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A Review of Heat and Mass Transfer Analysis for Absorption Process

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Key words: Heat and mass transfer, Bubble absorption, Falling film absorption, Absorption system

ABSTRACT: The absorber in which heat and mass transfer phenomena occur simultaneously is one of the most critical components in the absorption system. It has the most significant influence on the performance and the size of the absorption system. During the absorption process, heat and mass transfer resistances exist in both liquid and vapor regions, so that the heat transfer mode should be carefully selected to reduce them. The objective of this paper is to review the previous papers analysing mathematical models of simultaneous heat and mass transfer phenomena during the absorption process. The most conventional working fluids (H_2O/LiBr and NH_3/H_2O) are considered and the most common absorption modes (falling film and bubble mode) are dealt with in this review.

Nomenclature

b : gap [m]
c : molar concentration [kmol/kmol]
d : diameter [m]
D_A : diffusivity [m^2/sec]
H : height [m]
L : length [m]
l : liquid
N : molar flux [kmol/m^{2}sec]
Re : Reynolds number
Sc : Schmidt number
Sh : Sherwood number
T : temperature [K]
u : velocity [m/sec]
$\bar{u}$: average stream-wise velocity [m/sec]
u_t : terminal velocity [m/sec]
v : vapor
w : wall
z : composition of ammonia in absorbing vapor [kmol/kmol]

Greek symbols

α : thermal diffusivity [m^2/sec]
δ : film thickness [m]

1. Introduction

An absorption refrigeration system is a very prospective alternative to the vapor compression refrigeration system to solve the environmental problems. It does not provoke depletion of the ozone layer since natural refrigerants, such as NH_3 and H_2O, are used as the working fluids. Moreover, the absorption system can be driven by thermal energy, so that the utilization of absorption system can reduce CO_2 emission. In addition, the waste heat from the industrial processes can be reused as an energy source for the absorption system.

Although an absorption system has such many advantages, the vapor compression system is

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still the foremost system in the refrigeration marketplaces owing to a higher efficiency. However, due to the environmental problems, the usage of CFCs and HFCs will be prohibited in 2030 through the international agreements, such as the Montreal protocol and the Kyoto protocol. Therefore, the application of the absorption system which uses the natural refrigerants has been strongly recommended to solve the environmental problems.

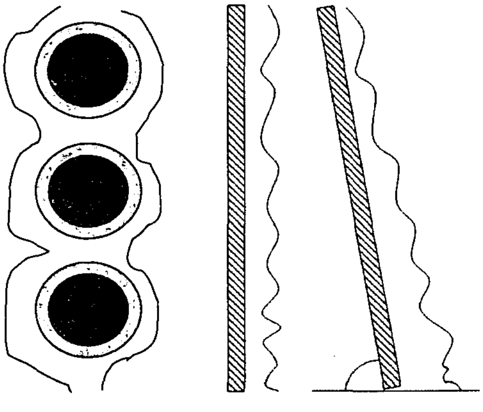
The absorber in which heat and mass transfer phenomena occur simultaneously is one of the most critical components in the absorption system. It has the most significant influence on the performance and the size of the absorption system. During the absorption process, heat and mass transfer resistances exist in both liquid and vapor regions, so that the heat transfer mode should be carefully selected to reduce them.

The objective of this paper is to review the previous papers analysing mathematical models of simultaneous heat and mass transfer phenomena during the absorption process in the absorption refrigeration system. The most conventional working fluids (H_2O/LiBr and NH_3/H_2O) are considered and the most common absorption modes (falling film and bubble mode) are dealt with in this paper.

2. Falling film type absorption process

A falling film type absorber is widely used for both NH_3/H_2O system and H_2O/LiBr system due to its potential for high heat and mass transfer rates with minimal pressure drops. Therefore, a lot of researches have been carried out to analyze the falling film type absorption process. In the H_2O/LiBr system, the vapor is pure water in the absence of non-absorbable gases because LiBr is essentially nonvolatile. In contrast, both NH_3 and H_2O can volatilize in the NH_3/H_2O system, so it is possible that mass transfer resistance exists in the vapor phase. Figure 1 shows the typical flow configurations for the falling film mode; horizontal tube bank and vertical or inclined surface. Figure 2 shows the representative profiles of temperature and concentration during the falling film type absorption process.

