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LOW POWER ABSORPTION HEAT PUMP DRIVEN BY SOLAR ENERGY WITH HEAT RECOVERY

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Abstract

The present paper proposes the improvement of an one-stage lithium-bromide absorption plant so that it can operate in two different modes. These modes are set out as follows: i) as a refrigeration plant where the heat generator is powered by solar panels, during the hot season; and ii) as a heat pump recovering waste energy from the condenser and from the absorber, during the cold season..

The team collected the empirical data by using the experimental stand from the Technical University of Civil Engineering Bucharest, Department of Thermodynamics. Water was heated by solar panels with the use of a 66m^2 array of flat-plate collectors and consequently used to drive a single-effect (LiBr/H_2O) absorption chiller. The latter had a nominal cooling capacity of 17kW.

The study has a two-fold aim. The first objective is to evaluate the plant's performance in different conditions. Second, the study explores the use of the experimentally recovered heat in increasing the air temperature in a heating coil, part of an air handling unit.

Keywords: heat recovery, absorption heat pump, solar energy

1. Introduction

Solar energy is a major form of renewable energy and it is therefore part of the current trend in reducing fossil fuel consumption. Absorption systems powered by solar heated hot water are bound to gain future importance beyond the area of air conditioning. These systems have proven their reliability in the field of both domestic and industrial applications.

Generally, applications with implemented solar panels are to be used either for air conditioning in summer or for preparing hot water in summer and winter alike.

In such cases, when the hot water prepared in the solar circuit arrives in the heat generator of an absorption plant, it transfers the heat onto a solution that can be either ammonia-water or lithium bromide-water. On account of this energy, the solution evaporates. Meanwhile, cold water needed for air conditioning is collected in the plant's evaporator.

Notably, solar panels can also capture solar energy in the cold season, energy coming especially from diffuse radiation. For this reason, it is useful to modify an absorption refrigeration scheme so that it can use that small amount of energy.

In this context, in the Thermodynamics Laboratory of the Technical University of Civil Engineering Bucharest, the authors have designed and developed an experimental stand. The latter is based on an absorption refrigeration system driven by hot water which operates as a heat pump. The purpose of the experimental stand is to use heat from both the plant's absorber and its condenser, in order to heat the air in a heating coil.

The research illustrated in this paper is based on the study of the lower temperature limits of the hot water prepared by the auxiliary heat source. These temperature limits are investigated in relation to the temperature of the outdoors fresh air introduced in the Air Handling Unit.

2. Experimental Stand

The experimental stand consists of the following elements:

- 30 solar collectors with a total area of 66 m^2 which deliver the thermal power to a water and 30% wt. ethylene glycol solution;
- Plate heat exchanger where the water-ethylene glycol solution transfers the heat to a hot water circuit that is used for driving the generator of the absorption refrigerating machine;
- Storage tank with a volume of 4000 l, which ensures the hot water supply;
- 17 kW Absorption refrigeration machine with lithium bromide solution;
- Auxiliary heat source represented by a 50 kW boiler actioned by natural gas. In the cold season, which is analysed in this paper, the boiler prepares the hot water needed in the generator;
- Hot water consumer (winter) or cold water consumer (warm season), represented by heating / cooling coils part of an Air Handling Unit.

The interest parameters for the analysed system were measured using the following sensors:

- Thermocouples K type with an accuracy ± 0.25 K;
- Flow meters with accuracy of ± 3% for the measurement of fluid flow in circulation (hot / cold);
- Hot wire anemometer with accuracy of ± 2% to measure air flow.

All the above sensors were connected to a data acquisition unit.

The experimental stand scheme is presented in Fig. 1. The changes made for the system to operate as a heat pump are highlighted with bold line.

