Green Energy and Technology

Ibrahim Dincer
Tahir Abdul Hussain Ratlamwala

Integrated Absorption Refrigeration Systems

Comparative Energy and Exergy Analyses

Springer

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Preface

Originally, humankind used wood as their fuel source fuel and later discovered fossil fuels, bringing about the industrial revolution as a starting point of technology developments. Since then, humankind has striven for greater prosperity and better wealth.

Energy-hungry devices, ranging from airplanes to mobile phones, are introduced to the consumers at a brisk rate to meet their perceived need for better lifestyle need. The extensive use of fossil fuels has been influential in changing the weather patterns and climatic cycles, due to the enormously increasing CO_2 emissions, resulting in harsher summers and winters around the globe. The earth's average temperature has constantly been increasing at a constant rate over the past few decades due to the extensive use of fossil fuels. The use of air-conditioning systems for the provision of heating and cooling has also increased due to the harsher climates with the drawback of a dependency on the energy-hungry technology. This increase has resulted in a sudden surge in peak electricity demand and government and private sector alike are unable to meet this demand. Extensive fossil fuel usage and environmental problems have drawn researcher focus to new refrigeration technology that can offset the use of fossil fuels and provide heating and cooling in a comparatively environmentally friendly manner.

The current book presents an overview of all the alternative refrigeration technologies that are either available on the market or are in the research phase, with a focus on an absorption refrigeration systems. An absorption refrigeration system is an attractive alternative to the conventional air-conditioning system, as it is mainly waste heat or low-grade heat dependent. However, as with all other technologies, absorption refrigeration systems also have some drawbacks that cannot be ignored.

The present book consists of eight chapters. Absorption refrigeration system background, components, operating principles, usage, and fundamentals are presented in Chap. 1. Also, the comparison of absorption refrigeration systems with other innovative refrigeration systems is presented in this chapter. Chapter 2 aims at helping the reader understand how to perform an in-depth energy, exergy, exergoeconomic, exergoenvironmental, and optimization analyses of a basic absorption refrigeration system. Detailed system description, energy, exergy, exergoeconomic, exergoenvironmental, and optimization studies of the single effect absorption refrigeration system with numerical values are presented in Chap. 3. Chapter 4 offers comprehensive system description alongside numerical energy, exergy, exergoeconomic, exergoenvironmental, and optimization analyses of the double effect absorption refrigeration system. A thorough system description of more advanced triple effect absorption refrigeration system with numerical energy, exergy, exergoeconomic, exergoenvironmental, and optimization analyses is presented in Chap. 5. The system description with numerical energy, exergy, exergoeconomic, exergoenvironmental, and optimization studies of the most advanced and novel quadruple effect absorption refrigeration system is provided in Chap. 6. Chapter 7 presents different case studies related to the integrated absorption refrigeration system. This chapter also presents analysis and results of the multigeneration systems shedding light on the usage of absorption refrigeration systems in different walks of life. Chapter 8 highlights recent developments in an area of absorption refrigeration systems. Also presented in this chapter are different energy sources based absorption refrigeration systems, novel designs, advanced numerical and optimization models, and unique working mixtures of the absorption refrigeration systems.

Detailed references are provided to direct the readers that require more information in the correct direction. We sincerely hope that this book provides an in-depth knowledge in the area of absorption refrigeration systems so that the world can move towards more environmentally friendly, cost-efficient, and sustainable heating and cooling technologies in near future. The book is written in a way that it can be helpful to undergraduate students, postgraduate students, as well as people requiring advanced knowledge, governmental organizations, and industries alike.

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Contents

Nomenclature

A	Area of PV module, m^2
b	Breadth of PV module, m
c	Cost, USD
C	Coefficient
$\dot{C}$	Cost rate, USD/s
COP	Coefficient of performance
cp	Specific heat capacity, kJ/kg K
ex	Specific exergy, kJ/kg
$\dot{\mathrm{En}}$	Rate of energy, kW
$\dot{\mathrm{Ex}}$	Rate of exergy, kW
f	Factor
h	Specific enthalpy, kJ/kg
h_{ba}	Heat transfer coefficient from black surface to air, W/m^2 K
h_{t}	Heat transfer coefficient from black surface to air through glass, W/m^2 K
h_{p1G}	Penalty factor due to the presence of solar cell material, glass and EVA for glass to glass PV/T system, W/m^2 K
h_{p2G}	Penalty factor due to presence of interface between glass and working fluid through absorber plate for glass to glass PV/T system, W/m^2 K
HHV	Higher heating value, kJ/kg
$\dot{I}$	Incident solar flux, W/m^2
L	Length of the PV module, m
$\dot{m}$	Mass flow rate, kg/s
MW	Molecular weight, kg/kmol
P	Pressure, kPa
$\dot{Q}$	Heat transfer rate, kW
Qu	Quality
R	Gas constant, kJ/kg K
RH	Relative humidity, %
s	Specific entropy, kJ/kg K

