

Manuscript Number: APEN-D-18-01556R1

Title: Vapour absorption enhancement using passive techniques for
absorption cooling/heating technologies: A review

Article Type: Review Article

Keywords: absorption cooling/heating technology; heat and mass transfer
intensification; nanofluids; additives; advanced surfaces.

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Abstract: The absorption cooling/heating system is an old technology that has been relegated by the more efficient mechanical vapour compression systems. However, if they were driven by residual heat or solar thermal energy, advanced absorption technologies for cooling or heating could supply current demand and have a much lesser impact on the environment. With the cost of electricity rising and the climate change more and more in evidence, it would be a positive move towards energy saving. Since the absorber is recognized the key component of the absorption system due to the complex heat and mass transfer process that take place there, the improvement of the absorption process would mean reducing the absorber and desorber sizes to make them more compact, or reducing the system driving temperature for low grade temperature applications. The objective of this paper is to identify, summarize, and review the experimental studies dealing with the enhancement of vapour absorption processes in absorbers by means of passive techniques i.e. advanced surface designs and the use of additives and nanofluids. This review also includes an exhaustive and detailed scrutiny on absorption processes in falling film, spray and bubble mode absorbers for different working fluids, evidencing the experimenting techniques, operating conditions, and latest advances in terms of heat and mass transfer enhancement in absorbers. Finally, the paper contains suggestions for future work to be carried out to obtain mass transfer enhancement in absorbers and absorption cooling/heating systems.

Vapour absorption enhancement using passive techniques for absorption cooling/heating technologies: A review

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Keywords: absorption cooling/heating technology, heat and mass transfer intensification, nanofluids, additives, advanced surfaces.

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1. Introduction

Natural resources depletion caused by the extreme increase in energy consumption requirements together with the depletion of the ozone layer and global warming are issues of great concern for the human race. The increase in energy consumption is in part a result of the improvement of our standard of living and the associated development of sectors such as building, industry and transport. The building sector which comprises the residential and commercial constructions consumes up to 32% of the total energy used globally [1] where almost half of the total energy consumption of buildings in developed countries is due to air conditioning [2].

This means that both developed and developing countries have an opportunity to work towards achieving the goal for CO₂ emission limits for 2030.

Air-conditioning equipment such as those using mechanical vapour compression technologies require significant electrical power and an appropriate refrigerant for operating. Both of these requisites can produce a high impact on the environment and contribute to depletion of the ozone layer and subsequent global warming. The need to adopt ozone and climate-friendly technologies and policies means that it is the ideal opportunity for the replacement of old technologies with alternative energy efficient options together with more efficient servicing practices. Society needs to work on the progress of advanced air-conditioning technologies in order to cater with the effects of climate change and to progress towards a much lower emission of greenhouse gases. To do so, it is necessary to identify which technologies can best be adapted to our current necessities and to remove any obstacles preventing the widespread diffusion of advanced air-conditioning technologies on the market.

Absorption cooling/heating technologies have been recognized as an interesting alternative technology to displace conventional electrically driven mechanical compression systems. Absorption cooling/heating technologies have proved that they have a high potential for energy saving compared with conventional electrically driven mechanical compression technologies, due to the fact that they can operate with environmentally friendly working fluids and be thermally driven to produce cooling or heating. However, these absorption technologies present some obstacles that have limited their wide diffusion, for instance: (i) initial investment, (ii) lack of consumer awareness regarding the technology, (iii) the low priority given to energy efficiency, (iv) import and export constraints and (v) insufficient government policies [1]. In order

1 to overcome these difficulties, the adoption of comprehensive policies that may include
2 fiscal and financial incentives, information campaigns, and other development policies
3 are necessary as well as adopting minimum energy performance standards and
4 requirements.
5

6
7 Over the last decade, the interest and need for progress in the development of new
8 absorption cooling/heating systems have led researchers to carry out studies with
9 several techniques and strategies to improve their performance and make them more
10 competitive in comparison with the well-established mechanical compression systems
11 [3]. However, current absorption systems with conventional working fluids, like those
12 used for cooling applications do still present some drawbacks. Examples of these are:
13 crystallisation, corrosion and vacuum operating pressures for $\text{H}_2\text{O}/\text{LiBr}$ systems; and
14 rectification of the refrigerant vapour leaving the desorber and high activation
15 temperatures for $\text{NH}_3/\text{H}_2\text{O}$ systems. These well-known drawbacks have spurred
16 researchers into finding new working mixtures [4], and passive heat and mass transfer
17 intensification techniques to apply to different components of absorption
18 cooling/heating systems.
19

20 Since the absorber is considered the key component of absorption cooling/heating
21 systems due to the complex heat and mass transfer process that take place there [5],
22 higher absorption rates reached by the application of passive intensification techniques
23 would allow for the absorber size to be decreased and made more compact, or for the
24 cycle driving temperature in solar or low thermal energy applications to be reduced.
25

26 Passive intensification techniques include the use of rough or extended surfaces or the
27 inclusion of small quantities of additives or nanocomposites to the base working fluids
28 to improve the heat and mass transfer processes. Furthermore, optimisation of
29 nanoparticle synthesis and a reduction in the acquisition price have also favoured using
30 nanotechnology in several applications [6] including cooling and heating systems that
31 involve heat and/or mass transfer processes [7-9].
32

33 This paper provides an extensive review of experimental investigations dealing with the
34 enhancement of the heat and mass transfer of different working fluids in absorbers by
35 means of passive heat and mass transfer intensification techniques. It includes operating
36 conditions, test characteristics, and main outputs from experimental investigations on
37 absorbers for cooling/heating absorption systems. In addition, the dominant mechanisms
38 for mass transfer enhancement by employing advanced surfaces, chemical additives and
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nanofluids are discussed. Finally, the paper deals with possible future work and research challenges.

2. Absorption cooling/heating technology

Research on absorption cooling/heating systems has resulted in the development of various absorption system designs such as simple-effect absorption systems, absorption heat transformers, diffusion absorption systems, and multiple effects and stage absorption systems among others, for use in different applications and driving temperatures [5, 10-14].

In terms of operation, absorption systems are partially similar to mechanical vapour compression systems and depending on the objective, they can be constructed to produce cooling (Absorption refrigeration system, ARS) or heating (Absorption heat pump, AHP). In the most basic design of an absorption system, eg. the simple-effect ARS, the refrigerant vapour at a high pressure and temperature is cooled down until becoming liquid in a condenser and throttled to low pressure and temperature toward an evaporation device where it is boiled to provide the cooling effect. The difference between the absorption and mechanical vapour compression systems lies in the way that a refrigerant vapour is compressed from a low pressure to a high pressure, **Figure 1**. In the case of the absorption system, the mechanical vapour compressor is replaced by ``a thermal compressor``. This sub-system consists mainly of a desorber (also called generator), a solution heat exchanger, a solution pump, an expansion valve, and an absorber.

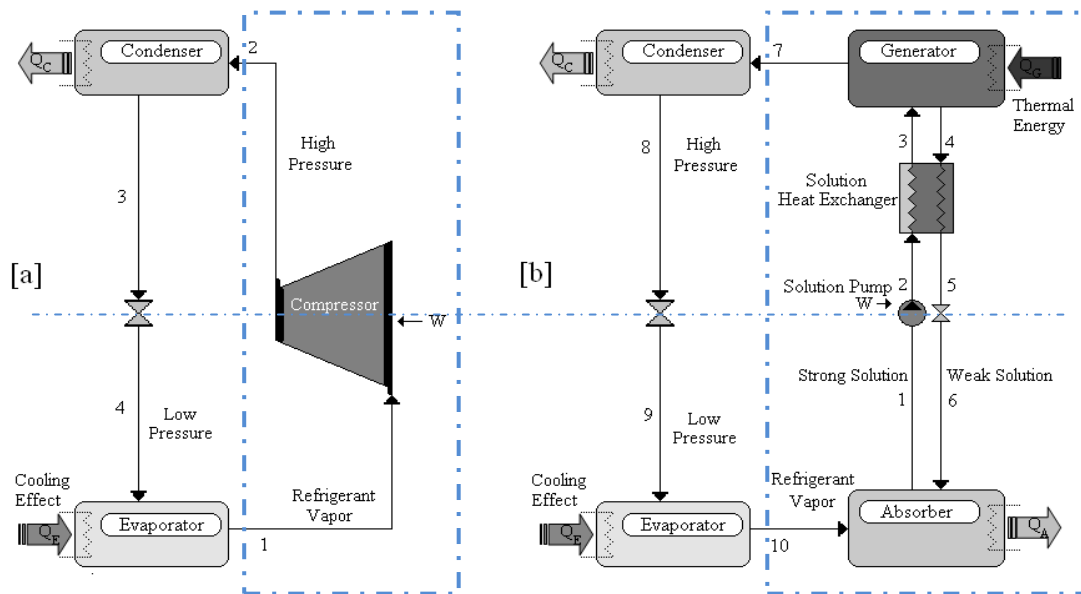


Figure 1 - Mechanical vapour compression system [a] and absorption refrigeration system [b].

1 In the absorber, the refrigerant in vapour state coming from the evaporation device is
2 absorbed by a solution mixture consisting of a proportion of the refrigerant and
3 absorbent with high affinity for the refrigerant in a liquid state (called solution weak in
4 refrigerant). The solution strong in refrigerant leaving the absorber is then pumped to a
5 high-pressure desorber. In the desorber, the refrigerant absorbed is once more boiled
6 and separated from the solution mixture by applying heat, which drives the cycle, at a
7 high temperature and then, the refrigerant vapour is sent to the condenser. Finally, the
8 remaining solution mixture leaving desorber is sent to the absorber to repeat the cycle.
9 The Coefficient of Performance (COP) of an absorption system is defined as the relation
10 between the ratio of the cooling or heating performance and the amount of heat input
11 plus the pump consumption.
12

13 Although absorption cooling/heating systems are not yet competitive with mechanical
14 vapour compression systems in terms of efficiency, size and cost, the relevance of the
15 absorption system lies in the following: low electricity consumption by a solution pump,
16 few moving parts leading to low noise and very low vibration levels. Furthermore, the
17 most interesting points about the absorption cooling/heating systems are the use natural
18 refrigerants which mean they cause zero ozone depletion, have zero global warming
19 potential and the fact that they can be activated by thermal energy such as solar [11, 15-
20 16], geothermal energy [17], or residual energy from industrial processes [14] or
21 cogeneration/trigeneration processes [18-19]. Moreover, further absorption system
22 designs can also include combined production of power and cooling [20-21].
23

24 In the case that a location is unable to support the use of vapour compression cooling
25 systems because electricity is not available from a power grid, absorption cooling
26 systems activated by thermal energy appear to be an attractive alternative. Further
27 development of absorption systems would lead to an important change in the
28 cooling/heating production world, and would definitely have an important impact on the
29 environment and save energy.
30

31 Although each one of the components that constitute the absorption system is important
32 in terms of design and efficient use of the heat transfer area, the absorber plays a
33 particular and critical role in the whole system. Heat transfer and the even more
34 important mass transfer taking place in the absorber greatly influence the performance
35 and size of the whole absorption system. The enhancement of the pure refrigerant
36 vapour rate absorbed here allows for efficient designs of the absorber, compactness, or
37 improved cooling/heating capacity of the absorption system.
38

The most common working fluids used in absorption cooling/heating systems, and main absorber characteristics and experimental studies are presented in the following sections.

2.1. Working fluids

According to the open literature, several working mixtures have been suggested for use in absorption systems but due to problems such as high cost, reduced miscibility limits, high corrosion, explosive, toxicity, environmental hazards, poor transport properties and chemically instability, most of them have been discarded. Moreover, the working mixtures ammonia/water ($\text{NH}_3/\text{H}_2\text{O}$) and water/lithium bromide ($\text{H}_2\text{O}/\text{LiBr}$) have proved to have better characteristics and nowadays are the most widely used pairs on the absorption cooling/heating systems market.

The absorption cooling/heating systems with $\text{NH}_3/\text{H}_2\text{O}$, the first one to be patented, is mainly used for refrigeration applications ($< 0\text{ }^\circ\text{C}$) due to the very low ammonia freezing point ($-77\text{ }^\circ\text{C}$ at 1 atm). Ammonia as refrigerant provides outstanding thermodynamic and thermophysical properties. Besides, ammonia is environmentally friendly and any possible emissions will not contribute to global warming. Furthermore, the use of plate heat exchangers or advanced surfaces heat exchangers and the great potential of ammonia for use in low charge systems allow reducing the impact of its toxicity [22].

Use of the $\text{NH}_3/\text{H}_2\text{O}$ mixture allows the absorption system to operate at high heat dissipation temperatures, so the system can be air-cooled and the use of humid cooling towers can be eliminated. However, $\text{NH}_3/\text{H}_2\text{O}$ systems require high activation temperatures ($> 110\text{ }^\circ\text{C}$) to keep the refrigerant cooling capacity at the desired low evaporation temperatures. Furthermore, NH_3 and H_2O are volatile at the conditions of interest thus making the use of an extra component necessary. This is to rectify the vapour leaving the desorber to ensure its high concentration in ammonia which prevents water accumulating in the condenser and evaporator. With the use of a rectifier, when reducing the evaporation temperature and increasing the generation temperature, the performance of the cycle with $\text{NH}_3/\text{H}_2\text{O}$ significantly decreases. Another important aspect of the $\text{NH}_3/\text{H}_2\text{O}$ system and the predominant reason why the double-effect absorption systems working with $\text{NH}_3/\text{H}_2\text{O}$ are not commercially available at the moment is the high pressure reached in the desorber.

1 Although other disadvantages of the $\text{NH}_3/\text{H}_2\text{O}$ system include toxicity and
2 incompatibility with copper-based metals, this mixture is environmentally friendly and
3 has a low cost. Thermodynamic properties and their correlations for the $\text{NH}_3/\text{H}_2\text{O}$
4 mixture can be found in the open literature at a wide range of solution concentrations
5 and temperatures [23-26]. The effects of different nanoparticles and high temperature on
6 viscosity, thermal conductivity and absorbance of $\text{NH}_3/\text{H}_2\text{O}$ have also been reported
7 lastly [27].

8
9 With regard to $\text{H}_2\text{O}/\text{LiBr}$ absorption systems, they appeared on the market some years
10 later than the $\text{NH}_3/\text{H}_2\text{O}$ ones, in response to the low performance of $\text{NH}_3/\text{H}_2\text{O}$ systems
11 for air-conditioning applications. The performance of $\text{H}_2\text{O}/\text{LiBr}$ systems at lower
12 activation temperatures is better than $\text{NH}_3/\text{H}_2\text{O}$ systems, which make $\text{H}_2\text{O}/\text{LiBr}$ systems
13 more suitable for solar cooling. Besides, the fact that LiBr is a salt (non-volatile) with a
14 great affinity for water allows for the system to be operated without the need of a
15 refrigerant vapour rectifier. Moreover, $\text{H}_2\text{O}/\text{LiBr}$ systems are only used for air-
16 conditioning applications ($> 0^\circ\text{C}$) due to the water (the refrigerant) freezing point (0°C
17 at 1 atm). Use of water as refrigerant also implies that the evaporator and absorber must
18 be operated under vacuum conditions all of which results in high vapour specific
19 volumes and consequently in bigger components.

20
21 The main problems of using the LiBr based absorption systems are, the solution
22 crystallisation that takes place at high salt concentrations in the absorber, the high
23 corrosion of some metals and the high cost of the salt. The crystallisation limits for
24 $\text{H}_2\text{O}/\text{LiBr}$ are very close to the operating concentrations required for practical $\text{H}_2\text{O}/\text{LiBr}$
25 absorption chillers. This has made it difficult to change from air-cooled $\text{H}_2\text{O}/\text{LiBr}$
26 prototypes to what may be highly attractive commercial systems. Based on the above
27 reasons, the use of humid cooling towers for heat dissipation is required and this
28 involves an increase in the cost of the whole system. In the case of small capacity
29 $\text{H}_2\text{O}/\text{LiBr}$ systems, cooling towers are not suitable because of the cooling tower
30 maintenance requirements. Thermodynamic properties and their correlations for the
31 $\text{H}_2\text{O}/\text{LiBr}$ working fluid are available in a wide range of compositions [28-30].

32
33 In order to overcome the crystallisation and corrosion problems of $\text{H}_2\text{O}/\text{LiBr}$, it is
34 necessary to implement diverse crystallization control actions such as the addition of
35 chemical inhibitors, heat and mass transfer intensification and thermodynamic cycle
36 adjustments. These have all been investigated in the last few years [31]. For instance,
37 Lithium iodide (LiI) could be used to enhance the solubility of salt and reduce the
38

crystallisation limits at conditions of interest for these systems [32], while lithium nitrate (LiNO_3) could be added to reduce corrosive effects [33].

Advances in the mitigation of the crystallisation and corrosion problems have allowed for $\text{H}_2\text{O}/\text{LiBr}$ systems to be developed with the objective of improving their performance at higher activation temperatures. $\text{H}_2\text{O}/\text{LiBr}$ systems with double and triple effects are some of the improvements made over the last few years.

Recently, Alvarez et al. [34-37] conducted a series of experimental and theoretical studies and proposed the use of Water/alkaline nitrate solution ($\text{LiNO}_3+\text{KNO}_3+\text{NaNO}_3$) as a potential alternative to conventional working fluid for air-conditioning applications driven by high-temperature heat sources (temperatures up to 260 °C). The main advantage of this working fluid is its high thermal stability and non-corrosive action in comparison with the $\text{H}_2\text{O}/\text{LiBr}$ mixture in double effect and triple effect system applications.

In the case of low-temperature heat sources or solar cooling applications, the ammonia/lithium nitrate mixture ($\text{NH}_3/\text{LiNO}_3$) appears to be a promising alternative proposed to overwhelm the disadvantages and limitations of the typically used working fluids [38]. The advantages of the $\text{NH}_3/\text{LiNO}_3$ working mixture over conventional $\text{H}_2\text{O}/\text{LiBr}$ are, therefore, very low crystallization risks at the conditions of interest for solar air-cooling systems so it allows the system to be air-cooled at the condenser; and operated at pressures above atmospheric pressure. This means low refrigerant specific volumes, and presents the possibility of designing smaller components. Compared with the $\text{NH}_3/\text{H}_2\text{O}$ working pair, absorption systems with $\text{NH}_3/\text{LiNO}_3$ do not require a rectifier for the vapour refrigerant at the desorber outlet since the absorbent is a salt. Additionally, it can operate at lower temperatures in the desorber according to studies based on thermodynamic simulations [39-42] and experimental investigations focused on the boiling process [43-44]. The major benefits of this working fluid, therefore, are the simplicity of the cycle and a greater potential for solar cooling. However, the primary limitation of this working fluid is its high viscosity in comparison to $\text{NH}_3/\text{H}_2\text{O}$ and this means it has a negative impact on the heat and mass transfer processes, especially in the absorber. To overcome this drawback, Ehmke and Renz [45], Bokelmann [46], and Reiner and Zaltash [49-50] proposed the addition of a small amount of water to the binary mixture of $\text{NH}_3/\text{LiNO}_3$ with an optimal water mass fraction of between 0.20 and 0.25 in the absorbent mixture [45]. Later, Bokelmann [46] conducted experiments on the performance of an absorption heat pump operating with

the $\text{NH}_3/(\text{LiNO}_3+\text{H}_2\text{O})$ mixture. Thermodynamic properties for the $\text{NH}_3/\text{LiNO}_3$ working fluid are available in a wide composition range [47-48, 51-52]. In addition, thermodynamic properties for the $\text{NH}_3/(\text{LiNO}_3+\text{H}_2\text{O})$ working fluid are also available in the literature [49-51].

2.2. Absorber configurations

Absorbers can have three conventional modes of design and operation: Falling film mode, spray mode, and bubble mode. Lately, proof of concept of membrane-based absorbers is attracting attention among researchers in the field of small thermal load capacity absorption systems.

Depending on the absorber operation mode, the way that the refrigerant vapour coming from the evaporator is introduced into the absorber and makes contact with the solution varies. The falling film absorber is the most commonly used in the absorption cooling/heating systems available on the market. Bubble absorbers are used in absorption chillers that provide a small cooling capacity while the spray absorbers are still at an early stage of development. In the case of the membrane absorber, the first studies have just been reported recently. A brief description of the main characteristics of each one of the absorber configurations is presented in the following sub-sections. It also includes a summary of the experimental studies reported in the literature on each absorber configuration.

2.2.1. Falling film absorber

There are mainly two arrangements for absorbers in falling film mode; in horizontal and vertical tube mode (**Figure 2**). In horizontal tube configuration, the solution enters the absorber through a distributor located in the upper section of the absorber (**Figure 2a**). The solution flows in a falling film along the cooling-water tube surfaces. The solution leaving the distributor has immediate contact with the saturated vapour phase of refrigerant which occupies the volume of the absorber. The weak solution falling film, which falls from one tube to the next one, is cooled by the bundle of tubes hence, the capacity of the solution to absorb refrigerant increases. The strong solution in refrigerant leaves the absorber through the lower section.

