

Effect of Surfactant on Water Vapor Absorption into Aqueous Lithium Bromide

by



Md. Abdullah Al Bari

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the department of Mechanical Engineering



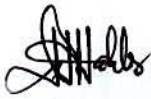
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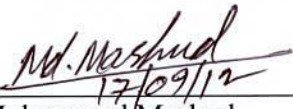
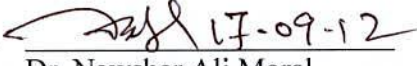




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ACKNOWLEDGEMENTS

Several people have assisted me during my research work. Although it is not possible to mention all in a few sentences, I would like to thank those who are particularly important to my work. I feel deep sense of gratitude, regard and sincere thanks to **Dr. Mihir Ranjan Halder**, Professor , Deaprtment of Mechanical Engineering and Head, Department of Energy Technology, Khulna University of Engineering & Technology (KUET), for his magnanimous guidance and valuable counsel in execution and completion of the project work, without which it would have been simply impossible to carry out the work.

I would like to express my sincere sentiments and great pleasure to Dr. Mohammad Ariful Islam, Professor, Department of Mechanical Engineering, for his help and guidance. Without his support and sincere cooperation throughout the research work, this project would not come to this stage.

I would like to Thank to Prof. Dr. Mohammad Mashud, Head Department of Mechanical Engineering for his valuable help and support.

I am extremely grateful to Professor Dr. Muhammed Alamgir, the Vice Chancellor of KUET for providing financial assistance of my project work.

Thanks are also extended to all the teachers of the Department and staff of Heat Engine Laboratory, Machine Shop and Computer laboratory. Special thanks to Mr. Pollob Jodder, technician, heat engine lab for his active cooperation and industry in this project.

Md. Abdullah Al Bari

ABSTRACT

The objective of the present study is to investigate the absorbing characteristics of water vapor in LiBr-H₂O (weak solution) and also the enhancement of absorption in presence of a surfactant in the absorber of a vapor absorption refrigeration system. It reveals from literature that the rate of absorption enhances for marangoni convection occurs due to inclusion of surfactant in the weak solution.

An experimental setup for testing the effect of surfactant on the absorption of water vapor in LiBr-H₂O solution in a Vapor Absorption Refrigeration (VAR) system is designed and constructed. The experiments were performed with four different concentrations of LiBr such as 45%, 50%, 55% and 60% in LiBr-H₂O solution by weight and three different surfactant concentrations such as 100, 200 and 300 ppm in the weak solution. 2-ethyl-1-hexanol was used as surfactant in this experiment. From the experimental results it can be said that, the absorption of water is found to increase with the increase of concentration of LiBr in the weak solution of LiBr-H₂O. The addition of surfactant enhances the absorption of water vapor. The maximum enhancement of water vapor absorption is obtained when surfactant concentration is 300 ppm and LiBr concentration is 50% in LiBr-H₂O weak solution by weight. Also the experimental results agree with the experimental results of Jung [68] et al. and Kim [65] et al. closely (the deviations of enhancement of present work are about 6.3% and 6.6% less than that work of Jung et al. and Kim et al. respectively).

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Nomenclature

Weak solution mass fraction	X
Density	ρ
Saturation pressure	h
Absorber heat rejected	Q_a
Heat transfer rate	Q
Wall Temperature of absorber	T_w
Temperature difference	ΔT_m
Total heat transfer area	A
Overall heat transfer coefficient	U
Logarithmic mean temperature difference	ΔT_{ln}
Reynolds number	Re
Prandtl number	Pr
Nusselt number	N_u
Film thickness	δ
Solution convective heat transfer coefficient	h_s
Heat transfer coefficients for inside flow	h_i
Heat transfer coefficients for outside flow	h_o
Thermal conductivity of tube material	k
Mass flow rate	m
Kinematic viscosity	ν



CHAPTER I

Introduction

1.1 Background and Motivation

The present world is now worried about global warming. Ozone layer depletion is one of the reasons of global warming and CFC based refrigerant is liable for this. The use of LiBr-H₂O based vapor absorption refrigeration (VAR) system may be one of the replacements of CFC based refrigeration system for cooling. Although the world concerns more and more on global climate change and depleting of conventional energy resources, solar energy technology receives increasing interests as an environment-friendly and sustainable alternatives. The use of Li-Br based VAR system also fulfills this desire of using solar energy. The effectiveness of a VAR system depends on many factors and one of the major is absorber performance. So the enhancement of absorption is very important to have a better performance of the absorber and thereby the refrigeration system.

Also the demand for air conditioning in summer is increasing more and more. Most refrigerators used for air conditioning are mainly driven by electricity. These electric refrigerators are almost perfect in performance but with their prevalence, power shortage is becoming a concern in the world now. Absorption refrigerators driven by gas or solar energy are utilized for air conditioning of large buildings with satisfactory results, but even further improvement in performance and downsizing are desired. On the other hand, these are mainly large-capacity machines. Small-capacity machines for household use have not yet been realized. To be accepted into households, air-cooled-type absorption refrigerators are more suitable compared to water-cooled type since their installations become easier without the unnecessary piping of cooling water. The parts to be cooled are absorbers and condensers, but generally absorbers take larger volumes and their improvement is especially necessary.

In water-lithium bromide vapor absorption refrigeration system, water is used as the refrigerant while lithium bromide (LiBr) is used as the absorbent. Thus in the absorber the lithium bromide absorbent absorbs the water refrigerant and solution of water and lithium bromide is formed. This solution is pumped by the pump to the generator where the solution is heated. The water refrigerant gets vaporized and moves to the condenser where it is condensed while lithium bromide flows back to the absorber where it further absorbs water vapor coming from the evaporator.

Falling film flows on solid surface are widely encountered in refrigeration and air conditioning, desalination, or other chemical engineering processes. In absorption cooling machines, the absorber has different configurations depending on the working fluid. In any case this element together with the evaporator is one which needs the highest heat transfer capacity to the external heat sink of the absorption cycle. Therefore many efforts have been made to reduce its size by increasing its performance. A common geometry in LiBr-H₂O systems is the gravity driven film, falling over a horizontal tube bundle. Structured surface tubes and additives are commonly used to increase the transfer rates.

The role of the additives or surfactant is to enhance the heat/mass transfer rate in the absorber [1]. It also enhances the rate in the condenser, although this is less significant for the economics. The surfactant flows around the absorber along with the refrigerant. The surfactant is soluble in the liquids, although the solubility in aqueous lithium bromide is quite low (on the order of 25 ppm). It is observed that the addition of surfactant additive such as 2-ethyl-1-hexanol (2EH), even on the order of 100 to 300 ppm, introduces a surface flow, which dramatically disrupts the absorption boundary layer and, thereby, enhances the absorption rate [2]. Thus, the use of a surfactant reduces the size of absorber significantly and reduces the cost of the entire machine.

The present work is to investigate the enhancement of absorption of water vapor into aqueous lithium-bromide using 2-ethyl-1-hexanol (2EH) as a surfactant for different concentration of lithium-bromide and surfactant on absorption. The enhancement role of the surfactant is newer technique and some studies observed the phenomenon of absorption with surfactant. Several

published theories attribute the enhancement to interfacial convection (Marangoni convection) due to surface tension gradients. However, there were no such studies found in our country.

1.2 Objective:

The objective of this work is to investigate the effect of surfactant (2-ethyl-1-hexanol) on water vapor absorption into aqueous lithium-bromide (LiBr).

CHAPTER II

Survey of Literature

In this chapter the most usable vapor absorption refrigeration system and relevant previous work on the effect of surfactants on absorption enhancement are reviewed. The review is divided into five sections: 1) Basic of vapour absorption system 2) various types of surface tension of aqueous lithium bromide (LiBr) with surfactants, 3) Marangoni convection in the presence of surfactants, 4) theories of surfactant enhancement, and 5) experimental work in absorption enhancement in the presence of surfactants.

2.1 Basic of Vapor Absorption System

2.1.1 History of Refrigeration System

In 1806, Frederic Tudor (who was later called as the “ice king”) began the trade in ice by cutting it from the Hudson River and ponds of Massachusetts and exporting it to various countries including India. In India Tudor’s ice was cheaper than the locally manufactured ice by nocturnal cooling. The ice trade in North America was a flourishing business. Ice was transported to southern states of America in train compartments insulated by 0.3m of cork insulation. Trading in ice was also popular in several other countries like Great Britain, Russia, Canada, Norway and France. In these countries ice was either transported from colder regions or was harvested in winter and stored in icehouses for use in summer. The ice trade reached its peak in 1872 when America alone exported 225000 tons of ice to various countries as far as China and Australia. However, with the advent of artificial refrigeration the ice trade gradually declined. After searching in the world market, only one manufacturer was found producing LiBr-water absorption refrigerators. Yazaki of Japan is the only producing company. The possibility of producing this type of vapor absorption cooling system is less.

In 1805, an American inventor, Oliver Evans, designed the first refrigeration machine that used vapor instead of liquid. Evans never constructed his machine, but one similar to it was built by an American physician, John Gorrie.

In 1842, the American physician John Gorrie, to cool sickrooms in a Florida hospital, designed and built an air-cooling apparatus for treating yellow-fever patients. His basic principle--that of compressing a gas, cooling it by sending it through radiating coils, and then expanding it to lower the temperature further--is the one most often used in refrigerators today. Giving up his medical practice to engage in time-consuming experimentation with ice making, he was granted the first U.S. patent for mechanical refrigeration in 1851.

In 1973, Prof. James Lovelock reported finding trace amounts of refrigerant gases in the atmosphere. In 1974, Sherwood Rowland and Mario Molina predicted that chlorofluorocarbon refrigerant gases would reach the high stratosphere and there damage the protective mantle of the oxygen allotrope, ozone. In 1985 the "ozone hole" over the Antarctic had been discovered and by 1990 Rowland and Molina's prediction was proved correct.

Commercial production began in 1923 by the newly formed company AB Arctic, which was bought by Electrolux in 1925. In the 60s the absorption refrigeration saw a renaissance due to the substantial demand for refrigerators for caravans. AB Electrolux established a subsidiary in the U.S, named Dometic Sales Corporation. The company marketed refrigerators for caravans under the Dometic brand. In 2001 Electrolux sold most of its Leisure Products line to the venture-capital company EQT which created Dometic as stand-alone company. At the 2007 TED Conference, Adam Grosser presented his research of a new, very small, "intermittent absorption" vaccine refrigeration unit for use in third world countries. The refrigerator is a small unit placed over a campfire that can later be used to cool 3 gallons of water to just above freezing for 24 hours in a 30 degree Celsius environment.

2.1.2 Principle of Operation

As the name implies, absorption refrigeration systems involve the absorption of a refrigerant

by transport medium or absorbent. The most widely used absorption refrigeration system is the ammonia-water system, where ammonia serves the refrigerant and water as the transport medium or absorber. Other useful system is water-lithium bromide system, where serves the refrigerant and lithium bromide as the absorber. In vapor absorption system is alike of vapor compression refrigeration system except that the compressor has been replaced by a complex absorption mechanism consisting of an absorber, a pump, a generator, an expansion valve, and a rectifier. The vapor refrigerant when come from generator is cooled and condensed in the condenser by rejecting heat to the surroundings, is throttled to the evaporator pressure, and absorbs heat from the refrigerated space as it flows through the evaporator. The refrigerant vapor leaves the evaporator and enters the absorber, where it dissolves and reacts with absorber to form a aqueous solution. This is an exothermic reaction; thus heat is released during this process. The amount of refrigerant absorbed into the absorber is inversely proportional to the temperature. After absorption the rich in refrigerant mixture pumped to the generator. Here heat is transferred to the solution from a source to vaporize the refrigerant and then it continues to run in condenser and the cycle completes.

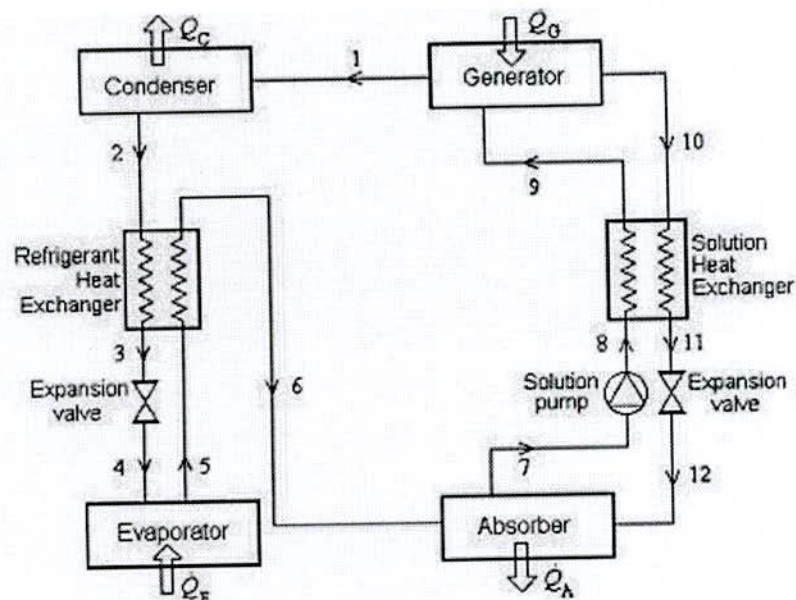


Figure 2.1: Basic principle of vapor absorption system

2.1.3 Working Fluid for Absorption Refrigeration Systems

Performance of absorption refrigeration systems is critically dependent on the chemical and thermodynamic properties of the working fluid. A fundamental requirement of absorbent/refrigerant combination is that, in liquid phase, they must have a margin of miscibility within the operating temperature range of the cycle. The mixture should also be chemically stable, non-toxic, and non-explosive. In addition to these requirements, the followings are desirable.

The elevation of boiling (the difference in boiling point between the pure refrigerant and the mixture at the same pressure) should be as large as possible. Refrigerant should have high heat of vaporization and high concentration within the absorbent in order to maintain low circulation rate between the generator and the absorber per unit of cooling capacity.

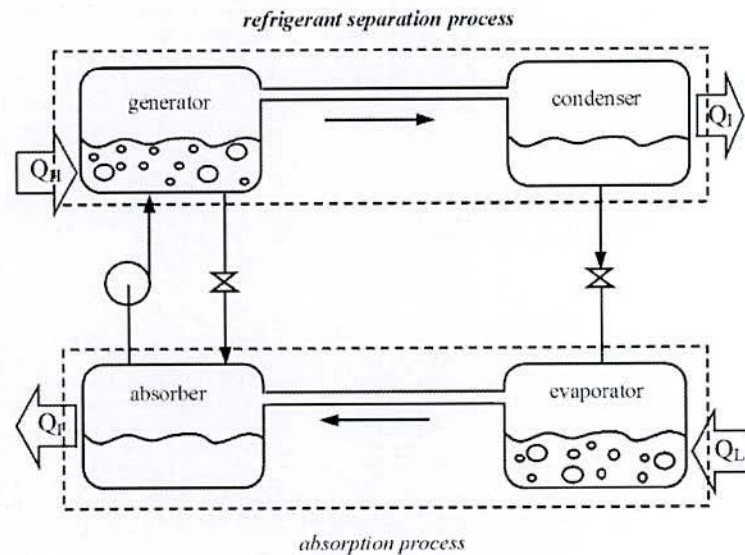


Figure 2.2: A continuous absorption refrigeration cycle composes of two processes

Transport properties that influence heat and mass transfer, e.g., viscosity, thermal conductivity, and diffusion coefficient should be favorable. Both refrigerant and absorbent should be non-corrosive, environmental friendly, and low-cost.

Many working fluids are suggested in literature. A survey of absorption fluids provided by Marcriss [3] suggests that, there are some 40 refrigerant compounds and 200 absorbent compounds available. However, the most common working fluids are Water/NH₃ and LiBr/water.

Since the invention of an absorption refrigeration system, water NH₃ has been widely used for both cooling and heating purposes. Both NH₃ (refrigerant) and water (absorbent) are highly stable for a wide range of operating temperature and pressure. NH₃ has a high latent heat of vaporization, which is necessary for efficient performance of the system. It can be used for low temperature applications, as the freezing point of NH₃ is -77°C. Since both NH₃ and water are volatile, the cycle requires a rectifier to strip away water that normally evaporates with NH₃. Without a rectifier, the water would accumulate in the evaporator and offset the system performance.

There are other disadvantages such as its high pressure, toxicity, and corrosive action to copper and copper alloy. However, water/ NH₃ is environmental friendly and low cost. Thermodynamic properties of water/ NH₃ can be obtained from [4].

The use of LiBr/water for absorption refrigeration systems began around 1930. Two outstanding features of LiBr/water are non-volatility absorbent of LiBr (the need of a rectifier is eliminated) and extremely high heat of vaporization of water (refrigerant). However, using water as a refrigerant limits the low temperature application to that above 0°C. As water is the refrigerant, the system must be operated under vacuum conditions. At high concentrations, the solution is prone to crystallization. It is also corrosive to some metal and expensive. Some additive may be added to LiBr/water as a corrosion inhibitor [5] or to improve heat-mass transfer performance.

Although LiBr/water and water/ NH₃ have been widely used for many years and their properties are well known, much extensive research has been carried out to investigate new working fluids. Fluorocarbon refrigerant-based working fluids have been studied. R22 and R21 have been widely suggested because of their favorable solubility with number of organic solvents. The two solvents, which have stood out are Dimethyl Ether of Tetraethylene Glycol (DMETEG) and Dimethyl Formamide (DMF). Research on these kinds of working fluids may

be obtained from the literature [6,7].