T	Temperature, K
t	Time, s
U_b	Overall heat transfer coefficient from bottom to ambient, W/m^2 K
U_L	Overall heat transfer coefficient from solar cell to ambient through top and back surface of insulation, W/m^2 K
U_t	Overall heat transfer coefficient from solar cell to ambient through glass cover, W/m^2 K
U_{tb}	Overall heat transfer coefficient from glass to black surface through solar cell, W/m^2 K
v	Specific volume, m^3/kg
w	Specific work, kJ/kg
$\dot{W}$	Power, kW
x	Concentration
y	Ratio of the work output from the power plant to the work input to the liquefaction cycle
$\dot{Z}$	Equipment cost rate, USD

Greek Letters

η	Efficiency
Σ	Summation
Θ	Index
α_c	Absorptance of solar cell
α_b	Absorptance of painted black surface
β_c	Packing factor of solar cell
τ_g	Transmittance of glass
ε	Utilization factor
ω	Humidity ratio

Subscript

a	Absorber; air
abs	Absorber; absorption system
ai	Air inlet
aux	Auxiliary
b	Binary power plant; painted black surface
bs	Back surface of PV/T
c	Condenser; solar cell
ch	Chemical
con	Condenser
comp	Compressor
cool	Cooling
d	Desalination; air-drying process; double

dest	Destruction
df	Double flash power plant
dp	Desalination pump
e	Evaporator
ei	Exergoenvironmental impact
eii	Exergoenvironmental impact improvement
el	Electrical
elec	Electrolyzer
en	Energy
eq	Equipment
es	Exergetic stability
est	Exergetic sustainability
ev	Expansion valve
eva	Evaporator
evr	Refrigerant expansion valve
evw	Weak solution expansion valve
ex	Exergy
f	Flash system
fw	Freshwater
G	Subscript for glass to glass PV/T system
g	Generator; glass
geo	Geothermal
h	Hextuple
HHX	High temperature heat exchanger
hw	Hot water
H_2	Hydrogen
i	Any state; inlet
in	Inlet
irr	Irreversible
iso	Isobutane
liq	Liquefied
LHX	Low temperature heat exchanger
LTG	Low temperature generator
MHX	Medium temperature heat exchanger
MTG	Medium temperature generator
o	Outlet
OPM	Operation and maintenance
out	Outlet
p	Pump; pentuple
ph	Physical
q	Quadruple
qf	Quadruple flash system
QFPP	Quadruple flash power plant
req	Required
rev	Reversible

s	Single
sw	Seawater
t	Triple
th	Thermal
tot	Total
turb	Turbine
uu	Unused fuel
VHHX	Very high temperature heat exchanger
VHTG	Very high temperature generator
w	Water
II	Second law
1…41	State numbers
0	Ambient; reference state

Abbreviations

abs	Absorber
AC	Alternate current
ACAR	Auto-cascade absorption refrigeration
ARS	Absorption refrigeration system
BFB	Bubbling fluidized bed
CaCl	Calcium chloride
CCHP	Combined cooling, heating and power generation
CFB	Circulating fluidized bed
CHX	Condenser heat exchanger
con	Condenser
COP	Coefficient of performance
DC	Direct current
DEARS	Double effect absorption refrigeration system
DFB	Dual fluidized bed
EES	Engineering equations solver
EVA	Ethyl vinyl acetate
eva	Evaporator
GAX	Generator absorber heat recovery heat exchanger
HHX	High temperature heat exchanger
HTG	High temperature generator
IR	Internal reforming
LEC	Levelized electricity cost
LH	Linde–Hampson
LHX	Low temperature heat exchanger
LiBr	Lithium bromide
LiCl	Lithium chloride
LINMAP	Linear programming technique for multidimensional analysis
LTG	Low temperature generator

MHX	Medium temperature heat exchanger
MTG	Medium temperature generator
ORS	Organic Rankine cycle
PV/T	Photovoltaic thermal
PV	Photovoltaic
QEARS	Quadruple effect absorption refrigeration system
QFPP	Quadruple flash power plant
SC	Subcooled
SEARS	Single effect absorption refrigeration system
SH	Superheated
SOFC	Solid oxide fuel cell
TEARS	Triple effect absorption refrigeration system
TRI	ThermoChem bubbling fluidized bed gasifier
TSVCS	Two-stage vapor compression system
USD	United States of America dollar
VCAS	Vapor compression–absorption system
VHHX	Very high temperature heat exchanger
VHTG	Very high temperature generator

