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Increase of COP for an experimental heat transformer using a water purification system

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ABSTRACT

The experimental results of a water purification system of single effect evaporation integrated into a heat transformer of 700 W are presented, using lithium bromide water as solution. It is demonstrated that it is possible to increase efficiency of energy use with heat recycling of a water purification system. The typical coefficients of performance values were increased from 24.7% to 30.3%, obtaining a maximum of 684 mL/h of distilled water. The behavior of the coefficient of performance in function of the absorber temperatures before and after the purification process is showed. Experimental and simulated data with the water purification system integrated into a heat transformer are analyzed.

Keywords: Energy saving; Water purification; Heat transformer; Efficiency of energy use; Desalination

1. Introduction

A great part of the world future depends of how to use energy to cover basic and complementary necessities. An immediate human necessity is to research alternatives for reusing waste heat of industrial processes, diminishing environmental pollution and increasing efficiency of energy use in thermodynamic processes.

Heat pumps have enormous potential for reducing the primary energy requirements of various processes. An efficient heat pump system is potentially attractive for use in single process plants which tend to predominate more in developing countries [1]. The most popular heat pumps are by compression and absorption. Absorption heat pumps are conventional absorption and inverse absorption, called heat transformer or temperature amplifier too. Compression heat pumps are by mechanical vapor or bottom flashing [2]

Many theoretical and experimental works have reported on a heat transformer for energy saving with waste heat and diminishing environmental pollution. A heat transformer is a device supplied with waste heat at a certain thermal level and it gives a lower heat quantity at a higher thermal level. A way to quantify the efficiency of energy use in a heat pump is by obtaining the coefficient of performance (COP), which is the ratio between the heat obtained and heat supplied to the components [3].

Scott et al. [4] reported the technical and economic feasibility of incorporating an absorption heat transformer to increase the efficiency of energy use of an evaporation-crystallization plant in a sugar mill. The simulation demonstrated that the total amount of live steam used in the evaporation plant can be reduced by 11.8–16.4%. The first industrial scale heat transformer by recovering waste heat from a synthetic rubber plant was reported by Ma et al. [5], the recovered heat was used to heat water from 95 to 110°C. Lithium bromide–water was used as a

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solution with heat flow of 5000 kW, mean COP of 0.47 was obtained with 25°C of gross temperature lift. A portable water purification system of single effect evaporation (SEE) integrated into a single stage heat transformer of 700 W has been designed and built to obtain distilled water, using 51–55.8% of initial concentrations by weight of a LiBr–water solution. The quality was similar to that obtained from an electric distiller [6].

There are only theoretical proposals for increasing the efficiency of energy use in thermodynamic processes applied to absorption heat pumps through alternative processes. An extraction system attached ammonia–water absorption heat pumps were derived from the conventional system as a strategy to improve the efficiency of energy use. Theoretical thermodynamic simulation showed that a higher COP and less irreversibility were obtained [7,8]. A quantity of the total heat gained with a water purification system of SEE integrated into a heat transformer can be recycled into the generator and evaporator of the equipment itself, with the recycled heat, the initial supplied heat in the generator and evaporator diminishes, causing an increase in their outlet temperatures. This makes it possible to obtain an increase of the conventional coefficients of performance [9]. A predictive model for a water purification process (SEE) integrated into an absorption heat transformer with and without energy recycling, using an artificial neural network, was proposed in order to obtain on line predictions of the coefficient of performance. This model provided insight on how to improve the operating strategy where even effects which are difficult to quantify, like heat losses and pressure drops in the tubing and in the components, are considered [10].

On the other hand, there are experimental works on purification systems of SEE integrated to heat pumps, where convectional COP was not modified. A mechanical vapor compression heat pump was used for water purification, obtaining values of COP from 2.5 to 4.5 and 14.4 to 37.8 kg/h of distilled water. The heat delivered in the condenser was recycled to the heat pump evaporator through water purification system. The COP was not modified, because it is the ratio between the heat delivered by the condenser and the work supplied to the compressor [11].

A water purification system was integrated into a convectional absorption heat pump, obtaining values of COP up to 1.56 and 1.30 with LiBr–water and Carrol– water solutions, respectively. Heat obtained in the condenser and absorber was recycled to the heat pump evaporator. The excess heat from steam condensation was rejected by an auxiliary condenser in order to obtain the energy balance in the system. The COP values were not affected, due to the fact that COP is defined by the ratio between the sum of the heat obtained in the condenser and absorber and the heat supply to the generator [12].