According to the configuration of the absorbers used in commercial absorption machines, the horizontal configuration with $\text{H}_2\text{O}/\text{LiBr}$ is found to be the most common

in comparison to the vertical tube arrangement. In vertical configuration (**Figure 2b**), cooling water usually flows upward through the tubes and the weak solution flows downward through the outer space while the refrigerant vapour flows in counter-current configuration. This configuration is also studied for the design of air-cooled absorbers, in which case the solution and refrigerant flow inside the tube arrangement.

It is important to point out the fact that even though H₂O/LiBr falling film absorbers in horizontal configurations are commonly used due to the insignificant pressure drop they involve; their design is really complicated due to the very low operating pressures, solution distribution limitations and inconvenient wetting of the cooling-water tube surface area all of which affects mass transfer.

Several studies dealing with the falling film mode absorption process at different operating conditions can be found in the open literature [53-70]. It's worthy of note that most of those experimental studies employed the mixture H₂O/LiBr. Some of them involving the effects of the flow configuration [53, 59], tube spacing [54-55], tube diameter [53-55, 60] and number of tubes [53, 68] on the absorber performance. Some studies also include the absorption performance for different configurations based on the effects of the absorber operating pressure [56, 59-60, 64-65, 69-70], solution flow [56, 58, 59, 61-70], solution temperature [58-59, 61, 66-67, 69-70], solution concentration [56, 59, 62-64, 68-70], coolant temperature [56, 58, 61-67, 70], and coolant flow [61, 32, 64, 66-67, 70]. As main outputs from these studies, it was identified that heat and mass transfer rates in falling film absorbers increase on increasing the solution and vapour pressure, solution flow rate, cooling water flow rate, and the tube spacing. It was also noted that heat and mass transfer rates decrease with increasing cooling water temperature and tube diameter. In addition, it was observed that heat and mass transfer increase when the absorbent concentration in the solution is increased, however, this enhancement is limited by the solubility and/or crystallization limits as is the case for LiBr-based solutions.

A summary of the experimental studies carried out on falling film absorbers with smooth surfaces for absorption systems is shown in Table 1. This summary includes those studies that employed basic configurations without the application of passive heat and mass transfer intensification techniques.

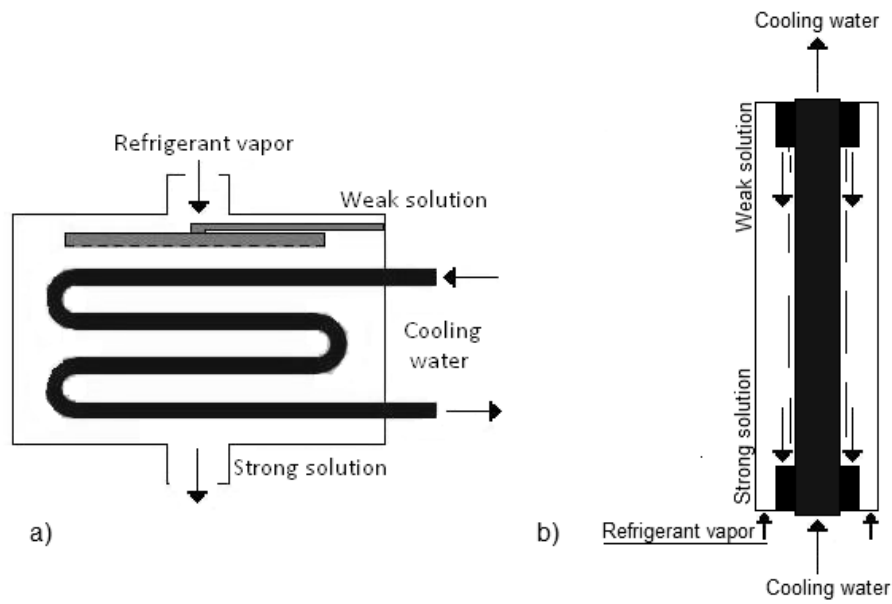


Figure 2 - Diagram of a falling film absorber in a) horizontal configuration and b) vertical configuration.

Table 1. Summary of experimental studies carried out on falling film absorbers with smooth surfaces for absorption cooling/heating systems.

Reference	Test Section	Working fluid	Test conditions	Note
[53]	Horizontal tubes	H ₂ O/LiBr	Ps (1.33 kPa), Ts (35 °C), Xs (57.5%), ms (0.10 - 1.25 kg.s ⁻¹ .m ⁻²), Tc (20 °C)	One row of 5 tubes with 19.5 mm external diameter and a second row of three tubes with 42.2 mm
[54]	Horizontal tubes	H ₂ O/LiBr	-----	Tube spacing of 0, 3, 15 and 24 mm
[55]	Horizontal tubes	H ₂ O/LiBr	Ps (0.86 kPa), Xs (60 and 62%)	Single-row bundle of 8 tubes
[56]	Vertical tube	H ₂ O/LiBr	Ps (1-1.5 kPa), Xs (60 - 64%), Res (100 - 400), Tc (35 - 46 °C), Rec (6000)	Stainless steel absorber tube with outer diameter of 19.05 mm and 1524 mm in length.
[57]	Horizontal tubes	H ₂ O/LiBr	Ps (1.33 kPa), Ts (40 - 46 °C), Xs (54 - 61%), ms (0.01 - 0.045 kg.s ⁻¹ .m ⁻²), Tc (30 - 37 °C)	14 horizontal smooth copper tubes
[58]	Vertical tube	H ₂ O/LiBr	Ps (1.33 kPa), Ts (34-39 °C), Xs (53%), ms (0.013- 0.025 kg.s ⁻¹), Res (50, 130, 350, 550) Tc (22.7 - 27 °C), mc (0.036 kg.s ⁻¹)	Smooth copper tube of 19.05 mm outer diameter and 400 mm long
[59]	Helical tube	NH ₃ /H ₂ O	Ps (48 - 193 kPa), Ts (45, 50, 55, 60 °C), Xs (3, 14, 30%), ms (4.43 - 90.9 g.m ⁻¹ .s ⁻¹), Tc (30 °C)	Helical coil absorber, coil tube diameter of 12.7 mm
[60]	Horizontal tubes	H ₂ O/LiBr	Ps (0.93 kPa), Ts (47 °C), Xs (61%), ms (0.014 - 0.03 kg.s ⁻¹ .m ⁻²), Tc (32 °C), Vc (0.044 - 0.067 lt.s ⁻¹)	Tube diameters of 15.88 mm (row of 10 tubes), 12.70 mm (row of 12 tubes) and 9.52 mm (row of 16 tubes)
[61]	Horizontal tubes	H ₂ O/LiBr	Ps (1 - 3.2 kPa), Ts (39.8 - 49.7 °C), Xs (39.6%), ms (0.0095 - 0.0191 kg.s ⁻¹), Tc (26 - 35.5 °C), mc (0.063 - 0.114 kg.s ⁻¹)	24 rows of horizontal smooth copper tube with outer diameter of 19 mm
[62]	Horizontal tubes	134a-DMAC	Xs (25.14-42.4%), ms (0.025 - 0.045 kg.m ⁻¹ .s ⁻¹), Tc (20 - 30 °C), mc (0.039 - 0.087 kg.s ⁻¹)	Tube bundle with 8 rows and 3 columns
[63]	Horizontal tubes	H ₂ O/LiBr	Res (13 - 39), Xs (60 - 63.8%), Tc (30 - 32 °C)	24 rows of horizontal smooth copper tubes
[64]	Vertical tubes	H ₂ O/LiBr	Ps (1 - 2.2 kPa), Ts (5 - 10 °C), Xs (57.9 - 60%), Res (50 -300), Tc (30 - 40 °C), Rec (6000)	Two stainless steel concentric tubes
[65]	Vertical tubes	H ₂ O+LiBr+LiI +LiNO ₃ +LiCl	Ps (1 - 2.2 kPa), Ts (5 - 10 °C), Xs (57.9% for base fluid, 61% and 64.2% for multicomponent salt), Res (50 - 300), Tc (30 - 45 °C), Rec (6000)	Two stainless steel concentric tubes
[66]	Helical tube	H ₂ O+LiBr+LiI +LiNO ₃ +LiCl	Ps (10.8 kPa), Ts (45 - 59 °C), Xs (58, 61, 64%), ms (0,01 - 0,04 kg.m ⁻¹ .s ⁻¹), Tc (30 - 35 °C)	Small helical absorber
[67]	Helical tube	H ₂ O/LiBr	Ps (0.93 kPa), Ts (45 - 50 °C), Xs (60%), ms (50 - 210 kg.h ⁻¹), Tc (28 - 34 °C), mc (300 - 900 kg.h ⁻¹)	Small helical absorber
[68]	Horizontal tubes	H ₂ O/LiBr	Ps (1 kPa), Xs (57 - 60%), ms (0.01 - 0.045 kg.s ⁻¹), Tc (30 °C), Vc (0.000126 m ³ .s ⁻¹)	Horizontal falling film tube of one column
[69]	Column chamber	H ₂ O/LiBr	Ps (2-7.8 kPa), Ts (26-55 °C), Xs (48-55%), ms (8-11 g.s ⁻¹)	Adiabatic absorption, falling film column
[70]	Vertical tube	H ₂ O/LiBr	Ps (0.85-1.3 kPa), Ts (46.6 - 52.2 °C), Xs (57.3 - 60.3%), Res (90 - 250), Tc (30.0 - 41.7 °C), mc (0.11 kg.s ⁻¹)	Single vertical tube inside a borosilicate glass, with a 22.0 mm outer diameter and 18.0 mm inner diameter.
Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms (solution flow), Res (solution Reynolds number), Tc (coolant temperature), mc, Vc (coolant flow), Rec (coolant Reynolds number). * concentration of ammonia for NH ₃ based fluids and concentration of LiBr for LiBr based fluids.				

2.2.2. Spray absorber

The spray absorption configuration consists of an adiabatic chamber and solution sprayer, **Figure 3**. The solution weak in refrigerant coming from the desorber is introduced into the adiabatic chamber in a fine spray mode where it gets into contact with the refrigerant in vapour state coming from the evaporator. Once the absorption process takes place, the solution mixture, which is strong in refrigerant, leaves the absorber through the lower section of the adiabatic chamber.

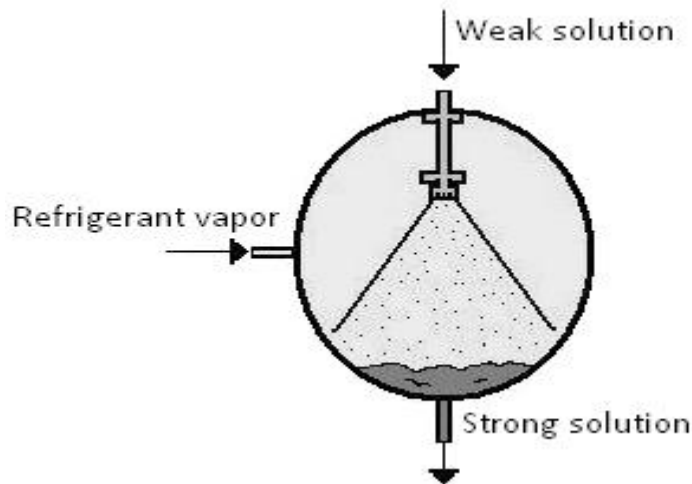


Figure 3 - Diagram of a spray absorber.

The use of the spray mode to disperse the solution into the chamber in very fine drops helps to reduce solution resistance for mass transfer and improves absorption potential. As can be noted in Figure 3, spray absorption occurs without simultaneous heat transfer in an adiabatic chamber. This makes the use of additional components necessary to sub-cool the weak solution in order to enhance its absorption potential. Also, it is necessary to recirculate part of the strong solution through the adiabatic absorber in order to increase absorption and approximate it to solution equilibrium conditions. Experimental studies on the absorption process in spray mode can be found in the literature emphasizing the use of different spray types with organic mixtures [71], $\text{H}_2\text{O}/\text{LiBr}$ [72-76, 78] or $\text{NH}_3/\text{LiNO}_3$ [77, 79-81]. Studies in the literature included the use of spiral [71], whirl jet [71, 73-74], hollow jet [71-72], full jet nozzle [71, 73], flat-fan nozzle [76-78], fog-jet [79-80] and full cone nozzle [75, 81]. Those studies also report the absorber performance based on the effects of absorber operating pressure [71-72, 75-76, 79-81], solution inlet temperature [40-50], solution inlet concentration [75-76, 79], solution mass flow [71-77, 79-81] and coolant temperature [71]. Main outputs from these studies highlight that the heat and mass transfer rates are positively affected when the

absorber pressure, solution mass flow and solution inlet sub-cooling increase and when the solution inlet temperature decreases.

The latest studies employing spray absorbers have shown that the use of full cone nozzles is preferable, mainly, due to their large hole diameter which allows high flow rates and avoids clogging [81]. A summary of the experimental studies carried out on spray absorbers for absorption technologies is shown in **Table 2**.

Table 2. Summary of experimental studies carried out on spray absorbers for absorption cooling/heating systems.

Reference	Test Section Spray type	Working fluid	Test conditions
[71]	Spiral, whirljet, hollowjet and fulljet nozzles	Organic fluid mixtures	Ps (2.5 - 15 kPa), Ts (20 - 22 °C), Xs (25%), ms (200 - 400 kg.h ⁻¹), Tc (30, 35, 40 °C)
[72]	Falling droplets, jet flow and falling film	H ₂ O/LiBr	Ps (0.72, 1.32, 1.62, 1.92, 2.80 kPa), Ts (20 - 22 °C), ms (2.7 - 10 g.s ⁻¹),
[73]	Whirl jet and full jet nozzles	H ₂ O/LiBr	Ps (1.23 kPa), Ts (65.5 - 82,2 °C), Xs (84%), ms (0.018 - 0.043 kg.s ⁻¹)
[74]	Whirl jet	H ₂ O/LiBr	Ps (1.23 kPa), Ts (65.5 - 82.2 °C), Xs (84%), ms (0.018 - 0.043 kg.s ⁻¹)
[75]	Cone nozzle	H ₂ O/LiBr	Ps (1.0 - 2.2 kPa), Ts (19 - 23 °C), Xs (58 - 60%), ms (28 - 47 kg.h ⁻¹)
[76]	Flat-fan nozzle	H ₂ O/LiBr	Ps (0.6 - 2.2 kPa), Ts (21 - 27 °C), Xs (58 - 60 %), ms (84 - 194 kg.h ⁻¹)
[77]	Flat fan nozzle	NH ₃ /LiNO ₃	Ts (24 - 30 °C), Xs (45.3%), ms (0.04, 0.06, 0.08 kg.s ⁻¹)
[78]	Falling droplets and fan sheets	H ₂ O/LiBr	Ts (21 - 32 °C), Xs (57.5 - 62.5%)
[79]	Fog-jet spray	NH ₃ /LiNO ₃	Ps (429, 601, 773, 945 kPa), Ts (26.67 - 30.66 °C), Xs (41.9 - 58.6%), ms (0.0542 - 0.0575 kg.s ⁻¹)
[80]	Fog-jet nozzle	NH ₃ /LiNO ₃	Ps (355 - 411 kPa), Ts (25.9 - 30.2 °C), ms (0.04 - 0.08 kg.s ⁻¹)
[81]	Full cone nozzle	NH ₃ /LiNO ₃	Ps (291 - 406 kPa), Ts (32.5 - 30.6 °C), ms (0.04 - 0.08 kg.s ⁻¹)
Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms (solution flow), Tc (coolant temperature), * concentration of refrigerant for ammonia based fluids and organic mixtures and concentration of LiBr for LiBr based fluids.			

2.2.3. Bubble absorber

The basic configuration of a bubble absorber consists of vertical absorber where the solution weak in refrigerant flows upward through the solution channel and the pure refrigerant vapour is injected at the bottom of the absorber (**Figure 4**). The refrigerant in vapour state comes in the absorber in bubble mode and is absorbed by the solution mixture as it rises. The heat load released during the refrigerant vapour absorption process is extracted by a cooling fluid (usually water) circulating on the outside of the solution channel.

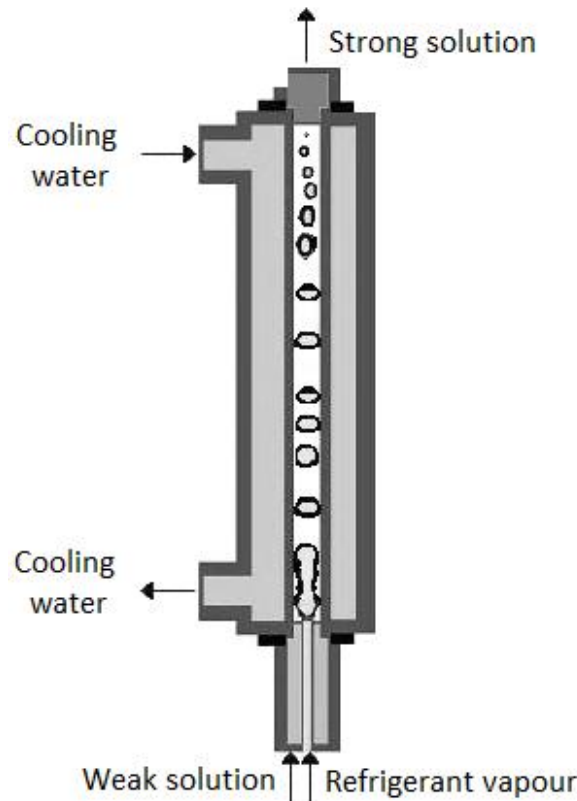


Figure 4 - Diagram of a bubble absorber.

According to the open literature, bubble absorbers provide higher heat and mass transfer coefficients, the mixing between solution and refrigerant is better, and absorption process is simpler in comparison to falling film absorbers [82-83].

Interest on the investigation of the bubble absorption process for absorption systems has also been increasing in the last years. Researchers have focussed on the description and explanation of the phenomena that take place in the absorption and the way to improve it in an effort to contribute to the technological development of absorption systems for refrigeration or heating [84-101]. Documents reported in the open literature include sensitivity studies of the heat and mass transfer processes in bubble absorbers with

different mixtures by analysing the effect of the absorption heat removal [85], internal tube diameter [85], solution flow [85-87, 94, 96, 98, 100-101], inlet solution temperature [84, 86, 88, 96-98, 100-101], solution concentration [85-86, 90-82, 94-98, 100-101], solution side pressure [85-86, 92, 96], coolant flow [87, 94-95], coolant temperature [87, 94, 101], inlet vapour temperature [88], inlet gas orifice size [90-91, 98-101], inlet vapour flow [90-91, 94-96, 98, 100-101]. In general terms, studies reported have shown that the heat and mass transfer coefficients increase on increasing the cooling water flow rate, solution flow rate, and the solution and vapour pressure. The opposite effect is observed on increasing the cooling water temperature and solution concentration. When the solution temperature is varied, just a very slight effect may be observed in the heat and mass transfer performance of the absorber. A summary of the experiments carried out on bubble absorbers for cooling/heating absorption systems is shown in Table 3. This summary includes those studies that employed basic configurations of absorbers, tray test sections and without the application of any passive heat and mass transfer intensification techniques. In the case of plate absorbers, these are considered advanced or compact absorber designs so they are listed in section 3.1.

Table 3. Summary of experimental studies done over basic bubble absorber configurations for absorption cooling/heating systems.

