

NH₃/H₂O absorption cycle – mathematical model

Ciclul de absorbție NH₃/H₂O - model matematic

Cătălin-George Popovici¹, Emilian-Florin Țurcanu¹, Vasilică Ciocan¹,
Nelu-Cristian Chereches¹, Sebastian-Valeriu Hudișteanu¹, Ana Diana
Ancas¹, Marina Verdeș¹, Marius-Vasile Atanasiu²

¹ Technical University "Gheorghe Asachi" of Iasi, Faculty of Civil Engineering and Building Services, Department Building Services, D. Mangeron 67 str., 700050, Romania;

² Technical University "Gheorghe Asachi" of Iasi, Faculty of Mechanical Engineering, Department of Mechanical Engineering and Road Automotive Engineering, D. Mangeron 67 str., 700050, Romania;
e-mail: florin-emilian.turcanu@academic.tuiasi.ro, seby_hudisteanu@yahoo.com

DOI: 10.37789/rjce.2025.16.2.9

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.

Key-words: *absortion cycle, carbon emissions*

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 ($\text{NH}_3/\text{H}_2\text{O}$) 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 NH₃/H₂O absorption cycle. The NH₃-H₂O 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 (NH₃). 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.

NH₃/H₂O absorption cycle – mathematical model

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 NH ₃ -H ₂ O	<ul style="list-style-type: none"> ✓ Absorber temperature, °C=30-35 ✓ Generator temperature, °C=80-90 ✓ Condenser temperature, °C=40-45 ✓ Hot air temperature, °C=35 ✓ Target cooled air temperature, °C=20 ✓ Evaporator temperature, °C=5-10 ✓ Cooling load, TR=varying ✓ Condenser effectiveness, %=80 ✓ Cooling tower effectiveness, %=60 ✓ Fan system efficiency, %=85 ✓ Pumping system efficiency, %=75 	Absorption Unit: <ul style="list-style-type: none"> ➤ 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:	<ul style="list-style-type: none"> ▪ Data are run out based on steady state operating conditions. ▪ Ambient temperature is fixed as 25°C for all process runs. ▪ *Design data means area, length, width, etc... 	