Based on bibliographic search, there are not experimental works on recycling heat into a heat transformer. This paper reports the experimental test results of the first water purification system of single effect evaporation integrated to a heat transformer of 700 W for increasing the efficiency of energy use. The water purification system is capable of recycling part of the total heat gained in the absorber into the heat source of the heat transformer, then the demand for initial heat in the generator and evaporator diminishes, which results in an increase of the typical COP values, because the COP is the ratio between heat obtained in the absorber and heat supplied to the generator and evaporator. Obtained experimental data are analyzed with a thermodynamic simulator.

2. The thermodynamic cycle

Fig. 1 shows a schematic diagram of temperature against pressure of a heat transformer. A heat transformer consists of five main heat exchangers: generator, evaporator, condenser, absorber and economizer. The working solution is made of an absorbent and a working fluid. The absorbent goes through the generator, the absorber and the economizer, while the working fluid goes, in a liquid or steam phase, through all components.

External heat is supplied at medium temperature to the generator and evaporator (T_{GE}, T_{EV}). A partial separation of the working fluid from the solution takes place when the saturation temperature is reached at absolute pressure in the generator. Using external heat extraction at a lower temperature (T_{CO}), the working fluid temperature is diminished in the condenser and the working fluid changes to liquid phase. In the evaporator (with an absolute pressure higher than those in the generator and the condenser), the working fluid is then evaporated and goes into the absorber where it is mixed with the strong solution that comes from the generator. In this process, heat liberation occurs at a high temperature (T_{AB}) and a weak LiBr–water solution is obtained. The weak solution goes back to the generator and preheats the strong solution in the economizer, while the strong LiBr–water solution goes to the absorber in order to repeat the thermodynamic cycle.

3. The water purification system

Fig. 2 shows a schematic diagram of the water purification system integrated into a heat transformer. The water purification system removes the useful heat obtained in the absorber of the heat transformer. Under specific conditions of atmospheric pressure and chemical composition, impure water reaches the boiling point and goes out in two phases (liquid and steam) to a phase separator [13]. In its liquid phase, the impure water returns to the suction pump in order to be taken again to the absorber; steam goes to an auxiliary condenser where heat is transferred to the heat source. The difference in temperature between

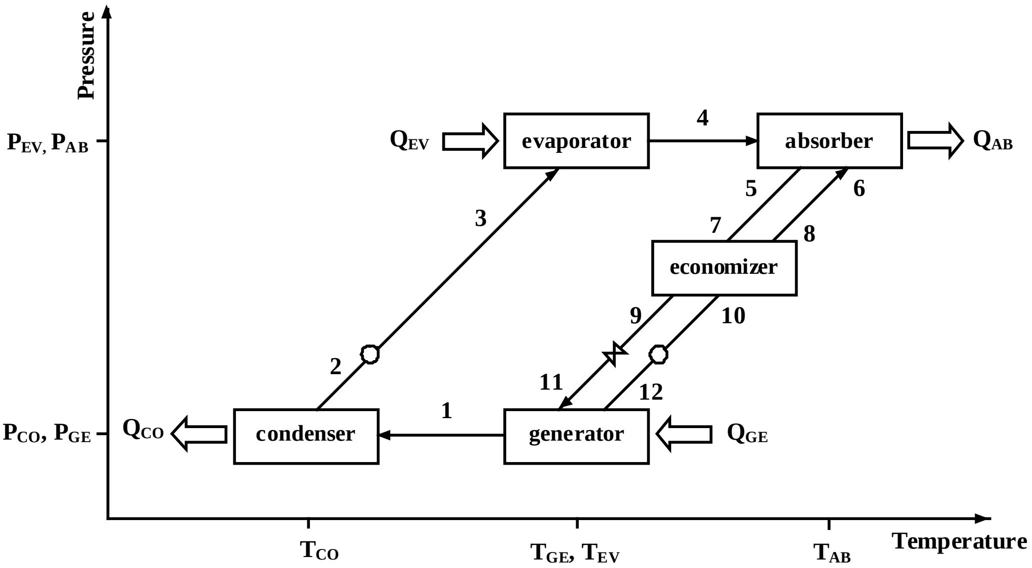


Fig. 1. Schematic diagram of a single stage heat transformer.

