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Recent Advances on Heat Exchanger-Absorber Design

Fan Y and Luo L*

Laboratoire de Thermique ET Energie de Nantes, University of Nantes, France

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***Corresponding author:** Luo L, Laboratoire de Thermique et Energie de Nantes, University of Nantes, La Chantrerie, Rue Christian Pauc, France, Tel: +33240683167; Fax: +33 240683141; Email: lingai.luo@univ-nantes.fr

Abstract

This paper presents the state-of-the-art and recent advances on the design of integrated heat exchanger-absorbers. A variety of geometries of HEX-absorber have been surveyed and categorized, including horizontal tubes, vertical tubes, plate type and others. A special focus is made on the use of different techniques to intensify the heat and mass transfers.

Keywords: Heat exchanger; Absorption; Heat and mass transfer; Intensification

Abbreviations: HE: Heat exchanger; HMT: Heat and mass transfer

Integrated Heat Exchanger-Absorber

Absorption process is now widely used for solar or waste heat driven cooling or refrigeration applications [1, 2], for heat or cooling transportation over long distance [3] and for solar energy storage [4,5]. The key component in an absorption machine is the absorber where the liquid solution (as absorbent) contacts with and absorbs gas vapor (as absorbent). The heat removal efficiency of the absorption heat determines the absorption rate in the absorber and consequently the global COP of absorption machines. As a result, the integration of absorption and heat exchange functions in a single device, the so called HEX-absorber (also named as absorber-heat transformer), is a natural and reasonable choice.

Table 1: Selected studies on integrated HEX-absorber with heat and mass transfer intensification.

Study	N/E	Geometry/ Dimension	Material	Working Medium	Flow Configuration	Intensification Techniques	Performance Improvement	Thermal compatibility θ (kW·m-3·K-1)
Hoffmann et al. [6]	E	24 horizontal tubes in serpentine	Copper tubes Glass column `	Tube inside: cooling water Tube outside: LiBr film and steam	Countercurrent flow for solution-gas contact Cross-countercurrent for heat exchange	Tube inside: helical rods Tube outside: knurled surface Surfactant additives for the LiBr solution	20% to 42% higher h (film) with knurled tubes compared to plain tubes 60% to 140% higher h (film) with surfactant additives	-
Islam et al. [10]	N/E	24 horizontal tubes d_i=0.017 mm; d_o=0.019 mm; l=160 mm A=0.23 m^2; V=7.94×10-2 m^3	Glass vessel Copper tubes	LiBr solution and steam Cooling water	Countercurrent flow for liquid-gas contact Cross-countercurrent flow for heat exchange	Short copper guiding fins installed between tubes for film inverting	100% increase in vapor absorption rate with the film inverting design compared to conventi onal design	-

