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Exergetic optimization of absorption chillers – A case study

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HIGHLIGHTS

- Introduction of the exergetic thermo-chemical efficiency and the thermochemical instability of cooling qualitative indicators.
- A chiller with a minimum cooling exergetic efficiency of greater than 50% is already optimized for cooling.
- Novel equations for the quantitative and qualitative indicators.
- Increasing the generator temperature is the best way to exergetically optimize absorption chillers.

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ABSTRACT

The best way to meet the European Union's energy awareness goals is to use a heat pump/refrigerator that requires renewable energy or waste heat to operate. Absorption machines are often powered by renewable energy or waste heat. This article, it was examined how absorption chillers can be optimized for cooling. This requires increasing the minima of the cooling exergy efficiency of absorption chillers. The effects of this increase on the quantitative and qualitative indicators were also examined. For this purpose, these indicators are described using secondary indicators instead of the basic data. This can simplify the identification of intervention points to increase the qualitative and quantitative indicators. Taking these effects into account, it was concluded that the three best choices for creating a cooling optimization are to change either the generator temperature only, the generator and condensation temperatures, the condensation temperatures only respectively. This article, it is introduced new qualitative indicators. Due could help better characterization of absorption chillers and can form the basis for further developments.

1. Introduction

The legislators of the European states are making efforts to mitigate the damage caused by global warming. One such goal is to increase the use of renewable energy [1]. Another such goal is a 32.5% reduction in energy consumption compared to 2007 levels [2]. One major step in this could be to reduce the energy demand of buildings, which account for nearly 40% of the EU's energy consumption [3,4]. Energy saving is thus a key challenge for the construction industry [5].

For existing buildings, the thermal renovation of the building envelope reduces the thermal transmittance of the structures and thus the heating and cooling energy demand [6,7]. But despite, the share of cooling systems in the energy balance of buildings is increasing [4]. Choosing the right basic design data is essential for the energy efficiency of cooling systems [8,9]. In most cases, a chiller is used to cool the building, and a heat pump is used in part or in full to supply the heating system [10,11]. The heat losses of HVAC (Heating, ventilation, and air conditioning) systems can be reduced by proper regulation [12], by proper thermal insulation of the components

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[13], or by reusing this heat in the energy flow of buildings [14].

A large amount of waste heat is ejected by the industrial players into the atmosphere [15]. But the waste heat could be used for power generation [16] or even desalination [17], as well. However, effective utilization of waste heat below 150 °C is difficult because of its poor quality due to its low exergy content [18]. But, if this waste heat is available in large amounts, it can be used to power ab- and adsorption chillers, as well.

Energy savings can be achieved not only by improving the energy efficiency of HVAC systems but also by optimizing these systems from an exergetic point of view [19,20]. Energy-saving potentials cannot be quantified by energy analysis alone, exergy analysis must also be taken into account [21]. The exergetic optimization of absorption chillers can be done in two ways by one-objective optimization or multi-objective optimization.

The target of one-objective optimization is to minimize or maximize a single parameter. The superiority of a solution over other solutions can be seen simply by examining their objective functions values [22]. For example, Chen et al. [23] optimized an NH_3–H_2O absorption cooling system for the highest COP value. However, they ignored the energy quality. For the optimization, GenOpt, which can solve one-objective optimization problems, was used by Calise et al. [24]. With this program, the primary energy savings of a solar absorption cooling system were maximized, and critical system parameters were determined, too. GenOpt usually requires 500–600 simulation runs, but it was successfully reduced to 324 [25]. In engineering practice, the results are wanted quickly, so this is unfortunately still too high. Furthermore, this method is sensitive to the supposed values. Hang et al. utilized linear regression analysis to data gained from the parametric study of the plant of a double-effect LiBr– H_2O absorption chiller, and three equations were obtained. These three equations were combined into one equation with different weights so that a one-objective optimization could be solved. However, this optimization process is sensitive to being locked into local optimum zones because data gained from the parametric study of the plant were used for the objectives.

Multi-objective optimization is used commonly in engineering practice [26]. This optimization contains more than one objective function to be minimized or maximized [27]. Because the targets to be achieved compete against each other, no single target can be improved without harming the others. There is no single best solution, but a set of solutions that determine the best compromise between competing targets. The final solution is at the decision of the designer [26,28,29].

The simplest solution is when the optimization is based on thermodynamic analysis only. Then the most important quantitative and qualitative indicators are treated as equal. Bagheri et al. [30] examined a double effect H_2O–LiBr absorption refrigerator from an exergetic point of view, and the COP and the exergetic efficiency were maximized with multi-objective optimization. If a chiller is maximized for only two indicators, there may be further optimization potentials remain. These can be exploited by considering the additional indicators. With the identical cooling capacity, a single and a double effect absorption refrigerant system was compared by Gomri [31]. It was experienced, there is a specific generator temperature for each evaporator and condenser temperature. At these generator temperatures, the exergetic efficiency and the COP have the maximum value, and the changing of the total exergy content has the minimum value. In this study, the cooling of the absorber and the condenser are independent of each other. More commonly, that these are cooled not in parallel but one after the other. Naturally, multi-objective optimization can be used for combined thermodynamic, environmental, and economic analysis, too [32].