A binary mixture using inorganic salt absorbent such as LiBr/water or NaOH/water may be the most successful working for an absorption refrigeration system. However, at high concentration such as at high temperature, the solution is prone to crystallization. It was found that the addition of a second salt as in a ternary mixture such as LiBr+ZnBr₂/water can improve the solubility of the solution. Various ternary mixtures have been tested for using with an absorption system.

2.1.4 Various Designs of Absorption Refrigeration Cycles

2.1.4.1 Single Effect Absorption System

A single-effect absorption refrigeration system is the simplest and most commonly used design. There are two design configurations depending on the working fluids used. Figure 2.3 shows a single-effect system using non-volatility absorbent such as LiBr/water.

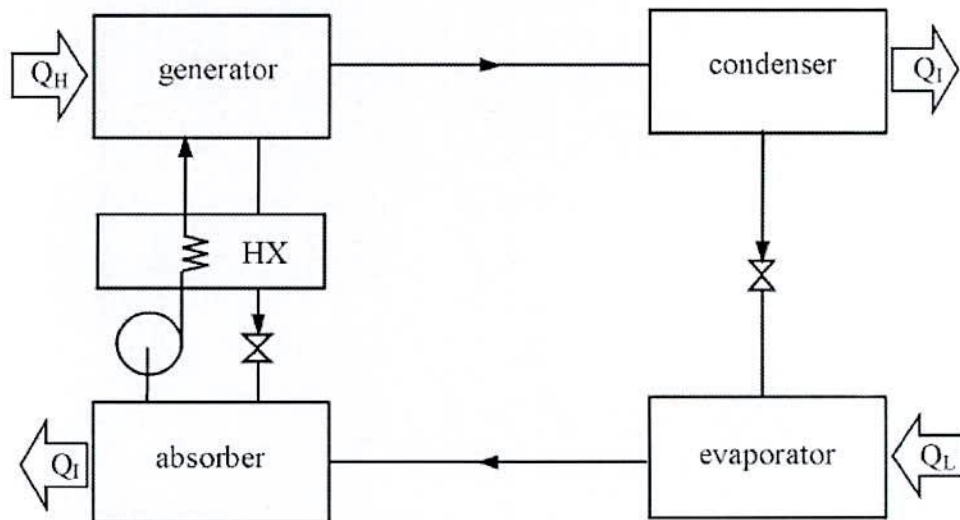


Figure 2.3: A single-effect LiBr/water absorption refrigeration system with a solution heat exchanger that helps decrease heat input at the generator

High temperature heat supplied to the generator is used to evaporate refrigerant out from the solution (rejected out to the surroundings of the condenser) and is used to heat the solution from the absorber temperature (rejected out to the surroundings of the absorber). Thus, irreversibility is caused as high temperature heat at the generator is wasted out at the absorber and the condenser. In order to reduce this irreversibility, a solution heat exchanger is introduced as shown in Figure 2.3. The heat exchanger allows the solution from the absorber to be preheated before entering the generator by using the heat from the hot solution leaving the generator. Therefore, the COP is improved as the heat input at the generator is reduced. Moreover, the size of the absorber can be reduced as less heat is rejected. Experimental studies show that COP can be increased up to 60% when a solution heat exchanger is used [8].

When volatile absorbent such as water/ NH_3 is used, the system requires an extra component called "a rectifier", which will purify the refrigerant before entering the condenser. As the absorbent used (water) is highly volatile, it will be evaporated together with ammonia (refrigerant). Without the rectifier, this water will be condensed and accumulated inside the evaporator, causing the performance to drop.

Even if the most common working fluids used are LiBr/water and water/ NH_3 , various researchers have studied performance of a single-effect absorption system using other kinds of working fluids such as $\text{LiNO}_3/\text{NH}_3$, $\text{LiBr}+\text{ZnBr}_2/\text{CH}_3\text{OH}$, LiCl/water , Glycerol/water [9,10].

2.1.4.2 Absorption Heat Transformer

Any absorption refrigeration cycle exchanges heat with three external reservoirs; low, intermediate, and high temperature levels. When an absorption system is operated as a refrigerator or a heat pump, the driving heat is supplied from the high temperature reservoir. Refrigeration effect is produced at a low temperature level and rejects heat out at an intermediate temperature level. The difference between them is the duty. For a refrigerator, the useful heat transfer is at a low temperature. For the heat pump, the useful heat transfer is at an intermediate temperature. Normally, the surrounding is used as a low temperature reservoir for a heat pump or as an intermediate temperature reservoir for the refrigerator.

Another type of absorption cycle is known as “an absorption heat transformer” or “a reverse absorption heat pump”. This system uses heat from an intermediate temperature reservoir as the driving heat (normally from industrial waste heat). The system rejects heat out at a low temperature level (normally to the surroundings).

The useful output is obtained at the highest temperature level. The use of an absorption heat transformer allows any waste heat to be upgraded to a higher temperature level without any other heat input except some work required circulating the working fluid.

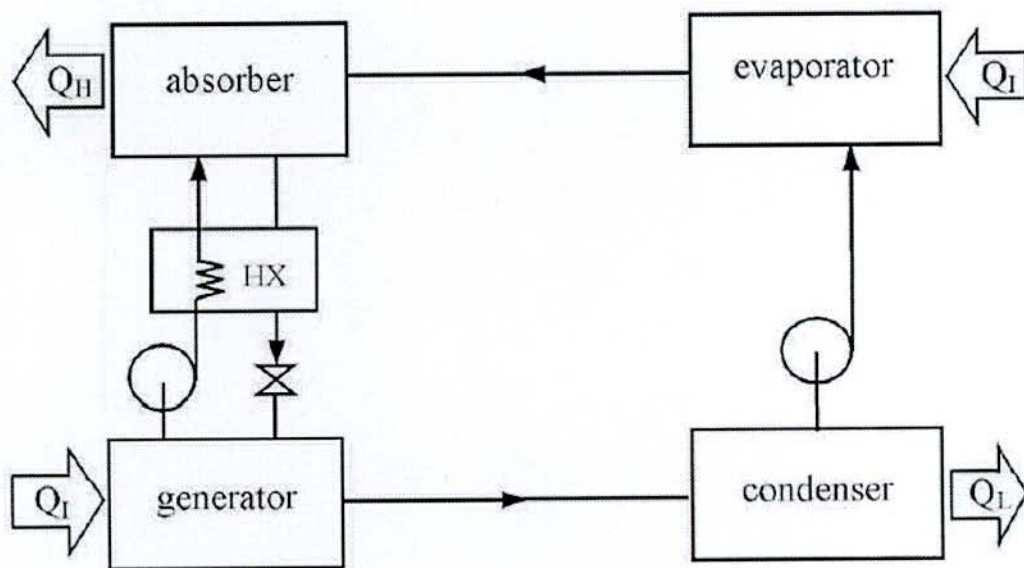


Figure 2.4: Absorption heat transformer absorbs waste heat at the generator. Liquid refrigerant is pumped to the evaporator to absorb waste heat. High temperature useful heat from the absorber is heat of absorption

Fig 2.4 shows a schematic diagram of an absorption heat transformer. This cycle has similar components as a single-effect absorption cycle. The difference is that an expansion device installed between the condenser and the evaporator is substituted by a pump. Waste heat at a relatively low temperature is supplied to the generator for refrigerant separation in the usual manner. Liquid refrigerant from the condenser is then pumped to the evaporator with elevated pressure. In the evaporator, it is vaporized by using the same low temperature waste heat used

to drive the generator (absorption heat transformers are usually operated so that the generator and evaporator temperatures are equal). The vapor refrigerant is then absorbed into solution in the absorber which rejects the useful heat out at a high temperature level. Low-grade heat can be upgraded by using a heat transformer e.g. solar energy [11], industrial waste heat. Performance of an absorption heat transformer with various working fluids has been studied; LiBr/water, LiBr+ZnBr₂/CH₃OH, DMETEG/R21, DMF/R21 [12,13].

2.1.4.3 Multi-Effect Absorption Refrigeration Cycle

The main objective of a higher effect cycle is to increase system performance when high temperature heat source is available. By the term “multi-effect”, the cycle has to be configured in a way that heat rejected from a high-temperature stage is used as heat input in a low-temperature stage for generation of additional cooling effect in the low-temperature stage. Double-effect absorption refrigeration cycle was introduced during 1956 and 1958 [14]. Figure 2.5 shows a system using LiBr/water. High temperature heat from an external source supplies to the first-effect generator. The vapor refrigerant generated is condensed at high pressure in the second-effect generator. The heat rejected is used to produce additional refrigerant vapor from the solution coming from the first-effect generator. This system configuration is considered as a series-flow-double-effect absorption system.

A double-effect absorption system is considered as a combination of two single effect absorption systems whose COP value is COP_{single}. For one unit of heat input from the external source, cooling effect produced from the refrigerant generated from the first-effect generator is $1 \times \text{COP}_{\text{single}}$. For any single-effect absorption system, it may be assumed that the heat rejected from the condenser is approximately equal to the cooling capacity obtained. Thus the heat supply to the second generator is $1 \times \text{COP}_{\text{single}}$. The cooling effect produced from the second-effect generator is $(1 \times \text{COP}_{\text{single}}) \times \text{COP}_{\text{single}}$. Therefore, the COP of this double-effect absorption system is $\text{COP}_{\text{double}} = \text{COP}_{\text{single}} + (\text{COP}_{\text{single}})^2$. According to this analysis, a double effect absorption system has a COP of 0.96 when the corresponding single-effect system has a COP of 0.6. Theoretical studies of a double-effect absorption system have been provided for various working fluids [15, 16].

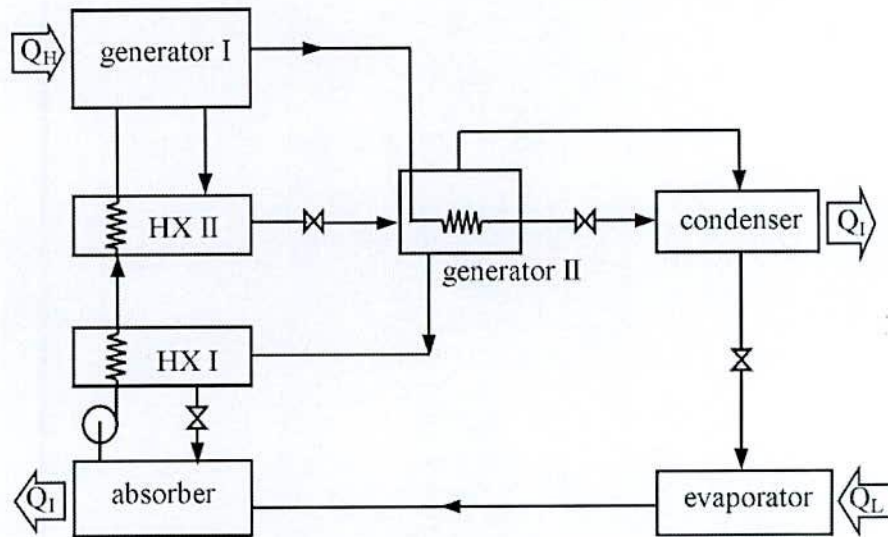


Figure 2.5: A double-effect water/LiBr absorption cycle. Heat released from the condensation of refrigerant vapor is used as heat input in generator II. This cycle is operated with 3 pressure levels i.e. high, moderate and low pressure

If LiBr/water is replaced with water/ NH_3 , maximum pressure in the first-effect generator will be extremely high. Figure 2.6 shows a double-effect absorption system using water/ NH_3 . In contrast to the system for LiBr/water, this system can be considered as a combination of two separated single-effect cycles. The evaporator and the condensers of both cycles are integrated together as a single unit as shown. Thus, there are only two pressures levels in this system and the maximum pressure can be limited to an acceptable level. Heat from external source supplies to generator II only as water is an absorbent, there is no problem of crystallization in the absorber. Hence, absorber II can be operated at high temperature and rejects heat to the generator I. This system configuration is considered as a parallel-flow-double-effect absorption system.

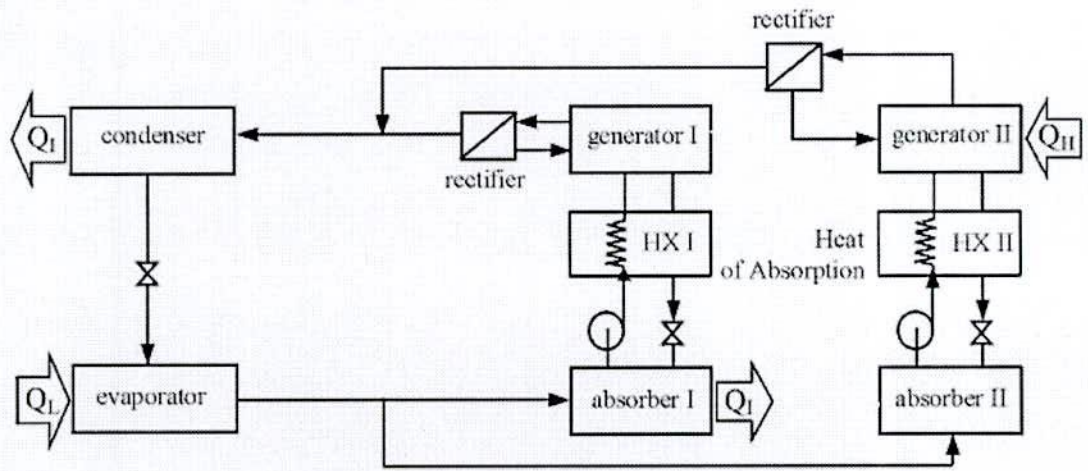


Figure 2.6: A double-effect absorption cycle operates with two pressure levels. Heat of absorption from absorber II is supplied to the Absorber I for the refrigerant separation process

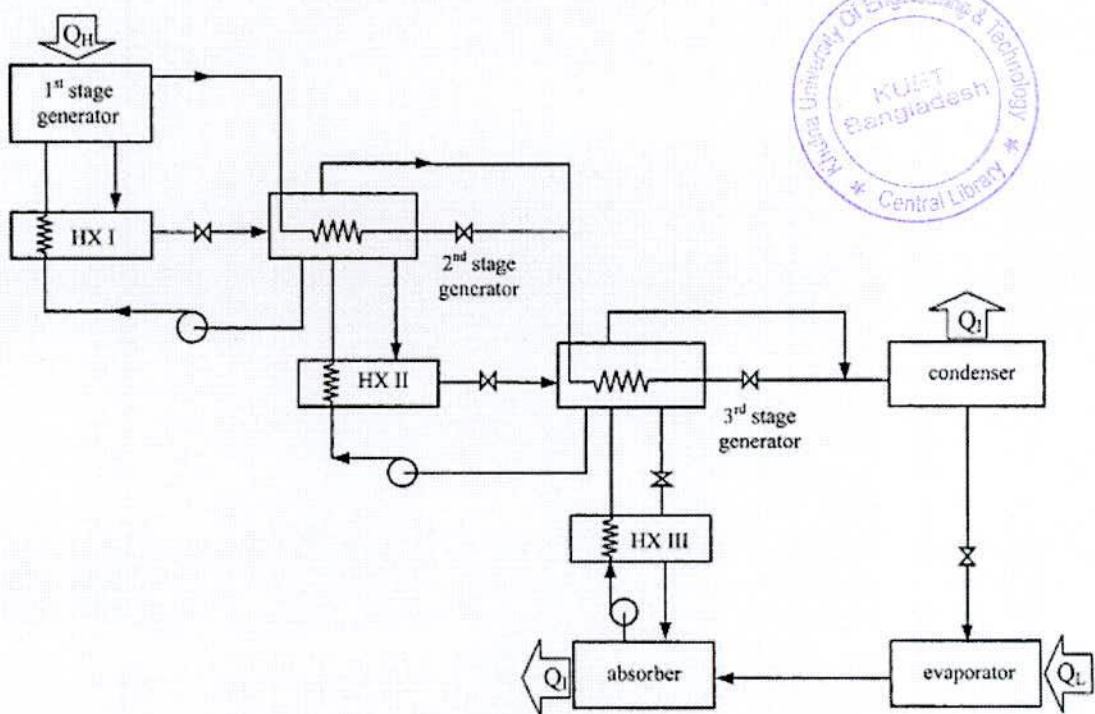


Figure 2.7: A triple-effect absorption cycle operates at 4 pressure levels. Heat of condensation from the higher pressure stage is used for refrigerant separation in the lower-pressure stage

Several types of multi-effect absorption cycle has been analyzed such as the triple-effect absorption cycle (Figure 2.7) and the quadruple-effect absorption cycle. However, an improvement of COP is not directly linked to the increment of number of effect. It must be noted that, when the number of effects increase, COP of each effect will not be as high as that for a single-effect system. Moreover, the higher number of effect leads to more system complexity. Therefore, the double-effect cycle is the one that is available commercially [17].

2.1.4.4 Absorption Refrigeration Cycle with GAX

GAX stands for generator/absorber heat exchanger or sometimes is called DAHX which stands for desorber/absorber heat exchanger. Higher performance can be achieved with a single-effect absorption system. Referring to the parallel flow double effect absorption system mentioned earlier, the system consists of two single-effect cycles working in a parallel manner. The concept of GAX is to simplify these two stage double effect absorption cycle but still produce the same performance. The ideal of GAX was introduced in 1911 by Altenkirch and Tenckhoff [18]. The simplified configuration is shown schematically in Figure 2.8.