Reference	Test Section	Working fluid	Test conditions	Note
[85]	Concentric vertical glass tubes	NH ₃ /H ₂ O	Ps (126 - 333 kPa), Ts (9.5 - 33.5 °C), Xs (34 - 45%), ms (2.1 - 26.2 g.s ⁻¹)	Tube ID of 10, 15 and 20 mm, HR included.
[86]	Concentric vertical glass tubes	NH ₃ /LiNO ₃ and NH ₃ -NaSCN	Ps (120 - 370 kPa), Ts (20 - 40 °C), Xs (35 - 45%), ms (2.0 - 9.5 g.s ⁻¹)	Tube ID of 10, 15.3 and 20.5 and 25.7 mm, HR included.
[87]	Concentric vertical steel tubes	HCFC22/DMF	Ps (450 - 600 kPa), Xs (52 - 65%), ms (0.05 - 0.14 l.s ⁻¹), Tc (20 - 30 °C), Vc (0.25 - 0.4 l.s ⁻¹)	Six mild steel risers, each consisting of two concentric tubes, HR included.
[88]	Vertical polystyrene vessel	NH ₃ /H ₂ O	Ps (101 kPa), Ts (1.2 - 17 °C), Tg (5.1 - 19.4 °C)	Bubble growth study without HR
[89]	Cone-shaped acrylic column	NH ₃ -N ₂ /H ₂ O	Ts (24.8 °C), Vg (0.000002 - 0.000007 m ³ .s ⁻¹)	Bubble growth study without HR
[90]	Rectangular glass column	NH ₃ /H ₂ O	Ps (101 kPa), Ts (22.5 °C), Vel,g (1.25-18.5 m.s ⁻¹)	Bubble growth study without HR
[91]	Rectangular glass column	NH ₃ /H ₂ O	Ps (101 kPa), Ts (22.5 °C), Vel,g (1.25-18.5 m.s ⁻¹)	Bubble growth study without HR
[92]	Rectangular cell	NH ₃ /H ₂ O	Ps (400 kPa), Ts (20 °C), Xs (30.5, 42.4, 53.7, 59.4%)	HR not included, no absorption obtained from an ammonia concentration of 60%
[93]	Cylindrical acrylic column	NH ₃ /H ₂ O	Ts (20 °C), Xs (0 - 28%), ms (0.3 kg.min ⁻¹), mg (0.878 - 7.902 g.min ⁻¹),	Solution and gas flow in counter-current configuration decrease the absorption process
[94]	Vertical glass tube	NH ₃ /H ₂ O	Ps (600 kPa), Ts (115 °C), Xs (2.5, 10.3, 21.6%), ms (1.2 - 5 kg.h ⁻¹), Tc (20, 30, 40 °C), Vc (0.25 - 0.4 l.s ⁻¹), mg (0.9 kg.h ⁻¹), Tg (30 °C)	Tube ID of 10 mm, HR included.
[95]	Concentric vertical glass tubes	R134a/DMF	Ps (120 kPa), Ts (30 °C), Xs (1 - 15%), Vs (0.0125 m ³ .h ⁻¹), Vg (0.006 - 0.006 m ³ .h ⁻¹)	Tube ID of 33 mm, bubble growth study with HR
[96]	Concentric vertical glass tubes	R134a/DMF	Ps (120 - 400 kPa), Ts (20 - 30 °C), Xs (1 - 20%), Vs (0.025 - 0.05 m ³ .h ⁻¹), Vg (0.03 - 0.15 m ³ .h ⁻¹), Vc (0.05 - 0.075 m ³ .h ⁻¹)	Tube ID of 33 mm, heat and mass transfer process with HR
[97]	Cylindrical glass column	H ₂ O/LiBr	Ts (111 - 141 °C), Xs (46, 51, 56%)	Bubble growth study without RH
[98]	Concentric vertical glass tubes	R124/DMF	Ps (165 kPa), Ts (26, 39, 45, 54 °C), Xs (26, 30, 40, 46%), Vs (2, 4, 6, 8 l.h ⁻¹), Vg (40 - 400 l.h ⁻¹), Tc (33 °C), Vc (44 l.h ⁻¹)	Nozzle orifice diameters of 1.0, 2.0, 2.8 mm, HR included.
[99]	Concentric vertical glass tubes	R124/DMF	Ps (165 kPa), Ts (53 °C), Xs (44%), Vs (4 l.h ⁻¹), Vg (400 l.h ⁻¹), Tc (33°C), Vc (40 l.h ⁻¹)	Nozzle orifice diameter of 1.0 mm with 3, 5 and 7 multi-orifices, HR included.
[100]	Concentric vertical glass tubes	R124/DMF	Ps (165 kPa), Ts (39 - 54 °C), Xs (30 - 41%), Vs (4 - 8 l.h ⁻¹), Vg (80 - 400 l.h ⁻¹), Tc (33 °C), Vc (80 l.h ⁻¹)	Nozzle orifice diameters of 1.0, 2.0, 2.8 mm, HR included.
[101]	Concentric vertical cooper tubes	R124/DMF	Ps (165 kPa), Ts (36 - 55 °C), Xs (35 - 45%), Vs (4 - 8 l.h ⁻¹), Vg (80 - 400 l.h ⁻¹), Tc (22-32 °C), Vc (40 l.h ⁻¹)	Nozzle orifice diameters of 1.0, 2.0, 2.8 mm, HR included.
Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms,Vs (solution flow), Tc (coolant temperature), mc, Vc (coolant flow), mg,Vg (gas flow), Vel,g (gas velocity), HR (heat removal), * concentration of refrigerant for ammonia based fluids and organic mixtures and concentration of LiBr for LiBr based fluids.				

2.2.4. Membrane absorber

Nowadays, the design of membrane-based absorbers appears to be an interesting option for small thermal load capacity cooling/heating absorption systems. Membrane absorbers consist of a constrained flow absorber which comprises a hydrophobic microporous membrane media located between the solution and the refrigerant vapour as shown in Figure 5. The membrane allows only the refrigerant vapour to seep through into the weak solution while a solution transfer is not possible in the opposite direction. In the case of the cooling water, it flows next to the solution flow separated by a wall. As a result, the use of a membrane and constrained solution flows provide a high specific surface area, and therefore high mass transfer rates [102]. The main characteristics of membrane contactors for absorption systems were described in a detailed review by Asfand and Bourouis [102]. Moreover, since this new concept has been recently introduced for application into absorption cooling/heating systems, very few investigations have been conducted to analyse the absorption potential of conventional absorption working fluids in membrane absorbers. Those studies available in the open literature include CFD analysis [103-104], theoretical studies [108-109] and some experimental approaches [105-106, 131-134]. Experimental studies report mainly on the absorber performance based on the effects of inlet solution temperature [105-106, 131-134], solution mass flow [105, 131-134], absorber pressure [131,132, 134], coolant temperature [105-106, 131, 132].

Main outputs from the experimental studies show that the mass transfer rates increase on increasing the solution inlet sub-cooling and solution mas flow. The opposite effect is obtained on the mass transfer with increasing the cooling water temperature. A summary of the experimental studies carried out on membrane absorbers for absorption systems is shown in Table 4.

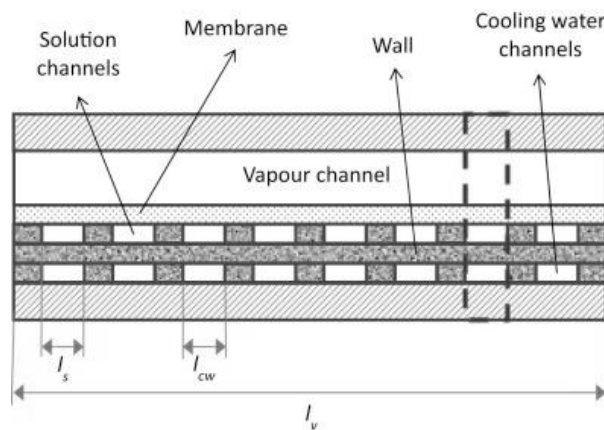


Figure 5 - Diagram of a membrane-based absorber [109].

Table 4. Experimental studies done over membrane-based absorbers for absorption cooling/heating systems.

Reference	Working fluid	Test conditions	Pore size
[105]	H ₂ O/LiBr	Ts (24 - 29 °C), Xs (50.8 - 54%), Tc (15 - 33 °C), ms (2.5 - 13.5 kg.h ⁻¹)	0.2 - 0.45 μm
[106]	H ₂ O/LiBr	Ts (31 - 43 °C), Xs (60%), Tc (25 - 35 °C), ms (2.5 kg.h ⁻¹)	1 μm
[131]	H ₂ O/LiBr	Ps (0.8 - 1.8 kPa), Ts (25 - 35 °C), Xs (60%), Tc (15 - 35 °C), ms (0.6 - 2.1 kg.h ⁻¹)	1 μm
[132]	H ₂ O/LiBr	Ps (0.8 - 1.8 kPa), Ts (25 - 35 °C), Xs (60%), Tc (15 - 35 °C), ms (0.6 - 2.1 kg.h ⁻¹)	1 μm
[133]	NH ₃ / H ₂ O	Ps (130 kPa), Ts (21 - 31 °C), Xs (31.5 - 32.5%), ms (15 - 45 kg.h ⁻¹)	0.05 μm
[134]	NH ₃ / H ₂ O	Ps (130 - 150 kPa), Ts (24 - 35 °C), Xs (29 - 32%), ms (50 - 100 kg.h ⁻¹)	0.03 μm
Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms (solution flow), Tc (coolant temperature), * concentration of ammonia for NH ₃ based fluids and concentration of LiBr for LiBr based fluids.			

3. Heat and mass transfer intensification in absorbers

The passive intensification of the heat and mass transfer phenomenon taking place in absorbers can be obtained mainly by applying three techniques: use of advanced surface designs or mechanical treatments, use of additives in working fluids, and nanotechnology [115]. Due to the fact that the predominant resistance to the heat and mass transfer is mainly found on the solution side, the techniques are usually applied to this side to enhance the mixing of liquid and vapour phases and therefore improve heat and mass transfer processes.

Investigations on these intensification techniques in absorbers have been conducted more frequently in the last years. A brief description of these enhancement techniques is presented in the following subsections. In addition, experimental studies dealing with this issue are identified, detailed and reviewed. Investigations presented for each case follow a chronological order.

3.1. Advanced surface designs

In falling film absorbers, for instance, heat and mass transfer take place generally on the outer tube surface, so advanced surfaces or mechanical treatments are employed on this side. Advanced surfaces can include treated surfaces such as scratched surfaces to increase the surface roughness, constant curvature tubes, fluted tubes, micro-finned tubes, corrugated plates, finned plates. Heat and mass transfer in bubble mode take place inside tubes or channels where the absorbent solution and the refrigerant flow. Therefore, mechanical treatments in bubble absorbers involve the use of internal extended surfaces or corrugated surfaces. In the case of microchannel tubes, or compact

and constrained designs such as plate and membrane absorbers, these are considered to be advanced designs, so they are also included in this section. A review of the experimental studies available in the open literature employing absorbers with advanced surface designs for absorption systems is presented below.

In early studies, compact absorbers were evaluated in order to identify potential designs for smaller absorbers [110-111]. For instance, Merrill et al. [110] evaluated the performance of three type of bubble absorbers with compact designs for desorber-absorber heat exchange absorption cycles applications (GAX). The designs tested involved roughness, spiral flutes, and internal spacers. Even though the estimated heat transfer coefficients were highly uncertain, experimental results did evidence an enhancement in the GAX load when compared to base values. The authors also concluded that the vapour injection process needed further improvement to foster absorption. Later on, Kang et al. [111] carried out experiments for $\text{NH}_3/\text{H}_2\text{O}$ falling film absorption processes in a compact heat exchanger consisting of plates with enhanced surfaces as shown in **Figure 6**. This particular absorber design had an offset strip fin between two plates on the absorption side and rectangular plain fins between two plates on the coolant side. The authors studied the effects of vapour and solution flow, inlet sub-cooling of the solution flow and inlet concentration difference on heat and mass transfer rates. From the sensitivity analysis, the authors noted that the solution Nusselt number was more affected by the falling film solution flow rather than by the vapour flow, while the Sherwood number was more affected by the vapour flow rather than by the solution flow. Finally, the authors reported correlations of heat and mass transfer coefficients for this design.

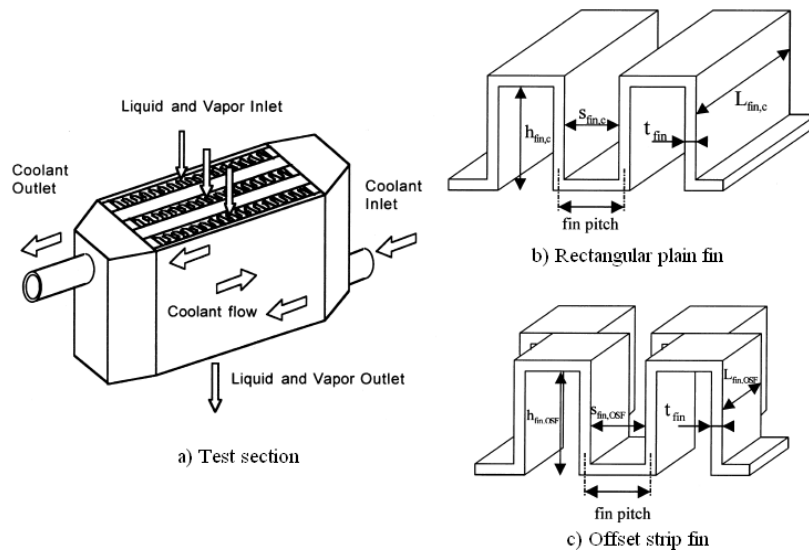


Figure 6 - Absorber with rectangular fin and OSF studied by Kang et al. [111].

Meanwhile, Yoon. et al. [112] evaluated the performance of a $\text{H}_2\text{O}/\text{LiBr}$ falling film absorber employing tubes with different surfaces (such as: a bare tube, a floral shaped tube, a twisted floral tube and a bumping bare tube). The experiments were conducted varying the solution and cooling-water flow rate from 1.7 to 8.3 $\text{kg}\cdot\text{min}^{-1}$ and from 80 to 310 $\text{kg}\cdot\text{min}^{-1}$, respectively. In this study, the authors observed that tubes wettability improved when the solution mass flow was increased, resulting in a positive effect on the heat and mass transfer rates. From tubes tested, the twisted floral tube reported about 40% higher heat and mass transfer rates in comparison to those with the bare tube.

Comparative analysis of the absorption process using $\text{NH}_3/\text{H}_2\text{O}$ in both the falling film and the bubble mode has also been reported. Helbing et al. [113], for instance, conducted experiments in a falling film in a vertical tube with a heat transfer area of 0.076 m^2 while experiments in bubble mode included a narrow plate channel with a heat transfer area of 0.048 m^2 and different corrugation angles (30° and 60°). In this study, the authors proved that for the plates tested the corrugation angle barely affected the heat transfer performance of the absorber, however, it did represent a significant increment in heat transfer (up to 3.0 times higher) when compared with using a plain surface plate. In addition, when comparing falling film and bubble absorption modes, the authors concluded that the absorption in bubble mode resulted in a significant advantage in terms of heat and mass transfer due to a more effective and intensive interaction between both the liquid and vapour phase. Also, the authors identified the gas distribution system as a crucial element for improving heat transfer in this bubble absorber configuration.

Lee et al. [114] evaluated the effect of solution and vapour flow rates on a plate-type $\text{NH}_3/\text{H}_2\text{O}$ bubble absorber and proposed correlations for the Nusselt and Sherwood numbers. Initially, three types of plates were tested: smooth plate, hair-lined plate treated by laser, and plate treated by sand paper. However, the main analysis was focused on the plate treated by sand paper due to its better wettability.

Kim et al. [115] and Park et al. [116] carried out a sensitivity analysis based on the effects of micro-scaled surface treatments on the wettability and absorption performance of a $\text{H}_2\text{O}/\text{LiBr}$ falling film absorber. In this study, three types of tubes were tested; a smooth tube, a tube N. 600 with a roughness of 0.384 μm and a tube N. 24 with a roughness of 6.986 μm as shown in **Figure 7a**. The absorber, tested at a pressure of 0.94

kPa, consisted of 28 copper tubes with a diameter of 16 mm and a length of 205 mm. The results from this study corroborated that the wettability for the hatched tubes was better than that of the smooth tube. **Figure 7b** depicts, for instance, that the absorption performance of the absorber with the micro-hatching tubes was improved up to twice as much compared with the smooth tubes.

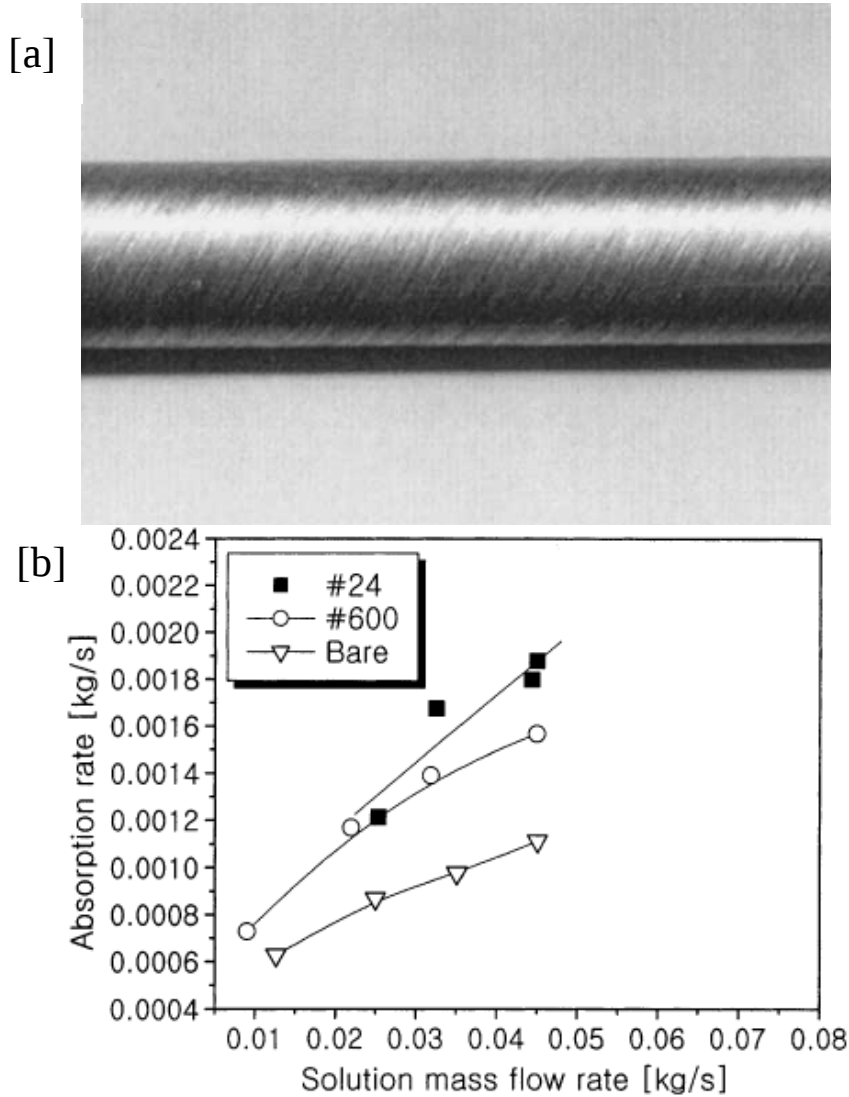


Figure 7 – [a] Micro-scaled hatched tubes N. 24, and [b] vapour absorption rate versus solution mass flow rate, by Park et al. [116].

Even though falling film absorbers usually occupy large volumes due to their low operating pressures and high specific volume of the refrigerant vapour, small designs are possible to obtain by using microchannel tube arrays [126, 118]. Meacham and Garimella [117] evaluated the ammonia absorption in a microchannel tube array absorber as shown in **Figure 8** (with dimensions of $0.162 \times 0.157 \times 0.150$ m and

surface area of 0.456 m^2). In this configuration, the weak solution flowed in falling film mode while the refrigerant vapour flowed upward in counter-current configuration. The authors reported absorption thermal loads of up to 15 kW and solution heat transfer coefficients as high as $1.648 \text{ kW.m}^{-2}\text{K}^{-1}$. In the case of the study reported by Goel and Goswami [118], experiments were based on falling film tube absorbers consisting of 4 columns, each one with 60 horizontal tubes, and tested with and without a screen mesh as shown in **Figure 9a**. The study was mainly focused on determining the absorber heat duty for each absorber configuration. **Figure 9b** shows as reported that the thermal load of the micro-channel absorber with the mesh was about 17% and 26% higher than that of the design without the mesh.

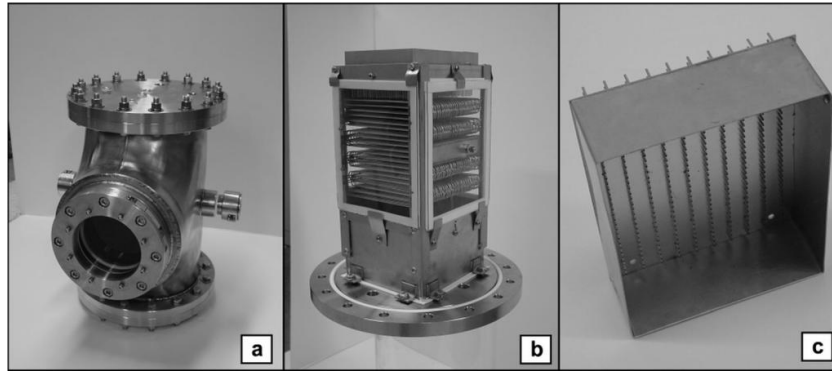
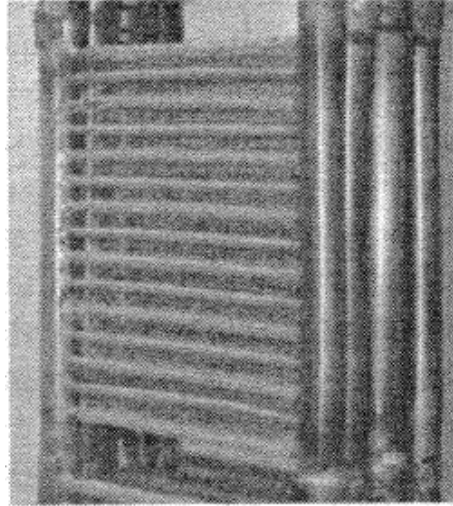


Figure 8 – Microchannel absorber tested by Meacham and Garimella [117].

