Modular dynamic model for absorption systems simulation

Model dinamic modular pentru simularea sistemelor cu absorbtie

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Abstract: *Absorption systems have attracted research interests because they can be driven by waste heat, solar or geothermal energy and they can reduce fossil fuel and electricity consumption with advantageous implications for pollution reduction, by decreasing CO_2 emissions. This paper presents a modular dynamic model for absorption systems simulation. The model is developed using the object-oriented modeling approach and it contains classes for all system components that can be easily reused in different configurations in order to investigate various cycle configurations such as single effect, double-effect or triple-effect and with different working mixtures. The program calculates the temperature, pressure, concentration and enthalpy at each state point in the system. The heat flux required for each component and the coefficient of performance are predicted. A graphical user interface enables the user to view the pressure-temperature-concentration diagram of the thermodynamic cycle for the specified operating parameters.*

Keywords: *absorption systems, object-oriented programming, dynamic model, modular*

Rezumat: *Sistemele cu absorbtie au atras interes în cercetare deoarece ele pot fi actionate de căldură deseu, energie solară sau geotermală si pot reduce consumul de combustibili fosili si electricitate cu implicatii avantajoase în reducerea poluării, prin scăderea emisiilor de CO_2. Acest articol prezintă un model dinamic modular pentru simularea sistemelor cu absorbtie. Modelul este dezvoltat folosind modelarea orientata-obiect si contine clase pentru toate componentele sistemului care pot fi unor refolosite in diferite configuratii cum ar fi cele cu un efect, dublu efect sau triplu efecte si cu diferite amestecuri. Programul calculează temperatura, presiunea, concentratia si entalpia în fiecare punct de stare al sistemului. Fluxul de căldura necesar pentru fiecare component si coeficientul de performantă sunt determinate. O interfată grafică permite utilizatorului sa vadă diagrama presiune – temperatură – concentratie a ciclului termodinamic pentru parametrii de functionare specificati.*

Cuvinte cheie: *sisteme cu absorbtie, programare orientată obiect, model dinamic, modular*

1. Introduction

Thermally driven absorption heat pumps have attracted increasing research interests since they can save primary energy using renewable sources and reduce electricity consumption. The most widely used refrigerant-absorbent combinations suitable for absorption systems have been ammonia-water and water-lithium bromide. The ammonia-water absorption cycles are mainly used for refrigeration temperatures below 0 °C while the water-lithium bromide absorption cycles are commonly employed for air-conditioning purposes because of their favorable operating conditions. Alternative refrigerant-absorption pairs were developed to improve system performance. Several publications suggested that ammonia with sodium thiocyanate salt or ammonia with lithium nitrate salt can improve the absorption system performance [4, 9].

This paper presents a dynamic modular model development using object-oriented concept for absorption system operating with one of the following solution: LiBr-H_2O, NH_3-$LiNO_3$ or NH_3-NaSCN.

The configuration of the ammonia-salt absorption system is similar to H_2O-LiBr system. The advantages obtained are due to the lower allowable evaporation temperature of ammonia compared to water as well as the lower generation temperature from 60 to 90 °C for NH_3-NaSCN cycles as compared to the range from 90 to 110°C for H_2O-LiBr cycles. The ammonia-salt absorption systems don't need a rectifier and a dephlegmator like the NH_3-H_2O systems because the salt is a non-volatile absorbent. This makes the ammonia-salt system simpler and cheaper. Previous studies have shown that the coefficients of performance for the systems operating with these solutions are about 10 per cent higher than the ones for NH_3-H_2O system working at the same conditions [4]. These combinations are suitable for refrigeration systems driven by a low temperature heat source such as solar energy collected using flat plate solar collectors.

A large number of computer programs have been developed for research in FORTRAN which is a procedural programming language. The whole structure of a program written in procedural language is very different from the structure of an equivalent object-oriented program. Object-oriented modeling treats models of physical systems or components as instances of classes with certain attributes represented by data and behaviors represented by equations. Objects are categorized into classes and class hierarchies, and each class contains attributes describing objects of that class and operations defining their behavior. Object-oriented programming supports encapsulation, inheritance and polymorphism. Encapsulation packs data and the operations that manipulate the data into a single named object. Inheritance enables the attributes and operations of a class to be inherited by all subclasses and the objects that are instantiated from the subclasses. Polymorphism allows the use of a common name for a method that acts differently among objects of different classes.

