SOFTWARE APPLICATION FOR AN AMMONIA-WATER ABSORPTION HEAT PUMP USED FOR PERFORMANCE EVALUATION

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Abstract: Thermally driven absorption heat pumps are attracting increasing research interests because primary energy can be saved and they can use waste heat or renewable sources such as solar or geothermal energy. These systems can replace the vapor compression systems, phasing out the ozone layer depletion effect of the refrigerants. This paper presents a mathematical model for ammonia-water absorption heat pumps developed for performance prediction. The system is analyzed based on the driven energy and the coefficient of performance. The thermal powers are calculated for each component of the heat pump based on heat and mass balance equations. The model uses non-linear equations for estimating the thermodynamic properties of ammonia-water mixture. The described model is implemented in a software application which is used to investigate the influence of the important operating parameters on the heat pump performance. The results reveal that the COP of the system increases slightly when increasing the evaporator water inlet temperature and decreases when increasing the condenser inlet water temperature and the inlet driving temperature.

Key Words: heat pump, absorption, ammonia-water, mathematical model, software application

1   INTRODUCTION

Absorption heat pumps have become more attractive because they are driven by thermal energy and they can use waste heat, geothermal or solar energy as a source of energy. These systems are working with combinations of a refrigerant and an absorbent which are environmentally friendly and do not cause ozone depletion. The total useful heat of the absorption heat pumps is higher than for the vapour-compression systems because of the presence of the absorber which produces almost two times more available heat than the condenser makes. Although the investment costs are higher for the absorption systems than for the vapour compression systems, the utility period for the absorption systems are minimum 25 year which is more than for vapour compression systems that are operating maximum 10 years (Hera, 2007). In Romania the most common mixture used in the absorption systems is ammonia-water. This working fluid is extremely used because it has a lower price than the refrigerants used in the vapour compression systems and other mixtures used in absorption systems.

Practical applications of the absorption heat pumps can be made for different heat sources starting from the heat of ambient medium to the renewable energy sources and for a large number and very different processes of heat producing and utilization: from building space

heating to industrial processes of drying and distillation. In this study, the application of ammonia-water absorption heat pumps to provide heating for residential buildings is investigated. The absorption system is used in combination with heating systems with low parameters such as: underfloor heating or fan coil units.

Several computer models for absorption systems simulation have proven to be very valuable tool for research and development and for design optimization (Sun 1997), (Grossman and Zaltash 2001). Although there are already some commercial programs available on the market developed with different technologies such as ABSIM or Engineering Equation Solver (EES), there is still a need for software programs that can be used for absorption research studies.

This paper presents the mathematical model for ammonia-water absorption heat pumps and the non-linear equations that are used to estimate the thermodynamic properties of ammonia-water mixture. A software application has been developed based on this model and it is used to investigate the influence of the important operating parameters on the heat pump performance.

