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NH3/H2O ABSORPTION CYCLE - MATHEMATICAL MODEL

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Abstract

The rising interest in absorption cycles for refrigeration and air conditioning systems is driven by their significant benefits in reducing carbon emissions. Among these cycles, the NH3/H2O absorption cycle is particularly appealing. This paper provides a comprehensive overview of the system process, simulation methodology, and mathematical NH3/H2O cycle model, including a detailed description of the modeling technique.

1. Introduction

There has been a significant surge in interest in refrigeration or air conditioning systems absorption cycles in recent times. It possesses substantial benefits that help decrease carbon emissions. The NH3/H2O cycle is the most appealing absorption cycle. This paper presents a concise overview of the system process, simulation methodology, and the NH3/H2O mathematical model. The modeling technique is also executed concisely.

1.1 Working principles & system description

An absorption refrigerator utilizes a heat source, such as solar energy, a flame fed by fossil fuels, waste heat from manufacturers, or district heating systems, to generate the necessary energy for the cooling process. The system employs two coolants, with the first coolant carrying out evaporative cooling and subsequently being absorbed by the second coolant. The restoration of the two coolants to their original states requires heat input. The method can also be applied to cool buildings by utilizing the excess heat generated by a gas turbine or water heater. Absorption refrigerators are frequently employed in recreational vehicles, campers, hotels, and caravans due to their ability to operate on propane fuel instead of electricity. Conventional absorption refrigerators employ a refrigerant that has a shallow boiling point, similar to compressor refrigerators, which is below -18°C (0 °F). Compression refrigerators commonly utilise HCFC or HFC refrigerants, whilst absorption refrigerators typically employ ammonia or water as the primary coolant. Absorption refrigerators also require a secondary fluid capable of absorbing the coolant, such as water (for ammonia) or brine (for water). Both kinds employ evaporative cooling, where the refrigerant undergoes evaporation (boiling), thereby extracting heat and producing the desired cooling effect. The primary distinction between the two systems lies in the method by which the refrigerant undergoes a transformation from a gaseous state to a liquid state, enabling the cycle to be repeated. An absorption refrigerator utilises a heat-based process to convert the gas back into a liquid, without the need for any moving elements other than the fluids involved. The absorption cooling cycle can be delineated into three distinct phases:Evaporation is the process in which a liquid refrigerant transforms into a gas in a low-pressure environment, thereby absorbing heat from its surroundings, such as the compartment of a refrigerator. Due to the low partial pressure, the temperature required for evaporation is correspondingly low.Absorption: The second fluid, which is in a state of reduced quantity, draws out the refrigerant that has now become gaseous, thereby creating a low partial pressure. As a result, a liquid saturated with refrigerant is generated, which subsequently moves on to the following stage:Regeneration: The liquid saturated with refrigerant is heated, causing the refrigerant to transition into a gaseous state.

Evaporation takes place in the lower section of a narrow tube, where the bubbles of refrigerant gas propel the liquid that has been depleted of refrigerant into a higher chamber. From there, the liquid will flow downward due to gravity into the absorption chamber. The hot gaseous refrigerant moves through a heat exchanger, releasing its heat to the environment (such as the surrounding air at ambient temperature), and condenses at an elevated location. The liquid refrigerant will flow downwards due to gravity to provide the evaporation process.

