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Parameters affecting the efficiency of a heat transformer with a particular focus on the heat solution

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Abstract

The heat transformer is a reverse cycle absorption machine, suitable for the direct exploitation of heat wastes and solar energy. Part of these wastes are "transformed" into thermal energy at a higher temperature than the one provided. Hence some studies concern the evaluation of the performances of the working fluids used. They must ensure a high level of efficiency which, as for the conventional absorption machines, depends on several parameters. One of these parameters is the heat solution: it is defined as the heat absorbed when a mole of a given component is mixed with the amount of the other component required to generate the desired solution at a certain temperature and pressure. This is the reason why the decision was to examine its influence with respect to machines exerting two different fluids which are generally used. The first one is NH_3-H_2O, whereas the second is H_2O-LiBr; they used as refrigerating substances ammonia and water respectively and as absorption substances water and lithium bromide.

Through an analytical modeling and the processing of experimental data provided by the bibliography, it was possible to show how, for these fluids, the terms of the sensible heat represent a moderate fraction of the global energy balance, at one condition though: highly efficient recovery exchangers must be present. Moreover there were reported values of the refrigeration effect of the order of thousands of kJ/kg with satisfying responses energetically speaking. Then a high stability of the fluid NH_3-H_2O was revealed, as testified by the high value of the difference between the concentration of the refrigerator in the absorber and the concentration of the refrigerator in the generator.

Keywords: ground heat exchangers, linear thermal source, soil, experimental setup, thermal conductivity.

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Nomenclature

g_r	rate of the refrigerant in output from the generator
g_s'	rate of the solution from the absorber
g_s	rate of the solution in output from the generator
H	enthalpy of solution
$H_{1,0}$	molar enthalpy of solute
$H_{2,0}$	molar enthalpy of solvent
i	integral heat of solution
L	work performed
m	ratio defined by the Eq. (6)
n_1	moles of solute
n_2	moles of solvent
Q_a	amount of heat released outward by the heat transformer into the absorber
Q_e	amount of heat received by the heat transformer from the outside into the evaporator
Q_g	amount of heat received by the heat transformer from the outside into the generator
$r(T_a)$	transforming heat of the refrigerant at a temperature T_a
s	differential heat of solution
$s(T_a, X_a)$	differential heat of solution at a temperature T_a and concentration X_a
$\gamma_{p,l}$	specific heat of the fluid refrigerant
$\gamma_{p,v}$	specific heat at a constant pressure of the vaporous refrigerant
γ_s	specific heat of the solution
v_r	refrigerant fluid specific volume
v_s	specific volume of the solution
X_1	molar fraction of solute
X_2	molar fraction of solvent
X_a	refrigerant concentration in the absorber
X_g	refrigerant concentration in the generator
Greek letters	
α	efficiency of the exchanger S_1
β	efficiency of the exchanger S_2
η	efficiency of the heat transformer
η_1	mechanical efficiency of the p_1
η_2	mechanical efficiency of the pump p_2

1. Introduction

The heat transformer is a reverse cycle absorption machine ideal for a direct exploitation of heat wastes without the exertion of further energy sources. As a matter of fact these wastes are "transformed" into thermal energy at a higher temperature than the one provided.

Even if over the past few years different plant solutions were proposed [1-5], the number of studies [6-8] carried out in the field of heat transformers has been increasing. Even if they were sometimes related to environmental aspects [9-10] and to the coupling of this technology with solution able to enhance indoor thermal comfort [11], particular attention was given to the analysis of the performances of the working fluids used. The fluid must ensure a high level of efficiency value; this depends on several parameters and a key role is played by the differential heat of solution. Therefore, while taking into consideration what has been previously mentioned, this study examines how the heat of solution affects the level of efficiency of heat transformers with respect to two different fluids: NH_3-H_2O and H_2O-LiBr.

2. Important relations

The performance of a heat transformer (Eq. (1)) can be defined as the ratio between the amount of heat released from the absorber to the environment and the sum of the work performed and the amounts of heat that the machine receives from the outside into both the generator and the evaporator:

$$\eta = \frac{Q_a}{Q_e + Q_g + L} \tag{1}$$

For what concerns the evaluation of the terms characterizing the Eq. (1), a solution could be the exertion of the Stierlin's approximation [12], which is reported in the Eq. (2):

$$Q_a = Q_g = Q_e \tag{2}$$

Through Eqs. (1) and (2), assuming that the work performed is not significant, Eq. (3) can be determined:

$$\eta = 0.5 \tag{3}$$

On the other hand, if the work performed and the heat loss are considered, the value determined through the Eq. (3) will inevitably decrease also affecting the reliability of the system (whose importance was demonstrated in different research fields [13,14]. However, thanks to the decision to exert fluids with a particularly high value of the heat of solution, this decrease can be counterbalanced and in some cases η values which are higher than 0.5 can be obtained. In order to understand how the type of fluid affects η, Eq. (1) must be rearranged; this is why a preliminary mass balance in the generator should be performed, as reported in Fig. 1.

