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Publication date:
2020

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):
Voloshchuk, V., Gullo, P., & Nekrashevych, O. (2020). *Evaluation of component interactions in heat pumps on the base of advanced exergetic analysis*. Paper presented at 6th International Conference on Contemporary Problems of Thermal Engineering.

6th International Conference on Contemporary Problems of Thermal Engineering
CPOTE 2020, 21-24 September 2020, Poland

Evaluation of component interactions in heat pumps on the base of advanced exergetic analysis

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Keywords: Advanced exergetic analysis, Heat pumps, Component interactions, Thermodynamic enhancement, Economic enhancement

Abstract

Advanced exergy-based analysis provides information concerning interdependencies among components of an energy-conversion system. Exogenous parts of exergy-based parameters can indicate how an improvement in one component affects (positively or negatively and by how much) the remaining components. This paper presents the evaluation of component interactions in air-source and water-source heat pumps using exogenous parts of exergy-based parameters and proposes possible ways for their simultaneous thermodynamic and economic enhancement. It has been found that for the air-source and water-source heat pumps about 53% and 39% of avoidable exergy destruction, respectively, are due to interdependencies among components. Almost the whole amount of avoidable exogenous exergy destruction belongs to the compressor and to the throttling valve. However, the share of the costs due to avoidable exogenous exergy destruction is smaller than the part avoidable exogenous exergy destruction. For the air-source heat pump this share accounts for 23% of costs due to exergy destruction, which can be avoided. For the water-source heat pump it accounts for only 8% of costs due to avoidable exergy destruction. Furthermore, the results of advanced exergoeconomic analysis have shown that for the air-source heat pump system exogenous investment costs of the compressor, as the most expensive component, are positive and caused by irreversebilities within the evaporator and condenser. Thus, in order to decrease the cost of this component, the thermodynamic efficiency of both heat exchangers needs to be increased. In case of water-source heat pump, the exogenous expenditures for the compressor due to irreversibilities occurring within the evaporator are negative, whereas the ones related to the condenser are positive. Therefore, in order to decrease investment expenditures for the compressor, thermodynamic efficiency of the condenser needs to be increased. On the contrary, decreasing irreversibilities within the evaporator increases investment costs of the compressor and thus it is not recommended.

1 Introduction

Vapour-compression heat pumping technologies play a vital role in attaining the ambitious goals of affordable and low-carbon energy systems for space heating. In order to considerably reduce the greenhouse gas (GHG) emissions related to the heating sector, the adoption of highly efficient vapour-compression heat pump units needs to be promoted. Such a target can be appropriately achieved through the implementation of the so called advanced exergy-based analysis. This method can effectively and simultaneously enhance the thermodynamic, economic and environmental performance of the investigated system [1 - 5].

The work [1] provides possible dependencies among exergy destruction, capital investment cost and construction-related environmental impact within each single component of an energy conversion system. Based on these relationships it is possible to make decisions for the simultaneous reduction of investment cost and environmental impact. Morosuk and Tsatsaronis [2] presented a way for combining the exergoeconomic and the exergoenvironmental analyses and for formulating common conclusions for further improvement of a simple air refrigeration machine by taking into account simultaneously the minimization of cost and of environmental impact. It was shown that the thermodynamic improvement of any of the components leads to a decrease in the values of total exergy destruction and specific environmental impact of the overall product. However, for the compressor and the expander the function of specific cost of the overall product had an optimum value for the investigated range of the thermodynamic improvement. The final conclusion was that the expander and the refrigerator have a higher potential for simultaneously decreasing cost and environmental impact of the overall product.

In [3] relationships between exergoeconomic and exergoenvironmental data under various operating conditions of three-pressure-level combined cycle power was studied for simultaneous decrease of the investment costs and the component-related environmental impacts. For most cases improvements in the exergetic efficiency of the components (a decrease in the exergy destruction) resulted in decreases in both costs and environmental impacts. The work [4] presents results of evaluation of interaction between environmental, technical and economical aspects within cascade absorption-compression refrigeration system. Based on 3D parametric analysis, it was determined which parameters had to be optimized for simultaneous improvement of thermodynamic efficiency, environmental impact and capital cost. Voloshchuk et al. [5] applied exergy, exergeconomic and exergoenvironmental analysis to a R134a heat pump unit for space heating. According to the results obtained for simultaneous enhancement of the thermodynamic, economic and environmental performance of the investigated solution the irreversibilities occurring in the evaporator and in the condenser should be decreased.

