International Journal of Heat and Mass Transfer 127 (2018) 209–223

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Hydrodynamic considerations and design concepts for optimal thermal compressors

Marcel A. Staedter, Khoudor Keniar, Srinivas Garimella *

Sustainable Thermal Systems Laboratory, GWW School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States

A R T I C L E I N F O

Article history:
Received 1 April 2018
Received in revised form 21 June 2018
Accepted 21 June 2018

Keywords:
Absorption cycles
Ammonia-water desorption
Hydrodynamic limitations
Flow visualization
Diabatic distillation

A B S T R A C T

Novel and highly compact design concepts for the desorber and rectifier components are presented to facilitate development of small capacity ammonia-water absorption systems for a wide range of applications. These designs enable thermodynamically optimal diabatic distillation and can be applied for direct-coupled waste heat recovery applications or for indirect heat source coupling. A hydrodynamic design methodology is developed and applied to address liquid–vapor countercurrent flow limitations. Feasibility of these designs is validated through air-liquid flow visualization experiments that simulate target flow patterns. The effects of geometric parameters and fluid properties are investigated to specify internal component features and dimensions. Parameters for coupled heat and mass transfer modeling of these designs are identified and quantified through high-speed video analysis. The results of this study guide the design and further development of highly compact and efficient desorption components for optimal thermal compressors.

1. Introduction

In thermally activated vapor absorption cooling and refrigeration cycles, the mechanical compressor of the vapor compression cycle is replaced with a set of heat and mass exchangers and a liquid pump. This is commonly referred to as the thermal compressor. Its key components are the absorber, the desorber and a recuperative heat exchanger, the solution heat exchanger. In the case of ammonia-water absorption systems (AAS), an additional vapor purification stage, i.e., a rectification stage, is added to the desorber. Research focus on improved absorber designs has resulted in increased heat and mass transfer fluxes and more compact components [28] that address the limitations of the absorber to the overall system, i.e., the system “bottleneck” [4]. However, additional research focus on the desorber and rectifier components is required to ensure optimal design and operation of the thermal compressor based on the following design criteria:

1. Optimal exergy utilization of heat input
2. High purity vapor generation
3. Compact component size
4. Flexible and reliable operation and control

The first criterion ensures optimal utilization of the driving heat source, allowing applications with low heat source temperatures and optimal primary energy utilization. Refrigerant vapor purity is of critical importance for many applications of AAS [6]. Fernandez-Seara and Sieres [13] quantify the detrimental effect of reduced purification performance of the desorber and rectifier on overall system performance. Hence, optimal thermal compressor design must allow for highest possible overall AAS performance, which requires delivery of high purity refrigerant to the remainder of the cycle, the simple cooling cycle (SCC). Highly compact components with simple geometries designed for manufacturing feasibility are of particular importance for small capacity applications. This enables economically feasible system designs with low weight and small envelopes [17]. Optimal thermal compressor design must also accommodate a range of operating conditions and reliable operation with flexible control schemes at part load operation.

Typical AAS designs use a conventional fractioning columns approach for desorption and rectification. Bogart [6] provides an overview of this approach as applied to AAS and identifies typical hydrodynamic challenges such as liquid entrainment and carry-over into the SCC. Anand and Erickson [3] present a design methodology for adiabatic sieve-tray columns applied to small capacity AAS to determine hydrodynamic limits and mass transfer efficiencies. Fernández-Seara et al. [15] developed a coupled heat and mass transfer model for a packed column and Sieres and

---

* Corresponding author at: Georgia Institute of Technology, GWW School of Mechanical Engineering, Love Building, Room 340, 801 Ferst Drive, Atlanta, GA 30332, United States.