As mentioned above, numerous research studies have been done on the energetic and exergetic optimization of the absorption

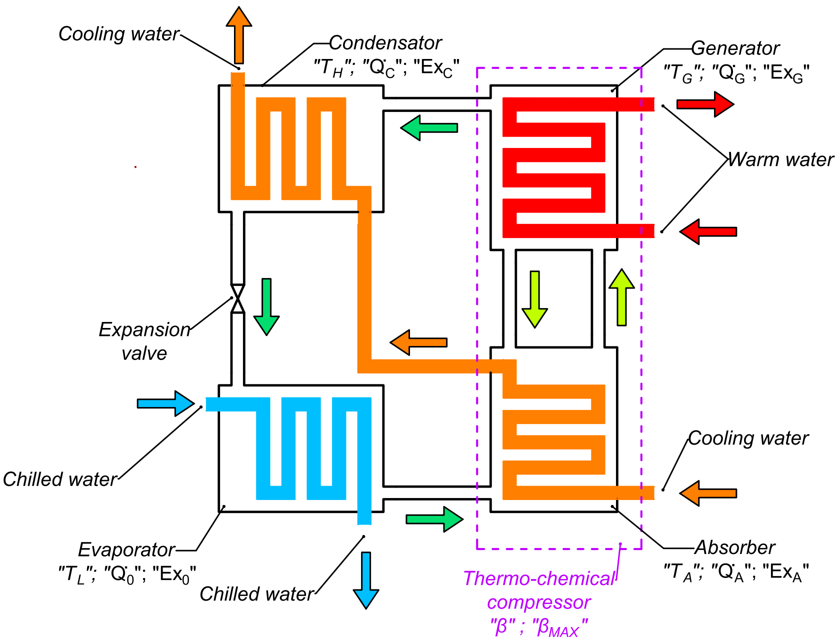

Fig. 1. *Simplified schema of the absorption machine.*

chillers, but an important question is overlooked mostly. The absorption chillers (and all heat pumps) are simultaneous to cool (at the evaporator) and to heat (at the condenser). The question arises: when would an absorption chiller used for cooling be more suitable for heating? To the answer, cooling and heating processes as a qualitative concept are treated, and the cooling exergetic efficiency ("$\eta_{Ex,C}$") was selected to be the basic criterion of the analysis. There is the basis of the presented optimization method in this article. This method is at the border between one and multi-objective optimization. There is a primary goal, and that is to increase the minimum cooling exergy efficiency ("$\eta_{Ex,min,C}$") above 50%. Achieving this target is not only dominant but also uncompromising. It is similar to one-objective optimization. However, if this target is achieved, other indicators are examined as well, the improvement of which will lead to competing targets. These targets can be treated as equals, but even a dominant indicator (e.g., "COP_A") can be selected from them, as well. For this reason, this optimization can be understood as multi-objective optimization, as well.

The optimization presented is based on the definition of the minimum cooling exergy efficiency ("$\eta_{Ex,min,C}$"). This secondary indicator can be determined using the thermo-chemical performance index ("β"). The thermo-chemical performance index was introduced in Refs. [33,34]. It is examined in this article how absorption chillers can be optimized for cooling. To this end, the options for increasing the minimum value of exergetic efficiency will be examined, and how these potentials have got secondary effects on other quantitative and qualitative indicators. For this, firstly, the theoretical background of the quantitative and qualitative indicators of absorption chillers is summarized. Then, the possibilities of increasing the minimum exergy efficiency are examined. Next, the secondary effects of these possibilities on the other indicators are analysed. Finally, the results are evaluated.

2. Materials and methods

2.1. Theoretical background of absorption chiller

Absorption chillers are machines equipped with a thermal compressor. A thermal compressor is a complex structure consisting of an absorber, a generator and, for larger machines, a solution circulating pump and a throttle valve. In order for the thermal compressor to function properly, there must be heat input ("$\dot{Q}_G$") into the generator and heat removal ("$\dot{Q}_A$") from the absorber [35–37]. Fig. 1 shown the simplified schema of the absorption chillers.

Absorption chillers can also be characterised by quantitative and qualitative indicators.

Quantitative indicators of absorption chillers are the coefficient of performance and thermo-chemical efficiency. The cooling coefficient of performance ("COP_A") is the ratio of the produced cooling capacity ("$\dot{Q}_0$") and "$\dot{Q}_G$ Thermo-chemical efficiency ("η_A") compares the "COP_A" value of a machine to its maximum possible value ("COP_{AC}"). Both indicators can be written using the thermo-chemical performance index ("β") and the operating temperatures [34,38]:

$$COP_A = \frac{\dot{Q}_0}{\dot{Q}_G} = \frac{T_L}{T_A}\cdot\frac{T_H - T_A}{T_H - T_L}\cdot\beta + \frac{T_L}{T_G}\cdot\frac{T_G - T_H}{T_H - T_L}\ ;\ [-] \quad (1)$$

$$\eta_A = \frac{COP_A}{COP_{AC}}\cdot 100 = \left[\frac{T_G}{T_A}\cdot\frac{T_H - T_A}{T_G - T_A}\cdot\beta + \frac{T_G - T_H}{T_G - T_A}\right]\cdot 100\ ;\ [\%] \quad (2)$$

Where "T_L" is the evaporation temperature, "T_A" is the absorber temperature, "T_H" is the condensation temperature and "T_G" is the generator temperature, in [K]. The "β" is the ratio of the energy flow discharged and introduced from the thermo-chemical compressor. It has got two extreme values [34,38]:

$$0 = \beta_{min} \le \beta = \frac{\dot{Q}_A}{\dot{Q}_G} \le \frac{T_A}{T_G} = \beta_{max} < 1 \quad (3)$$

The inside temperatures of a quantitatively controlled absorption chiller are constant, the machine can be controlled by varying the amount of energy inputs and outputs. In this case, in the equations of quantitative indicators, the "β" describes the effect of quantitative control.

Because there is a linear connection between the quantitative indicators and the "β", the quantitative indicators have got extreme values at the extremes of "β". Related to this, it was introduced the concept of thermo-chemical instability of quantitative indicators. This indicator relates the difference between the maximum and minimum values of the quantitative indicator to the maximum value of its [38]:

$$\mu_{EN} = \frac{COP_{AC,C} - COP_{A,min,C}}{COP_{AC,C}} = \frac{100 - \eta_{A,min,C}}{100} = \frac{T_H - T_A}{T_G - T_A}\ ;\ [-] \quad (4)$$

The higher the thermo-chemical instability of the chiller, the more sensitive the quantitative indicators of the machine are to fluctuations in the operating heat flows.