The literature review reveals that cases taking into account interactions and interdependencies among the components of an energy system deserve separate attention in tasks of simultaneous thermodynamic, economic and environmental improvement. Studies of different authors showed that from exergy point of view the interactions between different components can have different effect. The exergy destruction in the k-th component can be decreased with reducing irreversibilities in the r-th component. There are cases when exogenous part of exergy destruction is negative. It means that adding inefficiencies in the r-th component contributes to a reduction of the exergy destroyed in the k-th component. The information concerning negative values of exogenous exergy destruction is obtained in a series of works: [6] for a vapour-compression refrigeration machine with R407C, [7] for an absorption refrigeration machine, [8] for a water-source heat pump providing space heating, [9, 10] for geothermal district heating systems, [11] for a combined cycle power plant. Negative values of exogenous exergy destruction provides negative values of costs and environmental impact due to exergy destruction, as confirmed in [12, 13, 14]. In case of evaluation of investment cost due to interactions between different components adding irreversibilities within the r-th component can provide decreasing investment expenditures of the k-th component. However, there are also cases when additional irreversibilities in the r-th component increase investment expenditures of the k-th component. This is mentioned in [15] for a water-source heat pump providing space heating, in [16] for a trigeneration system using a diesel-gas engine and in [17, 18] for a power plants with CO_2 capture.

Therefore, the target of this work is to exhaustively investigate the component interactions in air-source and water-source heat pumps using exogenous parts of exergy-based parameters and propose possible solutions for their simultaneous thermodynamic and economic enhancement. As showed above and to the best of the authors' knowledge, no studies focusing on this goal have been carried out.

2 Methodology

According to the methodology of advanced exergy-based analysis the total exergy destruction and the total investments costs in each system component can be split into endogenous/exogenous ($\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX}$ and $\dot{Z}_k = \dot{Z}_k^{EN} + \dot{Z}_k^{EX}$), unavoidable/avoidable parts ($\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN}$ and $\dot{Z}_{D,k} = \dot{Z}_k^{AV} + \dot{Z}_k^{UN}$) and their combination ($\dot{E}_{D,k} = \dot{E}_{D,k}^{UN,EN} + \dot{E}_{D,k}^{UN,EX} + \dot{E}_{D,k}^{AV,EN} + \dot{E}_{D,k}^{AV,EX}$ and $\dot{Z}_{D,k} = \dot{Z}_{D,k}^{UN,EN} + \dot{Z}_{D,k}^{UN,EX} + \dot{Z}_{D,k}^{AV,EN} + \dot{Z}_{D,k}^{AV,EX}$) [6, 7, 19]. For the calculations of the split values of exergy-based parameters (namely, exergy destruction and the investments costs) the thermodynamic-cycle-based approach has been applied [6, 7, 19]. Cycle with unavoidable exergy destructions ($\dot{E}_{D,k}^{UN}$) considers only unavoidable irreversibilities. The avoidable exergy destruction is calculated as [6, 7, 19]

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \tag{1}$$

and should be considered during the improvement procedure.

For calculating the endogenous part of the exergy destruction ($\dot{E}_{D,k}^{EN}$) within each component of the heat pump the hybrid cycles with only one irreversible component is analysed [6, 7, 19]. The exogenous exergy destruction is obtained as [6, 7, 19]

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k} - \dot{E}_{D,k}^{EN}. \tag{2}$$

In case of calculation of the additional parts of exergy destruction, only the value of the unavoidable endogenous exergy destruction ($\dot{E}_{D,k}^{UN,EN}$) needs to be obtained using the thermodynamic-cycle-based approach [6, 7, 19]. The remaining parts of the exergy destruction are then calculated as follows [6, 7, 19]

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN}, \tag{3}$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN}, \tag{4}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN}. \tag{5}$$

To better understand the interactions among components, the exogenous exergy destruction within the k-th component should also be split.