Chapter 1
Fundamentals of Absorption Refrigeration Systems

1.1 Introduction

Since the industrial revolution, humankind's demand for a better lifestyle and greater comfort has increased considerably. In order to meet such demands, an increasing number of energy-consuming technological devices and products are being introduced almost daily. In countries around the globe, the demand for energy required for cooling and heating applications has risen dramatically and it is expected to increase exponentially every day, making it difficult for countries to meet the growing demand. At present, the majority of power plants run on fossil fuels, including coal, oil, and natural gas, due to their easy availability and low cost in certain countries, especially in the Gulf region. However, such systems release toxic gases, such as CO_2 and NO_x, etc., which are harmful not only to the environment, but to all living things. The maximum amount of energy available in the grid of countries situated in either hot or cold regions is used to provide cooling or heating, respectively, by installing conventional energy-hungry vapor-compression cycles. These cycles use an ample amount of energy to run the compressor to achieve the required cooling or heating rate of the system. This high energy consumption not only affects the environment but also affects the individual in terms of running cost. Therefore, it has become more crucial to design air-conditioning, cooling, and refrigeration systems that are more cost-effective, more eco-friendly, and can be operated using low-grade heat sources, such as solar, geothermal, biomass, as well as process/waste heat. The performance of such a cooling cycle is represented by the coefficient of performance (COP) which is the ratio of cooling rate provided to the energy input to the system. This chapter sheds light on fundamental and conceptual aspects of absorption refrigeration systems for various applications, ranging from the residential sector to the industrial sector, using various sources of low-grade heat.

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1.2 Absorption Process

Absorption is defined as a process in which two fluids entering at different states such as a gas or liquid are combined to leave at a single state, as either a gas or liquid as shown in Fig. 1.1. A cooling system that works on the principle of absorption is known as an absorption refrigeration system. It is important to differentiate between air-conditioning and refrigeration systems. Air-conditioning systems are used to provide cooling above 0 °C, whereas refrigeration systems are used to provide cooling both below and above 0 °C. A common example of an air-conditioning system is a cooling unit in a house and an example of a refrigeration system is a food storage unit. The absorption refrigeration system was first introduced in 1846 with the concept of producing ice while using heat as an energy input. The introduction of the absorption process in the cooling industry resulted in the ability to produce cooling using less electrical energy than conventional vapor-compression cooling systems. Absorption refrigeration technology is among the best alternatives to vapor-compression cooling with respect to energy diversification and environmental protection. Since absorption refrigeration technology is used extensively in practical applications, a number of high-performance absorption refrigeration cycles have been introduced for both residential and industrial applications.

1.3 Absorbents and Refrigerants

The word ``absorbent'' or ``refrigerant'' in an absorption refrigeration system refers to the working fluid of the system. As the name ``absorption refrigeration system'' implies, the absorbent or refrigerant is a mixture of two fluids, which are used in such a way that the saturation temperature of one fluid is lower than the other. The fluid with lower saturation temperature is selected based on the mixture used and the working environment. This lower saturation temperature fluid acts as a refrigerant

