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THE MATHEMATICAL MODELLING OF THE ABSORPTION REFRIGERATION MACHINES USED IN ENERGY SYSTEMS

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Abstract. In the paper the authors present the possible usage of absorption refrigeration machines in air-conditioning systems and tri- and cogeneration processes. One-stage and multi-stage absorption refrigeration cycles are described. The influence of temperature of cooling water or chilled water on refrigeration plant's COP is analyzed. The series of thermodynamic parameters are taking into consideration - the temperature of feeding medium of the desorber, the temperature of cooling water and the use of various energy carriers to drive absorption devices including biogas from organic and communal waste matter. Some comparative calculations of COP are presented to find the optimal absorption cycle for building energy systems.

Keywords: absorption, energy systems, air conditioning, trigeneration.

1. Introduction

The 95% of cooling and refrigeration machines use the different, mechanical type of compressors. The second place in the market is occupied by sorption systems where the absorption machines are preferred. The first absorption chillers came from the second half of 19th century. In 1860, the French, F. Carré, built absorption cooling machine where the ammonia was the working refrigerant. Now the need to install the absorption chillers in building energy systems is observed. The point is that ozone hole and greenhouse effect are the most urgent problems in environmental policy of the world now. That is why the 'old freons' with chlorine and bromide are gradually replaced from refrigeration and HVAC industry and new regulation of refrigerants with high GWP are established (F-gases). Moreover the tendency to regeneration of waste heat is up-to-date. It is connected with building of cogeneration and trigeneration systems where the absorption cycles are commonly used.

Absorption refrigeration machines are characterized by a lot of advantages. There is the possibility of waste heat recovery thanks to low utilization of the electric energy. It is used first of all for electric driven pumps and automatics. A very few moving parts give a long life time of the absorption machine with plain service (once per 55000 hours of work). Then a low exploitation costs are noticed with parallel a higher investment costs compare to compressor refrigeration and cooling. The compact structure with one or two shells built with wide range of construction materials used to heat and mass exchangers is observed. The great dimensions, usually the great weight and big space need are disadvantages. Moreover easy regulation of cooling capacity from 10 to 100 percent thanks to microprocessor controls is possible. Also wide range of cooling capacity from part of kW to MW is an advantage.

With the point of view of the ecology these devices use natural cooling fluids (water, ammonia) and emit the noise on the low level.

The supply of absorption cooling plants could be the gas burner, the hot water or steam produced in generators or waste heat coming from different processes. The increase of cooling machines usage is because of a lower temperature of the agent inflowing to the desorber and enlargement of the coefficient of performance: for the lithium bromide absorption apparatus the desirable temperature of the heating agent would be shaped up above 50^{o}C (Lucas et al.; 2003).

For the purpose of temperature decrease of the heating agent there are some possible solutions:

- the decrease of the temperature difference of media leaving heat and mass exchangers (Cui et al.; 2007; Estiot et al.; 2007; Takahashi and Koyama, 2007; Wang et al.; 2007);
- the modification of absorbate-absorbent pair (Kozioł and Gazda, 2002);
- the use of multistage devices (Figueredo et al.; 2008).

So there are double-stage absorption refrigeration machines described using water as the cooling agent.

The influence of the series of parameters on the coefficient of performance (COP) of cooling and the temperature of feeding medium of the desorber is introduced. The analysis of the influence of temperature of cooling water the use of various carriers of energies used to the drive of these devices on COP was done. There is the comparison of different carriers of the energy: the renewable sources of energy such as gas to burning from the process of gassing of waste material as organic biomass or communal wastes. In that way energy cumulated in wastes could be recycled and used for heating or for air conditioning in buildings thanks to absorption technology.

Below one-stage and double-stage cooling machines are described and some important thermodynamic parameters are discussed.