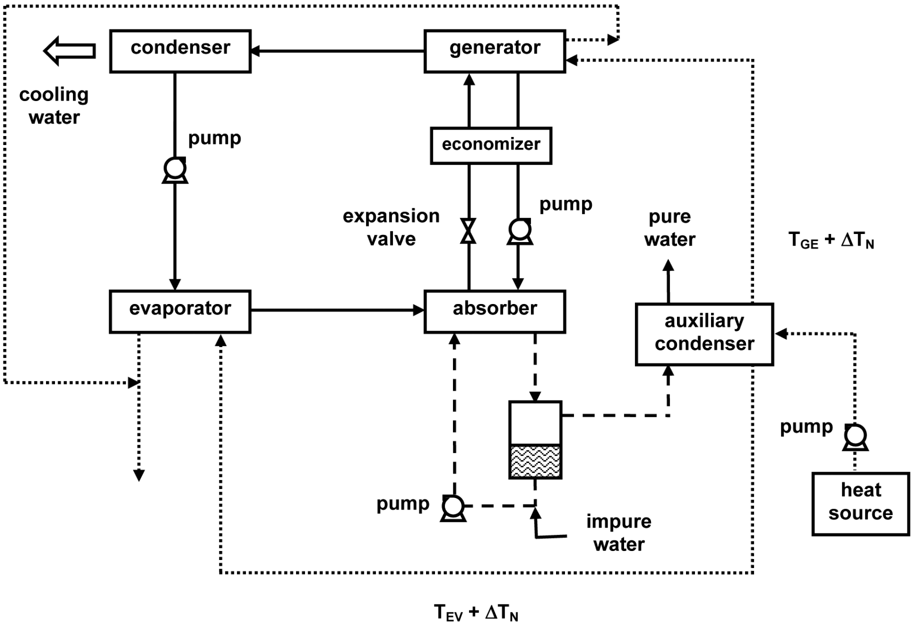


Fig. 2. Schematic diagram of water purification system integrated to a heat transformer.

steam and the heat source allows an increase of the heat source temperature, and thus the corresponding generator and evaporator temperatures increase proportionally. The water level to purify in the phase separator is constant and cumulative salts are periodically drained.

4. Description of experimental equipment

Fig. 3 shows the experimental equipment of the water purification system integrated into a heat transformer with a design of 700 W. Its size is 0.80 × 1.20 × 1.60 m. The heat transformer main circuit is made of 316L stainless steel. The water purification circuit is made of copper and stainless steel. The condenser and evaporator are heat exchangers made of double concentric coil-shaped tubes. The generator and absorber are heat exchangers made of shell and tubes. The generator works as a boiling pool and the absorber as a falling film with horizontal tubes. A thermal insulator made of an expanded elastomer with a thermal conductivity of 0.040 W/m K was used.

The heat supplied to the generator and evaporator was simulated with a thermal bath and a variable electric resis-

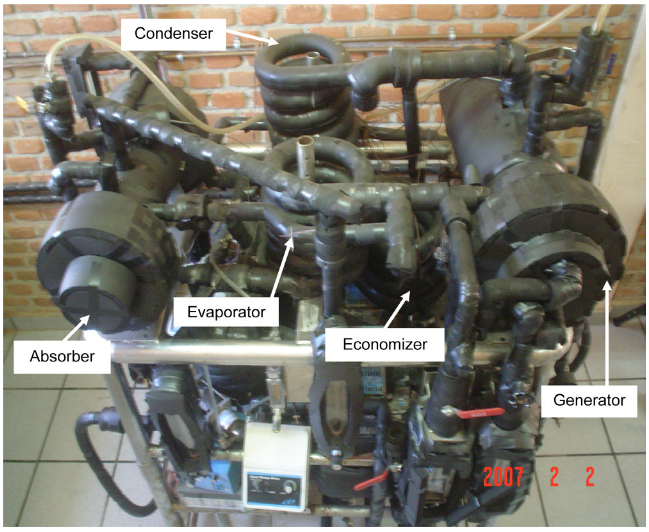


Fig. 3. Experimental equipment of water purification system integrated to a heat transformer of 700 W.

tance, used a commercial centrifuge pump of 0.5 HP and 3450 rpm. Heat was extracted from the condenser with an external circuit by using a commercial centrifuge pump of 1 HP and 3450 rpm. The gained heat in the absorber was removed by the water purification system by using a magnetic pump with variable speed of 0–5600 rpm. A revolution is 1.12 mL of fluid and main body is stainless steel 316.