Research on compact absorbers has also yielded to the proof-of-concepts of constrained film absorbers [119, 121]. For instance, Jenks and Narayanan [119] presented a constrained film $\text{NH}_3/\text{H}_2\text{O}$ horizontal absorber with different plate surfaces. In this study, the refrigerant flowed through a porous plate to the weak solution side where it was later absorbed and the coolant flowed in counter-current configuration. **Figure 10a** shows the tested plates which include three channels with different smooth-bottom-walls and structured bottom walls. For each configuration, the authors analysed the effects of the weak solution and ammonia flow on the absorber heat and mass transfer coefficients. According to the results in **Figure 10b**, the plate with the smallest channel depth provided the highest mass transfer flows. Meanwhile, Cardenas and Narayanan [121] tested the ammonia bubble absorption performance in a constrained thin-film plate with micro-channels as shown in **Figure 11**. Two absorber designs were tested, the first one with a 600 mm deep smooth-wall and the second one with a stepped microchannel wall. In both absorber designs, the refrigerant vapour entered the test

section in cross flow configuration to the solution through a porous area. The authors reported mass transfer rates between 0.025 and $0.155 \text{ kg.s}^{-1}.\text{m}^{-2}$ for the smooth wall option and between 0.025 and $0.235 \text{ kg.s}^{-1}.\text{m}^{-2}$ for the stepped microchannel absorber.

[a]



[b]

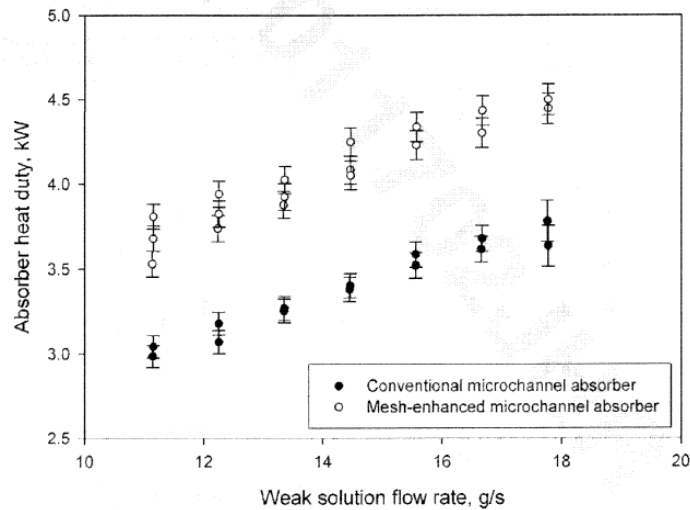
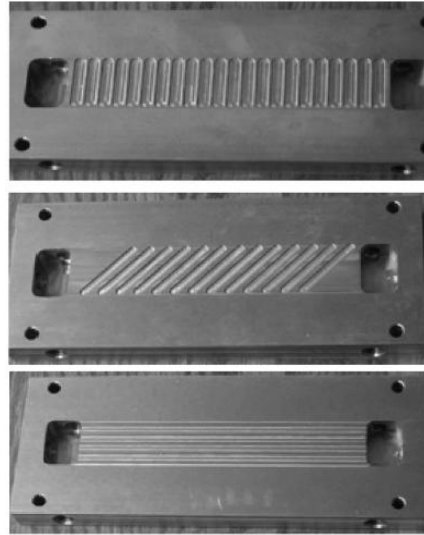


Figure 9 – [a] Close view of the screen mesh in between the tubes row and [b] absorber duty vs solution flow rate [118].

Cerezo et al. [120] reported a complete sensitivity analysis of the heat and mass transfer in a corrugated plate bubble absorber with $\text{NH}_3/\text{H}_2\text{O}$. The absorber was a plate heat exchanger L-type with three channels where ammonia vapour entered in bubble mode through the bottom of the central channel in co-current configuration with the solution flow. Experiments were performed varying parameters such as inlet solution concentration, solution temperature, solution flow rate, absorber pressure, and cooling-water temperature. Moreover, values of absorption mass flux, solution heat and mass transfer coefficients, and degree of sub-cooling of the leaving solution were reported.

Results evidenced that the absorption mass flux varied in the range between 0.0025 and 0.0063 $\text{kg.m}^{-2}\text{s}^{-1}$, the solution heat transfer coefficient between 2.7 and 5.4 $\text{kW.m}^{-2}\text{K}^{-1}$, the mass transfer coefficient between 3.6 and 7.2 m.h^{-1} , and the absorber load between 0.5 and 1.3 kW.

[a]



[b]

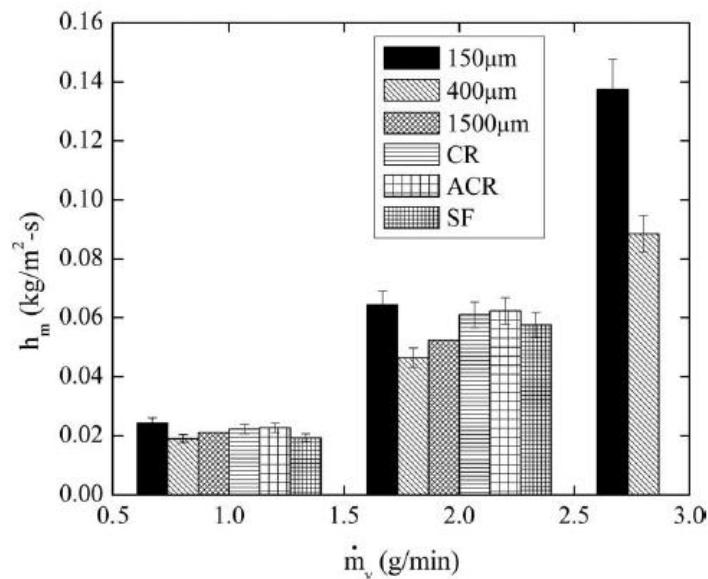


Figure 10 – [a] Three structured microchannels, CR, ACR, and SF, respectively, and [b] absorber mass flux vs gas flow rate for various geometry channels [119].

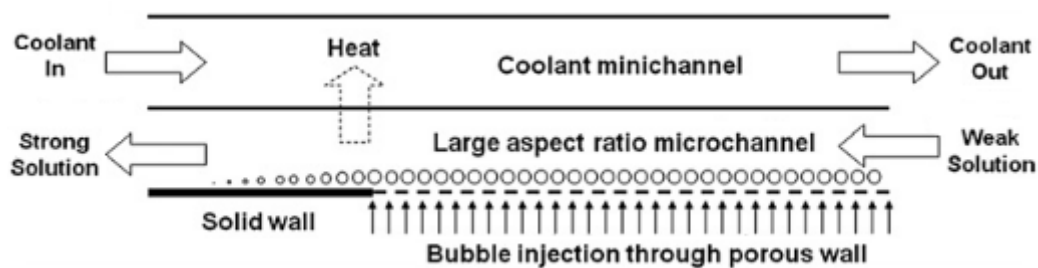


Figure 11 – Microchannel absorber concept [121].

Lee et al. [122], giving continuity to studies on $\text{NH}_3\text{-H}_2\text{O}$ falling film absorbers, tested the performance of a compact horizontal-tube falling film absorber consisting of four columns, each one of six tubes measuring 0.292 m in length and 9.5 mm in diameter, **Figure 12**. In this case, tests were conducted in a test facility which included all the components of a chiller and the effects of absorber operating pressure, inlet solution concentration and solution mass flow on the absorber performance were reported. Experimental results showed that the mass transfer coefficient in the liquid phase varied from 5.51×10^{-6} to $3.31 \times 10^{-5} \text{ m.s}^{-1}$ with an absorber heat duty ranging from 3.11 to 10.2 kW. Meanwhile, Alvarez and Bourouis [37] tested the performance of a falling film absorber consisting of 6 tubes with treated surfaces working with a mixture of H_2O and $\text{LiNO}_3+\text{KNO}_3+\text{NaNO}_3$ for systems driven by high-temperature heat sources. In this study, the vapour mass transfer was found to vary from 2.83 to $6.55 \text{ g.m}^{-2}.\text{s}^{-1}$ while the solution heat transfer coefficient ranged between 0.623 and $1.716 \text{ W.m}^{-2}.\text{°C}^{-1}$.

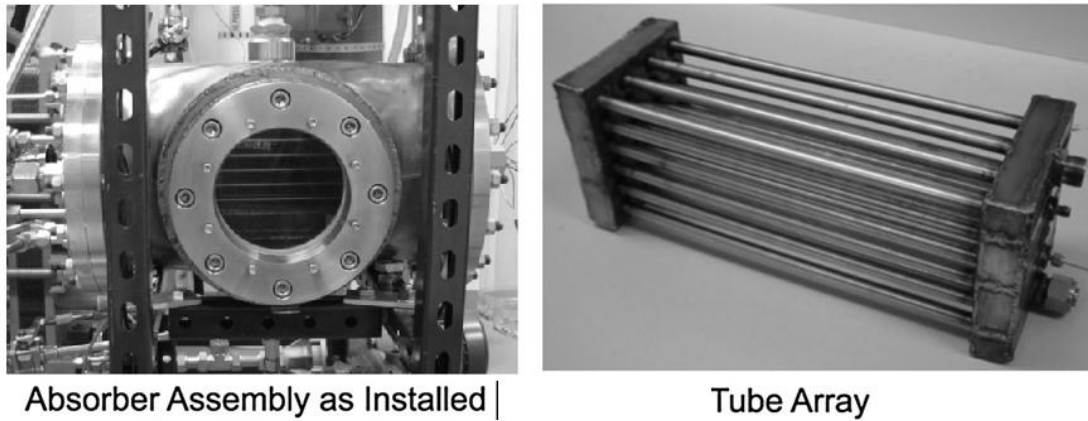


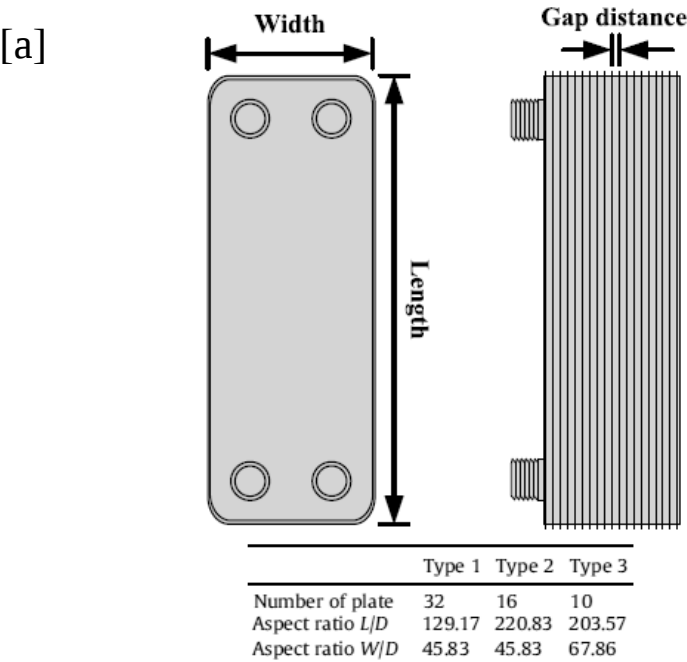
Figure 12 – Compact falling film tube absorber tested by Lee S., et al. [122].

More recently, Nagavarapu and Garimella [123] tested the absorber designed by Meacham and Garimella [117] in a single-effect absorption test facility. This study also evidenced on the effects of vapour and solution vapour flow rates, solution concentration, and fluid thermal conditions on the heat and mass transfer coefficients. Results showed that the absorber duty was up to 10 kW, the mass transfer coefficient up to 0.25 m.s^{-1} and the solution-side heat transfer coefficients varied between 1.450 and $3.450 \text{ kW.m}^{-2}.\text{K}^{-1}$.

Suresh and Mani [124], in turn, studied the heat and mass transfer aspects of Tetrafluoroethane (R134a) in Dimethyl formamide (DMF) solution in a compact place bubble absorber of a 1 TR capacity absorption refrigeration system. This study included

the effect of the circulation ratio, and absorber and generator temperatures on overall heat transfer coefficient, the heat and mass transfer effectiveness, and volumetric mass transfer coefficient. As a result, the authors observed that heat and mass transfer effectiveness of the absorber was higher at low circulation ratios and high generator temperatures. Also, the authors proposed a correlation for the mass transfer in the plate absorber based on a modified Sherwood number correlation which takes into account the Reynolds number, the Schmidt number as well as non-dimensional temperature gradients.

Jung et al. [125] estimated the thermal pperformance of ammonia bubble plate absorbers for hybrid compression/absorption heat pumps. This work included the effect of the inlet solution concentration, absorber internal pressure and absorber geometric dimensions on the system COP, absorber thermal capacity, hot water outlet temperature and ammonia solution heat transfer coefficient. **Figure 14a** shows the main characteristics of the three plate absorbers that were tested in this study, each one with a different physical dimension but with the same heat transfer area (0.08 m^2). From this study, the authors observed that the solution side heat transfer coefficient and the absorber capacity (see **Figure 13b**) increase with an increase in the aspect ratio (L/D), this being a more determining parameter than the aspect ratio (W/D).



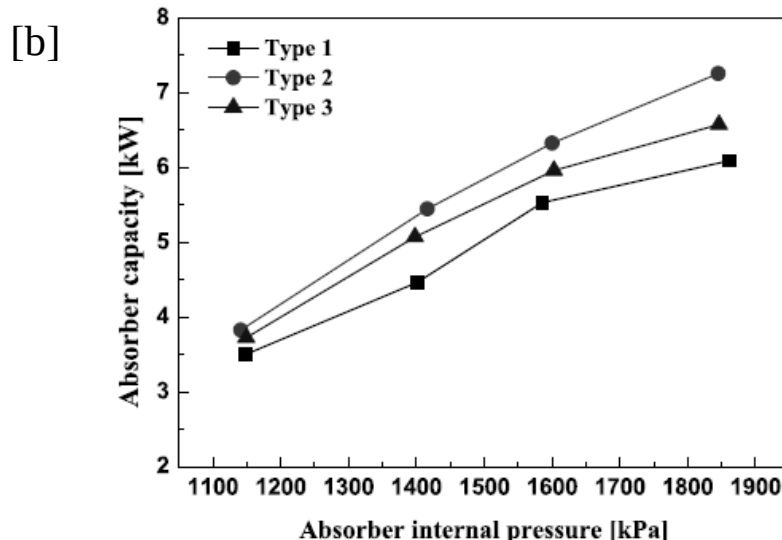


Figure 13 – [a] Schematic diagram of the plate absorber and [b] absorber duty vs absorber pressure for the different absorbers types [125].

Even though compact absorbers, such as plate or constrained flow absorbers, offer high absorption rates in small designs, they cannot be directly air-cooled, and therefore water-cooling is needed requiring additional components. In case of direct air-cooled absorption system designs, the absorption performance can be enhanced by using inner advanced surfaces to improve the interface area of both the liquid and vapour flow and facilitate the vapour absorption. Amaris et al. [126], for instance, studied the effect of inner advanced surfaces on the NH_3 absorption process using $\text{NH}_3/\text{LiNO}_3$ as working pair in a tubular bubble absorber, **Figure 14a**. Experiments in the bubble absorber with an internal smooth tube were also performed and compared with those achieved with the advanced surface tube. The absorber performance with advanced surfaces using two tube lengths (1 and 3 m) and two tube diameters (8 and 9.5 mm) was also investigated. Results from these experiments showed that the absorption rate increased on increasing the solution rate and that this trend was more pronounced with the advanced surfaces. It was also reported that higher absorption rates could be reached on reducing the tube diameter. Moreover, results showed that the maximum absorption rate with the advanced surfaces tube absorber was up to 1.7 times higher than that of the smooth tube, **Figure 14b**. Cerezo et al. [127] tested the NH_3 absorption performance in the double pipe absorber which includes a helical static mixer in both the central and annular sides. From these experiments, the authors reported an improvement of 20% in vapor absorption and 31.6% in thermal load with respect the configuration with smooth pipes.

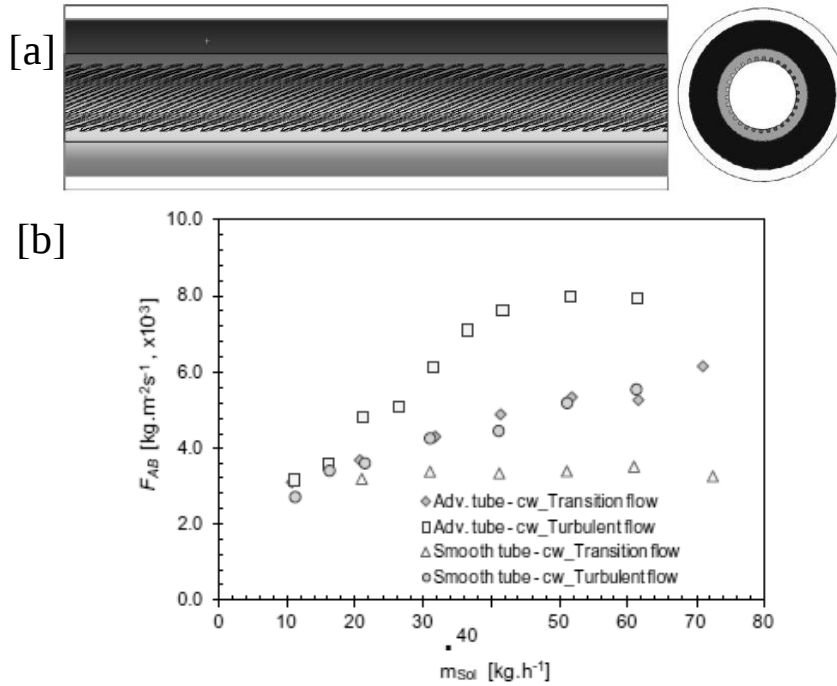


Figure 14 – [a] Cross-section view of the advanced surface tube and [b] Effect of advanced surfaces on NH₃ absorption mass flux [126].

Following the idea of Goel and Goswami [118], Wu et al. [128] evaluated the heat and mass transfer rate in a H₂O/LiBr falling film absorber including a stainless steel mesh packing structure. The mesh consisted of forty-stainless steel mesh screens folded as longitudinal troughs inserted between the horizontal tubes. Experiments were conducted at an absorber pressure of 2.5 kPa, LiBr solution concentration of 55.75% and at an inlet solution temperature of 40°C. The authors reported a maximum mass absorption rate of around 15 kg.h⁻¹ using the mesh while it was around 12 kg.h⁻¹ without it. Based on the results, the mesh increased the average solution mass transfer by 17.2% compared to that of the bundle of tubes without the mesh. It was also observed that the use of the mesh enhanced the solution heat transfer only at the highest solution flows. Finally, the authors highlighted that the advantage of the mesh is that it extends the retention time of the solution in the absorption zone. From the same test facility and in a similar study, Chen et al. [130] reported that for the falling film absorber with M–W mesh guider inserts, the heat and mass transfer coefficients were around 33.4% and 55.4% higher than those of the bare tubes.

More recently, Mortazavi et al. [129] designed and tested a H₂O/LiBr falling film plate absorber with sandblasted offset-strip fins as presented in **Figure 15**. The experiments were conducted varying the solution flow from 0,44 to 1,22 kg.min⁻¹.m⁻¹, the solution temperature from 30 to 38 °C and the cooling water temperature from 35 to 35 °C

among others. According to the authors, the new absorber design provided absorption rates up to two times higher than those values of conventional falling film absorbers in the literature.

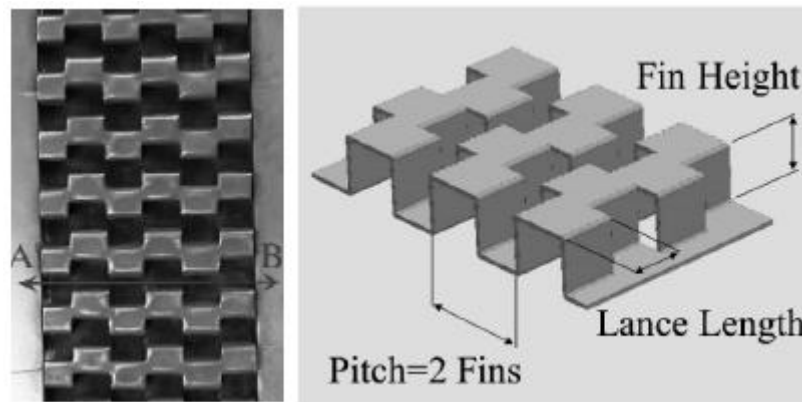


Figure 15 – plate absorber and lanced offset fins [129].