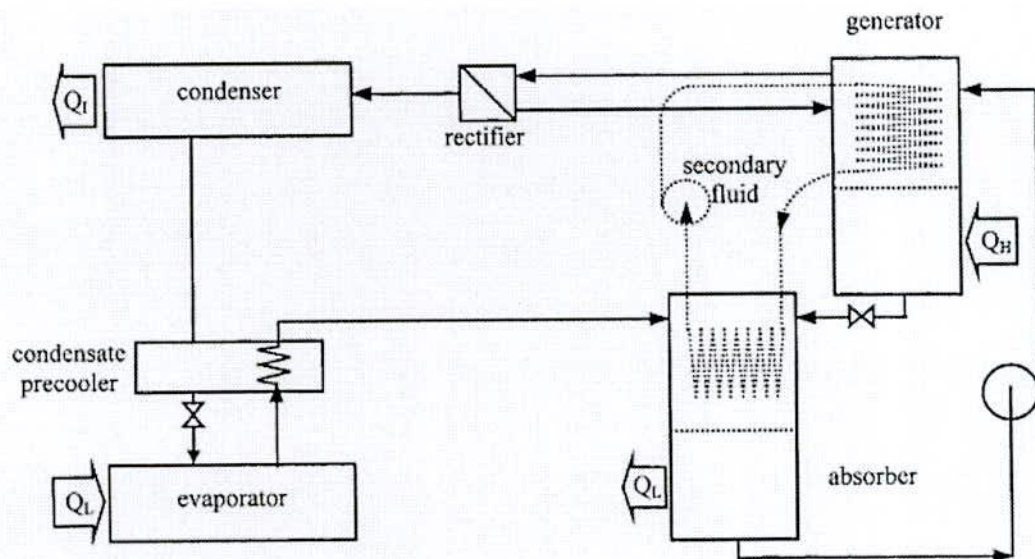


Figure 2.8: The dotted loop shows secondary fluid used for transferring heat from high the temperature section in the absorber to low temperature section in the generator

An absorber and a generator may be considered as a counter-flow-heat exchanger as shown in Figure 2.8. At the absorber, weak-refrigerant solution from the generator and vapor refrigerant from the evaporator enter at the top section. Heat produced during the absorption process must be rejected out in order to maintain ability to absorb the refrigerant vapor. At the top section, heat is rejected out at a high temperature. In the lower section, the solution further absorbs the vapor refrigerant while cooling down by rejecting heat to the surrounding. At the generator, rich-refrigerant solution from the absorber enters at the top section. In this section, the refrigerant is dried out from the solution as it is heated by using the heat rejected from the top section of the absorber. At the lower section of the generator, the solution is further dried as it is heated by the external source. Referring to Figure 8, there is an additional secondary-fluid, which is used for transferring heat between the absorber and the generator. Therefore, a single-effect absorption system can provide as high COP as that for the two-stage-double-effect absorption system by using GAX. This system has been studied [19].

2.1.4.5 Absorption Refrigeration Cycle with an Absorber Heat Recovery

It is already mentioned earlier that the use of a solution heat exchanger improves the system COP. Rich-refrigerant solution from the absorber can be preheated before entering the generator by transferring heat from hot solution coming from the generator. By introducing an absorber-heat-recovery, temperature of the rich-refrigerant solution can be further increased. Similar to the GAX system, the absorber is divided into two sections. Heat is rejected out at a different temperature. The lower temperature section rejects heat out to the surroundings as usual. However, the higher temperature section is used to preheat rich-refrigerant solution as shown in Figure 2.9. Therefore, the heat input to the generator is reduced causing the COP to increase. This system was studied theoretically by using various working fluids; water/NH₃ and LiNO₃/NH₃ [20, 21]. The cycle with an absorber-heat-recovery was found to have 10% improvement in COP. However, the machine based on this absorber design has not yet been built.

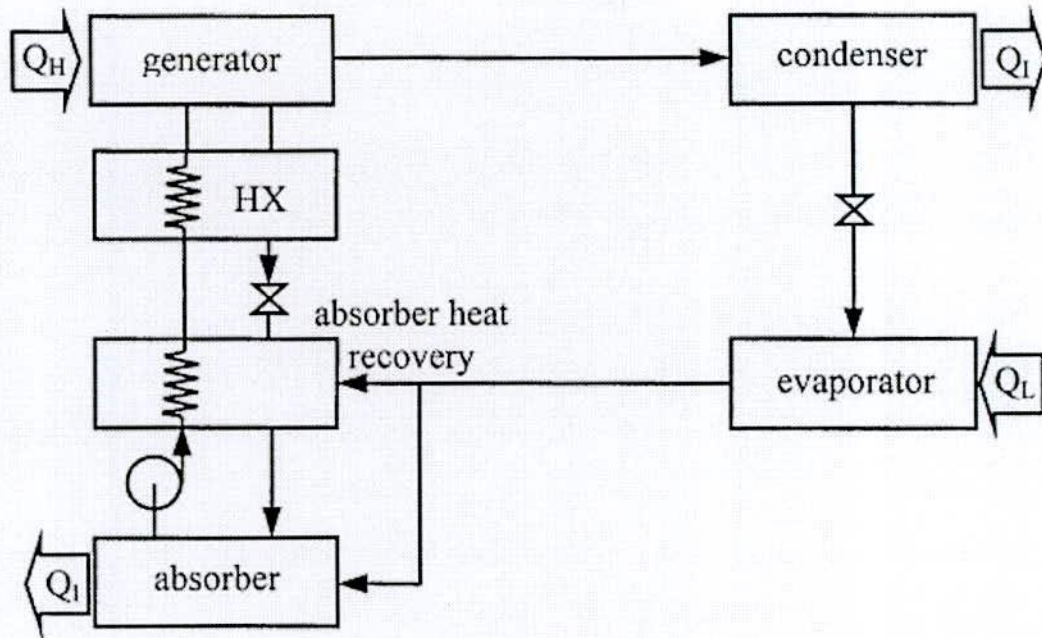


Figure 2.9: The cycle with absorber heat recovery uses heat of absorption to preheat the outgoing stream from the absorber to the generator

2.1.4.6 Half-Effect Absorption Refrigeration Cycle

It must be noted that, any absorption refrigeration system can be operated only when the solution in the absorber is richer in refrigerant than that in the generator. When the temperature increases or the pressure reduces, the fraction of refrigerant contained in the solution is reduced, and vice versa. When the generator temperature is dropped, the solution circulation rate will be increased causing the COP to drop. If it is too low, the system can be no longer operated.

A half-effect absorption cycle is a combination of two single-effect cycles but working at different pressure levels. Letting heat source temperature be lower than the minimum temperature is necessary for a single-effect cycle working at the same pressure level.

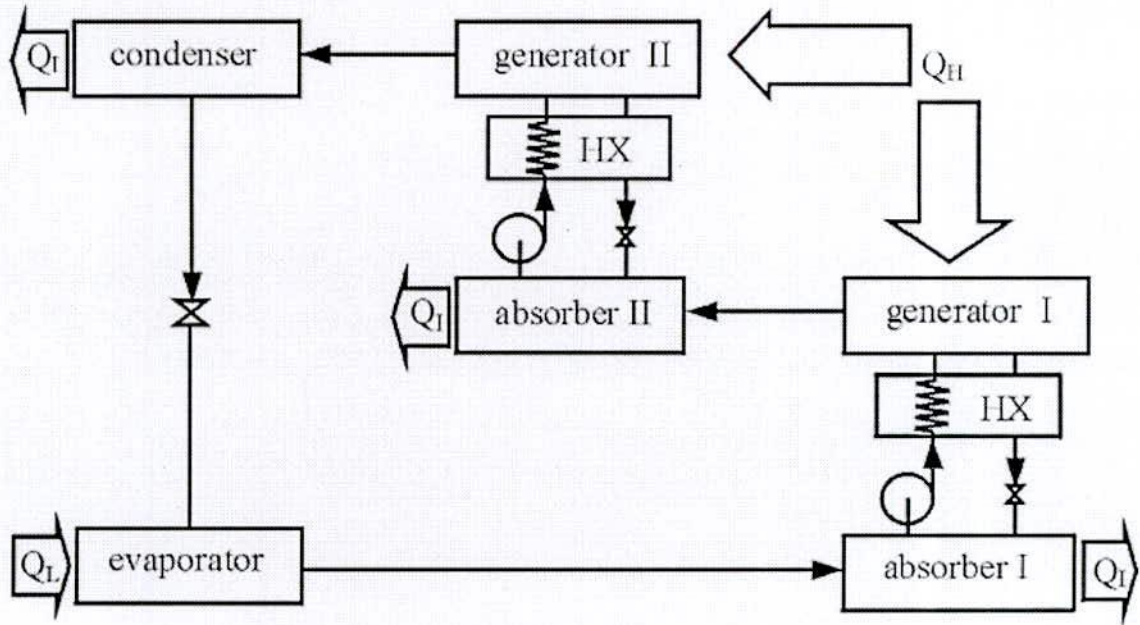


Figure 2.10: A half-effect absorption cycle

The half-effect absorption system was introduced for an application with a relatively low-temperature heat source [22]. Fig 2.10 shows a schematic diagram of a half-effect absorption refrigeration cycle. The system configuration is exactly the same as the double-effect absorption system using water/NH₃ except the heat flow directions are different. Referring to Fig 2.10, high temperature heat from an external source transfers to both generators and absorbers reject heat out to the surroundings. Absorber II and generator I are operated at an intermediate pressure level. Therefore, the circulation rate between generator I and absorber I and between generator II and absorber II can be maintained at acceptable levels. It must be noted that COP of the half-effect absorption system is relatively low as it rejects more heat than a single-effect absorption cycle around 50% [23]. However, it can be operated with the relatively low temperature heat source.

2.1.4.7 Combined Vapor Absorption-Compression Cycle

This system is usually known as an absorption-compression system. A schematic diagram of a typical absorption/compression cycle is shown in Fig 2.11(a). It can be seen that, a condenser and an evaporator of a conventional vapor-compression system are replaced with a vapor

absorber and a vapor generator. For given surrounding temperature and refrigerating temperature, the pressure differential across the compressor is much lower than a conventional vapor-compression system. Thus, the COP is expected to be better than a conventional vapor-compression system. Altenkirch did the first investigation in 1950 and proposed a potential for energy-saving [23]. The cycle can be configured as a heat pump cycle. Machielsen developed a heat pump cycle as shown in Fig 2.11(b).

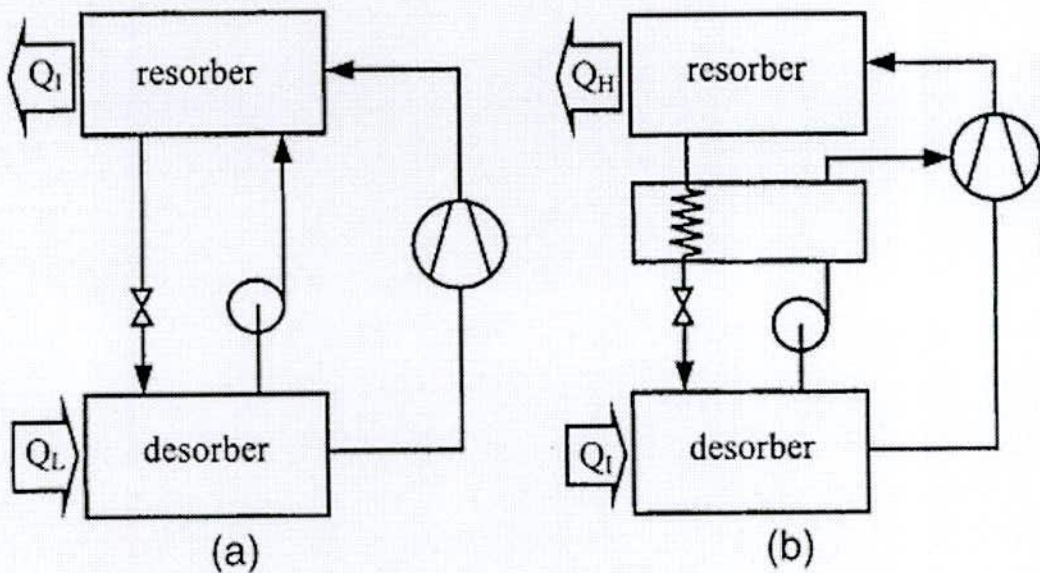


Figure 2.11: Combined vapor absorption/compression heat pump

An interesting configuration is a double-effect vapor absorption/compression cycle as shown in Fig 2.12. The rejected first stage absorber heat is supplied to the generator of the second-stage. The transfer of heat is done internally which overcomes the large temperature difference at the moderate pressure ratio. This concept has been shown successfully in several studies, [24].

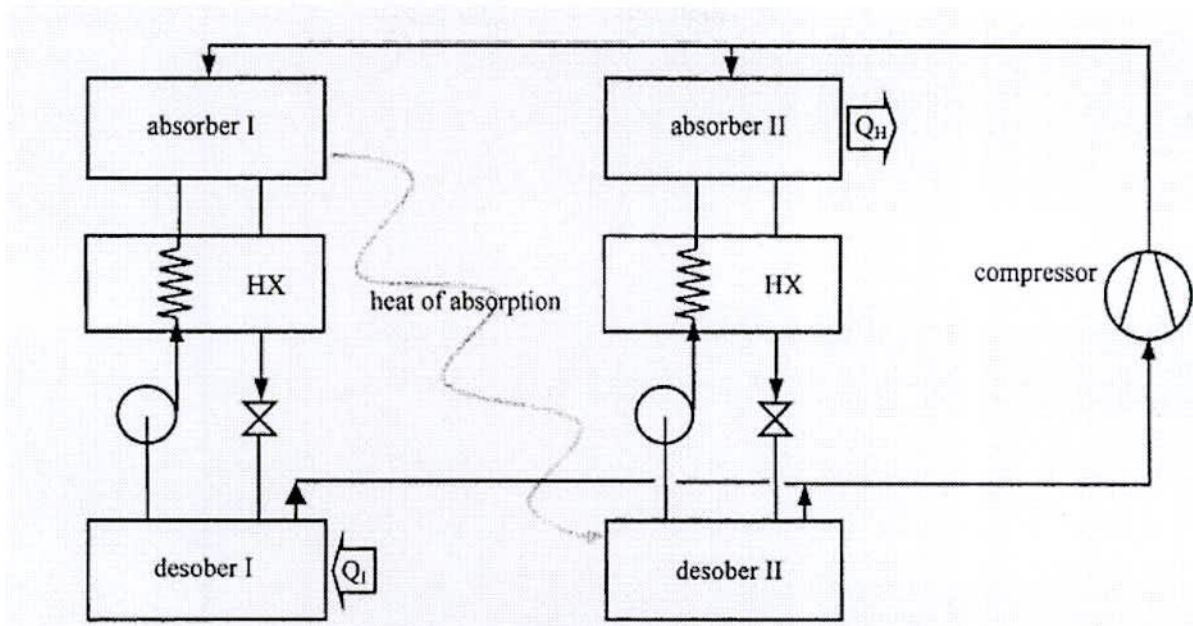


Figure 2.12: A double effect absorption-compression cycle is configured as a heat pump. Heat of absorption in the first stage will be supplied to the second stage for refrigerant separation

Another configuration of the vapor absorption/compression cycle, proposed by Cacciola [25] et al. is shown schematically in Figure 13 and employs two combinations of working fluids, water/NH₃ and KHO/water. This is a compromise of the water/NH₃ cycle and KHO/water cycle. The highest system pressure is reduced and the rectifier of water/NH₃ system is abstained. This cycle can be operated with an ambient temperature lower than 0°C without freezing or crystallization problems. The first experimental results of an absorption/compression cycle with direct desorber/absorber heat exchanger was presented by Groll and Radermacher [26].

This is a modified plant from a two stage-solution circuit proposed by Rane and Radermacher and Rane et al. This technology is the basis for the study of GAX cycle in these days. Various designs of combined vapor absorption/compression cycle have been introduced. They can produce attractively high COP. However, they are complex and the driving energy is in the form of mechanical work. Thus, they cannot be considered as a heat-operated system.