1.2 System description

The operation of the ammonia-water absorption refrigeration system is founded on the fundamental principles of vapour absorption refrigeration. Ammonia serves as the refrigerant, while water functions as the absorbent in this system. The ammonia-water absorption system (NH_3/H_2O) is utilised in both residential and commercial settings where temperatures exceeding 32 degrees Fahrenheit are necessary. An important benefit of the ammonia-water solution is that water exhibits a high affinity for ammonia, allowing them to dissolve in one other under a wide range of operating conditions commonly encountered in various refrigeration applications. In addition, the ammonia-water solution exhibits exceptional stability and compatibility with various materials, with the exception of copper and its alloys, which are susceptible to corrosion in the presence of ammonia. Figure (1) illustrates the standard NH_3/H_2O absorption cycle. The NH_3-H_2O absorption process includes the following components:Air conditioning serves as a cooling load and is connected to the evaporator unit. The fan cooling unit is connected to the air cooler unit. The cooling effect is produced in the evaporator by the liquid condition of the refrigerant, which is pure ammonia (NH_3). It absorbs thermal energy from the substance to be cooled and undergoes evaporation. Subsequently, the ammonia transitions to the absorber in its gaseous form.The weak solution of ammonia-water is already present in the absorber. The water, acting as the absorbent in the solution, is not fully saturated and has the ability to absorb additional ammonia gas. Upon entering the absorber, the ammonia from the evaporator is quickly absorbed by water, resulting in the formation of a concentrated solution of ammonia and water. Heat is released during the absorption process, which might decrease the ability of water to absorb ammonia. Therefore, the absorber is cooled using cooling water. The absorber creates a concentrated solution of ammonia-water as a result of ammonia absorption.The generator unit is connected to the solar component. The flash evaporation tank will provide sufficient steam to power the generator unit. The concentrated solution of ammonia refrigerant and water absorbent is heated using an external heat source, such as steam or hot water. Additionally, it can be heated by alternative sources such as natural gas, electric heaters, waste exhaust heat, and so on. As a result of being heated, the refrigerant ammonia undergoes vaporisation and exits the generator.As a result of the cooling process, the water vapour that is left mixes with the ammonia refrigerant and undergoes condensation, along with some ammonia particles. The dilute solution of water and ammonia flows downwards into the condenser and then into the generator. The vaporised ammonia refrigerant, in its pure form, is subjected to high pressure and subsequently directed into the condenser. In this component, the refrigerant is effectively cooled through the utilisation of water. Ammonia, a refrigerant, undergoes a phase change into a liquid form and then flows through the expansion valve, causing a dramatic decrease in both its temperature and pressure. The ammonia refrigerant is introduced into the evaporator, where it generates the desired cooling effect. This loop perpetually repeats without interruption. Meanwhile, while ammonia undergoes vaporization in the generator, a dilute solution of ammonia and water remains within it. The solution undergoes expansion in the expansion valve and is then returned to the absorber, where the cycle is repeated. The cycle is regarded as a closed system in relation to the flow of work passing through it.

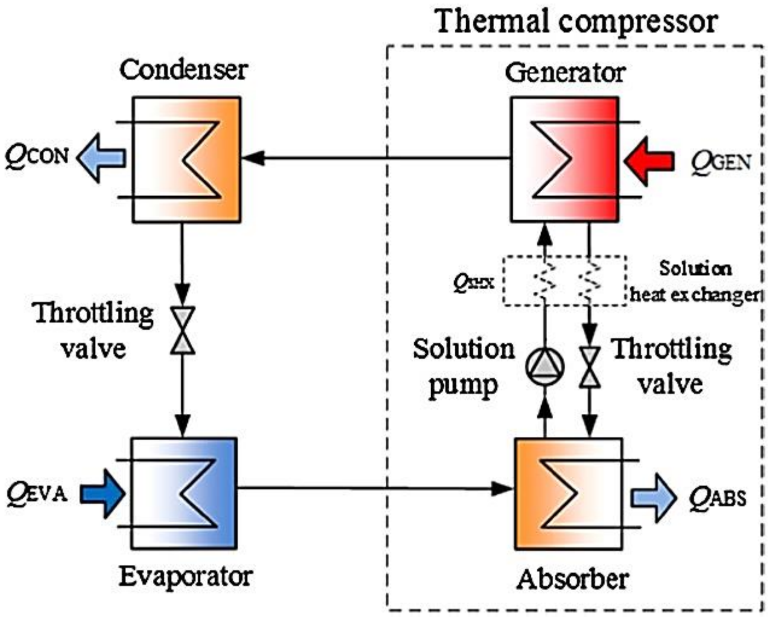

Figure (1) Typical NH3/H2O absorption cycle.

2.1 Modelling & simulation

2.2 The Modelling Methodology & assumptions

The characteristics that are not known include the areas, dimensions, mass flow rates, and the overall process temperatures, as well as any other computed physical qualities. In absorption operations, it is crucial to define the cooling load capacity in order to accurately calculate the thermal loads on the evaporator, absorber, condenser, and generator. In this work, the desired refrigerant load capacity in ton refrigerant $TR = \frac{Q_{evp},\ kW}{3.517}$ is specified as a known parameter in order to calculate all design aspects and mass flow rate through the cycle.

