MODEL FOR DOUBLE-EFFECT ABSORPTION REFRIGERATION CYCLE

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Abstract: Double-effect absorption cooling cycles improve the performance of absorption systems by using the input heat twice. This paper presents a detailed mathematical model for absorption double-effect cycle parallel flow and the corresponding flowchart. The model is validated using existing experimental data for air-conditioning applications. Using this model, the influence of the distribution ratio of the strong solution on the performance of the cycle is investigated. It is shown that there is an optimum value of the distribution ratio for which the cooling power has a maximum. Ratio 0.65 appears to be the most advantageous.

Key words: absorption, double-effect cycle, parallel configuration

1. INTRODUCTION

There is a significant requirement for refrigeration at deep-freezing temperatures in the food, pharmaceutical and chemical industries. Absorption systems may be operated by renewable energies and have the advantages: silent operation, high reliability, long service life and low maintenance.

Double-effect LiBr-H2O systems have proved to have significant higher COP’s than single effect but they need higher driving temperatures [1]. It is expected that also the double effect ammonia-salt systems will show comparable advantages. In the past, mainly lithium nitrate and sodium thiocyanate have been proposed as the most ideal salts that are mixed with ammonia for sub-zero temperature applications with sorption systems [2].

A double-effect absorption system has two stages of generation to separate the refrigerant from the absorbent. The overall efficiency of the absorption system is increased by indirectly using the inputted heat a second time.

Fig. 1. Ammonia-salt absorption refrigeration system:
A – absorber; E – evaporator; C – condenser; G – generator; HE – heat exchanger; V – valve.
Depending on the solution flow, double-effect absorption systems can be classified as follows according to ASHRAE [3]: series flow, parallel flow and reverse parallel flow.

A double-effect absorption refrigeration system with a parallel solution flow configuration has been chosen to study due to the range of operating conditions that are far away from the crystallization line. The results of comparisons of the performance of double-effect parallel flow and series flow water-lithium bromide absorption systems have shown that the maximum attainable COP for the parallel flow is greater than that for the series flow system throughout the conventional range of operating conditions [4-5].

This paper presents the mathematical model for double-effect absorption cycle and the corresponding flowchart. Using this model, the influence of the distribution ratio of the strong solution on the performance of the cycle is investigated.

2. SYSTEM DESCRIPTION

Figure 1 shows the parallel-flow double-effect refrigeration system that is working with ammonia-salt mixture. The main feature of the parallel flow configuration is that the strong solution pumped from the absorber is divided at the exit of the first solution heat exchanger and sent separately to the two generators. The first generator G1 is heated at relatively higher temperature to boil out the refrigerant vapour from the solution. The ammonia vapour coming out of the first generator G1 is condensed at high pressure in the second generator G2. The heat of condensation of the second condenser C2 is utilised to further drive off the ammonia vapour from the second generator G2. Refrigerant vapour passes to the condenser C1, rejecting the heat of condensation to the atmosphere. The total amount of liquid refrigerant leaving the condenser C1 is the sum of the refrigerant originating from the first and second generators. The refrigerant liquid from the condenser C1, after expansion, continues to the evaporator where it is evaporated at low pressure, extracting the heat of vaporisation from the space to be cooled. The cold vapours are then dissolved in the weak solution coming from the generators through the solution heat exchanger, rejecting its heat of absorption. The strong solution is then pumped to the generators and thus the cycle is completed.

The heat rejection fluid goes through the absorber and condenser in parallel. In this configuration the absorber temperature is lower and leads to a higher cycle performance.

The double effect absorption cycle has three pressure levels: the low pressure prevailing in the evaporator and absorber as determined by the evaporation temperature, the medium pressure in the condenser and second generator, as determined by the condensation temperature of condenser C1 and the high pressure in the first generator, as determined by the condensation temperature of the second condenser C2.

3. MATHEMATICAL MODEL

Several assumptions have been made:
- The pressure drops in pipelines and heat exchangers are negligible.
- The refrigerant at the outlet of the condenser is saturated liquid.
- The refrigerant at the outlet of the evaporator is saturated vapour.
- The solution at the outlet of the absorber and generator is in saturation state.
- The temperature of the refrigerant vapor is assumed to be equal to the temperature of the solution that enters the generator.