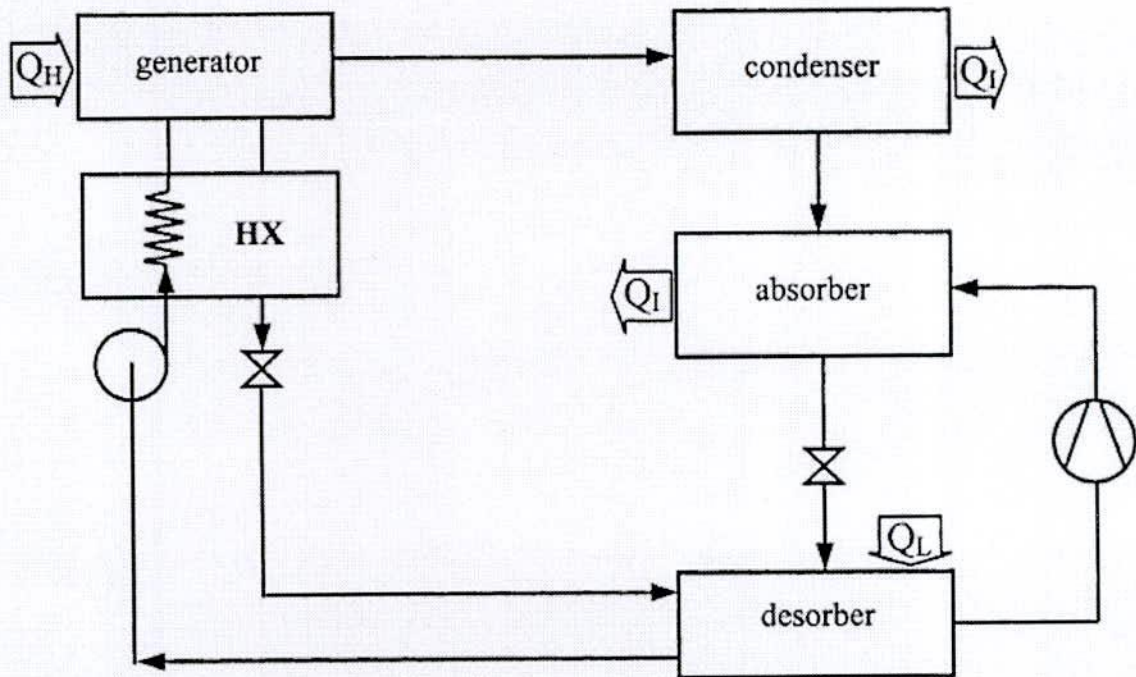


Figure 2.13: A combined cycle proposed by Caccoila et al. employing two combinations of working fluids i.e. $\text{NH}_3/\text{H}_2\text{O}$ and $\text{H}_2\text{O}/\text{KHO}$. The rectifier is absent and also the highest pressure is decreased

2.1.4.8 Dual-Cycle Absorption Refrigeration

The concept of a dual-cycle absorption system is similar to a parallel-double-effect absorption system. However, this system consists of two completely separated cycles using different kinds of working fluid. Hanna [29] et al. invented a dual-cycle absorption refrigeration and heat pump as shown in Figure 2.14. This system consists of two single effect absorption cycles using water/ NH_3 and LiBr/water.

The NH_3 system is driven by heat obtained from an external heat source. The heat reject from its absorber and condenser is used as a driving heat for the LiBr/water system. The LiBr/water system rejects heat out to the surrounding at the condenser and the absorber as usual. The cooling effect can be obtained from both evaporators.

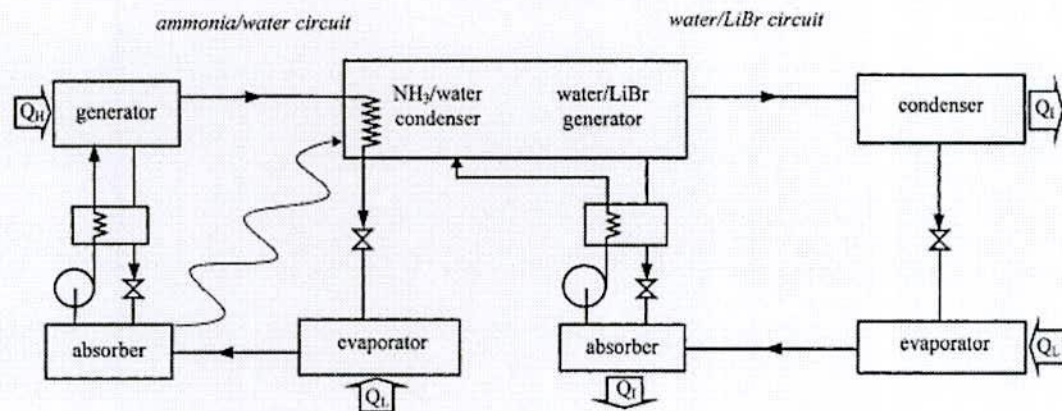


Figure 2.14: Solar driven dual cycle absorption employs two different working fluids i.e. NH₃/water and water/LiBr. Heat of absorption and condensation from NH₃/water cycle are supplied to the generator of water/LiBr cycle

2.1.4.9 Self-Circulation Absorption System Using LiBr/Water

Even if the prime energy for an absorption refrigeration system is in the form of heat, some electricity still required to drive a circulation pump. There is some absorption refrigeration systems that do not require any circulation pump. In such a system, working fluid is circulated naturally by a thermo syphon effect known as a bubble pump.

Yazaki Inc. of Japan introduced a self-circulate absorption refrigeration system based on a single-effect system using LiBr/water. Using water as a refrigerant, differential pressure between the condenser and the evaporator is very low and can be maintained by using the principle of hydrostatic-head. The solution from the absorber can be circulated to the generator by a bubble pump. Heat input to the generator is used for both circulation of working fluid and evaporation of refrigerant.

The weak-refrigerant solution returns gravitationally back to absorber. A schematic diagram of this system is shown in Figure 2.15. With the effect of the bubble pump, the solution is boiled and pumped at the same time. Smith and Khahra [30] carried out a study of performance of CH-900-B Yazaki absorption water chiller operated using propane gas.

Eriksson and Jernqvist, developed a 10 kW self-circulation absorption heat transformer using NaOH/water. Due to the high temperature and pressure differential between the condenser and the evaporator, the absorber and evaporator are located at 7 and 10 m below the condenser and generator, respectively. The lowest and highest point of this machine is 14 m. which is equivalent to a pressure difference of 1 bar inside the system.

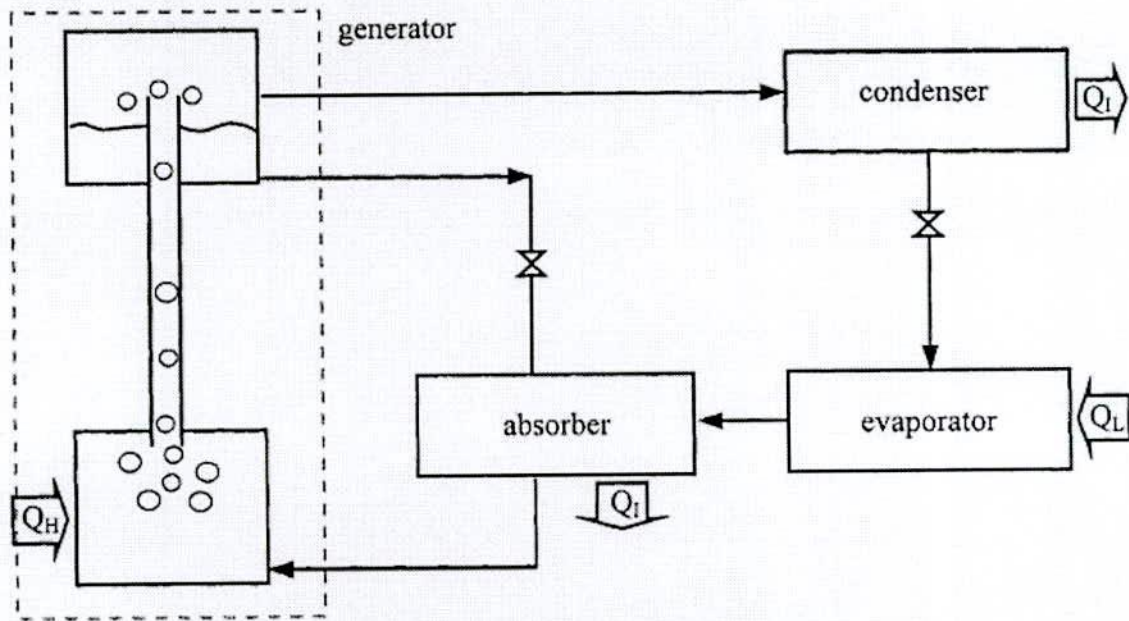


Figure 2.15: Bubbles pump in a generator module

2.1.5 Different types of Heat Exchanger

A variety of heat exchangers are used in various industrial purposes. The objective of this section is to describe most of these heat exchangers in some detail using classification schemes. Starting with a definition, heat exchangers are classified according to heat transfer processes, number of fluids, degree of surface compactness, construction features, flow arrangements, and heat transfer mechanisms. With a detailed classification in each category, the terminology associated with a variety of these exchangers is introduced and practical applications are outlined. Short mentions of various types of heat exchangers are given below.

2.1.5.1 Direct-Contact Heat Exchangers

In a direct-contact exchanger, two fluid streams come into direct contact, exchange heat, and are then separated. Common applications of a direct-contact exchanger involve mass transfer in addition to heat transfer, such as in evaporative cooling and rectification; applications involving only sensible heat transfer are rare. The enthalpy of phase change in such an exchanger generally represents a significant portion of the total energy transfer. The phase change generally enhances the heat transfer rate. Compared to indirect contact recuperates and regenerators, in direct-contact heat exchangers, very high heat transfer rates are achievable, the exchanger construction is relatively inexpensive and the fouling problem is generally nonexistent, due to the absence of a heat transfer surface (wall) between the two fluids.

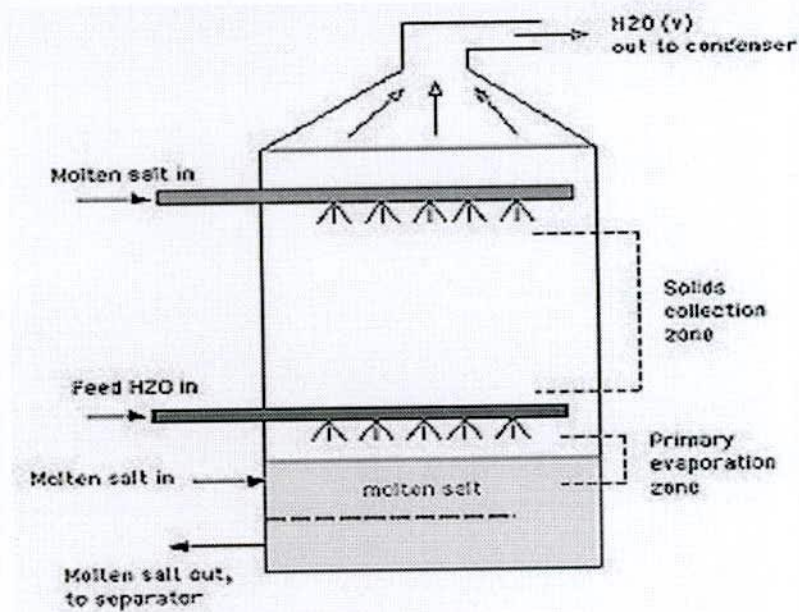


Figure 2.16: Direct-Contact Heat Exchangers

2.1.5.2 Storage Type Exchangers

In storage type exchanger, both fluids flow alternatively through the same flow passages, and hence heat transfer is intermittent. The heat transfer is generally cellular in structure and is referred to as a matrix or it is a permeable solid material, referred to as a packed bed. When

hot gas flows over the heat transfer surface, the thermal energy from the hot gas is stored in the matrix wall, and thus the hot gas is being cooled during the matrix heating period. As cold gas flows through the same passages later, the matrix wall gives up thermal energy, which is absorbed by the cold fluid. Thus, heat is not transferred continuously through the wall as in a direct-transfer type exchanger, but the corresponding thermal energy is alternately stored and released by the matrix wall. This storage type heat exchanger is also referred to as a regenerative heat exchanger, or simply as a regenerator

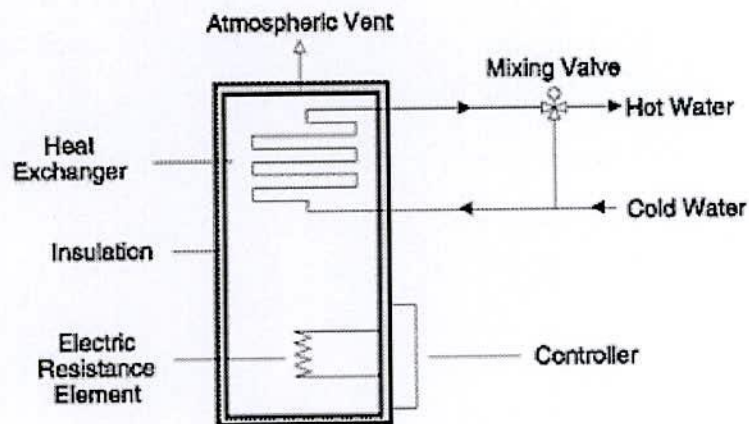


Figure 2.17: Storage Type Exchangers

2.1.5.3 Tubular Heat Exchangers

These exchangers are generally built in circular tubes, although elliptical, rectangular, or round/flat twisted tubes have also been used in some applications. There is considerable flexibility in the design because the core geometry can be varied easily by changing the tube diameter, length, and arrangement. Tubular exchangers can be designed for high pressures relative to the environment and high-pressure differences between the fluids. Tubular exchangers are used primarily for liquid-to-liquid and liquid-to-phase change (condensing or evaporating) heat transfer applications.

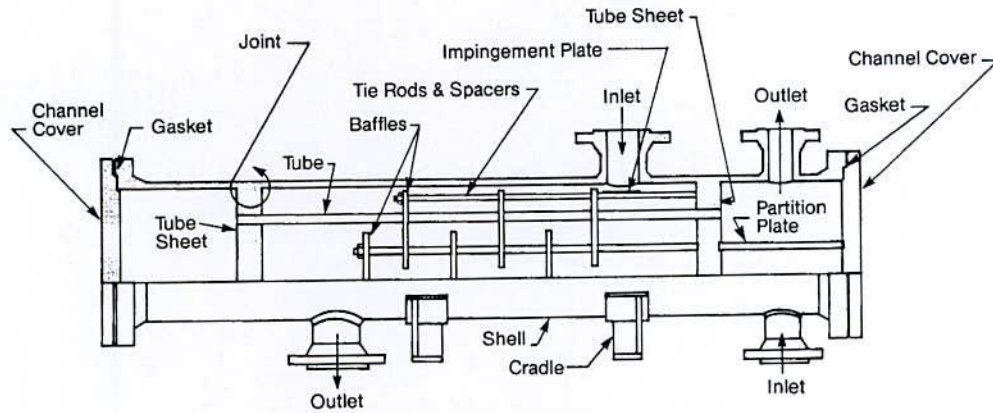


Figure 2.18: Tubular Heat Exchangers

They are used for gas-to-liquid and gas-to-gas heat transfer applications primarily when the operating temperature and/or pressure is very high or fouling is a severe problem on at least one fluid side and no other type of exchangers would work. These exchangers may be classified as shell and tube, double-pipe, and spiral tube exchangers. They are all prime surface exchangers except for exchangers having fins outside/inside tubes.

2.1.5.4 Shell-and-Tube Exchangers

Shell-and-Tube exchanger as shown in Fig 2.19 is generally built of a bundle of round tubes mounted in a cylindrical shell with the tube axis parallel to that of the shell. One fluid flows inside the tubes and the other fluid flows across the tubes surface continuously. The major components of this exchanger are tubes (or tube bundle), shell, front end head, rear-end head, baffles, and tube sheets. The three most common types of shell-and-tube exchangers are (1) fixed tube sheet design, (2) U-tube design, and (3) floating-head type. In all three types, the front-end head is stationary while the rear-end head can be either stationary or floating, depending on the thermal stresses in the shell, tube, or tube sheet, due to temperature differences resulting from of heat transfer.

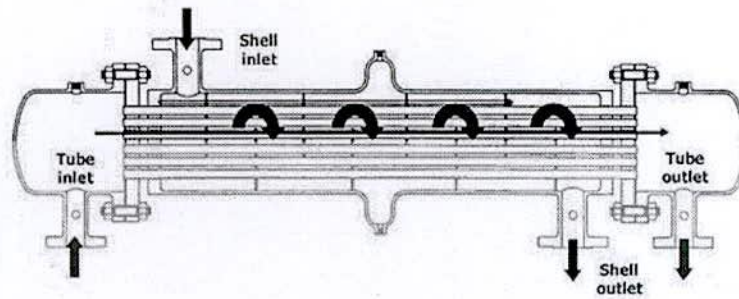


Figure 2.19: Shell-and-Tube Exchangers

2.2 Role of Surface Tension of Aqueous Lithium Bromide (LiBr) with Surfactants for Absorption

It is the fact that absorption of water vapor in aqueous LiBr increases with the decrease in surface tension of aqueous LiBr. Again the use of surfactant with aqueous LiBr reduces the surface tension of the solution and thereby increases the absorption. Studies on enhancement of absorption of water vapor into aqueous LiBr in the presence of surfactants require information about the surface tension, since surface tension gradients at the liquid surface induces Marangoni convection which is the key mechanism of enhancement of absorption. The following authors had worked on the surface tension of aqueous LiBr in presence of surfactant and their results have been presented in Figure 2.20.

Yao [30] et al. (1991) measured surface tension of aqueous LiBr with surfactant 2-ethyl-hexanol (2EH) using a drop-volume apparatus. In their experiments, the 2EH was added to the solution by a micropipet, and the samples were homogenized in an ultrasonic bath. The authors found considerable difference as compared to previous data by Grosman and Naumov (1984), Kashiwagi [31] et al. (1985), Hozawa et al. (1989) without clear explanations. None of these papers emphasized the effect of a key factor, the vapor side conditions, on the measurement results.