Type J thermocouples and an Agilent data acquisition unit of 6½ digits with a Bench Link Data Logger software for temperatures measurement were used. All temperatures were adjusted to a temperature standard with a maximum error of ±0.3°C in the interval from 0.0°C to 105.0°C. Two pressure transducers with design exactitude of ±0.25% in the total range were used to measure low and high pressure. The relation between direct voltage and pressure was obtained using an analogical pressure standard with a full scale accuracy of ±0.25% and with a resolution of 666.6 Pa.

The solution flows were measured with two analogical flowmeters with a reading accuracy of ±2%. Lithium bromide–water concentrations in the generator and absorber were measured using a refractometer with an accuracy of ±0.0002 and a correlation of the refraction index obtained in a previous work [12]. Two analogical flowmeters with a full scale accuracy of ±3% were used to measure water flows of the generator and evaporator, impure water flow was measured with an analogical flowmeter with a full scale accuracy of ±2% and an analogical flowmeter with a full scale accuracy of ±3% used to measure flows of the condenser.

Magnetic pumps were used to move LiBr–water solutions and working fluid with variable speed of 0–5600 rpm, every revolution was 0.92 mL of fluid and main body was stainless steel 316.

Lithium bromide–water solution presents good thermodynamic performance, lithium bromide is the absorbent and water is the working fluid. This pair has some advantages such as non toxic and non inflammable, high volatility ratio, high affinity and high latent heat. The main disadvantage is its high corrosive condition which can be reduced with inhibitors [14,15]. Experimental tests were carried out using lithium bromide–water without inhibitors, because correlations of thermodynamic properties were obtained similarly [16,17].

5. Procedure

Simulated and experimental results were analyzed considering absorber temperature and coefficient of performance, before and after recycling heat. The thermodynamic water properties were taken from the NIST/ASME steam software [18] and the thermodynamic properties of LiBr–water solutions from Feuerecker et al. [17]. Theoretical data were obtained by a simulator considering energy and mass balances and a proposal for improve efficiency of energy use with water purification system integrated with a heat transformer.

5.1. Energy and mass balance [19,20]

With heat and mass assumptions as heat losses and drop pressures are negligible, the system is in thermodynamic equilibrium and steady state condition, solution and working fluid exits in every component are saturated, fluxes through the valves are isenthalpic and the LiBr–water concentrations are zero in liquid and steam phases of the working fluid.

Knowing outlet temperatures of the main components and heat load from one component, it is possible to determine the thermodynamic conditions for performance of a heat transformer considering schematic diagram as shown in Fig. 1.

1. Considering outlet temperatures of the condenser and the evaporator (T_2, T_4), it is possible to obtain P_2 ($P_1 = P_2 = P_{11} = P_{12}$) and P_4 ($P_3 = P_4 = P_5 = P_6 = P_7 = P_8 = P_9 = P_{10}$) respectively.
2. Knowing generator temperature and pressure (P_{12}, T_{12}), it can be estimated X_{GE} ($X_6 = X_8 = X_{10} = X_{12}$) and with absorber temperature and pressure (P_5, T_5), X_{AB} ($X_5 = X_7 = X_9 = X_{11}$).
3. In every point, the outlet enthalpies of condenser and evaporator (h_2, h_4) can be estimated with temperature; the outlet vapor enthalpy of generator (h_1) with temperature and pressure, and outlet solution enthalpies of absorber and generator (h_5, h_{12}) can be calculated with temperature and concentration respectively.

Enthalpy heat balances were obtained by solution flows in each component

$$Q_{EV} = m_4\left(h_4 - h_3\right) \tag{1}$$

$$Q_{\mathrm{GE}} = m_{12}h_{12} + m_4h_1 - m_5h_{11} \tag{2}$$

$$Q_{\mathrm{CO}} = m_4\left(h_1 - h_2\right) \tag{3}$$

$$Q_{\mathrm{AB}} = m_{12}h_6 - m_4h_4 - m_5h_5 \tag{4}$$

Enthalpy based coefficients of performance were obtained with previous enthalpy heat balances

$$\mathrm{COP}_{\mathrm{ET}} = \frac{Q_{\mathrm{AB}}}{Q_{\mathrm{GE}} + Q_{\mathrm{EV}}} \tag{5}$$

5.2. A proposal for improving the efficiency of energy use with the water purification system integrated with a heat transformer [9]