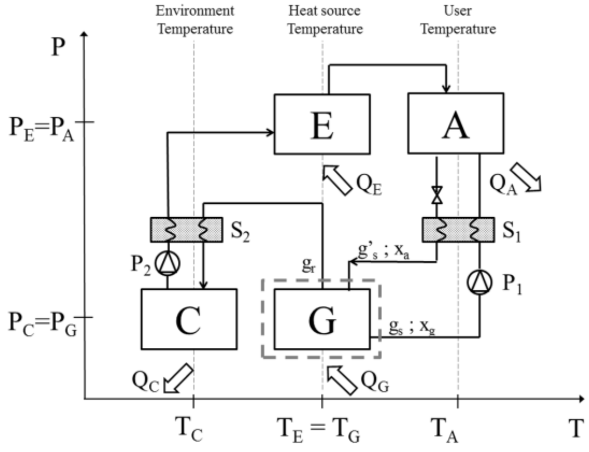

Fig. 1 –Diagram of a heat transformer.

With stationary conditions the law of conservation of mass can be represented according to the Eq. (4):

$$g'_s = g_r + g_s \tag{4}$$

Due to the fact that with stationary conditions the refrigerant mass in the G is also constant, it is possible to write the Eq. (5):

$$g_s' \cdot X_a = g_r + g_s \cdot X_g \tag{5}$$

Without taking into consideration the g_s', dividing each term by g_r and setting g_s/g_r=m, Eq. (6) can be determined:

$$m = \frac{1-X_a}{X_a-X_g} \tag{6}$$

It must be kept in mind that with traditional absorption heat machines the parameter m could be defined in an analogous way through the Eq. (7):

$$m = \frac{1-X_g}{X_a-X_g} \tag{7}$$

The difference between Eqs. (6) and (7) is due to the fact that, for what concerns the heat transformer, the generator is characterized by a lower pressure than the one of the absorber, hence the amount of g_s flowing through the pump is the one in output from the generator, as showed in Fig. 1. While taking into consideration Eq. (6) and with reference to the diagram reported in Fig. 1, the amount of heat Q_a that the machine is able to release to the user can be explained through Eq. (8):

$$Q_a = r(T_a) + s(T_a, X_a) - \gamma_{p,v}(T_a - T_e) - m\gamma_s(1-\alpha)(T_a - T_g) \tag{8}$$

The amount of heat Q_g and Q_e can be expressed through Eq. (9) and Eq. (10) respectively:

$$Q_g = r(T_g) + s(T_g, X_g) - m\gamma_s(1-\alpha)(T_a - T_g) \tag{9}$$

$$Q_e = r(T_e) + -\gamma_{p,l}(1-\beta)(T_e - T_c) \tag{10}$$

On the other hand L is equal to the sum of the values L_1 (Eq. (11)) and L_2 (Eq. (12)) performed in the pumps p_1 and p_2, since:

$$L_1 = \frac{1}{\eta_1} m v_s (p_a - p_g) \tag{11}$$

$$L_2 = \frac{1}{\eta_2} v_r (p_e - p_c) \tag{12}$$

Moreover, assuming that p_a=p_e, p_g=p_c, L is equal to what is reported in Eq. (13):

$$L = \left(\frac{1}{\eta_1} m v_s + \frac{1}{\eta_2} v_r\right)(p_a - p_g) \tag{13}$$

By substituting in Eq. (1) the Eqs. (8), (9), (10), (13) the result is the explicit expression of the performance of a heat transformer (Eq. (14)):

$$\eta = \frac{r(T_a)+s(T_a,X_a)-\gamma_{p,v}(T_a-T_e)-m\gamma_s(1-\alpha)(T_a-T_g)}{r(T_a)+s(T_a,X_a)-\gamma_{p,v}(T_a-T_e)-m\gamma_s(1-\alpha)(T_a-T_g)+r(T_e)+\gamma_{p,l}(1-\beta)(T_e-T_c)+L} \tag{14}$$

Through Eq. (14) it can be stated that, for what concerns the heat transformer, it is even more important the possibility to have a refrigerant with a higher transforming heat value than in the case of a refrigerant machine in order to minimize the influence of the secondary terms related to the sensible heat (present with a negative sign in the numerator).