Hihara and Saito [32] (1991) measured surface tension of LiBr solution with surfactant 2EH using a ring method. In the preparation of the samples, the surfactant 2EH was mixed with a

certain amount of LiBr solution to obtain the required concentration of the surfactant. They found that on increasing the concentration of the surfactant, the surface tension decreased and reached a plateau value at a certain concentration which was interpreted as the solubility limit. The solubility limit of 2EH in 55% aqueous LiBr (by mass) was determined to be about 100 ppm. Based on these experiments, they concluded that the 2EH concentration in the LiBr solution is a main factor in determining the surface tension. However, in their experiments, the effect of vapor side conditions was not mentioned.

Kim et al. [33] (1994) employed the Du Nouy ring method (a ring method using Du Nouy apparatus) to determine the surface tension of aqueous LiBr with surfactant 2EH. The 2EH was added into the solutions, which were then mixed by a magnetic stirrer and then left at room temperature for at least 48 hours. All preparations and measurements were at normal atmospheric pressure with surface exposed to air. The measurement results show that the surface tension in the presence of 2EH decreases as surfactant concentration increases, and increases as solution temperature increases. This is in contrast to the case without 2EH where the surface tension decreases with increasing solution temperature. The measured surface tension was found to be higher than the data from the drop volume method (Yao et al., 1991). The authors speculated that the measurement error could be traced to the Du Nouy ring method due to an additional volume detachment from the ring. The authors noticed that the values of surface tension varied with time, and proposed that a long time is required (48 hours in these experiments) to allow the solution to reach equilibrium with the 2EH. But in the context of the Vapor Surfactant theory, this procedure would be expected to cause the 2EH concentration in the vapor to vary with time due to evaporation of 2EH, which would also explain the high values of surface tension found since after 48 hours, most of the surfactant had been evaporated from the system.

Kim and Janule [34] (1994) measured surface tension of aqueous LiBr with 2EH using the maximum bubble pressure method. 2EH was added to aqueous LiBr solutions and then solutions were mixed by a magnetic stirrer. The surface tension of aqueous LiBr at the different time was measured in order to obtain the dynamic surface tension (i.e., surface tension before the solution reaches its equilibrium condition). Their results showed that the surface tension decreased versus time and was proportional to $1/t^{0.5}$ (where t is time), and the

time required for the solution to reach its equilibrium values are dependent on the mass diffusivity of surfactant in the aqueous LiBr.

Gustafsson et al. [35] (1996) measured the surface tension of aqueous LiBr with fluorinated alcohols as surfactants. The drop-volume method was employed and the effect of solution temperature and measuring time were tested. They found that for a given concentration of surfactant the solubility of the surfactant increases as the temperature increases, resulting in a lower surface excess and hence a higher surface tension. The authors also pointed out that because the equilibrium surface is not established as fast in highly concentrated electrolytes as compared to pure water, due to the lower diffusivity at the high salt concentration, measured surface tension values may depend on time.

Ishida and Mori [36] (1996) measured the surface tension of aqueous LiBr with surfactant 1-octanol using a surface tensiometer utilizing laser-beam reflection, and they speculated that the disagreement with previous measured data might be due to inappropriate use of non-static measuring techniques.

Kulankara and Herold [37] (2002) measured the surface tension of both aqueous LiBr and water with surfactant 2EH using a drop volume method. In order to achieve better accuracy in the surface tension measurement by this method, a correction factor recommended by Harkins [38] (1952), which is a function of the drop tip and the volume of drop, was included in the calculation of surface tension. They realized that during the measurements the surface tension of aqueous LiBr was strongly affected by the presence of surfactant vapor around the liquid drop interface. They attributed the scatter in surface tension data in the literature to the sensitivity to the 2EH vapor environment but were not equipped to measure the 2EH vapor concentration in their surface tension measurements. In summary, Figure 2.20 shows the surface tension data of aqueous LiBr with 2EH from the authors mentioned above.

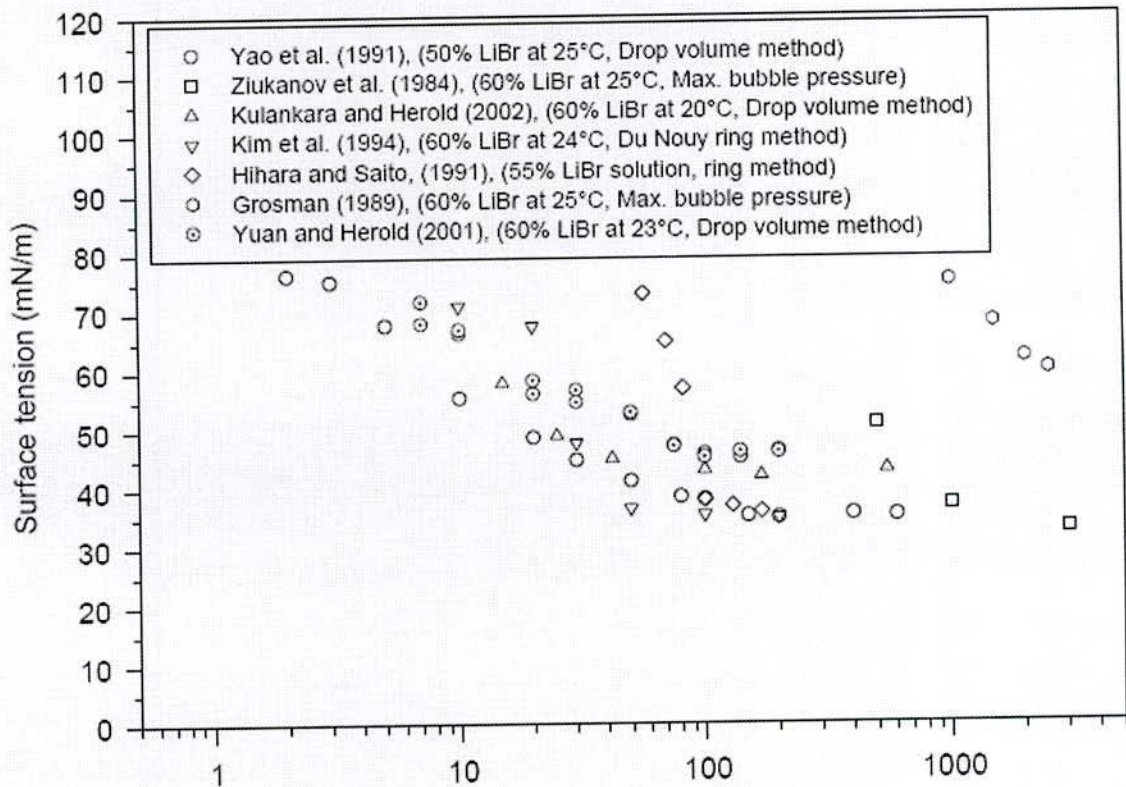


Figure 2.20: Surface tension of LiBr solution versus concentration of 2EH

2.3 Marangoni Convection in the Presence of Surfactants

It has been known since 1960-70's (Bourne and Eisberg, 1966; Albertson [39] et al., 1971, Chi et al., 1971 and Zawacki et al., 1973) that the addition of a traceable amount of alcohol additives, such as 2EH as surfactant, in an absorption refrigeration machine based on aqueous LiBr produces a substantial increase in the heat and mass transfer rates. It is widely accepted that the improved absorption rates are due to the surfactant properties of the alcohol that causes marangoni convection, a hydrodynamic instability at the liquid-vapor interface, arising from surface tension gradients. This instability enhances the mixing of the solution on the surface of heat transfer tubes and thereby improves the heat and mass transfer rates. This section summarizes prior experimental and theoretical studies on marangoni convection in the presence of surfactants.

During the 1950-60's marangoni convection was studied as a problem of hydrodynamic stability with diffusion and interfacial movement. The methods of linear stability theory were applied to determine the conditions for the onset of instability. Sternling and Scriven [40] (1959) were apparently the first to analyze the stability of a disturbance caused by a concentration gradient of solution in addition to thermal instability. A conclusion for vapor-liquid systems was that an increase in surface tension due to mass transfer (i.e. causing a concentration gradient) might lead to instability. Extensive studies on the basic mechanism of marangoni convection in aqueous LiBr systems started in the mid-1980's. Kashiwagi [41] (1988) did pioneering work on marangoni convection including a number of experiments that implied the importance of vapor side effects. However, this work did not get much attention.

Ji et al. [42] (1993, 1993b) performed a linear stability analysis for marangoni convection during absorption of water vapor into LiBr solution with surfactant 1-octanol. In their model, it was assumed that the bulk concentration of a surfactant in the gas phase is initially zero and that surfactant is desorbed from the solution to the gas. Their numerical analysis predicted that marangoni convection is triggered mainly by the absorption of water vapor when the surfactant causes a surface tension increase with increasing solution temperature. Their analysis also demonstrated that the absorption system is destabilized by desorption of the surfactant and stabilized by the adsorption of surfactant.

To identify the dominant factors in inducing marangoni convection, Suzuki [43] et al. (1996) carried out an experiment by using an ethanol-water binary mixture in an enclosed cell with an applied temperature difference across the cell. They concluded that the combined concentration and temperature gradients at the surface gave rise to surface tension gradients, but concentration induced marangoni convection dominates the surface motion, resulting in a surface flow in the opposite direction to the buoyancy-induced flow. This viewpoint, although very valid for ethanol-water, is not very useful for 2EH induced marangoni convection due to the unique properties of this system.

Fujita and Hihara [44] (1999) conducted an experiment in a thin liquid film of aqueous LiBr in the presence of surfactant n-octanol. In the experiment, temperature fluctuations on the vapor-liquid interface were measured using an infrared thermometer, and flow direction on the

vapor-liquid interface was recorded. Contrary to Suzuki's prediction, their tests showed that the surface flow induced by the surface tension gradient took place from the area of low temperature toward that of high temperature. Therefore, they concluded that the Marangoni convection is mainly dominated by the temperature effect rather than the LiBr concentration effect because the surface tension increases with increasing solution temperature in the presence of surfactant (Kim et al, 1994). It should be pointed that the surfactant concentration gradients on the interface and vapor surfactant concentration were not considered in these studies. Since these factors are understood now (proposed by Kulankara and Herold [38] (2002) and highlighted by Koenig and Grossman's study [45] (2003)) to be the most important factors, a reinterpretation of the experiments in terms of these variables is needed.

Kim et al. [46] (1996) conducted an experiment on water absorption into aqueous LiBr with surfactants and reported that Marangoni convection is initiated by the surface tension gradient caused by surfactant concentration and solution temperature as well as LiBr concentration. Again, several of the main variables (surfactant vapor concentration) are not reported or described.

Koenig and Grossman [47] (1999) numerically studied the Marangoni instability and found that in addition to the effect of solution temperature and solution concentration, for surfactants with high diffusion coefficient in the absorbent solution, surfactant concentration is highly variable along the interface, and its gradients affect surface tension in a way that reinforces the surface mixing, resulting in relatively significant absorption rate enhancement.

Kang [48] et al. (1999) investigated Marangoni convection experimentally in aqueous LiBr with various surfactants including 2EH. The effects of LiBr concentration, the surfactant concentration and the solution temperature on the surface tension gradients were studied. They concluded that the temperature gradient of the surface tension ($\partial\sigma/\partial T$) could not be the initial cause for inducement of Marangoni convection. They further concluded that the magnitude of the surface tension played an important role for inducement of Marangoni convection. The negative solution concentration gradient of the surface tension ($\partial\sigma/\partial x_{\text{LiBr}}$ (with surfactant) < 0) was found to be a trigger for inducement of Marangoni convection at surfactant concentration below the surfactant solubility limit, while the imbalance of the surface tension of aqueous LiBr solution and the interfacial tension between aqueous LiBr solution and

surfactant is a trigger above the solubility limit. Vapor concentration of the surfactants was not considered an important variable in this work.

Kim and Lee [49] (1999) carried out absorption experiments of water vapor into LiBr solution with eight-carbon alcohol surfactants using a simple static pool absorber. Sample solutions containing surfactant was prepared prior to each experiment and was placed in an absorption chamber. Four surfactants (n-octanol, 2-octanol, 3-octanol and 2EH) and four different solution concentrations were investigated. They found that the surfactant concentration required for onset of mass transfer enhancement is dependent on the surfactants, and most are in the range of 5 to 8 ppm. There was no mention of vapor concentration of surfactant in this work. Gustafsson (2000) presented a stability analysis for a vertical falling film system with aqueous LiBr solution and surfactant. The analysis showed that the rate of the surface tension decrease is more important than the surface tension value itself. The surfactant diffusivity appeared to be an important value for surface tension relaxation time and subsequently for the absorption rate. However, this analysis assumes that the surfactant arrives at the surface from the liquid side. The physics implied by the Vapor Surfactant theory implies that the stability considerations are much different from those included in this analysis.

Kim [50] et al. (1993) and Kulankara and Herold (2000) both conducted falling film absorption experiments on a single vertical tube. The surfactant 2EH with water vapor entered from the top of the absorber resulting in parallel flow with aqueous LiBr. Their observations confirmed that the intensity of the Marangoni convection decreased from the top to the bottom of the tube, possibly because the concentration of 2EH in the falling film increased along the tube and approached saturation near the bottom of the tube.

These studies demonstrated vapor effects very clearly since the Marangoni convection was observed to start immediately upon introduction of the surfactant at a location remote to the absorbing surface where the only communication was via the vapor.

Kim [51] et al. (2004a, 2004b) theoretically studied the effects of surfactant on the onset of Marangoni convection using the propagation theory. In their model, surfactant 2EH was assumed to pre-exist in the solution, and surfactant on the surface was assumed to be neither soluble in absorbent liquid nor volatile to gas phase when the absorbate transfers from the gas

phase to the liquid phase, and surface tension is positively related to the concentration of solute (i.e., $\partial\sigma/\partial x_{\text{LiBr}} > 0$) and negatively related to the surface excess concentration of surfactant (i.e., $\partial\sigma/\partial\Gamma < 0$). They found that it is not always advantageous to increase the mass transfer coefficient in the gas phase to enhance the absorption rate and that there is an optimum mass transfer condition in the gas phase to affect Marangoni instability at the surface and produce the maximum absorption rate. The surface properties of the surfactant were thought to be more significant than that of the solute (i.e., diffusivity) to analyze Marangoni instability. A higher surface excess concentration of surfactant acts as a stabilizer while a higher diffusivity of surfactant from the surface acts as a destabilize for the onset of Marangoni convection. This work did not address the vapor concentration of surfactant.

Studies of Marangoni convection have also been reported by several investigators in the case of condensation and in systems other than water and aqueous LiBr. Hijikata [52] et al. (1994) theoretically and experimentally studied the droplet growth mechanism in condensation in a water-ethanol binary mixture. In their theoretical work, instability analysis was used to determine a transition from the film wise condensation to pseudodropwise condensation. Both surface tension itself and the surface tension change due to the change in temperature and concentration were considered. Their results show that the Marangoni effect plays a more important role than the absolute value of the surface tension. The change of condensation type from film wise to pseudo-drop wise is only realized when the temperature dependency of the surface tension becomes positive.

Kang and Kashiwagi [53] (2002) conducted an experiment in an ammonia-water absorption pool to visualize Marangoni convection in the presence of surfactant, n-octanol, in the pool. They reported that Marangoni convection was observed near the interface only in the cases with surfactant, and that the Marangoni convection was very strong just after absorption started and weakened as time elapsed.

2.4 Absorption Enhancing Mechanism by Surfactant

As mentioned in the Introduction, a small amount of certain surfactants causes interfacial convection (marangoni convection) leading to higher heat and mass transfer performance in both condensation and absorption. The basic mechanism of marangoni convection in aqueous

LiBr has been extensively investigated for decades. This section summarizes the published surfactant enhancement theories.

Regarding enhancement theories by surfactants, most papers attributed the enhancement to marangoni convection due to surface tension gradients, which result from surfactant concentration gradients on the surface. However, the explanations for what causes the surfactant concentration gradients are divergent.

Kashiwagi [32] et al. (1985) suggested that marangoni convection is induced by the unbalance of surface tension around droplets of the surfactant floating on the solution surface. They proposed that the existence of surfactant droplets at the surface of the absorbent solution is necessary to obtain a drastic absorption enhancement. According to this theory, the onset of interfacial turbulence requires excess surfactant beyond the solubility limit. However, Elkassabgi and Perez-Blanco [54] (1991), Perez-Blanco and Sheehan's (1995) as well as work in their group showed that the enhancement did not require surfactant droplets. Thus, other theories were sought to explain a wider range of the observed phenomena.

Hozawa [55] et al. (1991) and Kim [50] et al. (1993, 1996) reported that the presence of an island of surfactant is not a necessary condition to initiate marangoni convection, but it can provide and maintain more violent convection for a longer time by acting as a reservoir of surfactant on the surface. Hozawa [55] et al. (1991) and Pearson [56] (1958) proposed the so-called "salting-out" theory. This theory holds that an increase in the concentration of aqueous LiBr causes a rejection of surfactant molecules from the liquid bulk, because the hydration force between water molecules and electrolyte ions, Li^+ and Br^- , is larger than the bonding force between water molecules and surfactants molecules. As a result, the surfactant molecules are segregated from the bulk solution and move to the surface and cause a decrease of surface tension. This theory proposed that the salting-out effect is the initial cause of marangoni convection. The data from Saito [57] (1991) and Hoffmann [58] et al. (1996) were interpreted to support this theory. However, Daiguji [32] et al. (1997) also pointed out that it was difficult to explain the marangoni instability only by the salting-out effect in the cases where the departure from equilibrium is large or the concentration of surfactant exceeds the solubility limit.

