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ABSTRACT

The reversible Carnot cycle process using to obtained the optimum coefficient of performance (COP) and ammonia/water ratio. In this experiment the refrigerant is anhydrous ammonia and the absorber is water and ammonia/water ratios used are in the range of 5% to 30% ammonia in water base on volume percentage in the solution. Assuming the absorption unit has complete cycle and stable system after 8 hours and the performance of the absorption chillers unit is constant for each experiment the value of coefficient of performance COP is calculated for each hour depending on the refrigerant/absorber ratio. The COP increased with increasing generator temperature and with decreasing absorber and condenser temperatures for all the systems. Also, the lowest temperature at the evaporator is important in order to control the temperature for all the system cycle that affects the value of COP in absorption chillers. In conclusion, the optimum ammonia/water ratios that obtained in this experiment are 30% ammonia purity with 2.97 coefficient of performance.

Then, to increase the performance of absorption refrigeration system Zeolite NaA was added in the ammonia water solution with different concentration in the range 0.0002M to 0.001M. The optimum concentration of additive is determined by referring to the lowest cooling box temperature which will give the lowest value of coefficient of performance (COP). The optimum concentration of additive that can be added to the absorption process is 0.0006M of Zeolite NaA. The optimum coefficient is 1.5 compare to the coefficient of performance for absorption without additive that is only 1.2.

ABSTRAK

Proses berbalik Carnot digunakan adalah untuk mengetahui jumlah maksimum nilai prestasi dan nisbah ammonia/air. Dalam penyelidikan ini ammonia bertindak sebagai bahan penyejuk dan air sebagai bahan penyerap dan nisbah yang digunakan adalah diantara 5% hingga 30% ketulenan ammonia mengikut peratusan isipadu larutan. Oleh kerana prestasi alat penyerapan kesejukan sama pada setiap penyelidikan, anggap alat penyerapan membuat kitaran lengkap dan stabil selepas 8 jam, maka nilai akan prestasi dapat di kira pada setiap 1 jam bergantung kepada nisbah ammonia/air yang digunakan. Nilai akan prestasi akan meningkat sekiranya suhu alat pembangkit tenaga bertambah dan penurunan suhu pada alat penyerap serta alat kondensasi berlaku. Manakala, suhu yang rendah pada alat penyerap penting untuk mengawal suhu pada keseluruhan sistem. Nilai maksimum yang dicapai untuk nilai prestasi adalah 2.97 iaitu pada nisbah ammonia/air adalah 30% ketulenan ammonia dalam larutan.

Kemudian untuk penambahbaikan kecekapan unit penjerapan, mangkin zeolite di tambah pada larutan ammonia dengan kepekatan diantara 0.0002M hingga 0.001M. Kepekatan mangkin yang sesuai diperolehi dengan melihat suhu terendah yang dapat dicapai oleh unit penjerapan. Kepekatan mangkin yang sesuai diperolehi adalah pada 0.0006M. Pemalar kecekapan yang dicapai oleh proses ini adalah 1.5 berbanding pemalar kecekapan yang dicapai oleh unit penjerapan tanpa mangkin di mana ia hanya mencapai 1.2.

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LIST OF ABBREVIATIONS

CFC	-	Chlorofluorocarbon
COP	-	Coefficient of Performance
CO_2	-	Carbon Dioxide
DMF	-	Dimethyl Formamide
FAU	-	Zeolite X,Y
g	-	gram
HCFC	-	Hydro Chlorofluorocarbon
H_2O	-	Water
kg/m^2	-	kilogram per meter
LPG	-	liquefied petroleum gas
LTA	-	Zeolite A
M	-	Molar
MFI	-	Zeolite ZSM-5
mL	-	milliliter
N_2	-	Nitrogen
NaOH	-	Sodium Hydroxide
NH_3	-	ammonia
nm	-	Nanometer
O_2	-	Oxygen
SD	-	Sodalite
SDA	-	structure directing agent
TEG.DME	-	Tetraethylene Glycol Dimethyl Ether

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

A chiller or refrigerator is a machine that removes heat from a liquid via a vapor compression or absorption refrigeration cycle. Chiller water is used to cool and dehumidify air in mid to large size commercial, industrial, and institutional facilities. There are two types of refrigerator that mainly used compression refrigerator and gas absorption refrigerator.

An absorption refrigeration system basically consists of an evaporator, a condenser, a generator, an absorber and economizer (Romero, Rivera, 2000). A quantity of waste heat is added at a relatively high temperature to the generator to vaporize the working fluid from the solution. The vaporized working fluid goes to condenser where it is condensed delivering an amount of heat at an intermediate temperature. The liquid leaving the condenser passes through a valve to evaporator where it is evaporated by means of a quantity of heat at a low temperature, producing the cooling effect. The vaporized working fluid then goes to the absorber where it is absorbed by the solution coming from the generator, delivering an amount of heat at an intermediate temperature. Finally, the solution leaving the absorber is pre-heated in the economizer and returns to generator, starting the cycle again.

In the industrialized nations and affluent regions in the developing world, refrigeration units are used chiefly to store foodstuffs. Most household refrigerators and freezers use vapor compression. Usually the refrigerant passes through chiller plates in the freezer section that contain coils. The refrigerant is partially evaporated and then continues to the main refrigeration compartment. Small fans circulate the cold air, which would otherwise settle at the bottom of the unit. Water vapor from the main storage compartment tends to freeze on the cold chiller plates, causing a build up of ice that reduces the cooling ability of the refrigerator. Thus, refrigerators require periodic defrosting in order to keep them working properly. This may be done manually by shutting off the refrigerator and either heating the cooling coils or allowing them to remain at room temperature until the ice melts. Automatic defrosting, or so-called frost-free, refrigerators heat the coils automatically at timed periods, usually by passing hot condenser gas to the coils or by rapidly adding heat from electrical resistors.

Refrigeration is also used to preserve foods in cold-storage warehouses until the food can be shipped to supermarkets and other stores. Temperatures are usually maintained at slightly above 32°F (0°C) to prevent the foods from actually freezing. In most cold-storage warehouses, an external refrigeration system cools a mixture of water and salt or water and antifreeze. Such a mixture has a lower freezing point than does pure water. The mixture is then circulated through pipes that run through the warehouse. Early refrigerated trucks, ships, and railcars that were used to transport foods and large blocks of ice cooled other materials. Today there are separate refrigerators for each storage compartment.

1.2 Problem Statement

Absorption chiller systems have greater resource efficiency than similar compressor systems and electric system. Only about 5% to 10% of the fuel resource is lost with an absorption chiller system. Additionally, electricity costs per Btu are typically three to four times the cost per Btu for electricity, so the cost of a unit of output (refrigeration) can often be lower with an absorption unit. Utilizing waste heat that would otherwise be unused greatly increases the cost-effectiveness of the systems, compared to consuming gas directly. The absorption system is the used of non-ozone depleting and low global warming potential working fluid pair, the most common of which is ammonia-water.

The disadvantage of ammonia/water absorption system is the temperature at evaporator is high compare to compression system and electric system. To ensure the absorption system can be competitive with compressor system, the effect of ammonia/water ratio to the temperature at evaporator of absorption chiller is studied and the efficiency of the system can be improved. Also, the coolest temperature at evaporator is important in order to control the temperature of the system

1.3 Objective

The objectives of this project are to:

i) Design and fabricate a multifuel gas adsorption refrigeration system to determine how effective the additive increases the performance of the system.

ii) Identify the fuel consumption and system efficiency of the developed absorption refrigeration system

iii) Study the effect of additive on the efficiency and performance of the absorption refrigeration system

1.4 Scope of Research

The scope of research work is to evaluate and improve the performance the absorption refrigerator unit found in lab. The basic operation of the absorption refrigeration system working without any additive using NH_3-H_20 as working fluid. Overview of operation in the main component in recent refrigeration system and effect when using any materials as an additive also necessary to be studied in turn to develop and fabricated a new refrigeration system using the new additive that can give better performance and also conventional for public using.

An absorption refrigeration system will be test-using zeolite NaA as an additive. The selected additives that will use in this experimental testing are zeolite NaA which have porous media are expected to be the better additive for this system. The whole system will test firstly using working fluid without any additive to measure the actual operating condition before testing continues by using additive.

The NH_3-H_20 ratio uses in this study are in the range of 5% - 30% ammonia in water based on volume percentage in the solution and the coefficient of performance (COP). value is calculated using a reversible Carnot cycle process of absorption chiller as the main scope of this research. Gas Absorption Refrigeration Unit (Model: RF 10) is a complete laboratory bench top unit for the demonstration of gas absorption refrigeration. The unit is a continuous absorption refrigeration system operated by application of a heat source either electrically or furnished by fuel gas.

CHAPTER 2

LITERATURE REVIEW

2.1 History

The first absorption refrigerator was invented by students at the Royal Institute of Technology Stockholm, Sweden named Baltzar von Platen and Carl Munters. This invention is start in 1922 (George, 2006). The invention was not end there; in 1923 the absorption refrigerator commercial production began by the newly formed company AB Arctic. Then in 1925 Electrolux bought the company.

2.2 Refrigeration Process Through Absorption

The basic absorption cycle employs two fluids, the absorbate or refrigerant, and the absorbent. The most commonly fluids are ammonia as the refrigerant and water as the absorbent. These fluids are separated and recombined in the absorption cycle. In the absorption cycle the low-pressure refrigerant vapor is absorbed into the absorbent releasing a large amount of heat. The liquid refrigerant/absorbent solution is pumped to a high-operating pressure generator using significantly less electricity than that for compressing the refrigerant for an electric chiller. Heat is added at the high-pressure generator from a gas burner, steam, hot water or hot gases. The added heat causes the refrigerant to desorbs from the absorbent and vaporize. The vapors flow to a condenser, where heat is rejected and condense to a high-pressure liquid. The liquid is then throttled though an expansion valve to the lower pressure in the evaporator where it evaporates by absorbing heat and provides useful cooling. The remaining liquid absorbent, in the generator passes through a valve, where its pressure is reduced, and then is recombined with the low-pressure refrigerant vapors returning from the evaporator so the cycle can be repeated. Absorption chillers are used to generate cold water (44°F) that is circulated to air handlers in the distribution system for air conditioning (Mildwest, 2007). The absorption refrigerator has a lot of advantages such as by using absorption refrigerator we can eliminate the use of CFC and HCFC refrigerant that can cause global warming. Compared to compression refrigerator, absorption refrigerator is more quiet and vibration-free operation. The maintenance is low due to lower pressure system with no large rotating component.

Not only that the absorption refrigerator can lower utility bills depending on rate structures and the difference in cost between natural gas and electricity, various strategies can be used to save energy costs. If natural gas costs are sufficiently low and electric rates high, all of the cooling load can be carried by an absorption chiller. If demand charges are high or there are high ratchets in the electrical rate structure, the peak loads can be cut using absorption cooling while the base load is carried by an electric chiller. Also, if a facility has a source of low grade heat currently going to waste, a single effect chiller may be ideal. Also, direct-fired, natural gas absorption chillers can cut sulfur dioxide emissions by 100%, nitrogen oxide by 68%, carbon dioxide by 57%, and particulates by 97% over oil-fired, peaking power plants and coal-fired, base load power plants (George, 2006). This refrigerator has limitation, for single effect absorption it has low thermal efficiency and made this model non-competitive except in situations with readily free waste heat. The double effect refrigerator is not cost-effective in many applications (Lazzarin *et.al*,1996). Basically absorption chiller can be classified as direct fired or in direct fired chiller. This chiller is class as single effect, double effect and triple effect absorption chiller.

Indirect-fired units, the heat source can be gas or some other fuel that is burned in the unit. Indirect-fired units use steam or some other transfer fluid that brings in heat from a separate source, such as a boiler or heat recovered from an industrial process.

2.3 Type of absorption refrigeration

Basically absorption refrigeration can be classified as single effect, double effect and triple effect absorption refrigeration. All the types of this absorption refrigeration have the same operating cycle and the only difference is additional device to improve the performance and efficiency. The explanations for the type of absorption refrigeration are discussed in the following sections.

2.3.1 Single Effect Absorption Refrigeration

The single-effect can be defined as the transfer of fluids through the four major components of the refrigeration machine – evaporator, absorber, generator and condenser. Single-effect absorption chillers use low pressure steam or hot water as the heat source. The water is able to evaporate and extract heat in the evaporator because the system is under a partial vacuum. The thermal efficiency of single-effect absorption systems is low. This low efficiency has inhibited the cost competitiveness of single-effect systems. The process flow is shown in Figure 2.1

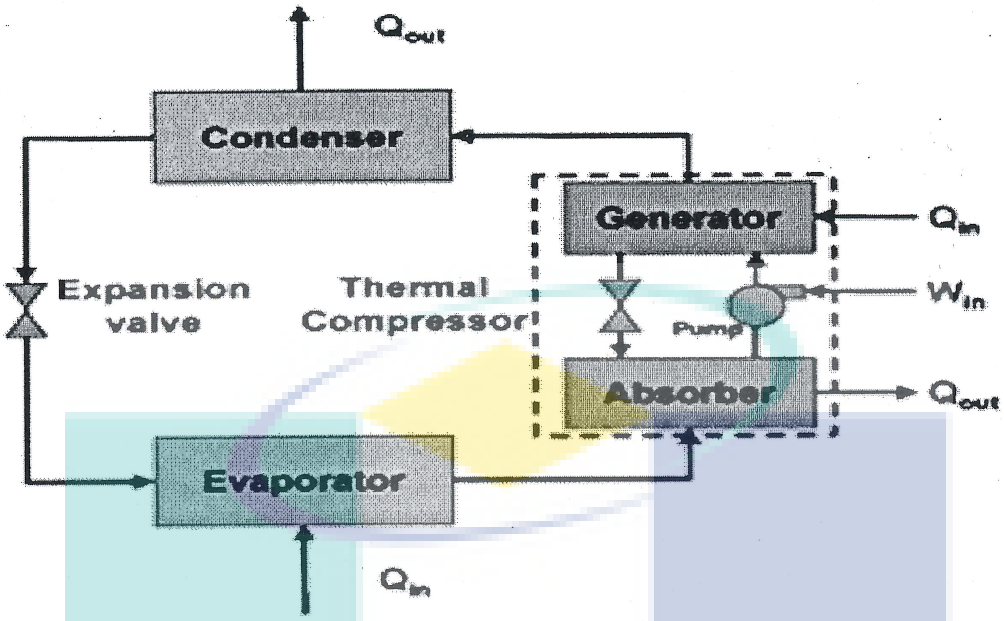

Figure 2.1: Single-Effect Absorption Refrigeration Cycle

2.3.2 Double Effect of absorption refrigeration

Basically double effect refrigerator is an improvement from single effect absorption refrigerator. The double-effect chiller differs from the single-effect in that there are two condensers and two generators to allow for more refrigerant boil-off from the absorbent solution. Figure 2.2 shows the double effect absorption refrigerator. The higher temperature generator uses the externally supplied steam to boil the refrigerant from the weak absorbent. The refrigerant vapor from the high temperature generator is condensed and the heat produced is used to provide heat to the low temperature generator. A double-effect refrigerator uses two generators paired with a single condenser, absorber, and evaporator. It requires a higher temperature heat input to operate and therefore they are limited in the type of electrical generation equipment they can be paired with when used in a CHP System.

Double-effect absorption chillers are used for air-conditioning and process cooling in regions where the cost of electricity is high relative to natural gas. Double-effect absorption chillers are also used in applications where high pressure steam, such as district heating, is readily available. Although the double-effect machines are more efficient than single-effect machines, they have a higher initial manufacturing cost. There are special materials considerations, because of increased corrosion rates (higher operating temperatures than single-effect machines), larger heat exchanger surface areas, and more complicated control systems.