The most important qualitative indicator for chillers is the cooling exergy efficiency ("$\eta_{Ex,C}$"). This is the ratio of the exergy content of "$\dot{Q}_0$" ("Ex_0") to the exergy content of "$\dot{Q}_G$" ("Ex_G"). This indicator can also be written using "β" [34].:

$$\eta_{Ex,C} = \frac{Ex_E}{Ex_G}\cdot 100 = \left[\frac{T_G}{T_A}\cdot\frac{T_H - T_A}{T_H - T_L}\cdot\frac{T_X - T_L}{T_G - T_X}\cdot\beta + \frac{T_G - T_H}{T_H - T_L}\cdot\frac{T_X - T_L}{T_G - T_X}\right]\cdot 100\ ;\ [\%] \quad (5)$$

Where "T_X" is the reference temperature, in [K].

Analogous to the "μ_{EN}" and "η_A", the *exergetic thermo-chemical efficiency* ("$\eta_{A,Ex}$") and the *thermo-chemical instability of the qualitative indicators* ("μ_{EX}") can be introduced. However, to describe these indicators, firstly the extreme values of "$\eta_{Ex,C}$" have to be determined. It reaches its minimum value at "$\beta = 0$" and its maximum value at "$\beta = T_A/T_G$" [34].:

$$\eta_{Ex,min,C} = \left[\frac{T_G - T_H}{T_G - T_X} \cdot \frac{T_X - T_L}{T_H - T_L}\right] \cdot 100 \; ; \; [\%] \tag{6}$$

$$\eta_{Ex,max,C} = \left[\frac{T_G - T_A}{T_G - T_X} \cdot \frac{T_X - T_L}{T_H - T_L}\right] \cdot 100 \; ; \; [\%] \tag{7}$$

Thus, the *exergetic thermo-chemical efficiency* ("$\eta_{A,Ex}$") can be introduced. This is the ratio between the exergetic efficiency ("$\eta_{Ex,C}$") of a machine and its maximum possible value:

$$\eta_{A,Ex} = \frac{\eta_{Ex,C}}{\eta_{Ex,max,C}} \cdot 100 = \left[\frac{T_G}{T_A} \cdot \frac{T_H - T_A}{T_G - T_A} \cdot \beta + \frac{T_G - T_H}{T_G - T_A}\right] \cdot 100 \; ; \; [\%] \tag{8}$$

This new indicator also has two extreme values, which can also be written with the two extreme values of the thermo-chemical performance index.

The *thermo-chemical instability of qualitative indicators* can be determined:

$$\mu_{EX} = \frac{\eta_{Ex,max,C} - \eta_{Ex,min,C}}{\eta_{Ex,max,C}} = \frac{100 - \eta_{A,Ex,min}}{100} = \frac{T_H - T_A}{T_G - T_A} \quad ; \; [-] \tag{9}$$

In the cooling mode of absorption machines, the values of "η_A" and "$\eta_{A,Ex}$", as well as "μ_{EN}" and "μ_{EX}" coincide. However, in heating mode they do not coincide.

2.2. The sample absorption chiller

In the building of the Kölcsey Centre in Debrecen, a THERMAX LT 65 S absorption chiller was installed. This machine is operated by the district heating company and the basic data for the analysis was provided by them. The operating data of this sample absorption chiller are summarized in Table 1. The device is only quantity controlled.

2.3. Exergetic optimization of absorption chillers

The most appropriate indicator for the optimization of absorption chillers is exergetic efficiency. The exergetic efficiency and the "COP_A", which is the most important quantitative indicator, form a pair. The "COP_A" is the ratio of energy flows, while exergetic efficiency is the ratio of the exergy content of the same energy flows. There is a strong connection between cooling's and heating's COP ($COP_{A,C}+1=COP_{A,H}$). Thus it is useful to examine the exergy conditions of absorption machines. The first step is to describe the exergetic balance equation of the machine, which can be done as follows [34]:

$$Ex_0 + Ex_C + Ex_A = Ex_G \tag{10}$$

Where the "Ex_C" is the exergy content of the "$\dot{Q}_C$, in [kW]; and the "Ex_A" is the exergy content of the "$\dot{Q}_A$", in [kW].

If we divide both sides by "Ex_G" we get the connection between the heating („$\eta_{Ex,H}$") and cooling exergy efficiency („$\eta_{Ex,C}$") of these machines [34]:

Table 1
The operating data of the sample absorption chiller.

Basic Data	Evaporation temperature	T_L; [°C]	5.0
	Reference temperature	T_X; [°C]	26.0
	Temperature in the absorber	T_A; [°C]	29.0
	Condensation temperature	T_H; [°C]	39.0
	Temperature in the generator	T_G; [°C]	67.0
	Cooling capacity	$\dot{Q}_0$; [MW]	2.0
	Heat consumed in the generator	$\dot{Q}_G$; [MW]	2.6
Secondary indicators	Thermo-chemical performance index	β_{ref}; [−]	0.354
		$\beta_{max,s}$; [−]	0.888
	Maximum value of coefficient of performance	$COP_{AC,s}$; [−]	0.914
	Thermo-chemical instability	$\mu_{EN} = \mu_{EX} = \mu_{C,s}$; [−]	0.263
	Exergetic efficiency	$\eta_{Ex,min,C,s}$; [%]	42.18
		$\eta_{Ex,max,C,s}$; [%]	57.25
Quantitative and qualitative indicators		$\eta_{Ex,ref,C,s=}$; [%]	48.19
	Coefficient of performance	$COP_{A,ref,s}$; [−]	0.769
	Thermo-chemical efficiency and Exergetic thermo-chemical efficiency	$\eta_{A,Ex,s} = \eta_{A,s}$; [%]	84.18

$$\frac{Ex_0}{Ex_G}+\frac{Ex_C+Ex_A}{Ex_G}=\frac{\eta_{Ex,C}}{100}+\frac{\eta_{Ex,H}}{100}=\frac{Ex_G}{Ex_G}=1 \quad 11$$

Where the „$\eta_{Ex,C}$" is the exergetic efficiency in cooling mode and the „$\eta_{Ex,H}$" is the exergetic efficiency in heating mode.