3. The solution heat

While examining a solution formed by n_1 moles of solute and n_2 moles of solvent, where H is the enthalpy of solution, $H_{1,0}$ and $H_{2,0}$ the molar enthalpies of the pure substances for assigned values in terms of temperature and pressure, the integral heat of solution could be defined through Eq. (15):

$$i = H - n_1 H_{1,0} - n_2 H_{2,0} \tag{15}$$

Usually i is referred to one mole of component (i/n_1) and it represents the heat absorbed when a mole of n_1 is mixed with the amount of the other component in order to have the required solution at a certain temperature and pressure. The integral heat of solution reports the typical trend showed in Fig. 2(1); i increases with the increasing of the moles of solvent and tends to a limit value called "integral heat of solution at infinite dilution" [15]. The differential heat of solution s is determined by differentiating the Eq. (15) with respect to n_1, while keeping constant the temperature, pressure and number of moles of solvent n_2 (Eq. (16)):

$$s = \left(\frac{\partial i}{\partial \eta_1}\right)_{n_2,T,p} \tag{16}$$

Through the Eqs. (15) and (16), Eq. (17) can be determined:

$$s = \left(\frac{\partial H}{\partial \eta_1}\right)_{n_2,T,p} - H_{1,0} \tag{17}$$

Fig. 2(1) shows how s can be identified as the ordinate of the point of intersection of the tangent at the curve with the axis of ordinates: it depends on the concentration of the solution at point P [15]. The parameter d, representing the differential heat of dilution, can be defined in an analogous way as s, that is by differentiating Eq. (15) with respect to n_2 and keeping the temperature, pressure and number of moles n_1 constant (Eq. (18)):

$$d = \left(\frac{\partial i}{\partial \eta_2}\right)_{n_1,T,p} \tag{18}$$

Through Eqs. (15) and (18), Eq. (19) can be also determined:

$$d = \left(\frac{\partial H}{\partial \eta_2}\right)_{n_1,T,p} - H_{2,0} \tag{19}$$

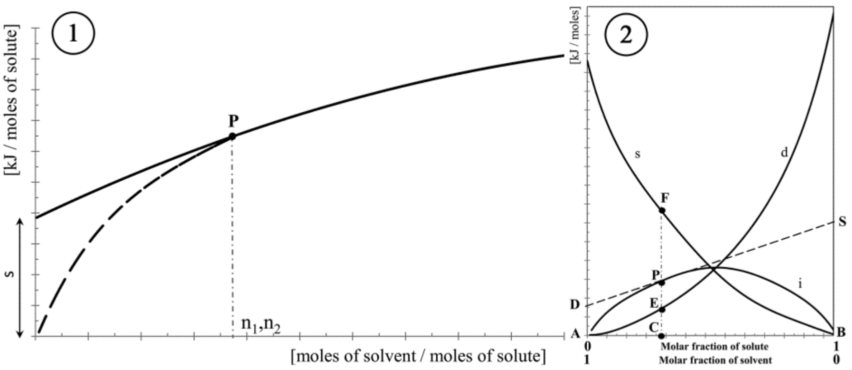

Fig. 2 – Trend of the integral heat of solution (1) and graphical method for the identification of s and d (2).

From a physical point of view, s represents the heat absorbed by the solution when a mole of solute is added to a big amount of solution for given values of concentration, temperature and pressure; d is the heat absorbed by the same solution when a mole of solvent is added.

Then it is possible to demonstrate [15] that among s, d and i the relation provided by Eq. (20) exists:

$$i = n_1 s + n_2 d \tag{20}$$

where i is expressed in kJ, s in kJ/ mole of solute and d in kJ/mole of solvent. On the other hand if i is expressed in kJ/mole of solution, Eq. (20) presents the form reported in Eq. (21):

$$i = X_1 s + X_2 d \tag{21}$$

where X_1 and X_2 are the mole fraction of solute and solvent. In terms of graphics, the relation between "i", "s" and "d" is represented through Fig. 2(2), where a graphical method used to determine s and d is also reported, since the value of "i" is known (intercepts method) [15]; with reference to point P the result is SB=CF=s and AD=EC=d.

4. Heat parameters of some fluids

Through the relations previously described and some experimental data [16-19], Tab. 1 was realized. It reports the values of the differential heat of solution and dilution according to different concentration values in reference to the couple refrigerant-absorbent NH_3-H_2O and H_2O-LiBr; since the solutions are exothermic the values are negative. A temperature of 20 °C was assumed and it was demonstrated how the variation in s and d with the temperature has not a relevant influence on the Eq. (14).