Grossman(1) solved the following equations with the assumptions of the fully developed laminar flow for the falling film absorption mode.



(a) Horizontal tube bank (b) Vertical or inclined surface

Fig. 1 Typical flow configurations for the falling film mode.

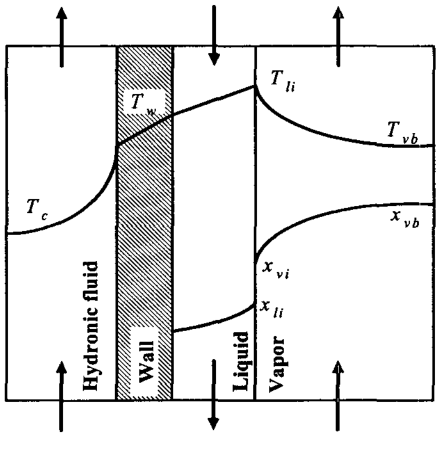


Fig. 2 Temperature and concentration profiles during typical falling film type absorption process.

$$u\frac{\partial T}{\partial x}=\alpha\frac{\partial^2 T}{\partial y^2} \tag{1}$$

$$u\frac{\partial c_A}{\partial x}=D\frac{\partial^2 c_A}{\partial y^2} \tag{2}$$

$$u(y)=\frac{3}{2}\bar{u}\left[2\left(\frac{y}{\delta}\right)-\left(\frac{y}{\delta}\right)^2\right] \tag{3}$$

where α is thermal diffusivity, δ film thickness, u stream-wise velocity, and $\bar{u}$ the average stream-wise velocity. He solved the problem by the Fourier method to find a series expansion solution. He also used a numerical technique based on the finite difference methods and developed a similarity solution for the concentration and temperature within the film for the range where the thermal effect of the wall does not reach the interface, which means the constant interfacial temperature and concentration.

Conlisk(2) solved temperature and mass fraction problems for a H_2O/LiBr falling film absorber. Min and Choi(3) developed the Navier-Stokes procedure to investigate the absorption phenomena about the free-falling film flow on a horizontal tube. They found that the surface tension played a key role in dictating the flow field especially when the flow rate is low. It is well known that falling films are inherently unstable, even at low Reynolds numbers. This instability induces the growth of waves on the film surface. Therefore, many researchers have analyzed wavy flows on the H_2O/LiBr falling film surface.(4-9) Killion and Garimella(10) reviewed the mathematical models of the combined heat and mass transfer in falling-film type absorption process.

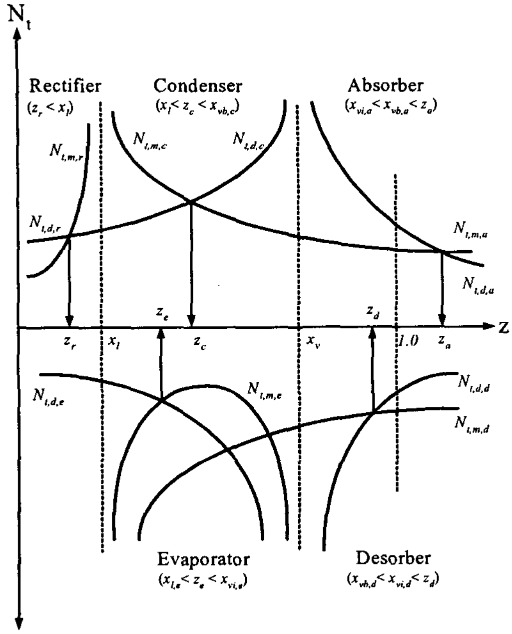


Fig. 3 Composition map for the ammonia-water absorption system.(12)

Although NH_3/H_2O systems have been studied longer than H_2O/LiBr systems, the state-of-the-art for the modeling techniques are not as well developed as those for H_2O/LiBr systems. As mentioned above, the vapor entering an absorber contains binary gases in NH_3/H_2O system. Therefore, mass transfer resistance in vapor phase should be considered in NH_3/H_2O system. Colburn and Drew(11) suggested the modeling method for considering vapor phase mass transfer resistance. However, the analytical models with the Colburn-Drew method neglect the liquid-phase mass transfer resistance. Kang et al.(12) suggested a generalized model to design NH_3/H_2O absorber by applying the Colburn-Drew method. They proposed a z-map to analyze the direction of heat transfer and mass transfer. The z factor is the composition of NH_3 in absorbing vapor and defined as Eq. (4).