The latest studies have also involved membrane-based absorbers which appear as a promising passive mechanical technique for miniaturising components [109,131,132]. For instance, Isfahani R.N. and Moghaddam [131] quantified the effects of cooling water temperature, water vapour pressure, solution flow velocity, and solution film thickness on the absorption rate in a $\text{H}_2\text{O}/\text{LiBr}$ absorber configured as shown in **Figure 13**. From the experiments, a positive effect on the mass transfer was observed on the increasing the vapour pressure and the solution flow. Interestingly, it was also observed that the mass transfer increased on reducing the solution film thickness. This was due to the fact that the contact interface between the vapour and solution was improved. Finally, the authors reported absorption mass fluxes varying from 0.0017 to 0.0077 $\text{kg.m}^{-2}.\text{s}^{-1}$ and highlighted that at a pressure of 1.3 kPa the absorption rate reached in the membrane-based absorber was up to two and half times higher than the rates reported in previous falling film studies.

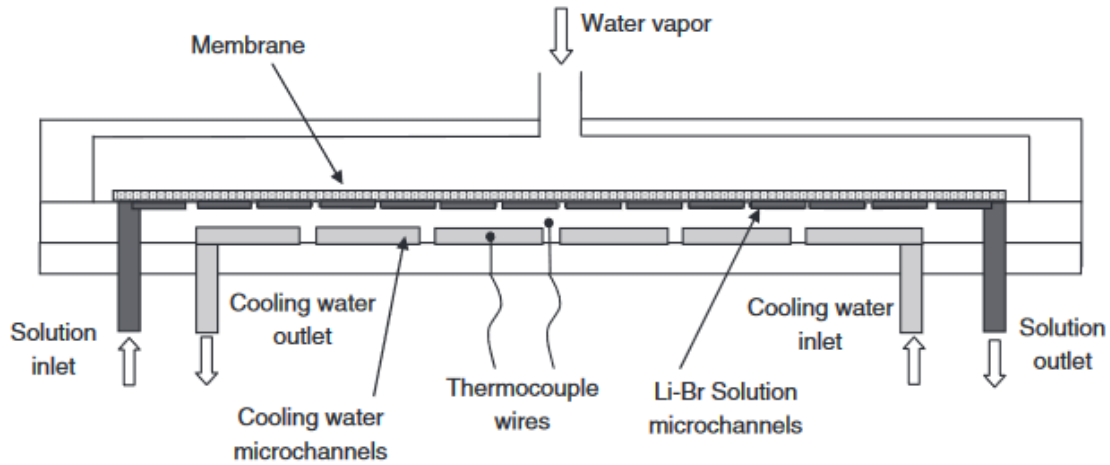


Figure 16 – Membrane-based plate absorber [131].

Berdasco et al. [133] evaluated the NH_3 mass transfer in an adiabatic flat sheet membrane absorber (with dimensions 14.6 cm x 9.5 cm) as a function of the solution inlet sub-cooling and solution mass flow. In this study, the authors employed a hydrophobic polytetrafluoroethylene (PTFE) laminated membrane reporting absorption rates up to $4.7 \times 10^{-3} \text{ kg.m}^{-2}\text{s}^{-1}$ at a solution mass flow of 45 kg.h^{-1} . Then, Berdasco et al. [134] reported on the NH_3 mass transfer this time in adiabatic polymeric hollow fiber membranes resulting in absorption rates up to $3.0 \times 10^{-4} \text{ kg.m}^{-2}\text{s}^{-1}$ at a solution mass flow of 100 kg.h^{-1} .

A summary of the experimental studies available in the open literature employing absorbers with advanced surface designs for absorption systems is listed in Table 5.

Table 5. Summary of experimental studies applying mechanical treatments in absorbers for absorption cooling/heating systems.

Reference	Test Section	Working fluid	Test conditions	Note
[111]	Falling film - plate type	H ₂ O/LiBr	Ts (17 - 37.2 °C), Xs (5 - 15%), ms (4.0 - 10.15 g.s ⁻¹), yg (64.7 - 79.7%), Tg (54.5 - 66.5 °C), mg (0.62 - 0.90 g.s ⁻¹), mc (98.83 - 121.25 g.s ⁻¹)	Plate with offset strip fins on the absorption side, and rectangular plain fins on the coolant side
[112]	Falling film - Tube arrays	H ₂ O/LiBr	Ts (40 °C), Xs (58%), ms (1.7 - 8.3 kg.min ⁻¹), Tc (28°C), mc (80 - 310 kg.min ⁻¹)	Tests with a bare tube, twisted floral tube, floral shape tube, bumping bare tube. tube bank of 6 rows and 8 tubes
[113]	falling film/bubble mode	NH ₃ /H ₂ O	Ts (24.8 - 39.8 °C), Xs (5 - 20%), ms (29 - 90 kg.h ⁻¹), Tg (9.8 - 29.8 °C)	Plate type heat exchanger with corrugation angle of 30° and 60° and without corrugation.
[114]	Bubble mode - Plate type	NH ₃ /H ₂ O	Ts (20 °C), Xs (0-30%), ms (0.3 kg.min ⁻¹)	Tests with a plate treated by sand paper
[115]	Falling film - Tube arrays	H ₂ O/LiBr	Ps (94 kPa), Ts (30 - 50 °C), Xs (50 - 62.1%), ms (0.74 - 2.71 kg.min ⁻¹)	Three types of tubes tested: a smooth tube, and tubes with a roughness of 0.384 um and 6.986 um, wettability and mass transfer improved by using micro-hatching tubes.
[116]	Falling film - Tube arrays	H ₂ O/LiBr	Ps (0.94 kPa), Ts (36 - 46 °C), Xs (55-61%), Tc (24-32 °C), mc (1-9 l.min ⁻¹)	Absorption performance with the micro-hatching tubes improved up to 2 times compared with the smooth tubes.
[117]	Falling film - Tube arrays	NH ₃ /H ₂ O	Ps (355 - 680 kPa), Ts (52 - 81 °C), Xs (28-35.1%), ms (0.0151-0.0266 kg.s ⁻¹), yg (0.93-0.98%), Vc (0.000095-0.000158 m ³ .s ⁻¹)	Microchannel tube arrays
[118]	Falling film - Tube arrays	NH ₃ /H ₂ O	Ps (281 kPa), Ts (43 °C), Xs (30%), ms (11.1 - 17.8 g.s ⁻¹), yg (95.6%), Tg (58 °C), mc (88.7 g.s ⁻¹), Tc (20 - 30 °C)	Falling film absorber with and without screen mesh-enhanced micro-channels
[119]	Bubble mode - Plate type	NH ₃ /H ₂ O	Ps (400 kPa), Ts (22.5 °C), Xs (15%), ms (10 - 30 g.min ⁻¹), Tg (22.4 °C), mg (1-3g.min ⁻¹), Tc (10.6 °C), mc (269 g.min ⁻¹)	Plates with different smooth-bottom-walled and structured bottom walls channels.
[120]	Bubble mode - Plate type	NH ₃ /H ₂ O	Ps (160 - 200 kPa), Ts (35 - 55 °C), Xs (30 - 38%)	Plate heat exchanger with corrugations
[121]	Bubble mode - Constrained plate type	NH ₃ /H ₂ O	Ps (620 kPa), Ts (75 °C), Xs (29%), ms (10 - 55 g.min ⁻¹), mg (1-5 g.min ⁻¹), Tc (30 - 58 °C)	Two plate absorbers, one with a 600 mm deep smooth-wall and one with a stepped microchannel
[122]	Falling film - Tube arrays	NH ₃ /H ₂ O	Ps (150, 345 and 510 kPa), Xs (5, 15, 25, 40%), ms (0.019, 0.026 and 0.034 kg.s ⁻¹)	Compact falling-film absorber consisting of 4 columns of 6 tubes
[37]	Falling film - Tube arrays	H ₂ O+ LiNO ₃ +KNO ₃ +NaNO ₃	Ps (30-35 kPa), Ts (90 - 110 °C), Xs (75 - 82%), ms (0.010 - 0.021 kg.m ⁻¹ .s ⁻¹), mc (150 - 235 l.h ⁻¹), Tc (70 - 86 °C)	6 copper tubes with treated surfaces. Tube outer diameter of 16 mm and 400 mm long
[123]	Falling film - Tube arrays	NH ₃ /H ₂ O	Xs (20 - 40%), ms (0.011-0.023 kg.s ⁻¹), Xg (40 - 55 °C), Tc (20 - 40 °C), mc (0.139 kg.s ⁻¹)	Falling-film absorber with microchannel tube arrays
[124]	Bubble mode - Plate type	R134a/DMF	Ts (17 - 35 °C)	Compact bubble absorber (plate heat exchanger)
[125]	Bubble mode - Plate type	NH ₃ /H ₂ O	Ps (1150 - 1850 kPa), Xs (49 - 55%), ms (0.09 kg.s ⁻¹), Tc (50 °C), mc (0.05623 kg.s ⁻¹)	Three plate absorbers with different physical dimensions
[126]	Bubble mode - double pipe	NH ₃ /LiNO ₃	Ps (510 kPa), Ts (45 °C), Xs (45%), ms (10 - 72 kg.h ⁻¹), Tc (35 - 40 °C), Vc (80 - 435 l.h ⁻¹)	Tests with smooth and internal helical micro-fined surface tubes, absorption rate with the advanced surfaces up to 1.7 times higher than that with the smooth tube
[127]	Bubble mode – double pipe	NH ₃ /H ₂ O	Ps (570 kPa), Xs (40.5%), ms (0.03 kg.s ⁻¹), mc (0.255 kg.s ⁻¹)	Helical static mixer in both the central and annular sides, improvement in vapor absorption of 20%
[128, 130]	Falling film - Tube arrays	H ₂ O/LiBr	Ps (2.5 kPa), Ts (40 °C), Xs (55.75%), Tc (10.5 °C), Vc (40 l.min ⁻¹)	Forty-stainless steel mesh screens with wire diameter of 0.2 mm inserted between the horizontal tubes
[129]	Falling film - plate type	H ₂ O/LiBr	Ps (0.8 - 1.4 kPa), Ts (30 - 38 °C), Xs (54 - 59%), ms (0.44 - 1.22 kg.min ⁻¹ .m ⁻¹) Tc (25 - 35 °C)	Sandblasted fins made of copper. Thickness, fin height, lanced length, and pitch of 0.15 mm, 6.35 mm, 6.35 mm and 11.6 mm, respectively.
[131,132]	Constrained flow - membrane	H ₂ O/LiBr	Ps (0.8 - 1.8 kPa), Ts (25 - 35 °C), Xs (60%), ms (0.6 - 2.1 kg.h ⁻¹), Tc (25 - 35 °C)	Membrane with pore size of 1 µm and is 80% porous. Solution flow micro-channels of 160 and 100 µm deep
[133]	Constrained flow - membrane	NH ₃ /H ₂ O	Ps (130 kPa), Ts (21 - 31 °C), Xs (31.5 - 32.5 wt.%), ms (15 - 45 kg.h ⁻¹)	Flat sheet membrane absorber with an average pore diameter 0.05 µm
[134]	Constrained flow - membrane	NH ₃ /H ₂ O	Ps (130 - 150 kPa), Ts (24 - 35 °C), Xs (29 - 32 wt.%), ms (50 - 100 kg.h ⁻¹)	Polymeric hollow fiber membranes with an average pore diameter of 0.03 µm
Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms,Vs (solution flow), Tc (coolant temperature), mc, Vg (coolant flow), mg,Vg (gas flow), Vel,g (gas velocity), yg (vapour concentration), * concentration of ammonia for NH ₃ based fluids and concentration of LiBr for LiBr based fluids.				

3.2. Additives in working fluids

Use of additives in working fluids, which have been extensively investigated, consists in the addition of small quantities of active agents (surfactants) to induce surface tension gradients in the solution and vapour. This causes the Marangoni effect (interfacial turbulence as visualized in **Figure 17**) and leads to higher heat and mass transfer coefficients [135]. Other additives were used to improve the transport properties of the working fluids [151].

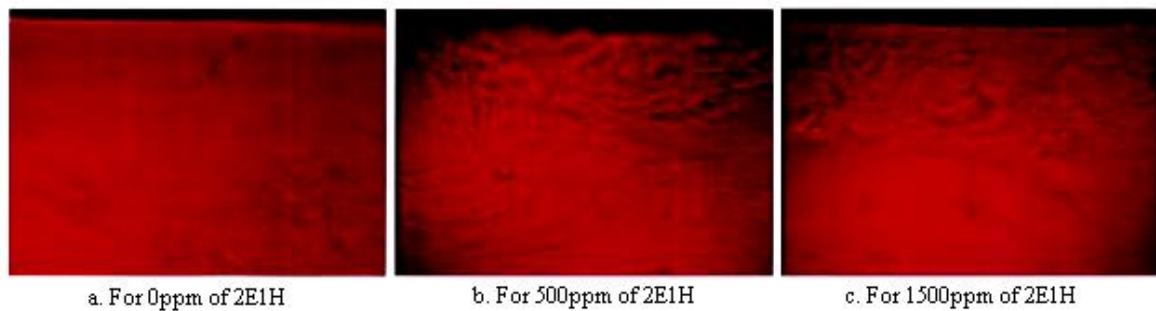


Figure 17 - Visualisation of Marangoni convection by Kang et al. [142].

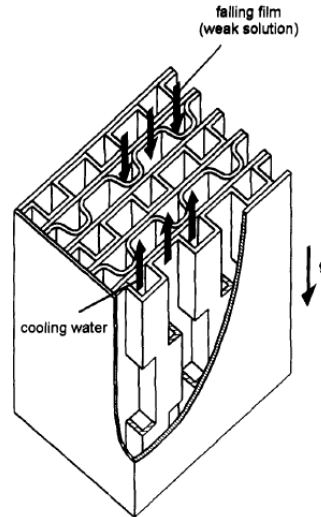
Studies have highlighted that the presence of additives in the vapour flow may have a higher effect on the surface tension than on the absorbent solution [135]. It was also found that the surface tension of the absorbent solution with the presence of additives decreases as the absorbent solution concentration increases [136]. Based on those findings, it can be concluded that the surface tension affects flow patterns to a large degree. In the bubble mode absorption, the interfacial area between the liquid and vapour phase is significantly affected by the surface tension of the liquid. The higher the surface tension is, the lower the total interfacial area and bubble breaking phenomena is. In configurations like those in a falling film flow, the wettability on the tubes is also affected by the surface tension of the solution, limiting the heat transfer, and the mass transfer. The higher the tension of the surface is, the lower the tube wettability and absorption potential are.

Based on the results mentioned above, several studies have focused on the addition of small quantities of a third component to a base fluid or vapour in order to reduce surface tension and facilitate refrigerant vapour absorption. Characteristics such as the components and concentration of the additive and the concentration of base fluids have been identified as key factors which influence heat and mass transfer enhancement in absorbers for absorption cooling/heating systems.

This sub-section explores the experimental investigations employing surfactants or other substances in binary mixtures to improve the absorption process for absorption systems.

Following the studies reporting the effect of additives on the surface tension of aqueous solutions, Hihara E. and Saito [137] carried out a study on water vapour absorption into H₂O/LiBr in falling film mode with the addition of 2-ethyl-1-hexanol. In this study, a flat plate was used as an absorber and the influence of parameters such as the concentration of the additive, solution flow rate, and the plate angle inclination on the vapour absorption were studied. The main output from this work was a significant mass transfer enhancement up to 5 times higher than that of the base fluid. It was also observed that no difference on the absorption rate was observed when varying the additive concentration from 60 to 100 ppm. Some years later, Hoffmann et al [138] experimentally evaluated the single and combined effect of knurled tubes and additives on the heat transfer of a LiBr solution in a falling film tube absorber. The absorber consisted of 24 tubes arranged in a row. In the case, 2-ethyl-1-hexanol was also employed at various concentrations. Results from this study showed that improvements in the heat transfer coefficient obtained with the knurled tubes were up to 40% higher than those obtained with the plain tube, especially at low flow rates. In addition, the use of additives represented improvements in the heat transfer coefficient of up to 140% with respect to the base case. Meanwhile, Moller and Knoche [139] selected the NH₃/H₂O mixture and evaluated the effect of different surfactants on the absorption process in a compact absorber. The compact absorber was a compact brazed plate heat exchanger with an offset strip fin (OSF) as illustrated in **Figure 18a**. The authors employed surfactants to reduce the surface tension of the solution and the interfacial tension between solid surface and solution, and to improve the wettability of the walls of the channels and mass transfer. In this case, the surfactants used were Marion PS (0.25 wt.%, 0.4 wt.%), Marion A (0.25 wt.%, 0.5 wt.%), Dehydol LT 14 (0.5 wt.%), Emulgin B1 (0.5 wt.%, 0.91 wt.%), 1-Octanol (50, 100 and 500 ppm). From this study, the authors confirmed that the use of surfactants strongly reduced the surface tension and improved the wettability of the compact heat exchanger plates and mass transfer. The authors also found that the best result in terms of the measured absorption rates was achieved with 50 ppm of dissolved 1-octanol, **Figure 18b**.

[a]



[b]

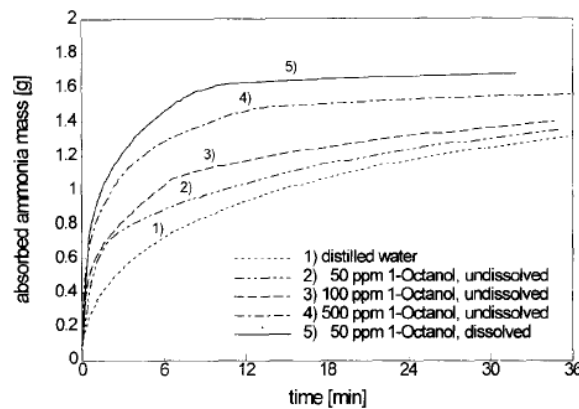


Figure 18 – [a] Compact absorber and [b] ammonia absorption in water-octanol solutions, by Moller and Knoche [139].

Similarly, Nordgrent and Setterwall [140] reported the effect of the addition of 1-Octanol to a mixture of water and glycerol on the wave pattern that takes place in the falling film mode absorption process. Experiments were conducted with different mass flow rates (Re 40-260) and varying the surface tension of the mixture by changing the surfactant concentration. The absorber was a column of 6 m with an outside diameter of 51 mm and a wall thickness of 1.2 mm placed within a glass cylinder. Based on the experimental results the authors observed that the interfacial tension of the fluid decreased sharply when the surfactants were added resulting in more uniform waves in the falling film. The authors also noted that the surfactant concentrations under the saturation limit stabilised the falling film meanwhile concentrations over the limit destabilised the film.

Kim et al. [141] also reported on the absorption of water vapour to aqueous lithium bromide in a vertical falling film mode adding 2-ethyl-1-hexanol (1 to 100 ppm). In this case, the absorber tested, shown in **Figure 19**, consisted of two concentric tubes with an inner stainless-steel tube (measuring 1.83 m in length) and an outer Pyrex tube to

facilitate the observation. In this absorber, the LiBr solution flowed down the outside of the inner tube. The absorption took place at the outer wetted surface of the inner tube and the heat released by the absorption process was evacuated by cooling water flowing upward inside the inner tube. The authors observed that the film became highly turbulent during the absorption, starting from a surfactant concentration of 3-6 ppm and reaching a maximum effect near to 30 ppm. As a result, the heat and mass transfer was significantly enhanced. The authors concluded that the interfacial turbulence obtained was due to surface-tension gradients caused by the additive concentration, LiBr concentration, and the high temperature produced in the interface.

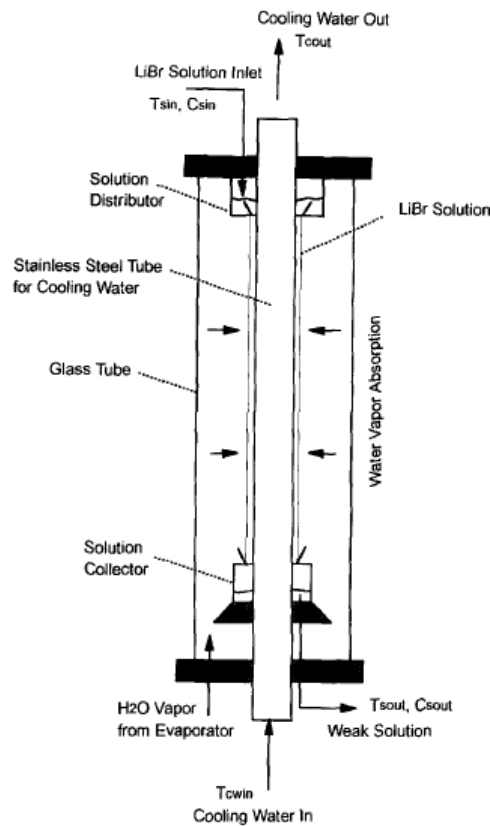


Figure 19 - Vertical Falling film absorber tested by Kim et al. [141].