2   CYCLES DESCRIPTION

The ammonia-water absorption system can be used either for heating or cooling at negative temperatures. Figure 1 presents the detailed schematic diagram of the ammonia-water absorption heat pump configuration. The system consists of a generator, rectifier, condenser, evaporator and absorber. The ammonia vapour exits the generator and the weak solution returns to the absorber through the valve. The weak solution that comes from the generator heats the strong solution that is pumped through the solution heat exchanger and comes from the absorber. The strong solution enters the generator and the ammonia is separated from the solution. Ammonia liquid is produced in the condenser at high pressure and passes through the valve reducing its pressure. At low pressure ammonia enters the evaporator and takes the heat from the sink.
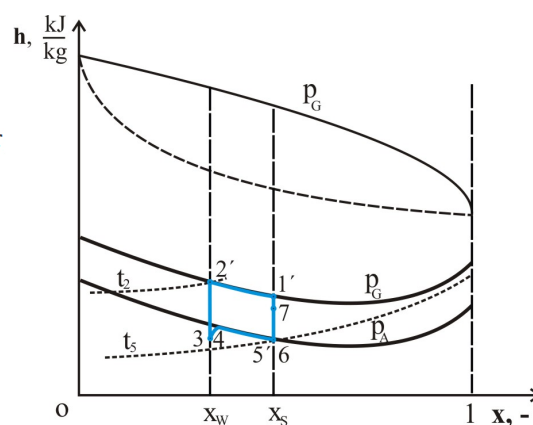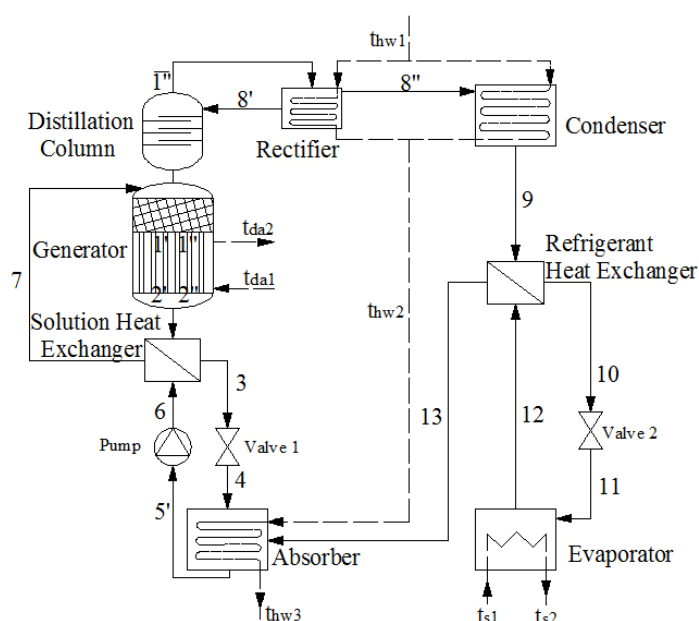

Figure 1 –Ammonia-water absorption heat pump

Figure 2 - Ammonia-water absorption cycle

In order to improve system performance, a solution heat exchanger and a refrigerant heat exchanger are included in the cycle. A distillation column and a rectifier are used in order to remove water vapour from the refrigerant that leaves the generator and reaches the condenser. The heat transferred from the absorber, rectifier and condenser is available for heating applications.

The driving energy required to boil the ammonia-water mixture is produced with a heating fluid with the temperature between 80 and 120 °C. Lower driving agent temperatures obtained from waste heat, geothermal or solar energy can be used for double-stage absorption cycles or compression-resorption cycles.

Figure 2 shows the ammonia-water absorption cycle on the enthalpy-concentration diagram. The state points on the cycle correspond to the numbered positions in Figure 1.

3   MODEL

The model has been implemented using object-oriented concept which allows a high degree of modularity and flexibility of the code. The components of the absorption system are described by objects that are treated as instances of classes with certain attributes represented by data and behaviors represented by equations of heat and mass balances. The main advantage of this technique is that the code can be reuse, so the models of each component can be reused to compose new systems such as double-stage absorption heat pump or compression-resorption system. The input data to the model are: inlet heating fluid temperature, inlet chilled fluid temperature, inlet hot water temperature and heating power.

3.1   Mathematical model

The model predicts the temperature, pressure, concentration and enthalpy for each point of state using the thermodynamic properties of ammonia and ammonia-water solution that are specified in the section 3.2.

Pressure drops are considered between evaporator and absorber and between generator and condenser and can be in the range 0.2 - 0.4 bar depending on the plant. The following assumptions are made: the solution at the outlet of the absorber and generator is in saturation state and at the condenser and evaporator outlets is saturated refrigerant. The power of the solution pump is neglected. The absorber, the generator, the condenser, the evaporator and the heat exchanger are modelled as shell-tube heat exchangers.