By specifying the system cooling load, one may determine the necessary thermal load. In addition, the necessary design constraints and performance estimates would be immediately approved. The modelling assumptions can be found in Table 1. The modelled blocks and lookup tables contain data for the saturated liquid and vapour phases, including information on pressure, temperature, enthalpy, specific volume, and specific entropy. The NIST [1] web chemistry book is the primary source for obtaining physical characteristics. Table 1 presents the design operating conditions and the assumptions that have been taken into account in this study. Table 2 presents the mathematical model utilised in this study. The suggested model control panel (refer to Figure 2) is a graphical user interface designed to manage the system inputs. All units have been created with a consistent approach, taking into account the behaviour of input and output streams that connect them. An iteration loop has been implemented to calculate the forward and backward streams. The model browser was developed using the Matlab/Simulink model environment. It possesses several characteristics, including:The model facilitates the effortless modification of plant factors and adaptation to various operating situations, while providing maximum flexibility in stream allocation.The stream connection will be crucial in establishing connections between various units.

Table 1: Data assumptions for the ETC/PTC-H2O/LiBr and NH3/H2O configurations.

Unit Process	Assigned Data	Calculated Data
NH3/H2O: - **Absorption working fluid is NH3-H2O**	✓ Absorber temperature, ºC=30-35 ✓ Generator temperature, ºC=80-90 ✓ Condenser temperature, ºC=40-45 ✓ Hot air temperature, ºC=35 ✓ Target cooled air temperature, ºC=20 ✓ Evaporator temperature, ºC=5-10 ✓ Cooling load, TR=varying ✓ Condenser effectiveness, %=80 ✓ Cooling tower effectiveness, %=60 ✓ Fan system efficiency, %=85 ✓ Pumping system efficiency, %=75	**Absorption Unit:** ➢ Weak & strong solutions, kg/s ➢ *Design data ➢ Thermal power, kW ➢ Total cycle flow rate, kg/s ➢ Generator power, kW ➢ Cooling fan power, kW ➢ COP ➢ Relative performance ➢ Exergy destruction, kW
Notes:	▪ Data are run out based on steady state operating conditions. ▪ Ambient temperature is fixed as 25ºC for all process runs. ▪ *Design data means area, length, width, etc…	