Goel and Goswami [12]	N/E	240 horizontal tubes d_i=2.375 mm; d_o=3.175 mm; l=98 mm A=0.24 m^2; V=4.84×10-3 m^3	Aluminum vessel Stainless steel tubes	Ammonia-water solution Cooling water	Countercurrent flow for liquid-gas contact Cross-countercurrent flow for heat exchange	A screen mesh/ fabric stretched in between horizontal tubes Wire diameter of 0.2 mm with 16×16 meshes / inch2	UA value found to increase by about 50%±17% with the introduction of the screen mesh	~103 (with screen mesh) ~72 (without mesh)
Lee et al. [19]	E	24 horizontal tubes in 6 rows and 4 columns d_i=8.1 mm; d_o=9.5 mm; l=292 mm A=0.21 m^2; V=3.53×10-2 m^3	Stainless steel outer shell Stainless steel tubes	Ammonia-water solution Cooling water	Co-current flow for liquid-gas contact Cross-countercurrent flow for heat exchange	-	-	7.7
Curries et al. [7]	E	Single vertical concentric shell and tube d_o=22 mm; l=0.8 m A=0.06 m^2; V=0.3×10-3 m^3	Stainless steel tube Copper shell	Tube side: LiBr solution and steam Shell side: gas	Countercurrent flow for solution-gas contact Countercurrent flow for heat exchange	Tube side: "Heatex" inserts constructed form looped, 22 gauge, stainless wire Shell side: extended surface area 50 times than that of a plain tube	14 times higher heat transfer compared to plain tubes	40
Bourouis et al. [27]	E	Single vertical concentric shell and tube d_i=22.1 mm; l=1.5 m	Stainless steel	Tube side: water-(LiBr+LiI+LiNO3+LiCl) Shell side: cooling water	Countercurrent flow for solution-gas contact Countercurrent flow for heat exchange	LiBr solution with additive	Thermal load and mass absorption flux increased by 28% and 50%, respectively with additive	-
Vallès et al. [9]	E	Plate heat exchanger; CB76L, 60 plates; A=5.5 m^2; V=21.2×10-3 m^3	AISI316	Organic fluid mixtures: methanol-tetraethyleneglycol dimethylether (TEGDME) and trifluoroethanol (TFE)-TEGDME Cooling water	Countercurrent for heat exchange	Independent spray nozzle (spiral, whirljet, hollowjet, fulljet) to spray week solution into the refrigerant vapour	Improved mass transfer by the spray nozzle Limited absorption due to high pressure drop	43.8
Kim and Ferreira [2008]	E	Falling film plate; Single vertical plate (95×540 m2) A=0.051 m^2; V=15.9×10-3 m^3	Glass vessel Copper plate	LiBr solution and steam	Co-current flow for liquid-gas contact Countercurrent flow for heat exchange	Copper wire screen (22 meshes per inch) on plate surface; 2-EH as additive	Heat transfer enhanced by twice, mass transfer enhanced by 2.5 and 3.5 times by additive Marginal enhancement by wire screen	-
Jenks and Narayanan [14]	E	Microchannel HEX-absorber; Cooling side channel dimension: 10×2×0.88 cm3 A=0.002 m^2; V=0.78×10-3 m^3	Polyethere therketone	Ammonia-water solution Cooling water	Crossflow for liquid-gas contact Countercurrent flow for heat exchange	Stainless-steel sintered porous plate (0.5 µm pore size) for gas bubbling Microchannel (smooth or ribbed) for heat exchange	Highest U observed for 400 µm smooth microchannel absorber	~7.7

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Cerezo et al. [15]	E	Bubble plate; model NB51, type L with three plates $A=0.1\ m^2$; $V=1\times10\text{-}3\ m^3$	Stainless-steel	Ammonia-water solution Cooling water	Co-current flow for liquid-gas contact Countercurrent flow for heat exchange	Corrugated plate Bubble injection	h (film) around 2.7-5.5 kW·m-2·K-1 kL around 0.001-0.002 m·s-1	-
Oronel et al. [16]	E	Bubble plate; chevron-L type corrugation; 4 plates making 3 channels $A=0.1\ m^2$; $V=\sim1.1\times10^{-3}\ m^3$	Stainless-steel	NH3/LiNO3 or NH3/(LiNO3+H2O) Cooling water	Co-current flow for liquid-gas contact Countercurrent flow for heat exchange	Corrugated plate Ternary mixture to reduce the viscosity	Mass absorption flux 1.3-1.6 times higher; h (film) 1.4 times higher than those of binary mixture	-
Meacham and Garimella [46]	E	Microchannel array, 660 tubes in total d_i=1.168 mm; d_o=1.575 mm; l=0.137 m $A=0.456\ m^2$; $V=\sim8.2\times10^{-3}\ m^3$	Stainless-steel	Ammonia-water solution Cooling water	Countercurrent flow for solution-gas contact Cross-countercurrent flow for heat exchange	Microchannel array arranged in parallel and in series; Improved dip tray	U~545 to 940 W·m-2·K-1	~41.3
Chen et al. [11]	N	Hybrid hollow fiber membrane HEX-absorber (HFMAE)	Porous fibers for solution gas mixing Nonporous fibers for heat exchange	Ammonia-water	Countercurrent	Higher interfacial area for heat and mass transfers	COP increased by 14.8% and exergy loss reduced by 26.7% when compared to a falling film plate heat exchanger`	-
Olarte-Cortés et al. [17]	E	Graphite disks HEX-absorber 18 tar-impregnated graphite disks, outside diameter=0.1 m; $A=0.18\ m^2$; $V=1.27\times10^{-3}\ m^3$	Stainless-steel for the column tar-impregnated graphite disks	LiBr solution and steam Cooling water	Countercurrent flow for solution-gas contact Countercurrent flow for heat exchange	High thermal conductivity of tar-impregnated graphite (50-80 W·m-1·K-1) Resistance to corrosion and to high temperature	h (film) around 723-1535 W·m-2·K-1 U around 168-317 W·m-2·K-1	~3.44