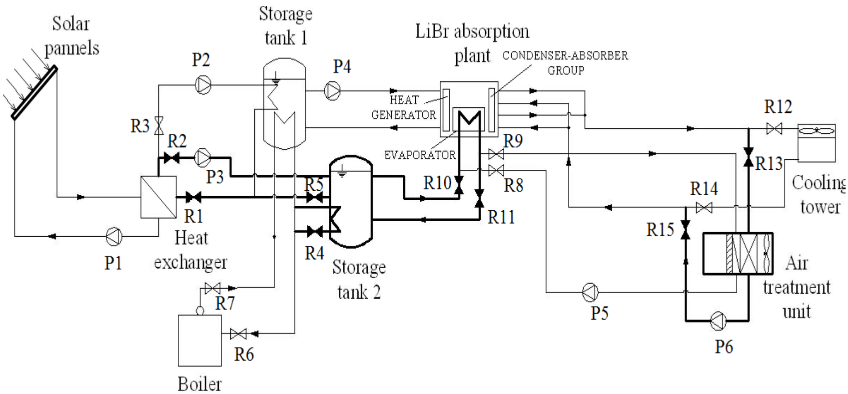

Fig. 1. The experimental stand in the heat pump regime

The working principle of a refrigeration plant is as follows: in the solar circuit, 30 solar collectors deliver the thermal power to a solution consisting of water and 30% wt. ethylene glycol. In the flat-plate heat exchanger, the water-ethylene glycol solution transfers the heat to a hot water circuit used for driving the generator of the absorption refrigerating machine. The valves R1 and R3 are open and the valves R2, R4, and R5 are closed.

If the hot water parameters, as recorded for the solar system, do not meet the functional requirements of the absorption machine, an auxiliary heat source must be used. This source is represented by a 50 kW boiler actioned by natural gas.

Following this, the heat absorbed by the water from the condenser-absorber group is dissipated in a cooling tower, where the valves R12 and R14 are open, and the valves R13 and R15 are closed.

When working as refrigeration plant, the installation prepares cold water in the evaporator, which is used to cool down the air in the cooling coil of the air handling unit (AHU). The valves R8 and R9 are open, and R10 and R11 are closed.

In the heat pump operation mode, the warm water prepared in the solar collector's circuit must have an average temperature around 15°C; it is used in the storage tank 2 as simulated load for the evaporator. The valve R3 is closed and the valves R1, R2 and R5 are open. If the desired temperature is not reached, additional heat needs to be taken from the outlet boiler's circuit. This can be done by operating the valve R4.

In order to ensure a cyclic operation, the temperature for the cold water in storage tank 2 must be raised. This cold water is that prepared in the evaporator and it is of no use in winter time.

The valves R8 and R9 are closed, and R10 and R11 are open.

The boiler provides all the necessary heat needed by the heat pump generator. The hot water, with an average temperature of 80°C, is stored in the Storage tank 1.

The condensation and absorption heat is transferred to the water circuit connected by R13 and R15 to the AHU heating coil (HC). In this given situation, R12 and R14 are closed. Both of these valves connect the condenser and absorber to the cooling tower.

3. Methodology

The study consists of a theoretical analysis and an experimental analysis. The research looks at the thermal power of a heat pump when in different functioning regimes. Both the absorber and the condenser of the heat pump are taken into consideration.

This thermal power is used to heat the air in a 10x6x6 m laboratory, which requires a thermal power of 20 kW for the heating coil.

The purpose of the study is to determine the influence that the heating fluid temperature (hot water) prepared by the boiler has on the thermal power of the condenser and of the absorber. This is done in order to meet the minimum requirement for the laboratory to be properly heated in the cold season.

Furthermore, it is important to determine the heat pump's performance coefficient when working in different operational conditions.

The heating coil of the AHU is supplied with warm water resulting from the parallel cooling of the condenser and of the absorber, both of which have the same cooling water inlet temperature, t_{w1}.

The air treatment unit is fed by an air mixture consisting in:

- 20% fresh air from outdoors with an average considered temperature of $t_{ext.}$ = -10°C and an average relative humidity $\varphi_{ext.}$ = 50%;
- 80% recirculated air from the laboratory with an average temperature $t_{rec.}$ = 22°C and average relative humidity φ_{rec} = (60÷ 80)%.

The authors have determined the inlet temperature of the air in the heating coil. This was done under the experimental conditions described above and by using the Mollier diagram; the resulting value is t_{air1} = 15.5°C.