1. A water purification system takes heat in absorber (Q_{AB}) as sensible and vaporization heat

$$Q_{\mathrm{AB}} = m_W(\Delta h_S + \Delta h_V) \tag{6}$$

2. Part of absorber heat (hQ_{AB}) is recycled to equipment itself by auxiliary condenser, because water thermal level to purify is higher than heat supply temperature

$$Q_{\mathrm{HS}} = Q_{\mathrm{EV}} + Q_{\mathrm{GE}} = m_{\mathrm{HS}}Cp\Delta T_{\mathrm{HS}} \tag{7}$$

3. The recycling heat quantity is in function of initial and boiling water temperature at a given altitude [21]. The value of h is higher when the distillation process is carried out at low atmospheric pressure according to the relation of the sensible and latent enthalpies of water which increases the recycling heat quantity.

$$\eta = \frac{\Delta h_V}{\Delta h_V + \Delta h_S} \tag{8}$$

4. The temperature of heat supply increases (ΔT_{N}) with recycling heat

$$\eta Q_{\mathrm{AB}} = m_{\mathrm{HS}}Cp\Delta T_{\mathrm{N}} \tag{9}$$

5. Substituting Q_{AB} and m_{HS} of Eqs. (5) and (7) respectively in Eq. (9) and considering that *Cp* of the flow does not change for the heat source (both before and after recycling heat)

$$\Delta T_{\mathrm{N}} = \eta\mathrm{COP}_{\mathrm{ET}}\Delta T_{\mathrm{HS}} \tag{10}$$

6. The outlet steam temperature from the evaporator (T'_{EV}) and the outlet solution temperature from the generator (T'_{GE}) are increased.

$$T'_{\mathrm{EV}} = T_{\mathrm{EV}} + \Delta T_{\mathrm{N}} \tag{11}$$

$$T'_{\mathrm{GE}} = T_{\mathrm{GE}} + \Delta T_{\mathrm{N}} \tag{12}$$

New outlet temperatures from the generator and evaporator conditions allow reaching a typical value of COP increase with recycling heat. A new COP is obtained.

6. Experimental data

Experimental tests were carried out with industrial grade LiBr and distilled water in concentrations from 51.0% to 54.6% by weight of LiBr. In every test, relative standard deviation was used for to determinate steady state [22], the variations permitted were less than ±0.3% in process variables by 30 min; the parameter values were then registered during a period of 20 min in order to calculate the quantity of transferred heat in each component. Experimental evaluations of each test were done before and after the water purification process in order to obtain distilled water and to quantify the heat transferred to the heat source.

The conventional heat in each component was obtained using the following equations:

$$Q_{\mathrm{EV}} = m_{\mathrm{EV}}Cp\left(T_{\mathrm{IN}} - T_{\mathrm{OUT}}\right) \tag{13}$$

$$Q_{\mathrm{GE}} = m_{\mathrm{GE}}Cp\left(T_{\mathrm{IN}} - T_{\mathrm{OUT}}\right) \tag{14}$$

$$Q_{\mathrm{CO}} = m_{\mathrm{CO}}Cp\left(T_{\mathrm{IN}} - T_{\mathrm{OUT}}\right) \tag{15}$$

$$Q_{\mathrm{AB}} = m_{\mathrm{AB}}Cp\left(T_{\mathrm{IN}} - T_{\mathrm{OUT}}\right) + m_{\mathrm{PW}}\Delta h_V \tag{16}$$

The general evaluation of the water purification system integrated into a heat transformer was done through conventional coefficient of performance [23]:

$$\mathrm{COP} = \frac{Q_{\mathrm{AB}}}{Q_{\mathrm{GE}} + Q_{\mathrm{EV}}} \tag{17}$$

When steam gave heat to the heat source through the auxiliary condenser, the temperature of the external circuit increased (ΔT_{N}), thereby making the outlet steam temperature from the evaporator (T'_{EV}) and the outlet solution temperature from the generator (T'_{GE}) increase as well but in a lower proportion than expected by Eqs. (11) and (12) by heat losses, because of low heat transfer between the stainless steel heat exchange surfaces.