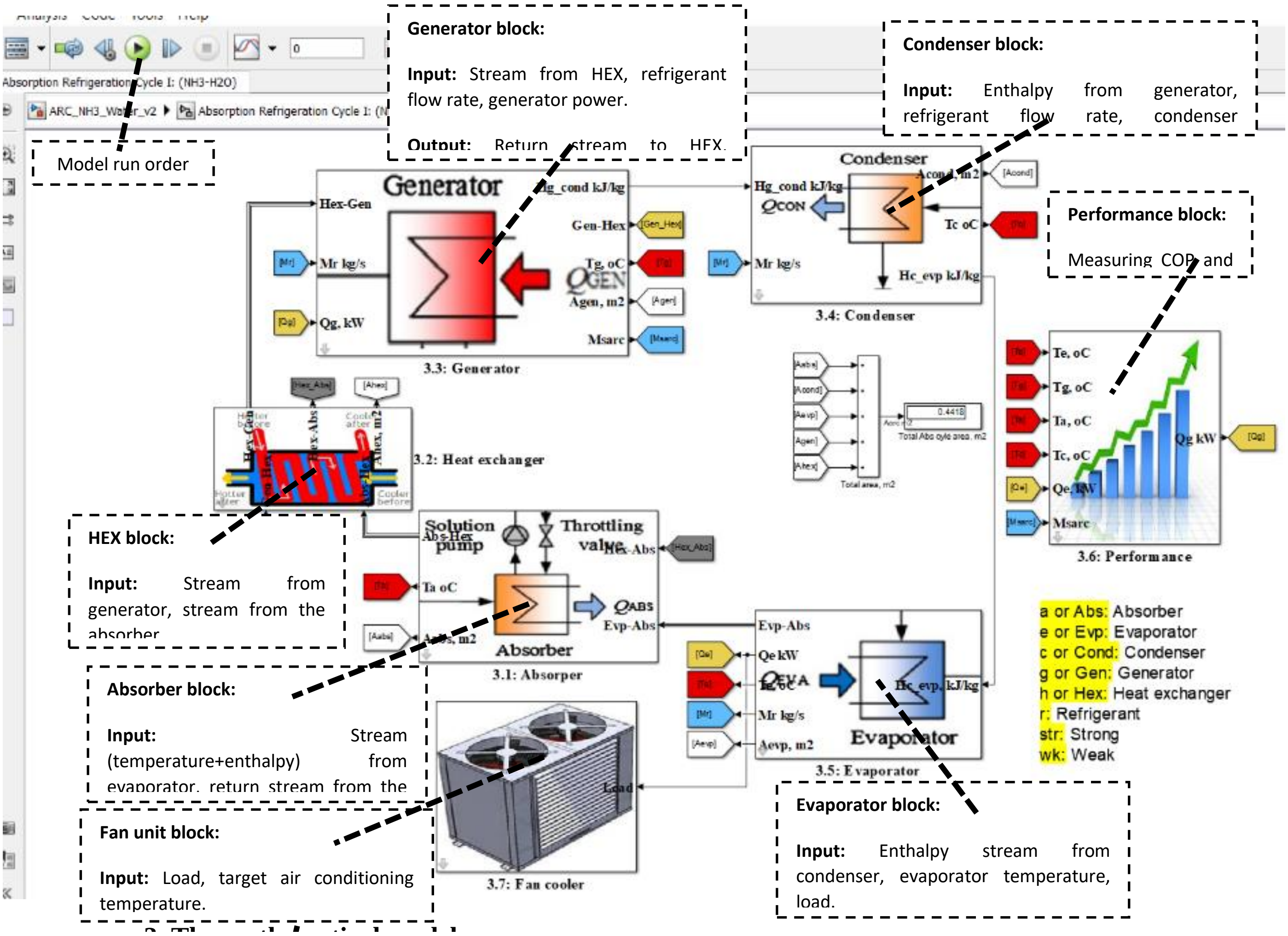

Figure (2) NH3/H2O model browser control panel under matlab/simulink toolbox.

The process modelling via MATLAB/Simulink toolbox has been performed based on the following mathematical model that been presented in Table 2.

Table 2: The mathematical model of the system units.

Absorption unit [2, 5]:

1. The absorber unit [2, 4]:

For absorber unit, the flow factor parameter is an especially important parameter in the calculation procedures of the thermal power through the mode. The flow rate ratio factor *f* is calculated based on the absorber temperature as following [2]:

$$f = 0.4067 \times exp(0.05606 \times T_a) + 5.09e - 07 \times exp(0.3293 \times T_a) \ldots\ldots (1)$$

The strong solution mass flow rate, kg/s, M_{str} is calculated based on total refrigerant flow rate and the flow factor:

$$M_{str} = M_r \times f \ldots\ldots (2)$$

The weak solution mass flow rate, kg/s:

$$M_{wk} = M_{str} - M_r \ldots\ldots (3)$$

The Absorber thermal power, kW is calculated based on the energy balance across the absorber between inlet and outlet streams, where *H* denotes to enthalpy, kJ/kg:

$$Q_a = M_r \times \left(H_{e-abs} + (M_{wk} \times H_{hex-a}) - (M_{str} \times H_{a-hex})\right) \ldots\ldots (4)$$

Overall heat loss, kW/m^{2o}C [5]:

$$U_a = 1.6175 + 0.1537e - 3 \times T_a + 0.1825e - 3 \times T_a^2 - 8.026e - 8 \times T_a^3 \ldots\ldots (5)$$

The absorber area, m^2:

$$A_a = \frac{Q_a}{U_a \times \Delta T} \ldots\ldots (6)$$

2. Heat exchanger unit [2-5]:

For heat exchanger unit, the mass flow ratio is obtained as following:

$$f = \frac{M_{str}}{M_{str} - M_{wk}} \ldots\ldots (7)$$

The NH3 concentration percentage [2, 3]:

$$XNH3 = \frac{\frac{M_{str}}{f}}{M_r + M_{wk}} \ldots\ldots (8)$$

The outlet heat exchanger stream temperature towards the absorber unit, ^{o}C is calculated based on the heat exchanger effectiveness:

$$T_{hex\_a} = T_g - \left(\varepsilon_{hex} \times \left(T_g - T_a\right)\right) \ldots\ldots (9)$$