The circulation ratio is the ratio of the mass flow rate of strong solution to the mass flow rate of refrigerant:

$$f = \frac{\dot{m}_S}{\dot{m}_{\mathrm{Re}f}} \tag{1}$$

The mass balance for generator, distillation column and rectifier is:

$$\dot{m}_S \cdot x_S = \dot{m}_{\mathrm{Re}f} \cdot x_{8''} + \dot{m}_W \cdot x_W \tag{2}$$

From equations (1) and (2), the circulation ratio can be expressed in terms of concentrations:

$$f = \frac{x_{8"} - x_W}{x_S - x_W} \qquad (3)$$

The enthalpy of the state point 3 is calculated from the heat balance of the solution heat exchanger:

$$h_3 = h_{2'} - \frac{f}{f-1}(h_7 - h_6) \qquad (4)$$

The performance of the system is evaluated by the coefficient of performance for heating purposes which is defined as the heating rate over the rate of heat addition at the generator:

$$COP = \frac{\dot{Q}_A + \dot{Q}_C + \dot{Q}_R}{\dot{Q}_G} \qquad (5)$$

3.2   Thermodynamic properties

The thermodynamic properties are necessary for simulation the absorption heat pump cycle. These properties are: temperature, pressure, concentration and enthalpy. In the ammonia-water absorption systems, ammonia is the refrigerant and water is the absorbent. The thermodynamic properties at states (8") - (13) are found from the ammonia properties and the thermodynamic parameters at states (1) - (8) are calculated based on the ammonia-water mixture properties.

It is very important to have accurate information of the thermodynamic properties of the working fluid. The specific enthalpies of saturated liquid and vapour for the ammonia-water mixture have been expressed from the enthalpy-concentration diagram in terms of concentrations for different temperatures and pressures:

$$h = a_0 + a_1 \cdot x + a_2 \cdot x^2 + ... + a_{10} \cdot x^{10} \qquad [kJ/kg] \qquad (6)$$

The coefficients of equation (6) for different temperatures are listed in Table 1. The coefficients of equation (6) for low pressures required at the evaporator and absorber are shown in Table 2 and for high pressures required at the condenser and generator are shown in and Table 3.

Table 1 - Coefficients of equation (6) for different temperatures

T[°C]	20	30	40	50	60	70
a_0	2.203E+01	3.141E+01	4.195E+01	5.120E+01	6.067E+01	7.172E+01
a_1	-1.493E+02	-9.127E+01	-1.365E+02	-9.822E+01	-8.261E+01	-1.211E+02
a_2	6.806E+02	-4.003E+02	5.255E+02	-5.838E+01	-9.140E-02	5.220E+02
a_3	-5.069E+03	4.566E+03	-2.299E+03	1.476E+03	-3.810E+02	-3.721E+03
a_4	2.201E+04	-2.336E+04	5.204E+02	-1.002E+04	4.146E+02	1.356E+04
a_5	-4.907E+04	7.143E+04	2.994E+04	3.787E+04	1.027E+04	-2.115E+04
a_6	5.484E+04	-1.262E+05	-9.464E+04	-7.300E+04	-3.079E+04	9.707E+03
a_7	-1.054E+04	1.276E+05	1.286E+05	7.485E+04	3.321E+04	1.168E+04
a_8	-4.430E+04	-6.882E+04	-8.402E+04	-3.917E+04	-1.267E+04	-8.519E+03
a_9	4.640E+04	1.540E+04	2.160E+04	8.246E+03		-1.306E+04
a_{10}	-1.471E+04					1.201E+04

The thermodynamic parameters calculated with the equations presented above have been compared with the parameters obtained based on ammonia-water enthalpy-concentration diagram and tables of ammonia properties and they were in good agreement.