For obtaining a deeper understanding of the interactions among components, the exogenous exergy destruction (as well as the exogenous unavoidable and the exogenous avoidable exergy destruction) within the k-th component is split [19]

$$\dot{E}_{D,k}^{EX} = \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{EX,r} + \dot{E}_{D,k}^{mexo}, \tag{6}$$

where $\dot{E}_{D,k}^{EX,r}$ represents part of the exogenous exergy destruction within the k-th component that is caused by the irreversibilities occurring within the r-th component;

$\dot{E}_{D,k}^{mexo}$ – the remaining part is called mexogenous exergy destruction (from mixed exogenous exergy destruction) within the k-th component and is caused by the combined interactions of two or more components.

The thermodynamic-cycle-based approach [19] has been used for the evaluation of the components of the investments costs ($\dot{Z}_k^{EN}$, $\dot{Z}_k^{EX}$, $\dot{Z}_k^{AV}$, $\dot{Z}_k^{UN}$). The values of the unavoidable investment cost ($\dot{Z}_k^{UN}$) are determined assuming an extremely inefficient version of the considered component [19]. These values will always be exceeded as long as a similar component is used in a real system. Endogenous (capital investment cost $\dot{Z}_k^{EN}$) are the parts of variables within a component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system [19]. The cost rates caused by the irreversibilities within the kth component can be estimated as [19]

$$\dot{C}_{D,k}^{X} = c_{F,k} \cdot \dot{E}_{D,k}^{X}, \tag{7}$$

in which $c_{F,k}$ presents the cost per unit of exergy for fuel of the k-th component and X denotes the part of exergy destruction.

The contribution of the investments cost, $\dot{Z}_k$, to the total costs associated with investments and exergy destruction in exergoeconomic assessment is expressed by the exergoeconomic factor [19]

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k} \cdot \dot{E}_{D,k}}. \tag{8}$$

In case of applying exergy-based approach to the heating and cooling systems in buildings, one of the challenging issue is the definition and selection of the reference environment [20]. In this research selection of an appropriate reference state corresponds to the selection of an appropriate reference temperature. Pressure and humidity as other parameters of the reference environment have not been taken into account as having negligible effect in the climate conditions specified in the study. The reference temperature exactly follows the fluctuations of ambient (outdoor) conditions [21]. So, exergy always cancels out for the ambient air temperature. For the sensitivity analysis the following cost equations have been used for estimating the purchase equipment costs as functions of the thermodynamic parameters of the heat pump components [19]

$$PEC_{CM} = \frac{k_{CM} \cdot \dot{m}_{CM}}{\eta_{CM}^{UN} - \eta_{CM}} \left(\frac{p_2}{p_1} \right) ln \left(\frac{p_2}{p_1} \right) \text{ - for compressor} \tag{9}$$

$$PEC_{CD} = k_{CD} \left(A_{CD} \right)^{0.6} \text{ - for condenser} \tag{10}$$

$$PEC_{EV} = k_{EV} \left(A_{EV} \right)^{0.6} \text{ - for evaporator} \tag{11}$$

where k_{CM}, k_{CD}, k_{EV} are constants; $\dot{m}_{CM}$ is mass flow rate of the working fluid through the compressor; p_2 / p_1 - pressure ratio in the compressor; η_{CM} and η_{CM}^{UN} are isentropic efficiencies of the compressor in real cycle and unavoidable conditions, respectively; A_{CD} and A_{EV} are the heat transfer areas of the condenser and evaporator calculated for the design mode, respectively. All these values are estimated for the design operating conditions (nominal mode) of the system.

For exergetic, exergoeconomic and exergoenvironmental assesment of the heat pump providing space heating it is proposed to consider annual (seasonal) values of parameters [5, 8].

For different operational modes ambient temperature can be referred in a different manner to temperatures of working fluids of the heat pump. The reference temperature can be above, below or cross the temperatures of the heat source medium and the refrigerant. In such conditions different formulas should be used for calculating exergy associated with the fuel and product in the components of the system and associated costs per unit of exergy of the fuel and product respectively. Taking into account this features it is proposed to apply the exergoeconomic model for the every 24-hour time step of the assumed quasi-steady state approximation. In calculation of annualized exergoeconomic parameters the averaged for the heating season values of cost per unit of exergy associated with the fuel and product for the kth component have been estimated using the formulas [8, 5]

$$c_{F,k}^{year} = \frac{\sum\limits_{\tau_n=1}^{N} c_{F,k}\left(\tau_n\right)\cdot E_{F,k}\left(\tau_n\right)}{\sum\limits_{\tau_n=1}^{T} E_{F,k}\left(\tau_n\right)}; \qquad (12)$$