$$z=\frac{N_{NH_3}}{N_{NH_3}+N_{H_2O}} \tag{4}$$

From the definition of z factor, it can be inferred that H_2O is desorbed into the vapor region if z becomes larger than 1.0 while NH_3 vapor is absorbed into the liquid if z is less than 1.0. The absorbed vapor composition, z-map proposed by Kang et al.(12) is presented in Fig. 3. The map shows the ranges of z for each component of the absorption system.

Grossman and Gommed(13) developed a theoretical model for the film absorption in the presence of non-absorbable gases and analyzed the effect of non-absorbable gases on the simultaneous heat and mass transfer process. Perez-Blanco(14) developed a model for the absorption of NH_3 into a falling film on coiled tubes. The model used the assumed transfer coefficients for each transport process in the absorber. Potnis et al.(15) used a modified Colburn-Drew method for analyzing a coiled, fluted tube NH_3/H_2O GAX absorber. Absorption occurs on the outside of the coiled tubes with falling film flow around the tubes. In their model, it was not assumed that the liquid film is fully mixed. Instead they estimated the mass transfer coefficient in the falling film from heat and mass transfer analogies.

3. Bubble type absorption process

Bubble absorption mode has been studied in chemical engineering for years, with the objective of designing compact and inexpensive gas-liquid contacting equipment.(16) Bird et al.(17) employed a simple film model to predict the gas absorption rate from a rising spherical bubble. The molar flux from the bubble interface is given as

$$N_i = \sqrt{\frac{4DU_t}{\pi d}}\, c_{io} \tag{5}$$

where c_{io} is the molar concentration of species i at the bubble interface and U_t the bubble terminal velocity. Though it is simple in its form, this result has been experimentally substantiated for gas bubbles of about 0.3~0.5 cm in diameter rising through purified water. However, heat transfer was not considered in their study.

Ferreira et al.(18) developed a model for calculation of simultaneous heat and mass transfer processes in vertical tubular bubble absorbers as used for NH_3/H_2O absorption systems. The objective of their research was to find the overall heat transfer coefficient and the overall mass transfer coefficient. They suggested the empirical correlation of modified Sherwood number as Eq. (6).

$$\mathrm{Sh} = \exp(0.86307)\,\mathrm{Re}^{0.853}\,\mathrm{Sc}_L^{0.50}\left(\frac{H}{d}\right)^{-1.00} \tag{6}$$

where Sh is the Sherwood number, Re the Reynolds number, Sc_L the liquid phase Schmidt number, z absorption height, and d internal diameter of absorber tube. However, local values for important parameters such as temperature and concentration could not be obtained from their study.

Herbine and Perez-Blanco(19) described a design model of the absorption process in an NH_3/H_2O bubble absorber with a vertical tube.

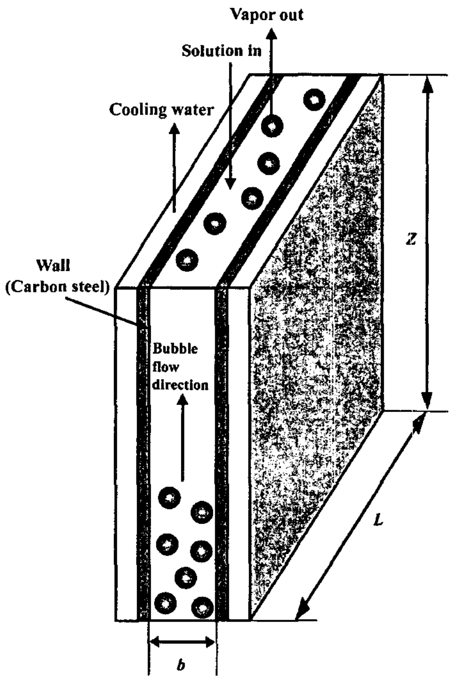


Fig. 4 Schematic diagram of the bubble type plate absorber.