The evaporation temperature is determined from:

\[
t_E = \frac{t_{af2} - t_{af1} \cdot e^{-\frac{(U/A)g}{m_{af}c_p_{df}}} - \frac{m_{af}c_p_{df}}{1 - e^{-\frac{m_{af}c_p_{df}}{m_{af}c_p_{df}}}}}{(1)}
\]

The condensation temperature is obtained from:

\[
t_C = \frac{t_{cw2} - t_{cw1} \cdot e^{-\frac{(U/A)c}{m_{cw}cP_{cw}}} - \frac{m_{cw}cP_{cw}}{1 - e^{-\frac{m_{cw}cP_{cw}}{m_{cw}cP_{cw}}}}}{(2)}
\]

The temperature of the solution at the outlet of the high pressure generator is assumed to be 5K lower than the heating medium inlet temperature:

\[
t_{HG} = t_{hm1} - 5K
\]
The temperature of cooling water at the outlet of the absorber is:

\[ t_{cw3} = t_{cw1} + \frac{\dot{Q}_A}{m_{cw2} \cdot c_{cw}} \]  

(4)

The temperature of the solution at the outlet of the absorber is:

\[ t_A = t_{cw3} + 5K \]  

(5)

The circulation ratio of the low pressure generator is defined [6]:

\[ f_{LG} = \frac{\dot{m}_{w2}}{\dot{m}_{R2}} \]  

(6)

The mass balance at the low pressure generator:

\[ \dot{m}_{t2} x_s = \dot{m}_{w2} x_{w2} + \dot{m}_{R2} x_{R2} \]  

(7)

Using equations (6) and (7) the circulation ratio can be expressed in terms of concentrations:

\[ f_{LG} = \frac{x_{R2} - x_{w2}}{x_s - x_{w2}} \]  

(8)

The circulation ratio of the high pressure generator is:

\[ f_{HG} = \frac{x_{R1} - x_{w1}}{x_s - x_{w1}} \]  

(9)

Mass flows of the high pressure generator:

\[ \dot{m}_{t1} = D \cdot \dot{m}_s \]  

(10)

\[ \dot{m}_{R1} = \frac{\dot{m}_{t1}}{f_{HG}} \]  

(11)

\[ \dot{m}_{w1} = (f_{HG} - 1) \dot{m}_{R1} \]  

(12)

Mass flows of the low pressure generator:

\[ \dot{m}_{t2} = (1 - D) \dot{m}_s \]  

(13)

\[ \dot{m}_{R2} = \frac{\dot{m}_{t2}}{f_{LG}} \]  

(14)

\[ \dot{m}_{w2} = (f_{LG} - 1) \dot{m}_{R2} \]  

(15)

The concentration of the weak solution returning to the absorber is calculated:

\[ x_w = \frac{x_{w1} \dot{m}_{w1} + x_{w2} \dot{m}_{w2}}{\dot{m}_{w1} + \dot{m}_{w2}} \]  

(16)

The circulation ratio for the absorber is similarly determined:

\[ f_A = \frac{x_w - x_R}{x_w - x_s} \]  

(17)

Mass flow of the absorber:

\[ \dot{m}_R = \frac{\dot{m}_s}{f_A} \]  

(18)

The mass flow at the outlet of the condenser is:

\[ \dot{m}_R = \dot{m}_{R1} + \dot{m}_{R2} \]  

(19)

Enthalpy at mixing point outlet:

\[ h_{i2} = \frac{h_{i1} \cdot \dot{m}_{w1} + h_{i1} \cdot \dot{m}_{w2}}{\dot{m}_{w1} + \dot{m}_{w2}} \]  

(20)

The energy balance at the low temperature heat exchanger is:

\[ \dot{Q}_{LG} = \dot{m}_{w2} \cdot (h_{i2} - h_{i1}) \]  

(21)

The power of low pressure generator is:

\[ \dot{Q}_{LG} = \dot{m}_{w1} \cdot (h_{i1} - h_{i2}) \]  

(22)

The enthalpy at the inlet of the condenser:

\[ h_{C,in} = \frac{h_{i1} \cdot \dot{m}_{R1} + h_{i1} \cdot \dot{m}_{R2}}{\dot{m}_{R1} + \dot{m}_{R2}} \]  

(23)

The power of high pressure condenser:

\[ \dot{Q}_{HC} = \dot{m}_{R1} \cdot (h_{i9} - h_{i20}) \]  

(24)

The power of low pressure generator is equal to the power of the high pressure condenser:

\[ \dot{Q}_{LG} = \dot{Q}_{HC} \]  

(25)

The performance of the system is evaluated by the coefficient of performance:

\[ COP = \frac{\dot{Q}_E}{\dot{Q}_{HG} + W_p} \]  

(26)