Table 2 - Coefficients of equation (6) for low pressures

p [ata]	2	3	4	5	6
a_0	1.219E+02	1.355E+02	1.462E+02	1.542E+02	1.615E+02
a_1	-4.950E+02	-4.455E+02	-4.514E+02	-4.583E+02	-4.153E+02
a_2	1.771E+03	5.341E+02	5.274E+02	7.763E+02	-1.536E+02
a_3	-1.228E+04	-7.175E+01	2.625E+02	-2.146E+03	6.188E+03
a_4	5.627E+04	-4.847E+03	-6.404E+03	4.829E+03	-3.219E+04
a_5	-1.528E+05	1.753E+04	2.014E+04	-8.996E+03	7.811E+04
a_6	2.529E+05	-2.135E+04	-2.224E+04	2.005E+04	-8.306E+04
a_7	-2.486E+05	1.255E+03	-4.591E+02	-3.058E+04	2.503E+03
a_8	1.329E+05	1.950E+04	2.017E+04	2.322E+04	7.739E+04
a_9	-2.970E+04	-1.658E+04	-1.511E+04	-6.758E+03	-6.676E+04
a_{10}		4.413E+03	3.507E+03		1.832E+04

Table 3 - Coefficients of equation (6) for high pressures

p [ata]	12	13	14	15	16	17
a_0	1.914E+02	1.945E+02	1.990E+02	2.024E+02	2.065E+02	2.089E+02
a_1	-3.227E+02	-3.333E+02	-3.318E+02	-3.908E+00	-3.808E+02	-3.351E+02
a_2	-1.293E+03	-1.023E+03	-1.044E+03	-1.179E+03	4.693E+01	-6.319E+02
a_3	1.173E+04	9.884E+03	9.199E+03	5.310E+00	-6.602E+02	4.201E+03
a_4	-4.411E+04	-3.780E+04	-3.200E+04	2.723E+03	1.361E+04	-5.901E+03
a_5	8.590E+04	7.373E+04	5.641E+04	-3.456E+00	-6.268E+04	-1.574E+04
a_6	-7.428E+04	-6.233E+04	-4.083E+04	-2.990E+03	1.397E+05	7.043E+04
a_7	-8.191E+03	-8.801E+03	-1.144E+04	1.908E+00	-1.645E+05	-1.030E+05
a_8	6.931E+04	5.792E+04	3.788E+04	1.353E+03	9.838E+04	6.821E+04
a_9	-5.165E+04	-4.095E+04	-2.219E+04		-2.357E+04	-1.729E+04
a_{10}	1.283E+04	9.633E+03	4.280E+03			

4   RESULTS

The developed software application is used to investigate the influence of the important operating parameters on the heat pump performance. In this study, it is assumed that the refrigerant vapour at the outlet of the generator contains 99.8% ammonia. The fallowing results are obtained when the heating power supplied by the absorber, condenser and rectifier is 100kW.
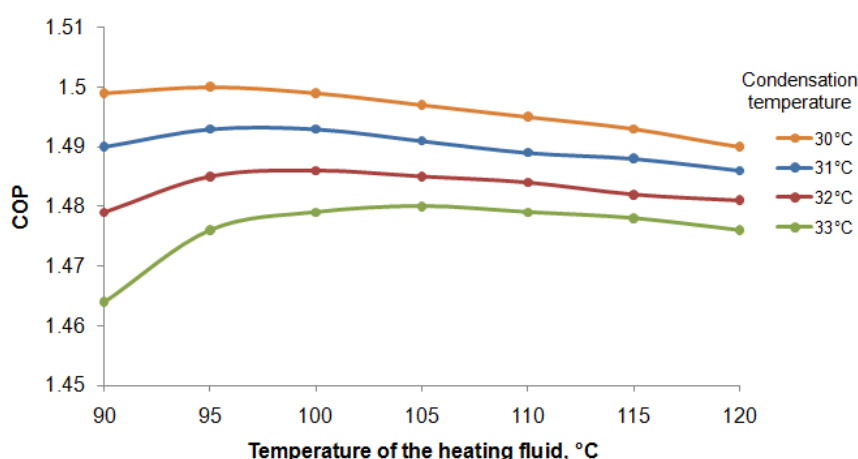