This means that the cooling exergetic efficiency of absorption machines can only be increased to the detriment of their heating exergetic efficiency.

Based on this, a chiller can be considered to be optimized for cooling if the "$\eta_{Ex,C}$" is always higher than the "$\eta_{Ex,H}$". If this is described with the extreme values:

$$\eta_{Ex,max,H}<50\%<\eta_{Ex,min,C} \quad 12$$

If a quantitatively controlled absorption refrigerator is wanted to be optimized for cooling, then the "$\eta_{Ex,min,C}$" must be further investigated. Its value does not depend on the "T_A", only on the other three operating temperatures.

3. Results and discussion

3.1. Investigation of increasing the minimum exergetic efficiency in cooling mode

In the following, it will be investigated which temperature changes are appropriate to increase the value of "$\eta_{Ex,min,C}$". The effect of changing each temperature is shown in Fig. 2 for the sample machine.

Fig. 2a shows how many folds the value of "$\eta_{Ex,min,C,s}$" changes when the temperatures are modified by a given percentage. Fig. 2b shows how much the value of "$\eta_{Ex,min,C,s}$" changes when the temperature is modified by a given degree. The diagrams show that the increase of "$\eta_{Ex,min,C}$" can be achieved by decreasing "T_L" and "T_H" and increasing "T_G". The highest modify can be achieved by changing "T_H", then "T_L" and finally "T_G".

To facilitate further investigations, the concept of the *effective temperature difference* ("ΔT_{eff}") was introduced. This non negative value must be subtracted from "T_L" and "T_H" temperatures and added to "T_G". This simplifies the specification of how much temperature change is required to increase the value of "$\eta_{Ex,min,C}$", without positive and negative sign.

By varying and non-varying the three temperatures, seven cases can be created. In the following, these seven cases will be examined. Let us examine how much change in "ηEx,min,C,s" can be generated. This shown Fig. 3.

Fig. 3 shows that the seven examined cases fall into two groups. One group includes "T_L", "T_G" and the combined effect of "T_L" and "T_G", the others belong to the other group. The largest increase in "$\eta_{Ex,min,C}$" can be achieved by changing all three temperatures. This is followed by the combination of "T_H" and "T_L" and then "T_H" and "T_G".For a more significant increase, a modification in the "T_H" is also essential. Of course, changing temperatures will not only affect the value of "$\eta_{Ex,min,C}$". In the next section, these effects are examined for qualitative and quantitative indicators.

3.2. The impact of exergetic optimization on qualitative and quantitative indicators

Firstly, the cooling indicators are described with "$\eta_{Ex,min,C}$". The exergetic efficiency is:

$$\eta_{Ex,C}=\mu_{EX}\cdot\frac{\beta}{\beta_{max}}\cdot\eta_{Ex,C,max}+\eta_{Ex,min,C}\ ;\ [\%] \quad 13$$

The thermo-chemical efficiency and the exergetic thermo-chemical efficiency is:

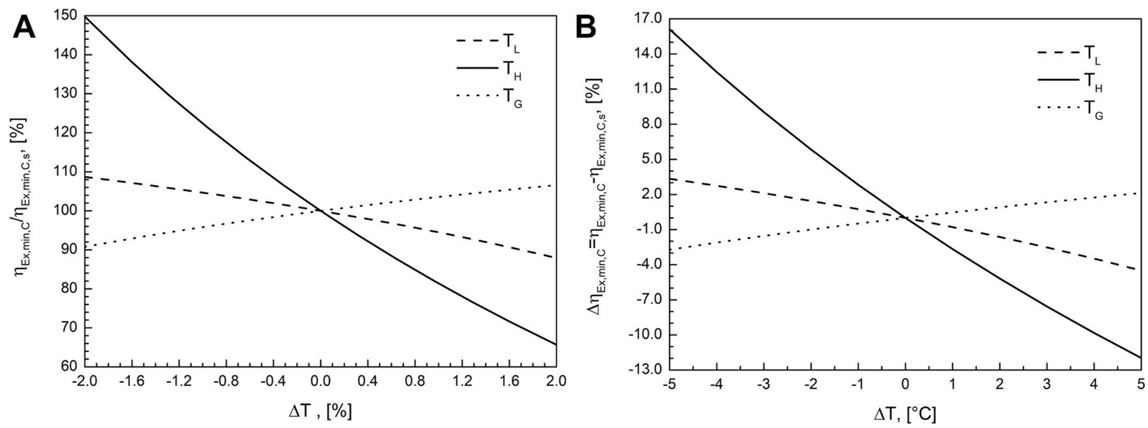

Fig. 2. *Effect of varying the three tested operating temperatures to* **(a)** *the exergetic efficiency,* **(b)** *changing of the exergetic efficiency.*