The mass flow rates of air and water were determined using the following relations:

$$\dot{Q}_{HC} = \dot{m}_{air} \cdot c_{p,air} \cdot (t_{air2} - t_{air1}) = \dot{m}_{w} \cdot c_{p,w} \cdot (t_{w1}^{HC} - t_{w2}^{HC}) \quad (1)$$

$$\dot{Q}_{HC} = \dot{Q}_{A} + \dot{Q}_{C} = \dot{m}_{wA} \cdot c_{p,w} \cdot (t_{w2}^{HC} - t_{w3}) + \dot{m}_{wC} \cdot c_{p,w} \cdot (t_{w2}^{HC} - t_{w4}) \quad (2)$$

Where:
$\dot{Q}_{HC}$ = thermal power of the heating coil [kW], $\dot{Q}_A$ = thermal power of the absorber [kW], $\dot{Q}_C$ = thermal power of the condenser [kW], $\dot{m}_{air}$ = heated air mass flow [kg/s], $c_{p,air}$ = specific heat of air at average temperature [kJ/kg·K], t_{air1} / t_{air2} = air temperature at the inlet/outlet of the heating coil [°C], $\dot{m}_w$ = water mass flow [kg/s], $c_{p,w}$ = specific heat of water at the average temperature [kJ/kg·K], $t_{w1}^{HC} / t_{w2}^{HC}$ = water temperature at the inlet/outlet of the heating coil [°C], t_{w3} = water temperature leaving the absorber [°C], t_{w4} = water temperature at the outlet of the condenser [°C].

Simplifying assumptions:

- The system is simulated under steady state conditions;
- The pressure drop in pipe and vessels is negligible;
- There is saturated refrigerant at condenser and evaporator outlets;
- The difference between concentrations (strong solution and weak solution) $\Delta\xi = \xi_B - \xi_S > 5\%$;
- The pressure losses between generator - absorber and evaporator - condenser are neglected ($p_A = p_0$; $p_G = p_C$.);
- The heat loss from generator to the surroundings and the heat gains in evaporator from surroundings are negligible.

The efficiency of the solution pump was considered to be equal to 0.90.

The coefficient of performance for the heat pump is:

$$COP = \frac{\dot{Q}_C + \dot{Q}_A}{\dot{Q}_G + P_{pump}} \tag{3}$$

Where:

- $\dot{Q}_G$ - Thermal power of the heat generator, [kW];
- P_{pump} - Solution pump power, [kW].

4. RESULTS

Throughout the measurements, the flow rates were maintained constant. This applies to the hot water prepared by the boiler, to the cooling water from the condenser and from the absorber, as well as to the air passing through the heating coil.

The air flow rate is maintained constant in order to satisfy the comfort conditions that require a relatively low air velocity through the Air Handling Unit (AHU).

As part of the research, the hot water that feeds the heat pump generator had a fluctuating temperature. The purpose of this was to determine, when in different functioning regimes, the amount of heat transferred in the condenser and in the absorber. Implicitly, the heat power of the heating coil was also calculated. Lastly, the heat power needed in the heating coil was correlated with the temperature of the fresh air introduced in the AHU. The parameters of interest are presented in Table 1.

Table 1. Parameters acquired by the system in real time

$t_{G,in}$ (°C)	Hot water inlet temperature at the generator
$t_{G,out}$ (°C)	Hot water outlet temperature at the generator
t_{w2}^{HC} [°C]	Cooling water inlet temperature at the absorber and condenser
t_{w3} [°C]	Cooling water outlet temperature at the absorber
t_{w4} [°C]	Cooling water outlet temperature at the condenser
$\dot{m}_G$ [kg/s]	Hot water flow rate at generator
$\dot{m}_{wC}$ [kg/s]	Cooling water flow rate at the condenser
$\dot{m}_{wA}$ [kg/s]	Cooling water flow rate at the absorber

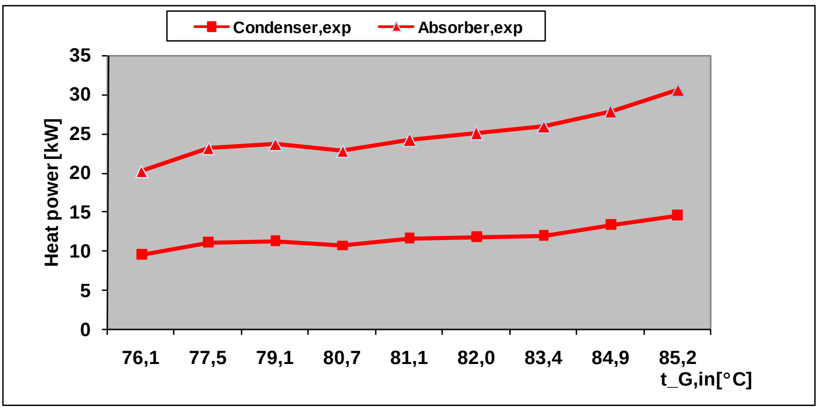

Fig. 2. Absorber and condenser thermal power vs. supplying hot water temperature

The hot water temperature was given different values between 76.1÷85.2°C. This temperature range was chosen so that it can ensure the proper functioning of the heat pump ($\Delta\xi > 5\%$). Fig. 2 shows the relation between the variation of absorber and condenser thermal power versus the temperature of the heating fluid entering the generator.