Kang [48] et al. (1999) compared the Kashiwagi [31] model (1985) with the salting-out model (Hozawa [55] et al., 1991) and concluded that the salting-out effect is a trigger for the inducement of marangoni convection at the concentration below the surfactant solubility while the imbalance of the surface tension of the solution and interfacial tension between the solution and surfactant is a trigger inducing marangoni convection above the solubility limit.

The mechanism of enhancement by surfactants was also the subject of intense study in our group where a new theory was introduced to explain surfactant enhancement. This new theory, called the Vapor Surfactant theory, was proposed by Kulankara and Herold [37] (2002). This theory maintains that the surfactant circulates through the machine and arrives at the liquid surfaces by bulk flow along with water vapor. Previous theories emphasized the presence of the surfactant in the liquid phase. The major departure provided by the Vapor Surfactant theory is the emphasis on the presence of the surfactant in the vapor phase. The surfactant arrives at the liquid surface along with the absorbing vapor by bulk flow, not by diffusion. The action of the surfactant occurs on the surface of the liquid in the form of marangoni convection that continuously renews the surface layer, sweeping away the dilute layer and exposing the high-affinity concentrated liquid. For aqueous LiBr at high concentration, once the surfactant reaches the surface, it tends to stay on the surface due to its strong affinity for the surface. The presence of the surfactant on the surface disrupts the bonding between water molecules and thus reduces the surface tension. Based on this theory, an effective surfactant should have several properties that enable a surfactant cycle. These include solubility in water that enables transport from condenser to evaporator and sufficient vapor pressure in addition to the surfactant properties. The authors have verified this theory in their absorption, condensation, static pool and surface tension measurements. Further experimental and numerical studies from our group on surface tension measurements (Yuan and Herold [59], 2001), enhancement of absorption by 2EH in an absorption machine (Ghosh and Herold [60], 2002), surface tension driven flow due to condensation with a vapor surfactant (Qiao [61] et al., 2000) and study of phase distribution of surfactant (Zhou and Herold [62], 2002) strongly support this theory.

Regarding other theories, one called the steric hindrance or catalytic effect theory holds that the surfactant provides a lower energy path for the absorption of water by lithium ions. Since

branched surfactants have a weaker bond than straight chain surfactants in combining with lithium ions, the branched surfactants should be more effective and faster in forming Li-H₂O bonds. Therefore, it is also not necessary for the surfactant to exist in a separate liquid phase for the enhancement to occur. Indeed, Chandler's experiment (1993) found an enhancement at small surfactant concentrations that are below the solubility limit. However, Perez-Blanco and Sheehan's data conflict with this theory. A constant enhancement in their experiments was not expected from steric hindrance theory, since as the hydration limit is approached, the surfactant effectiveness should decrease. Based on their experiment, both branched and straight chain surfactants provide effective enhancement, and relatively constant enhancement was observed with brine concentration.

Hihara and Saito [63] (1993) proposed an instability theory that relates the surface tension change to the properties of solution with surfactants. They concluded that surface tension changes with temperature and LiBr mass fraction are the key variables to predict enhancement. The data from Jao et al. (1991) and Kim et al. (1994) showed that the enhancement was related to the property of $\partial\sigma/\partial T > 0$ for LiBr solution with surfactants and this seemed to support their theory.

Sheehan and Perez-Blanco [64] (1996) proposed an explanation of enhancement, called the diffusion theory where the time taken for the diffusion of the surfactant to the liquid-vapor interface is considered as a key factor. According to this theory, the ability of a surfactant to enhance mass transfer may be related not so much to its activity at the interface, but to its ability to diffuse and adsorb at the interface. This theory seemed to be supported by the fact that surfactants are more effective when presented in the vapor phase, rather than in the liquid (Bennett, 1995; Kulankara and Herold, 1999). Although vapor effects are mentioned in this paper, the main focus of the paper is on liquid side effects. Koenig and Grossman (2003) also proposed a similar mechanism of enhancement by surfactant and stated that an effective surfactant must not only reduce the surface tension of the solution; it must do so quickly enough to cause the marangoni instability within the short absorption process time. The effect of the absorption process on the surface tension relaxation rate is mainly influenced by initial solution concentration and temperature, cooling side heat flux and vapor phase pressure. A key difference between these theories and the Vapor Surfactant theory is that the Vapor

Surfactant theory holds that the surfactant arrives at the surface primarily by bulk flow and not by diffusion.

2.5 Absorption Enhancement by Surfactants

The purpose of this part of the literature review is to summarize different experimental results of using different surfactant in different condition.

Hozawa et al. [54] observed marangoni convection in 50 - wt% aqueous LiBr - solution with n-octanol and n-decanol. Different additive concentrations were tested, and the absorption rate reached a maximum between 3×10^{-3} and 1 wt%. The maximum absorption rate was 2 to 2.5 times that without n-octanol. Although, LiBr-water solution with n-decanol as a surfactant possesses less surface tension value, cited Schlieren photographs of the marangoni convection during steam absorption by 50 wt% LiBr aqueous solution with 6.15×10^{-3} wt% n-decanol demonstrated that intensity of the marangoni convection was smaller compared to n-octanol. It was also concluded that the presence of islands of surfactant on the interface was not a necessary condition to induce instabilities.

Jung et al. [65] presented an experimental study of the effect of four different additives (1-Heptanol, 3-octanol, 1-octanol, and 2-ethyl-1-hexanol) on mass transfer rates in a falling film absorber. The LiBr concentration was kept constant, as well as additive concentration, at 58.5 wt% and 9000 ppm (part per million) respectively for all runs. It was found that 1-heptanol enhanced the absorption rate by 7 to 24% compared to the case without surfactant. 1-octanol did not appear to enhance mass absorption. It enhanced absorption rate by 2.8% on the average. The maximum enhancement of mass absorption caused by 2-ethyl-1-hexanol turned out to be 14.8 % compared to the case without surfactant. 3-octanol was found to be the worst of all the additives tested in this study. 3-octanol decreased mass absorption by 4.0% on the average. 1-octanol was the best of the four additives in stagnant pool experiments, whereas n-octanol provided only 2.8% of mass absorption enhancement in falling films. 3-octanol was almost as effective as the other additives in stagnant pools, while it provided negative effect on the absorption in falling film. 1-Heptanol has turned out to have superior performance to 2-ethyl-1-hexanol in falling films as in stagnant pools.

Kim et al. [50] reported the results of vertical falling film experiments on the absorption of water vapor into aqueous LiBr solutions with 2-ethyl-1-hexanol at additive concentrations ranging from 0 to 200 ppm. The additive experiments were performed to investigate the onset of marangoni convection and to determine the enhancement in terms of film heat transfer coefficient. Liquid film heat transfer coefficients were found to increase at approximately 3-6 ppm and reached a maximum value near 30 ppm. The total heat transfer rate was accelerated by a factor of as much as 3 compared to the case without surfactant. This also indicates that there is no further improvement in absorption efficiency no matter how much surfactant is added to the LiBr solution. Mass transfer rates were accelerated by a factor of as much as 3 compared to the case without 2-ethyl-1-hexanol. However, visualization of the flow patterns showed that induced mixing was not the same all along the length of the falling film. When absorption takes place, the flow can be divided into two different regimes, "marangoni flow regime" and "Gravity flow regime". The liquid film of the upper part in the absorber showed a "ropy" structure moving forth and back around the tube. However, this chaotic flow turned out to decay along the absorber length. The mass transfer was enhanced by a maximum factor of 4.1 in the "marangoni flow regime" compared to a wavy flow regime without surfactant. The "Gravity flow regime" showed no mass transfer enhancement. The enhancement of mass transfer was higher for 50-wt% LiBr solutions than for the 60-wt% solution.

Cosenza and Vliet [66] investigated the effect of surfactant on water vapor absorption into an aqueous LiBr solution flowing over a smooth horizontal tubular surface. The additives showed a nominal three-fold increase in terms of film heat transfer coefficient compared to the case without the additive. During the absorption, totally destructured film flows moving back and forth laterally along the tubes were observed. Reiner et al. [14] reported dynamic performance enhancement results for four additives: 2-ethyl-1-hexanol, 1-heptanol, 1H, 1H, 7H-dodecafluoro-1-heptanol (DFH) and 1,1,1-trifluoro-2-octanol (TFO). The average performance enhancement was 1.2-fold for 2-ethyl-1-hexanol, 1.25-fold, 1.07-fold and 0.74-fold for 1-heptanol, DFH and TFO respectively. Thus, 1-heptanol turned out to be the best additive.

Hihara & Saito experimentally investigated heat and mass transfer rates for the case of water vapor absorption into aqueous solutions of lithium bromide flowing on a flat plate. They

considered variables such as flow rate of inlet solution, additive concentration and inclination angle of the plate. 2-ethyl-1-hexanol was used as an additive and the absorption rate was increased by four to five times as compared to the additive free case. Furthermore, they observed that the absorption mass transfer rate decreased with time and approached the values of the case without additive. The lower part of the absorber did not show any enhanced mass transfer. Golovin [67] considered that such decays are due to a rapid decrease in mass transfer driving potential. However in the case of absorption of water vapor in an aqueous LiBr solution, calculations have shown that the driving force does not change much along the length of the absorber [68].

Bennett et al. [69] investigated high temperature additives for advanced absorption machine. They identified candidate additives and their performance was tested in a minisorber. The most promising additives were also tested for thermal stability. Although many additives reached performance levels comparable to 2-ethyl-1-hexanol, few showed the required thermal stability. 2-ethyl-1-hexanol, 1-heptanol and a commercial surfactant (FC-171) offered the best alternatives for high temperature systems. Hoffman & Ziegler [70] tested the influence of 2-ethyl-1-hexanol and 1-octanol on the heat transfer coefficient when water vapor was absorbed and desorbed in an ammonia-water solution. The absorber was a horizontal tube bundle type and in contrast to aqueous LiBr systems, the additive showed a negative effect on the heat transfer coefficient when water vapor was absorbed. On the other hand, when water was desorbed from the ammonia-water mixture containing additive, the heat transfer coefficient actually increased. A stability analysis was also carried out by Gustafsson to investigate how changes in additive properties and system properties will affect the interfacial turbulence. By expressing the wave number α as a function of physical and transport properties related to the absorbent solution and the additive itself, it was possible to investigate their influence on the wave number and hence their influence on interfacial disturbance - marangoni convection. The results show that the three most critical parameters related to the additive that affects the disturbance wavelength, and hence the absorption rate, were the additive diffusivity, the additive surface tension gradient and the surface excess of additive.

More recently, Glebov and Setterwall [71,72] reported experimental results about additive effect on the cooling capacity of the absorption chiller utilizing lamellas as heat transfer surfaces. Experimental tests and analysis were performed in three steps utilizing three absorption chillers of different sizes: 5 kW, 30 kW and 1.15 MW cooling capacity respectively. New additive – 2-methyl-pentanol was used in order to enhance heat and mass transfer process in the absorber. This additive was found to increase the cooling effect in the evaporator up to 20% compared to the case without additive when it was injected into LiBr solution. The effect became more emphatic when this additive was injected into refrigerant. Cooling effect was found to increase up to 32% compared to the case without additive.

In a study by Miller [73] the synergism between heat & mass transfer additives and advanced surfaces in a horizontal tube absorber was investigated. Testing demonstrated a synergetic effect, which doubled the mass absorbed from that observed with only the advanced surface. The overall film-side heat transfer coefficient for the advanced tube bundles doubled with the addition of 55-wppm of 2-ethyl-1-hexanol.

CHAPTER III

Design of Absorber

3.1 Absorber Heat Exchanger Design

For this design at first the design of previous developed absorber heat exchangers have been studied. In this case, the water vapour produced in the evaporator is absorbed by the flow of the LiBr-water solution and not condensing directly on the heat exchanger tubes. The design of the heat exchanger, therefore, requires values for the heat and mass transfer co-efficients. A number of researchers have studied the absorption of water vapour in falling films of LiBr-water solutions. Morioka et al [74] conducted experiments on steam absorption by films flowing down on a vertical pipe. They obtained experimental results, which show that for film Reynolds number in the range of 40-400, the heat transfer coefficients of the film are between 1500 and 3000 $\text{w/m}^2\text{K}$ the average absorption of mass flux ($\text{kg/m}^2\text{s}$) is compared with the numerical results derived from a laminar flow theoretical model proposed by the authors. The agreement of the results were found good for film Reynolds number up to 100, but the experimental values are far higher above film Reynolds number of 200.

Grossman [75] described a theoretical analysis of the combined heat and mass transfer process in the absorption of gas or vapor into a laminar liquid film. Simultaneous equations are described that give the temperature and concentration variation at the liquid-gas interface and at the wall. A constant temperature and an adiabatic wall case were considered. The Nusselt and Sherwood numbers were found to depend on the Peclet and Lewis numbers as well as on the equilibrium characteristics of the working fluids.

Conlisk [76] developed a design procedure for predicting the absorption capacity of a given tube based on the governing geometrical and physical parameters. The theoretical approach developed can predict the amount of mass absorbed in a given length of tube.

Patnaik et al. [77] presented a model based on the solution of differential equations to calculate the axial solution concentration and temperature distributions along a vertical tube absorber. The absorption of water vapour into the falling film of the solution of LiBr was modeled, employing equations extracted from the literature, incorporating information on wavy-laminar flows. The usefulness of the model was demonstrated by generating absorber performance charts.

A practical model for absorption of vapors into a laminar film of water and LiBr falling down along a constant temperature horizontal plate was described by Andberg and Vliet (1983) [78]. The developed model considered non-isothermal absorption and the equations presented showed good agreement to experimental results. For this reason this method was chosen for the design of the absorber. Because of the complexity of the problem involving the solution of the momentum, energy and diffusion equations with their boundary conditions, a simplified method was developed for diffusion equations with their boundary conditions; a simplified method was developed for determining the various quantities involved. Because of the simplicity and the good agreement with experimental results, this method was chosen for determining the number of absorber tubes required.

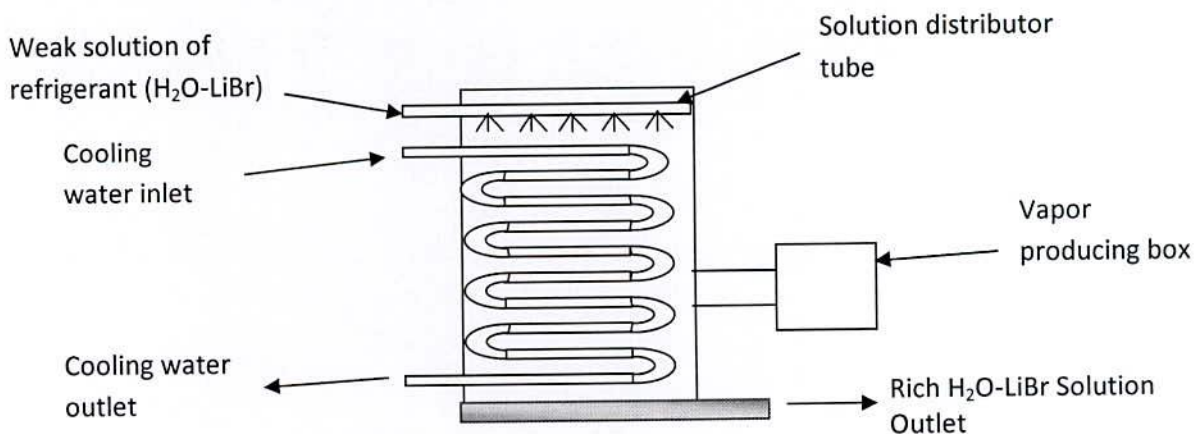


Figure 3.1: Schematic representation of absorber

For this design, the solution film can flow downward on bank of tubes. In this experiment the water vapor produced in the vapor producing box is absorbed by the flow of the LiBr-water

and LiBr-water-surfactant solutions. The design of the heat exchanger therefore, requires values for heat and mass transfer coefficients.

The independent variables which affect the problems are mass flow rate and inlet concentration of solution, absorber pressure and heat exchanger tube wall temperature. The data are correlated with the introduction of the “absorption percentage (A_p)”, defined as:

$$A_p = \frac{c_{in} - c_{out}}{c_{in} - c_{eq}} \times 100 \quad (1)$$

Where, C_{in} is the concentration of the LiBr in weak solution and C_{out} is the concentration of the LiBr in strong solution.

Determination of the equilibrium concentration, C_{eq} requires the solution of the following set of expressions [78]:

$$A = -2.00755 + 0.16976 X - 3.133362 \times .001 X^2 + 1.97668 \times 0.00001 X^3$$

$$B = 321.128 - 19.322 X + 0.374382 X^2 - 2.0637 \times .001 X^3$$

$$C = 6.21147$$

$$D = -2886.373$$

$$E = -337269.46$$

$$T' = (-2 E / [D + (D^2 - 4 E (C - \text{Log} (P / 6894.8)))]^{.5}) - 459.72$$

$$T_w = (5 / 9)(AT' + B - 32)$$

The above set of expressions requires an iterative type of solution to find C_{eq} , given T_w and P .