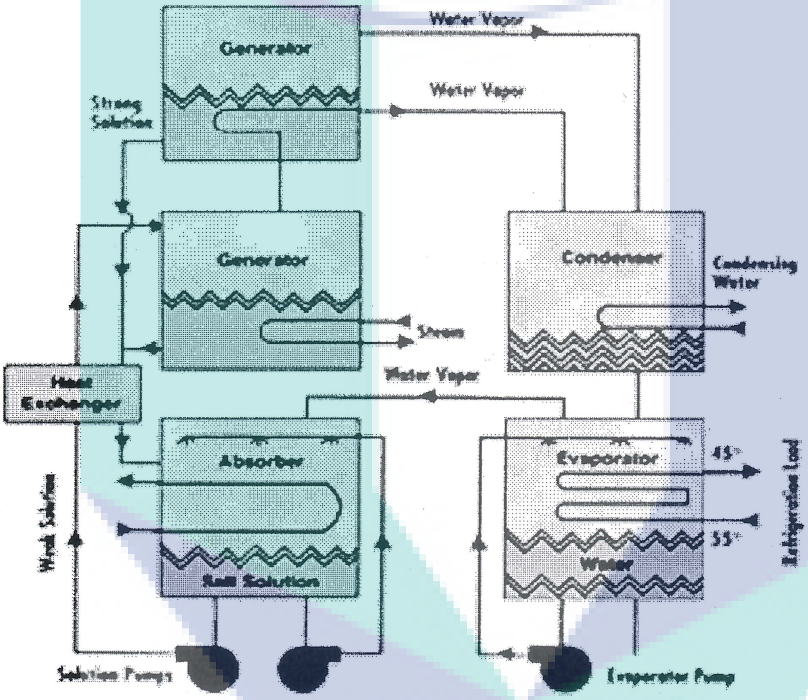

Figure 2.2: Double-Effect Absorption Refrigeration Cycle

2.3.3 Triple Effect Absorption Refrigeration

The triple-effect cycles are the next logical improvement over the double-effect. Triple-effect absorption chillers are under development, as the next step in the evolution of absorption technology. Figure 2.3 shows the triple effect absorption cycle on a Pressure-temperature diagram. The refrigerant vapor from the high and medium temperature generators is condensed and the heat is used to provide heat to the next lower temperature generator. The refrigerant from all three condensers flows to an evaporator where it absorbs more heat. Triple-effect systems offer the possibility of thermal efficiencies equal to those of electrical chillers. The cost, however, will be higher, so system cost effectiveness will need to be evaluated on a case-by-case basis. The higher efficiency levels would open wider markets for absorption chillers. Triple-effect chillers can achieve even higher efficiencies than the double-effect chillers. These chillers require still higher elevated operating temperatures that can limit choices in materials and refrigerant/absorbent pairs. Triple-effect chillers are under development by manufacturers working in cooperation with the U.S. Department of Energy

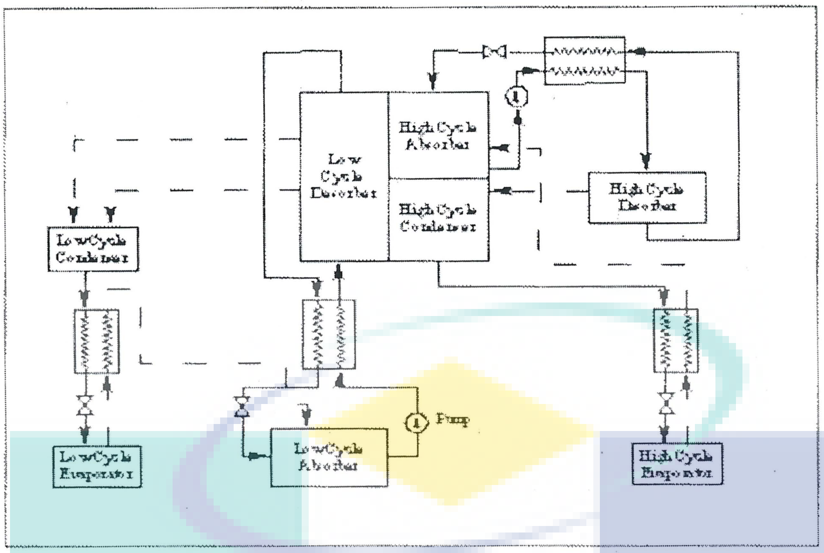

Figure 2.3: Triple-Effect Absorption Refrigeration Cycle

2.4 Efficiencies

Efficiencies of absorption chillers are described in terms of coefficient of performance (COP), which is defined as the refrigeration effect, divided by the net heat input (in comparable units such as kBtu). Single effect machines have a single generator as previously described and require 15 psig steam or 180 – 270 ^{0}F hot water. Single effect machines have COPs of 0.6 to 0.7 (Lazzarin *et.al*, 1996). Double effect machines have a second generator (called the first stage generator) and condenser which operate with 100 to 150 psig steam or a 550 to 1,500 heat source. Refrigerant vapor is recovered from the first stage generator in the first stage condenser. The refrigerant vapor is then condensed at a higher temperature (in the first stage condenser) and the heat from this process is then used to vaporize additional refrigerant from a lower temperature, second stage generator. Double effect machines are more efficient than single effect machines with COPs around 1.04(Lazzarin *et.al*, 1996). A triple effect machine is now on the market which adds a third generator and condenser and is even more efficient with a COP of 1.5 to 1.6

(Lazzarin *et.al*, 1996). In low pressure, steam available in the absorption refrigerator is between 100 to 1500 ton. Absorption chillers come in two commercially available designs: single-effect and double-effect. Single-effect machines provide a thermal COP of 0.7[5] and require about 18 pounds of 15-pound-per-square-inch-gauge (psig) steam per ton-hour of cooling. Double-effect machines are about 40% [5] more efficient, but require a higher grade of thermal input, using about 10 pounds of 100- to 150-psig steam per ton-hour. Table 2.1 refers to the comparison of COP between absorption chiller and electric chiller. The absorption refrigeration system is in Equation 2.1

Table 2.1: Comparison of COP

Chiller	Site COP	Source -to-Site Factor	Resource COP
Electric	2.0 - 6.1	0.27	0.54 - 1.65
Absorption	0.65 - 1.2	0.91	0.59 - 1.1

$$COP = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right)$$

Equation. 2.1 (Engineering Thermodynamic, Yunus Cengal)

2.5 The previous work in improving COP for absorption chiller unit

There are a lot of research have been made to improve the performance of absorption chiller unit. One of the researches is relatively related to my study. The previous research is about designing heat exchanger designed around the refrigerator's existing boiler and zeolite as refrigerant (Kowalski,2006). A device was designed to provide a refrigeration effect using the waste heat generated from a portable generator. The device is primarily intended for emergency situations, disaster relief, or remote military locations. The waste heat in the generator's exhaust is used to power an absorption refrigeration cycle which eliminates electrical demand, allows for smaller generators and reduces fuel consumption and emissions. A 8 HP engine/3500 W peak power generator was used for prototyping.

2.5.1 Heat integration

The heat exchanger needed to be designed around the refrigerator's existing boiler. The idea of running the exhaust through the refrigerator's stock propane heat exchanger was investigated, but it was found that it would not have high enough effectiveness to power the system. Therefore, a new heat exchanger was designed around the existing one, incorporating the existing heat exchanger as conductive fins.

2.5.2 Additive

Valerie H. Johnson, an engineer from the National Renewable Energy Laboratory, tells us "In an evacuated (airless) environment, during absorption the zeolite attracts water in a forceful manner and internal pressure drops dramatically. The remaining water evaporates, cools down and freezes immediately due to the heat of evaporation. The resulting ice can be used for cooling" (Valerie,2002). The major downfall of these types of systems is that continuous cooling systems using zeolite have not been created.

2.5.3 Solar Application

Recent work at the Lawrence Berkeley Laboratory (LBL)(Wahlig, 1984) has resulted in significantly improved absorption cycle performance. Researchers at LBL, working to improve absorption cycle performance for solar application, have developed two advanced versions of the ammonia/water machine. Ammonia/water was chosen as the working fluid pair in order to allow the use of an air-cooled condenser for potential heat pump operation (Kevin D.). For a solar radiation of 800 W/m^2, the lowest solar collector investment level is obtained in combination with a flat-plate collector operating with an average heating medium temperature of 100°C. Solar driven systems will become more competitive if systems requiring lower heating medium temperature would be applied.

CHAPTER 3

REFRIGERATION SYSTEM

3.1 Introduction

Most of industrial process uses a lot of thermal energy by burning fossil fuel to produce steam or heat for the purpose. After the processes, heat is rejected to the surrounding as waste. This waste heat can be converted to useful refrigeration by using a heat operated refrigeration system, such as an absorption refrigeration cycle. Electricity purchased from utility companies for conventional vapor compression refrigerators can be reduced. The use of heat operated refrigeration systems help reduce problems related to global environmental, such as the so called greenhouse effect from CO_2 emission from the combustion of fossil fuels in utility power plants. Another difference between absorption systems and conventional vapor compression systems is the working fluid used. Most vapor compression systems commonly use chlorofluorocarbon refrigerants (CFCs), because of their thermo physical properties.

It is through the restricted use of CFCs, due to depletion of the ozone layer that will make absorption systems more prominent. However, although absorption systems seem to provide many advantages, vapor compression systems still dominate all market sectors. In order to promote the use of absorption systems, further development is required to improve their performance and reduce cost. The early development of an absorption cycle dates back to the 1700's. It was known that ice could be produced by an evaporation of pure water from a vessel contained within an evacuated container in the presence of sulfuric acid. *(Gosney, 1982)*

In 1810, ice could be made from water in a vessel, which was connected to another vessel containing sulfuric acid. As the acid absorbed water vapor, causing a reduction of temperature, layers of ice were formed on the water surface. The major problems of this system were corrosion and leakage of air into the vacuum vessel. In 1859, Ferdinand Carre introduced a novel machine using water/ammonia as the working 345 *P. Srikhirin et al. / Renewable and Sustainable Energy Reviews 5 (2001) 343–372* fluid. This machine took out a US patent in 1860. Machines based on this patent were used to make ice and store food. It was used as a basic design in the early age of refrigeration development.

In the 1950's, a system using lithium bromide/water as the working fluid was introduced for industrial applications. A few years later, a double-effect absorption system was introduced and has been used as an industrial standard for a high performance heat-operated refrigeration cycle.

3.2 Absorption Refrigeration System

An absorption refrigeration system basically consists of an evaporator, a condenser, a generator, an absorber and an economizer *(Romero, Rivera, 2000)*. A quantity of waste heat is added at a relatively high temperature to the generator to vaporize the working fluid from the solution. The vaporized working fluid goes to the condenser where it is condensed delivering an amount of heat at an intermediate temperature. The liquid leaving the condenser passes through a valve to the evaporator where it is evaporated by means of a quantity of heat at a low temperature, producing the cooling effect. The vaporized working fluid then goes to the absorber where it is absorbed by the solution coming from the generator, delivering an amount of heat at an intermediate temperature. Finally, the solution leaving the absorber is pre-heated in the economizer and returns to the generator, starting the cycle again.

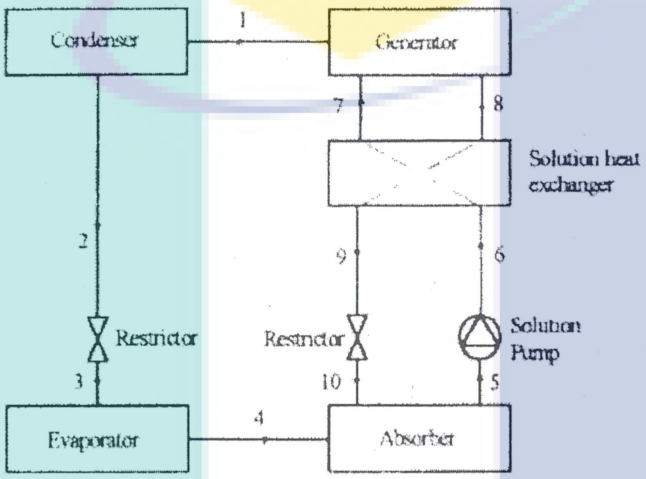

Figure 3.1: Schematic diagram for absorption refrigeration cycle

3.2.1 Refrigeration Cycle Systems

The basic components for an ejector refrigeration cycle include an ejector, a boiler, an evaporator a condenser, an expansion valve and a circulator pump *(Da-Wen Sun, 1999)*. The operating principle is as follows:

i. Low-grade heat Q_b is delivered to the boiler, where liquid refrigerant is vaporized at high pressure. The vapor flows through the primary nozzle and accelerates within it.

ii. At the nozzle exit, the accelerated flow becomes supersonic. A low-pressure region is formed at the exit. This cause the vapor from the evaporator to be sucked into the ejector.

iii. The primary and secondary fluids then mix in the mixing section and undergo a pressure recovery process in the diffuser section. The combined stream flows to the condenser where it condenses. The heat of condensation Q_c is rejected to the environment.

iv. The condensate is divided into two parts, one is pumped back to the boiler and the other expands through an expansion valve to a low pressure state and enters the evaporators, where it is evaporated to produce the necessary cooling effect Q_e.

v. The ejector finally entrains the vapor, thus completing the cycle.

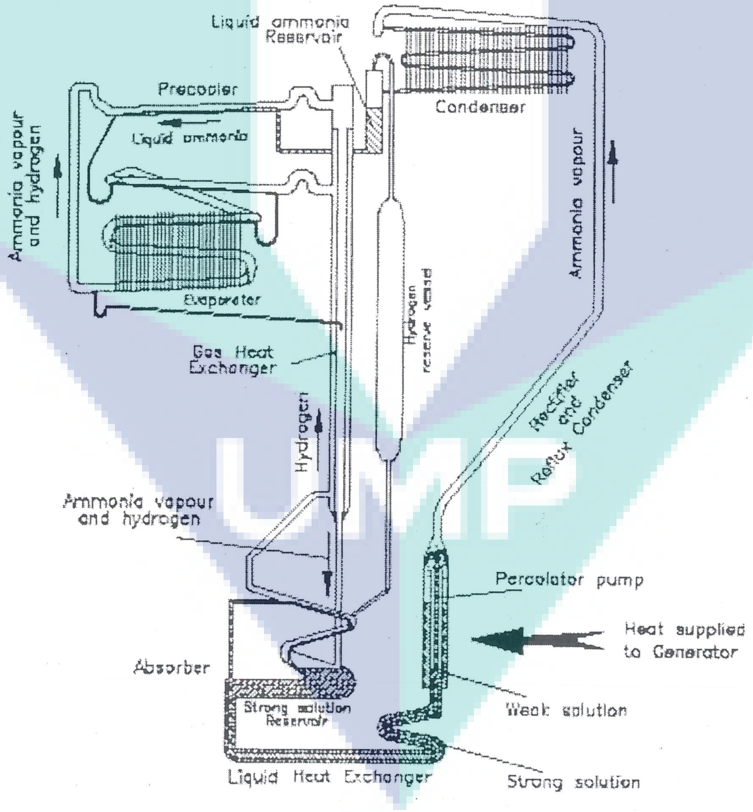

Figure 3.2: Absorption refrigeration system unit *(Bokelmann et al, 1983)*

In order to improve the system performance, a regenerator and a pre-cooler can be added to the cycle. The regenerator uses the sensible heat from the ejector exhaust to heat the condensate pumped by the circulation pump, before it flows into the boiler. The pre-cooler uses the cold vapor from the evaporator to cool the condensate before it enters the expansion valve.

3.3 Applications of Refrigeration System

In the industrialized nations and affluent regions in the developing world, refrigeration units are used chiefly to store foodstuffs. Most household refrigerators and freezers use vapor compression. Usually the refrigerant passes through chiller plates in the freezer section that contain coils. The refrigerant is partially evaporated and then continues to the main refrigeration compartment. Small fans circulate the cold air, which would otherwise settle at the bottom of the unit.

Water vapor from the main storage compartment tends to freeze on the cold chiller plates, causing a buildup of ice that reduces the cooling ability of the refrigerator. Thus, refrigerators require periodic defrosting in order to keep them working properly. This may be done manually by shutting off the refrigerator and either heating the cooling coils or allowing them to remain at room temperature until the ice melts. Automatic defrosting, or so-called frost-free, refrigerators heat the coils automatically at timed periods, usually by passing hot condenser gas to the coils or by rapidly adding heat from electrical resistors.

Refrigeration is also used to preserve foods in cold-storage warehouses until the food can be shipped to supermarkets and other stores. Temperatures are usually maintained at slightly above 32°F (0°C) to prevent the foods from actually freezing. In most cold-storage warehouses, an external refrigeration system cools a mixture of water and salt or water and antifreeze (Such a mixture has a lower freezing point than does pure water). The mixture is then circulated through pipes that run through the warehouse. Early refrigerated trucks, ships, and railcars that were used to transport foods and large blocks of ice cooled other materials. Today there are separate refrigerators for each storage compartment.

3.4 Absorption Chiller Systems

Similar to the vapor compression cycle, absorption chillers rely on a cycle of condensation and evaporation to produce cooling. The mechanical compressor of the vapor compression cycle is replaced by a heat source in the absorption chiller. It can be used with steam, natural gas, propane or heat exhaust gases for a heat sources to make it work.

There are two basic types of absorption chillers, direct and indirect-fired units. Direct-fired absorption chiller typically burns natural gas to generate heat to drive the cycle. Indirect-fired units use low-pressure steam, hot water or waste process heat. Single, double or triple effects classify absorption systems. Stages and effect refers to the number of generators in the given system. Direct-fired absorption equipment is limited to single and double effect. Double effect or two stage cycles are more effectively compared to the single effect system. Absorption refrigeration uses basically two working substances, these are refrigerant and absorbent. There are two systems available in the market, using lithium bromide/water as working fluids and using ammonia/water as other working fluids.

However, there are other elements that can be studied to enhance the performance of the absorption chiller system. The elements such as the working fluid composition, effect of additive and other fuel utilization can be considered to study the performance of the refrigeration system. One of the elements that will be studied in this project is working fluid composition. Various ammonia-water composition will be studied to get the optimum composition to obtain better system performance. Additive will also be studied in this research to examine the effects on the system efficiency and performance.

3.5 Zeolites

The term zeolite designates a variety of crystalline, hydrated and microporous aluminosilicates of general formula $M_{x/n} \bullet \left[(AlO_2)_x (SiO_2)_y\right] \bullet zH_2O$ with a framework structure based on a well-defined system of channels and cavities. This term was first proposed by the Swedish geologist A.F. Constedt in 1756 for a family of natural minerals whose main properties are the exchange of ions and a reversible desorption of water. Since then, more than 135 types of zeolites have been reported, either natural or artificial. According to the symmetry of the structure, zeolites are usyally classified with a three letter code given by the International Zeolite Association (IZA).

3.5.1 Framework structure

The basic elements of zeolite frameworks are TO_4 tetrahedra (T=Si, Al) linked each other through the oxygen atoms. According to the IUPAC, the description and classification of the topology of zeolites is based on the concept of larger units known as secondary building unit (SBUs) proposed by Meier in 1967. These can consist for instance of simple rings and prisms of various sizes. By combining such basic units, the known zeolite frameworks can be constructed. For instance, LTA consists of single 4 ring, 6 ring and double 4 ring(D4R), while FAU consists of single 4 ring, single 6 ring and double 6 ring (D6R). Alternative concepts are based on more complex chains or layer structures known as structural subunits (SSUs)

The various zeolite structures differ not only in the type and dimensionally of their pore systems, but also in the size of their pore apertus. According to these latter aspects, zeolites can be broadly classified as:

i) narrow pore (0.35-0.45 nm)
ii) medium pore (0.45-0.60 nm)
iii) wide pore (0.60-0.90 nm)
iv) super wide pore (> 0.90 nm)

Sodalite (SD) and zeolite A (LTA) can be catalogued as narrow pore zeolites, zeolite ZSM-5 (MFI) as medium pores size and zeolite X,Y (FAU) and modernite (MOR) as wide pore. The regular nature of these pores and their apertus, whose dimensions are of the same order of magnitude as the kinetic diameters of molecules as shown in Figure 2.1a, enables zeolite to behave as molecular sieves. This is an outstanding property that gives zeolites their value as selective absorbents for separating substances and shape selective catalysts.

Table 3.1 shows the type of zeolite and its pore system. Depending on it, the molecules can penetrate into the cavity system or can be excluded from it. Zeolite pores structure can be classified in two groups as shown in Figure 3.3b. While LTA and FAU type zeolites have super cages in their structures, MFI and MOR type have cylindrical structured pores. In addition, the cations required to compensate the negative structural charge due to the presence of AlO_4 occupy well- defined positions in the cavities or channels. Their nature and distribution throughout the zeolites structure is relevant in terms of their applications because the effective pore diameter of zeolites depends on the kind and number of cations present.

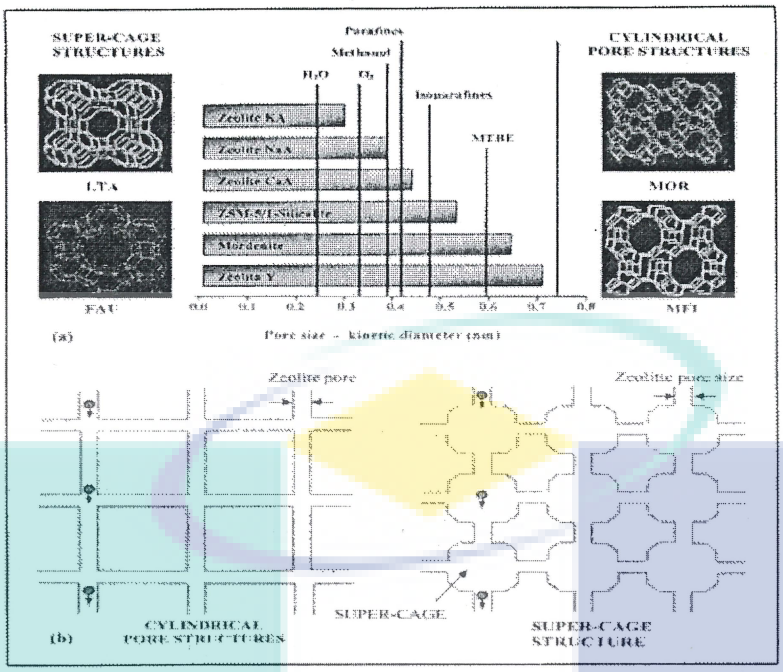

Figure 3.3: Framework structure of zeolite s. (a) Mean pore sizes of some zeolites and kinetics diameter of several molecules; (b) zeolitic pore structures

Table 3.1: Summary of the structural features of the main zeolites

Zeolite[1]	*Structure Type*[2]	*No. tetrahedra in the ring*	*Pore apertures [nm]*	*FD*[3]	N_T[4]	SiO_2/Al_2O_3 *molar ratio*
Zeolite A	LTA	8	0.41	12.9	24	2.0-6.8
Zeolite P	GIS	8	0.31 x 0.45 0.28 x 0.48	12.9	24	2.0-5.0
ZSM-5 / Silicalite-1	MFI	10	0.53 x 0.55 0.51 x 0.56	17.9	96	25 - ∞
Zeolite X Zeolite Y	FAU	12	0.74	12.7	192	2.0-3.0 3.0-6.0
Mordenite	MOR	12	0.65 x 0.70 0.26 x 0.57	17.2	48	9.0-35

[1] The dimensionality of zeolites A, P, X and Y is 3 and 2 for mordenite and ZSM-5. The density of these zeolites is in the range 1.9-2.3 g cm^{-3}

[2] Code used by the International Zeolite Association (IZA)

[3] Density of the structure in number of tetrahedral atom per Å^3

[4] Number of tetrahedral positions in a unit cell

3.5.2 Physical and chemical properties

Most of chemical and physical properties of zeolites are essentially determined by their framework aluminium content, which is usually expressed by the Si/Al or SiO_2/Al_2O_3 ratio. According to the Lowenstein rule (Barrer, 1982) Al-O-Al groups cannot occur in crystalline aluminosilicates and therefore a SiO_2/Al_2O_3 ratio < 2 is far impossible for zeolites. Each zeolite structure type exhibits a phase breadth with respect to the SiO_2/Al_2O_3 ratio. A distinction can be made between the zeolites as:

i. low silica ($SiO_2/Al_2O_3<4$)
ii. intermediate silica ($4<SiO_2/Al_2O_3<20$)
iii. high silica ($20<SiO_2/Al_2O_3<200$)

An increase in the silica content leads to an increasingly hydrophobic character, occurring the transition from hydrophilic to hydrophobic behaviour at a SiO_2/Al_2O_3 ratio ca. 20. The most hydrophilic zeolite is zeolite A (LTA) having a ration $SiO_2/Al_2O_3 = 2$, while the most hydrophobic is silicate -1 (MFI) having no aluminum in its structure. The SiO_2/Al_2O_3 ratio can be varied in some range, keeping the structure almost the same. For example, the zeolite with FAU structure having SiO_2/Al_2O_3 ratio aroung 2-3 is called zeolite X, while that with a ratio 3-6 is called zeolite Y.

The surface selectivity of zeolites as adsorbents also depends on the SiO_2/Al_2O_3 ratio. Aluminum rich zeolites preferentially adsorb strongly polar molecules, and are therefore widely used as drying agents. Furthermore, due to the mobility of cations in their cavities and channels, zeolites exhibit ionic conductivity, which depends on the diameter of the channels, the nature and concentration of the cations in the structure and the water content. This property is of high importance, because it makes them suitable for applications as ion exchangers.

As a general rule, zeolite are thermally stable up to 1000 K and they also show a high hydrothermal stability, namely the ability to retain structure without undergoing any phase transformation in the presence of water vapor. Strong acids decompose low silica zeolites such as NaA and NaX by dissolving the aluminum atoms out of the framework, with the consequent breakdown of the crystal structure. By increasing the SiO_2/Al_2O_3 ratio, zeolites become less sensitive to dealumination by acids, being high silica zeolites structurally stable even in a strong mineral acidic environment. On the other hand, aqueous alkalis lead to phase transitions in high aluminum zeolites and to dissolution in very high silica zeolites.

3.5.3 Zeolite A

According to the IUPAC, zeolite A belongs to the LTA group (Linde Type A). The fully hydrated Na-exchanged LTA structure, of general formula $Na_{12}(Si_{12}Al_{12}O_{48}) \bullet 27H_2O$ is built up by truncated cubo-octahedron units known as sodalite or β-cages (diameter 0.66 nm), which are linked together via the cubic D4R unit to form larger cavities α-cages (diameter 1.23 nm) with the shape of a trubcated cubo-octahedron as shown in Figure 2.3. The structure are interconnected by windows formed by rings consisting of 8 atoms either Si or Al of 0.41 x 0.41 nm generating a uniform 3D pore system according to the cubic system at which zeolite NaA crystallizes. When fully hydrated, the α-cages and β-cages have space for 20 and 4 water molecules respectively, while the 8 rings contains 3 molecules of water.

The general physical and chemical properties of zeolite NaA are summarized in Table 3.2. Because of zeolite A is a low silica content zeolite, its framework is rich in sodium ions. Therefore, zeolite A presents a high ionic conductivity and a high ion exchange capacity, but it is not stable in acid and alkaline environments because it can suffer from dealumination. Furthermore, zeolite A shows a hydrophilic character namely, it tends to adsorb polar molecules in particular water. The aluminium positions show an acid nature as shown in Figure 3.4.

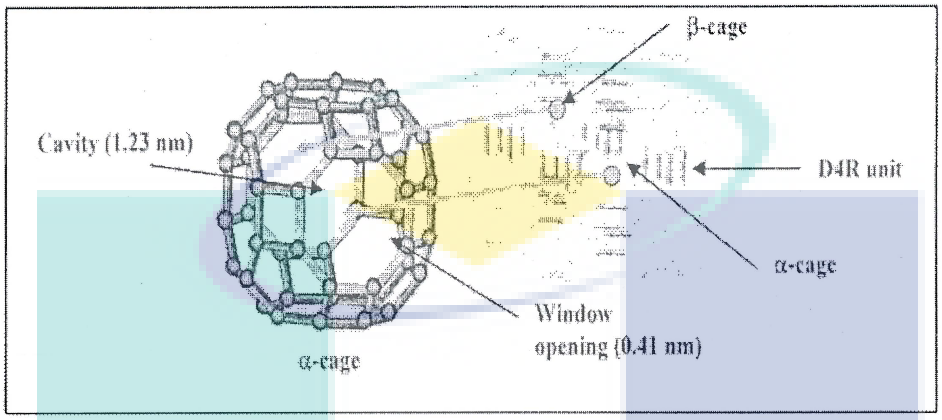

Figure 3.4: Unit cell of the structure LTA

Table 3.2: Chemical and Physical properties of Zeolite NaA

FORMULA		$Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]\cdot 27H_2O$
COLOR		White
DENSITY		~2.00 g cm^{-3}
STABILITY	Thermal	< 933 K
	Chemical	To acid ⇒ It dissolves at a pH <6 To alkali ⇒ Phase transition to hydroxysodalite
SOLUBILITY		Negligible
pH IN AQUEOUS SOLUTION		9 – 12 (partial hydrolysis)
SiO_2/Al_2O_3 RATIO		2.0 – 6.8
ION-EXCHANGE		> 160 mg CaO/g dry zeolite NaA (20°C)

Zeolite A is directly used as additive in detergents and constitutes the essential material of a great variety of adsorbents which are used in many separation and purification processes. The position f sodium ions in the cages are important because they act as adsorption sites. Among the total number of sodium atoms in a unit cell, 12, 8 of them are placed inside the α-cages, while the other 4 are placed in the β-cages. Therefore, α-cages play a more important role than β-cages in the adsorption process of small molecules.

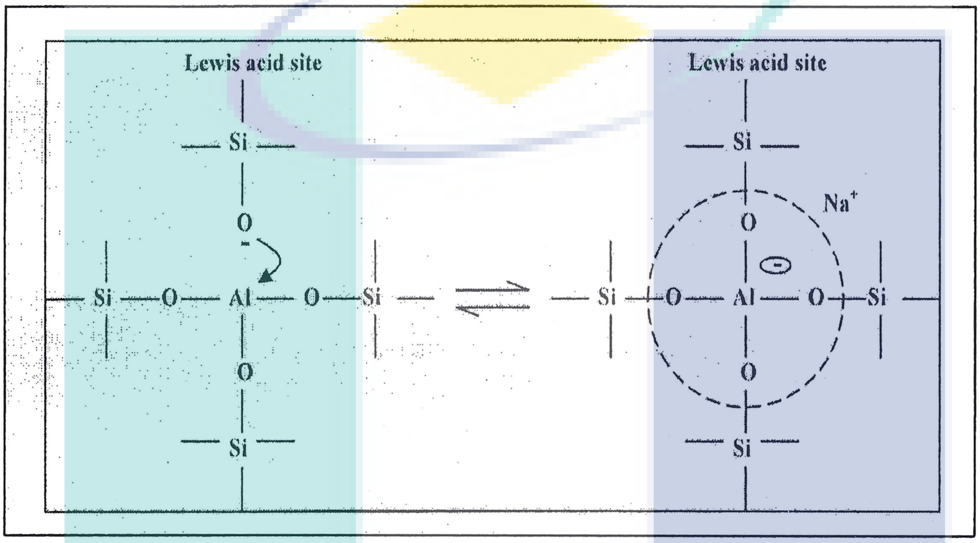

Figure 3.5: Representation of the acid sites of Zeolite NaA

3.5.4 Applications of zeolites

The most relevant applications of zeolites are related to their adsorptive and ion-exchange properties. In this way, zeolites are generally employed as:

i. Detergent additive: Zeolite NaA constitutes the most extended zeolite in use due to its high ion exchange behaviour which enable it to capture and remove ions from water responsible for its hardness and also trace ions of heavy metals. This zeolite has allowed the substitution of phosphate additive in detergents for hardness reduction, because they are unsuitable due to environmental reasons

ii. Adsorbents: Zeolites are relevant industrial adsorbents with a widespread field of applications not only in the adsorption of species but also in separation and purification processes due to high selectivity. Zeolite A and X are the most employer zeolite in adsorption processes both in gaseous and liquid phases. Their main application in this field are the following ones:

a) adsorption of water from gaseous and liquid streams with zeolite A and Y
b) air and gas purification : removal of CO_2, H_2S, dioxins with zeolite A, X and Y
c) separation of mixtures: O_2/N_2, xylene isomers with zeolite A and X

iii. Catalyst: Except for zeolites A and X, which are not suitable in acidic conditions, zeolites can be transformed into the acidic form, exhibiting Lewis acidity which confers them catalytic activity. Furthermore, zeolites show shape selectivity when their pore size are similar to the kinetic diameters of the molecules. Zeolite catalysts are mainly used in the following four industrial fields:

a) oil refining
b) gas conversion
c) petrochemistry
d) environmental protection

3.6 History of Refrigeration System

Gas absorption was known as early as 1770. Absorption refrigeration originated in 1824 by Faraday, who proved that certain gasses, which were believed to exist only in, vapor form could be liquefied. One of these gasses was ammonia, which could be absorbed, in vast quantities by silver chloride crystals. His apparatus consisted of a closed inverted "V" tube, which contained in one end the ammonia silver chloride crystals, Figure 3.3. That end of the tube was heated and the opposite end cooled with water. Soon the ammonia gas was released from the compound and liquid ammonia appeared in the cool end of the tube. When he removed the heat and the water container, he observed that the liquid began to boil violently changing again into vapor and at the same time the crystals reabsorbed the ammonia vapor. The region of the apparatus containing the liquefied ammonia was intensely cold as the ammonia drew heat from its environment in order to evaporate *(Althouse, 1943)*. Faraday's experimental apparatus was the first absorption machine of the intermittent type.

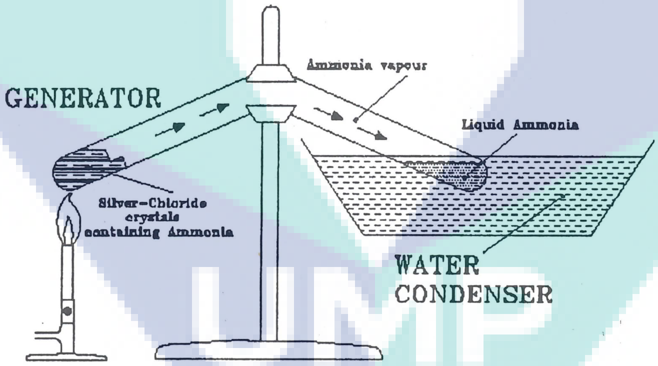

Figure 3.6: Faraday experimental apparatus *(Althouse, 1943)*

The first continuously working absorption refrigeration system using sulphuric acid and water as absorbent and refrigerant respectively was invented by Carrè in 1859, who in the same year, operated the first ammonia-water absorption refrigerator. His system consisted of components capable of assisting the refrigerant through a continuous cycle, as shown in Figure 3.4

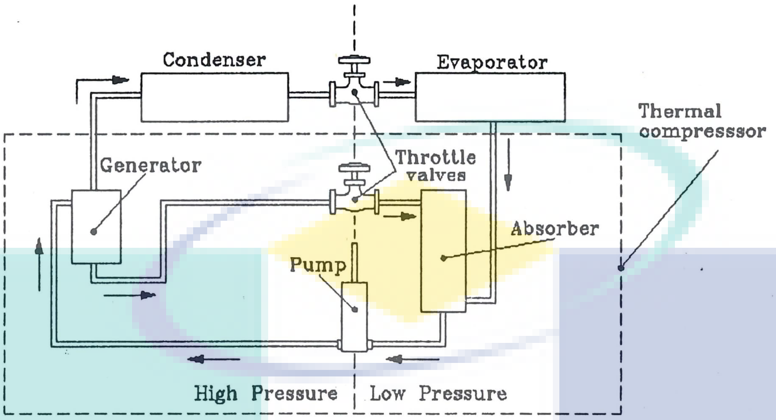

Figure 3.7: Schematic arrangement of the simple two-fluid absorption cycle *(Bokelman, 1983)*

The refrigerant enters the evaporator where it evaporates at low pressure and temperature by drawing heat from the environment. The vapor leaving the evaporator is absorbed in a liquid, which has high affinity for the refrigerant and transferred via a liquid pump into the boiler or generator. There, heat is applied which reduces the affinity of the liquid, and drives off the refrigerant vapor at high pressure, which then passes to the condenser to be liquefied.

The liquid refrigerant enters the evaporator again and the cycle is repeated. The remaining liquid in the generator, which is weak in refrigerant, passes through a throttling valve in the absorber to receive new vapor refrigerant. After it has been enriched, it flows through its own cycle. Since the generator, solution throttle valve, absorber and pump are involved in compressing the refrigerant vapor by thermal action; they are called the "thermal compressor".

Early in the 20th century the idea and the application of the absorption system was shelved, mainly due to its high power consumption, giving ground to the development of the fully enclosed ammonia compression refrigeration. In other words, the thermal compressor was substituted by the mechanical compressor, which was placed there to withdraw the refrigerant vapor from the evaporator and then to compress it. In all other respects, the refrigeration cycle is identical in both systems

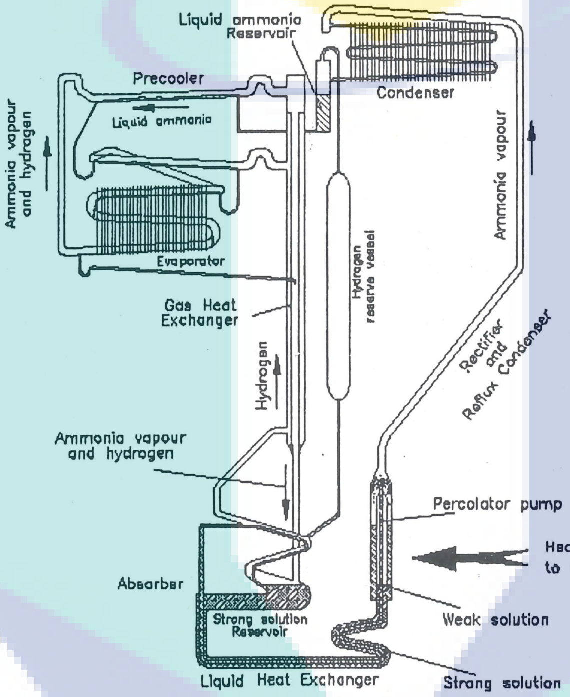

Figure 3.8: Line diagram of the three-fluid absorption refrigeration unit *(Bokelman, 1943)*

Absorption refrigeration was revived again around the 1930's with the invention of the so called "candle fridge", Figure 3.5, by the two Swedish researchers, B. Von Platen and C. Munsters. It is a domestic-size, three-fluid system (refrigerant, absorbent and a pressure equalizing inert gas), the cycle of which is based on the theory of partial pressures. To boil the refrigerant off the solution, the system used initially the heat from paraffin or a gas burner *(Bokelman, 1983)*. It was further developed to utilize gas, as well as either a 12V, 120V or 240V supply, but still only for domestic purposes.

The main reason for its limited size is due to the solution pumping arrangement, which relies upon a percolator-type pump. This pump brings the generator's solution into a higher level and thereafter the fluid circulation depends upon potential levels. Since medium and large scale industrial refrigerators require large and definite amounts of fluid flow, the percolator type pump cannot meet the requirements. A further drawback to the potential level flow is its inability to survive movement and inclination, as this would disturb the fluid levels.

Despite this ingenious development by the two Swedish researchers, the absorption unit has acquired a bad reputation due to the irresponsible craftsmanship of various manufacturing firms and due to lack of understanding of the absorption behavior. The development was mainly through a trial and error construction with a minimal backing of theoretical knowledge *(Stierlin, 1981)*

Studies in the last two decades improved the absorption refrigerator and showed that the unit is capable of meeting the demands of the modern refrigeration industry. Indeed, refrigeration units of cooling capacity in the order of 2 to 5MW exist in some parts of the world, which by far exceed the maximum capacity obtained by a single vapor compression refrigerator *(Jordan, 1977).*

For example, there are two absorption refrigeration installations each capable of 22.1MW cooling capacity at -5°C evaporator temperatures. These were built in 1981 for the former USSR, by BORSIG GmbH, Berlin *(Holdrof, 1981).* They are both powered by superheated steam and are used to cool by-products from the process of synthetic un-vulcanized rubber (caoutchouc). Unfortunately, there is no performance reports published.

3.7 Powering Methods of the Absorption Cycle

The absorption cycle could use a low-grade heat source, in the temperature range of 70 °C to 120 °C. Sources of low-grade heat are numerous, as for example, solar energy, low-pressure steam, flue and exhaust gases, geothermal, etc. These sources of energy are available; at least some of them at minimal cost and their utilization have obvious advantages.

A number of countries have launched research programme to convert solar energy into heat, to power absorption type refrigerators, air-conditioners and heat pumps directly.

Lazarin (1988) has published results of a two-year experiment in North Italy, describing how solar energy was used, either directly or stored, in order to create a working temperature environment for an ammonia-water absorption heat pump. The plant was provided with a seasonal storage, so that useful solar heat could be collected by solar collectors all year round and used when the solar energy was poor or non-available. The earth storage was connected with an energy roof installation and alternated in providing the cold source between the winter and summer months. The performance of the plant was anything but satisfactory.

The main source of inefficiency was the poor heat exchange between the ground and the earth storage components and even greater, the low performance of the absorption heat pump within the experimental working temperatures.

Exell (1984) published their work on mathematical modeling of an intermittent ammonia-water absorption refrigerator powered through flat solar collectors. Their results show that for the climate of Thailand, the average daily yield of ice should be 3.2 kg per m^2 of collector.

Agarwal (1983) reported on results from a laboratory model of a solar powered intermittent refrigeration system-using refrigerant R22 and DMF (Dimethyl Formamide), capable of cooling 60 kg of water daily from 30°C to 15°C. In the month of July the average refrigeration temperature was 5°C for about 1.5 hours, while in January the average temperature was maintained at -3°C for a period of 3 hours.

Their proposed water-cooler system uses a water-cooled condenser during daytime vapor generation and a water-cooled absorber during night time. From the performance specifications it could be deducted that their intermittent refrigeration unit requires enormous amounts of cooling water to produce the required effect. On the other hand, the authors claim that the importance of an intermittent system lies in its simplicity of its operation on, account of the combined use of the solar collector as generator and absorber. However, in their design the two components are independent and separate so as to overcome the problem of cooling. This results in a sequence of opening and closing of control valves at sunset and in the early hours of the morning. If this sequence is automated their unit could require the usage of high forms of energy.

Professor I. Borde of Israel, advisor of GALIL Advanced Technologies gives evidence about the development of an absorption refrigerator utilizing waste heat and solar energy, to provide refrigeration in the range of 0°C to -3°C. According to the report, a "novel" combination of working fluids was used, with the intention of moving away from the conventional ammonia-water system. Without the constituents of the refrigerant-absorbent pair being revealed, it is stated that the refrigerant belongs to the "FREON" group and the absorbent is an organic liquid solvent. Subsequent papers by the same author report on hydrogenated chlorofluorocarbons and Dimethyl Formamide (DMF) or Tetraethylene Glycol Dimethyl Ether (TEG.DME) combinations.

The project was for a 250 ton capacity refrigeration plant, to be used in agricultural centre. The company produced an analysis, which compares the proposed absorption refrigerator to the vapor compression refrigerator, showing the former to be about 60% more economical in the machinery set-up and service, and about 50% more economical in power consumption.

Alvares and Trepp (1987) from the University of Brazil report on a mathematical model of a solar driven aqua-ammonia absorption refrigeration system. The modeling was done in such a way that the coefficient of performance (COP) could be calculated with the components of the system being able to be "turned on" or "turned off" or varied in characteristics. In this way thirteen absorption cycles were studied in the search for the optimum coefficient of performance. The cycle, which gave the highest performance, was that which had the highest refrigerant concentration, and included a solution heat exchanger and a vapor-liquid heat exchanger (pre-cooler). The COP achieved by this cycle was 0.602.

Kaushik and Bhardwaj (1982) from the Indian Institute of Technology investigated an ammonia water absorption cycle for solar refrigeration, heat pump, and air conditioning operations. With the aid of a numerical analysis, it was found that at high generator temperatures the COP was reduced. It was also shown that an increase of condenser's temperature improves the performance at higher generator temperatures. In a subsequent paper by *Kaushik, Kumar and Chandra (1985)* a study is presented of a cascade system of two absorption refrigerators powered by separate solar collectors. Their system could achieve lower evaporator temperatures than the single stage absorption refrigerator, but the overall COP is lower than that of the single stage.

El-Shaarawi and Ramadan (1986) from Al-Azhar University in Egypt manufactured and tested an intermittent solar absorption refrigerator. Their paper describes the construction of the refrigeration unit as well as the solar collectors. The experimental data compare favorably with the proposed theoretical model.

Al-Marafie, Suri and Maheshwari (1988) from the University of Kuwait, analyzed in a techno-economic study three cycles: an absorption system powered by flat plate solar collector, an absorption system powered by a solar pond and a vapour compression refrigerator powered either directly through the network or through solar photovoltaic collectors. Their results show that while the flat plate solar collector was not economically viable, the solar pond showed a promising and attractive alternative. On the other hand solar photovoltaic cells could become competitive in the future only if their unit cost drops drastically.

The above mentioned publications indicate that it is a world wide tendency to utilize the most abundant source of energy for refrigeration and air-conditioning purposes and it is for this reason that the research on absorption refrigeration, inclines towards utilizing solar energy. However, the efforts are focused on refining the solar panels and the solar generator. Studies on the steam-powered absorption cycle and on the refinement of the thermodynamic analysis of the absorption refrigeration cycle itself have been neglected. The steam-powered absorption refrigerator is being regarded as a "standard absorption system" and is only reexamined if other machinery and cycles are incorporated.

This approach of investigation was adopted by *Agarwal et al. (1987)* from the Indian Institute of Technology, who analyzed with the aid of computers a combined refrigeration cycle. The cycle consisted of a vapor compression refrigerator, the compressor of which was powered by a steam turbine, and an absorption refrigerator powered by the exhaust steam of the turbine. Amongst other performance observations, they praise that the proposed system as a whole, was superior to the absorption system alone. This conclusion however, is erroneous, as the performance of the vapor compression refrigerator and that of the absorption refrigerator cannot be compared, let alone when the absorption cycle is compared with a whole combined cycle.

Beasley and Hester (1988) from University of Clemson, USA proposed a study for a pressure driven absorption cycle. The cycle utilizes a semi-permeable membrane to separate the refrigerant from the absorbent. The flow of refrigerant across the membrane is achieved by a pressure differential in excess of the osmotic pressure. Since the refrigerant is separated in a, liquid form and also in the absence of heat, there is no need for a condenser. The proposed system is only a theoretical model, as the performance of the membrane is unpredictable. But on the other hand, the predicted coefficients of performance reach values matching the vapour compression cycle.

3.8 Principle of Operation

The working fluid in an absorption refrigeration system is a binary solution consisting of refrigerant and absorbent. In Figure.3.9 (a), two evacuated vessels are connected to each other. The left vessel contains liquid refrigerant while the right vessel contains a binary solution of absorbent/refrigerant. The solution in the right vessel will absorb refrigerant vapor from the left vessel causing pressure to reduce. While the refrigerant vapor is being absorbed, the temperature of the remaining refrigerant will reduce as a result of its vaporization.

This causes a refrigeration effect to occur inside the left vessel. At the same time, solution inside the right vessel becomes more dilute because of the higher content of refrigerant absorbed. This is called the "absorption process". Normally, the absorption process is an exothermic process; therefore, it must reject heat out to the surrounding in order to maintain its absorption capability. The refrigerant must be separated out from the diluted solution.

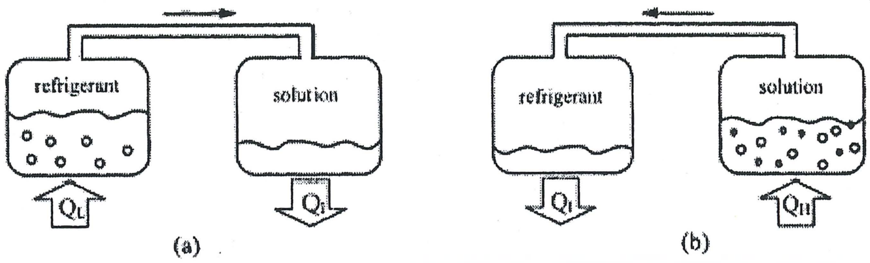

Figure 3.9: Principle of operation (a) Absorption process occurs in right vessel causing cooling effect in the other; (b) Refrigerant separation process occurs in the right vessel as a result of additional heat from outside heat source. (*Srikhirin 2001)*

Heat is normally the key for this separation process. It is applied to the right vessel in order to dry the refrigerant from the solution as shown in Figure. 3.9(b). The refrigerant vapor will be condensed by transferring heat to the surroundings. With these processes, the refrigeration effect can be produced by using heat energy. However, the cooling effect cannot be produced continuously as the process cannot be done simultaneously.

Therefore, an absorption refrigeration cycle is a combination of these whole processes as shown in Figure 3.10. As the separation process occurs at a higher pressure than the absorption process, a circulation pump is required to circulate the solution.

Coefficient of Performance of an absorption refrigeration system is obtained from;

$$COP = \frac{cooling\ capacity\ obtained\ at\ evaporator}{heat\ input\ for\ the\ generator + work\ input\ for\ the\ pump}$$

The work input for the pump is negligible relative to the heat input at the generator; therefore, the pump work is often neglected for the purposes of analysis.

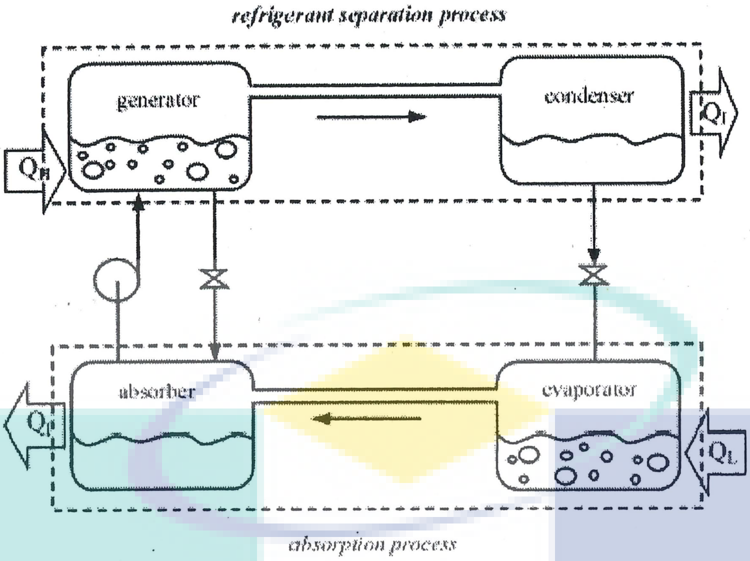

Figure 3.10: A continuous absorption refrigeration cycle compose of two processes *(Srikhirin,2001)*

3.9 Working Fluid for Absorption Refrigeration System

Performance of an absorption refrigeration system is critically dependent on the chemical and thermodynamic properties of the working fluid *(Perez-Balnco, 1984)*. 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 following are desirable *(Holmberg, 1990)*

- 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.

- 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 (1988)* suggests that, there are some 40 refrigerant compounds and 200 absorbent compounds are available. However, the most common working fluids are Water/NH_3 and LiBr/water.

Since the invention of an absorption refrigeration system, water NH_3 has been widely used for both cooling and heating purposes. Both NH_3 (refrigerant) and water (absorbent) are highly stable for a wide range of operating temperature and pressure. NH_3 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 NH_3 is 77°C. Since both NH_3 and water are volatility, the cycle requires a rectifier to strip away water that normally evaporates with NH_3. 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/NH_3 is environmental friendly and low cost. Thermodynamic properties of watre/NH_3 can be obtained from *Sonntag (1990)*. The use of LiBr/water for absorption refrigeration systems began around 1930 *(Berenstneff, 1949)*. 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. Thermodynamic properties of LiBr/water can be obtained from standard reference books. Some additive may be added to LiBr/water as a corrosion inhibitor *(Wen and Lim, 1992)* or to improve heat-mass transfer performance *(Chang, 1971)*.

Although LiBr/water and water/NH_3 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 *(Aphornratana, 1995)*. The two solvents, which have stood out are Dimethyl Ether of Tetraethylene Glycol (DMETEG) and Dimethyl Formamide (DMF).

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 *(Best and Holland, 1990)*. 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+$ZnBr_2$/water can improve the solubility of the solution. Various ternary mixtures have been tested for using with an absorption system *(Idema, 1987, Herold, 1991, Barragan, 1998)*.

3.10 Function of the Main Component in Absorption Refrigeration System

3.10.1 Generator

A precise heat is applied to the boiler to begin operation. Heat is transferred from the outer shell of the boiler through the weak ammonia solution to the perk tube. This style of boiler is referred to as the new style boiler. The old style boiler had the heat element holder and chimney connected directly to the perk tube, without the benefit of the outer shell to slow over heating in situations like being run out of level.

The perk tube is provided with a rich ammonia solution from the absorber tank. When heated, the ammonia in the rich ammonia solution begins to vaporize creating bubbles and a percolating effect. The ammonia vapor pushes the now weakening solution up and out of the perk tube. The ammonia vapor leaving the perk tube goes upward towards the top of the cooling unit, passing through the rectifier. The rectifier is just a slightly cooler section of pipe that causes water that might have vaporized to condense and drop back down. The water separator at the top of the cooling unit prevents any water that might have escaped the rectifier to condense and fall back. After this point, pure ammonia vapor is delivered to the condenser.

Meanwhile, back at the perk tube, the weaker solution expelled from the perk tube by ammonia vapor drops into the weak ammonia solution surrounding the perk tube. Here, a little more ammonia vapor is generated and rises. The weak ammonia solution flows downward and through the outer shell of the liquid heat exchanger, where heat is transferred to the rich ammonia solution on its way to the perk tube. The weak ammonia solution then flows to the top of the absorber coils and enters at a cooler temperature.

3.10.2 Condenser

Ammonia vapor enters the condenser where it is cooled by air passing through the metal fins of the condenser. The cooling effect of the condenser coupled with a series of step-down in pipe size forces the ammonia vapor into a liquid state, where it enters the evaporators section.

3.10.3 Evaporator

Liquid ammonia enters the low temperature evaporator (freezer) and trickles down the pipe, wetting the walls. Hydrogen, supplied through the inner pipe of the evaporator, passes over the wetted walls causing the liquid ammonia to evaporate into hydrogen atmosphere at an initial temperature of around -20°F. The evaporation of the ammonia extracts heat from the freezer. At the beginning stages, the pressure of the hydrogen is around 350 psi while the pressure of the liquid is near 14 psi. As the ammonia evaporates and continues to trickles down the tube, its pressure and therefore its evaporation temperature rise.

The liquid ammonia entering the high temperature evaporator is around 44 psi, while the pressure of the hydrogen has dropped to 325 psi. Under these conditions, the evaporation temperature of the liquid ammonia is 15°F. Heat is removed from the refrigerator box through the fins attached to the high temperature evaporator. The ammonia vapor created by the evaporation of the liquid ammonia mixed with the already present hydrogen vapor, making it heavier. Since the ammonia and hydrogen vapor mixture is heavier that the purer hydrogen, it drops down through the evaporators through the return tube to the absorber tank.

3.10.4 Absorber

Ammonia and hydrogen vapor mixture enters the absorber tank through the return tube; much of the ammonia vapor is absorbed into the surface of the rich ammonia solution which occupies the lower half of the tank. Now lighter, the ammonia and hydrogen mixture begins to raise up the absorber coils. The weak ammonia solution tricking down the absorber coils from generated by boiler is for the ammonia vapor rising up the absorber coils with the hydrogen. This weak ammonia solution eventually absorb all the ammonia form the ammonia and hydrogen mixture it rises allowing pure hydrogen to rise up the inner pipe of the evaporator section and once again passing over the wetted walls of the evaporator. The absorption process in the absorber section generates heat which is dissipated.

CHAPTER 4

METHODOLOGY

4.1 Introduction

Currently commercially available gas absorption refrigerators are used for freezer unit in the housing and office area. However, such units are only available in certain areas in Malaysia. Such available units are now running with electrical power. The absorption refrigerator commonly used ammonia (NH_3) as the refrigerant and chilled water as the second medium or absorbent.

The system in this research is operated by electrical power. In order to carry out to experiments, the system was modified accordingly. To carry out the first task, some changeable will be made to the system to adjusting for the testing. In this research, additives are added to the system for the purpose of boosting its performance.

A series of experimental works is carried to ensure a high reactivity and stability for the chiller system performance. The experimental works can be divided into four major phases, which are:

a) Experimental rig setup.
b) Overall system testing.
c) Performance testing
d) Performance analysis study

After the experimental rig setup was finished, an overall system test was done to ensure that there is no leaking in the piping line area. The experimental rig uses ammonia-water as the working pair of refrigerant-absorbent and electricity and liquefied petroleum gas (LPG) as the energy sources. The overall experimental methodology is shown in Figure 4.1.

The first stage of this experimental work is the preparation of ammonia/water ratio base on volume. Detail calculation and assumption in order to prepare the solution refer to Appendix A.1. Then, the prepared solution was placed in the absorber vessel gas absorption refrigeration unit (model: RF 10). Next, general operating procedure and equipment verification procedures is followed. Then, data collection method of gas absorption refrigeration unit is used (refer chapter 4.5.5). All procedures above are repeated for the next sample of ammonia/water ratio. Finally, the value of coefficient of performance (COP) each sample is calculated and the graph is plotted.

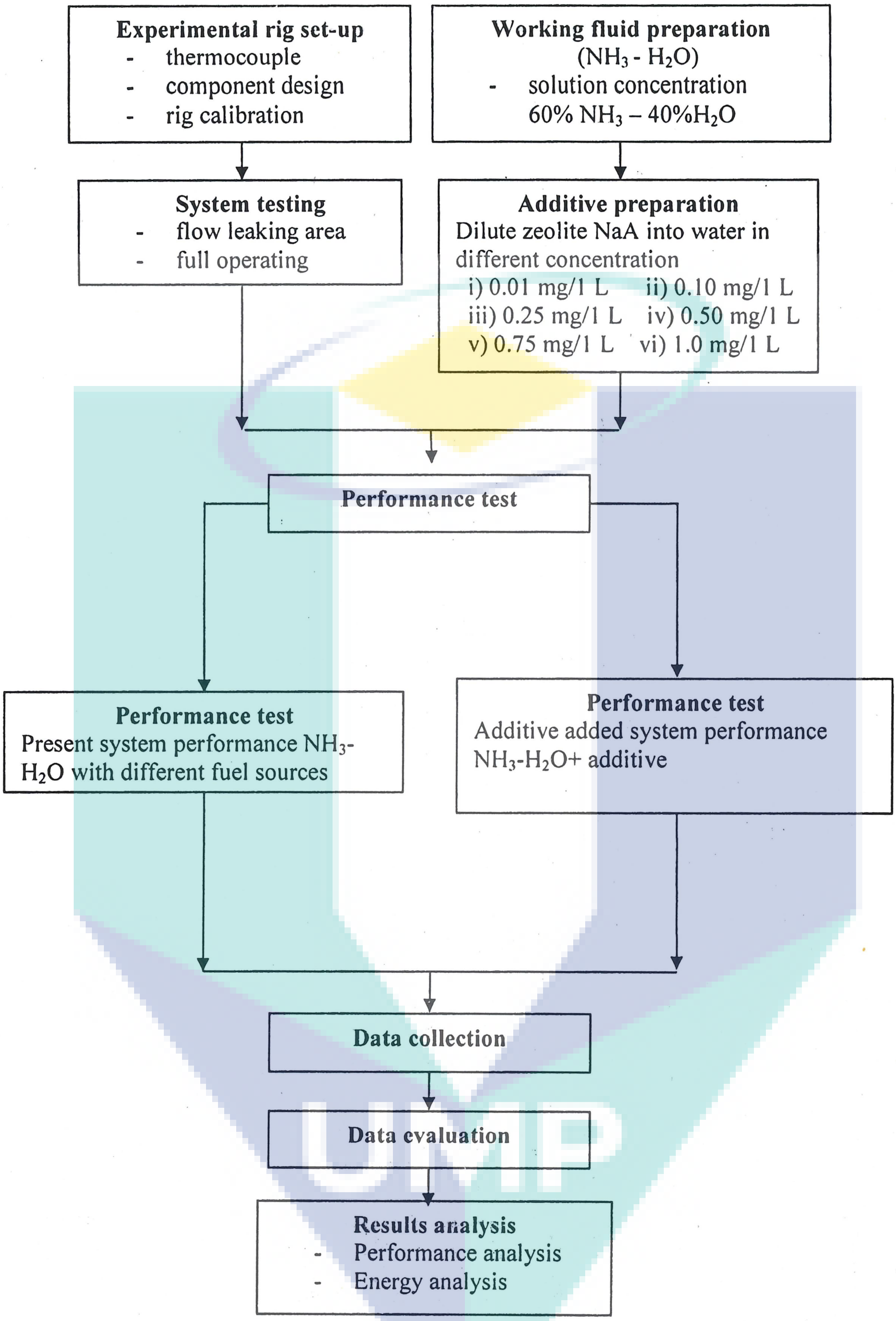

Figure 4.1: Flow chart of overall experimental work

4.2 Materials

4.2.1 Refrigerant

Ammonia is used as a refrigerant for this system testing. The ammonia vapor is the best refrigerant for now that can give the better performance for the system. Ammonia has a saturated liquid temperature at an atmospheric pressure (1.0132 bar) of $t_s = -33.4°C$. Its density, at temperature of 273 K, approximately is ρ=638 kg/m^3. Ammonia vapor is colorless and has a strong unpleasant odor, as well as irritable effects on mucous membranes, especially of the eyes. Ammonia may be recognized in the surrounding air at a concentration of 46.6 pm volume. However, at a concentration of 0.5%, it is dangerous to rest in a closed, unventilated room longer than half an hour.

Ammonia has a very good thermodynamic efficiency and the cost for the refrigerant is lower than the cost for HFCs and HCFCs. Ammonia is flammable and at concentration in the air of 16-26 % volume it is explosive. Ammonia is not miscible with oil. Its separation is easy because oil density at a temperature of 273 K is 900 kg/m^3 higher than the density of a liquid refrigerant. Ammonia is highly corrosive to zinc, copper and their alloys. Large concentrations of ammonia easily dissolve in water. At ambient pressure and temperature, one liter of water may dissolve 700 liters of 0.5 kg of gas ammonia. This property of ammonia makes it suitable for application in absorption refrigeration system.

Table 4.1: Properties of available refrigerants. *(Wilson, B. 1996)*

Refrigerant	Reference number	Boiling point	Ozone depletion potential (ODP)	Global warming potential (GWP)	Atmospheric life
CFC	R11	24°C	1	1	55
	R12	-30°C	1	3.05	11.6
HCFC	R22	-41°C	0.05	0.34	15.3
CFC/HCFC	R502	-45°C	0.23	4.01	55
HFC	R134a	-26°C	0	-	-
CO_2	R744	-78°C	0	-	-
Ammonia	R717	-33°C	0	-	-

Table 4.2: Criteria for ammonia application in refrigeration system. *(Cerepnalkovski, 1991)*

Criterion	Single stages	Double stages	Triple stages
Evaporating temperature (°C)	0 to – 30	-30 to – 66.8	-66.8
Condensing temperature (°C)	≤ 40	40 – 20	20
Compression ratio ρ_c/ρ_o	≤ 8	< 64	< 64
Pressure difference (ρ_c-ρ_o) bar	≤ 12	$\rho_{02}-\rho_{01} < 12$	$\rho_{02}-\rho_{01} < 12$

Table 4.3: Thermo physical properties and hazardous properties of ammonia

Product : Ammonia Formula : NH3 State : Liquefied gas	
Thermo physical properties	
Molecular Weight	17.03
Vapor Pressure at 70Â>	114
Specific Gravity at 70Â° F (1 atm)	0.6
Critical Temp (Â°F)	270.4
Critical Pressure (psia)	1639
Specific Volume (cf/lb)	22.6
Heat Capacity (Btu/lb.-Mole Â°F)	8.6
Hazardous properties (Flammability)	
Flammable limits in Air (Vol. %)	15-28
Ignition Temp., (Â°F)	1024
Physiological Properties	Corrosive and Toxic
Threshold Limit Value (ppm)	25

*Above critical temperature @ 21.1 Â°C. SA-Simple asphyxiant

4.2.2 Energy sources.

The system used electrical power and also LPG to operate. This is because; the comparison on the system performance will be done for the both energy sources. It is so easy process done by electrical heating compared to gas burner using liquefied petroleum gas as energy sources but when going to the performance aspect that will see some conclusion to be made.

4.2.3 Zeolite as an additive

Zeolites a re usually formed as powder of micrometer size by spontaneous nucleation growth in a synthesis or solution under hydrothermal conditions, although crystals up to 5 nm can be produced under special conditions. The synthesis gel/solution usually contains the silicate and aluminates precursors, an alkaline component, water and might also included a structure directing agent (SDA) which is sometimes referred in the literature as template. The use of SDA is necessary to synthesis zeolites with high SiO_2/Al_2O_3 ratios, which must be subjected to a calcinations step after their preparation to remove water and the SDA filling the zeolite pores.

Figure 4.2 shows schematically the general mechanism of zeolite synthesis. The synthesis gel is constituted by a number of long-chain polymers and cycles formed the polymerization of the aluminates and silicate precursors. The composition and structure of the hydrated gel are strongly dependent on the shape and structure of the polymerizing species. In the process of crystallization of the gel under hydrothermal conditions, the alkaline ions and the aluminates and silicate chains react and tend to build free TO_4 units. The nature of the final zeolite obtained is strongly determined by the synthesis conditions namely by the kind of precursors used as reactants, their concentration, the pH, the synthesis time and the temperature

One of the main characteristics of the synthesis zeolites is the existence of an induction period, namely the presence of a time at the beginning of the synthesis with no detectable crystal formation. The rate of nucleation ang growth of crystal is often described by a population balance model (Barrer, 1982). The crystal size shows a linear increase with the synthesis time, while the crystallinity of zeolites shows a S-shaped curve. Higher pH or temperature or aging results in shorter crystallization time.

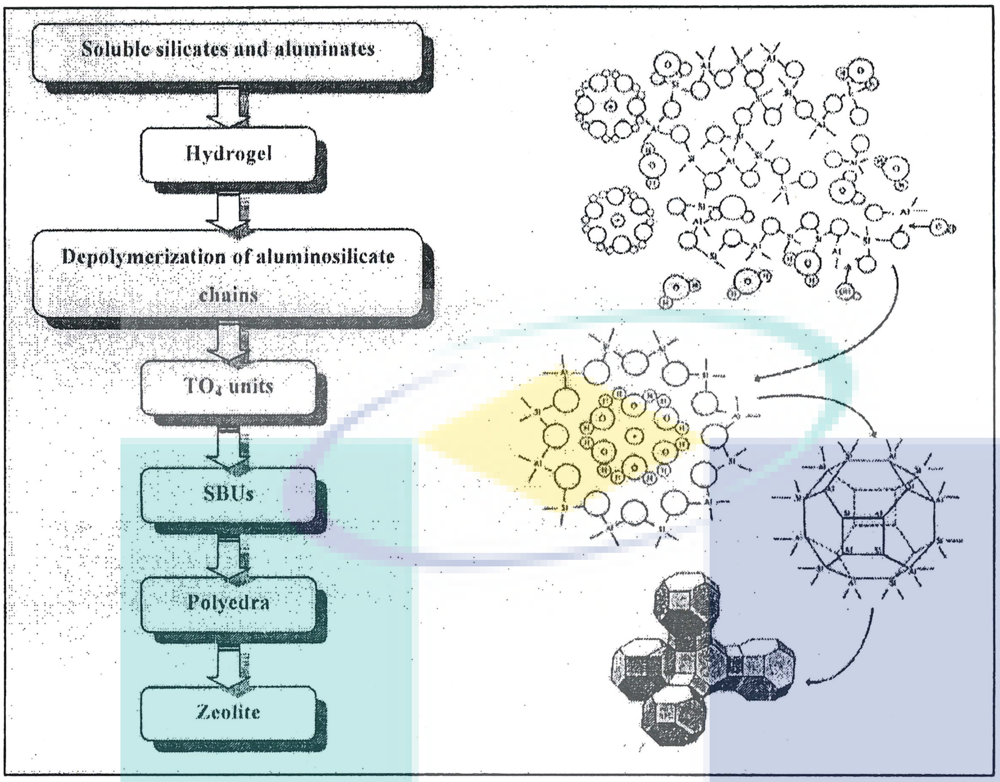

Figure 4.2: Scheme of the step involved in zeolitilization process

4.3 Preparation of Zeolite NaA

a) Type Material

i. $Na_{12}[(AlO_2)_{12}(SiO_2)_{12}] : 27\ H_2O$

b) Source Materials

i. deionized water
ii. sodium hydroxide (Fisher Scientific, 99+% NaOH)
iii. sodium aluminate (Fisher Scientific, NaO_2: Al_2O_3: 3 H_2O)^b
iv. sodium metasilicate (Fisher Scientific, Na_2SiO_3: 5 H_2O)

c) Batch Preparation (for 10 g dry product)

i. [80 mL water + 0.723 g sodium hydroxide], mix gently until NaOH is completely dissolved. Divide into two equal volumes in polypropylene bottles.

ii. [One-half of (1) + 8.2 58 g sodium aluminate], mix gently in capped bottle until clear.

iii. [Second half of (1) + 15.48 g sodium metasilicate], mix gently in capped bottle until clear.

iv. [(2) + (3)], pour silicate solution into aluminate solution quickly; a thick gel should form. Cap tightly and mix until homogenized

d) Crystallization

i. Vessel : 100-150 ml polypropylene bottle (sealed)
ii. Incubation : none required
iii. Temperature : 99 ± 1°C
iv. Time : 3-4 hours
v. Agitation : stirred or unstirred

e) Product Recovery

i. Remove from heat source and cool to below 30°C.

ii. Filter to recover solids and wash with deionized water until filtrate pH is below 9

iii. Dry product on filter paper and watch glass at 80-110°C overnight.

iv. Yield: 28.1 g (hydrated) or 10.4 g (dry)

f) Product Characterization

i. XRD LTA; characteristic strong reflections at d = 4.107, 3.714, 3.293 and 2.987 Å
ii. Competing phases (if present): SOD (HS), GIS (Pc)
iii. Elemental Analysis: $Na_2O.\ Al_2O_3.\ 2\ SiO_2$
iv. Crystal Size and Habit: cubic crystals, 2-3 um

g) Notes

i. Zeolite NaA can be synthesized from a wide range of batch compositions as noted in Breck (Southern Carlifornia Gas, 1998) and temperatures other than used in this example, *e.g.,* 60-110°C. Also, it can be made from a variety of alumina and silica source materials other than those used in this example, e.g., pure aluminum powder or aluminum wire, fumed silica, sodium disilicate, Ludox, silica gels, etc. The actual weights of these other sources used must be compensated for the presence of water of hydration, Na^+ ions, etc.
ii. Assumed 100%.
iii. Could take 10-20 minutes.
iv. May be done with laboratory mixer or vigorously by hand for 5-10 minutes.
v. The turbid gel phase will be observed to diminish in height as the reaction proceeds, accelerating rapidly in the final stages of the crystallization, leaving a clear supernatant above the precipitated crystalline phase.
vi. One-half liter should be sufficient for this preparation.
vii. Zeolite NaA crystals are typically cubic. Dodecahedral crystals have been observed frequently, but there is little fundamental understanding of why this habit forms. Additions of triethanolamine are known to result in larger crystals, but the particle size distribution becomes broader, synthesis times are extended, and the impurity zeolite phases appear with increased abundance. (Lazzarin et.al, 1996)

viii. Special care must be taken if powdered aluminum is dissolved in a caustic solution to make the aluminate solution. Since its dissolution is exothermic, the solution can become quite warm and hydrogen evolves.

4.4 Sample preparation procedures

The specific gravity of the liquid ammonium hydroxide (30%) is 0.90 and the molecular weight is 35 g/mole [24]. So, the molar concentration of ammonium hydroxide (30%) is 7.714 M. In order to prepare 500ml ammonium hydroxide (5%), the number of mole ammonium hydroxide (30%) needed is 0.6425 with the volume is 83.3 ml. Finally, dilute 83.3 ml ammonium hydroxide (30%) to 500ml solution. Make sure used fume box and glove for sample dilution. All the sample preparation procedures are repeated in order to get ammonium hydroxide purity 10%, 15% 20% and 25% because only ammonium hydroxide (30%) is available in FKKSA lab. Detail calculation is showed in Appendix A. The total volume ammonium hydroxide (30%) needed in order to prepare 500ml sample solution is showed in Table 4.4

Table 4.4: Total volume ammonium hydroxide (30%) needed in preparation 500 ml sample solution

Ammonium hydroxide purity (%)	Volume of ammonium hydroxide (30%) ml
5	83.3
10	166.6
15	249.9
20	333.2
25	416.5
30	500.0

4.5 Purging and refilling procedures

The apparatus for this procedure are funnel, 500 ml beaker, aluminum foil, adjustable wrench and ammonium hydroxide solution. Mask, glove and goggle are needed for personal protection equipment for these procedures. Figure 4.3 shows all the apparatus needed in purging and refilling ammonia solution in absorption vessel.

Firstly, the absorption chiller unit is placed outside the gas engineering lab for good ventilation and space (Suggestion: early in the morning because ammonium hydroxide is easy to vaporize at ambient temperature and toxic to human). Before purging the existing ammonium hydroxide solution inside the absorption vessel, wear all personal protection equipment for the safety. Then, the screw at the bottom of absorption vessel is slowly removed using adjustable wrench. Make sure the solution is completely purged and collected. Figure 4.4 Absorption chiller position for purging existing solution. The beaker consist of purging solution must covered by aluminum foil and drain at the fume box.

Figure 4.3: Apparatus for purging and refilling ammonia solution in absorption vessel

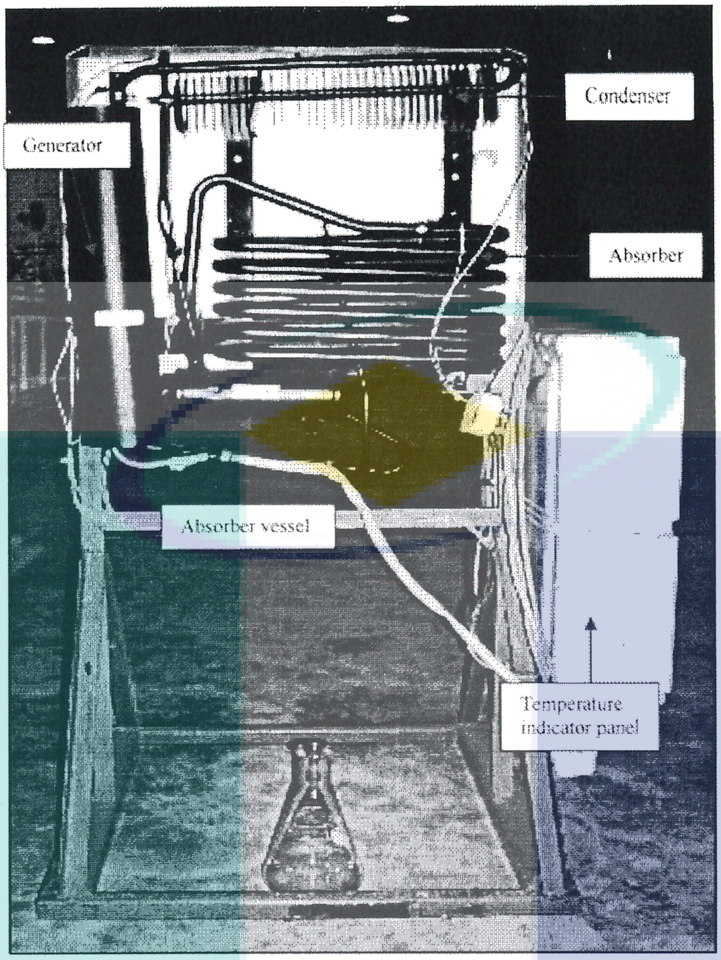

Figure 4.4: Absorption chiller position for purging existing solution

Figure 4.5 show the position of absorption chiller unit for refilling procedure of ammonium hydroxide solution at the absorption vessel. The solution is poured slowly and gently to the absorption vessel through the funnel as shows in Figure 4.6 Finally, the screw at the absorption vessel is tightening back and the absorption chiller moved to the gas engineering lab. The experiment is ready to run and the data can be collected

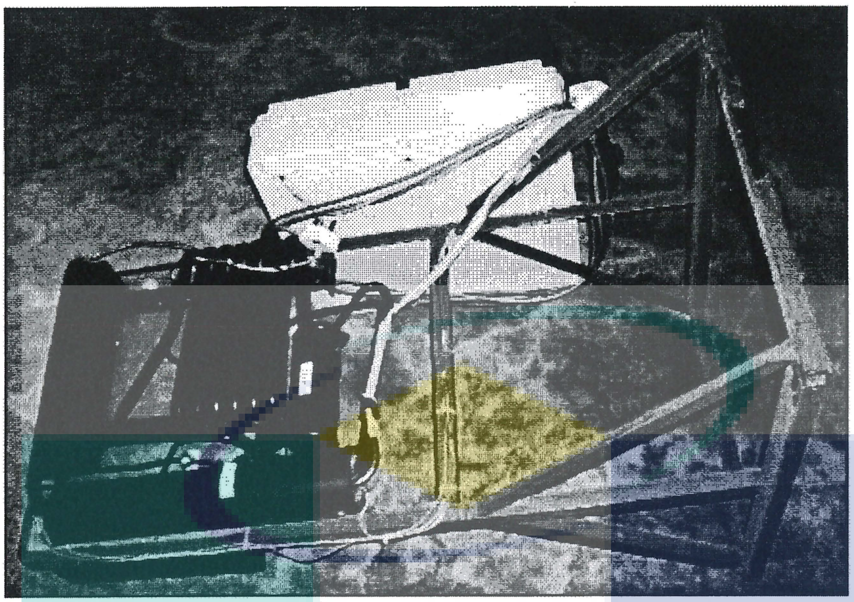

Figure 4.5: Absorption chiller position for refilling procedure

Figure 4.6: Ammonia solution pour to absorption vessel

4.6 Experimental procedures

This subchapter are discussed how to operate and the precaution steps if the absorption chiller unit not function properly until data collection method.

4.6.1 Start-Up Procedures

The Gas Absorption Refrigeration Unit (Model: RF 10) can be run on either electricity using 240 VAC or fuel gas using LPG. Changing between these modes of operation is carried out by means of control buttons positioned at the bottom of the unit. Meanwhile, the main switches and indication of all temperature measurement points are located at the control panel at the side of the unit.

First, the main power supply is switched on for the control panel and all temperature sensors are checked it functioning properly by using the selector switch to test all temperature measurement points. For operation using electricity, switch on the heater and set the energy selector to position (I). Adjust the thermostat setting to 4.For operation using fuel gas: Check that all gas pipes are properly connected between the LPG supply and the unit. Make sure all valves at the gas lines are open. Press the safety button and hold it down while pressing the ignite button. Check the flame viewer to see whether the flame is alight. If not, repeat step. Once the flame is alight, keep the safety button depressed for a further 10 to 15 seconds. Release the safety button and check whether the flame is alight. After initial installation, servicing or changing of cylinders, the gas pipes may contain some air which should be allowed to escape. This will ensure that the flame lights immediately. The gas absorption refrigeration unit will take about 1 hour to reach normal operating temperature. Monitor the readings at all four temperature measurement points for any changes. If all the temperature readings do not change after a considerable amount of time (about half an hour), the unit fails to operate properly. To overcome this problem, the electricity supply is available and the fuse in the control panel is intact are checked (troubleshooting procedures).

4.6.2 Troubleshooting procedures

If the gas absorption refrigeration unit fails to operate properly, ensure all start-up procedures in Section 4.5 have been carried out correctly and confirm that the unit is located on a level surface. If the unit fails to operate on fuel, gas check that the gas cylinder is not empty, all valves at the gas lines are open, and pressure regulator at the cylinder is functioning. If the unit fails to operate on electricity, check that the electricity supply is available and the fuse in the control panel is intact.

After the troubleshooting procedures are success, wait until all temperature reading are constant and record all the temperature at regular intervals (every 1 hour for 8 hours).

4.6.3 Shut-Off Procedures

After using the using the absorption refrigerator unit, the energy selector must be set back to position (0). Then switch off the heater and the fan. Finally switch the main power supply for control panel.

4.6.4 Maintenance Procedures

To ensure the safety of the equipment, maintenance has to be made. The gas hose need to be inspecting periodically for cracks or deep chafing marks. Connections can be tested for leaks using a soap solution. All surface of the refrigeration system must be clean with brush or damp cloth from to time. Make sure the unit is turned off while cleaning.

4.6.5 Data collection

Figure 4.7 shows the temperature indicator of absorption chiller unit. The indicators are detecting the temperature at generator in, generator out, condenser in, condenser out, evaporator in, evaporator out, absorber and cooling box. All temperature is collected every hour until 8 hours. The procedures in sub-sub section 4.6.1 until 4.6.5 is repeated for the next sample solution.

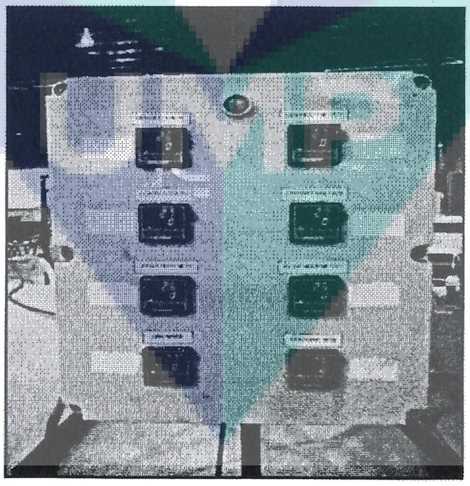

Figure 4.7: Temperature indicator of absorption chiller unit

Table 4.5: Temperature (°C) each indicator for ammonium hydroxide (5%)

First trial

Time (hr)	Gen. in	Gen. out	Cond. in	Cond. out	Evap. in	Evap. out	Absorber	Cooling box
0	25	26	26	27	25	25	25	25
1	85	63	33	30	31	29	28	26
2	90	88	33	30	31	31	30	26
3	96	90	37	34	31	31	34	27
4	103	90	39	34	32	31	39	28
5	111	92	40	36	33	33	43	28
6	117	95	42	39	33	33	41	29
7	117	97	51	39	35	36	41	29
8	117	97	62	38	35	36	40	29

Second trial

Time (hr)	Gen. in	Gen. out	Cond. in	Cond. out	Evap. in	Evap. out	Absorber	Cooling box
0	25	25	25	26	26	25	25	25
1	86	63	32	30	29	29	28	26
2	91	88	35	30	31	29	30	27
3	95	92	37	33	32	31	34	27
4	105	93	39	33	32	33	39	28
5	113	94	40	37	33	33	43	28
6	117	96	42	39	33	36	41	29
7	117	98	53	39	34	36	41	29
8	117	98	62	38	35	35	40	29

4.7 Method of analysis for coefficient of performance (COP)

The coefficient of performance is calculated for each hour within 8 hours for every ammonia/water ratio. All the calculation for coefficient of performance COP refers to absorption chiller in sub section 2.4 efficiencies. The graph COP vs. ammonia/water ratio is plotted and the most efficient ammonia/water ratio in absorption chiller is measured.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

5.1.1 Effect of ammonia purity to the temperature

Table 5.1 showed the effect of ammonia purity (%) to the temperature at the cooling box after 8 hours operation. It is shown that the temperature at cooling box varies from 24°C to 33°C. Ammonia purity 5% and 10% has temperature more than ambient temperature (30°C) which is 33°C and 32°C means that the absorption refrigeration unit performance is low. Meanwhile, ammonia purity 15% until 30% has lower temperature than ambient temperature which around 29°C to 24°C. Low temperature means that the ammonia purity gives high performance to absorption refrigeration unit. Then, the graph cooling box temperature (°C) vs. ammonia purity (%) is plotted in Figure 5.1. Base on this figure the temperature at cooling box decrease when the purity of ammonia in the absorption vessel is increases.

Table 5.1: Ammonia purity (%) and cooling temperature (°C)

Ammonia Purity (%)	Cooling Box Temperature (°C)	Ambient Temperature (°C)
0	-	30
5	33	30
10	31	30
15	29	30
20	28	30
25	26	30
30	24	30

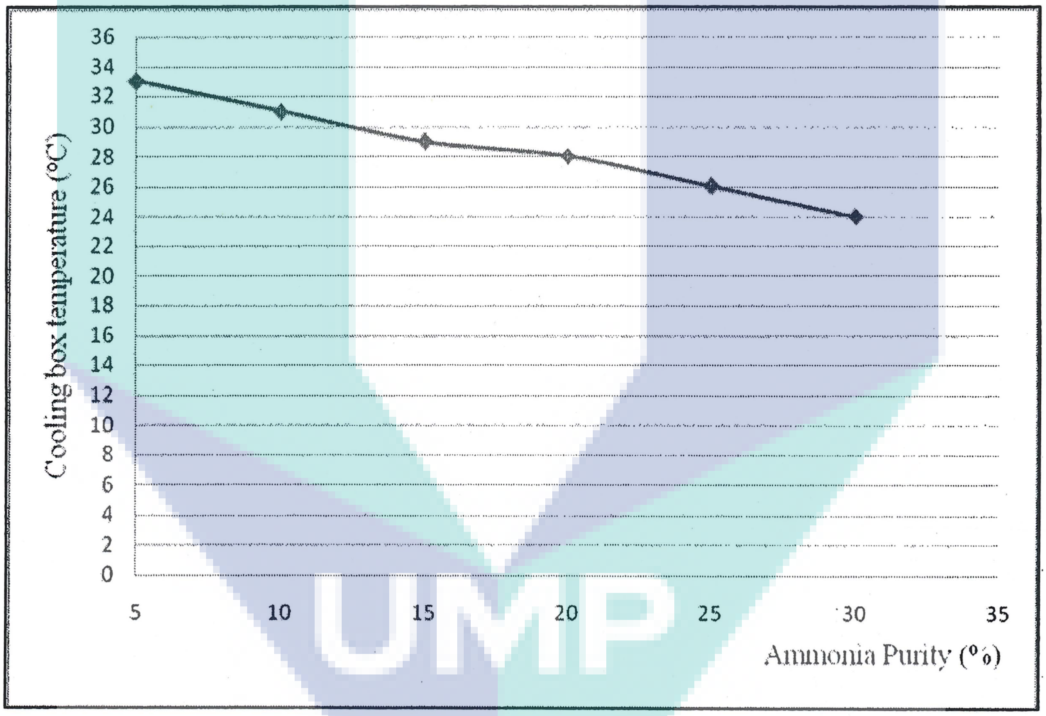

Figure 5.1: Graph cooling box temperature (°C) vs. ammonia purity (%)

5.1.2 Coefficient of Performance (COP) values for ammonia purity

Figure 5.2 showed the graph coefficients of performance (COP) vs. time (hour). The COP of absorption refrigerant is inversely proportional to the temperature at cooling box referring from the equation to calculate the COP of the absorption chiller in sub section 2.4. The poorest performance of absorption refrigeration unit is at 5% and 10% ammonia purity with the value of COP is -8.18 and -23.05 after 8 hour operation. This happen because of the amount of ammonia in the solution is too little and cannot effectively function as refrigerant medium compare to the huge amount of water as absorption medium in the system. It makes the revisable cycle of absorption refrigerant unbalance and increases the temperature at cooling box. The final temperature at cooling box for 5% purity of ammonia is 33°C and 31°C for 10% ammonia purity which are more the ambient temperature which is 30°C. That why the value of COP of these purity is negative. But, the unbalance condition at refrigerate area become more and more balance by adding the purity of ammonia in the working fluid in the system. It show by decreasing temperature at the cooling box and decreasing the value of COP when more amount of ammonia added in the system that shows at the graph above. With the value of COP is 2.97 and 30% ammonia purity in the working fluid give the most efficient performance of absorption chiller unit.

5.1.3 Result of the absorption process with additive with various concentrations

By adding additive to the system, the flows will rich with ammonia and make the system cooler. Table 5.3, Table 5.4, Table 5.5, Table 5.6 and Table 5.7 shows the data of absorption process with additive with concentration 0.0002M, 0.0004M, 0.0006M, 0.0008M and 0.001M respectively. The duration time of the experiment is 8 hour. The assumption that has been made is performance of the absorption chiller unit is the same in each experiment conducted. The first experiment 0.0002M of zeolite NaA is added to the 30% Ammonia water solution. At the first hour of the experiment the temperature at cooling box is 25°C, this happen because the absorption chiller unit is not stable. After 5 to 8 hours temperature is decreasing until the final temperature is 24°C.

Table 5.3: Absorption process with additive 0.0002 M

Time (Hour)	Generator in (°C)	Cooling Box (°C)	Ambient Temperature (°C)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	25	30	-0.200	5.000	-1.000
2	85	27	30	0.647	9.000	5.824
3	86	26	30	0.651	6.500	4.233
4	90	26	30	0.667	6.500	4.333
5	95	25	30	0.684	5.000	3.421
6	110	24	30	0.727	4.000	2.909
7	115	24	30	0.739	4.000	2.957
8	117	24	30	0.744	4.000	2.974

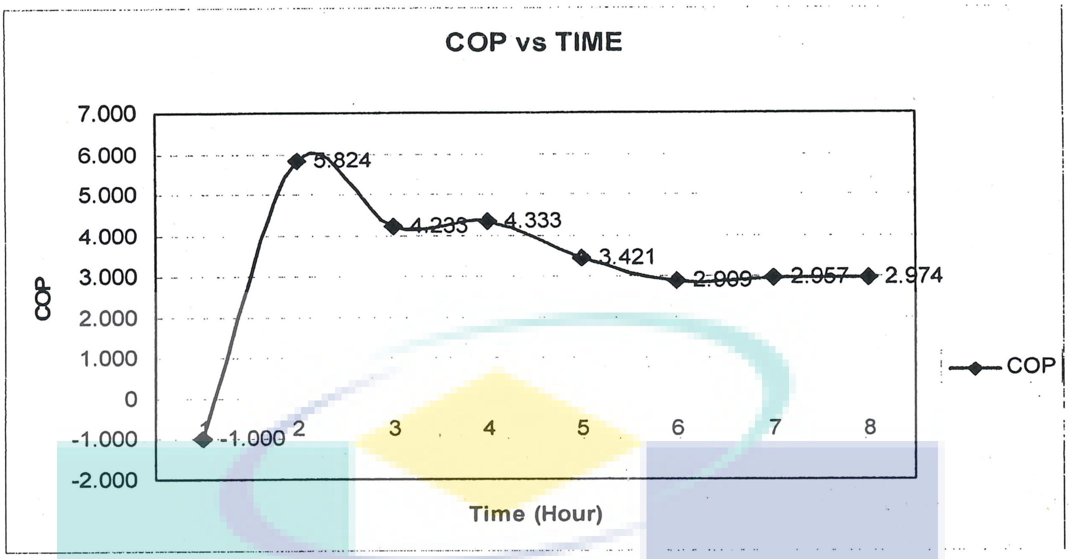

Figure 5.3: Absorption process with additive 0.0002 M

Same goes to the next experiment which the additive is added 0.0004M. The different is the final temperature that the unit achieves after 8 hours is lower than the first experiment. From the table 5.2 we can see that the temperature is higher compare to the other temperature. This happen because of the absorption chiller unit is not in stable condition at the early stage of the experiment stated. After 8 hours the COP that can be achieved is 2.063.

Table 5.4: Absorption process with additive 0.0004 M

Time (Hour)	Generator in (oC)	Cooling Box (oC)	Ambient Temperature (oC)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	25	30	-0.200	5.000	-1.000
2	85	27	30	0.647	9.000	5.824
3	87	26	30	0.655	6.500	4.259
4	90	26	30	0.667	6.500	4.333
5	99	25	30	0.697	5.000	3.485
6	100	23	30	0.700	3.286	2.300
7	115	22	30	0.739	2.750	2.033
8	120	22	30	0.750	2.750	2.063

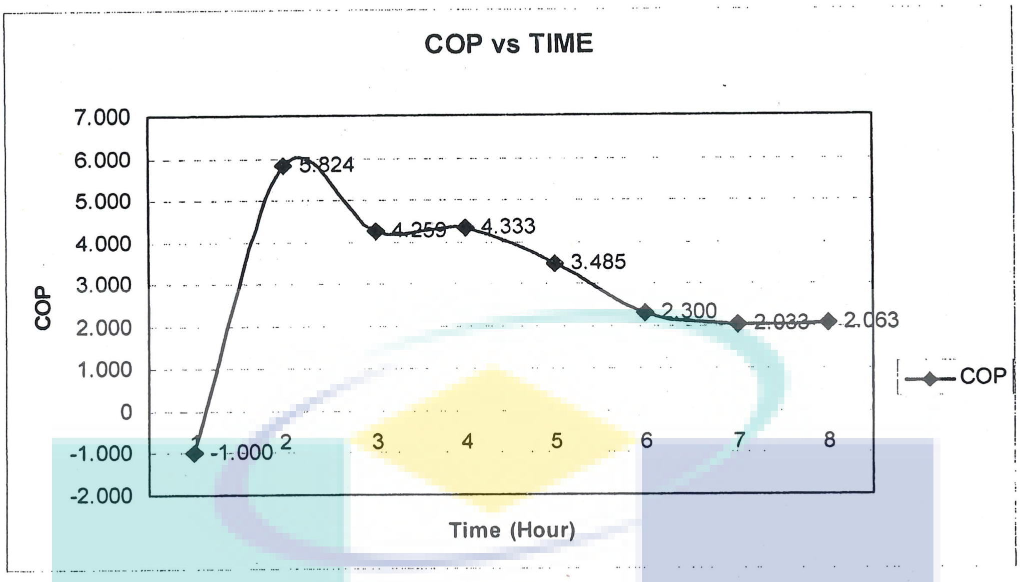

Figure 5.4: Absorption process with additive 0.0004M

Then after adding another concentration of additive that is 0.0006M of zeolite NaA, the temperature become lower than before. The cooling box temperatures achieve 20°C. At this stage assumption have been made that the decreasing of cooling box temperature is proportional to the increasing of concentration of Zeolite NaA added to the system.

Table 5.5: Absorption process with additive 0.0006 M

Time (Hour)	Generator in (oC)	Cooling Box (oC)	Ambient Temperature (oC)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	27	30	-0.200	9.000	-1.800
2	85	25	30	0.647	5.000	3.235
3	87	26	30	0.655	6.500	4.259
4	90	24	30	0.667	4.000	2.667
5	99	23	30	0.697	3.286	2.290
6	100	21	30	0.700	2.333	1.633
7	115	20	30	0.739	2.000	1.478
8	120	20	30	0.750	2.000	1.500

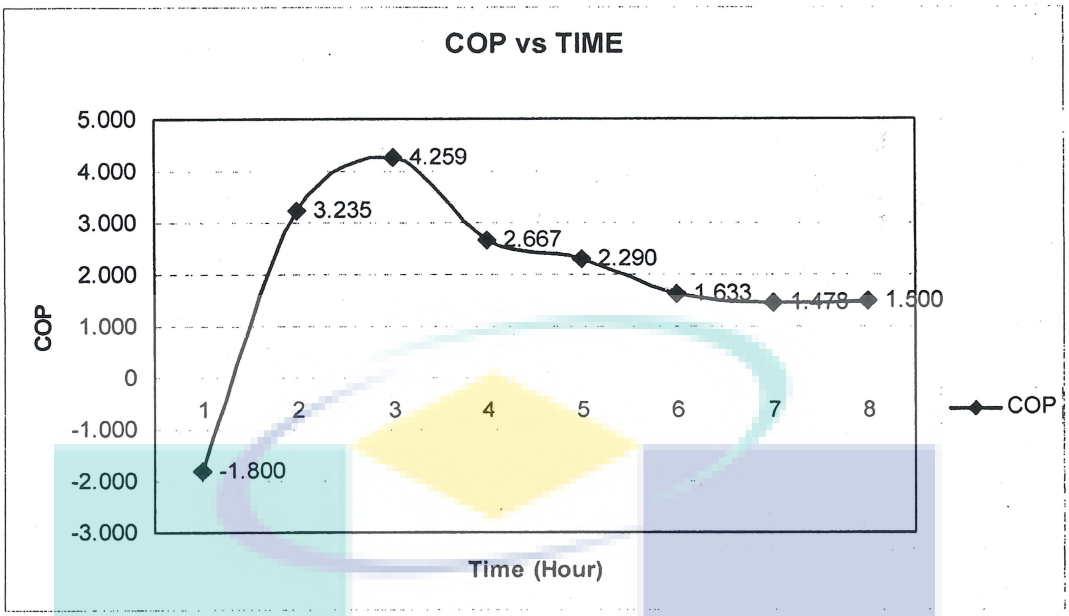

Figure 5.5: Absorption process with additive 0.0006 M

Then experiment is proceed by adding another 2 concentration of additive that is 0.0008M and 0.001M. For the last 2 experiments the result shows that the assumption made before this is wrong. The cooling temperature is increasing to 25°C and 27°C respectively. This indicates that there are certain range of additive concentration can be added in the absorption process.

Table 5.6: Absorption process with additive 0.0008 M

Time (Hour)	Generator in (°C)	Cooling Box (°C)	Ambient Temperature (°C)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	25	30	-0.200	5.000	-1.000
2	80	26	30	0.625	6.500	4.063
3	85	27	30	0.647	9.000	5.824
4	87	24	30	0.655	4.000	2.621
5	95	24	30	0.684	4.000	2.737
6	100	25	30	0.700	5.000	3.500
7	120	25	30	0.750	5.000	3.750
8	122	25	30	0.754	5.000	3.770

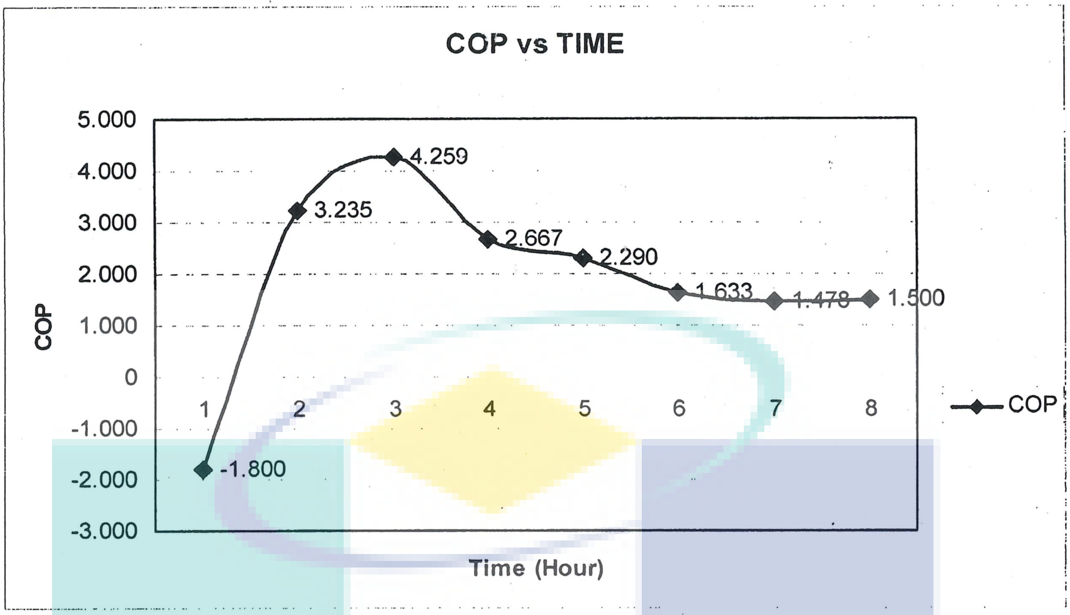

Figure 5.5: Absorption process with additive 0.0006 M

Then experiment is proceed by adding another 2 concentration of additive that is 0.0008M and 0.001M. For the last 2 experiments the result shows that the assumption made before this is wrong. The cooling temperature is increasing to 25°C and 27°C respectively. This indicates that there are certain range of additive concentration can be added in the absorption process.

Table 5.6: Absorption process with additive 0.0008 M

Time (Hour)	Generator in (^{o}C)	Cooling Box (^{o}C)	Ambient Temperature (^{o}C)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	25	30	-0.200	5.000	-1.000
2	80	26	30	0.625	6.500	4.063
3	85	27	30	0.647	9.000	5.824
4	87	24	30	0.655	4.000	2.621
5	95	24	30	0.684	4.000	2.737
6	100	25	30	0.700	5.000	3.500
7	120	25	30	0.750	5.000	3.750
8	122	25	30	0.754	5.000	3.770

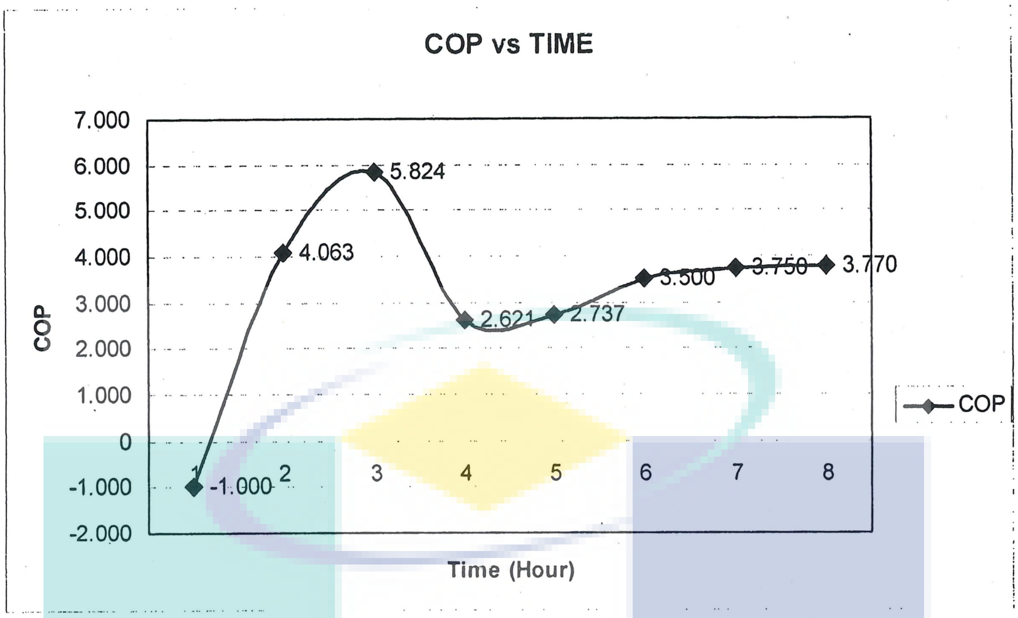

Figure 5.6: Absorption process with additive 0.0008 M

Table 5.7: Absorption process with additive 0.001 M

Time (Hour)	Generator in (°C)	Cooling Box (°C)	Ambient Temperature (°C)	1-(To/TS)	Tl/(To-Tl)	COP
1	25	25	30	-0.200	5.000	-1.000
2	50	28	30	0.400	14.000	5.600
3	55	27	30	0.455	9.000	4.091
4	98	25	30	0.694	5.000	3.469
5	99	25	30	0.697	5.000	3.485
6	99	26	30	0.697	6.500	4.530
7	100	27	30	0.700	9.000	6.300
8	100	27	30	0.700	9.000	6.300

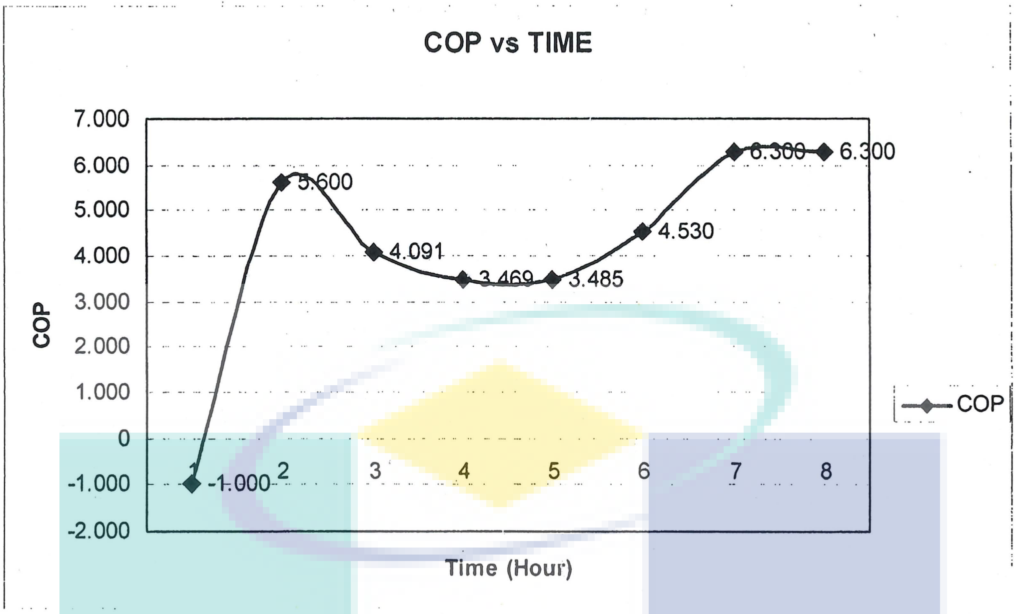

Figure 5.7: Absorption process with additive 0.001 M

To determine the optimum concentration of additive, the additive that give the lowest cooling box temperature is the optimum concentration of additive. Table 4.6 and Figure 4.6 show the relationship between concentration of additive and cooling box temperature. Meanwhile in Table 4.7 and Figure 4.7 it shows the relationship between additive concentration and coefficient of performance of the absorption chiller unit. From Figure 4.7, the optimum concentration of additive is 0.0006M of zeolite NaA. From the graph the COP is decreasing when the concentration is 0.0006M. This happen because at this concentration, it achieve the lowest cooling box temperature. When the cooling temperature is decreasing the COP of the unit will also decreasing.

Table 5.8: Relationship between concentration and cooling temperature

Concentration (M)	Cooling temperature
0	24
0.0002	24
0.0004	22
0.0006	20
0.0008	25
0.001	27

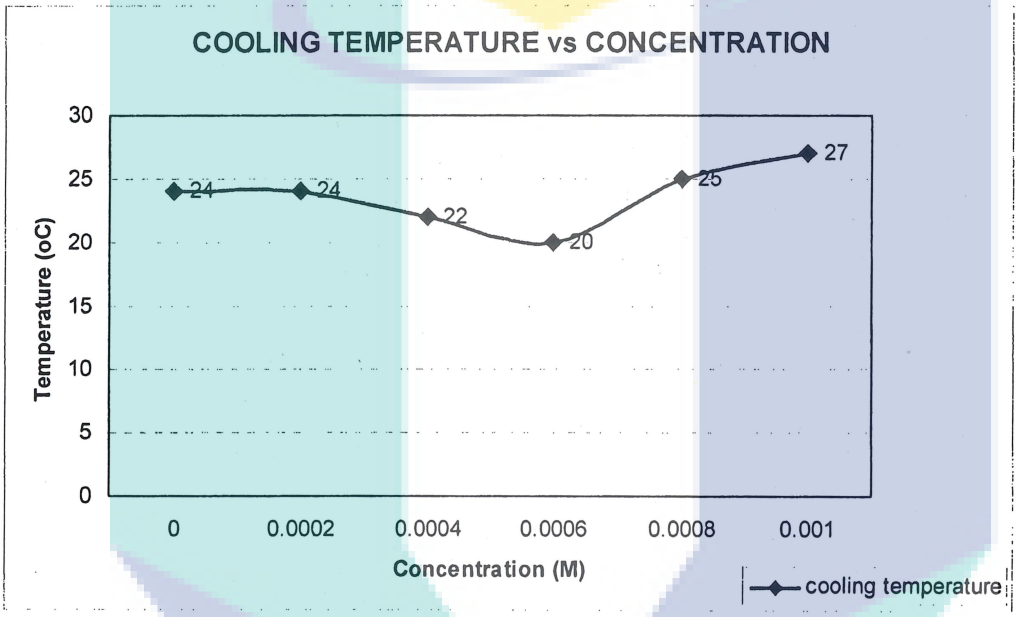

Figure 5.8: Relationship between concentration and cooling temperature

Table 5.9: Relationship between concentration and COP

Concentration (M)	COP
0.0002	2.947
0.0004	2.063
0.0006	1.500
0.0008	3.770
0.001	6.300

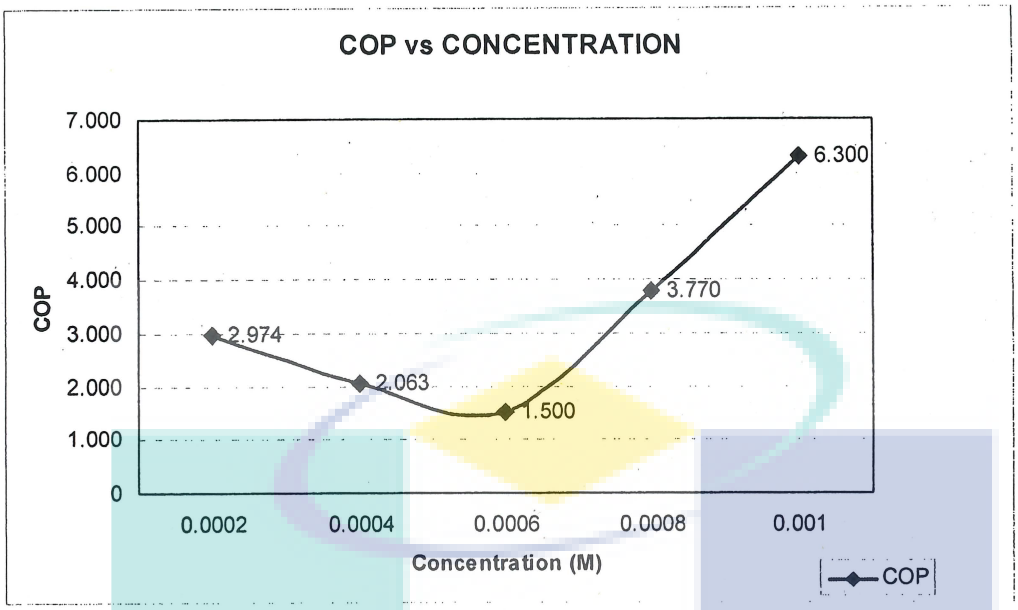

Figure 5.9: Relationship between concentration and COP

5.2 Discussion

The main problem that occurred while doing this thesis using Gas Absorption Refrigeration Unit (Model: RF 10) is the time that the system to archive stable condition which all the temperature constant at all the temperature indicator. The precaution step to overcome this problem in this experiment is by assuming the absorption unit has complete cycle and stable system after 8 hours. Furthermore, another assumption is the performance of the absorption chiller unit is constant for each experiment. By using kerosene or gas as heat supplied by the burner rather than using electricity is an option to make the system archive stable condition faster. The COP increased with increasing generator temperature and with decreasing absorber and condenser temperatures for all the systems. Also, the lowest temperature at the evaporator is important in order to control the temperature for all the system cycle that affects the value of COP in absorption chillers.