2. One-stage absorption cooling machines

On the basis of mathematical model of a one-stage absorption cooling machine the calculations were executed and the profile of influence of chosen parameters on cooling efficiency was done. The basic assumptions are:

- The steady state refrigerant is pure water.
- There are no pressure changes except through the flow restrictors and the pump.
- At points 1, 4, 8 and 11, there is only saturated liquid.
- At point 10, there is only saturated vapour.
- Flow restrictors are adiabatic.
- The pump is isentropic.
- There are no jacket heat losses.

The scheme of absorption cycle is presented in the Figure 1 with assign of the most important devices and parameters in theoretical absorption investigations. Then the working parameters are analyzed with diagram presentation.

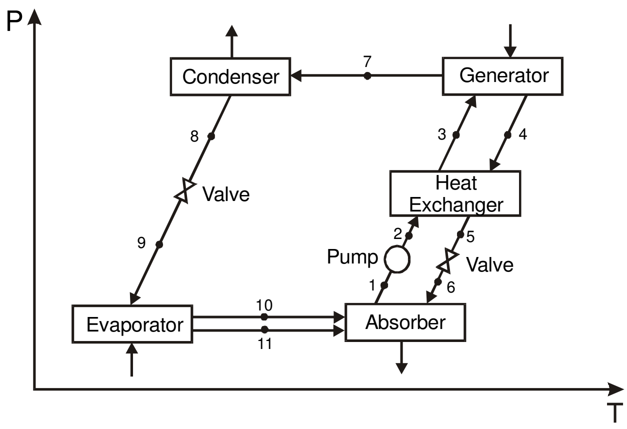

Fig 1. The diagram of one-stage absorption cooling machine cycle

The influence of LiBr solution weight concentration into absorber on COP, the solution temperature out of absorber and solution mass flow (Fig 2).

The input data for calculations:

- Cooling capacity, $Q_o = 10$ kW
- The evaporation temperature, $t_{10} = 6$ °C
- The weak solution temperature $t_4 = 90$ °C
- The weak solution mass fraction, $\xi_4 = 60$ %
- The outlet temperature of weak solution (heat exchanger), $t_3 = 65$ °C
- The condensation temperature, $t_7 = 85$ °C
- The mass flow fraction of liquid refrigerant, $m_{11}/m_{10} = 0{,}025$

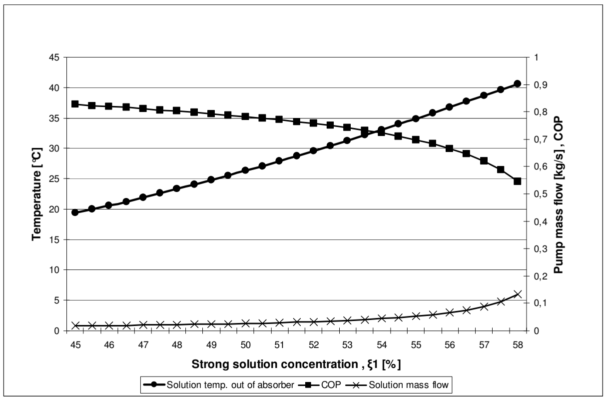

Fig 2. The infuence of the rich solution on COP, the solution temperature out of absorber and solution mass flow

The influence of rich solution temperature after generator on COP and pressure in generator (Fig 3).

The input data for calculations:

- Cooling capacity, $Q_o = 10$ kW
- The evaporation temperature, $t_{10} = 6$ °C
- The strong solution mass fraction, $\xi_1 = 55$ %
- The weak solution mass fraction, $\xi_4 = 60$ %
- The outlet temperature of weak solution (heat exchanger), $t_3 = 65$ °C
- The condensation temperature, $t_7 = 85$ °C
- The mass flow fraction of liquid refrigerant, $m_{11}/m_{10} = 0{,}025$