An example of a modular simulation code is ABSIM, developed by Grossman [2, 3] for the Oak Ridge National Laboratory. This software can be used for steady state simulation of the absorption system. Ammonia with sodium thiocyanate mixture or ammonia with lithium nitrate solution was not included in the working fluids

database considered. Kim [6] developed a modular code to simulate a half-effect LiBr-water absorption cooling system. An object-oriented dynamic modeling library, named ABSML was developed by Fu et al. [1].

A user-friendly software package for simulating the performances of absorption refrigeration systems has been developed using Delphi programming language by Karamangil et al. [5]. The working fluid can be selected from a list that contains: water-LiBr, ammonia-water, ammonia-$LiNO_3$ and acetone-$ZnBr_2$. The input parameters are the temperatures of the main components, heat exchanger effectiveness and pump efficiency. Using this software, the authors compared the effect of operating temperature on the performance of the cycle. They concluded that NH_3-$LiNO_3$ solution is more advantageous especially at low generator temperature (75□C).

A dynamic simulation program for double-effect absorption chiller with an object-oriented formulation and a parallel processing architecture has been presented by Matsushima [7]. The governing equations were solved with Runge-Kutta-Gill method.

Shin et al. [8] presented a dynamic model of a double-effect LiBr-H_2O absorption chiller developed in Microsoft Visual C++ using object-oriented programming language. Their simulation results were compared with the test data of a commercial medium size chiller and they found a good agreement except for the first 83 min during which different flow rates of the weak solution caused some discrepancy.

The purpose of this study is to develop a modular model for LiBr-H_2O, NH_3-$LiNO_3$ and NH_3-NaSCN absorption systems using object-oriented concept in C# programming language that can predict the yearly performance of the systems that are driven by solar energy.

2. Description of the model

The schematic representation of the absorption system configuration operating with LiBr-water solution or ammonia-salt mixture is provided in Figure 1.

The solution exits the absorber, is pumped through the solution heat exchanger and is heated by the solution that comes from the generator. The refrigerant is separated from the solution in the generator. The refrigerant vapor exits the generator and the solution returns to the absorber through the valve. Refrigerant liquid is produced in the condenser at high pressure and passes through the throttling valve reducing its pressure. At low pressure the refrigerant enters the evaporator and takes the heat from the sink. Then, low pressure vapor from the evaporator is absorbed in the absorber by the solution. The heat generated during the absorption process is removed by cooling water or environmental air. In order to improve the system performance, a refrigerant heat exchanger is included in the cycle which precools the condensate before expansion and superheats the refrigerant vapor before entering the absorber.