As can be observed in the above figure, the absorber thermal power is higher than the condenser thermal power with 10÷12%.

Thermal power is increasing proportionally with the temperature of the hot water. Thus, by increasing the hot water temperature with 9ºC, the thermal power increases with approximately 50%. There is a variation of the total thermal power transferred by the condenser and absorber to the cooling water, and further on to the heating coil. This variation is in the range of 20 kW to 30 kW.

The authors conducted a comparative analysis between experimental and theoretical values. The results are presented in Figures 3 and 4. Theoretical values follow the evolution of experimental values, with small differences occurring in the case of hot water temperatures exceeding 83ºC. As Figure 3 suggests, theoretical values are superior to the experimental ones with 7÷14%.

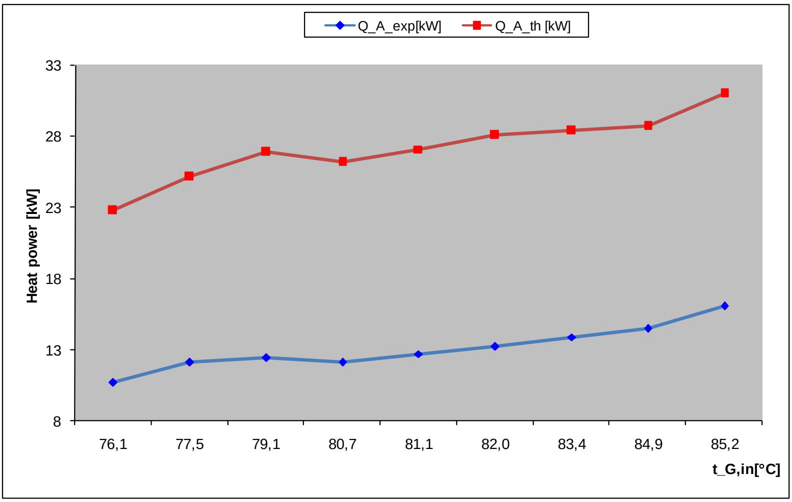

Fig. 3. Experimental and theoretical values for the absorber thermal power vs. hot water temperature

Fig. 4 shows that the experimental values have a large dispersion in relation to the theoretical ones. This applies to temperatures higher than

83ºC. The deviation between the theoretical values and the experimental ones is 1 ÷ 16%.

Fig. 5 shows the theoretical and experimental evolution of COP, depending on the hot water temperature which supplies the heat pump's generator. Theoretical values are superior to the experimental ones with 5 ÷ 10%. The maximum value for COP, respectively, 1.77, corresponds to a hot water temperature of 76.1ºC.

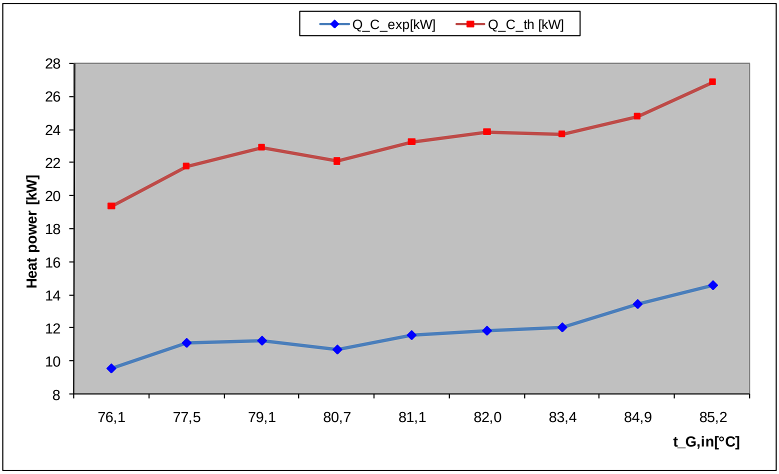

Fig. 4. Experimental and theoretical values for the condenser thermal power vs. hot water temperature