In the case of this study $T_w = 31$ °C and $P = 1227$ Pa therefore $C_{eq} = 0.52$ and from Eq. (1) $A_p = 62.5$. A_p is correlated with the length of plate (L) by the expression:

$$L = am^b \quad (2)$$

$$\text{Where, } a = -132 \left(\frac{\ln(100 - A_p)}{86} \right), b = 1.33$$

An iterative solution gives, $m = 0.006$ kg/m-s corresponding to the area of 4.8 m length pipe.

The next step is to check the area of pipes needed to cool the solution to the required level.

Patnaik *et al.* (1993), suggest that Wilke's correlation [77], valid for constant heat flux wall with progressively decreasing difference from isothermal wall outside the entrance region, can

be used for the falling film. It is assumed that the flow is fully developed in a wavy, laminar regime and that the bulk solution temperature profile is linear with respect to the transverse coordinate (Patnaik *et al.*, 1993). Wilke's correlation is:

$$h_s = \frac{k_s}{\delta} (0.29(Re_s)^{0.53} Pr_s^{0.344}) \quad (3)$$

The film thickness δ is given by,

$$\delta = \left(\frac{3\mu\Gamma}{\rho^2 g} \right)^{1/3} \quad (4)$$

And the solution Reynolds number (Re_s) for the tube is:

$$Re_s = 4\Gamma/\mu \quad (5)$$

The overall heat transfer coefficient (U) is given by,

$$U = \frac{1}{(D_o/D_i)(1/h_i) + (D_o/D_i)F_i + (1/2k)D_o \ln(D_o/D_i) + F_o + 1/h_o} \quad (6)$$

The Petukhov-Popov equation for turbulent flow inside a smooth tube gives:

$$Nu = \frac{Re.Pr f}{X} \frac{f}{8} \quad (7)$$

$$\text{Where, } X = 1.07 + 12.7(Pr^{2/3} - 1) \left(\frac{f}{8} \right)^{1/2}$$

In this study, the mean properties of the solution at 44.6°C and 57.5% LiBr are;

$$\rho = 1663 \text{ kg/m}^3$$

$$\mu = 4.20 \times 10^{-3} \text{ N-s/m}^2$$

$$k = 0.453 \text{ W/m-}^\circ\text{C}$$

$$c_p = 1991 \text{ J/kg-}^\circ\text{C}$$

$$Pr = 18.46$$

Assuming 4.8 m pipe and substituting the above values into Eq. 4 - 6, a solution convective heat transfer coefficient h_s of 865 W/m²-°C results.

Assuming,

Temperature of cooling water inlet = 25°C

And Temperature of cooling water outlet = 26°C

The cooling water properties at the mean temperature of $(25+26)/2=25.5^\circ\text{C}$ are;

$$\rho = 997 \text{ kg/m}^3$$

$$\nu = 0.7876 \times 10^{-6} \text{ m}^2/\text{s}$$

$$k = 0.615 \text{ W/m}\cdot^\circ\text{C}$$

$$Pr = 5.34$$

$$c_p = 4177.5 \text{ J/kg}\cdot^\circ\text{C}$$

Therefore, substituting the above values into Eq. 7 and replacing $N_u = h_i D_i / K$, $h_i=6175 \text{ W/m}^2\cdot^\circ\text{C}$.

By substituting the above values in Eq. 6 the resulting overall heat transfer coefficient (U) based on the outside surface of the tube is $650 \text{ W/m}^2\cdot^\circ\text{C}$.

In this case $\Delta T_{lm} = 9.3^\circ\text{C}$. Therefore from Eq. 4, the resulting length of pipe is 4.877m instead of 4.8 m assumed. This means that the area of 4.877 m length pipe is needed to cool the solution to the required level. Checking for 4.877 m long pipe by repeating the above procedure, a length of 4.8 m results, with $h_s = 840 \text{ W/m}^2\cdot^\circ\text{C}$, $h_i = 5450 \text{ W/m}^2\cdot^\circ\text{C}$ and $U = 625 \text{ W/m}^2\cdot^\circ\text{C}$, which indicates that 4.877 m long pipe is adequate to cool the solution.

Table 3.1 Obtained Heat exchanger size for absorber

Parameter	Value/Type
Tube diameter	outside diameter $Do = 16 \text{ mm}$ and inside diameter $Di = 14.5 \text{ mm}$
Tube length	4.877 m
Tube material type	Copper

CHAPTER IV

Performance Test

4.1 Description of the Test Rig

A schematic diagram and a photograph of the test-rig are shown in Figure 4.1 and Figure 4.2, respectively. The main components of the experimental test-rig are the test section, vapor producing box, weak solution tank, heat exchanger pipes, flow control valves, vacuum pressure gauges and collector. The test section consists of 14 rows of horizontal tubes assembled in a single column. These tubes act as the heat exchanger tubes. The weak solution from a container is supplied to a distributor tube at the topmost portion of the absorber and which is dropped on the heat exchanger tubes so that a thin film of solution flows down over the both surfaces of the tubes. After leaving the test section, the strong solution is collected in the collector and then removed from absorber. The experiments were performed with and without the use of surfactant. The use surfactant it was mixed with weak solution. The various flow control valves maintained the desired flow rates of weak solution and cooling water.

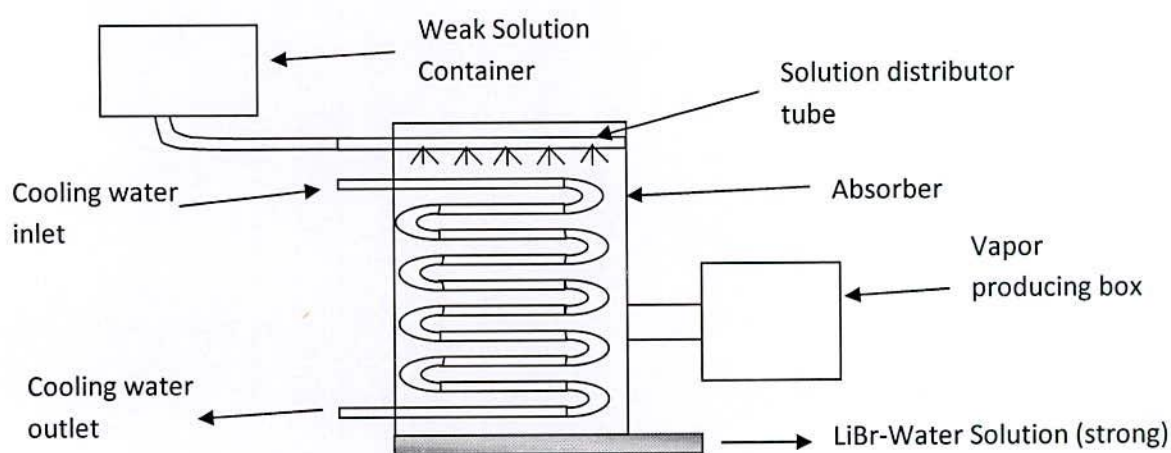


Figure 4.1: The schematic diagram of the absorber of the experimental setup



Figure 4.2: The photographic view of the experimental setup

4.1.1 Test section

The components of the test section are shown schematically in Figure 4.3. The figure represents a front view of the test section assembly. The main components are: (i) Solution distributor (ii) heat exchanger tubes and (iii) collector. The test section is actually an absorber of VAR system. The box of the test section was made of cast iron sheet of thickness 8 mm. The height, length and width of the test section box are 102, 41 and 8 cm respectively. The 8 mm thickness sheet causes heavy weight of the construction which makes difficulties to move the box from one point to another but it was chosen for the inside vacuum pressure of the absorber. In the first step, it was planned to cover the main two sides of the test section box by glass for the visualizing purposes, but it was not possible finally for inside vacuum pressure. Practically the pressure inside the absorber or test section box was observed nearly 14.66 kPa and no available glass in local market could sustain this high vacuum pressure. For that the

thickness of the cast iron sheet for making cover of the test section was selected 8 mm. The solution distributor was a copper pipe of 8 mm diameter. After every 5 mm linear interval the pipe was drilled with 1 mm diameter as shown in figure below for the distribution of the weak solution. The weak solution comes from weak solution tank via a vinyl tube. The heat exchanger tubes were the copper pipes of 16 mm diameter and with wall thickness of 0.75 mm. The collector was at the lower portion of the test section box where the strong solution was collected after absorbing the water vapor.

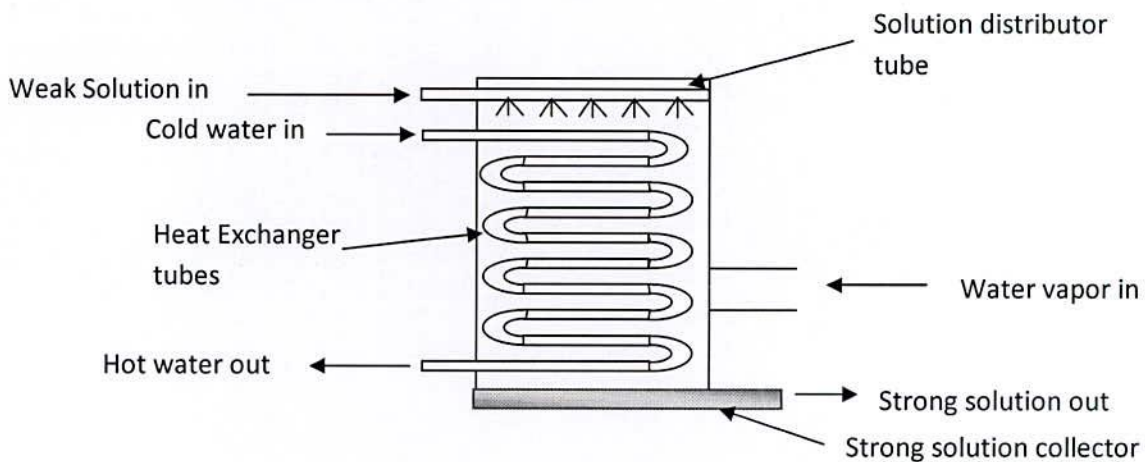


Figure 4.3: The schematic view of the test section

4.1.2 Vapor Producing Box

The vapor producing box was made of same material of test section box. The vapor producing box was a cube shaped one of size 18 mm in each side. This box was connected with test section box by a 38 mm diameter pipe. The length of this connecting pipe was 25 mm with a gate valve to open and close the vapor line and also to regulate the vapor flow rate.

4.1.3 Weak Solution Container

This tank was also made of same material and used as a reservoir of weak solution. It was placed outside of test section box and connected by vinyl tube with a flow control valve. This tank was a cube shaped one of dimension 30.5 mm in each side. In this tank there was also a

provision for providing vacuum and when undertaking operation the pressure was maintained nearly 34.66 kPa, slightly higher than the test section pressure. A vacuum pressure gauge was mounted on the tank to show the inside pressure.

4.1.4 Flow Control Valves

In this experimental setup two flow control valves were fastened. One was in the connection pipe between the vapor producing box and test section box. It was used to control the flow of vapor into the test section from vapor producing box. The other was used after the weak solution reservoir to regulate the rate of weak solution flow to the test section box.

4.1.5 Vacuum Pressure Gauges

Two vacuum pressure gauges were used in the setup. One was in test section box and another was in weak solution reservoir. Both were used to indicate the inside vacuum pressure of the respective boxes. The range of these gauges were 0 to -76 cm Hg.

4.2 Experimentation

Generally in VAR system, water vapor is generated in the evaporator after evaporating liquid water coming from the condenser was absorbed in the absorber. Instead of usual practice, in this experiment water vapor was artificially produced and reserved in the vapor producing box at the evaporator environment. Similarly, instead of weak solution coming from generator in VAR system, here weak solution was prepared and reserved in the weak solution container with various concentrations as per requirement. Once the vapor production got ready, the overall system pressure was maintained by using a vacuum pump. Then the flows of weak solution and water vapor were permitted from their respective reservoirs sequentially. Finally, strong solution was collected from the bottom of the test section. The experiment, were performed with 4 different concentrations of LiBr in weak solution. The experiments were conducted with and without the use of surfactant. The surfactant concentration were also varied in 3 types from 100 ppm to 300 ppm.

4.3 Experimental Data

The results obtained from the experimental investigation of enhancement of absorption are presented in this chapter. For four different concentration of LiBr-H₂O solution the experiment were accomplished with and without the use of surfactant (2EH). The concentration of surfactant also varies from 100 ppm to 300 ppm for different experiments but for almost same mass flow rates. Absorber pressure was kept constant in all the cases, and it was 14.66 kPa. Absorption rate varies for time to time was recorded for one experiment only due to the complexity of taking this type of data. In most of the experiments the rate of absorption measures after the end of the experiment. Also it was tries to set the flow rates constant of all cases.

The data for experiments with and without the use of surfactant are given below.

Table 4.1: Experimental data for absorption of water vapor without the use of surfactant

Absorber Pressure = 14.66 kPa

Concentration of weak solution by weight %LiBr	Rate of flow (kg/s)		Amount of weak solution (gm)	Cooling water temperature, °C		Concentration of strong solution by weight %LiBr	Absorption of water vapor (gm)
	Weak solution	Cooling water		Inlet	Outlet		
45	0.00673	0.0733	2222.22	30	31	43.29	87.78
50	0.00667	0.0733	2000.00	30	31	47.82	91.17
55	0.00637	0.0733	1818.18	30	31.5	52.24	96.06
60	0.00680	0.0733	1666.67	30	31.5	56.54	101.99

Table 4.2: Experimental data for absorption of water vapor with the use of 100 ppm surfactant

Absorber Pressure = 14.66 kPa

Concentration of weak solution by weight %LiBr	Rate of flow (kg/s)		Amount of weak solution with surfactant (gm)	Cooling water temperature, °C		Concentration of strong solution by weight %LiBr	Absorption of water vapor (gm)
	Weak solution	Cooling water		Inlet	Outlet		
45	0.00654	0.0733	2222.44	30	31	43.09	98.50
50	0.00677	0.0733	2000.20	30	31.5	47.59	101.28
55	0.00616	0.0733	1818.36	30	31.5	52.02	104.16
60	0.00685	0.0733	1666.84	30	32	56.29	109.84

Table 4.3: Experimental data for absorption of water vapor with the use of 200 ppm surfactant

Absorber Pressure = 14.66 kPa

Concentration of weak solution by weight %LiBr	Rate of flow (kg/s)		Amount of weak solution with surfactant (gm)	Cooling water temperature, °C		Concentration of strong solution by weight %LiBr	Absorption of water vapor (gm)
	Weak solution	Cooling water		Inlet	Outlet		
45	0.00656	0.0733	2222.66	30	31	42.99	103.90
50	0.00668	0.0733	2000.40	30	31.5	47.44	107.93
55	0.00619	0.0733	1818.54	30	31.5	51.86	110.09
60	0.00685	0.0733	1667.00	30	32	56.09	116.18

Table 4.4: Experimental data for absorption of water vapor with the use of 300 ppm surfactant

Absorber Pressure = 14.66 kPa

Concentration of weak solution by weight %LiBr	Rate of flow (kg/s)		Amount of weak solution (gm)	Cooling water temperature, °C		Concentration of strong solution by weight %LiBr	Absorption of water vapor (gm)
	Weak solution	Cooling water		Inlet	Outlet		
45	0.00660	0.0733	2222.88	30	31	42.93	107.15
50	0.00674	0.0733	2000.60	30	31.5	47.37	111.04
55	0.00616	0.0733	1818.72	30	31.5	51.76	113.81
60	0.00688	0.0733	1667.17	30	32	56.00	119.04

4.4 Results and Discussion

4.4.1 Rate of Vapor Absorption Without the Use of Surfactant

In the table 4.1 the rate of change of concentration of LiBr-H₂O solution are observed without the use of surfactant. In this experiment the weak solution flow rates were intended to keep constant but it was not possible in every case for practical difficulties. Also the rate of cooling water and absorber pressure were kept constant and the value of absorber pressure was 14.66 kPa. Finally at the end of the experiment the concentration of LiBr by weight was recorded. From these data it is observed that the rate of absorption increases with the increase of concentration of LiBr in the solution.

4.4.2 Rate of Vapor Absorption With the Use of Surfactant

Table 4.2, 4.3 and 4.4 represents the data recorded from the experiments for the changes of solution concentrations 45%, 50%, 55% and 60% thereby the absorption of water vapor using surfactant (2EH) with the concentration of 100 ppm, 200 ppm and 300, ppm respectively. From table 4.2, the solution concentration was found to decrease by 0.20 to 0.25 for weak solution than that was in case of without surfactant. The same was found to decrease by 0.30 to 0.45 and 0.36 to 0.54 in tables 4.3 and 4.4 respectively. The decrease of LiBr concentration in strong solution means the enhancement of absorption of water vapor. Furthermore, the enhancement of water vapor absorption was also found from table 4.2 to 4.4 to increase with the increase of surfactant concentration in the weak solution.

4.5 Enhancement of Absorption

In this section the amount of water vapor absorbed is plotted and also compared with other published results. The enhancement of absorption is observed by carefully measuring the weight of the weak solution and strong solution before and after the experiment. At first the data were taken for four concentration value of LiBr by weight without the surfactant and in every case the amount of water vapor absorbed were measured carefully. The absorption of water vapor and its enhancement are shown in the figure 4.4 below.