Outlet heat exchanger temperature to the generator unit, ^{o}C:

$$T_{hex\_g} = T_a + \left(\varepsilon_{hex} \times \left(T_g - T_a\right)\right) \ldots\ldots (10)$$

The enthalpy of NH3/H2O solution outlet to the absorber unit, kJ/kg is calculated based on temperature, ^{o}K and specific heat capacity, kJ/kg^{o}K:

$$H_{hex\_a} = Cp_{NH3}(T_{hex-a} + 273) \times (T_{hex-a} + 273) \ldots\ldots (11)$$

Where the specific heat capacity for NH3, kJ/kg^{o}K:

$$Cp_{NH3} = \frac{27.31+0.02383\times T+1.707e-5\times(T^2)-1.185e-8\times(T^3)}{17.0305} \ldots\ldots (12)$$

The enthalpy of NH3/H2O solution outlet to the generator unit, kJ/kg:

$$H_{hex\_g} = Cp_{NH3}\left(T_{hex-g} + 273\right) \times \left(T_{hex-g} + 273\right) \ldots\ldots (13)$$

The heat exchanger thermal power is then calculated based on the thermal energy balance between inlet and outlet streams, kW:

$$Q_{hex} = (M_{str} - M_{wk}) \times (f - 1) \times \left(H_{g-hex} - H_{hex-a}\right) \ldots\ldots (14)$$

Enthalpy stream from the absorber towards the heat exchanger, kJ/kg:

$$H_{a-hex} = H_{hex-g} - \left(\left(\frac{f-1}{f}\right) \times \left(H_{g-hex} - H_{hex-a}\right)\right) \ldots\ldots (15)$$

Mean temperature, ^{o}C:

$$T_{hex_m} = \frac{T_{hex-a}+T_{hex-g}}{2} \ldots\ldots (16)$$

Overall heat loss, kW/m^{2o}C:

$$U_{hex} = 1.6175 + 0.1537e - 3 \times T^1_{hex_m} + 0.1825e - 3 \times T^2_{hex_m} - 8.026e - 8 \times T^3_{hex_m} \ldots\ldots (17)$$

Heat exchanger area, m^2:

$$A_{hex} = \frac{Q_{hex}}{U_{hex}\times \Delta T} \ldots\ldots (18)$$

3. Generator unit [3-5]:

Outlet enthalpy to the HEX, kJ/kg is calculated based on energy balance between both units and flow rate ratio:

$$H_{g\_hex} = \frac{\left(\frac{Q_g}{M_r}\right)-H_{g-cond}+\left(f\times H_{hex-g}\right)}{f-1} \ldots\ldots (19)$$

Overall heat loss, kW/m^{2o}C through the generator tubes is calculated as following [4]:

$$U_g = 1.6175 + 0.1537e - 3 \times T^1_g + 0.1825e - 3 \times T^2_g - 8.026e - 8 \times T^3_g \ldots\ldots (20)$$

Generator area, m^2:

$$A_g = \frac{Q_g}{U_g \times \Delta T} \ldots\ldots (21)$$

Inlet driving steam mass flow rate, kg/s is calculated based on the latent heat, kJ/kg from the heat source:

$$Ms = \frac{Q_g}{0.95 \times h_{fg}} \ldots\ldots (22)$$

Where, h_{fg} is the latent heat of distillate vapor evaporation (pure Ammonia) [2-5]:

$$h_{fg} = -46.53 \times exp(0.02096 \times T) + 1305 \times exp(-0.001835 \times T) \ldots\ldots (23)$$

4. Condenser unit:

Condenser thermal power, kW:

$$Q_c = M_r \times \left(H_{g-cond} - H_{cond-e}\right) \ldots\ldots (24)$$

The overall heat loss, kW/m^{2o}C:

$$U_c = 1.6175 + 0.1537e - 3 \times T_c^1 + 0.1825e - 3 \times T_c^2 - 8.026e - 8 \times T_c^3 \ldots\ldots (25)$$