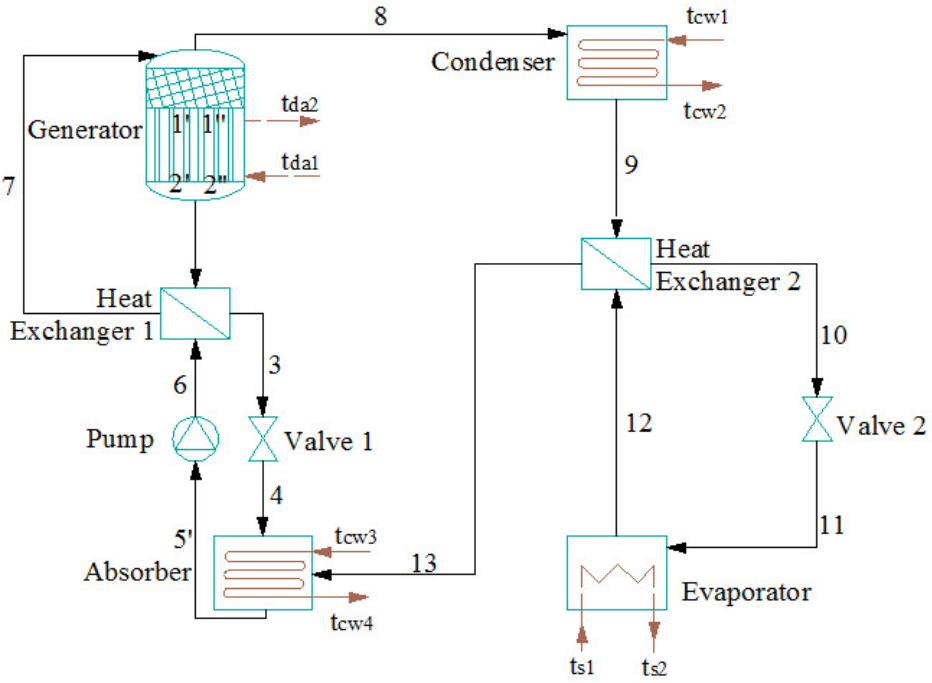


Figure 1- Schematic representation of the absorption system
′ - saturated liquid, ″ - saturated vapor

Several operating conditions and assumptions were made:

- The pressure drops in pipelines and heat exchangers are negligible.
- The temperature of the coolant at the condenser outlet is 5 K higher than the temperature at the inlet.

$$\Delta t = t_{w,o} - t_{w,i} = 5 \text{ K}$$

- The refrigerant at the outlet of the condenser is saturated liquid.
- The refrigerant at the outlet of the evaporator is saturated vapour.
- The difference between the temperature of the chilled fluid at the inlet and outlet of the evaporator is:

$$\Delta t = t_{s,i} - t_{s,o} = 3 \text{ K}$$

- The pressure of the generator is assumed to be equal to the condenser pressure:

$$p_G = p_C$$

- The temperature of the vapor is assumed to be equal to the temperature of the solution that enters the generator.
- Solution is at equilibrium condition at the exit of the absorber.
- The difference between the temperature of the heat rejection fluid at the inlet and outlet of the absorber is:

$$\Delta t = t_{ca,o} - t_{ca,i} = 5 \text{ K}$$

- The pressure of the absorber is assumed to be equal to the evaporator pressure:

$$p_A = p_E$$

The condenser can be cooled with air or with water. The heat transfer rate for a condenser is expressed as follows:

$$\dot{Q}_C = U_C A_C \Delta t_{mc} = \dot{m}_w c_{p_w} \left(t_{w,o} - t_{w,i} \right) \tag{1}$$

where U_C is the overall heat transfer coefficient, A_C is the heat transfer area of the condenser and Δt_{mc} is the log mean temperature difference of condenser and is expressed as follows:

$$\Delta t_{mc} = \frac{t_{w,o} - t_{w,i}}{\ln\left(\frac{t_c - t_{w,i}}{t_c - t_{w,o}} \right)} \tag{2}$$

The specific heat relates to the heat rejection fluid: air or water.
The condenser temperature will be:

$$t_c = \frac{t_{w,o} - t_{w,i} \cdot e^{-\frac{U_c A_c}{\dot{m}_w c_{p_w}}}}{1 - e^{-\frac{U_c A_c}{\dot{m}_w c_{p_w}}}} \tag{3}$$

The evaporator temperature is expressed in a similar way:

$$t_E = \frac{t_{s,i} - t_{s,o} \cdot e^{-\frac{U_E A_E}{\dot{m}_E c_{p_E}}}}{1 - e^{-\frac{U_E A_E}{\dot{m}_E c_{p_E}}}} \tag{4}$$

The generator mass balance is:

$$\dot{m}_7 \cdot x_7 = \dot{m}_8 \cdot x_8 + \dot{m}_2 \cdot x_2 \tag{5}$$

with x_8 the concentration of refrigerant in the vapor flow.

The flow ratio is defined as the ratio of the mass flow rate of the solution from the absorber to the mass flow rate of the refrigerant:

$$f = \frac{\dot{m}_7}{\dot{m}_8} \tag{6}$$

From the previous equations, the circulation ratio is obtained:

$$f = \frac{x_8 - x_2}{x_7 - x_2} \tag{7}$$

Considering the states indicated in Figure 1, the following energy balances can be derived.