Figure 3 – Variation of the coefficient of performance of ammonia-water heat pump (t_E=1°C)

Figure 3 shows the performance of the heat pump as a function of temperature of the heating fluid when the heat sink is the water from an air-conditioning application. In this way the absorption system provides simultaneous heating and cooling. The practical applications are

the bank centers where the space heating can be provided by underfloor heating and the cooling of the computing centres is needed even in the winter. In this case, the absorption cycle has the evaporation temperature starting at 1 °C and ending at 4 °C due to the water presence. The COP values are in range of 1.46-1.5. The COP initially shows significant increase with an increasing heating fluid temperature and then the slope of the COP curves becomes almost flat. Increasing the heating fluid temperature higher than a certain values does not provide much improvement for the COP. The temperature of the heating fluid and the condensation temperature have an influence on the performance of the heat pump. The COP increases as the heating fluid temperature and condenser temperature decrease. There is a minimum heating fluid temperature that corresponds to a maximum COP.
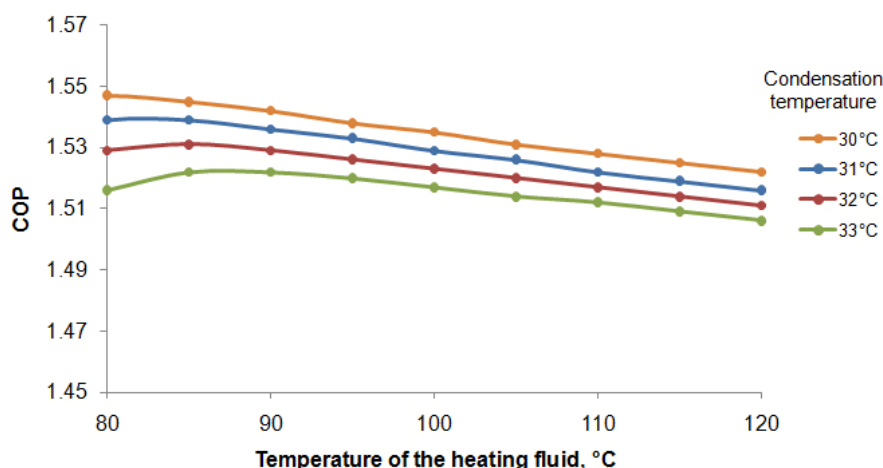

Figure 4 – Variation of the coefficient of performance of ammonia-water heat pump (t_E=9°C)

Figure 4 shows the performance of the ammonia-water heat pump as a function of the heating fluid temperature when the heat sink is the groundwater. In this case, the evaporation temperature inlet that corresponds to this sink is 9 °C. It can be seen that the COP values are slightly higher when the evaporator temperature is increased.

The results show that the COP of the system increase slightly when increasing the evaporator water inlet temperature and decrease when increasing the condenser inlet water temperature and the inlet driving temperature.

5   CONCLUSIONS

A software application for absorption heat pumps has been developed. Using this program the performance of the ammonia-water absorption system has been investigated. The results showed that the COP of the system increase slightly when increasing the chilled fluid inlet temperature and decrease when increasing the condenser inlet water temperature and the inlet driving temperature.

When the condenser temperature is low (between 30°C and 35°C), it is difficult to find heat consumers. The application suitable for this temperature is the underfloor heating which requires low temperatures.

It is hoped that this software application could serve as a useful tool for designing the absorption systems and choosing and optimizing suitable operating conditions.

Acknowledgments

Nomenclature

COP coefficient of performance

f   circulation ratio

h   enthalpy, $kJ\ kg^{-1}$

$\dot{m}$ mass flow, $kg\ s^{-1}$

$\dot{Q}$ heat flow, W

t   temperature, K

x   ammonia concentration, $kg\ kg^{-1}$

Subscripts:

A   absorber

C   condenser

E   evaporator

G   generator

R   rectifier

Ref   refrigerant

S   strong solution

W   weak solution

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