The transport mechanism in such device involves the contact and mixing between absorbent solution and the absorbat vapor on one hand, and the heat exchange between the solution and the coolant fluid on the other hand. As a result, conjugated and complicated heat and mass transfer occurs in such HEX-absorbers. A variety of geometries of HEX-absorber have been proposed and studied, including horizontal tubes, vertical tubes, plate type and others. Different techniques were employed, as presented in (Table 1) to intensify the heat and mass transfers.

Horizontal Tubes

In horizontal tubes configuration, a fluid distributor is generally installed above the tubes to spray liquid droplets which then flow down by gravity to form liquid film outside the tubes. Vapor is usually generated at the bottom of the shell and then rises and contacts with the liquid film in a countercurrent manner. Coolant fluid circulates inside the tubes to evacuate the absorption heat. Depending on the arrangement of tubes in serpentine [6-8], in parallel (Yoon et al. 2002) or mixed [9-11] the heat exchange could be in cross-countercurrent or in pure cross flow manner.

For this configuration, the wettability of falling film is of great importance to the absorption performance, so that usually structured tube external surfaces are employed [12]. These complex surface structures include finned tubes, knurled tubes [6], micro-scale hatched tubes [13,7], hydrophilic tubes and floral tubes. Most studies reported improved wettability and transfer coefficients with structured surface tubes. However, it is also reported that on the presence of surfactant, the effect of structured surface may be negligible or even negative because it might actually degrade the convective mixing action of the surfactant [12].

Helical coil pipe HEX-absorbers are also proposed as a special case of the horizontal tubes type since the tubes are slightly inclined to the falling film direction [14-18]. Solution usually trickles down as a falling film outside of the coil while the coolant circulates inside the helical coil in concurrent or countercurrent flow [19,20]. The absorber could be operated in different modes, either concurrent or countercurrent flow of refrigerant and solution. It is generally considered that the helical arrangement makes the system more compact compared to the conventional horizontal tubes type.

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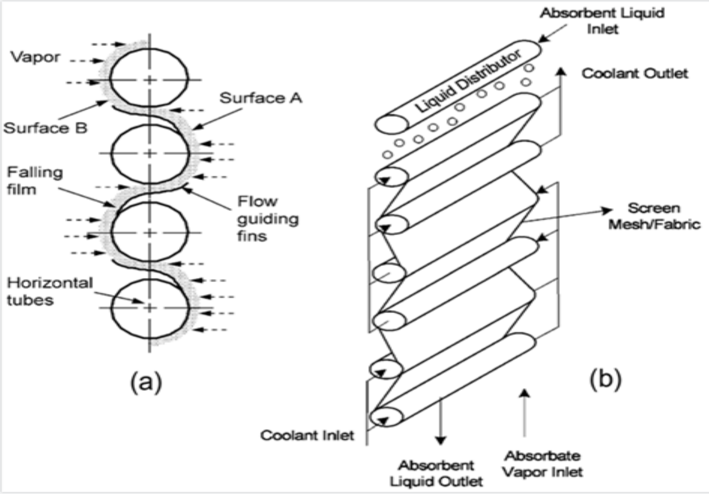

Figure 1: Schematic principle of film guiding devices for horizontal tubes HEX-absorber.

a) Adapted from Islam et al. [8].

b) Adapted from Goel & Goswami [13].

To further augment the transfer surface area, film guiding devices were introduced as shown in (Figure 1) Islam et al. [10] introduced film-guiding fins between tubes to produce a film inverting arrangement. Experimental results showed that the vapor absorption rate with the film inverting arrangement could be doubled compared to that of conventional tubular absorber [21]. Also proposed using a screen mesh/fabric stretched between the horizontal tubes for the establishment of a double sided falling film. The mesh was made of aluminum woven wire, wire diameter being 0.2mm with a density of 16×16 meshes per square inches. Experimental results on ammonia-water absorption [9]. indicated about 50%±17% increase on UA value with the introduction of screen mesh.