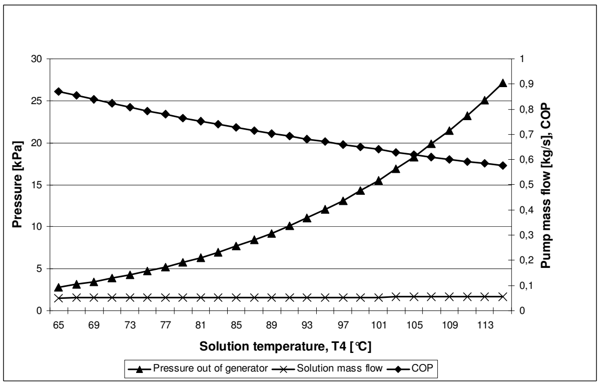

Fig 3. The influence of rich solution temperature after generator on COP and pressure in generator

The influence of weak solution concentration on COP and outflow pressure in generator (Fig 4).

The input data for calculations:

- Cooling capacity, $Q_o = 10$ kW
- The evaporation temperature, $t_{10} = 6$ °C
- The weak solution temperature $t_4 = 90$ °C
- The strong solution mass fraction, $\xi_1 = 55$ %
- The outlet temperature of weak solution (heat exchanger), $t_3 = 65$ °C
- The condensation temperature, $t_7 = 85$ °C
- The mass flow fraction of liquid refrigerant, $m_{11}/m_{10} = 0{,}025$

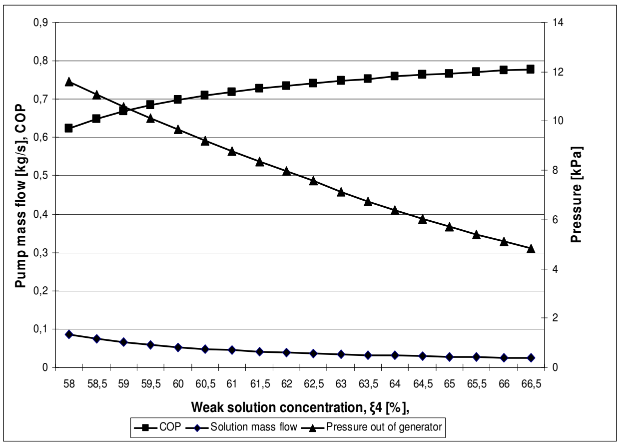

Fig 4. The influence of weak solution concentration on COP and outflow pressure in generator

3. The double-stage absorption refrigeration machines

The introduction of double-stage absorption refrigeration machines projects with the increase of the coefficient of performance on the level 1.2 (Mahone, 1998). However the temperature of the heating agent of high-temperature desorber considerably grows up to the level over 120^{o}C. The whole system of the cooling machine goes to the further development for additional heat and mass exchangers, fitting and systems of the monitoring. Then both the capital cost of such plant and the degree of the complication of the installation grow up. The advantage of such solution is the utilization of low-temperature source of the warmth for low-temperature desorber coming from eg. solar collectors. On Fig 1 there is schematically presented the double-stage series-cycle absorption chiller. The machine consists of five main elements: the high-temperature generator (desorber) G1, the generator (desorber) G2 and the condenser C working under the average pressure and the low-pressure evaporator E and the absorber A. Additionally, the system is equipped with two heat exchangers of solutions HE1 and HE2 and the pump of solution. Cooling water flows through the absorber and condenser and then is cooled in the cooling tower. The chilled water is taken off from the evaporator to the cooling system of the air-conditioning. The high-temperature stream of the warmth Qg carried to the generator G1 in double-stage absorption machine can come from different sources. It could be water about the temperature of 180^{o}C or the water steam or combustion gases. In accepted solution the water vapour, being the cooling agent leaving the generator G1 and it is also the source of the warmth for the generator G2. The water vapour condenses in the condenser C. From the condenser water flows to the evaporator E, where the pressure is decreasing in the expanding valve (which is schematically situated in Fig 5). In real devices the roles of the expanding element play the nozzles splashing water in the evaporator E. In the evaporator the vaporization of water in the low pressure and the recovering of the warmth from chilled water and the flow of the water vapour to the absorber a takes place. In the absorber the water is absorbed by water solution of lithium bromide from the generator G2. Then the water solution of lithium bromide is transported by the pump through exchangers of solutions to the generator G1 (Baran and Turski, 1995; Molenda, 1993).