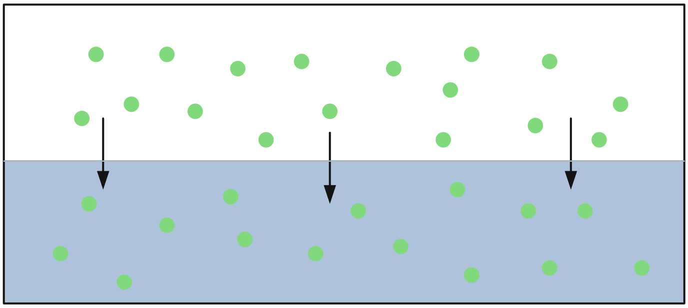


Fig. 1.1 Schematic illustration of an absorption process

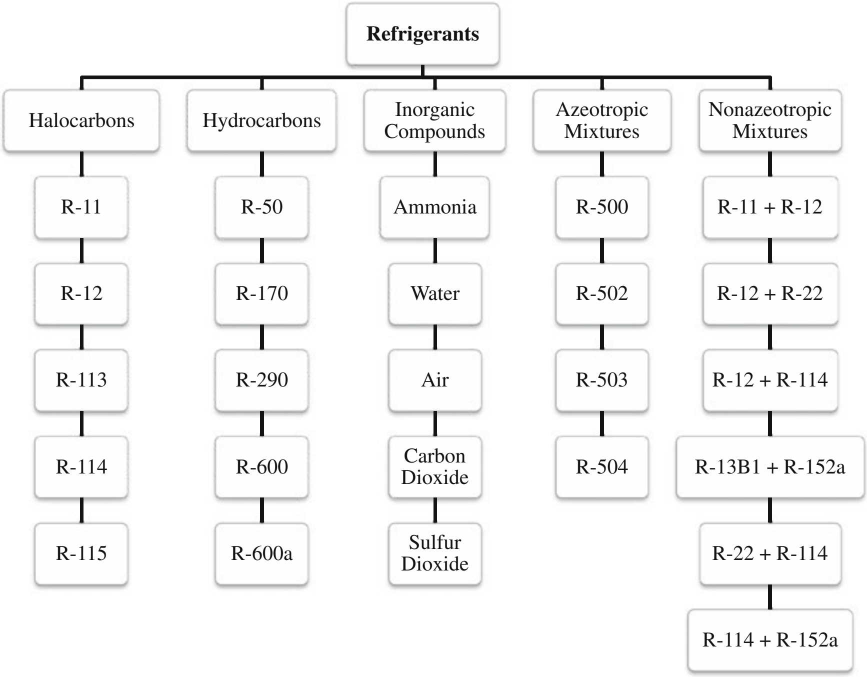


Fig. 1.2 Classification of refrigerants for various applications

and the other fluid acts as an absorbent that absorbs the refrigerant in an absorber. The refrigerants used in absorption refrigeration systems are classified into five categories namely halocarbons, hydrocarbons, inorganic compounds, azeotropic mixtures, and nonazeotropic mixtures as shown in Fig. 1.2. Different types of absorbents used in these systems include water, LiBr, LiCl, $ZnCl_2$, Li_2ZnCl_4, Li_2CaCl_4, and $CaZnCl_4$. Several working fluids are used in an absorption refrigeration system which include ammonia–water, lithium–bromide–water, Tridroxide–water, and Alkitrate–water. The most commonly used among them are ammonia–water and lithium–bromide–water. For residential air-conditioning applications, the lithium–bromide–water solution is preferred due to its high coefficient of performance and easy management. However, a major drawback to the LiBr–water system is the high operational costs that arise because of corrosion that occurs with working temperatures above 473.15 K as well as crystallization issues. The working temperature restriction in lithium–bromide–water working fluid prevents it from being used on a large scale, and the salt used in the system to solve the corrosion problem is expensive, which drives the operation cost of the system high. On the other hand, the ammonia–water system is preferred for industrial use as it can run at high temperatures without the problem of crystallization. Although the ammonia–water absorption refrigeration system also faces the problem of corrosion, the cure for this problem is sea salt which helps to reduce the operational costs . Other proposed working fluids are still in the testing phase and are not able to compete with the COP or operation cost of the conventional LiBr–water and ammonia–water absorption refrigeration systems.

1.4 Classification of Absorption Refrigeration Systems

Concerns related to the harmful effects of using fossil fuels for power generation have resulted in a push for the development of a cooling system that can run on low-grade energy and can minimize the use of power in the cooling or heating process. One such technology to provide cooling is the absorption refrigeration system. Absorption refrigeration systems can be classified into several categories which are single effect absorption refrigeration systems, half effect absorption refrigeration systems, and multiple effect absorption refrigeration systems as shown in Fig. 1.3. This classification is made based on the number of generators used and the way they are connected to each other. A single effect absorption refrigeration system is the simplest form and consists of a generator, a condenser, an absorber, an evaporator, a pump, and expansion valves. These components can be arranged either in series or in parallel depending on the application and the provided space. An enhanced form of single effect absorption refrigeration system is the half effect absorption refrigeration system which makes it possible to provide cooling while using a heat source at relatively lower temperature than the single effect absorption

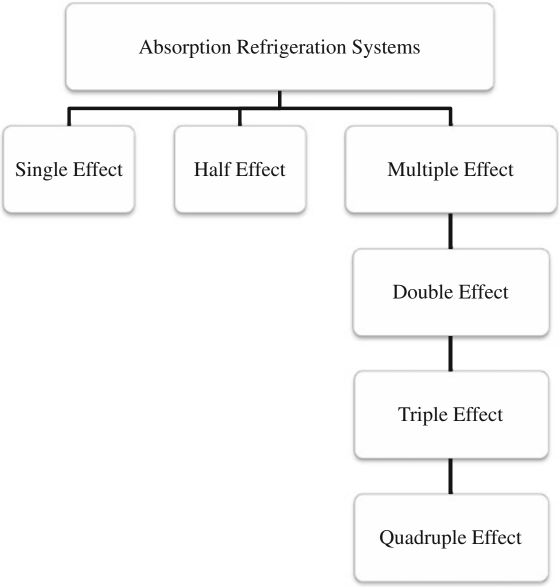


Fig. 1.3 Classification of absorption refrigeration systems

refrigeration system. A half effect absorption refrigeration system consists of two generators, two absorbers, two pumps, three expansion valves, a condenser, and an evaporator. In the half effect absorption refrigeration system, heat is supplied to both generators from a single source. The drawback to using a half effect absorption refrigeration system is that it has very low COP compared to the single effect absorption refrigeration system. In order to enhance the COP of the absorption refrigeration system, researchers have introduced multiple effect absorption refrigeration systems varying from double effect to quadruple effect.