Tab.1 – Differential heat of solution and dilution of NH_3-H_2O and H_2O-LiBr at 20 °C and with different concentrations for what concerns the weight of the solute.

Fluid		X% solute weight (NH_3 and LiBr)										
		0	10	20	30	40	50	60	70	80	90	100
NH_3-H_2O	s	-	-1,981	-1,890	-1,781	-1,651	-1,491	-1,292	-1,039	-713	-311	0
	d	0	0	-5	-25	-90	-275	-806	-2,441	-8,445	-41,958	-
H_2O-LiBr	s	-564	-539	-520	-491	-445	-335	-141	-	-	-	-
	d	0	0	-4	-14	-39	-132	-370	-405	-	-	-

5. Discussion

In order to carry out a comparison between the fluids NH_3-H_2O and H_2O-LiBr, the following conditions were taken into consideration in reference to the exertion of the heat transformer in residential buildings: T_c=5 °C (outdoor temperature = -5 °C); T_e=T_g=45 °C (heat wastes temperature =50 °C); T_{amin}=85 °C (user temperature =80 °C). Through the diagrams P-T-X of the substances used, it is possible to determine the working conditions (Tab. 2):

Tab.2 – Working conditions of the fluids examined.

Fluid	T_{amax} [°C]	X_a [%]	X_g [%]	m (Eq. 7)	$r(T_g)$,$r(T_e)$ [kJ/kg]	$r(T_a)$ [kJ/kg]	$s(T_g,X_g)$ [kJ/kg]	$s(T_a,X_a)$ [kJ/kg]	γ_s [kJ/kg °C]	$\gamma_{p,v}(T_a-T_e)$ [kJ/kg]
NH_3-H_2O	95	55	47	6.7	1,076	839	1,539	1,391	4.51	106
H_2O-LiBr	93	44	40	15	2,394	2,295	370	275	2.94	75

Fluid	m γ_s $(1-\alpha)(T_a-T_g)$ (α=0.9) [kJ/kg]	$\gamma_{p,l}$ $(1-\beta)(T_e-T_c)$ (β=0.9) [kJ/kg]	p_a-p_g [kPa]	v_s [liters/kg]	v_r [liters/kg]	Work (η_1=η_2=0.8) [kJ/kg]	Level of efficiency
NH_3-H_2O	121	20	1,160	1.18	1.64	14	0.556
H_2O-LiBr	177	17	9.2	0.58	1.00	0.15	0.464

It can be noticed how, for both fluids, the terms of the sensible heat represent a moderate fraction of the global energy balance, at one condition though: highly efficient recovery exchanger must be present. Moreover the refrigerant effect is of the order of thousands of kJ/kg and the substances present a satisfying behavior energetically speaking. In these operating conditions, however, the couple NH_3-H_2O is the most stable, as the high difference value (X_a-X_g) shows.

Finally, it should be stressed the importance of the term $s(T_a,X_a)$ which, in the case of the fluid NH_3-H_2O, represents more than half of the useful heat.

6. Conclusions

During the past few years the exertion of absorption heat machines has been restricted due to a low reliability level determined by unsteady conditions of the absorption-refrigeration system in the operating temperatures characterizing machines. Sometimes, for what concerns heat transformers (whose exertion could be useful in many thermal processes as: desalination, solar energy used for heating, industrial processes etc.), the machine can present problems while operating due to the wrong choice of the refrigerating and absorption substances, thus limiting their exertion. Therefore the machine must be planned while taking into consideration the operating temperatures (that might vary according to different types of exertion) and identifying the combination of refrigerating and absorption substances that should be used. In this study, the couple of fluids with a higher reliability in the considered range of temperatures is water-ammonia. However, the ammonia sets some limits determined by its toxicity and an interesting analysis might be the evaluation of other types of couple with the same practical advantages.

This work is a first methodological approach that takes into consideration specific physical-chemical parameters with the goal to increase the number of combination of absorption-refrigeration systems examined and tested (it would be interesting to extend this type of study to the field of solid solutes).

The relevance of absorption heat transformers has been proved, though it is important to have a system reliability that might amortize the costs related to the supplying and installation of the machine. This is possible if the chemical-physical properties of absorption-refrigeration machines are exploited in order to increase the performances of the machine and improve its characteristics. In this way they will be more attractive, commercially speaking, on the market.

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