input and adiabatic distillation stages [12]. In this approach, heat input is distributed throughout the component and integrated with vapor purification stages. This also allows for the design of more compact components compared to the conventional design of a reboiler in combination with an adiabatic column. Fig. 1 shows the conceptual component layout and flow pattern. The design relies on liquid/vapor countercurrent flow. Concentrated solution enters the column at the top and dilute solution leaves the column at the bottom. Vapor is generated throughout the component. Hot gas tubes span the height of the component for heat source distribution. The component consists of a multitude of trays with pool boiling and bubble regions. Liquid enters the pool region through the downcomer. Trays in the pool region are joined to the hot gas tubes to create a liquid pool and provide heat transfer area. Solution flows over the weir into the bubble region, where vapor from lower trays passes through annuli formed between the tray and gas tubes. Bubbling of vapor through built-up liquid achieves vapor generation and purification. A more detailed review of desorber designs and a description of the proposed design is available in [24].

Several design considerations govern the optimal configuration. Gas-side optimization is particularly important and is the focus of this paper. The primary objective is to minimize pressure drop while maximizing heat transfer coefficients. The key independent parameters are gas-side tube diameter and number of tubes. The design problem is further constrained with the secondary objectives to minimize the number of tubes to reduce tube-wall joints, improve economic viability and facilitate fabrication. However, the bubble region of the tray relies on liquid-vapor interaction in the annuli formed between the tubes and trays. This necessitates a larger number of tubes to minimize the possibility of flooding and flow reversal. Also, the lowest feasible component shell size is sought. This reduces shell wall thickness requirements given the linear relationship between shell diameter and hoop stress. Finally, it is advantageous to minimize overall component height to limit overall system size.

Solution-side design is based on the component geometry determined by the gas-side constraints. Solution-side considerations include number of trays, weir height, and cross-sectional area of tube-tray annuli in the bubble region of the tray. The solution-side design methodology and associated hydrodynamic limitations are discussed by Staedter et al. [24].

Desorber operating conditions are listed in Table 1. Typical pressure and concentrated solution conditions are chosen. Dilute solution temperature is based on thermodynamically optimal performance [23].