Vertical Tubes

In vertical tubes configuration, the falling film of solution can be formed in outer or inner surfaces of tube(s). In the former case [22] the absorbent solution flows down the outside of the inner tube to absorb the upward flowing vapor, while the absorption heat is removed by the upward flow of cooling water inside the tube. In the latter case [23-26]. Falling film is formed inside the vertical tube and the vapor flowing concurrently upward. Cooling water or gas flows upward in annulus (or in shell) to remove the absorption heat. Most of the studies on this configuration employ smooth tube(s), with the exception. who used “Heatex” inserts as turbulence promoter inside the tube and extended external surface area to enhance heat transfer. 14 times higher heat transfer is observed compared to that of plain tubes. When multiple tubes are involved, absorption in bubble mode is recommended for easier vapor distribution than liquid distribution needed in the falling film mode. Moreover, bubble mode doesn’t have wettability problem. In bubble mode, solution and vapor enter at the bottom of the tubes and flow upward concurrently, the liquid-gas two phase flow pattern being successively churn flow, slug flow, and bubbly flow. The coolant could flow in countercurrent manner for concentric tubes [27] or in cross-countercurrent manner in the shell side [28].

Plate-Type

In recent years, plate-type heat exchangers have been used as absorber due to their high compactness and enhanced heat and mass transfer. The solution vapor contact could be realized in falling film mode [29,30] or in bubble mode [31-33]. To improve the performance of absorbers, different surface structures such as wire screen (Kim and Ferreira), micro ribs or fins [34] or corrugated chevrons [31,32] have been applied to the external or internal surfaces of plates. Cui et al. [35] also proposed a film-inverting configuration, analogue to the principle shown in Fig. X, for plate falling film HEX-absorber.

Vallès et al. [36] presented a plate HEX-absorber consisting of a mixing chamber with a spray of solution into the refrigerant vapor. A two-phase mixture was formed and entered into a plate HEX, where the solution is cooled. Different types of spray nozzles were studied, including spiral type, whirl jet type, hollow jet type and full jet type. Improved heat and mass transfer was observed with a thermal compatibility about 43.8 $kW{\cdot}m^{-3}{\cdot}K^{-1}$.

Novel Designs

Garimella et al. [37-39] developed a micro channel arrays heat and mass exchanger for absorption application. The novel miniaturized device consists of short lengths of micro channels arranged in multiple square arrays, with successive arrays oriented transversely perpendicular to the adjacent

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arrays as shown in (Figure 2). Vapor generated at the bottom of the device flows upward countercurrent to the solution in falling film outside the micro channels. Coolant flows through individual tubes in arrays, from bottom to the top of the device in cross flow-countercurrent manner to the solution. Due to the small size of the micro channels, the tube-side heat transfer coefficient is extremely high while the pressure drop is relatively low because of the parallel arrangement. Experimental results with ammonia-water absorption showed an overall heat transfer coefficient of about 133 to 403 W·m-2·K-1 [38]. Further enhancement could be achieved by improved wettability of the falling film (U~545 to 940 W·m-2·K-1, [39]). or by a modified dripper tray and a rotated orientation (U~540 to 1160 W·m-2·K-1, [37]).