7. Results and discussion

Fig. 4 shows the results obtained from the thermodynamic simulator at different operating conditions. There are two ranges of COP, one of them from 19% to 25.5% and the second from 60.3% to 148.8% with a 1°C increase in the temperature of the generator and evaporator. Ranges of high values (60.3–148.8%) correspond to small COP values (less than 0.283), while the ranges of lower values (19–25.5%) correspond to elevated COP values (higher than 0.376). Corresponding to small COP values for a certain generator and evaporator temperature, the increases in COP values are high in percentages. These $\mathrm{COP}_{\mathrm{ET}}$ values are higher than $\mathrm{COP}_{\mathrm{ET}}$ values reported by Siqueiros and Romero [9], because the economizer was considered in the experimental work and thermodynamic simulator, which increases the equipment performance.

COP values obtained in experimental tests without recycling heat varied from 0.220 to 0.258. These values are in the lower range of curves proposed by the simulator (Fig. 4). Therefore, the increase in COP values should be between 25.5% and 60.3% with a 1°C increase in the temperature of the generator and evaporator. In the experimental tests, the COP values increases vary from 24.7% to 30.3%, with outlet solution temperature increases from the generator varying from 0.6°C to 2.2°C and outlet steam temperature from the evaporator varying from 0.0°C to 1.2°C. These COP values are up to 33.7%, less than those from the thermodynamic simulator due to the equipment heat loss, because the system is of small capacity and low heat transfer between the stainless steel heat exchange surfaces [23,24]. The obtained COP values in the simulator are enthalpy based COP values (COP_{ET}) and the reported values are conventional COP values [25,26].

Fig. 5 shows conventional COP values and the increases of COP values against outlet solution temperatures from the absorber. Before the auxiliary condenser removed heat from steam and gave it to the heat source, a COP of 0.241 was reached at T_{AB} of 98.9°C. When the water purification system gave heat in a constant way to the heat source, a new COP of 0.309 was reached at a higher T_{AB} of 101.3°C. The maximum COP increase was 27.8%. The maximum temperature increase of the absorber reached both before and after water purification was of 97.1°C and 101.3°C respectively, with a COP increase of 30.3%.

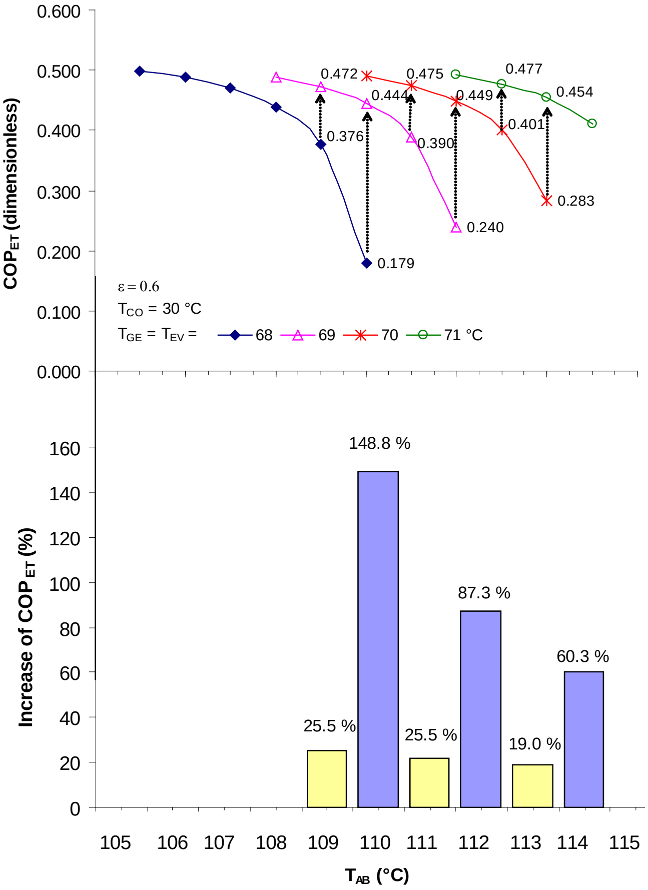


Fig. 4. COP_{ET} and its percentage increase for $\Delta T_N = 1$°C against T_{AB} for different operating conditions.