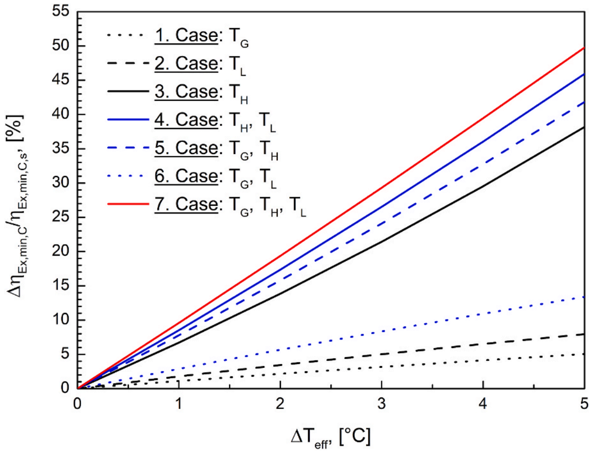

Fig. 3. *Increase in minimum exergy efficiency due to "ΔTeff".*

$$\eta_A = \eta_{A,Ex} = \left[\mu_{EX} \cdot \frac{\beta}{\beta_{max}} + \frac{\eta_{Ex,min,C}}{\eta_{Ex,max,C}}\right] \cdot 100\ ;\ [\%] \quad 14$$

And the cooling coefficient of performance is:

$$COP_A = COP_{AC} \cdot \left[\mu_{EN} \cdot \frac{\beta}{\beta_{max}} + \frac{\eta_{Ex,min,C}}{\eta_{Ex,max,C}}\right]\ ;\ [-] \quad 15$$

Based of the equations, the qualitative and quantitative indicators depend on some secondary indicators. Such secondary indicators are for example "COP_{AC}", "β_{max}", "μ_{EX}" ("μ_{EN}") "$\eta_{Ex,max,C}$" or "β". The secondary indicators can be determined from the basic data. This is illustrated in Fig. 4.

Considering Fig. 4., before the qualitative and quantitative indicators, it is important to examine the secondary indicators. Let us investigate these indicators in function of "ΔT_{eff}" in the seven examined cases. This is illustrated in Fig. 5.

From Fig. 5a, the value of "COP_{AC}" is reduced by the "T_L". So, the best case is 5. Based on Fig. 5b, varying the "T_G" is reduced the value of "β_{max}". If value of "β_{max}" decreases, absorption chiller is quantitatively controled more difficult.From Fig. 5c it can be seen that the thermo-chemical instability does not depend on the "T_L", as can be seen from equation (9). Moreover, if the increase of "$\eta_{Ex,\ min,\ C}$" is achieved not by decreasing "T_L", then the thermo-chemical instability reduces. The order of cases in Figs. 3 and 5d is identical. But the seven examined cases fall into five groups instead two.

In the following, let us investigate the impact of "ΔT_{eff}" on the qualitative and quantitative indicators for the seven examined cases ("$\beta = \beta_{ref}$"). This is illustrated in Fig. 6.

It can be seen in Fig. 6a that in this condition, although the curves are similar and in the same order as in Fig. 3, but their apparent slope is much smaller. Even here, the seven examined cases can be also compiled into two groups, as opposed to Fig. 5d. From Fig. 6b and d, the value of "$\eta_{A,Ex,s}$" and "$\eta_{A,\ s}$" is unaffected by the change in "T_L". For this reason, three cases containing a change of "T_L" have the same value as cases without "T_L". From Fig. 6c the most important change compared to the qualitative indicators is that the reduction of "T_L" worsens the value of "COP_A". This is not the case for the other two temperatures. In the cases with two or three

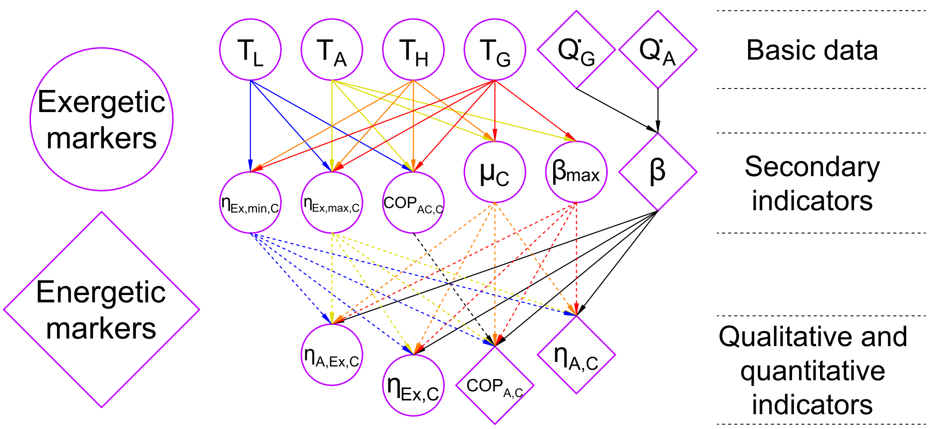

Fig. 4. Relationship between the qualitative and quantitative indicators, the secondary indicators and the basic data.