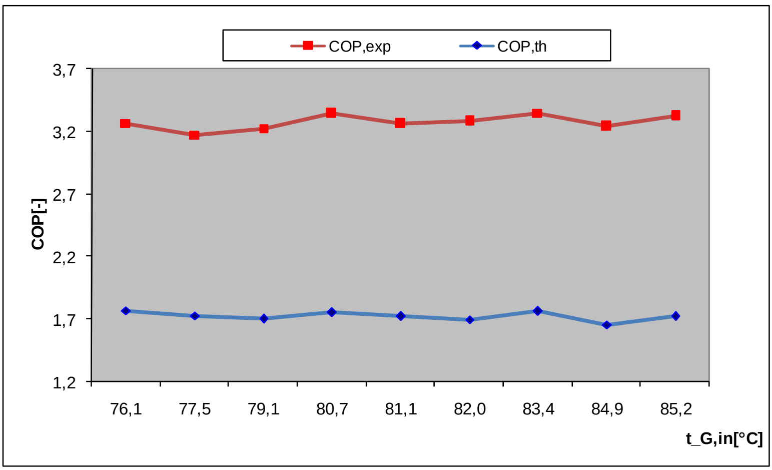

Fig. 5. COP vs. supplying hot water temperature

As represented in the above diagrams, the condenser and absorber can provide a thermal power between 20 to 30 kW for the hot water temperature interval considered here. As a result of this, the authors followed up with a study aiming to correlate the heat flux required by the heating coil and the outdoors fresh air temperature, which is introduced in the AHU.

Using the Mollier diagram and the parameters given in the Methodology section, the authors obtained the values presented in the Table 2. The connection between fresh air temperature and the heating coil flux (from the heat pump's absorber and condenser) can be seen in Fig. 6.

Table 2. Heating coil required heat flux vs. exterior temperature

Fresh air temperature, t_{ext} [°C]	Inlet air temperature in the heating coil, $t_{air,1}$ [°C]	Heating coil heat flux, [kW]
-10	15.5	30
-5	16.4	25.5
0	17.3	21
5	18.3	16.5

Based on a parallel analysis of Fig. 2 and Fig. 6. The following observations can be made:
- The maximum heat flux needed in the heating coil, respectively 30 kW, corresponds to a fresh air temperature of -10°C. This value can be achieved from the condenser and absorber only if the hot water temperature which feeds the generator is greater than 85°C;
- For a fresh air temperature of -5°C the hot water temperature must be greater than 82°C.

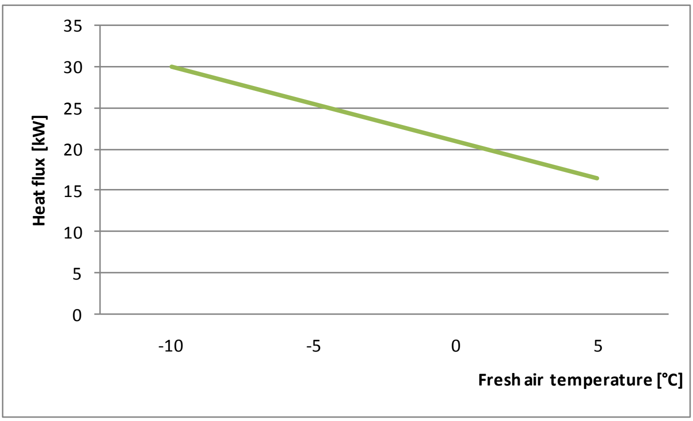

Fig. 6. Heating coil required heat flux vs. exterior temperature

For a fresh air temperature greater than 0°C, the hot water temperature must be greater than 76°C.

5. Acknowledgment

Waste heat resulted from condenser and absorber cooling water processes can be used successfully to provide the necessary heat of a heating coil. For the analyzed conditions, the heat power obtained was in the range of 20 kW to 30 kW. This necessary heat is variable, depending on the temperature of the ambient outside. To ensure the heating of the laboratory, the maximum heat flux required in the heating coil corresponds to a fresh air temperature of -10°C. In this situation, the hot water prepared by the boiler must have a temperature greater than 85°C. For a fresh air temperature greater than 0°C, the hot water temperature can be down to 9° lower, thus enabling a reduction in the boiler's energy consumption and increasing the heat pump performance. As a result, the maximum value for the COP corresponds to a lower hot water temperature, respectively, 76.1°C.

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