Although the increasing the number of effects drastically enhances the COP of the system from 0.7 for single effect to 2.5 for quadruple effect, it does so at the cost of a higher temperature heat source requirement compared to a lower effect absorption refrigeration system. A recent advancement in energy recovery from the cycle also led to the advancement of absorption refrigeration system working on the concept of internal heat recovery. The absorption refrigeration systems working on the concept of the heat recovery consist of an additional heat exchanger and are classified as absorption refrigeration systems with agenerator absorber heat exchanger (GAX). The addition of GAX in the cycle helps recovery of heat from the weak solution returning from the generator in the form of preheating of the strong solution going toward the generator.

1.5 Components of Absorption Refrigeration Systems

Absorption refrigeration systems are cooling generating devices that rely more on thermal energy than electrical energy to provide the desired output. An absorption refrigeration system generally comprises six basic subsystems which are generator, absorber, condenser, evaporator, pump, and an expansion valve as shown in Fig. 1.4. Each of these subsystems has a specific task to perform in order successfully to run the absorption refrigeration system.

1.5.1 Generator

Generator is a subsystem of the absorption refrigeration system whose job is to separate the refrigerant from the working fluid mixture using heat as an energy source. A generator of the absorption refrigeration system has the structure of a shell–and– tube heat exchanger with two inlets and three outlets as shown in Fig. 1.5. In the generator, the strong solution (a mixture of refrigerant and absorbent) from the absorber enters from the bottom where it is heated from the high temperature fluid from the heat source. As the strong solution boils, the refrigerant

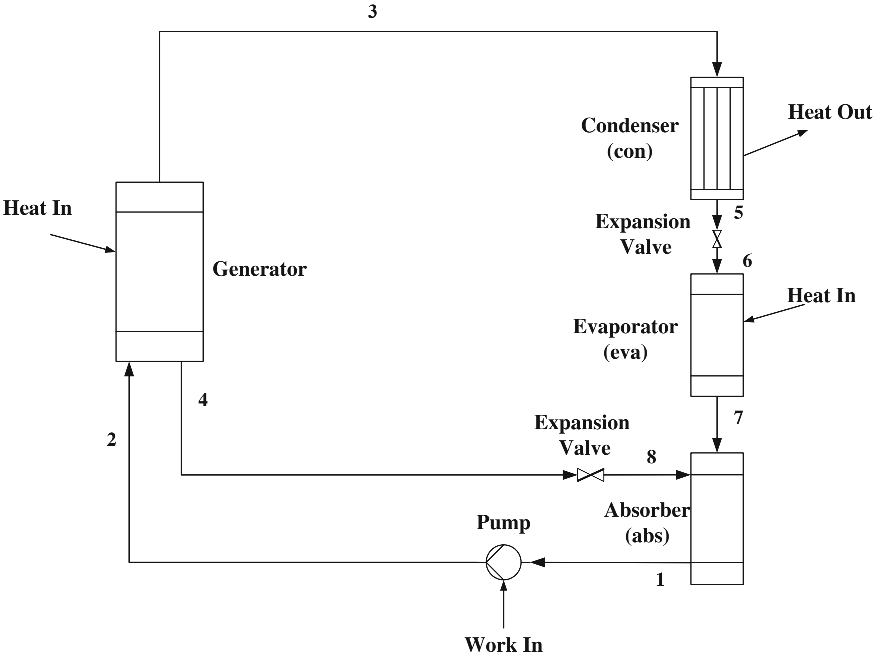
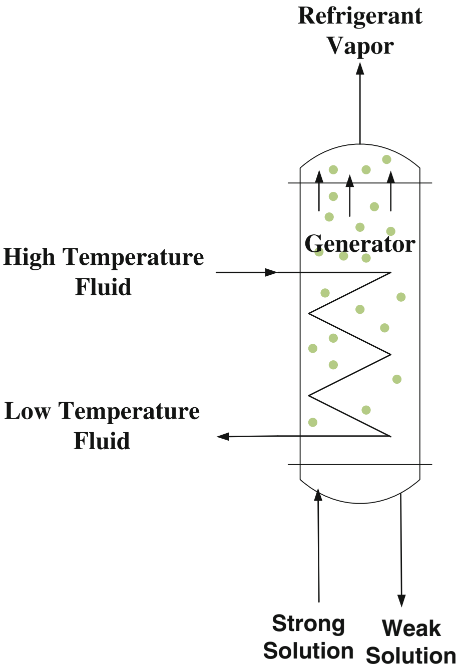