For their part, Kang et al. [142] contributed to the development of $\text{NH}_3/\text{H}_2\text{O}$ systems, reporting interfacial tension and surface tension data for $\text{NH}_3/\text{H}_2\text{O}$ systems and various surfactants. The authors also visualised the Marangoni convection effect resulting from the use of surfactants. In this study, experiments with eight additives were carried out; 2-ethyl-1-hexanol (2E1H), n-Octanol (n-O), 2-Octanol (2-O), 3-Octanol (3-O), 4-Octanol (4-O), n-Decanol (n-D), 2-Decanol (2-D) and 3-Decanol (3-D). It was then observed that the limits of solubility of the additives in $\text{NH}_3/\text{H}_2\text{O}$ varied from 500 to

3000 ppm depending on the type of additive. It represented much larger values compared to those in H₂O/LiBr solution (70 to 400 ppm). The authors also reported that the surface tension rose by increasing the ammonia concentration for n-O, 2-D, 2-O, 3-D and 2E1H while it decreased for n-D, 3-O, 4-O. Finally, the authors reported a new model for the Marangoni convection using the best additives for NH₃/H₂O absorption systems.

Given the potential of obtaining a synergistic effect combining the use of advanced surfaces and additives [138], Miller [24] measured the absorption rate and determined the heat transfer coefficient in a H₂O/LiBr horizontal tube absorber comparing several advanced surface tubes and additives such as 2-ethyl-1-hexanol. The bundle of tubes consisted of six tubes made of copper, each one with an outer diameter of 15.9 mm and a length of 320 mm. The author reported that the tested advanced surfaces increased the mass transfer up to 1.75 times those values with the smooth surface tubes while the improvement with the additive was up to 2 times, **Figure 20**. The author also noted that the mass absorbed with the combined use of advanced surface tubes and additive increased by about 10 to 25% compared with the values of the additive and the smooth surface. Finally, the author concluded that the enhancement brought about by the mechanical mixing of advanced surfaces was not as effective as the enhancement induced by the chemical agitation of the additive and only produced a rather slight synergistic effect.

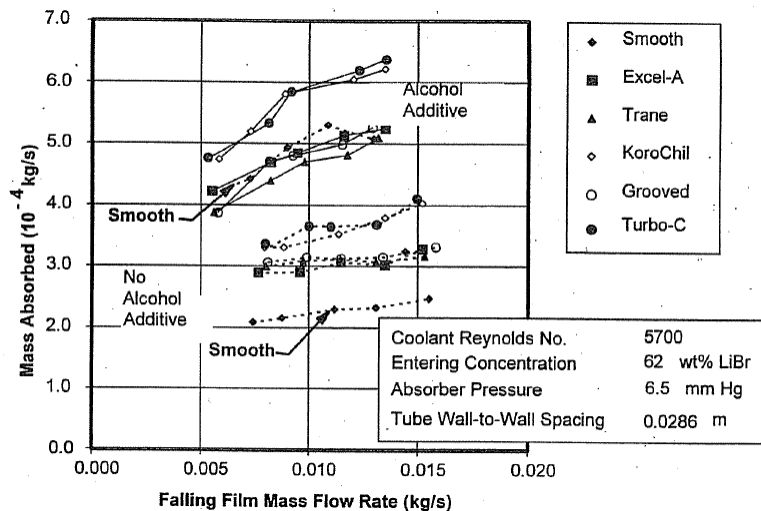


Figure 20 – Smooth tube and advanced tube bundles tested with and without 500 ppm of 2-ethyl-1-hexanol [24].

Yoon et al. [143] focused on the enhancement of the heat transfer by n-Octanol into H₂O/LiBr solutions. It also included the use of different tube surfaces, such as a bare tube, a floral tube and a hydrophilic tube, in a horizontal configuration as presented in **Figure 21a**. From this study, the authors obtained the highest wettability and heat transfer coefficient with the hydrophilic tube, however, higher heat transfer coefficients were achieved with the floral tube when the additive was added, **Figure 21b**. The authors also highlighted that the addition of surfactant concentrations higher than 3500 ppm did not show improvements in the heat transfer coefficient.

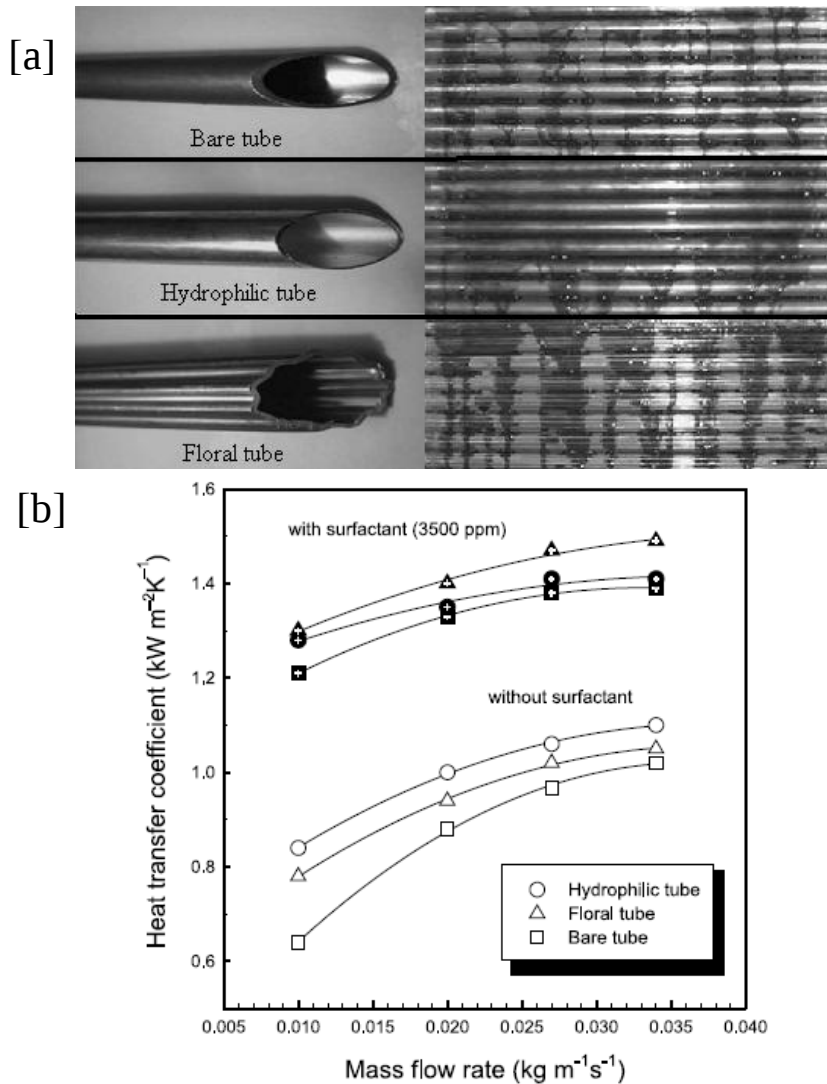
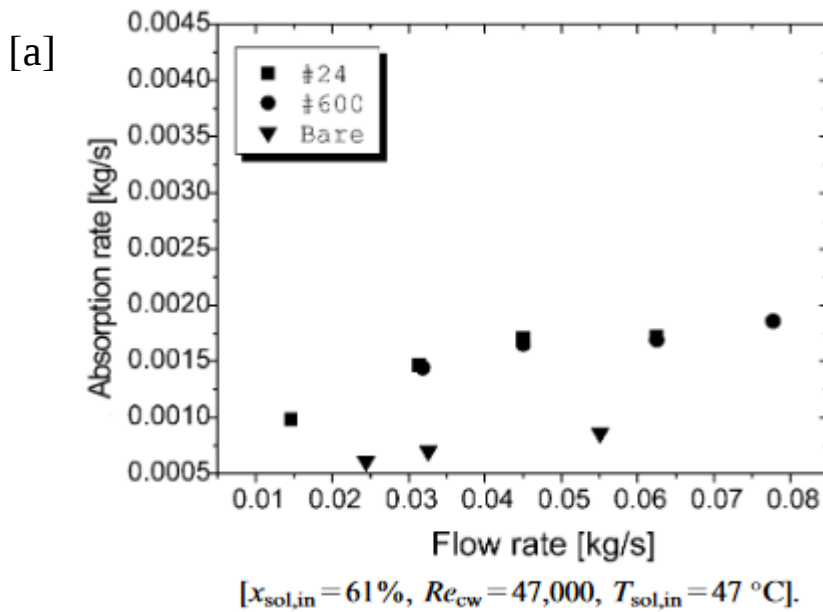


Figure 21 – [a] Tubes and flow patterns and [b] heat transfer coefficient for the three case studies, by Yoon et al. [143].

Kyung and Herold [144] also added 2-Ethyl-Hexanol to a mixture of H₂O/LiBr in order to analyse its absorption enhancement potential. Tests were conducted in a falling film absorber consisting of 4 and 8 tubes, with tube lengths of 360 mm and 470 mm, and an

outer diameter of 19.05 mm. The authors obtained a maximum effective heat transfer coefficient enhancement of 1.67 at an additive concentration of 100 ppm, solution concentration of 60% and employing a 4 tube bundle. For higher additive concentrations, no enhancement was noted. Finally, the authors supported their results based on the driving Marangoni convection effect. Meanwhile, Kang and Kashiwagi [145] employed n-octanol as surfactant but in an $\text{NH}_3/\text{H}_2\text{O}$ solution. The authors also visualised the Marangoni convection induced by the additive and noted that it occurred near the vapour-liquid interface. Reported absorption heat transfer enhancement was as high as 3.0 - 4.6 times the result of the base solution.

Park et al. [146] evaluated the combined effect of N-octanol and surface roughness of micro-hatched tubes on the absorption performance for a $\text{H}_2\text{O}/\text{LiBr}$ horizontal tube absorber. The test facility was the same used by Kim et al. [141] and Park et al. [116]. From this study, the authors reported that for the bare tube, absorption mass rate with the additive was improved up to 3.76 times more than that without the additive fluid, **Figure 22a,b**. Also, the effect of the additives on the heat transfer rate was noted to be more meaningful in the bare tube than that in the micro-hatched tubes. Finally, the authors obtained that the absorption mass rate for the micro-hatched tube and the additive was up to 4.5 times higher than that produced by the bare tube without the additive (**Figure 22a,b**).



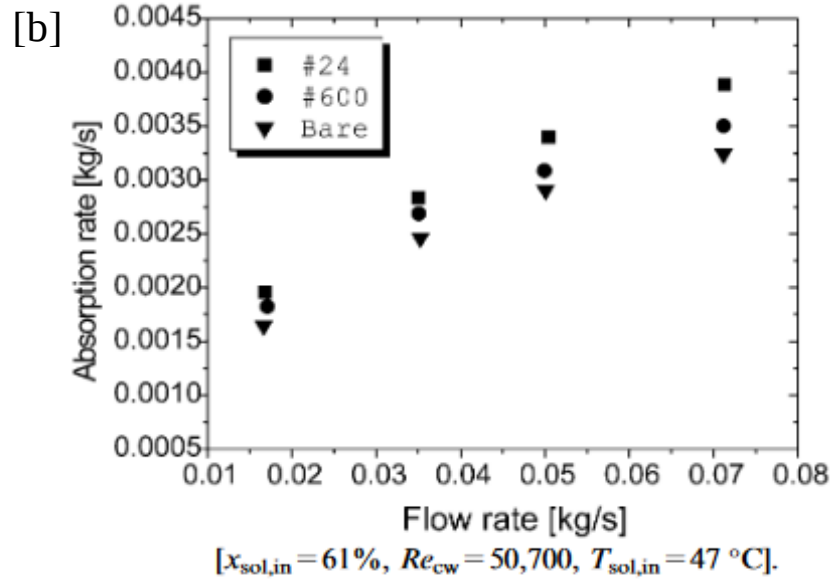


Figure 22 – Absorption rate vs flow rate, [a] without additive and [b] with additive, by Park et al. [146].

Cheng et al. [147] studied the enhancement effects of additives (2-ethyl-1-hexanol and 1-octanol) on a vertical falling film absorber with $\text{H}_2\text{O}/\text{LiBr}$. The absorber consists of two concentric tubes in a vertical disposition. The outer tube, which had an outer diameter of 90 mm and a thickness of 5 mm, was made of acrylic glass. The inner tube, which was made of stainless steel, had an outer diameter of 15.88 mm and a thickness of 1 mm. The effective length of the absorption tube was 1 m. The cooling water flowed upward through the inner tube and the solution flowed in a falling film on the outer surfaces of the inner tube. According to the experimental results, the authors confirmed that small amounts of 2-ethyl-1-hexanol or 1-octanol (5, 10, 30, 50, 100 ppm) enhanced the heat transfer during the absorption process significantly and also that the additive concentration was a key parameter to be taken into account. Kim et al. [148] observed that surfactants also enhanced the absorption rates during the bubble absorption process and that the 2-Ethyl-1-hexanol showed the highest effect on the absorption rates from the considered surfactants (2-Ethyl-1-hexanol, n-octanol, and 2-octanol). In addition, results showed that the addition of 700 ppm of 2-ethyl-1-hexanol enhanced the absorption performance up to 4.81 times more in an ammonia solution with a concentration of 18.7% (see **Figure 23**).

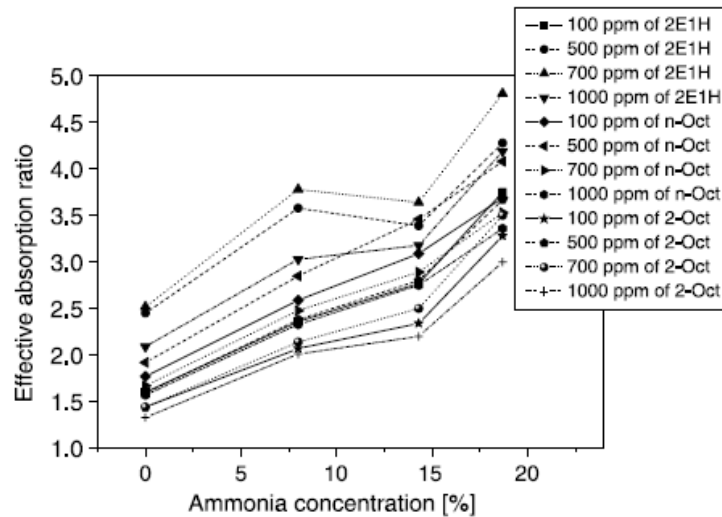


Figure 23 – The effective absorption ratio for the addition of surfactant [148].

Nakoryakov et al. [149] measured the heat and mass transfer intensification of the water vapour absorption into $\text{H}_2\text{O}/\text{LiBr}$ using the additive n-octanol (25 - 400 ppm). Experiments were conducted in a vacuum cylindrical chamber made of stainless steel (165 mm in diameter and 87 mm in length) which was filled with a solution of $\text{H}_2\text{O}/\text{LiBr}$ (58%) and additives. The water vapour was introduced into the chamber from the top of it. The water vapour pressure in the vacuum chamber was kept at about 2 kPa. The local characteristics of heat and mass transfer and surfactant effect were visualised through an infrared glass and recorded by a high-resolution camera. From this study, the authors confirmed that addition of surfactants into a solution generated surface convection even if the solution layer is initially immobile. Fu and Shigang [150] evaluated the absorption process in a $\text{H}_2\text{O}/\text{LiBr}$ vertical falling film tube absorber with (2-Ethyl-1-hexanol) and without additives. Mass transfer coefficients of up to $5 \text{ g.m}^{-2}.\text{s}^{-1}$ were observed at a cooling water temperature of around 25°C . The additive enhanced the mass transfer rates almost twice as much compared with the solution without additives at an inlet solution temperature of 40°C . When the cooling water temperature increased, the mass transfer coefficients decreased.

Lastly, Oronel et al. [151] conducted a sensitivity study of an absorption process in an L-type plate heat exchanger bubble absorber using the $\text{NH}_3/\text{LiNO}_3$ mixture. The authors analysed the effect of the solution mass flow, cooling water temperature and ammonia concentration on the absorber performance parameters (absorption mass flux, solution heat and mass transfer coefficient, and outlet subcooling degree) with $\text{NH}_3/\text{LiNO}_3$. Then, experiments were conducted with a ternary mixture $\text{NH}_3/(\text{LiNO}_3+\text{H}_2\text{O})$ which

included the addition of a small amount of water in the absorbent (25 wt.%). Experimental results with the $\text{NH}_3/\text{LiNO}_3$ were correlated and Nusselt and Sherwood numbers correlations were reported. The main conclusion from this study highlighted the fact that the addition of a small amount of water to the binary mixture resulted in the lower viscosity of the $\text{NH}_3/(\text{LiNO}_3+\text{H}_2\text{O})$ and improved the heat and mass transfer processes taking place in the absorber. For instance, the absorption mass flux achieved with the ternary mixture ranged from 0.00400 to 0.00595 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ as illustrated in **Figure 24a**. In the case of the solution heat transfer coefficient, it varied from 3.5 to 8.1 $\text{kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ as shown in **Figure 24b**. Results indicated that the absorption mass flux obtained with the ternary mixture was between 1.3 and 1.6 times higher than those of the binary mixture at similar operating conditions. In the case of the heat transfer coefficient, the improvement obtained was up to 1.4 times higher.

Table 6 lists the experimental investigations available in the open literature and their main test characteristics.

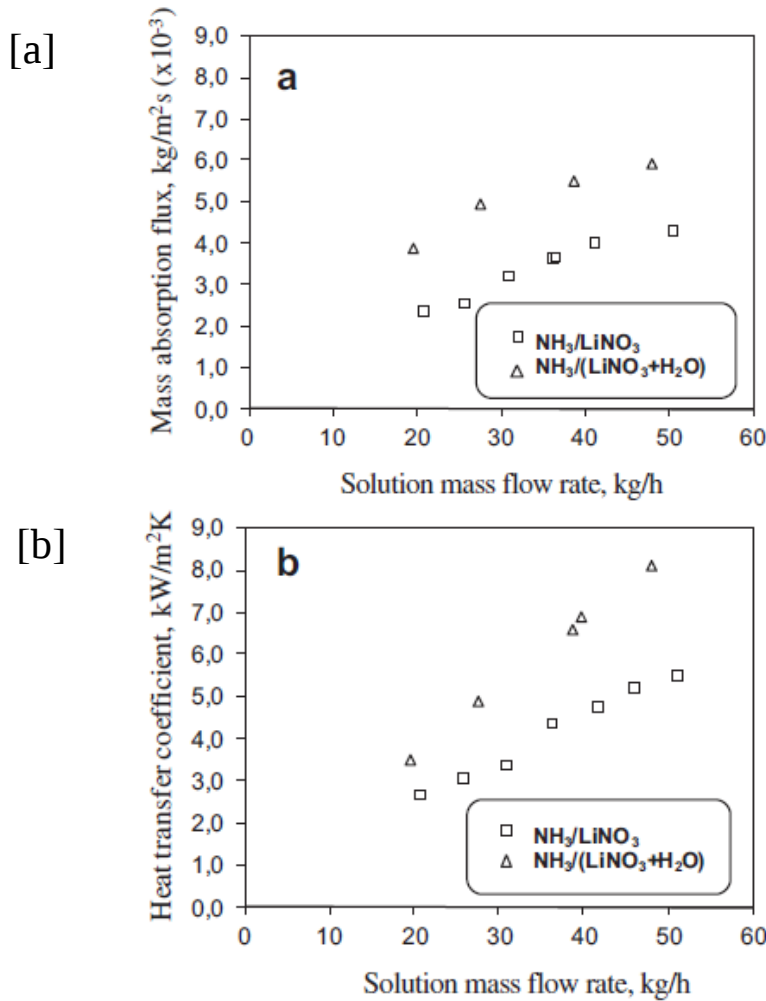


Figure 24 – Effect of the solution flow rate on: [a] mass absorption flux and [b] solution heat transfer coefficient for $\text{NH}_3/\text{LiNO}_3$ and $\text{NH}_3/(\text{LiNO}_3+\text{H}_2\text{O})$ mixtures [151].

Table 6. Summary of experimental studies employing additives in binary mixtures for absorption cooling/heating systems.