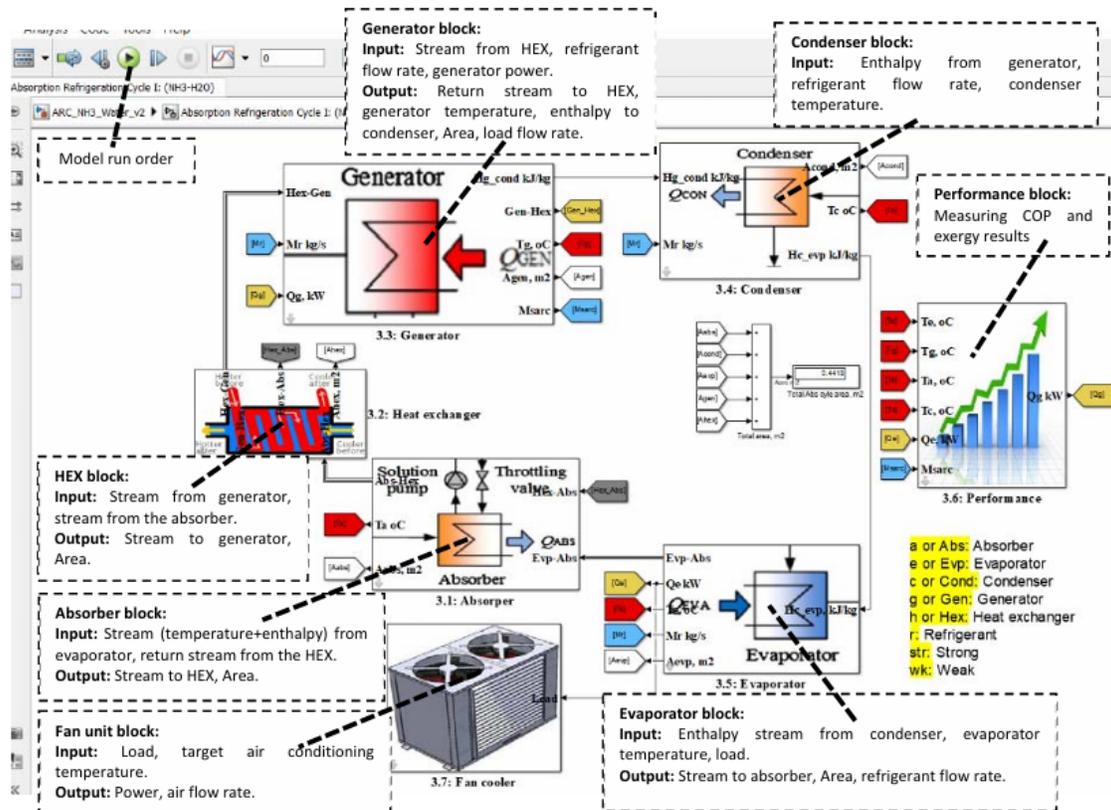


Figure (2) NH₃/H₂O model browser control panel under matlab/simulink toolbox.

3. The mathematical model

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]:
<p>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]: $f = 0.4067 \times \exp(0.05606 \times T_a) + 5.09e - 07 \times \exp(0.3293 \times T_a) \dots (1)$ The strong solution mass flow rate, kg/s, M_{str} is calculated based on total refrigerant flow rate and the flow factor: $M_{str} = M_r \times f \dots (2)$ The weak solution mass flow rate, kg/s: $M_{wk} = M_{str} - M_r \dots (3)$ 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: $Q_a = M_r \times (H_{e-abs} + (M_{wk} \times H_{hex-a}) - (M_{str} \times H_{a-hex})) \dots (4)$ Overall heat loss, kW/m²C [5]: $U_a = 1.6175 + 0.1537e - 3 \times T_a + 0.1825e - 3 \times T_a^2 - 8.026e - 8 \times T_a^3 \dots (5)$ The absorber area, m²: $A_a = \frac{Q_a}{U_a \times \Delta T} \dots (6)$</p>
<p>2. Heat exchanger unit [2-5]: For heat exchanger unit, the mass flow ratio is obtained as following: $f = \frac{M_{str}}{M_{str} - M_{wk}} \dots (7)$ The NH3 concentration percentage [2, 3]: $X_{NH3} = \frac{\frac{M_{str}}{f}}{M_r + M_{wk}} \dots (8)$ The outlet heat exchanger stream temperature towards the absorber unit, °C is calculated based on the heat exchanger effectiveness: $T_{hex-a} = T_g - (\varepsilon_{hex} \times (T_g - T_a)) \dots (9)$ Outlet heat exchanger temperature to the generator unit, °C: $T_{hex-g} = T_a + (\varepsilon_{hex} \times (T_g - T_a)) \dots (10)$ The enthalpy of NH3/H2O solution outlet to the absorber unit, kJ/kg is calculated based on temperature, °K and specific heat capacity, kJ/kg°K: $H_{hex-a} = Cp_{NH3}(T_{hex-a} + 273) \times (T_{hex-a} + 273) \dots (11)$ Where the specific heat capacity for NH3, kJ/kg°K: $Cp_{NH3} = \frac{27.31 + 0.02383 \times T + 1.707e - 5 \times (T^2) - 1.185e - 8 \times (T^3)}{17.0305} \dots (12)$ The enthalpy of NH3/H2O solution outlet to the generator unit, kJ/kg: $H_{hex-g} = Cp_{NH3}(T_{hex-g} + 273) \times (T_{hex-g} + 273) \dots (13)$</p>

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

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

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

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

Mean temperature, °C:

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

Overall heat loss, kW/m²°C:

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

Heat exchanger area, m²:

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

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:

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

Overall heat loss, kW/m²°C through the generator tubes is calculated as following [4]:

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

Generator area, m²:

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

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

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

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

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

4. Condenser unit:

Condenser thermal power, kW:

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

The overall heat loss, kW/m²°C:

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

The condenser area, m²:

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

Inlet cooling water enthalpy, kJ/kg:

$$H_{c_cwi} = 421.2 \times \exp(0.004008 \times T_{c_cwi}) - 435.9 \times \exp(-0.007559 \times T_{c_cwi}) \dots \dots (27)$$

Outlet cooling water enthalpy, kJ/kg:

$$H_{c_cwo} = \left(\frac{Q_c}{M_{cw}} \right) + H_{c_cwi} \dots \dots (28)$$

5. Evaporator unit:

Thermal load on evaporator unit, kW [6]:

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

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

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

Cătălin-George Popovici, Emilian-Florin Țurcanu, Vasiliță Ciocan, Nelu-Cristian Chereches, Sebastian-Valeriu Hudișteanu, Ana Diana Ancas, Marina Verdeș, Marius-Vasile Atanasiu

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:

$$M_{air} = \frac{Load \times 3.517}{C_p(T_{am}) \times (T_{ai} - T_{ao})} \dots (28)$$

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

$$V_{air} = \frac{M_{air}}{\rho_a(T_{am}) \times \left(\frac{\pi}{4}\right) \times (D_{ia}^2)} \dots (29)$$

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

$$\Delta P = \frac{\sqrt{\frac{(V_{air} \times \rho_a(T_{am}))}{0.85}}}{2 \times 9.81 \times \rho_a(T_{am})} \dots (30)$$

Fan Power, kW:

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

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.

$$\sum m_{in} - \sum m_{out} = 0, kg/s$$

$$\sum e_{in} - \sum e_{out} = 0, kJ/kg$$

$$\sum s_{in} - \sum s_{out} = 0, kJ/kg°C$$

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 A_w can be further simplified. And $I = T_{amb} \times S_{gen}$ is the availability destruction in the process. The flow availability expressed as $A_{fi,o} = \sum_{i,o} m_{i,o} a_{fi,o}$. 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.

Bibliography

- [1] <https://webbook.nist.gov/chemistry/name-ser/>
- [2] M Conde, Theoretical Analysis of NH₃-H₂O Refrigeration System Coupled with Diesel Engine: A Thermodynamic Study, Zurich, 2004.
- [3] Y.T. Ge, S.A. Tassou, I. Chaer, Modelling and performance evaluation of a low-temperature ammonia–water absorption refrigeration system, International Journal of Low-Carbon Technologies 2009, 4, 68–77.
- [4] N. Shankar Ganesh, T. Srinivas, Evaluation of thermodynamic properties of ammonia/water mixture up to 100bar for power application systems, Journal of Mechanical Engineering Research Vol. 3. (1), pp. 25-39, January 2011.
- [5] CECIL E. VANDERZEE, DELBERT L. KING, The enthalpies of solution and formation of ammonia, J. Chem. Thermodynamics 1972, 4, 675-683.
- [6] S. Bittanti, A. De Marco, M. Giannatempo, V. Prandoni, A Dynamic Model of an Absorption Chiller for Air Conditioning, <https://doi.org/10.24084/repqj08.428>
- [7] Abdul Rahman Mallah, Mohd Nashrul Mohd Zubir, Omer A. Alawi, Kazi Md Salim Newaz, Ahmad Badarudin Mohamad Badry, Plasmonic nanofluids for high photothermal conversion efficiency in direct absorption solar collectors: Fundamentals and applications, Solar Energy Materials and Solar Cells 201 (2019) 110084.
- [8] F. L. Lansing, Computer Modeling of a Single-Stage Lithium Bromide/Water Absorption Refrigeration Unit, JPL DEEP SPACE NETWORK PROGRESS REPORT 42-32, In it's The Deep Space Network p 247-257 (SEE N76-23304 14-12)
- [9] A.S. Nafey, M.A. Sharaf, Lourdes Garcia-Rodriguez, A new visual library for design and simulation of solar desalination systems (SDS), Desalination 259 (2010) 197–207.