From figure 4.4 it is observed that the absorption of water vapor was found to increase with the increase of LiBr concentration in the weak solution. These experimental results without surfactant showed similar results but with a lower intensity in comparison to the work of Antonio De Lucas [80] as presented in fig 4.5. Both the experiments were not performed in the same environment i.e. amount of mass of weak solution in these cases were different.

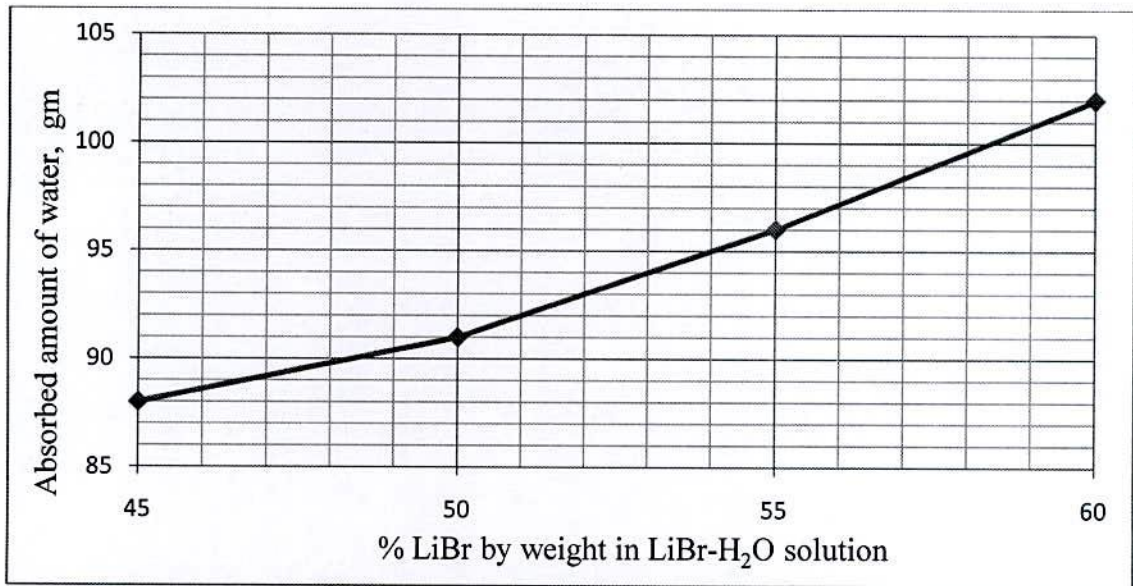


Figure 4.4: Influence of LiBr concentration in absorption rate without use of surfactant

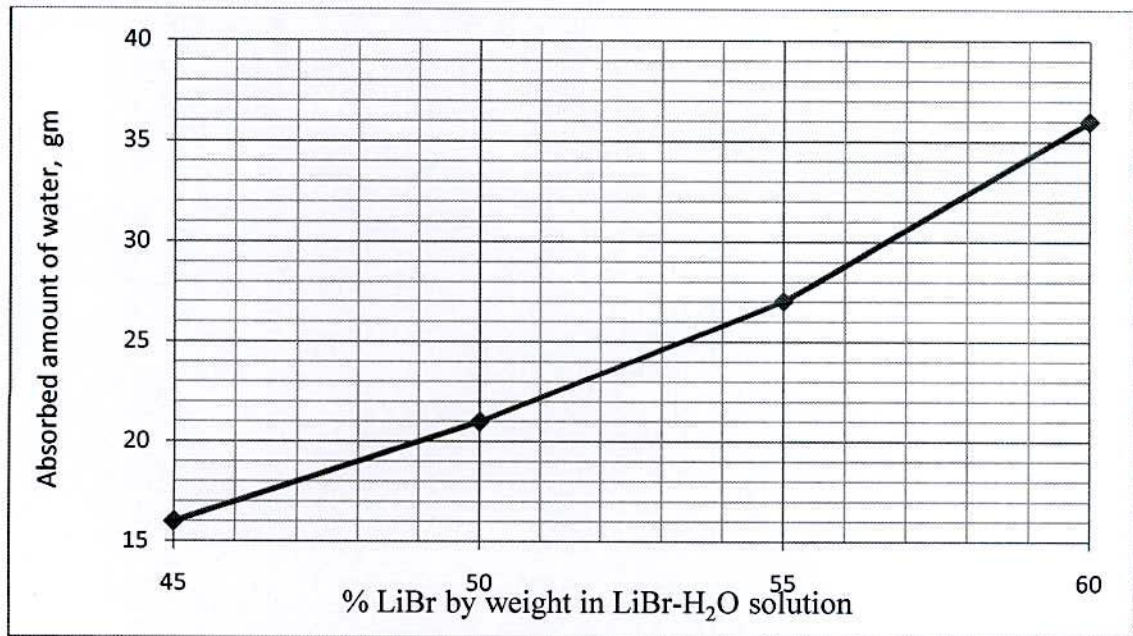


Figure 4.5: The results of Antonio De Lucas work

The data obtained from the experiments in presence of surfactant (2-ethyl-1-hexanol) into the LiBr-H₂O solution (weak) with surfactant concentrations 100, 200 and 300 ppm are plotted in figures 4.6 to 4.8 respectively.

Figure 4.6 shows that amount of absorption with surfactant was found always higher than that without surfactant. But the increment of absorption was found to decrease with the increase of LiBr concentration in LiBr-H₂O solution. The maximum enhancement of water vapor absorption was found about 12 % in 45% LiBr concentration from the experiment but Jung [65] et al reported that the maximum enhancement of mass absorption caused by same surfactant (2-ethyl-1-hexanol) with concentration 100 ppm was 14.8%.

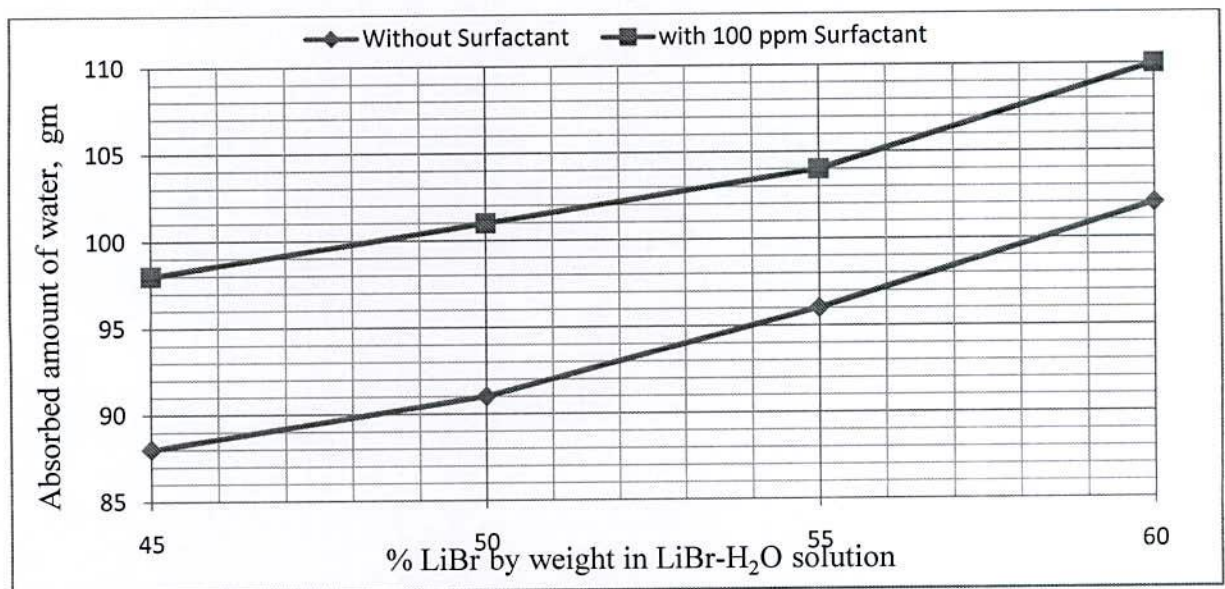


Figure 4.6: Variation of absorption with LiBr concentration in presence of 100 ppm surfactant

Figure 4.7 and 4.8 show the same trend as figure 4.6. From the present experiments the maximum enhancement of absorption of water vapor were found 18% and 22% with surfactant concentrations 200 ppm, and 300 ppm respectively at 45% & 50% concentration of LiBr in LiBr-H₂O solution by weight. Kim [68] et al reported from their experimental work with surfactant concentration 200 ppm in aqueous LiBr solution that the enhancement of absorption of water vapor was 25% for 50% concentration of LiBr in LiBr-H₂O solution. He also reported that a less enhancement of absorption was found with 60% concentration of

LiBr. The present experimental results are found very close to the results of Kim [68] et al's results.

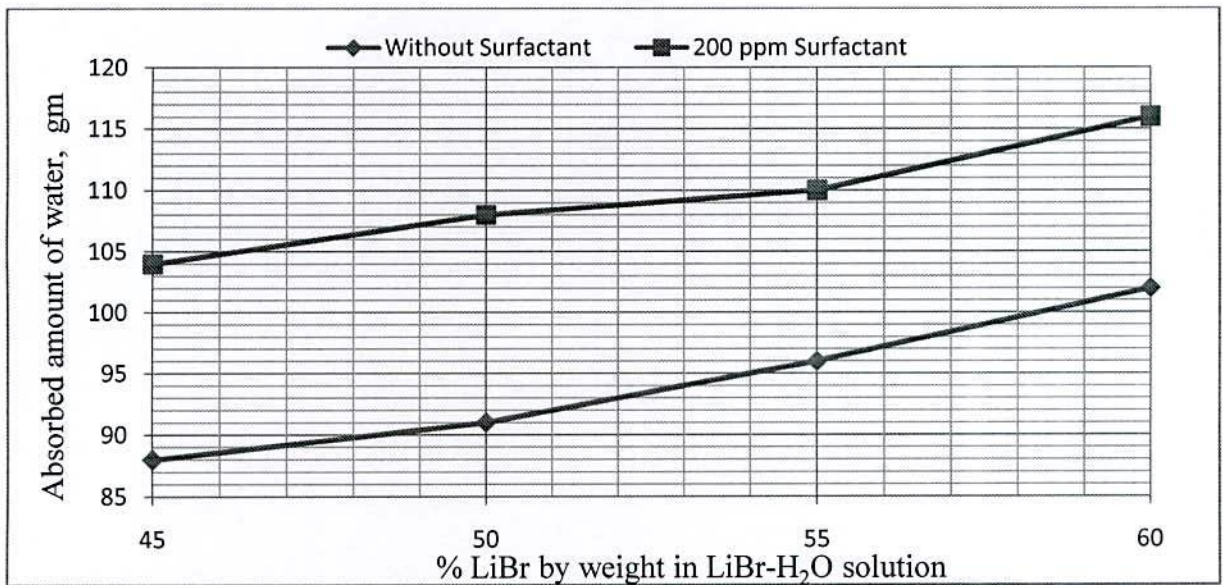


Figure 4.7: Variation of absorption with LiBr concentration in presence of 200 ppm surfactant

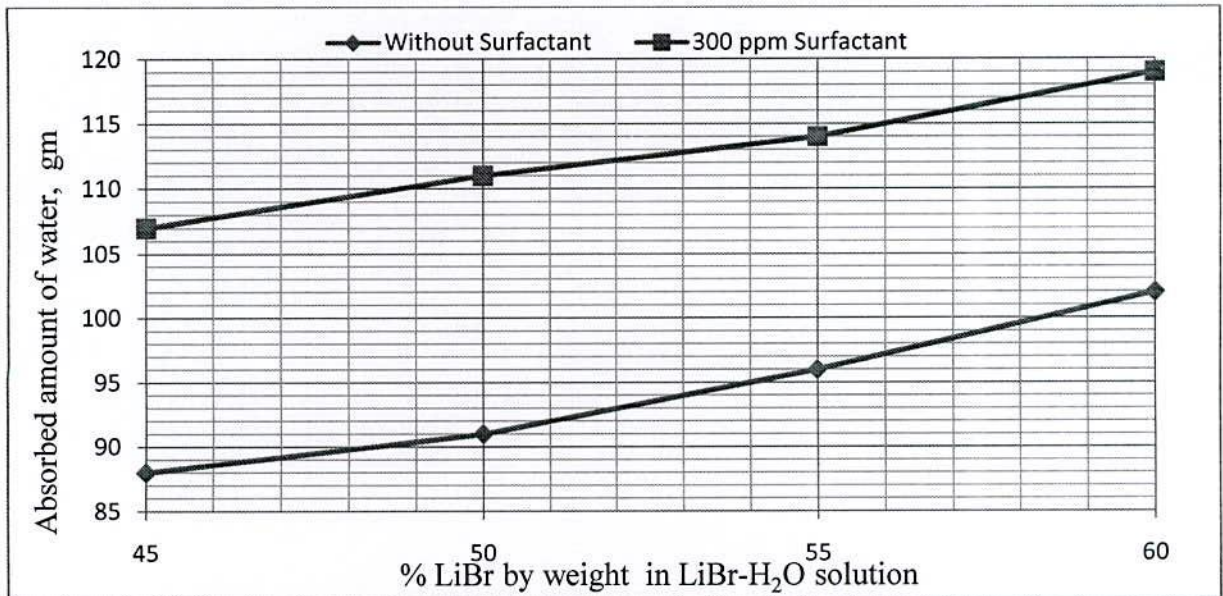


Figure 4.8: Variation of absorption with LiBr concentration in presence of 300 ppm surfactant

The enhancements of absorption of water vapor absorption for different cases as discussed earlier are presented in bar chart in figure 4.9 for a clear view.

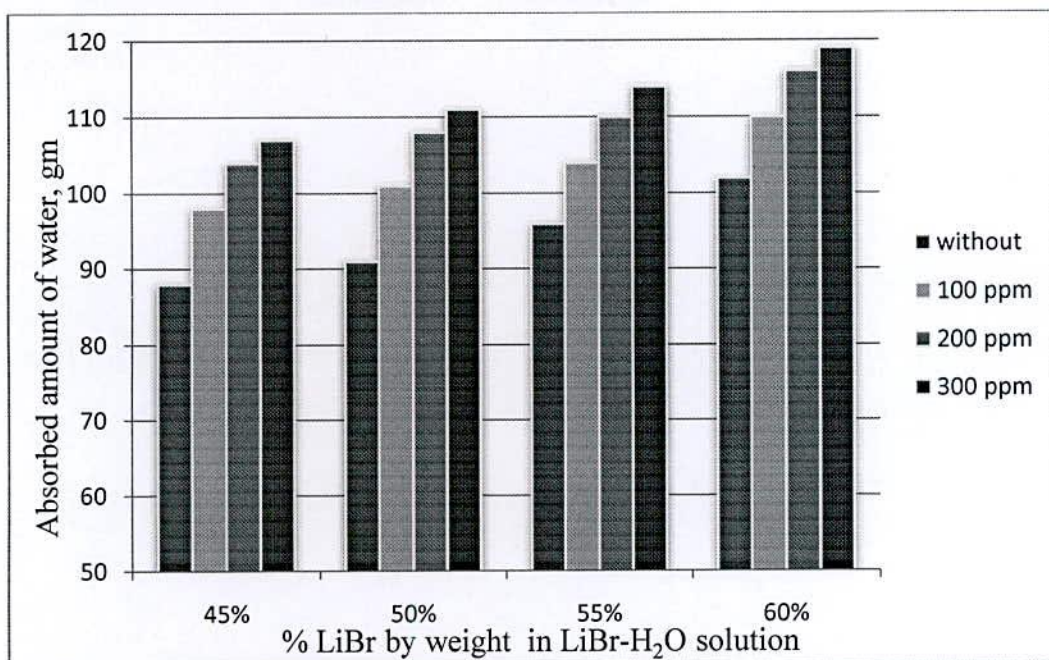


Figure4.9: Enhancement of absorption at different condition

CHAPTER V

Conclusions

5.1 Conclusions

An experimental setup for testing the effect of surfactant on the absorption of water vapor in LiBr-H₂O solution in a VAR system is designed and constructed. The experiments were performed with four different concentrations such as 45%, 50%, 55% and 60% of LiBr-H₂O solution by weight and three different surfactant concentrations such as 100, 200 and 300 ppm in the weak solution. 2-ethyl-1-hexanol was as surfactant in this experiment. From the experimental results the followings can be concluded.

- The absorption of water vapor is found to increase with the increase of concentration of LiBr in the weak solution of LiBr-H₂O
- The addition of surfactant enhances the absorption of water vapor
- The maximum enhancement of water vapor absorption is obtained when surfactant concentration is 300 ppm and LiBr concentration is 50% in LiBr-H₂O weak solution by weight
- The experimental results agree with the experimental results of Jung [68] et al. and Kim [65] et al. closely (the deviations of enhancement of present work are about 6.3% and 6.6% less than that work of Jung et al. and Kim et al. respectively)

5.2 Future Recommendations

In the present work, the effect of surfactant is only measured by the use of 2-ethyl 1-hexanol as a surfactant. But there are many other types of surfactant which may be used in the same purpose for this type of work. So there is a scope of work with other surfactant. Also in this

study and work the surfactant concentration is varied from 100 to 300 ppm only and observed the rate of enhancement is increasing with the increase in concentration of surfactant. So this work will be further extended by increasing the concentration of surfactant as well as varying the concentration of LiBr in wide range.



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