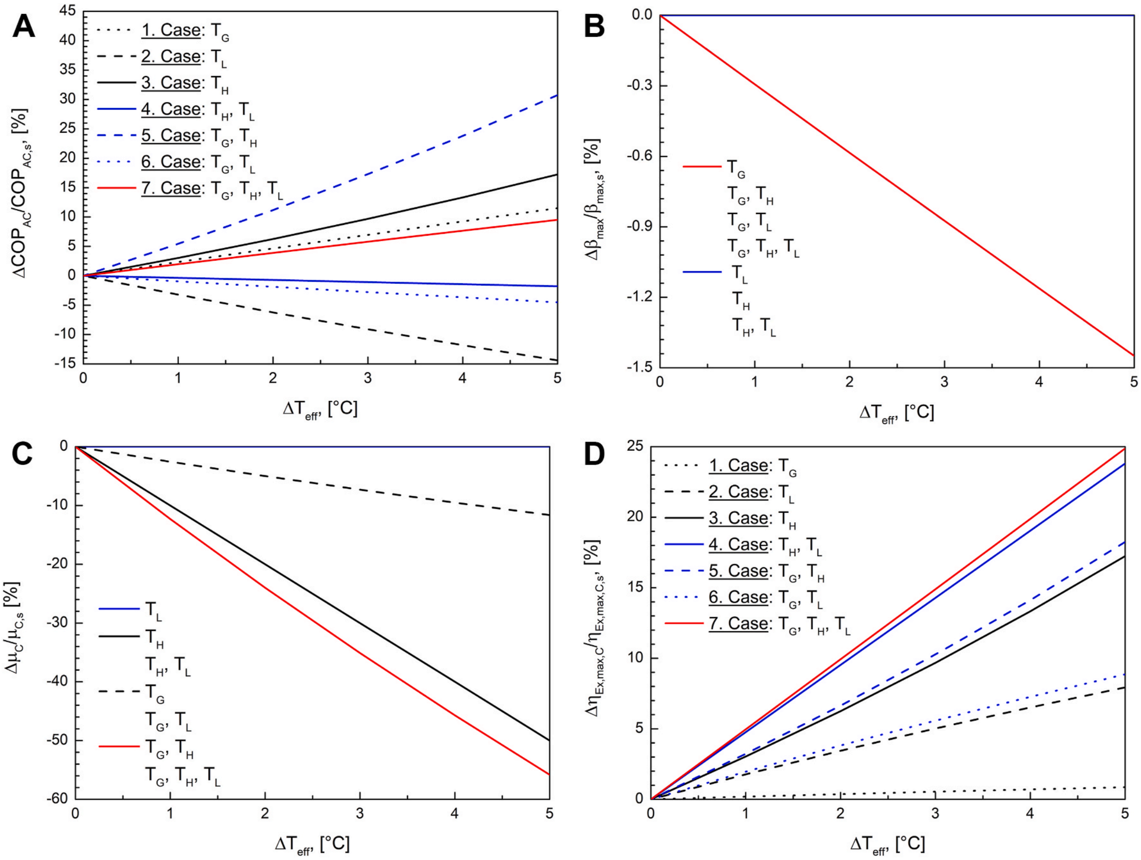

Fig. 5. *Change in* **(a)** *"COP_{AC}",* **(b)** "β_{max}", **(c)** "μ_{EX}" **(d)** "$\eta_{Ex,max,C}$" *for the same "ΔT_{eff}" in the seven examined cases.*

temperature changes, this decrease causes the change in "T_L" to reduce the increasing effects of the other two temperatures. For this reason, also the combined change of "T_L" and "T_G" reduce "$COP_{A,s}$". The highest increase in "$COP_{A,s}$" is obtained by varying "T_G" and "T_H" This is followed by the effect of changing only the "T_H" and all three temperatures.

Table 2 shows the secondary indicators and their changes in the seven examined cases at $\eta_{ex,min,c,s} = 50\%$.

Based on Table 2 the value of "COP_{AC}" is increased best by a change in "T_G" (case 1.) and is decreased most by a change in "T_L" (case 2.). The value of "β_{max}" decreases best in case 1., but does not change in cases 2.,3. and 4. The thermo-chemical instability decreases in six cases, best by modifying "T_G". But in case 2., its value does not change. The maximum value of exergetic efficiency is increased best by modyfing the "T_L" (case 2.) and worst by changing the "T_G" (case 1.). The based on secondary indicators, the best destination is modyfing "T_G" or "T_L".

Finally, let us investigate the qualitative and quantitative indicators, in seven examined cases, at $\eta_{ex,min,c,s} = 50\%$ (Table 3.).

Based on this table, the "ΔT"$_{eff}$ required for exergetic optimization is the largest in case 1. (27.3 °C), followed by case 2. (14,5 °C) and case 6. (7,2 °C). In the other four cases it is only below 3 °C. If only the exergetic efficiency is examined, the best choice is case 2. (only changing "T_L", 18,5%), then case 6. (changing "T_G" and "T_L", 15,8%) and case 4. (changing "T_H" and "T_L", 14,6%).But if we take the quantitative and qualitative indicators into account, the best choice for exergetic optimization is to change the generator temperature (case 1.), followed by changing the generator and condensation temperatures (case 5.), and finally to change the condensation temperature (case 3.).

Based on Fig. 7, the best option for exergetic optimization is always to change only one temperature. To achieve $\eta_{x,min,c} = 50\%$, the diverse temperatures have to be varied to different degrees, but the practical implementations and feasibility of these changes were not examined.

4. Conclusion

Several cases were examined when a heat pump was considered to be a cooling machine. It was concluded that heating and cooling processes are qualitative concepts. The most important qualitative indicator is exergetic efficiency. The sum of the cooling and heating exergetic efficiencies is exactly 100%. A quantitatively controlled absorption chiller is optimized for cooling if its exergetic efficiency during the operation is above 50%. To achieve it, the minima of cooling exergy efficiency has to be at least 50%. Thus investigation made how to increase the value of the minimum exergetic efficiency. It was concluded that it depends on three temperatures