Reference	Test Section	Working fluid	Test conditions	Additives	Note
9 10 [137]	Vertical falling film absorber - flat plate	H ₂ O/LiBr	Ts (40 °C), Xs (57.3%) Res (180 - 480), Tc (30 °C), plate angle (15, 30, 49, 90°)	2-ethyl-1-hexanol (2E1H) (0, 60, 100 ppm)	Mass absorption increases from 4 to 5 times with respect to the base fluid
11 12 [138]	Horizontal falling film tube absorber (with smooth and knurled tubes)	H ₂ O/LiBr	Ts (40 - 43 °C), Xs (40 - 61%)	2-ethyl-1-hexanol (2E1H)(10, 20, 640 ppm)	Heat transfer coefficient enhancement up to 40% with the knurled tubes and up to 140% with the additives
13 14 [139]	Vertical falling film absorber - Compact plate heat exchanger with offset strip fin	NH ₃ /H ₂ O	Ps (4.9 kPa), Ts (20 °C), Xs (0.25 - 0.91%)	Marion PS (0.25 wt.%, 0.4 wt.%), Marion A (0.25 wt.%, 0.5 wt.%), Dehydol LT 14 (0.5 wt.%), Emulgin B1 (0.5 wt.%, 0.91 wt.%), 1-Octanol (50, 100 and 500 ppm)	The highest absorption rates were obtained with 1-octanol.
15 16 [140]	Falling film column - Tray column made of glass	H ₂ O and glycerol	Ts (25 °C), Xs (54%)	1-Octanol (100-950 ppm)	Interfacial tension of the fluid decreases sharply until a 300 ppm concentration when the surfactants were added.
17 18 [141]	Vertical falling film tube absorber with an inner stainless-steel tube	H ₂ O/LiBr	Ps (1.0 kPa), Ts (40 °C), Xs (60%), Tc (30 °C)	2-ethyl-1-hexanol (1 to 100 ppm)	Maximum interfacial film turbulence effect on the absorption process reached near to 30 ppm.
19 20 [142]	Tray column made of tempered flat glass with vapour inlet from the top	NH ₃ /H ₂ O	Ps (101 kPa), Ts (15 °C), Xs (5, 10, 15, and 20%)	2-ethyl-1-hexanol (2E1H), n-Octanol (n-O), 2-Octanol (2-O), 3-Octanol (3-O), 4-Octanol (4- O), n-Decanol (n-D), 2-Decanol (2-D) and 3-Decanol (3-D) (0 - 8000 ppm)	The limit of solubility was the lowest for 3-Decanol (500 ppm), while it was the highest for 4-Octanol (3000 ppm).
21 22 23 [21]	Horizontal falling film tube absorber (with smooth and advanced surfaces)	H ₂ O/LiBr	Ps (0.86 kPa), Xs (60 and 62%)	2-ethyl-1-hexanol (500 ppm)	Mass transfer involving the individual use of advanced surfaces tubes and additives around 1.75 and 2 times higher than those values with the smooth surface tube, respectively. Mass absorbed by using both techniques was up to 1.25 times that with only the additives
24 25 [143]	Horizontal falling film tube absorber (with smooth and advanced surfaces)	H ₂ O/LiBr	Ps (0.93 kPa), Ts (45 °C), Xs (60%)	n-octanol (500 - 5500 ppm)	Improved heat transfer until a surfactant concentration of 3500 ppm
26 27 [144]	Horizontal falling film tube absorber	H ₂ O/LiBr	Xs (60%), ms (0.01 - 0.045 kg.s ⁻¹), mc (0.000126 m ³ .s ⁻¹), Tc (30 °C)	2-ethyl-1-hexanol (0 - 500 ppm)	Heat transfer improvement up to 1.67 times with respect to the base solution
28 29 [145]	Horizontal flow absorber with upper vapour injection	NH ₃ /H ₂ O	Ps (200 kPa), Ts (20 °C), Xs (0, 5 and 20%)	n-octanol (0 - 800 ppm)	Heat transfer enhancement as high as 3.0 - 4.6 times with respect to the base solution
30 31 [146]	Horizontal falling film tube absorber (with smooth and advanced surfaces)	H ₂ O/LiBr	Ps (0.94 kPa), Ts (36, 41 and 46 °C), Xs (55, 58 and 61%)	n-octanol (400 ppm)	Absorption rate enhancement up to 3.76 times with heat transfer additive and up to 4.5 times combining both advanced surfaces and additives
32 33 [147]	Vertical falling film tube absorber	H ₂ O/LiBr	Ps (0.9 kPa), Ts (40 °C), Xs (60%)	2-ethyl-1-hexanol and 1-octanol (5, 10, 30, 50 and 100 ppm)	Even small amounts of additives can enhance the heat transfer during the absorption process
34 35 [148]	Bubble mode - Vertical test column	NH ₃ /H ₂ O	Ps (100 kPa), Ts (20 °C), Xs (0, 8, 14.3 and 18.7%)	2-Ethyl-1-hexanol, n-octanol, 2-octanol (0- 1000 ppm)	Maximum effective absorption ratio of 4.81 was obtained with 700 ppm of 2-ethyl-1-hexanol in an 18.7% ammonia solution.
36 37 [149]	Cylindrical chamber with vapour entering the test section from the top	H ₂ O/LiBr	Ps (2 kPa), Ts (20 -50 °C), Xs (58%)	n-octanol (25 - 400 ppm)	Confirmation of solution surface convection generation by addition of surfactants
38 39 [150]	Vertical falling film tube absorber	H ₂ O/LiBr	Ts (35-45 °C), Xs (57.2 - 60%), Tc (25.8 - 38.2 °C)	2-ethyl-1-hexanol	Maximum mass transfer rate enhancement was almost twice the mass transfer reached without additive
40 41 [151]	Bubble mode - Plate type absorber	NH ₃ /LiNO ₃	Ps (510 kPa), Ts (45 °C), Xs (43.5 - 48%), Tc (35 - 40 °C)	H ₂ O (25% in the absorbent)	Mass absorption flux with the ternary mixture up to 1.6 times higher than that of the binary mixture

Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms,Vs (solution flow), Res (film Reynolds number), mc (coolant flow), Tc (coolant temperature), * concentration of ammonia for NH₃ based fluids and concentration of LiBr for LiBr based fluids.

3.3. Nanoparticles in working fluids

Advances in nanoparticle synthesis and the reduction in the acquisition prices have resulted in an interesting opportunity to employ nanotechnology in absorption cooling/heating systems as a technique for enhancing heat and mass transfer processes taking place in the main components of these systems. In this case, the working fluid including nanoparticles is usually called binary nanofluid, which means a binary mixture with evenly suspended nano-sized particles ($d_p < 100$ nm), (Choi, [152]).

Studies in the literature have shown that the thermal conductivity of the conventional absorption working fluids can be enhanced if a small amount of nanoparticles is added to the fluid. For instance; the effect of adding carbon nanotubes (CNTs) to the thermal conductivity of the $\text{NH}_3/\text{H}_2\text{O}$ mixture resulted in an $\text{NH}_3/\text{H}_2\text{O} + \text{CNTs}$ mixture thermal conductivity up to 16% higher than that of the base mixture [153]. In the case of the thermal conductivity of the $\text{H}_2\text{O}/\text{LiBr}$, an increase of only 0.1% was observed with an Al_2O_3 nanoparticle volume concentration of 2.2% in 50 wt.% LiBr solution [154] and of 3.6% with 1% (v/v) of n-decane oil droplets in 30 wt.% $\text{H}_2\text{O}/\text{LiBr}$ [155]. In addition, Cuenca et al. [156] determined the thermal conductivity of the mixture $\text{NH}_3/\text{LiNO}_3 + \text{Carbon nanotubes}$. Experimental measurements were carried out at concentrations of NH_3 and CNTs in weight, varying from 30% to 50% for NH_3 , and from 0.005% to 0.2% for CNTs. The thermal conductivity of the nanofluid under study was determined at temperatures ranging from 303.15 K to 353.15 K, at 1.5 MPa. In this investigation, the highest thermal conductivity value was obtained with 40 wt.% of NH_3 concentration and 0.01 wt.% of CNTs. The maximum enhancement value was 7.5% higher than that of the base mixture.

Nanoparticles can enhance not only the effective thermal conductivity of the base fluid but also directly affect the heat and mass transfer conditions of the fluid.

Researchers have studied and discussed the mechanisms that may justify the increase in the thermal conductivity and heat transfer coefficient of nanofluids with respect to the base fluid (Kebllinski et al. [157], Das et al. [158], Buongiorno [159], Haddad et al. [160], Ding et al. [161]). In their study, Das et al. [158] concluded that a potential explanation for the increase in the thermal conductivity of nanofluids could be the stochastic motion of the nanoparticles and that its effect is more significant when the fluid temperature is increased. In addition, Buongiorno [159] explained that the nanoparticle absolute velocity can be deduced as the sum of the base fluid velocity and

1 a relative slip velocity. Also, the author highlighted and defined seven slip mechanisms,
2 some of them with higher effects than the others on heat transfer: inertia, Brownian
3 diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity
4 settling [159]. Meanwhile, Ding et al. [161] suggested that the particle migration could
5 be the major factor responsible for the heat transfer enhancement and highlighted that
6 the enhanced thermal conductivity from the nanoparticles did not guarantee a significant
7 enhancement in the convective heat transfer. Recently, Bahiraei [162] in his critical
8 review concluded that migration of nanoparticles caused by Brownian motion, among
9 other reasons, should be further studied by experimentation, since theoretical and
10 numerical analyses available in the literature are still not that satisfactory. Based on the
11 proposed mechanisms and explanations above, it is clear that heat transfer enhancement
12 with nanofluids is not only due to the increase in thermal conductivity but also to the
13 combination of slip mechanisms such as Brownian motion and thermophoresis with the
14 effect of these two being the more predominant.

25 Since heat and mass transfer are analogue processes, investigations into nanofluids have
26 also shown outstanding mass transfer enhancements in different applications [163-168,
27 172-177]. Krishnamurthy et al. [172], for instance, reported that an optimum
28 nanoparticles volume fraction could result in a mass transfer improvement even higher
29 than that observed in thermal conductivity. These studies also reported that possible
30 reasons for the mass transfer enhancements in bubble absorbers are, the induced micro
31 disturbances and the increase in the gas-liquid interfacial bubble area due to motion and
32 interaction of the nanoparticles (see **Figure 25**). However, more studies need to be
33 conducted as there is limited and also inconsistent experimental data proving the
34 dominant mechanism of mass transfer in nanofluids in many different applications [169,
35 170]. In addition, more work on the selection of nanoparticles for cooling/heating
36 absorption systems working fluids needs to be done due to the very few studies
37 available in the literature [171].

Without nanoparticles

With nanoparticles

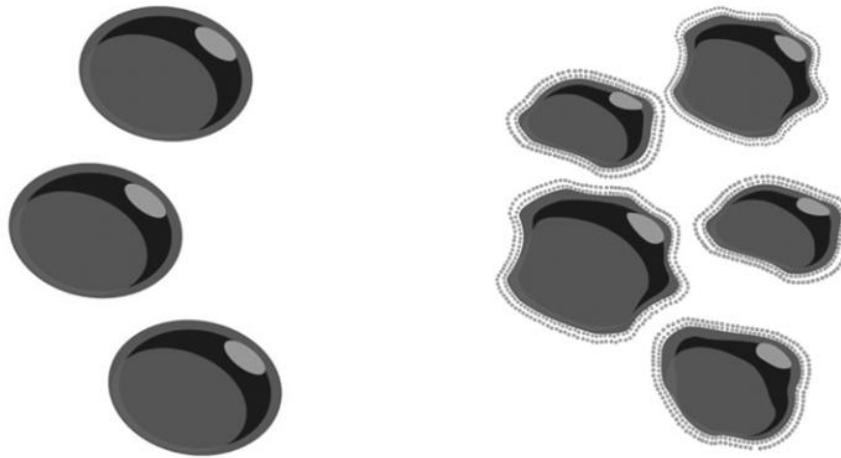


Figure 25 - Bubble breaking model, the nanoparticles cover the bubble surface area and break them into smaller bubbles, by Torres Pineda et al. [177].

From this part, experimental studies dealing with the effect of nanofluids in absorbers for absorption cooling/heating systems are reviewed. The first studies employing nanoparticles in absorbers included the use of Cu, CuO, and Al₂O₃ in NH₃/H₂O solutions (see **Figure 26**) [163,164]. They also involved the effect of surfactants (2-ethyl-1-hexanol, n-octanol, and 2-octanol) on the bubble absorption performance. Kim et al. [163], for instance, tested an absorber made of transparent acrylic resin plates where the bubble behaviour was observed with a visualisation system. In this study, the solution was introduced into the test section and bubbles were injected from the bottom through a vapour orifice. The average diameter of all nanoparticles was under 50 nm. In the case of the surfactants, the concentration varied between 0 and 1000 ppm.

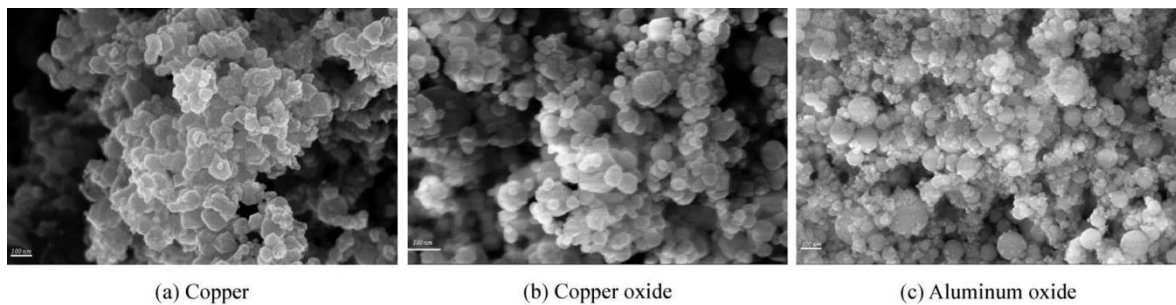
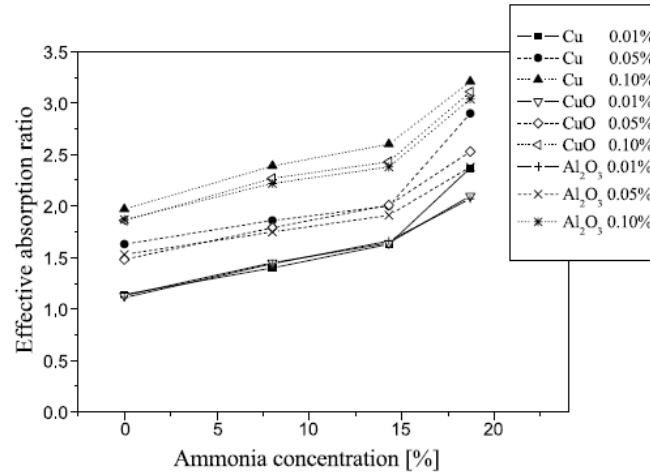


Figure 26 - SEM pictures of different nano particles [163].

As presented in **Figure 27a**, initial results showed that the Cu nanoparticles provided the most prominent effect on the absorption of the considered nanoparticles [163]. The addition of nanoparticles improved the absorption up to 3.21 times compared to the base fluid when a 0.1 wt.% Cu nanoparticles concentration was added to an ammonia solution with a concentration of 18.7%. In the visual study, Kim et al. [163] observed that the bubble shape was spherical in the case with nano-particles, while it became hemispherical in the case without nano-particles, **Figure 28**. The authors also explained that the bubble diameter in the binary nanofluids is smaller than that in the base mixture because the vapour bubble was absorbed quicker than that in the base mixture. Moreover, Kim et al. [164] also showed that the addition of both surfactants and nanoparticles improved mass transfer performance during the ammonia bubble absorption process. When 2-ethyl-1-hexanol and Cu nanoparticles were used simultaneously, the absorption performance was enhanced up to 5.32 times more as presented in **Figure 27b**. Finally, the authors concluded that the ammonia concentration in the solution, the kind of nanoparticles and the concentration, and the kind of surfactant and concentration are the key parameters. The authors also emphasized that the absorption rate enhancement is stronger if the concentration of the nanoparticles, surfactants and ammonia is increased.

[a]



[b]

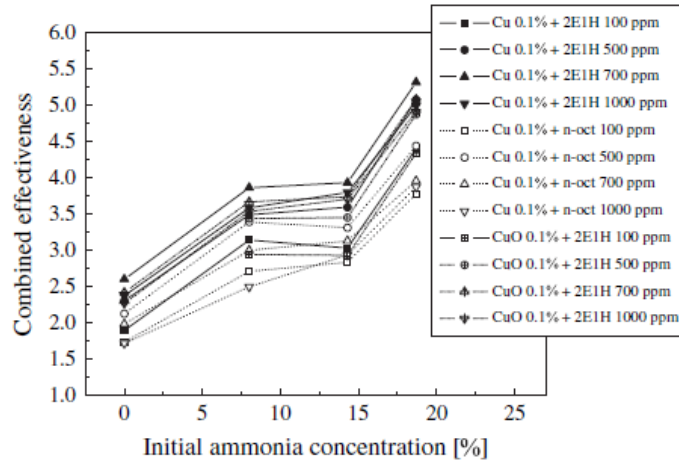
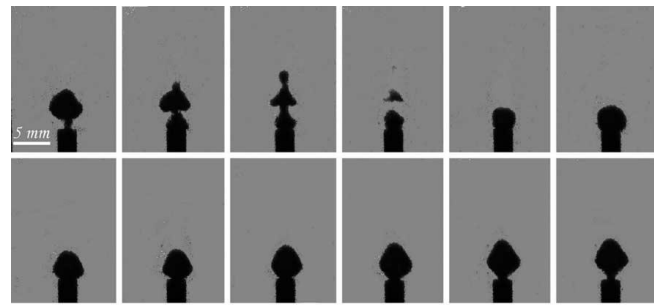
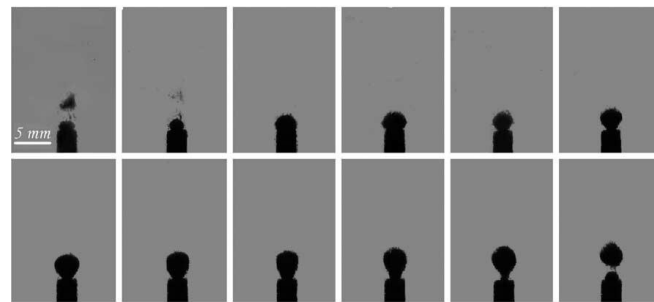


Figure 27 - Effective absorption ratio for [a] the binary nanofluids [154] and [b] binary nanofluids with surfactants [164].



(a) without nano-particles



(b) with Cu nano-particles 0.1% (binary nanofluid)

Figure 28 - The bubble behaviour with and without nanoparticles (Cu, 0.1 wt.%) for an ammonia concentration of 8.0% reported by Kim et al. [163].

Kim et al. [165] also visualised the dispersion of nanoparticles, in this case in a $H_2O/LiBr$ solution, and determined the absorption and heat transfer rates for falling nanofluid film flows. SiO_2 nanoparticles with a size between 10 and 20 nm were selected for this study. Experiments were also conducted without and with 2E1H in a concentration of 150 ppm to reduce the surface tension of the solution. The test section

consisted of an absorber with eight copper tubes, with a length of 500 mm and diameter of 15 mm all installed in a column. According to the flow configuration, the cooling water flowed inside the tubes from the bottom to the top while the solution was distributed at the top of the absorber. As the main output from this study, maximum improvements of mass transfer and heat transfer rate reached were 18% and 46.8%, respectively, when the concentration of SiO₂ nanoparticles was 0.005 vol.%, therefore, the authors recommended the addition of SiO₂ nanoparticles into the H₂O/LiBr solution at concentrations lower than 0.01 wt.%. The authors also observed that the maximum enhancement achieved with the nanofluids was obtained without surfactant. Ma et al. [166], in turn, studied the enhancement of heat and mass transfer processes in a bubble absorber with NH₃/H₂O employing multi-wall carbon nanotubes (MWCNT, with diameter of 10-20 nm). The authors also measured the thermal conductivity of the NH₃/H₂O mixture with the nanoparticles. The authors justified the use of carbon nanotubes because carbon nanotubes do not chemically react with ammonia as could occur with metal-based nanoparticles. In this study, the experimental test facility consisted of an absorber (200 mm in length and 20 mm in diameter) without a heat removal system and it was observed that the maximum effective absorption rate was up to 1.16 with an ammonia concentration of 24.80% and a nanotube concentration of 0.23 wt.%, **Figure 29**. As previously concluded by Kim et al. [163], Ma et al. [166] also observed that nanofluids improve bubble absorption when the absorption potential is lower (high solution concentrations). Similarly, Lee et al. [167] used carbon nanotube (CNT) and Al₂O₃ nanoparticles (**Figure 30a**) to enhance the absorption process for NH₃/H₂O absorption systems. Experiments were performed in a chamber filled with the nanofluids. The vapour entered the test section through the distributor located at the top of the test section. From this study, the authors noted that the maximum heat transfer and absorption rate enhancement were reached with a nanoparticle concentration of 0.02 vol.%, **Figure 30b**. In this case, the heat transfer and absorption rates enhanced 17% and 16% when the CNTs were added, respectively, and 29% and 18%, respectively, when the Al₂O₃ was employed.