For the condenser:

$$\dot{Q}_C = \dot{m}_r (h_8 - h_9) \tag{8}$$

For the generator:

$$\dot{Q}_G = \dot{m}_r \left[h_8 + (f - 1) h_2 - f \cdot h_7 \right] \tag{9}$$

For the absorber:

$$\dot{Q}_A = \dot{m}_r \left[h_{13} + (f - 1) h_4 - f \cdot h_5 \right] \tag{10}$$

The refrigerant mass flow is obtained from the energy balances at the evaporator:

$$\dot{Q}_E = \dot{m}_r (h_{12} - h_{11}) \tag{11}$$

For the solution heat exchanger:

- hot side

$$\dot{Q}_{she-h} = \dot{m}_r (f - 1)(h_2 - h_3) \tag{12}$$

- cold side

$$\dot{Q}_{she-c} = \dot{m}_r f (h_7 - h_6) \tag{13}$$

For the pump:

$$\dot{W}_P = \dot{m}_r f (h_6 - h_5) \tag{14}$$

The coefficient of performance for refrigeration is defined as:

$$COP_R = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_P} \qquad (15)$$

The coefficient of performance for heating is the ratio of the rejected heat to the external heat input:

$$COP_H = \frac{\dot{Q}_A + \dot{Q}_C}{\dot{Q}_G + \dot{W}_P} \qquad (16)$$

3. Results

The model has been implemented using C# programming language in Microsoft Visual Studio 2005. Each component of the system is represented by a class. Thermodynamic properties for LiBr-H_2O mixture have been provided with a FORTRAN subroutine developed by Kim [6] and C# programming language has been used to link the FORTRAN subroutine to the model. Equations for the thermodynamic properties for ammonia-lithium nitrate and ammonia-sodium thiocyanate solutions have been taken from Infante Ferreira [4].

Each component of the absorption system is simulated by providing the physical equations such as energy balance, conservation of mass, heat and mass transfer and thermodynamic equilibrium. These equations use the thermodynamic properties of the working fluid.

The input parameters for the absorption cycle are: the inlet heating medium temperature, the inlet cooling medium temperature, the inlet application fluid temperature and the cooling power [Figure 2].

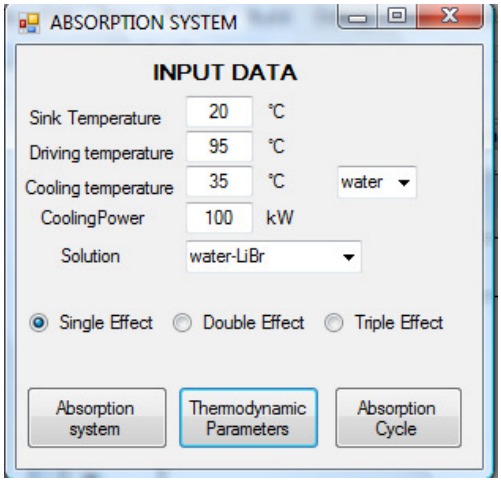
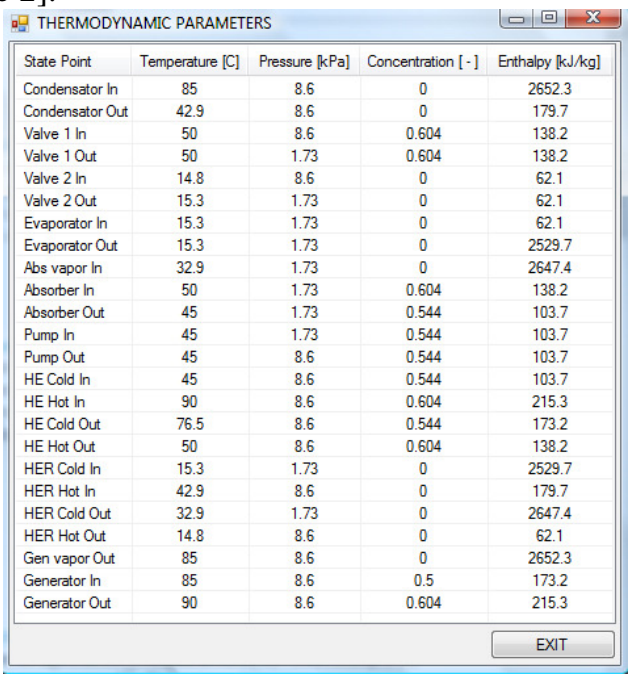