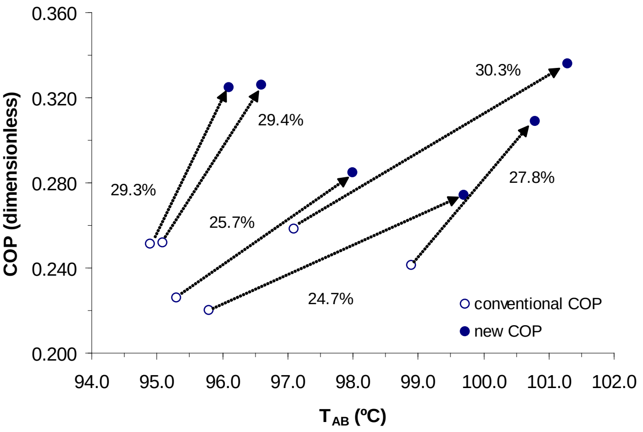


Fig. 5. Conventional COP values and the increases of COP values against outlet solution temperatures from absorber.

Fig. 6 shows the obtained distilled water quantity (m_{PW}) against heat in the absorber (Q_{AB}) in different tests. The maximum quantity of obtained distilled water was 684 mL/h with a Q_{AB} of 0.524 kW and the minimum quantity was of 396 mL/h with a Q_{AB} of 0.396 kW. Whenever a greater amount of Q_{AB} is obtained, a greater amount of m_{PW} is likewise obtained because Q_{AB} is the caloric energy transferred to the impure water under the same condition of atmospheric pressure. The behavior was similar to two previous works on a water purification system absorption heat pump with LiBr–water [27] and Carrol–water solutions [3].

The results obtained both before and after recycling heat in experimental tests are shown in Table 1. The

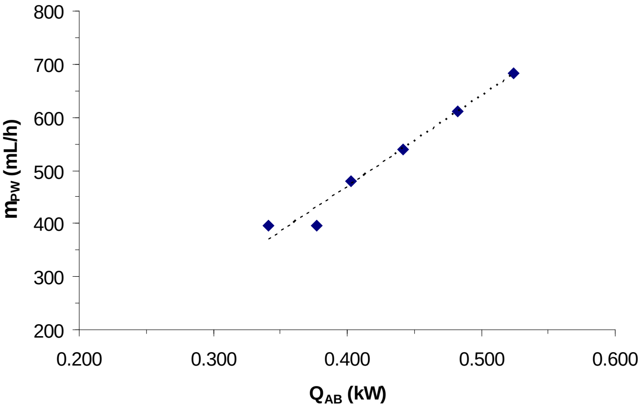
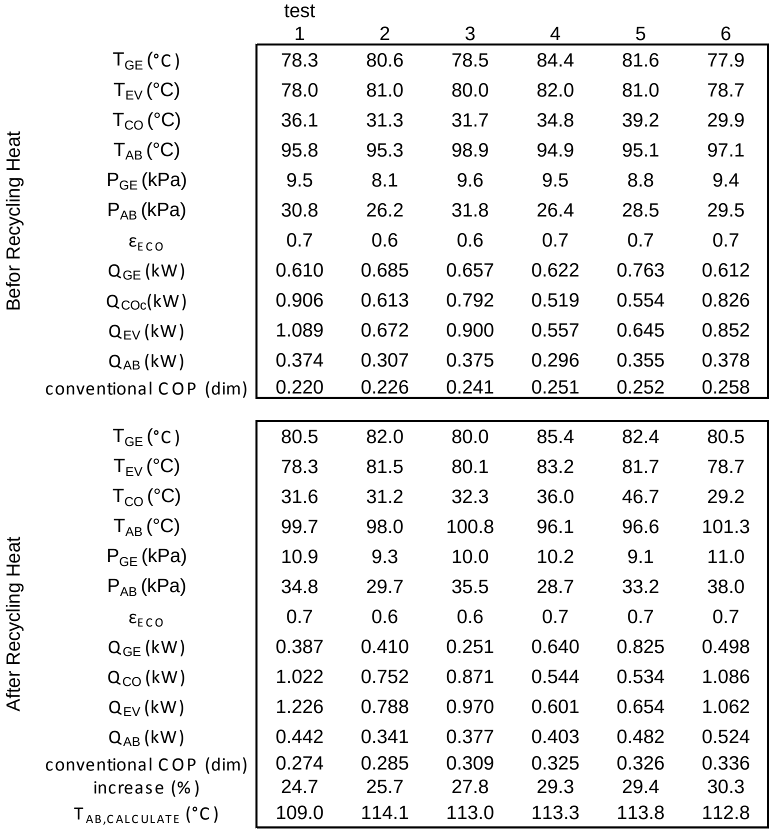


Fig. 6. Distilled water quantity against obtained heat in absorber.