The distribution ratio is the fraction of strong solution pumped to the high pressure generator out of the entire solution from the absorber:

\[ D = \frac{\dot{m}_{t1}}{\dot{m}_s} \]  

(27)

**Calculation procedure**

1) Set the input data: the inlet temperature, \( t_{afi} \), and mass flow of application fluid, \( \dot{m}_m \), the inlet temperature of heating fluid, \( t_{hmi} \), the inlet temperature, \( t_{cw1} \), and mass flows of cooling water through the condenser, \( \dot{m}_{cw1} \), and absorber, \( \dot{m}_{cw2} \), respectively, the mass flow through the solution pump, \( \dot{m}_p \), and the overall heat transfer coefficient for evaporator \( (UA)_E \) and for condenser \( (UA)_C \).

2) Calculate the temperatures of absorber \( t_A \), evaporator \( t_E \) and condenser \( t_C \).

3) Calculate the pressures of the evaporator \( p_E \) and condenser \( p_C \).
4) Calculate the solution concentration at the outlet of the absorber $x_w$.
5) Assume the distribution ratio, D, that represents the fraction of strong solution pumped to the high pressure generator out of the entire solution from the absorber.
6) Assume the condensation temperature of the refrigerant in the low pressure generator $t_{c2}$.
7) Calculate the outlet temperature of the solution out of the low pressure generator $t_{11}$.
8) Calculate the outlet concentration of the solution out of the low pressure generator $x_{w2}$.
9) Calculate the pressure of the high pressure condenser $p_{HG}$.
10) Calculate the outlet concentration of the solution out of the high pressure generator $x_{w1}$.
11) Assume the inlet temperature of the cold stream from the high temperature heat exchanger $t_9$.
12) Calculate the enthalpy of the mixing point of the flows out of both generators, $h_{11}$.
13) Calculate the outlet temperature of the cold stream from the energy balance of the low temperature heat exchanger $t_9$.
14) Compare the assumed temperature of the inlet cold stream $t_9$ from the high temperature heat exchanger with the calculated temperature at the outlet cold stream from the low temperature heat exchanger.
15) Adjust the condensation temperature of high pressure condenser until they satisfy the energy balance of the low pressure generator and high pressure condenser.
16) Calculate the mass flows, the thermal powers of each component and the COP of the system.

A modular computer simulation program was developed using object-oriented programming in C# language in Microsoft Visual Studio 2005 that can predict the performance of the double-effect refrigeration cycle. The main components of the absorption cooling system have been simulated separately based on the conservation of mass and energy and considering thermodynamic equilibrium [7].

Thermodynamic properties for LiBr-H2O mixture have been provided with a FORTRAN subroutine developed by Kim and Infante Ferreira [8] and C# programming language has been used to link the subroutine to the model. The thermodynamic properties for the solutions of NH3-LiNO3 and NH3-NaSCN have been obtained using equations developed by Infante Ferreira [9].

The model predicts the temperature, pressure, concentration and enthalpy for each state of the cycle.

![Fig. 3. Flowchart of the double-effect absorption system model](image)

The heat flux for each component of the system, mass flows and circulation ratios are calculated. An example of the output is given in Figure 4.

![Fig. 4. Powers and mass flows of the double effect cycle.](image)
4. MODEL VALIDATION

The simulation results for double-effect absorption cycle are validated for an air-conditioning application by comparing them with experimental data from Matsushima et al. [10]. The experimental apparatus consisted of a compact double-effect absorption chiller driven by gas as fuel with the temperature of inlet cooling water of 32 °C and inlet chilled water of 12 °C.

All the simulation results are obtained when the inlet temperature of chilled water is set at 12°C. The temperature of the high pressure generator reported in the experimental data is directly used as input data to the simulation. It is assumed that the temperature of the cooling water is 27 °C after 10 minutes and rises to 32 °C after 50 minutes.

The simulation results were obtained assuming the condensation temperature of the high pressure condenser, \( t_{HC} \), is 13 K higher than the temperature of the lower pressure generator, \( t_{10} \).

Figure 5 shows a comparison of the pressure at the high pressure generator. Although the experimental line shows slightly higher values than the simulated case, the pressures are in relatively good agreement.

![Fig. 5. Comparison of simulated and experimental pressure.](image)

One of the most important parameters of the cycle is the concentration of the solution. The comparison of solution concentrations is shown in Figure 6. It is seen that the simulation results and the experimental data are in good agreement except for the first 30 minutes. This was expected since the model only predicts equilibrium quasi-static conditions.