They obtained one dimensional temperature and concentration profiles along the absorber length using empirical correlation for local overall heat and mass transfer coefficients from literature. In the design model, the mass transfer resistance inside the bubble was neglected.

Kang et al.(20) developed a design model for a bubble absorber by using a combined heat and mass transfer analysis. They considered the heat and mass transfer resistance both in the liquid region and inside the bubble by solving diffusion and mass balance equations simultaneously. Kang et al.(21) analyzed a combined heat and mass transfer for an NH_3/H_2O absorption process and found that the mass transfer resistance was dominant in the liquid flow while the heat transfer resistance was dominant in the vapor region for bubble absorption mode. Figure 4 shows the schematic diagram of bubble type plate absorber.

Merrill et al.(22) analyzed the compact bubble absorber with three passive heat transfer enhancement techniques: roughness, spiral flutes, and internal spacers. They designed the bubble absorber by the boundary-layer theory approach. Sujatha et al.(23) analyzed a co-current flow vertical bubble absorber by the finite element method. Merrill and Perez-Blanco(24) described the subcooled liquid temperature and concentration fields surrounding a collapsing bubble by the finite difference method.

Staicovici(25) developed the model of NH_3 bubble absorption by combining classical equilibrium phenomenological theory with non-equilibrium phenomenological theory. He found that the NH_3/H_2O absorption process was not a

Table 1 Summary of the reviewed researches

Absorption mode	Authors	Subject
Falling film mode	Grossman(1)	Simultaneous heat and mass transfer in the laminar flow
	Conlisk(2)	Temperature and mass fraction problem
	Min and Choi(3)	To develop the Navier-Stokes procedure on a horizontal tube
	Kim and Cho,(4) Jeong and Garimella,(5) Killion and Garimella,(6) Uddholm and Setterwall,(7) Yang and Wood,(8) Patnaik and Perez-Blanco(9)	To analyze wavy and droplet flows
	Colburn and Drew(11)	To develop the modeling method for considering vapor phase mass transfer
	Kang et al.(12)	To suggest a generalized model
	Grossman and Gommed(13)	To consider the presence of non-absorbable gases
	Perez-Blanco(14)	To analyze for coiled tube
	Potnis et al.(15)	To consider coiled fluted tubes
Bubble mode	Ferreira et al.(18)	Simultaneous heat and mass transfer process
	Herbine and Perez-Blanco(19)	Bubble absorber with a vertical tube
	Kang et al.(20,21)	Combined heat and mass transfer analysis
	Staicovici(25)	To consider the non-equilibrium phenomenological theory
	Merrill(26)	Thermally controlled bubble collapse

surface phenomenon but a mass phenomenon. Merrill(26) studied the thermally controlled bubble collapse in binary solutions. He predicted bubble mass transfer rates for an NH_3/H_2O system and found that the predicted bubble mass transfer rates increased with the square of the bubble radius and with increasing the absorber cooling rates.

Lee et al.(27) developed mathematical models for bubble mode absorber from the material balance for the gas and liquid phases by neglecting the heat and mass transfer of water from liquid to gas phase. They used the Treybal's correlations(28) to describe bubble diameter and mass transfer coefficient and derived the terminal velocity of bubble from the balance of gravity, buoyant force, and total drag force of the solution. From the terminal velocity of bubble, they described the bubble rising velocity. They finally expressed bubble absorption process based on the differential variation of bubble radius.

4. Conclusions

This paper presents a comprehensive review of selected previous works on the heat and mass transfer during the absorption process. The numerical analyses have been carried out based on the heat and mass transfer modes: falling film type and bubble type. In Table 1, the reviewed papers are summarized for these two modes. For the falling film type, the film flow pattern is the most important parameter. Various researches assumed the film flow pattern to explain the heat and mass transfer characteristics. Especially, in the NH_3/H_2O system, desorption of water from solution to gas should be considered in the falling film type. For the bubble type, the bubble behavior is the most important parameter. Although the bubble type absorber is generally applied to NH_3/H_2O system, desorption of water to the NH_3 bubble can be neglected due to the very fast disappearance of bubble.

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