Fig. 1.4 A schematic diagram of basic absorption refrigeration system

Fig. 1.5 Schematic of generator

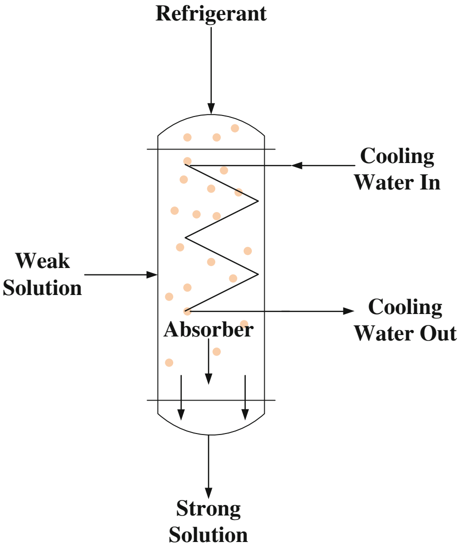


with comparitively lower boiling temperature than the absorbent leaves the generator from the top in superheated vapor form. The mixture containing a smaller amount of refrigerant compared to the strong solution leaves the generator as a weak solution to be recirculated back to the absorber.

1.5.2 *Absorber*

An absorber is a sub-system of the absorption refrigeration system, whose task is to mix together the refrigerant from the evaporator and the weak solution from the generator. An absorber is a simple mixing chamber in which two fluids enter the chamber to leave as a single fluid as shown in Fig. 1.6. The refrigerant from the evaporator first gains heat from the cooled space then enters the absorber from the top. The weak solution from the generator first passes through the expansion valve, where its pressure drops to that of the absorber before it enters the absorber. The use of an expansion valve before the absorber is necessary to ensure that both fluids entering the absorber are at the same pressure for mixing to take place. The refrigerant and the weak solution mix together in the absorber and release heat to the cooling water. After mixing and releasing heat in the absorber, the mixture leaves as a strong solution to be supplied to the generator.

Fig. 1.6 Schematic of absorber



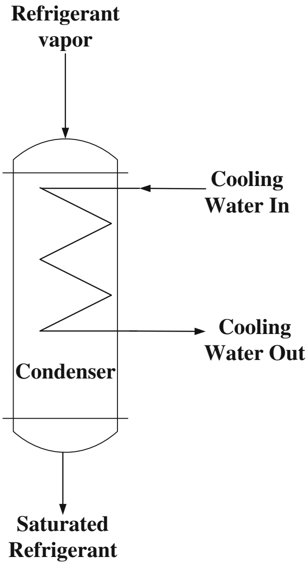
1.5.3 *Condenser*

The condenser of an absorption refrigeration system acts as a heat exchanger whose job is to cool the refrigerant from the generator. In the condenser, the vaporized refrigerant from the generator ejects heat to the cooling water as shown in Fig. 1.7. The cooled refrigerant leaving the condenser then passes through the expansion valve to enter the evaporator. The cooling water used to cool the refrigerant leaves the condenser at a relatively higher temperature that can be further used for domestic heating purposes.

1.5.4 *Evaporator*

An evaporator of the absorption refrigeration system is a simple heat exchanger, tasked with cooling the space by absorbing heat from the cooled space as shown in Fig. 1.8. The refrigerant leaving the condenser passes through the expansion valve before entering the evaporator. In the expansion valve, the pressure of the refrigerant is suddenly drops which results in a saturated mixture of refrigerant that is high in vapor content. This high vapor content refrigerant then enters the evaporator where it absorbs heat from the cooled space and leaves as a saturated mixture refrigerant. This saturated mixture refrigerant then enters the absorber to be absorbed in the weak solution.

Fig. 1.7 Schematic of condenser



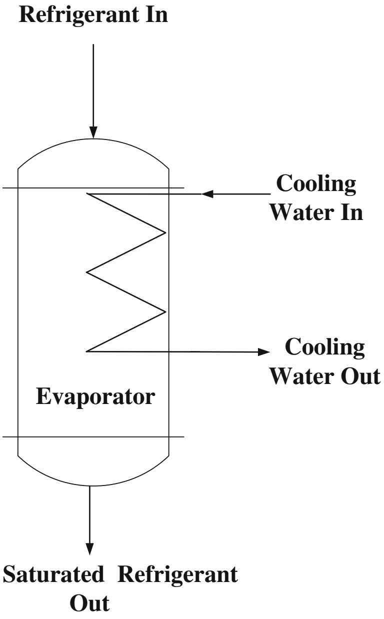


Fig. 1.8 Schematic of evaporator

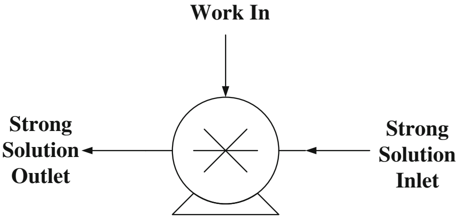


Fig. 1.9 Schematic of positive displacement pump

1.5.5 Pump

The pump used in an absorption refrigeration system is a positive displacement pump. The pump is used to increase the pressure of the strong solution to be supplied to the generator as shown in Fig. 1.9.