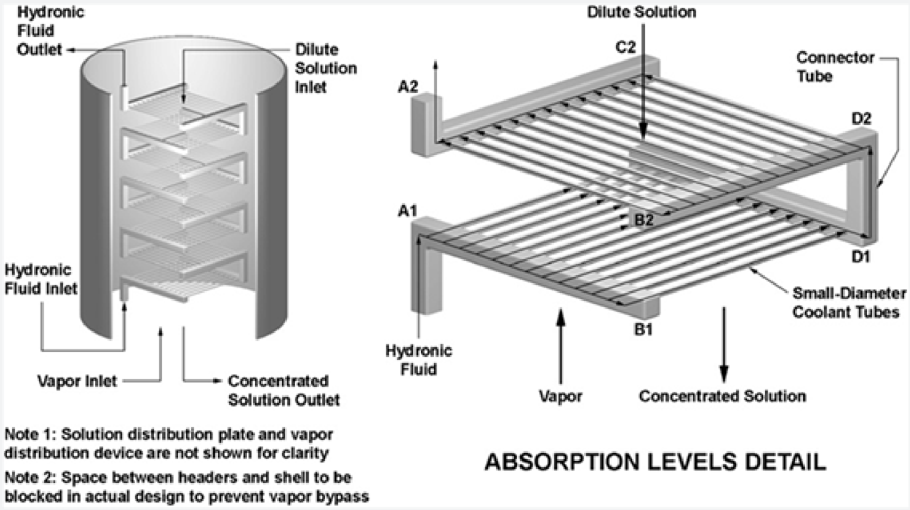

Figure 2: Microchannel heat and mass exchanger concept. Adapted from Garimella et al. [45].

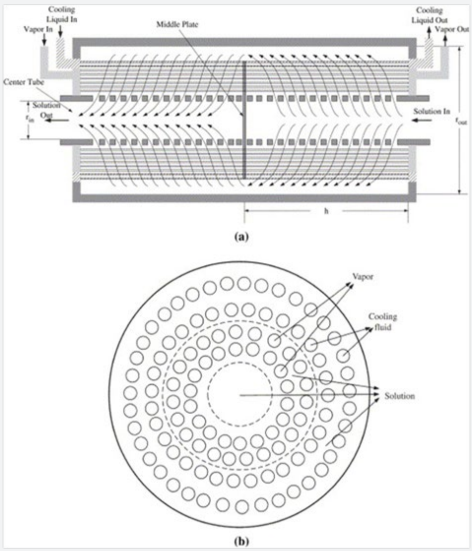

Figure 3: Hollow fiber membrane module as a hybrid absorber and heat exchanger. Adapted from Chen et al. [11].

Chen et al. [40] proposed a novel hybrid hollow fiber membrane HEX-absorber, as shown in (Figure 3). Two types of fibers are used in this hybrid device: porous fibers permit the mixing of absorption solution and vapor (countercurrent or concurrent) while nonporous fibers form material interface for heat exchange between absorption solution and cooling fluid (countercurrent). The high interfacial area of fibers enhances the heat and mass transfer so that 14.8% increase on COP can be obtained compared to that of a falling film plate heat exchanger.

Olarte-Cortés et al. [41] developed a novel HEX-absorber with stainless-steel shell and graphite disks laminated internally in a column to carry out the LiBr-water absorption. The structure of the HEX-absorber is shown in (Figure 4). Rich solution of LiBr enters through the top of the device and descends through the disks where it gets distributed, while the water vapor enters through the bottom of the device and contact with the descending solution. Cooling water circulates in the annul space between the column wall and the disks in a countercurrent manner regarding the solution [42-44]. The

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main intensification action in this HEX-absorber is the use of tar-impregnated graphite disks as the support for heat and mass transfers. This kind of corrosion resistant material has a high thermal conductivity (50-80W·m-1·K-1) that favors the heat transfer. Moreover, the roughness of disk surface serves as micro-fins which augment the heat transfer surface area. The wetting of the surface can also be improved, providing larger interfacial area for liquid gas contact [45-47]. Experimental results showed that the U ranged from 168 to 317W·m-2·K-1. The thermal compatibility could reach about 3.44kW·m-3·K-1.

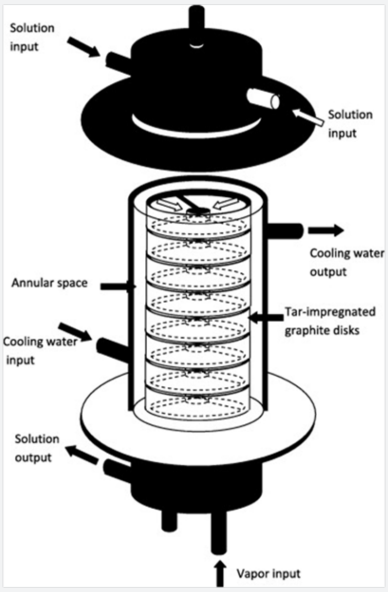

Figure 4: Structure of the graphite disks absorber and its connections. Adapted from Olarte-Cortés et al. [17].

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