Figure 2 - The input data form



State Point	Temperature [C]	Pressure [kPa]	Concentration [-]	Enthalpy [kJ/kg]
Condensator In	85	8.6	0	2652.3
Condensator Out	42.9	8.6	0	179.7
Valve 1 In	50	8.6	0.604	138.2
Valve 1 Out	50	1.73	0.604	138.2
Valve 2 In	14.8	8.6	0	62.1
Valve 2 Out	15.3	1.73	0	62.1
Evaporator In	15.3	1.73	0	62.1
Evaporator Out	15.3	1.73	0	2529.7
Abs vapor In	32.9	1.73	0	2647.4
Absorber In	50	1.73	0.604	138.2
Absorber Out	45	1.73	0.544	103.7
Pump In	45	1.73	0.544	103.7
Pump Out	45	8.6	0.544	103.7
HE Cold In	45	8.6	0.544	103.7
HE Hot In	90	8.6	0.604	215.3
HE Cold Out	76.5	8.6	0.544	173.2
HE Hot Out	50	8.6	0.604	138.2
HER Cold In	15.3	1.73	0	2529.7
HER Hot In	42.9	8.6	0	179.7
HER Cold Out	32.9	1.73	0	2647.4
HER Hot Out	14.8	8.6	0	62.1
Gen vapor Out	85	8.6	0	2652.3
Generator In	85	8.6	0.5	173.2
Generator Out	90	8.6	0.604	215.3

Figure 3 - Thermodynamic parameters

The program calculates the temperature, pressure, concentration and enthalpy at each state point in the system and the heat flux at each unit from which the coefficient of performance is determined. The parameters for each component of the system are presented in a table [Figure 3] or they can be displayed at their location in the system. The cycle can be viewed in a pressure-temperature-concentration (P-T-X) diagram. Figure 4 shows the predicted crystallization line which gives the limit of operation of the different cycles.

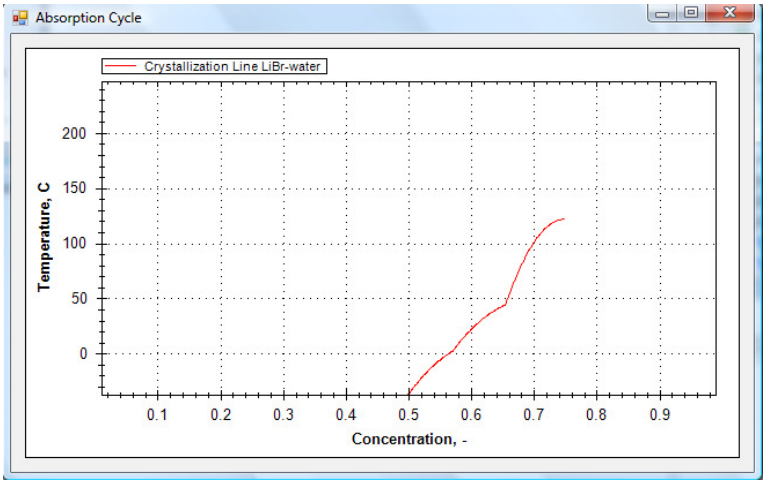


Figure 4- Representation of LiBr-H_2O crystallization line

4. Conclusions

In this paper a modular dynamic model for absorption systems is presented. The modular approach is obtained with the object-oriented concept. This model allows flexible simulation for absorption systems, where the system components can be reused to compose new systems. In the future, double effect or triple effect cycles operating with different working fluids will be investigated with this model.

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