$$c_{P,k}^{year} = \frac{\sum\limits_{\tau_n=1}^{N} c_{P,k}\left(\tau_n\right)\cdot E_{P,k}\left(\tau_n\right)}{\sum\limits_{\tau_n=1}^{T} E_{P,k}\left(\tau_n\right)}, \qquad (13)$$

where $E_{F,k}\left(\tau_n\right)$ and $c_{F,k}\left(\tau_n\right)$ are the exergy of fuel and the cost per unit of exergy associated with the fuel of the kth component for the specified time step τ_n; $E_{P,k}\left(\tau_n\right)$ and $c_{P,k}\left(\tau_n\right)$ are the exergy of product and the cost per unit of exergy associated with the product of the kth component for the specified time step τ_n; N - the total number of time steps within the heating season.

The analysis is performed for a typical Ukrainian house. The dwelling has two floors with a gross floor area of 170 m^2 and a volume of 470 m^3. The weighted average insulation U-value of non-glazed external surfaces is 0.5 $W \cdot m^{-2} \cdot K^{-1}$. U-value of windows including frames is 1.67 $W \cdot m^{-2} \cdot K^{-1}$. Internal heat gains are defined with a constant value of 5 $W \cdot m^{-2}$. Setpoint for the indoor temperature is 18 ºC. The fraction of east and west oriented glazing is 30%, of the south one – 50%, of the north one – 20%. Natural ventilation is used in the dwelling. The design heating capacity of the house is 25 kW. Hydronic system is used for space heating. The heat pump is a basic heater covering 12 kW of heating demand in the design mode. R134a is chosen as a working fluid in the heat pump.

In the design operating conditions (nominal mode) of the air-source heat pump the following parameter values are set: the low temperature heat source medium (air) is cooled in the evaporator from -10 ºC to -15 ºC; the minimal temperature differences in the evaporator is 12 K and in the condenser is equal to 5 K. The calculated value of the real isentropic efficiency of the compressor in the nominal mode is equal to 0.7. For evaluating unavoidable exergy destructions in nominal mode the following parameter values are assumed: the unavoidable temperature differences in the evaporator and the condenser are equal to 3 K and 1 K, respectively. The unavoidable compressor efficiency is equal to 0.96. The temperature the heat source in off-design modes varied in a range from +10ºC to -16ºC. For creating the theoretical cycle of the air-source heat pump the following assumptions are used: the minimal temperature differences in the evaporator and the condenser are equal to 0 K; the efficiency of the working fluid compression is equal to 1; the throttling process is replaced by an ideal expansion process [6]. The supply and return temperatures in a constant-flow space heating system for the design mode are equal to 70 ºC and 50 ºC respectively.

In case of using water-source heat pump the low temperature heat source medium (water) is cooled in the evaporator from +6°C to +3°C. The variation of the heat source temperature in off-design modes is within the range +6°C÷+12°C. For the design mode the supply and return temperatures in a constant-flow space heating system are equal to 90 ºC and 70 ºC, respectively. The minimal temperature differences in the evaporator and the condenser are equal to 5 K. The calculated value of the real isentropic efficiency of the compressor in the nominal mode is equal to 82%. For evaluating unavoidable exergy destructions in nominal mode the following parameter values are assumed: the unavoidable temperature differences in the evaporator and the condenser are equal to 1 K and the unavoidable compressor efficiency is equal to 92%. In case of calculating the theoretical cycle of the water-source heat pump the same assumptions made for air-source heat pump are applied.

In order to determine thermodynamic parameters of the vapour compresion heat pump cycle in different operating modes (off-design modes) during a heating season, which is typical for such kind of solutions, the mathematical model proposed in [22] is used. The model is based on quasi-steady state approach. A set of nonlinear equations, involving heat, mass balances, heat transfer and equations for calculation of thermodynamic properties of working fluids, have been utilized. The equations, solved simultaneously with a gradient numerical method, have been established to describe the behaviour of each component and of the system as a whole. CoolProp software [23] has been employed for providing the thermophysical properties of the working fluids, while the simulation model of the heat pump is implemented in MathCad math environment. Daily weather data within a heating season for the city of Rivne located in the western part of Ukraine are used for the analyses. So, 24-hour time step are assumed for quasi-steady state modelling. The weather data have been provided by the Ukrainian Hydrometeorological Institute [24]. The total value of heating degree days is 3500°C·day.