1.5.6 Expansion Valve

In an absorption refrigeration system, at least two expansion valves are used, one for the weak solution and one for the refrigerant as shown in Fig. 1.10. The expansion valve used for the weak solution is tasked with reducing the pressure of the weak solution to that of the absorber. The expansion valve used for the

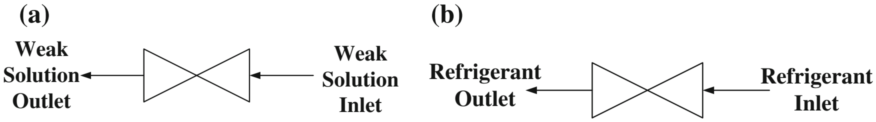


Fig. 1.10 Schematic of expansion valve for **a** weak solution and **b** refrigerant

refrigerant acts as a throttling valve in which the pressure of the refrigerant is suddenly dropped to increase the vapor content in the saturated mixture entering the evaporator.

1.6 Operating Principle

A basic absorption refrigeration system consists of a generator, an absorber, a condenser, an evaporator, a pump, and two expansion valves as shown in Fig. 1.4. Heat is supplied to the generator where strong solution enters at state 2. This strong solution is heated to in order to separate the refrigerant from the solution on the basis of saturation temperature difference between refrigerant and absorbent. The vaporized refrigerant leaves the generator at state 3 and the weak solution leaves the generator at state 4. The vaporized refrigerant at state 3 then enters the condenser where it rejects heat to the cooling fluid to leave at state 5 as a saturated mixture. The saturated mixture then passes through the expansion valve where its pressure drops suddenly to increase the vapor content in the saturated mixture and leaves at state 6 to enter the evaporator. In the evaporator, the saturated refrigerant mixture of the refrigerant gains heat from the cooled space and leaves at state 7 to enter the absorber. The weak solution returning from the generator passes through the expansion valve where its pressure drops to leave at state 8 to enter the absorber. The weak solution and the refrigerant then mix together in the absorber and reject heat to the cooling fluid to leave as a strong solution in liquid form at state 1. The strong solution leaving the absorber at state 1 first passes through the pump, where the pressure of the strong solution increases before it enters the generator at state 2, respectively.

1.7 Types of Absorption Refrigeration Systems

An absorption refrigeration system can be designed in several different ways based on generator arrangement. A simple absorption refrigeration system, also known as single effect absorption refrigeration system, consists of a generator, an absorber, a condenser, an evaporator, a pump, and two expansion valves. The present work considers, several absorption refrigeration designs including single effect, double effect, triple effect, and multiple effect absorption refrigeration systems.

1.7.1 Single Effect Absorption Refrigeration System

A single effect absorption refrigeration system is the simplest form of absorption refrigeration system.It is made up of a generator, an absorber, a condenser, an evaporator, a heat recovery heat exchanger, a pump, and two expansion valves as shown in Fig. 1.11. The process starts when the strong solution leaves the absorber at state 1 to enter the pump. In the pump, the pressure of the strong solution increases to the generator pressure and it leaves at state 2. The strong solution then enters the heat recovery heat exchanger at state 2, where it gains heat from the returning weak solution to leave at a slightly higher temperature at state 3. The strong solution at state 3 then enters the generator, where it gains heat from the heat source and starts boiling. The refrigerant mixed with the strong solution vaporizes before the absorbent and leaves at state 7. Once the refrigerant vaporizes from the strong solution, what is left in the generator is a weak solution which leaves at state 4. The vaporized refrigerant leaving at state 7 later enters the condenser, where it rejects heat to the surroundings to leave at a relatively lower temperature at state 8. The precooled refrigerant then enters the expansion valve, where it experiences a sudden pressure drop to leave at state 9 as a vapor-heavy saturated mixture. This vapor-heavy saturated mixture later enters the evaporator, where it gains heat from the cooled space to leave at state 10. The refrigerant leaving at state 10 then enters