E-mail address: sgarimella@gatech.edu (S. Garimella).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.109

Nomenclature

A	area [m^2]
a	specific area [m^2 m^{-3}]
AAS	ammonia-water absorption system
C	Wallis parameter [–]
CCFL	countercurrent flow limitations
D	diameter [m]
E	error [–]
E0	distilled water
E60	fluid with 60% *wt.* ethanol and 40% *wt.* distilled water
Fr	Froude number [–]
g	gravitational acceleration [m s^{-2}]
j	superficial velocity [m s^{-1}]
L	length [m]
m	Wallis parameter [–]
Mo	Morton number [–]
Oh	Ohnesorge number [–]
SCC	simple cooling cycle
U	velocity [m s^{-1}]
V	volume [m^{-3}]
$\dot{V}$	volumetric flow rate [m^3 s^{-1}]

Greek

γ	generic exponent variable [–]
Δ	difference [–]
δ	film thickness [m]
ε	gas holdup [–]
Θ	generic hydrodynamic variable [–]
λ	generic scaling variable [–]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]

Subscripts/superscripts

B	bubble
c	characteristic
G	gas phase
h	hydraulic
i	inner
in	inlet
int	interface
k	phase
L	liquid phase
o	outer
out	outlet
S	sauter diameter
$tray$	tray
x	cross section
$*$	modified superficial velocity

Fernández-Seara [36] present an experimental investigation of mass transfer characteristics of a structured packing in an AAS adiabatic column. Few deviations from the conventional column design have been reported. Various rectification column configurations in combination with the conventional reboiler and stripping sections are compared by Fernandez-Seara et al. [14]. Partial condensation with internal heat recovery through the concentrated solution was shown to be thermodynamically most favorable. More recently, designs that deviate from conventional kettle type reboiler designs have been developed for small capacity applications. Determan and Garimella [12] present a small capacity falling film type desorber and a coupled heat and mass transfer model with experimental validation. Delahanty et al. [11] present a design that employs heat source coupling through microchannels for application in 3.5 kW cooling capacity AAS.

Further development of the desorber is presented here with the introduction of two novel, highly compact design options that remove the need for a separate stripping section and address all of the design criteria discussed above. A wide range of applications is addressed by developing two designs for various types of heat source integration, e.g., direct gas coupled, and coupling through the use of a heat source coupling fluid flowing through microchannel geometries. A microchannel based design concept for the rectifier component is also presented. It is suitable for close-coupled integration with both desorber concepts discussed here.

Successful implementation of these designs depends on the feasibility of specific hydrodynamic flow conditions, i.e., liquid-vapor countercurrent flow, which have inherent limitations such as flooding and weeping. In contrast to conventional hydrodynamic evaluations of adiabatic columns, the distribution of vapor generation along the height of the diabatic column results in significant variation of vapor flow rates. Therefore, relevant geometric variables are identified for each design and a hydrodynamic design methodology is developed to specify optimal geometries. An experimental evaluation is conducted and hydrodynamic feasibility of the proposed designs is demonstrated. In addition, parameters relevant for the development of a detailed heat and mass transfer model are identified and quantified through a high-speed video analysis of flow visualization experiments. The results of this investigation can be applied to the development of components based on the proposed design concepts.

2. Design concepts

In the concepts considered here, diabatic distillation is employed, where the heat source and vapor generation are integrated with vapor purification stages. The thermodynamic advantage of this approach is discussed in general terms by Kotas [23]. The benefits of this design approach to AAS are shown by Staedter and Garimella [37]. Exergy destruction caused by temperature differences between the heat source and the working fluid can be minimized through targeted distribution of heat transfer area that achieves matching of the heat source temperature profile to that of the zeotropic mixture undergoing a boiling process. This also reduces heat source temperature requirements. Integration of vapor purification within each heat transfer stage allows for the lowest possible vapor temperatures leaving each stage, which is determined by the tray efficiency. Proper design allows for a close approach of vapor temperature leaving the desorber to that of the concentrated solution feed in the top tray. This eliminates the need for an analyzer section, i.e., no dedicated stripping column is required. This approach is therefore conducive to highly compact component designs.

The first design, Concept A, is a microchannel based desorber as shown in Fig. 1. A coupling fluid delivers heat from a generic heat source to the component through a microchannel assembly. The solution-side assembly consists of liquid-vapor countercurrent flow paths formed by trays. Each tray has three distinct regions: