

Theoretical and Experimental Evaluation of a Low Temperature Lithium-Bromide/Water Absorption System

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Abstract

With an increasing desire that the generation of power occurs in an environmentally friendly manner, new technologies have to be developed while older technologies can be refined or implemented in innovative manners. An older technology that has been garnering attention over the last few decades is vapour absorption. A vapour absorption system is driven by a source of heat and is typically used to produce refrigeration, but the possibility for the incorporation of power generation into vapour absorption has been considered in the past and has to be further investigated.

The primary goals of this study are the development of a steady state simulation; the design, construction and control of a vapour absorption system as well as the identification of manners in which to recover and utilize low temperature waste heat using vapour absorption. Secondary goals that may be incorporated into the study are the development of a transient simulation of a vapour absorption system as well as the theoretical and possibly experimental implementation of a turbine for power generation. It is hoped that this relatively exploratory study will assist future research in the field of vapour absorption at Stellenbosch University and in South Africa.

Keywords: Waste Heat Recovery, Vapour Absorption, Dual Function Vapour Absorption

1 Introduction

Improvements in the overall efficiency at which a large system or plant operates can have significant implications to performance and operation costs and due to this there has always been a desire to increase the efficiency at which industrial processes operate. In a situation where the overall operating efficiency of, for example, a coal fired or nuclear power plant is improved, it would reduce the amount of fuel required to produce a similar amount of energy thereby reducing the pollution that is generated by the plant as well as reducing the running costs of the plant. While it is desired that the efficiency of a process be as high as possible, there is always an

upper limit to the extent in which the efficiency of a plant can be improved before any additional improvements will simply no longer be feasible from an economical point of view.

A resource that is largely untapped in many processes is the waste heat streams that are generated which are simply “thrown away” into the environment. This process heat that is discarded is referred to as waste heat and the possibility of recovering and reusing this energy can improve the overall efficiency at which a process operates at. A large portion of waste heat is only available at low temperatures and there are few viable methods for the recovery and utilization of waste heat that has a low temperature. One of the methods for the recovery of low temperature waste heat is vapour absorption.

What makes vapour absorption cycles an attractive technology is that the system is thermally activated systems where the vast majority of the energy requirements of the system can be provided by a source of low temperature heat such as heating water from a solar panel or a low temperature source of waste heat. Although vapour absorption is old technology it is not as widely known as more mainstream technologies like the vapour compression cycle as it lost popularity in the early 19th century due to the advantages offered by vapour compression technology.

To better understand and theoretically simulate the operation, heat transfer and working fluid behaviour in a vapour absorption system it is intended that an experimental system be designed. The engineering work done to date in this regard will be presented. The derivation of the theoretical model describing the behaviour as well as the implementation of it in a simulation will be discussed. Conclusions and recommendations based on the based on the work that has been performed will be made.

1.1 Waste Heat Recovery

Whether it is cooling water, a process stream or the exhaust from a kiln or furnace there are numerous process in which there is potential for the recovery of process heat. In place of either cooling down these process streams for the purpose of reuse or discarding them into the atmosphere or the ocean the goal of waste heat recovery is to facilitate the capture of the energy contained in a waste stream and use it for a practical purpose. Waste heat recovery can be used to generate power, preheat another stream or generate cooling via a refrigeration process.

There are many complications in the implementation of a waste heat recovery system which contribute as to whether or not it is viable which include the temperature and quality of the waste stream, heat exchanger material selection as well as size, possible corrosive or radioactive contaminants present in the waste stream, capital costs of the waste heat recovery system, the costs of altering and retrofitting an existing system and even the political policy can contribute as to whether waste heat recovery methods are attractive. There are also occasions when it is physically unrealistic to attempt a recovery of waste heat. The addition complications associated with the implementation of waste heat recovery do not form part of the goals of this study and will not be further discussed.

1.1.1 Sources of Waste Heat

In a 2008 report evaluating waste heat recovery opportunities in the United States it was found between 20 and 50 % of the energy that is used in industrial processes is lost as waste heat [1]. It was also estimated that roughly 60 % of all waste heat is at a low temperature which shows that if the methods of recovering low temperature waste heat became more effective and thereby more attractive the possibility exists that a significant quantity of energy could be recovered.

There are numerous sources of waste heat in a wide variety of industrial processes and is typically classified into three different categories by the temperature of the waste heat. These categories are high, medium and low temperature waste heat. Depending on the literature that is referenced, the values which determine the boundaries of these groupings can vary but for the purposes of this project the temperature range of the three different classes of waste heat will be defined as:

- High Temperature Waste Heat: above 650 °C
- Medium Temperature Waste Heat: from 200 to 650 °C
- Low Temperature Waste Heat: below 200 °C

With high temperature waste heat it is possible to obtain a larger temperature difference between mediums allowing for a larger quantity of energy to be transferred using a minimal heat exchanger surface area, but there are drawbacks to high temperature waste streams such as the selection and design of a suitable heat exchanger to account for thermal stresses, corrosion and possible chemical reactions. Medium temperature waste heat has none of these drawbacks to take into consideration while still being suitable for practical applications. Lastly, low temperature waste heat has the advantage of being abundantly available but at the drawback of requiring large heat transfer surface areas, inefficient recovery methods and the possibility that drawing energy from an already low temperature stream will lead to contaminants condensing in the heat exchanger and damaging it. Table 1 contains a number of examples of waste heat sources, adapted from [1], grouped into the three different categories of high, medium and low.

Table 1: Examples of Waste Heat Sources

| Temperature Class | Description | Temperature |
|-------------------|-------------------------------|-----------------|
| High | Nickel Refining Furnace | 1370 to 1650 °C |
| | Aluminium Furnace | 1100 to 1200 °C |
| | Coke Oven | 650 to 1000 °C |
| Medium | Steam Boiler Exhaust | 230 to 480 °C |
| | Engine Exhaust | 320 to 590 °C |
| | Cement Kiln | 450 to 620 °C |
| Low | Cooling Water | 40 to 200 °C |
| | Exhaust from Recovery Systems | 70 to 200 °C |
| | Ovens | 90 to 200 °C |

1.1.2 Methods of Waste Heat Recovery

It is possible to classify methods of waste heat recovery to internal and external methods. Where internal methods of waste heat recovery transfer thermal energy from one location or stream in a system to another location in the system. While external methods of waste heat recovery would be the production of electricity or for example refrigeration by fuelling an entirely separate external system with the waste heat stream. Examples of methods for internal waste heat recovery are a recuperator, a regenerator or a heat exchanger for pre-heating. External methods of waste heat recovery would be the implementation of a Rankine cycle, an Organic Rankine cycle, a Kalina cycle or a vapour absorption cycle.

The methods available for waste heat recovery are also dependant on the temperature of the waste heat stream from which it is desired to recover waste heat as different methods of waste heat recovery are most efficient under certain operating temperatures. Of the methods previously mentioned, the Rankine cycle would be used to recover high temperature waste heat, the Organic Rankine cycle for medium temperature waste heat and the Vapour absorption cycle for low temperature waste heat. While only a few examples of methods for waste heat recovery were discussed, the focus of this project is on the Vapour absorption cycle and due to this additional methods of waste heat recovery will not be discussed further.

1.2 Absorption Cycles

In order to introduce the operation of a vapour absorption system, the similarities between a vapour absorption and vapour compression system will be discussed. In the case of a typical vapour compression refrigeration system, the system is driven by a compressor which is powered by an electric motor whereas a vapour absorption system is driven by a source of heat. In Figure 1, a schematic of a vapour compression system can be seen where the working fluid or refrigerant of the system passes through the evaporator and evaporates thereby cooling an external stream after which the refrigerant is compressed to a higher pressure and temperature before it passes through a condenser where energy can be removed from the refrigerant. Thereafter, the refrigerant passes through an expansion device and continues to the evaporator where it can continue the operational cycle.

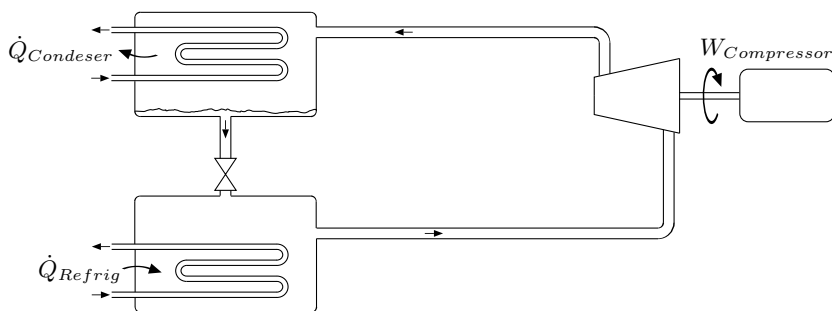


Figure 1: Type I Heat Pump Using a Compressor

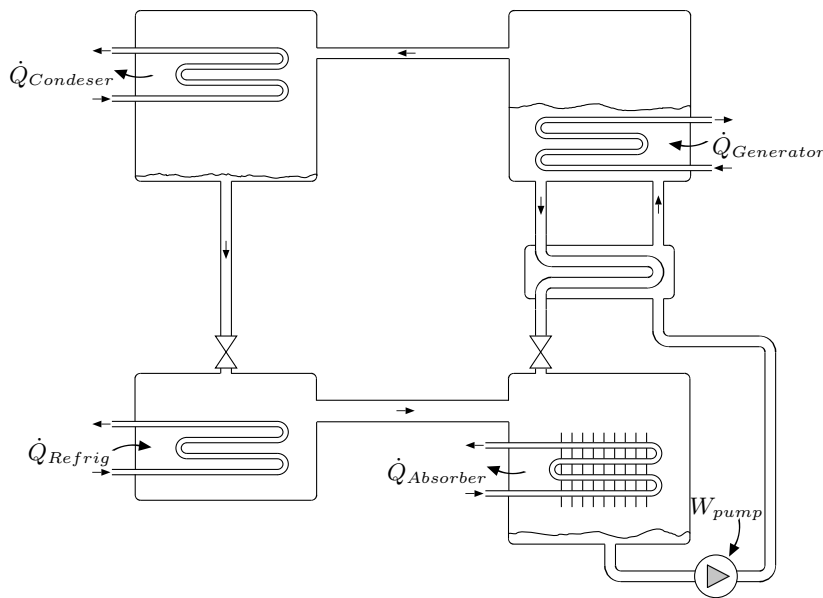


Figure 2: Type I Heat Pump Using the Principle of Vapour Absorption

Figure 2 shows the schematic diagram of a vapour absorption system where, similarly to a vapour compression system, a high temperature, high pressure refrigerant in vapour form is cooled in a condenser, after which it passes through an expansion device to an evaporator where it can provide cooling to an external stream. This is where the similarities between the vapour absorption and compression cycles end. In the case of a vapour absorption system, once the refrigerant is evaporated it enters the absorber where the vapour refrigerant is absorbed into the liquid solution. Due to the properties of the substances used in a typical vapour absorption system, the absorption of refrigerant vapour into the liquid solution is an exothermic process and because of this, the liquid solution has to be cooled in order to ensure operation of the system. The electric pump is used to pump the liquid solution to the generator, which is in the high pressure side of the system, where the liquid solution is heated and a small portion of the refrigerant is boiled off. A medium that has been heating by the sun can be used to heat the liquid solution in the generator, but the source of heat that is of interest to this project is process heat or waste heat. While a portion of the refrigerant is boiled off the liquid solution the remainder of the liquid solution, which is warmer than it was when it entered the generator, returns to the absorber and the refrigerant that was boiled off continues to the condenser.

The purpose of the solution heat exchanger is to transfer energy from the hot solution returning to the absorber from the generator to cooler stream that is entering the generator. A vapour absorption system will function without a solution heat exchanger, but the inclusion of a solution heat exchanger will improve the coefficient of performance (COP) of the system by reducing the amount of energy needed to heat the solution in the generator as well reducing the amount of energy that has to be removed from the system in the absorber.

Another means of highlighting the differences between the operation of a vapour compression cycle and a vapour absorption cycle is to investigate the manner in which the COP is defined for the two different systems. COP is defined as the ratio between the quantity of useful work produced by the system and the amount of energy or work supplied to the system. In the case of a vapour compression system, where \dot{Q}_{Refrig} is the amount of refrigeration work that the system provided and $W_{Compressor}$ is the amount of work that the compressor required to drive the system, the following equation describes the COP:

$$COP_{VCS} = \dot{Q}_{Refrig} / W_{Compressor} \quad (1)$$

Whereas for a vapour absorption cycle the manner in which the system is powered differs with the vapour compression system, the amount of energy supplied to the system is comprised of the quantity of heat energy that is supplied to the generator or $\dot{Q}_{Generator}$ as well as the work performed by the pump, W_{Pump} . The amount of energy required to pump the liquid solution is significantly smaller than the \dot{Q}_{Refrig} and $\dot{Q}_{Generator}$ and due to this it is at times ignored in the calculation of the COP. The sum of these two quantities, $\dot{Q}_{Generator}$ and W_{Pump} , is the total amount of energy which is supplied to the system to produce the refrigeration \dot{Q}_{Refrig} .

$$COP_{VAS} = \dot{Q}_{Refrig} / (\dot{Q}_{Generator} + W_{Pump}) \quad (2)$$

Although the COP of a vapour absorption system is typically lower than 1 and therefore lower than the typical COP of a vapour compression system, it can be reasoned that due to the vapour absorption system being driven by a resource that would have been thrown away instead of electrical energy in the case of a compressor driven system that its operational costs are less than those of a vapour compression system. This advantage of reduced operational costs by recovering waste heat are offset by the capital costs associated with the construction of a vapour absorption system, but the cost analysis of a vapour absorption system is beyond the scope of this document and will not be discussed further.

1.2.1 Working Fluid

In a vapour absorption system the working fluid is made up of a two, or in specialized cases three, substances where these two substances are referred to as the sorbent and the refrigerant. In this document, this pair of substances is referred to as the liquid solution. The function of the sorbent is to absorb the fluid refrigerant and allow it to be boiled off at a lower temperature than would be possible if it was a pure substance. There are numerous criteria which a pair of substances have to fulfil in order to be viable for use in an absorption system and it has been shown that many combinations are feasible [5], but this will not be discussed further in this document (for additional information please refer to [6]).

When working with a liquid solution composed of two substance such as the combinations of water/lithium-bromide and ammonia/water the concentration of the solution has to be defined in order to properly describe the state of the solution. Equation 3 describes the manner in which the concentration of a solution is defined and it can be seen from the manner in which concentration is defined that as the solution loses refrigerant in the generator, the concentration of the solution will increase. The solution entering the generator is often referred to as the “weak”

solution and as a portion of the refrigerant is boiled off, the concentration increases and leaves the generator. This solution leaving the generator is referred to as the “strong” solution as it is stronger in sorbent than when it entered.

$$C = \text{mass}_{\text{sorbent}} / (\text{mass}_{\text{refrigerant}} + \text{mass}_{\text{sorbent}}) \quad (3)$$

Currently the most widely used combinations are ammonia/water, water/lithium-bromide and ammonia/hydrogen/water [7]. Where ammonia/hydrogen/water are typically used in caravan and hotel fridges and ammonia/water as well water/lithium-bromide are widely used to provide for refrigeration. In an ammonia/water system it is possible to provide for refrigeration at temperatures below zero degrees Celsius due to ammonia being the refrigerant while in the case of a water/lithium-bromide system, water is the refrigerant and this limits the system’s refrigeration potential to temperatures above the freezing point of water. An additional drawback of water/lithium-bromide is that there is the possibility that under specific conditions, the solution crystallizes which will lead to the system ceasing to function in a proper manner.

Although an ammonia/water and a water/lithium-bromide system can be represented in a very similar schematic diagram the actual physical characteristics differ vastly. An ammonia/water system operates at pressures well above atmospheric pressure and requires large pressure vessels while a water/lithium-bromide system operates at vacuum which in itself has its own complications. Additionally, in an ammonia/water system the vapour produced in the generator is not pure ammonia and if the water present is not removed it will negatively affect the operation of the system [2]. Material selection also has to be taken into account as copper and its alloys cannot be used in the presence of ammonia and with the water/lithium-bromide system if the quality of the vacuum is not satisfactory, the liquid solution will corrode copper and steel.

Due to the complications and hazards associated with the use of ammonia, it was decided to focus on water/lithium-bromide vapour absorption technology for this project. In addition to this, it was desired that it be possible to visually inspect the operation of the vapour absorption system and this would be infeasible with ammonia/water system.

The properties of a liquid solution like water/lithium-bromide are available in literature. The American Society of Heating, Refrigerating and Air-Conditioning Engineers fundamentals handbook [6] contains tables, graphs and equations detailing the properties of water/lithium-bromide as well as ammonia/water. The enthalpy of saturated water or steam is a function of only temperature, but for liquid solutions like water/lithium-bromide the enthalpy of the liquid solution is dependant on the temperature and the concentration of the solution, this can be seen in Figure 3.

1.2.2 Dual Function

Vapour absorption technology has been used for a significant amount of time to generate refrigeration [3], but the possibility to generate electricity from a vapour absorption cycle by incorporating a turbine and electrical generator has been previously considered and investigated [4, 8]. The concept of “dual function” applied to a vapour absorption system would be that the system either generates power or refrigeration depending on the demand of environmental conditions, but the possibility exists that both power and refrigeration can be provided concurrently.

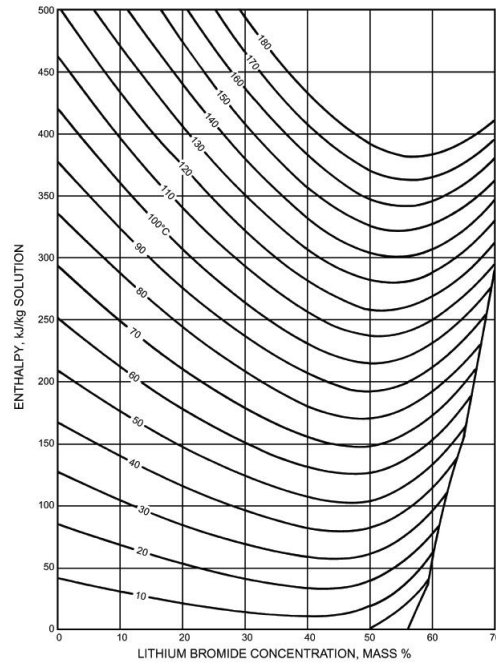


Figure 3: Enthalpy Diagram for Water/Lithium-Bromide

Figure 4 shows the schematic layout of a dual function absorption system (DF-VAS) where the condenser and expansion device have been replaced by a turbine. The shaft of the turbine would be connected to a electrical generator to produce usable electricity while the heat exchanger can provide for refrigeration. An additional component that is included is the super-heater which is implemented to ensure that the vapour entering the turbine is at the highest possible temperature based on the temperatures available to the system. The vapour generation and absorption portion of system would operate as a typical vapour absorption system. The refrigerant would be undergo additional heating before passing through the turbine and the evaporative heat exchanger to be absorbed back into the liquid solution in the absorber. Due to the incorporation of additional components into the dual function system, the COP for a dual function vapour absorption system would be defined as:

$$COP_{DFVAS} = (\dot{Q}_{Refrig} + W_{Turbine}) / (\dot{Q}_{Super-heater} + \dot{Q}_{Generator} + W_{Pump}) \quad (4)$$

Where the useful outputs of the system are the refrigeration work, \dot{Q}_{Refrig} , and the shaft output of the turbine, $W_{Turbine}$. Similarly to the typical vapour absorption system, the system required heat in the generator and pump work but in this configuration of a dual function system, additional energy is added to super-heat the vapour entering the turbine.

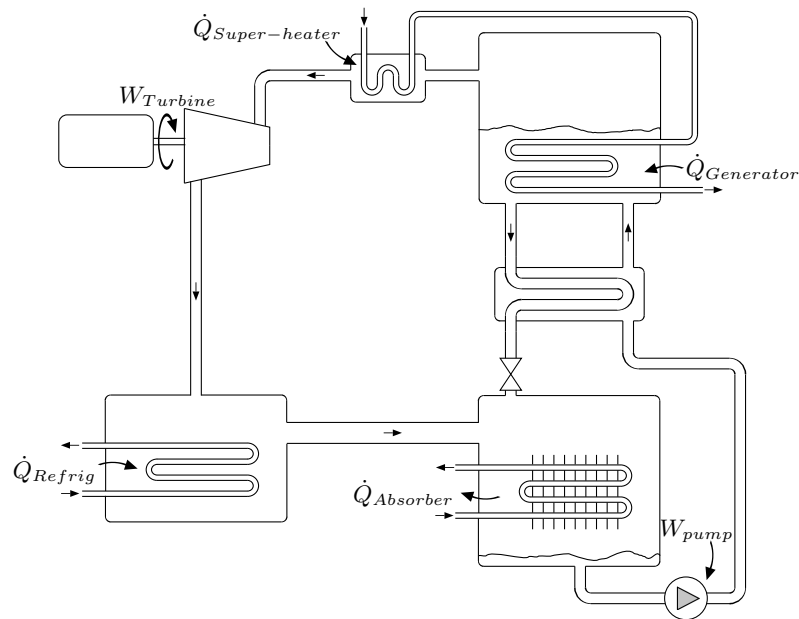


Figure 4: Schematic of a Dual Function Vapour Absorption System

1.3 Objectives

The objectives of this project all build towards the future, further investigation and development of a dual function vapour absorption system. The activities that are planned for this project are:

- Steady State Simulation
- Experimental Apparatus
- Verification of Steady State Simulation:
- Transient Simulation

The development of a steady state simulation that describes an operating point of a vapour absorption system will be the first objective of the project. The design, fabrication and operation of an experimental apparatus will not only help in attaining a greater understanding of the behaviour of a vapour absorption system, but will allow for the results obtained from the theoretical simulation to be verified. An additional benefit of having an operational vapour absorption system in the university will be that it can be incorporated into other projects in the future. The development of a transient simulation to describe the transient behaviour of a vapour absorption system may be incorporate into the study.

2 Proposed Methods

To model the steady state operation of a vapour absorption system, the system was broken up into four main control volumes upon which the principles of the conservation of energy and the conservation of mass were applied. Thereafter, a computer program was developed to iteratively solve for a steady state solution.

2.1 Theory

This subsection of the report will illustrate and describe the manner in which the control volumes were established for the major components of the vapour absorption system and how the steady state versions of the conservation of mass (Equation 5) and the conservation of energy (Equation 6) were applied to them. Equation 7 shows the manner in which the heat transfer in the components will be handled. Due to the size limitations of this document the complete derivation of the all of the equations that describe the different control volumes in the components cannot be discussed, but the equations of importance will be discussed for each component.

$$0 = \sum \dot{m}_i - \sum \dot{m}_o \quad (5)$$

$$0 = \sum \dot{m}_i \times h_i + \sum \dot{Q}_i - \sum \dot{m}_o \times h_o - \sum \dot{Q}_o \quad (6)$$

$$\dot{Q} = UA \times \Delta T \quad (7)$$

The function of the generator is to separate a portion of the refrigerant from the liquid solution and this is done by heating the solution via a heat exchanger. Figure 5 shows the streams that are of relevance to the generator. Which include the waste heat stream passing through the heat exchanger, the “weak” stream of solution entering the generator and the “strong” solution leaving it after a portion, \dot{m}_{evap} , was boiled off.

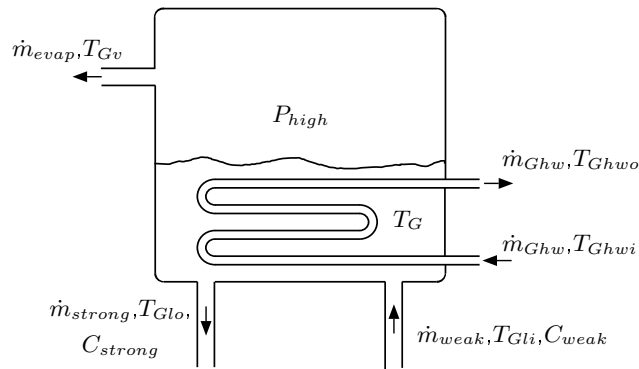


Figure 5: Model of Generator Streams

The conservation of mass applied to the total mass flow rates passing through the generator and the total mass flow rate of lithium-bromide passing through the generator yields the following equations:

$$\dot{m}_{strong} = \dot{m}_{weak} - \dot{m}_{evap} \quad (8)$$

$$C_{strong} = (\dot{m}_{weak} \times C_{weak}) / \dot{m}_{strong} \quad (9)$$

The following equation describes the amount of energy that will be transferred to the liquid solution via the heat exchanger:

$$\dot{Q}_{Generator} = U A_G \times (\bar{T}_{Ghw} - T_G) \quad (10)$$

The conservation of energy applied to the entire generator gives the following equation:

$$0 = \dot{m}_{weak} \cdot h_{Gli} - \dot{m}_{strong} \cdot h_{Glo} - \dot{m}_{evap} \cdot T_{Gv} + \dot{Q}_{Generator} \quad (11)$$

Where, after substituting equations rearranging the equation with T_G as the subject of the formula gives:

$$T_G = \bar{T}_{Ghw} + (\dot{m}_{weak} \cdot h_{Gli} - \dot{m}_{evap} \cdot h_{Gv} - (\dot{m}_{weak} - \dot{m}_{evap}) \cdot h_{Glo}) / (U A_G) \quad (12)$$

When the conservation of energy and that of mass is applied to the the streams of the condenser as seen in Figure 6, the following equation for the value of the liquid refrigerant can be derived:

$$T_C = \bar{T}_{Ccw} + (\dot{m}_{evap} \cdot h_{Gv} - \dot{m}_{evap} \cdot h_{Csat}) / (U A_C) \quad (13)$$

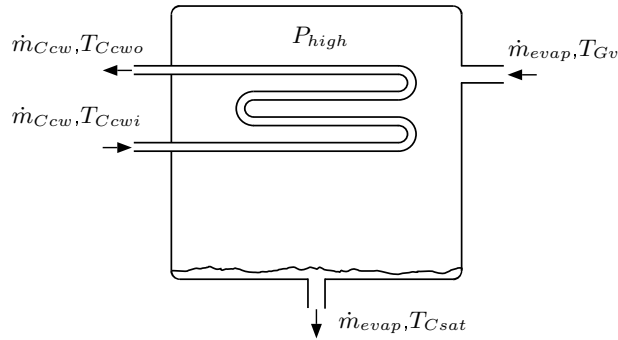


Figure 6: Model of Condenser Streams

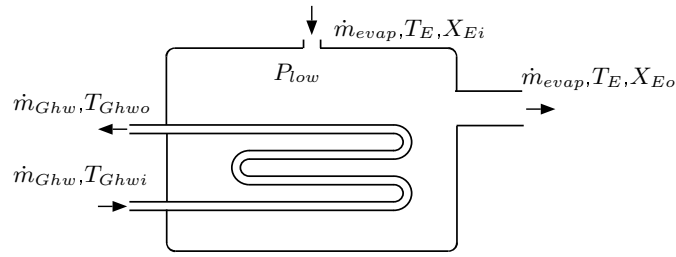


Figure 7: Model of Evaporator Streams

In a similar fashion an equation for the temperature in the evaporator, see Figure 7, can be derived:

$$T_E = \bar{T}_{E_{cw}} + (\dot{m}_{evap} \cdot h_{C_{sat}} - \dot{m}_{evap} \cdot h_E) / (U A_E) \quad (14)$$

When determining an equation for the last of the major components, the absorber seen in Figure 8, the following equation is derived:

$$T_A = \bar{T}_{A_{cw}} + (\dot{m}_{evap} \cdot h_E + (\dot{m}_{weak} - \dot{m}_{evap}) \cdot h_{G_{lo}} - \dot{m}_{weak} \cdot h_A) / (U A_A) \quad (15)$$

The pressures in the in the system are dependant on the temperature at which condensation and evaporation is occurring. The “high” and “low” pressures of the system can be calculated from a saturation pressure function:

$$P_{high} = P_{sat}(T_C) \quad (16)$$

$$P_{low} = P_{sat}(T_E) \quad (17)$$

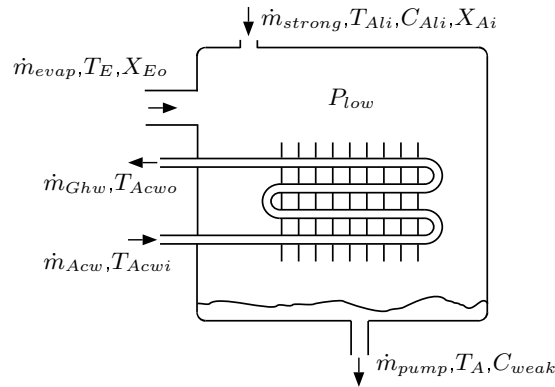


Figure 8: Model of Absorber Streams

2.2 Computer Program

The equations described in the previous section were incorporated into a computer simulation written in SciLab ©, the equations describing the properties of water/lithium-bromide [6] as well as water [9] were also incorporated into the program. The program starts with declaring the values of the external streams that heat the generator, cool the condenser, undergo cooling in the evaporator and cool the absorber. Thereafter initial assumptions are made for the temperatures in the four main components of the system, after which the iterative calculation of a steady state solution begins. Figure 9 shows the process in which the computer code attempts to determine the steady state operating point of a vapour absorption system.

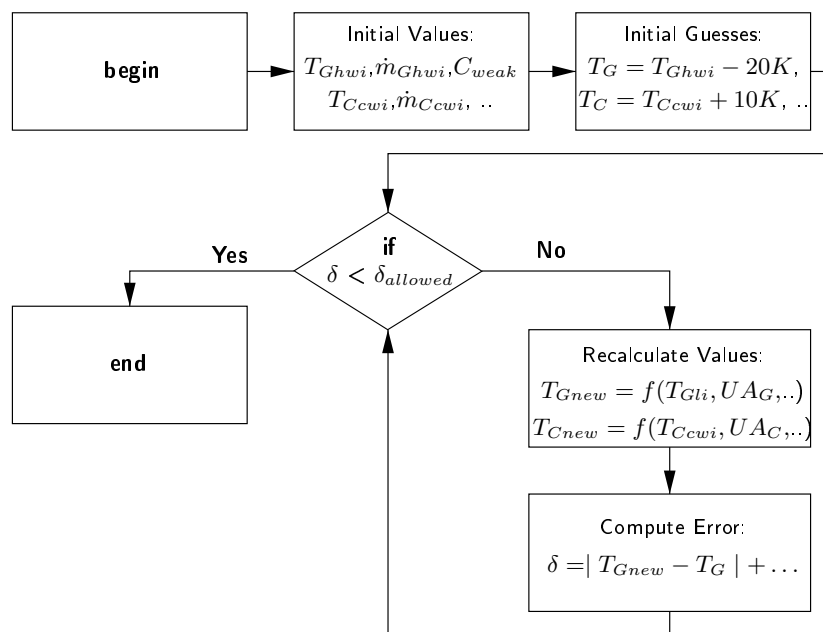


Figure 9: Flow Diagram

The solution heat exchanger was not included in the current version of the theoretical simulation. This was done in order to focus on the operation of the four major components of the vapour absorption system and will not have a significant impact on the results.

3 Research Methodology

After the completion of the literature study, work began on the steady state simulation as well as the experimental apparatus. Results obtained from the steady state simulation can be compared with results found in literature. Once the experimental apparatus is operation it will be possible to obtain experimental results. Also, the steady state simulation will be adjusted to incorporate the physical characteristics of the experimental apparatus and thereafter it will be possible to make an assessment as to validity of the results obtained in the simulation. Once this has been

completed it will be possible to make an assessment concerning whether or not the results of the project have fulfilled the initial goals and objectives of the project.

4 Results

As far as the theoretical simulation of a vapour absorption system are concerned the current approach that is implemented to simulate the operating conditions of a vapour absorption system as seen in the previous section produces feasible results as seen in seen Table . There are various simulation packages that are used to simulate the operation of a vapour absorption system, but these packages are not currently accessible to the author in order to verify the results. In addition to this,

Table 2: Results from Theoretical Simulation

| | Symbol | Value |
|---------|------------------|---------------|
| Inputs | U_{AG} | 400 W/(m.K) |
| | U_{AC} | 1600 W/(m.K) |
| | U_{AE} | 800 W/(m.K) |
| | U_{AA} | 500 W/(m.K) |
| | T_{Ghwi} | 85 °C |
| | T_{Cwi} | 25 °C |
| | T_{Ewi} | 12 °C |
| | T_{Acwi} | 25 °C |
| | C_{weak} | 50 % |
| | \dot{m}_{weak} | 0.03 kg/s |
| Outputs | T_G | 63.80 °C |
| | T_C | 28.07 °C |
| | T_E | 7.01 °C |
| | T_A | 36.09 °C |
| | P_{high} | 3799.17 Pa |
| | P_{low} | 1003.04 Pa |
| | \dot{Q}_G | 6479.83 W |
| | \dot{Q}_G | 4918.57 W |
| | \dot{Q}_G | 3988.91 W |
| | \dot{Q}_G | 5546.56 W |
| | COP | 0.615 |
| | \dot{m}_{evap} | 0.001983 kg/s |
| | C_{strong} | 54.54 % |

5 Conclusions and Recommendations

The initial direction that this project had was the implementation of an ammonia/water system and the design for an experimental apparatus using ammonia/water system was started, but due to the complications attached to the use of the combination of ammonia/water the decision was made to focus on simulating and constructing a water/lithium-bromide system. Progress has been made with theoretical simulation of a vapour absorption system, but the validity of the results obtained has not been extensively verified. The design of the water/lithium-bromide experimental apparatus is currently in its fourth iteration and once the design has been finalized, the construction of the apparatus will commence.

The project will continue from its current state with the finalization of the design for the experimental apparatus, followed by the construction and operation. Concurrently with the work on the experimental apparatus, improvements will be made to the computer simulation. Once the experimental apparatus is operation it will be possible to gather experimental data from the system which.

There is still a significant amount of work to be performed in order to complete the goals of the project and although alterations have been made to the planned manner in which the goals would be achieved, the goals of the project are still within reach.

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