The condenser area, m^2:

$$A_c = \frac{Q_c}{U_c \times \Delta T} \ldots\ldots (26)$$

Inlet cooling water enthalpy, kJ/kg:

$$H_{c_{cwi}} = 421.2 \times exp\left(0.004008 \times T_{c_{cwi}}\right) - 435.9 \times exp\left(-0.007559 \times T_{c_{cwi}}\right) \ldots\ldots (27)$$

Outlet cooling water enthalpy, kJ/kg:

$$H_{c_{cwo}} = \left(\frac{Q_c}{M_{cw}}\right) + H_{c_{cwi}} \ldots\ldots (28)$$

5. Evaporator unit:

Thermal load on evaporator unit, kW [6]:

$$Q_e = Load_{TR} \times 3.517 \ldots\ldots (29)$$

Refrigerant mass flow rate, kg/s can be calculated based on the energy balance across the evaporator:

$$M_r = \frac{Q_e}{H_{e-abs} - H_{cond-e}} \ldots\ldots (30)$$

Fan unit [5]:

Cooling air mass flow rate, kg/s is calculated based on thermal power (Q_e, kW), specific heat capacity of the air, C_p, kJ/kg°C and the temperature difference between input and outlet cases, °C:

$$M_{air} = \frac{Load \times 3.517}{C_p(T_{a_m}) \times (T_{a_i} - T_{a_o})} \ldots\ldots(28)$$

Air flow velocity, m/s based on air duct diameter, D_{ta}, m mass flow rate, and air density:

$$V_{air} = \frac{M_{air}}{\rho_a(T_{a_m}) \times \left(\left(\frac{\pi}{4}\right) \times \left({D_{t}}_a{}^2\right)\right)} \ldots\ldots(29)$$

Pressure drop across the air-cooled condenser, kPa based on air density, air velocity, and mean air temperature, Ta_m, °C:

$$\Delta P = \frac{\sqrt{\left(\frac{V_{air} \times \rho_a(T_{a_m})}{0.85}\right)}}{2 \times 9.81 \times \rho_a(T_{a_m})} \ldots\ldots(30)$$

Fan Power, kW:

$$FHP = \frac{\left(\left(\frac{\pi}{4}\right) \times {D_{t}}_a{}^2\right) \times V_{air} \times \Delta P}{\eta_{fan}} \ldots\ldots(31)$$

Exergy & Performance [7-9]:

For any system goes under steady state, the mass, energy, and entropy balances equations under steady state condition should be developed as following.

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0, kg/s$$

$$\sum \dot{e}_{in} - \sum \dot{e}_{out} = 0, kJ/kg$$

$$\sum \dot{s}_{in} - \sum \dot{s}_{out} = 0, kJ/kgoC$$

The general form of the availability is defined by the following equation.

$$A_2 - A_1 = A_q + A_w + A_{fi} - A_{fo} - I$$

Where A_2-A_1=0 is the non-flow availability change in steady state condition, $A_q = \sum_J (1 - T_{amb}/T_J) Q_J$ is the availability transfer due to the heat transfer between the control volume and its surroundings, $A_w = -W_{cv} + P_o(V_2 - V_1)$ is equal to the negative value of the work produced by the control volume but in most cases the control volume has a constant volume, therefore Aw can be further simplified. And $I = T_{amb} \times S_{gen}$ is the availability destruction in the process. The flow availability expressed as$A_{fi,o} = \sum_{i,o} \dot{m}_{i.o}\, a_{fi,o}$. So, the general form in steady state condition would become;

$$0 = A_q + A_w + A_{fi} - A_{fo} - I$$

For performance calculations, the C.O.P is calculated based on evaporator and generator thermal powers, $COP = \frac{Q_e}{Q_g}$, where the Max C.O.P is found as $COP_{max} = \frac{(T_e+273.15)\times(T_g-T_a)}{(T_g+273.15)\times(T_c-T_e)}$, and the relative performance ratio could be then estimated as $RPR = \frac{COP}{COP_{max}}$

4. Conclusion

A model and presentation of an absorption refrigeration cycle utilizing NH3/H2O has been developed. The components of the cycle include the evaporator unit, absorber, condenser heat exchanger unit, and generator. The following highlights can be retracted: A description of the process has been provided. The model code has been executed and showcased. The outcome of processing the data has been demonstrated.

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