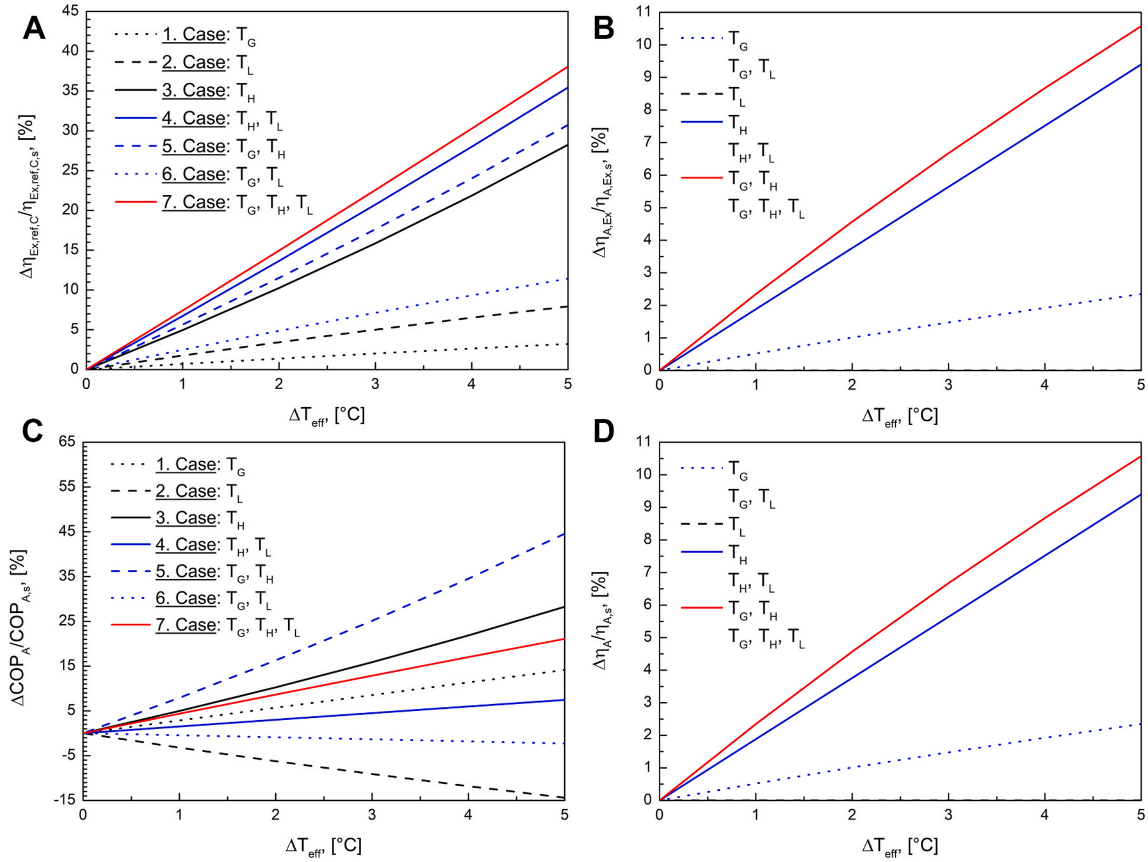

Fig. 6. *Varying of* **(a)**"$\eta_{Ex,ref,C}$" **(b)**" $\eta_{A,Ex}$" **(c)**"COP_A" **(d)**" η_A"*as function of the effective temperature difference.*

Table 2
The value of secondary indicators by the examined cooling optimized absorption chiller.

	COP_{AC} [−]	$\frac{\Delta COP_{AC}}{COP_{AC,ref,s}}$ [%]	β_{max} [−]	$\frac{\Delta \beta_{max}}{\beta_{max,ref,s}}$ [%]	μ_C [%]	$\frac{\Delta \mu_C}{\mu_{C,ref,s}}$ [%]	$\eta_{ex,max,c}$ [%]	$\frac{\Delta \eta_{ex,max,c}}{\eta_{ex,max,c,s}}$ [%]
1. CASE: T_G	1.45	59.0	0.82	−7.4	0.15	−41.8	59.0	3.2
2. CASE: T_L	0.61	−33.6	0.89	0.0	0.26	0.0	67.9	18.5
3. CASE: T_H	0.99	8.4	0.89	0.0	0.19	−26.3	62.0	8.4
4. CASE: T_H; T_L	0.91	−0.8	0.89	0.0	0.21	−21.3	63.1	10.2
5. CASE: T_G; T_H	1.03	13.2	0.88	−0.7	0.19	−27.8	61.7	7.8
6. CASE: T_G; T_L	0.86	−6.4	0.87	−2.1	0.22	−16.0	64.2	12.1
7. CASE: T_G; T_H; T_L	0.95	3.7	0.88	−0.6	0.20	−23.1	62.7	9.5

Table 3
The value of energetic and exergetic indicators by the examined cooling optimized absorption chiller.

	ΔT_{eff} [°C]	Qualitative indicators				Quantitative indicators			
		$\Delta\eta_{ex,ref,c}$ [%]	$\frac{\Delta\eta_{ex,ref,c}}{\eta_{ex,ref,c,s}}$ [%]	$\Delta\eta_{A,Ex}$ [%]	$\frac{\Delta\eta_{A,Ex}}{\eta_{A,Ex,s}}$ [%]	ΔCOP_A [−]	$\frac{\Delta COP_A}{COP_{A,ref,s}}$ [%]	$\Delta\eta_A$ [%]	$\frac{\Delta\eta_A}{\eta_{A,s}}$ [%]
1. CASE: T_G	27.3	53.9	11.9	91.3	8.4	1.33	72.4	91.3	8.4
2. CASE: T_L	14.5	57.1	18.5	84.2	0.0	0.51	−33.6	84.2	0.0
3. CASE: T_H	2.6	54.8	13.7	88.3	4.9	0.87	13.7	88.3	4.9
4. CASE: T_H; T_L	2.1	55.2	14.6	87.5	4.0	0.79	3.2	87.5	4.0
5. CASE: T_G; T_H	2.3	54.7	13.5	88.6	5.3	0.92	19.2	88.6	5.3
6. CASE: T_G; T_L	7.2	55.8	15.8	86.9	3.2	0.74	−3.4	86.9	3.2
7. CASE: T_G; T_H; T_L	1.9	55.1	14.3	87.9	4.4	0.83	8.3	87.9	4.4