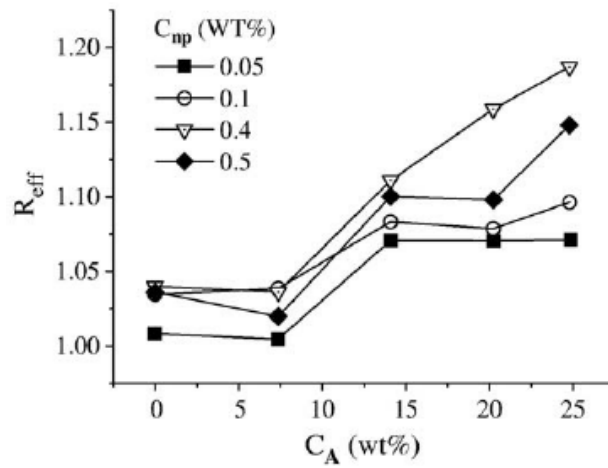
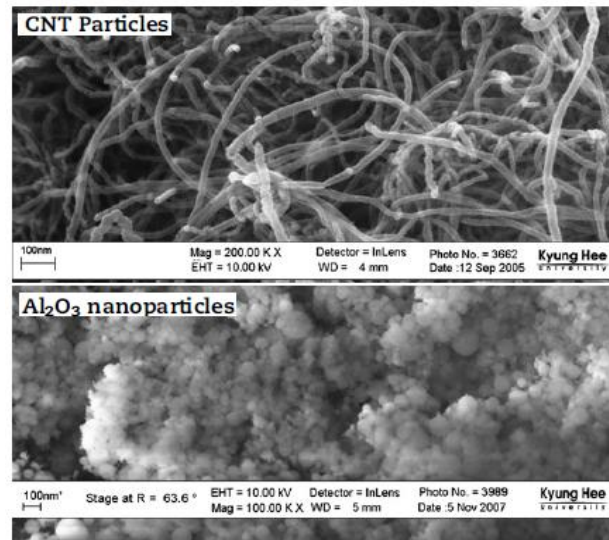


Figure 29 - Effective absorption ratio vs initial ammonia concentration in binary nanofluid [166].

[a]



[b]

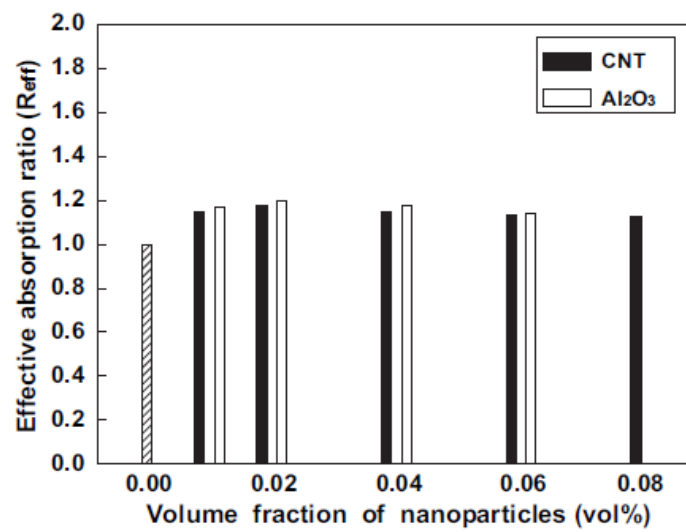


Figure 30 – [a] SEM pictures of different CNT and Al_2O_3 , and [b] Effective absorption ratio vs volume fraction of nanoparticles [167].

Pang et al. [168] proposed the use of mono silver (Ag) nanoparticles in the $\text{NH}_3/\text{H}_2\text{O}$ mixture. Experiments for this study were performed with and without heat removal. The size of the nanoparticles was 15 nm and the concentration used varied from 0 to 0.02 wt.%. For experiments with heat removal, the inlet cooling-water temperature was set to 15 °C. The authors concluded that the mass transfer enhancement with nanofluids was higher with heat removal compared with the case without heat removal. The maximum absorption rate achieved was 1.55 times higher than values with the base mixture at Ag nanoparticles concentration of 0.02 wt.%, **Figure 31**. Finally, the authors justified that the mass transfer intensification by nanofluids was the result of to two main factors, the improved heat transfer and gas bubble breaking mechanism.

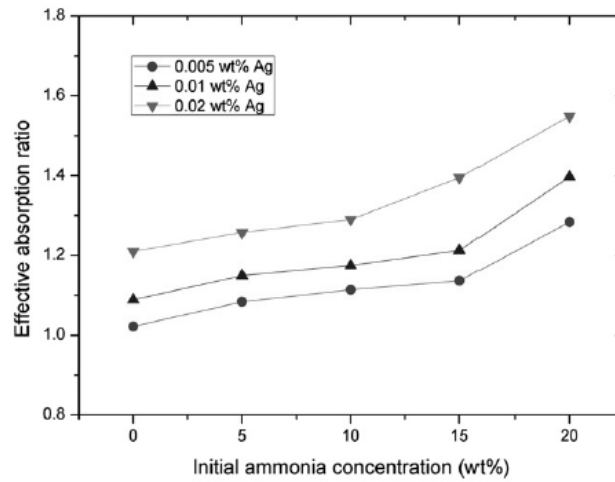
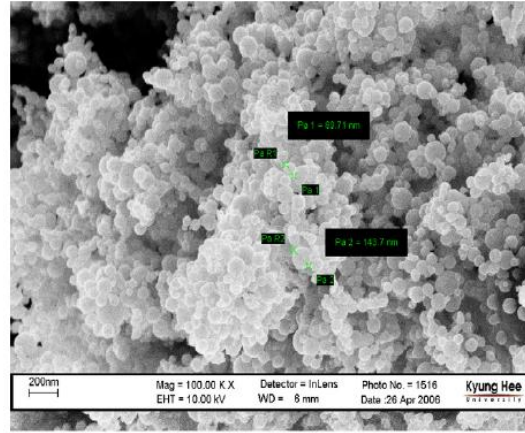


Figure 31 – Effective absorption ratio vs initial ammonia concentration employing Ag nanoparticles [168].

In the case of Kang et al. [178], the authors studied the falling film absorption process with $\text{H}_2\text{O}/\text{LiBr}$ and the addition of nanoparticles such as Fe (with a diameter of 100 nm) and Carbon nanotubes (CNT) (with a diameter of 25 nm and length of 5 mm). The test section consisted of eight copper tubes (with the length of 500 mm and diameter of 15 mm) installed in column disposition. In this study, the authors found that the absorption rate using CNT in the $\text{H}_2\text{O}/\text{LiBr}$ solution became higher than that using the Fe nanoparticles. A maximum mass transfer enhancement was achieved using 0.01 wt.% of CNT. This enhancement was 2.48 times higher than that of the base solution while it was 1.90 times higher with the Fe nanoparticles. Finally, the authors concluded that the absorption rate increased by increasing the solution flow rate and nanoparticles concentration. It is worthy of note that the heat transfer rate increase obtained was not

significantly affected by the nanoparticles concentration. Therefore, the addition of nanoparticles had a much more significant effect in mass transfer than in heat transfer.

[a]



[b]

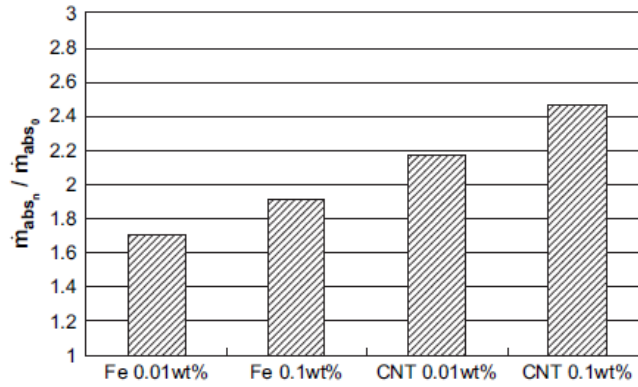


Figure 32 – [a] SEM pictures of different Fe nanoparticles and [b] mass transfer enhancement ratio for case study [178].

Pang et al. [179] also evaluated the effect of Al_2O_3 nanoparticles on the absorption performance in NH_3/H_2O bubble absorption process. In this study, the nanoparticle average size was 20 nm and the mass fraction varied from 0.2% to 1.0%. The absorber size was 20 mm × 20 mm × 200 mm and the diameter of the ammonia injector was 2 mm. From this study, the authors obtained a maximum effective absorption rate of 2.017 with an initial ammonia concentration of 20% and the Al_2O_3 nanoparticle mass fraction of 0.5%. Meanwhile, Yang et al. [180] used Al_2O_3 , Fe_2O_3 and $ZnFe_2O_4$ in a mixture of NH_3/H_2O in a falling film mode. Additionally, sodium dodecyl benzene sulfonate (SDBS) was added to the nanoparticles in the NH_3/H_2O mixture to reduce the nanofluid viscosity. The average sizes of the Al_2O_3 , $ZnFe_2O_4$ and Fe_2O_3 nanoparticles were less than 20 nm, 30 nm and 30 nm, respectively. The container of the absorber was made of stainless steel with a plexiglass to observe the falling film flow. From this work, the authors concluded that absorption performance could be enhanced by adding

a small nanoparticles mass fraction with matched surfactants. Finally, the authors achieved an absorption ratio enhancement of 70%, 50%, and 30% with Fe_2O_3 (0.2 wt.%), ZnFe_2O_4 (0.1 wt.%), and Al_2O_3 (0.2 wt.%) nanofluids, respectively, when the initial mass fraction of ammonia was 15%, see **Figure 33**. Kim et al. [181] evaluated the bubble absorption from an $\text{NH}_3/\text{H}_2\text{O}$ -based nanoemulsion in a cylindrical column. The nanoemulsions consisted of n-decane oil, and C_{12}E_4 (polyoxyethylene lauryl ether), and Tween20 (polyoxyethylene sorbitan monolaurate) as non-ionic surfactants. The experiments were conducted at different solution concentrations and n-decane oil concentrations. According to the authors, the nanoemulsions provide the advantage of reducing the sedimentation problems which could occur with solid nanoparticles. Their experimental results showed that an effective absorption ratio of up to 17% was achieved with 2.0 vol.% oil and 14.3 wt.% $\text{NH}_3/\text{H}_2\text{O}$. Later on, Lee et al. [182] tested the binary nano-emulsions proposed by Kim et al. [181] in a 100 W cooling capacity diffusion absorption refrigerator with a COP of up to 0.15 with 2.0 vol.% oil. Similarly, Sozen et al. [183] conducted experiments in a 75 W cooling capacity diffusion absorption refrigerator with alumina nanofluids ($\text{NH}_3/\text{H}_2\text{O}$ + 2.0 wt.% Al_2O_3) reporting COP values from 0.14 to 0.145.

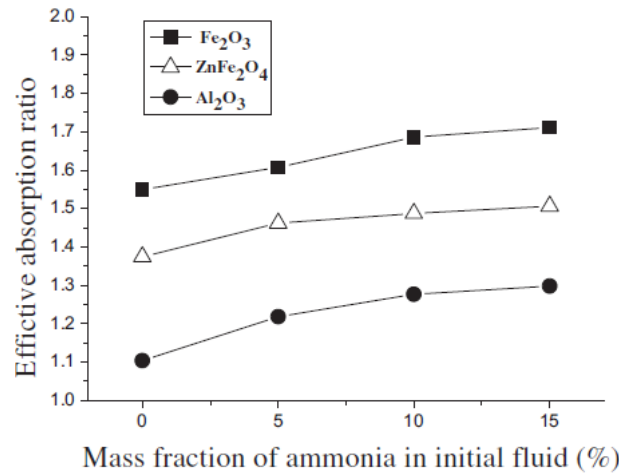


Figure 33 - Effective absorption ratio of optimal nanofluid vs mass fraction of ammonia in initial solution [180].

More recently, Amaris et al. [184] studied the single and combined effect of advanced surfaces and CNTs on the ammonia vapour absorption process with $\text{NH}_3/\text{LiNO}_3$ in a tubular bubble absorber. The absorber, which was a double tube with the solution and

ammonia flowing in the internal tube, operated with heat dissipation by circulating cooling water at 40 and 35 °C in a counter-current configuration. Results from this study indicated that the absorption mass flux increased up to 1.64 times the value of the base solution when 0.01 wt.% of CNTs were used at a cooling water temperature of 40 °C. however, the enhancement was only up to 1.48 times higher with the base solution at a cooling water temperature of 35 °C. This study also showed that when using simultaneously the CNT and advanced surfaces, the absorption capacity increased up to 1.80 times higher than the values obtained with the base fluid and the smooth tube at low solution flows. As shown in **Figure 34**, it was also noted that the combined effect of CNTs and advanced surfaces on the mass transfer enhancement decreased on increasing the solution flow to higher values. In that case, mass transfer values were slightly higher than those obtained when using the advanced tube and CNTs individually. Finally, Zhang et al. [185] reported on the enhancement of the absorption process in falling film mode by adding Cu, Al₂O₃ and CNT nanoparticles. In this study, the authors studied the effect of parameters such as solution flow, nanoparticles mass fraction, size and type, and highlighted the positive effect on mass transfer of larger mass fraction and smaller size of nanoparticles. The author also observed that the Cu nanoparticles provided higher mass transfer in comparison to the Al₂O₃ and CNT nanoparticles.

The experimental studies dealing with the effect of nanofluids in absorbers for absorption cooling/heating systems are listed in Table 7.

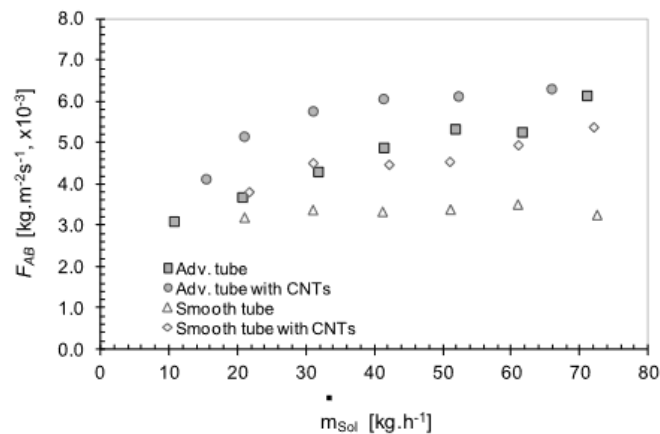


Figure 34 - Combined effect of carbon nanotubes and advanced surfaces on ammonia absorption mass flux, [184].

Table 7. Summary of experimental studies employing nanofluids for absorption cooling/heating systems.

Reference	Test Section	Base Working fluid	Test conditions	Surfactants	Nanoparticles	Note
10 11[163] 12	Transparent acrylic resin column - Bubble absorber	NH ₃ /H ₂ O	Ps (100 kPa), Ts (20 °C), Xs (0 - 18.7%)	---	Cu, CuO and Al ₂ O ₃ (0 - 0.10 wt.%)	Cu reported the highest effective absorption rate (up to 3.21)
13 14[164] 15	Transparent acrylic resin column - Bubble absorber	NH ₃ /H ₂ O	Ps (101 kPa), Ts (21 °C), Xs (1 - 18.7%)	2-ethyl-1-hexanol, n-Octanol and 2-Octanol (100 - 1000 ppm)	Cu, CuO and Al ₂ O ₃ (0 - 0.10 wt.%)	Absorption rate enhanced up to 5.32 times when 2-ethyl-1-hexanol and Cu nanoparticles were used simultaneously
16 17[165]	Horizontal falling film tube absorber	H ₂ O/LiBr	Ts (40 °C), Xs (53%)	2-ethyl-1-hexanol (150 ppm)	SiO ₂ (0.001 - 0.05 wt.%)	Maximum improvement of the mass transfer rate was up to 18% by using only the SiO ₂ nanoparticles
18 19[166]	Bubble absorber	NH ₃ /H ₂ O	Ps (140 kPa), Ts (14 °C), Xs (0 - 25%)	---	MWCNT (0 - 0.5 wt.%)	Maximum effective absorption rate up to 1.16 with nanotubes concentration of 0.23 wt.%
20 21[167] 22 23	Chamber with vapour entering through a distributor located at the top of it	NH ₃ /H ₂ O	Ps (500 kPa), Xs (20%)	---	Al ₂ O ₃ (0 - 0.06 vol%) and CNT (0 - 0.08 vol%)	Maximum absorption rate enhancement up to 16% with the CNTs and up to 18% with the Al ₂ O ₃
24 25[168]	Bubble absorber	NH ₃ /H ₂ O	Ps (200 kPa), Xs (0 - 20%)	---	Ag (0 - 0.02 wt.%)	Maximum absorption rate up to 1.55 times with a Ag nanoparticles concentration of 0.02 wt.%.
26 27[178] 28	Horizontal falling film tube absorber	H ₂ O/LiBr	Ps (10 kPa), Ts (40 °C), Xs (55%)	---	Fe and CNTs (0 - 0.1 wt.%)	A maximum mass transfer enhancement up to 2.48 times with 0.01 wt.% of CNT and up to 1.90 times with 0.01 wt.% of Fe.
29 30[179] 31	Squared bubble absorber	NH ₃ /H ₂ O	Ps (200 kPa), Xs (0 - 20%)	---	Al ₂ O ₃ (0.2 - 1.0 wt.%)	Maximum effective absorption rate up to 2.0 times higher with an initial ammonia concentration of 20% and Al ₂ O ₃ mass fraction of 0.5 wt.%.
32 33[180] 34	Horizontal falling film tube absorber	NH ₃ /H ₂ O	Ps (90 kPa), Xs (0 - 15%)	Sodium dodecyl benzene sulfonate (SDBS) (0.1 - 0.5 wt.%)	Al ₂ O ₃ , Fe ₂ O ₃ and ZnFe ₂ O ₄ (0.1 - 1.5 wt.%)	Maximum absorption rate enhancement up to 1.70 times higher with Fe ₂ O ₃ and up to 1.50 times higher with ZnFe ₂ O ₄
35 36[184] 37	Bubble absorber (with and without advanced surfaces)	NH ₃ /LiNO ₃	Ps (510 kPa), Ts (45 °C), Xs (45%), ms (10 - 72 kg.h ⁻¹), Tc (35 - 40 °C), Vc (80-100 l.h ⁻¹)	---	CNTs (0.1 - 0.2 wt.%)	Maximum absorption mass flux enhancement up to 1.64 times with 0.01 wt. % of CNTs and up to 1.80 when combining the use of CNTs and an advanced surface tube
38 39 40[185] 41	Falling film vertical absorber	H ₂ O/LiBr	Ts (16.8 °C), Xs (57%), ms (100 - 375 l.h ⁻¹)		Cu, Al ₂ O ₃ , CNTs (0.01, 0.05, 0.1 wt.%)	Nano particles size Cu (50, 80, 100 nm), Al ₂ O ₃ (25, 50, 100 nm). maximum absorption rate enhancement up to 2.0 times higher with Cu at a solution flow of 200 l.h ⁻¹
42	Ps (Absorber operating pressure), Ts (solution temperature), Xs* (solution concentration), ms (solution flow), Tc (coolant temperature), Vc (coolant flow), * concentration of ammonia for NH ₃ based fluids and concentration of LiBr for LiBr based fluids.					

4. Conclusions and future challenges

The present study aimed to identify and review the investigations published based on experimental studies dealing with the enhancement of the vapour absorption process in absorbers with passive intensification techniques. Initially, experimental studies of the absorption process on conventional falling film, spray and bubble absorbers including their main test conditions and characteristics were presented. Then, advances in terms of vapour absorption enhancement in absorbers using advanced surface designs, additives and nanofluids were reviewed. Each section included experimental studies, applied intensification techniques, characteristics of the test section, working fluid and composition, and maximum enhancement.

Following the literature review, studies were initially focused on the understanding of the dominant mechanisms and different operating conditions of the absorption process for different absorption modes and working fluids. For that, most studies were mainly focused on analysing the effects of the operating conditions such as solution flow, temperature, concentration, pressure and coolant temperature while few studies were based on geometrical characteristic variations such as tube spacing, the number of tubes and diameters among others.

Review on conventional falling film, spray and bubble absorbers evidenced that the dominant resistance for heat and mass transfer was on the solution side and that it was highly dependent on the solution flow and concentration. Studies also showed that mass transfer was improved as the cooling-water inlet temperature was decreased since the absorber capacity to dissipate the heat released by the absorption increased.

It was also observed that necessity of improving the performance of absorption cooling/heating systems has yielded more complex absorber designs and enhanced mass transfer in working fluids by adding surfactants and nanoparticles. In addition, potential explanations of the effects of these additional components on the vapour absorption process are being unified. Since then, employing intensification passive techniques have demonstrated significant positive effects for improving the absorption process of refrigerants in absorbers. Investigations have indicated that the absorption process in absorbers can be significantly improved by applying passive intensification techniques on the solution side, however, the magnitude of the benefits depends to a great extent on the working fluid operating conditions. For instance, major enhancements in mass transfer were obtained for low solution flows by applying passive techniques, however,

1 the benefits in mass transfer by these intensification techniques might be reduced by the
2 characteristics of the fluid itself at high regime flows. It means that further studies
3 should involve synergy effect analysis from the combined use of advanced surfaces and
4 additives/nanoparticles on the heat and mass transfer processes taking place in more
5 practical absorber designs.
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7
8 Furthermore, the shortage of studies dealing with working fluids with surfactants or
9 nanoparticles at the required conditions has raised the concern about the thermodynamic
10 properties and stability of these advanced fluids during the heat and mass transfer
11 processes that take place in absorption cooling/heating systems [186]. This implies that
12 a lot of work needs to be done in order to identify and understand the dominant
13 mechanism taking place during the processes that involve complex heat and mass
14 transfer of these advanced working fluids at the different operating conditions of the
15 cooling/heating absorption systems.
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25 **Acknowledgements**

26
27 This study was part of an R&D project funded by the Spanish Ministry of Science and
28 Innovation (ENE2008-00863).
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