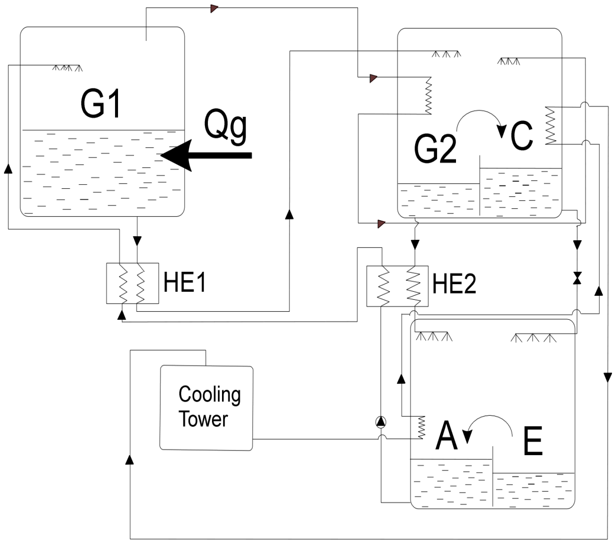

Fig 5. A schematic diagram of a double-stage series-cycle absorption chiller

4. The analysis of application of the double-stage absorption machine

The lithium bromide – water refrigeration machine about the cooling power Q_o =174 kW is investigated. The machine is used to prepare a coolant on needs of the air-conditioning systems (in office buildings, show halls, etc.) about temperatures from 5 to 12^{o}C at the nominal flow of 30 m^3/h of chilled water. The average temperature of the evaporation is 4.1^{o}C. The temperature of cooling water (the absorber and the condenser) is changing in the range from 24 to 34^{o}C at the nominal flow of 40 m^3/h. The device is supplied with water of the temperature about 180^{o}C or with the water steam or with combustion gases coming from the gas- or oil-burner.

Below (Tab. 1), there are presented the examples of volumetric streams of fuel gases proposed to supply the device. The volumetric streams on gas found 60%

efficiency of the gas burner (the range of the heating power from 94 to 163 kW) are used to supply the generator G1.

Table 1. The volumetric streams of gases proposed to supply the absorption refrigeration machine

Gas	Heat of combustion [MJ/m^3]	Consumption [Nm^3/h]
Natural gas (high-methane) E	39,5	18,9
Natural gas (with nitrogen) Lw	32,0	23,3
Natural gas (with nitrogen) Ls	28,8	25,9
Biogas	20,0 – 24,0	37,3 – 31,0
Gas from communal wastes	13,8	54,1

The plant can work both in cogeneration systems producing warmth and coolness and in trigeneration systems with additional microturbine or with the compression-ignition engine for electric power production. The own electric power consumption of the electric devices (current pumps, solution pumps, vacuum-pumps and automatics) is below 1% of the cooling power. Some parameters of the machine under examination are presented in Table 2. Weight concentrations of water solutions of the lithium bromide refer to solutions leaving specific heat and mass exchangers.

Table 2. The choosen parameters of examined double-stage refrigeration machine

Exchanger	Power [kW]	Pressure [kPa]	Temp. [^{o}C]	Weig. Conc. [%]
Evaporator E	174,0	0,8	4,1	0,0
Generator G1	124,2	97	165,0	62,0
Generator G2	127,0	7,5	40,3	65,0
Condenser C	168,0	7,5	40,3	0,0
Absorber A	130,2	0,8	4,1	58,5

The inspection of the temperature of chilled water takes place thanks to the change of inflow heating agent to the generator. Also, if the temperature of chilled water will set up below 6^{o}C, the valve diminishes the inflow of the warm agent to the generator, what consequently will cause the diminution of the cooling capacity. The change of the cooling capacity of the device is realized similarly. The valve changes the efficiency of the generator of cooling water in the range from 100% to 10%. In the Fig 6 the influence of the selection of the temperature of chilled water leaving the device (6, 7, 8^{o}C) on the coefficient of performance is presented and the temperature of cooling water is taken under consideration. It is clearly seen the decrease of COP in the function of increasing temperature of cooling water and temperature reduction of chilled water leaving the machine.