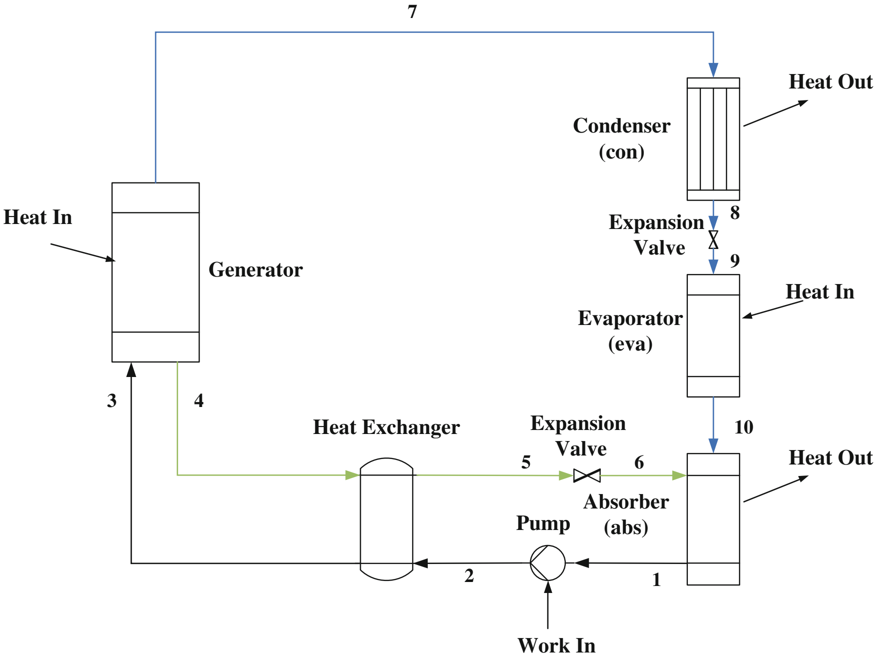


Fig. 1.11 Schematic of single effect absorption refrigeration system

the absorber. The weak solution exiting the generator at state 4 enters the heat recovery heat exchanger, where it loses heat to the incoming strong solution to leave at state 5 at comparatively lower temperature. The weak solution at state 5 then enters the expansion valve, where its pressure drops to the absorber pressure before entering the absorber at state 6. In the absorber, the weak solution and the refrigerant mix together and release heat to leave as a strong solution at state 1.

1.7.2 Double Effect Absorption Refrigeration System

A double effect absorption refrigeration system differs from a single effect absorption refrigeration system in that it double effect absorption refrigeration system has two generators and three heat recovery heat exchangers as shown in Fig. 1.12. In the double effect absorption refrigeration system, a strong solution leaves the absorber at state 1 to enter the solution pump. In the pump, the pressure of the strong solution increases and leaves at state 2. The strong solution at state 2 is then separated into two streams for energy recovery purposes. One strong solution stream at state 3 enters the low temperature heat exchanger, where it gains heat from the returning weak solution to leave at state 4 as a preheated stream. This preheated strong solution then divides into two streams from which one is directed

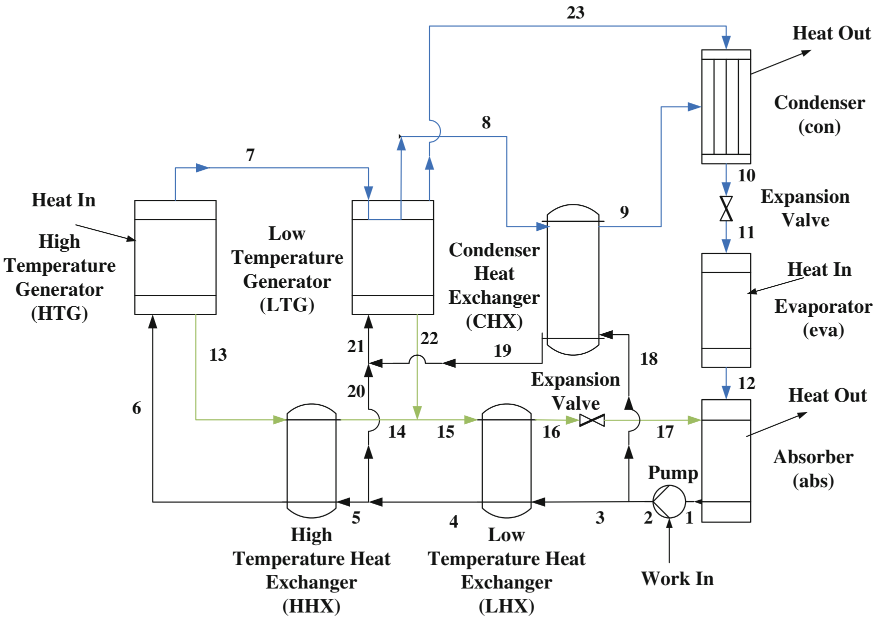


Fig. 1.12 Schematic of double-effect absorption refrigeration system