![Fig. 6. Comparison of simulation and experimental concentrations](image)

The results presented above demonstrate the reliability of the developed model that uses LiBr-H\(_2\)O properties. This model can be applied further to investigate the influence of the distribution ratio of the strong solution on the performance of the ammonia-lithium nitrate absorption cycle.

5. RESULTS

The double-effect ammonia-lithium nitrate refrigeration system was designed and the performance of the cycle and the cooling capacity produced were studied. The absorption refrigeration system has been designed for a condensation temperature of ca. 28 °C and an evaporation temperature of ca. -25 °C for the imposed load conditions. The parameters of the system are specified in Table 1.

The influence of the distribution ratio on the performance of the ammonia-lithium nitrate absorption refrigeration system has been investigated.

<table>
<thead>
<tr>
<th>Design parameters of the absorption system</th>
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<tbody>
<tr>
<td>Description</td>
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<tr>
<td>Overall heat transfer coefficient for evaporator</td>
</tr>
<tr>
<td>Overall heat transfer coefficient for condenser</td>
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<tr>
<td>Chilled fluid mass flow</td>
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<tr>
<td>Cooling water mass flow for condenser</td>
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<tr>
<td>Cooling water mass flow absorber</td>
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<td>Mass flow of strong solution</td>
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![Fig. 7. The effect of the distribution ratio on the COP.](image)

Figure 7 presents the effect of distribution ratio and heating fluid temperature of the first generator (G1) on the COP of the system for constant condensation temperature and evaporation temperature. It indicates that the COP increases with the heating fluid temperature. For each heating fluid temperature, there is a distribution ratio that gives the maximum performance of the system. As the heating fluid temperature rises, the distribution ratio should decrease in order to obtain the highest performance of the system. At lower temperatures of heating fluid, the system can operate only with distribution ratio higher than 0.5.
Figure 8 shows the cooling power as a function of the distribution ratio and heating fluid temperature for constant condensation temperature and evaporation temperature. The maximum amount of cold energy is produced when the distribution ratio is around 0.65. This value of the distribution ratio is advantageous at lower temperatures of the heating fluid, although at high temperatures of the heating fluid, the COP of the system is slightly decreased.

![Fig. 8. The effect of the distribution ratio on the cooling power.](image)

The cooling capacity of the refrigeration system is a function of the inlet temperatures of cooling water, chilled fluid and heating fluid. Figure 9 shows the cooling power of the ammonia-lithium nitrate refrigeration system for different inlet temperatures of cooling water and when the chilled fluid inlet temperature is -20°C.

![Fig. 9. Cooling capacity of the refrigeration system.](image)

6. CONCLUSIONS

A model for double-effect absorption systems operating with LiBr-H_2O, NH_3-LiNO_3 and NH_3-NaSCN has been presented. The model has been validated using existing experimental data for air-conditioning applications.

It has been shown that, in the double-effect parallel flow refrigeration system operating with ammonia-lithium nitrate, the distribution ratio of the strong solution influences the performance of the cycle and also the amount of cold energy produced. The most advantageous value for the operating conditions studied is the ratio of 0.65.

This model can be applied further to investigate the feasibility of double-effect ammonia-salt sorption systems for refrigeration applications with sub-zero evaporating temperatures.

### Nomenclature

- \( c_p \) specific heat, J/kg K
- \( D \) distribution ratio, -
- \( f \) circulation ratio, -
- \( h \) enthalpy, J kg\(^{-1}\)
- \( m \) mass flow, kg s\(^{-1}\)
- \( p \) pressure, kPa
- \( Q \) heat flow, W
- \( t \) temperature, K
- \( UA \) overall heat transfer coefficient, W K\(^{-1}\)
- \( W \) electrical power, W
- \( x \) ammonia concentration, kg kg\(^{-1}\)

### Subscripts

- \( A \) absorber
- \( af \) application fluid
- \( C \) condenser
- \( cw_1 \) cooling water of the condenser
- \( cw_2 \) cooling water of the absorber
- \( E \) evaporator
- \( hm \) heating medium
- \( HC \) high pressure condenser
- \( HG \) high pressure generator
- \( LG \) low pressure generator
- \( R \) refrigerant at the outlet of the first condenser
- \( R_1 \) refrigerant at the outlet of the high pressure generator
- \( R_2 \) refrigerant at the outlet of the low pressure generator
- \( s \) strong solution
- \( w \) weak solution at the inlet of the absorber
- \( w_1 \) weak solution at the outlet of the high pressure generator
- \( w_2 \) weak solution at the outlet of the low pressure generator

### Abbreviations

- COP coefficient of performance

### REFERENCES