Moreover, 30% ammonia purity is not the optimum COP of absorption refrigeration unit because the optimum performance of gas cooling equipment in single-effect absorption chillers has COPs of approximately 0.6-0.8. Base on safety and health regulation for chemical engineering lab, the ammonia purity more than 30% cannot storage in the FKKSA lab. So that, the research for more than 30% ammonia purity has not been study and the optimum ammonia/water ratio that give optimum value COP cannot obtained.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

As a conclusion, the objectives already achieve which is to study effect of ammonia/water ratio in the coefficient of performance (COP) for absorption chiller and to find the optimum ammonia/water ratio that gives the optimum efficiency. From the study, the effect of ammonia purity is directly proportional with the coefficient of performance. The optimum ammonia/water ratio is 30/70 percent with the coefficient of performance (COP) is 2.97 and the temperature at cooling box is 24 °C. The optimum ratio is at 30/70 because the effect of ammonia purity more than 30 percent to the performance of absorption chiller not included in this research. Also, the maximum ammonia purity at engineering lab is 30 percent only base on rules and regulation of material storage in educational building.

On the economic matter is worthy to improve the performance of absorption chiller system because roughly the price of HCFC-22 is 3 to 5 times ammonia refrigerant and the power consumption for ammonia is also least compared to other refrigerants. Also, the coefficient of performance for ammonia is better than other refrigerants. The discharge temperature however, is higher with ammonia installations due to higher index of compression and higher compression ratio. So, continuous process improvement is needed to be done to ensure the discharge temperature is same or lower than compressor refrigerator.

6.2 Recommendations

There are some of recommendations that should been done on this project for the future purposes which are :

i. Study the effect of ammonia purity more than 30 percent and additive such as zeolite NaA in order to improve and get optimum performance of absorption chiller system.

ii. Applying the heat integration from absorber to generator so that the fuel consumption is reduced.

iii. Using computer simulation such as hysis to study the effect of ammonia/water ratio in the performance absorption chiller and compare the result with experimental study.

iv. Installing an absorption system in parallel with an electric vapor compression system so that the best of both gas and electric usage is captured.

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APPENDIX A

Calculation for Sample Preparation

A) Sample preparation

The specific gravity of the liquid ammonium hydroxide (30%) is 0.90 and the molecular weight is 35 g/mole.

The molar concentration of ammonium hydroxide is

$$\frac{0.90 \times 10^{3}\ \text{g reagent}}{\text{L reagent}} \times \frac{30\ \text{g}\ NH_4OH}{100\ \text{g reagent}} \times \frac{1\ \text{mole}\ NH_4OH}{35\ \text{g}\ NH_4OH} = 7.714\ \text{M}$$

The preparation of the 5 percent pure ammonia of 500 ml solution

$$\frac{0.90 \times 10^{3}\ \text{g reagent}}{\text{L reagent}} \times \frac{5\ \text{g}\ NH_4OH}{100\ \text{g reagent}} \times \frac{1\ \text{mole}\ NH_4OH}{35\ \text{g}\ NH_4OH} = 1.285\ \text{M}$$

The number of mole of 30% ammonium hydroxide required is given by

$$500\ \text{ml} \times \frac{1\ \text{L}}{1000\ \text{ml}} \times \frac{1.286\ \text{mole}\ NH_4OH}{\text{L}} = 0.6425\ \text{mole}$$

Finally, to obtain the volume of concentrated reagent, we write

$$0.6425\ \text{mole}\ NH_4OH \times \frac{1\ \text{L reagent}}{7.714\ \text{mole}\ NH_4OH} = 0.0833\ \text{L}$$

Thus, dilute 83.3 ml ammonium hydroxide (30%) to 500ml solution. [25] The solution is putted in absorber vessel at Gas Absorption Refrigeration unit (Model RF: 10) Repeat all the sample preparation for another ammonia/water ratio. But, if the entire ammonia/water ratio can be provided the sample preparation procedure will not apply in this experiment.

B) Sample calculation of Preparation of Additive

i) Preparation of Additive 0.0002M

No. of mol = MV/1000
= (0.0002M x 500ml of solution) / 1000
= 0.0001

No. of mol = mass/molecular weight
Mass = 0.0001 x 2178
= 0.2 gram

ii) Preparation of Additive 0.0004M

No. of mol = MV/1000
= (0.0004M x 500ml of solution) / 1000
= 0.0002

No. of mol = mass/molecular weight
Mass = 0.0002 x 2178
= 0.4 gram

iii) Preparation of Additive 0.0006M

No. of mol = MV/1000
= (0.0006M x 500ml of solution) / 1000
= 0.0004

No. of mol = mass/molecular weight

Mass = 0.0004 x 2178
= 0.8 gram

iv) Preparation of Additive 0.0008M

No. of mol = MV/1000
= (0.0008M x 500ml of solution) / 1000
= 0.0006

No. of mol = mass/molecular weight
Mass = 0.0006 x 2178
= 1.3 gram

v) Preparation of Additive 0.001M

No. of mol = MV/1000
= (0.001M x 500ml of solution) / 1000
= 0.001

No. of mol = mass/molecular weight
Mass = 0.001 x 2178
= 2.1 gram

C) Sample calculation of Coefficient of Performance

$$\boxed{COP_{rev,absorption} = QL/Q\ gen = \eta_{th,rev}\ COP_{R,rev} = (1-T_o/T_s)\ [T_L/(T_o-T_L)]}$$

Calculation COP value for adding 0.0006M of additive

i) Time = 1 hour,

$T_o = 30°C,\ T_s = 25°C,\ T_{L} = 27°C$

$COP_{rev,absorption} = (1-30/25)\ [27/(30-27)$
$= (-0.2)\ (9)$
$= -1.8$

ii) Time = 2 hour

$T_o = 30°C,\ T_s = 85°C,\ T_{L} = 25°C$

$COP_{rev,absorption} = (1-30/85)\ [25/(30-25)$
$= (0.647)\ (5)$
$= 3.235$

iii) Time = 3 hour

$T_o = 30°C,\ T_s = 87°C,\ T_{L} = 26°C$

$COP_{rev,absorption} = (1-30/87)\ [26/(30-26)$
$= (0.6552)\ (6.5)$
$= 4.2588$

iv) Time = 4 hour

$T_o = 30°C,\ T_s = 90°C,\ T_{L} = 24°C$

$COP_{rev,absorption} = (1-30/90)\ [24/(30-24)$
$= (0.666)\ (4)$
$= 2.66$

v) $T = 5$ hour

$T_o = 30^\circ C$, $T_s = 99^\circ C$, $T_{L} = 23^\circ C$

$COP_{rev,absorption}$ = (1-30/99) [23/(30-23)

= (0.6969) (3.2)

= 2.28

vi) Time = 6 hour

$T_o = 30^\circ C$, $T_s = 100^\circ C$, $T_{L} = 21^\circ C$

$COP_{rev,absorption}$ = (1-30/100) [21/(30-21)

= (0.7087) (2.3)

= 1.65

vii) Time = 7 hour

$T_o = 30^\circ C$, $T_s = 115^\circ C$, $T_{L} = 20^\circ C$

$COP_{rev,absorption}$ = (1-30/85) [20/(30-20)

= (0.7391) (2)

= 1.47

viii) Time = 8 hour

$T_o = 30^\circ C$, $T_s = 120^\circ C$, $T_{L} = 20^\circ C$

$COP_{rev,absorption}$ = (1-30/120) [20/(30-20)

= (0.75) (2)

= 1.5

APPENDIX B

Material Safety Data Sheet Ammonium Hydroxide (30%)

Material Safety Data Sheet
J. R. Simplot Company
AgriBusiness
M11005

Trade Name: Ammonium Hydroxide Solution 29.4%
Registration No: None

SECTION 1 CHEMICAL PRODUCT & COMPANY INFORMATION

Manufacturer or Formulator: J.R. Simplot Company
Product Name: Ammonium Hydroxide Solution 29.4%
P.O. Box 70013
Common Name: Ammonium Hydroxide NH_4OH
Boise, ID 83707
Chemical Type: Strong Base
Emergency Phone - Chemtrec: 1-800-424-9300

SECTION 2 COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name and Synonyms C.A.S. No. Chemical Formula WT% TLV PEL
Hazardous
Ammonium Hydroxide 1336-21-6 NH_4OH 10-35% 18 mg/M^3 Not available
(% expressed as NH_3) 25 ppm
ACHIH
Ammonia Vapor: 50 ppm Cl, 25 ppm TLV, 35 ppm STEL
Non-Hazardous
Water 7732-18-5 H_2O Balance

SECTION 3 HAZARDS INFORMATION

Ingestion: Toxicity Data: see Section 11.
Inhalation: Toxicity Data: see Section 11.
Eye Contact: Irritation Data: see Section 11.
Skin Absorption: Absorption not known to occur--refer to skin contact.
Skin Contact: Ammonia, because of its alkalinity and water solubility, tends to break down and disrupt the outer cell layers, permitting rapid penetration. Even so, ammonia is not a systemic poison and the effects will be limited to local effects. May cause slight to severe irritation. May cause burn with prolonged contact.
Effects of Overdose Irritation and possible burns of the skin and mucous membranes. Headache, salivation, nausea, and vomiting. Dyspnea and cough with bloody mucous discharge. Bronchitis, laryngitis, hemoptysis, and pulmonary edema or pneumonitis. Ulceration of the conjunctiva and cornea, and corneal and lenticular opacities. Damage to the eyes may be permanent.

SECTION 4 FIRST AID MEASURES

Ingestion: Not generally possible, however, if ingestion occurs and person is conscious, give large quantities of water and, if possible, diluted vinegar, lemon juice, orange juice, or other citric juices to neutralize the ammonia.
Inhalation: REMOVE IMMEDIATELY FROM EXPOSURE AREA TO FRESH AIR. Support breathing and call a doctor.
Eyes: IMMEDIATELY FLUSH EYES with fresh flowing water for a minimum of 15 minutes. Draw back eyelids and flush thoroughly. Call and take to a doctor.
Skin: REMOVE CONTAMINATED CLOTHING AND FLUSH SKIN THOROUGHLY WITH RUNNING WATER FOR 15 MINUTES AND CALL A DOCTOR. DO NOT USE SALVES OR OINTMENT ON SKIN. Take to a doctor.

SECTION 5 FIRE FIGHTING MEASURES

Extinguishing Media: Water spray, water fog. (Dry chemical or CO_2 in small fire only.)

Special Fire Fighting Procedures: Stop the flow of gas or liquid. Use water to keep fire exposed containers cool and to protect persons affecting the shut-off. Wear self-contained breathing apparatus and full protective clothing. Approach fire upwind and evacuate area downwind.

Unusual Fire and Explosion Hazards: The presence of oil or other combustible materials will increase the fire hazard. The explosive (flammable) range of ammonia is broadened by a mixture of oxygen replacing air, and by temperature and pressure higher than atmospheric.

SECTION 6 ACCIDENTAL RELEASE MEASURES

Environmental Precautions: Toxic to fish and aquatic life. Reportable quantity for spill is 1000 lbs. Do not contaminate any body of water by direct application, cleaning of equipment or disposal.

Steps to be taken in case material is released or spilled:
Stop the flow. Wear self-contained breathing apparatus and full protective equipment and clothing. Approach spill upwind and evacuate area downwind. Prevent runoff from entering streams or drinking water supply or sewers. Dike around spill. Dilute with water, if necessary to reduce ammonia vaporization. Can be neutralized with dilute phosphoric or sulfuric acids. Vinegar will effectively neutralize small spills of aqua ammonia.

SECTION 7 HANDLING AND STORAGE

Precautions to be taken in handling and storing:
Avoid heating containers of aqua ammonia. Avoid storing in close proximity to strong acids. Avoid contact with skin and eyes. Avoid inhalation of vapors.

Trade Name: Ammonium Hydroxide Solution 29.4% **M11005** **Registration No:** None **Disclaimer:** This information relates to the specific material designated and may not be valid for such material used in combination with any other materials or in any process. Such information is to the best of our knowledge and belief, accurate and reliable as of the date compiled. However, no representation, warranty or guarantee is made as to its accuracy, reliability or completeness. **NO WARRANTY OF MERCHANTABILITY, FITNESS FOR ANY PARTICULAR PURPOSE, OR ANY OTHER WARRANTY, EXPRESS OR IMPLIED, IS MADE CONCERNING THE INFORMATION HEREIN PROVIDED.** It is the user's responsibility to satisfy himself as to the suitability and completeness of such information for his own particular use. We do not accept liability for any loss or damage that may occur from the use of this information nor do we offer warranty against patent infringement.

SECTION 8 EXPOSURE CONTROLS/PERSONAL PROTECTION

Ventilation Protection: Local exhaust essential. Spark-proof fans desirable with mechanical ventilation. Ducts should be located at ceiling level and lead upwards to the outside. Local exhaust must be adequate to reduce NH_3 concentration below 25 ppm.

Respiratory Protection: 0-200 ppm--cartridge type 1/2 mask respirator. 200-500 ppm--type "N" gas mask with full face piece. Over 500 ppm requires SCBA.

Protective Clothing: Rubber or synthetic chemical protective suit and boots, and chemical gauntlet type gloves.
Eye Protection: Tight fitting chemical splash-proof goggles and face shield should be worn.
Other: Eyewash fountain and safety shower in area.

SECTION 9 PHYSICAL AND CHEMICAL PROPERTIES

Boiling Point: 80°F **Solubility in Water:** Complete

Density: Sp. Gr. 0.88 - 0.90 @ 20°C **% Volatiles (by volume):** 25 - 30%
Flashpoint: Not applicable **Vapor Pressure, mm Hg:** Not available
pH: +13 **Reaction with Water:** None
Appearance: Colorless liquid with pungent odor.
Extinguishing Media: Water spray, water fog. (Dry chemical or CO_2 in small fire only).

SECTION 10 STABILITY AND REACTIVITY

Stability (Normal Conditions): Stable
Conditions to Avoid: Heat, open flames, and electrical equipment and fixtures which are not vapor-proof or grounded.
Incompatibility (Material to Avoid): Contact with mercury, chlorine, bromine, iodine, calcium, silver oxide, or hypochlorite can form explosive compounds.
Hazardous Decomposition Products: Ammonia is lightly reactive, easily undergoing oxidation, substitution and additional reactions. Combustion of ammonia will yield small amounts of nitrogen and water.
Hazardous Polymerization: Will not occur

SECTION 11 TOXICOLOGY INFORMATION

Ingestion: Toxicity Data: Oral human LDLo: 43 mg/kg; Oral rat LD_{50}: 350 mg/kg; Oral cat LDLo: 750 mg/kg.
Inhalation: Toxicity Data: Inhalation human LDLo: 5000 ppm; Inhalation human TCLo: 408 ppm.
Eye Contact: Irritation Data: Eye-rabbit: 750 ug SEV; 44 ug SEV.
Skin Contact: ivn--rabbit LDLo: 10 mg/kg.

SECTION 12 ECOLOGICAL INFORMATION

None listed.

SECTION 13 DISPOSAL CONSIDERATIONS

Waste Disposal Procedures: Can be used as a fertilizer material. Consult local authorities for disposal. May be diluted with large amount of water and absorbed into soil.

SECTION 14 TRANSPORT INFORMATION

Shipping name: RQ Ammonium Solutions, 8, UN2672, P.G. III **Packaging Group:** III
Hazard Class: 8 **C.A.S. Number:** 1336-21-6
Reportable Quantity (RQ): 1000 lbs/454 kg **D.O.T. Number:** UN2672
Labels Required: Corrosive **Haz Waste No:** D002
Placard: Corrosive **EPA Regist No:** None
Refer to 49 CFR 172.101 Hazardous Materials Table for further provisions, packaging authorizations and quantity limitations.

SECTION 15 REGULATORY INFORMATION

Carcinogenicity: by IARC?: Yes ( ) No (X) by NTP?: Yes ( ) No (X)
This product contains ammonia, CAS No. 1336-21-6, which is subject to the reporting requirements of section 313 of Title III of the Superfund and Reauthorization Act of 1986 and 40 CFR Part 372.

SECTION 16 OTHER INFORMATION

Flash Point (Test Method): Non-flammable **Flammable Limits LOWER UPPER Autoignition Temperature:** 850°C; 1560°F (% BY VOLUME) N/A N/A
Hazard Rating (N.F.P.A.): Health: 3 **Fire:** 1 **Reactivity:** 0 **Specific:** Not applicable
Vessel stowage requirements: This material may be stowed "on deck" or "under deck" on a cargo vessel and a passenger vessel, per 49 CFR 172.101. Material must be stowed "clear of living quarters" per 49 CFR 176.84, provision 40 and under deck stowage must be in a well-ventilated space, per 49 CFR 176.94, provision 85.
MSDS Version Number: 3 (revisions to Section 15)

Reviewed by: The Department of Regulatory Affairs June 1999 (208)672-2700