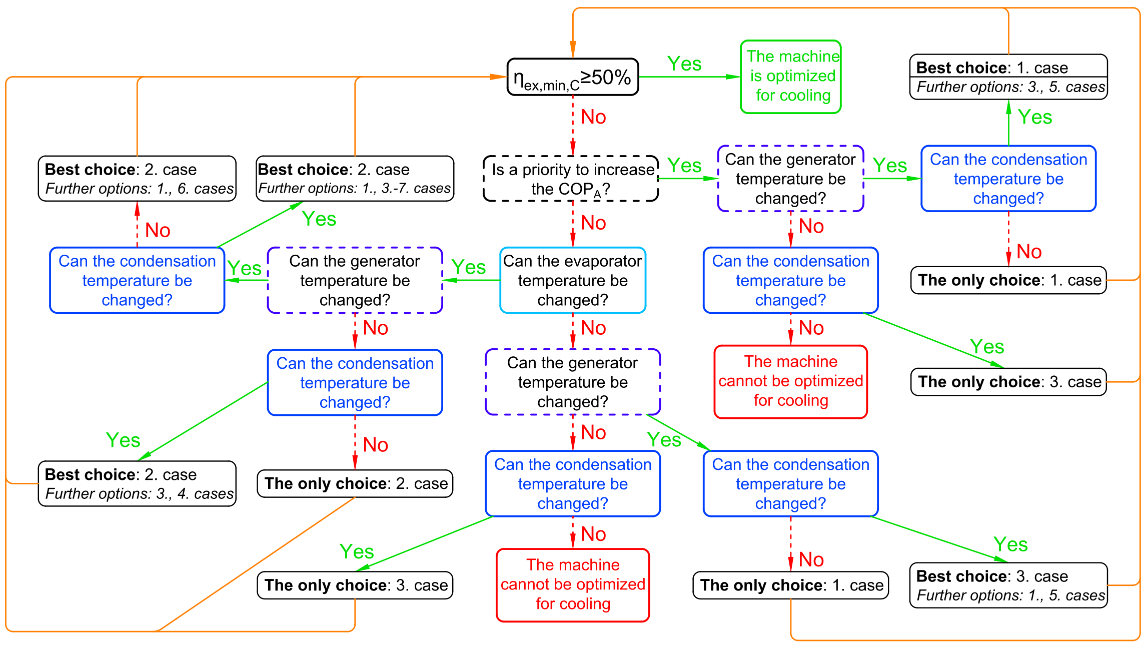

Fig. 7. is a summary flowchart of the exergetic optimization of absorption chillers.

(evaporation, condensation and generator). By varying the applied temperature combinations (in total 7 cases) the cooling exergy efficiency minima increase was compared.

Due to the fact that qualitative indicators (e.g. exergetic efficiency) are not really used in engineering practice, the effects of the seven examined cases on the other qualitative and quantitative indicators were examined, as well. It was investigated how can the exergetic efficiency, the coefficient of performance, the exergetic thermo-chemical efficiency and the thermo-chemical efficiency develop in the reference operating conditions of the chiller.

Generally, the best choice to optimize the machine for cooling firstly is to change the generator temperature, secondly, the generator and condensation temperature, and thirdly the condensation temperature, if we consider all qualitative and quantitative indicators as well. If only the exergetic efficiency as the most important qualitative indicator is examined, then the choice order is the evaporation temperature, next to the evaporation and generator temperature, finally the evaporation and condensation temperature. The choice order can be significantly affected by the feasibility of varying the temperatures of each. For example, it is easier to reduce the condensation and evaporation temperature by 2.1 °C and thus increases the value of the other indicators only minimally, than to increase the generator temperature by 27.3 °C, although this would significantly increase the other indicators, as well.

The introduced new indicators could help better characterization of absorption chillers and can form the basis for further developments. The proposed optimization method can complement the exergetic optimization of absorption chillers. The impacts of secondary indicators can be revealed by a new approach to quantitative and qualitative indicators. These can simplify the identification of intervention points to increase these characteristics.

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Author contributions

Gábor L. Szabó: Conceptualization; methodology; investigation; data curation, writing original draft preparation; writing review and editing; visualization; supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

$\dot{Q}_0$ is the cooling capacity, in W
$\dot{Q}_A$ is the heat released in the absorber, in W
$\dot{Q}_C$ is the heat released in the condenser, in W
$\dot{Q}_G$ is the heat consumed in the generator, in W
Ex_0 is the exergy content of $\dot{Q}_0$, in W
Ex_A is the exergy content of $\dot{Q}_A$, in W
Ex_C is the exergy content of $\dot{Q}_C$, in W
Ex_G is the exergy content of $\dot{Q}_G$, in W
T_L is the evaporation temperature, in K
T_A is the temperature in the absorber, in K
T_H is the condensation temperature, in K
T_G is the temperature in the generator, in K
T_X is the reference temperature, in K
ΔT_{eff} is the effective temperature difference, in K
β is the thermo-chemical performance index
β_{MAX} i s the maximum value of the thermo-chemical performance index
$COP_{A,C}$ is the coefficient of performance (cooling mode, absorption chiller)
$COP_{AC,C}$ is the maximum value of coefficient of performance (cooling mode)
$COP_{A,min,C}$ is the minimum value of coefficient of performance (cooling mode)
$\eta_{A,C}$ is the thermo-chemical efficiency (cooling mode), in %
$\eta_{A,min,C}$ is the minimum value of the thermo-chemical efficiency (cooling mode), in %
$\mu_{EN,C}$ is the thermo-chemical instability index (cooling, quantitative indicators)
μ_{EX} is the thermo-chemical instability index (cooling, qualitative indicators)
η_{EX} is the exergetic efficiency (cooling mode), in %
$\eta_{Ex,min,C}$ is the minimum value of the exergetic efficiency (cooling mode), in %
$\eta_{Ex,max,C}$ is the maximum value of the exergetic efficiency (cooling mode), in %
$\eta_{Ex,H}$ is the exergetic efficiency (heating mode), in %
$\eta_{Ex,max,\ H}$ is the maximum value of the exergetic efficiency (heating mode), in %
$\eta_{A,Ex,C}$ is the exergetic thermo-chemical efficiency (cooling mode), in %

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