Table 1
Experimental tests results before and after recycling heat



		test					
		1	2	3	4	5	6
Befor Recycling Heat	T_{GE} (°C)	78.3	80.6	78.5	84.4	81.6	77.9
	T_{EV} (°C)	78.0	81.0	80.0	82.0	81.0	78.7
	T_{CO} (°C)	36.1	31.3	31.7	34.8	39.2	29.9
	T_{AB} (°C)	95.8	95.3	98.9	94.9	95.1	97.1
	P_{GE} (kPa)	9.5	8.1	9.6	9.5	8.8	9.4
	P_{AB} (kPa)	30.8	26.2	31.8	26.4	28.5	29.5
	ε_{ECO}	0.7	0.6	0.6	0.7	0.7	0.7
	Q_{GE} (kW)	0.610	0.685	0.657	0.622	0.763	0.612
	Q_{COc}(kW)	0.906	0.613	0.792	0.519	0.554	0.826
	Q_{EV} (kW)	1.089	0.672	0.900	0.557	0.645	0.852
	Q_{AB} (kW)	0.374	0.307	0.375	0.296	0.355	0.378
	conventional COP (dim)	0.220	0.226	0.241	0.251	0.252	0.258
After Recycling Heat	T_{GE} (°C)	80.5	82.0	80.0	85.4	82.4	80.5
	T_{EV} (°C)	78.3	81.5	80.1	83.2	81.7	78.7
	T_{CO} (°C)	31.6	31.2	32.3	36.0	46.7	29.2
	T_{AB} (°C)	99.7	98.0	100.8	96.1	96.6	101.3
	P_{GE} (kPa)	10.9	9.3	10.0	10.2	9.1	11.0
	P_{AB} (kPa)	34.8	29.7	35.5	28.7	33.2	38.0
	ε_{ECO}	0.7	0.6	0.6	0.7	0.7	0.7
	Q_{GE} (kW)	0.387	0.410	0.251	0.640	0.825	0.498
	Q_{CO} (kW)	1.022	0.752	0.871	0.544	0.534	1.086
	Q_{EV} (kW)	1.226	0.788	0.970	0.601	0.654	1.062
	Q_{AB} (kW)	0.442	0.341	0.377	0.403	0.482	0.524
	conventional COP (dim)	0.274	0.285	0.309	0.325	0.326	0.336
	increase (%)	24.7	25.7	27.8	29.3	29.4	30.3
	$T_{AB,CALCULATE}$ (°C)	109.0	114.1	113.0	113.3	113.8	112.8

differences in outlet temperatures from the generator, evaporator, condenser and absorber (before and after recycling heat) were different in each experimental test. This was due to the fact that the operation conditions were different too. The reported temperature values from the absorber were calculated with absolute pressure and solution concentration of absorber using correlations reported by Feuerecker et al. [17]. These calculated saturated temperature values of the absorber were higher than the outlet temperatures obtained with recycling heat up to 17.2°C. This high difference was due to the different solution flows in the absorber and different heat transfer rates to impure water.

8. Conclusions

It has been experimentally demonstrated that a water purification system of single effect evaporation integrated into a heat transformer increases the efficiency of energy use. An increase in the coefficient of performance is obtained by applying an increase in the outlet initial temperature from the generator and evaporator. Increases in the outlet temperatures are obtained by a heat transfer from the water purification system to the heat source. COP values without recycling heat ranged from 0.220 to 0.258 and COP values with recycling heat were increased to values between 0.274 and 0.336. These increases represent up to a 30.3% of typical conventional COP values. The maximum COP increase reached with the highest Q_{AB} was of 30.3%, and it resulted in 684 mL/h of distilled water and a 4.2°C increase in the outlet solution temperature of the absorber.

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Symbols

Cp — Heat capacity, kJ/kg °C
COP — Coefficient of performance, dimensionless
h — Specific enthalpy, kJ/kg
m — Mass flow rate, kg/s
Q — Heat flow rate, kW
P — Absolute pressure, kPa
T — Temperature, ºC
T' — Temperature increased as result of recycling

heat, °C
X — Mass fraction of LiBr in solution, %

Greek

η — Fraction of transferred heat
ε — Economizer efficiency

Subscripts

AB — Absorber
CO — Condenser
ET — Enthalpy
EV — Evaporator
GE — Generator
HS — Heat source
IN — Input
N — New
OUT — Outlet
S — Sensible
V — Vaporization
W — Water
PW — Purified water

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