In the case of the change of the cooling capacity of the double-stage of the absorption machine the quantity of COP does not surrender to greater changes, how this was presented in Fig 7. The decrease of the cooling capacity, and consequently enlarging of the surface of exchangers and the decrease of the temperature difference of media leaving heat and mass exchangers does not cause the significant height of COP. This manner of enlarging COP in the case of double-stage absorption plants has not such meaning as in single-stage machines (Kozioł and Gazda, 2002; Rusowicz, 2008).

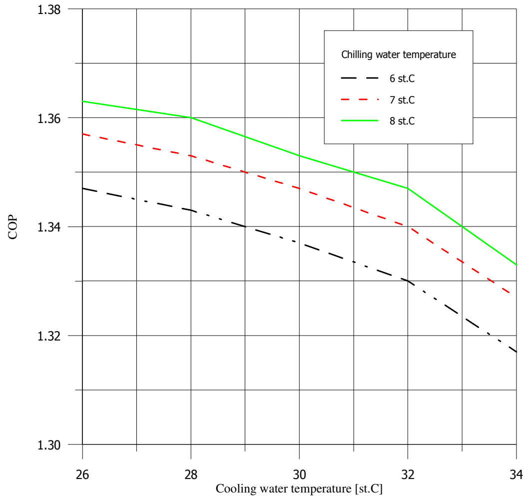

Fig 6. The influence of cooling water and chilled water temperature on coefficient of performance

5. Conclusions

Absorption refrigeration machines are the alternative for compressor plants according to the protection of the natural environment. The main interest in absorption cooling technology is connected with advantages as environment friendly substances used, a few moving parts installed (except pumps). The minimum demand for the electrical energy is also important for the growing demand in the country, especially in rush periods. Additionally, there is the large possibility of putting into a composition of absorption refrigeration machines into cogeneration and trigeneration systems.

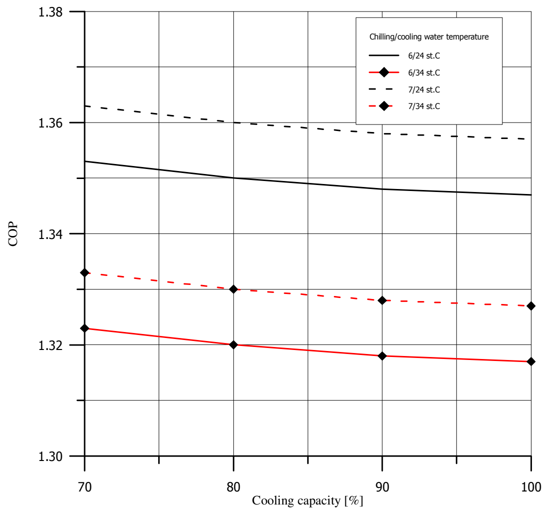

Fig 7. The influence of cooling capacity change on COP

In the case of double-stage absorption refrigeration machines there unfortunately high parameters of provided media to generators are required (higher than for single-stage machines). Instead of this, the significant height of the level of COP is observed from 0.6-0.7 to 1.2-1.4. The examination do not show greater changes of COP in the function of the change of the cooling capacity of the double-stage refrigeration machine, as it takes place in single-stage plants. What is important, the scale and the character of changes of COP in the function of the temperature both of chilled water leaving the machine and cooling water are considerably smaller than in single-stage machines.

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