3 Results and discussion

Table 1 summarizes the selected variables of conventional exergy and exergoeconomic analysis used for evaluating components of the investigated heat pumps. Using results obtained from the conventional (without splitting the exergy destruction) exergetic analysis the following conclusions can be formulated. For the air-source heat pump the biggest seasonal exergy destructions (1752 kWh and 1632 kWh, respectively) belong to the compressor and the throttling valve. The evaporator and condenser are of the third and the forth order of importance with seasonal exergy destructions of 1144 kWh and 726 kWh, respectively.

For the water-source heat pump the most important component from thermodynamic viewpoint is the throttling valve with seasonal exergy destruction $E_{D,TV}^{year}$ equal to 898 kWh. The compressor has the second position for which $E_{D,CM}^{year}$ is equal to 623 kWh. The third position is associated with the condenser ($E_{D,CD}^{year} = 480$ kWh). The evaporator is the last important component for which $E_{D,EV}^{year} = 438$ kWh.

According to the results provided in Table 1 it can be concluded that from the exergoeconomic point of view the compressor is the most important component for both heat pumps. The sum $Z_{CM}^{year} + C_{CM}^{year}$ associated with the compressor for the air-source heat pump is equal to 1692 €·year^{-1} and for the water-source pump is equal to 1135 €·year^{-1}. Evaporator is of the second priority of exergoeconomic improvement. For this component the sums $Z_{EV}^{year} + C_{EV}^{year}$ are equal to 805 and 519 €·year^{-1} respectively. Compared with the compressor and the evaporator the condenser and the throttling valve have lower values of the cost associated with capital investment and exergy destruction for both heat pumps.

Table 1: Values of selected exergoeconomic variables for the air-source and water-source heat pumps

Component	$E_{D,k}^{year}$, kWh		Z_{k}^{year}, €·year^{-1}		$C_{D,k}^{year}$, €·year^{-1}		$Z_{k}^{year} + C_{D,k}^{year}$, €·year^{-1}		f_{k}^{year}, %	
	air-source	water-source	air-source	water-source	air-source	water-source	air-source	water-source	air-source	water-source
CM	1752	623	1631	1113	61	22	1692	1135	96	98
CD	726	480	130	135	203	140	334	275	39	49
TV	1632	898	0	0	334	111	334	111	0	0
EV	1144	438	128	99	766	420	805	519	16	19

The low values of the f_k^{year} (less than 50%) for the evaporator and condenser mean that the cost effectiveness of the heat pumps might be improved by improvement of the exergy efficiency of these components (at the expense of increasing investment costs). On the other hand, the high values of the exergoeconomic factor f_k^{year} (more than 96%) for the compressor indicate that reducing the investment cost for this component can substantially decrease the total cost of the investigated heat pumps. Taking into account the formula (9) it is possible due to decreasing compressor isentropic efficiency (η_{CM}). However, the decision concerning increasing irreversibilities within the compressor is not preferable because this provides additional exergy destruction. Taking into account this constraint the possibility of decreasing investment expenditures of the compressor with the help of improving thermodynamic efficiency of other component due to components interaction is of big interest.

Table 2 shows the results of splitting the seasonal exergy destruction and costs due to exergy destructions into avoidable endogenous and avoidable exogenous ones for the air-source heat pump. The same parameters for the water-source heat pump are presented in Tables 3. Also, the results summarized in Table 2 and Table 3 highlight the considerable potential of splitting exergy destruction into endogenous/exogenous and unavoidable/avoidable parts to improve understanding the processes taking place and the quality of the conclusions made.

Table 2: Splitting avoidable exergy destruction and costs due to exergy destruction for the air-source heat pump

Component	Avoidable endogenous		Avoidable exogenous		
	$E_{D,k}^{AV,EN,year}$, kWh	$C_{D,k}^{AV,EN,year}$, €·year^{-1}		$E_{D,k}^{AV,EX,year}$, kWh	$C_{D,k}^{AV,EX,year}$, €·year^{-1}
CM	448	16	sum	834	29
			caused by: CD TV EV mixed	 111 3 634 87	 4 0 22 3
CD	234	65	sum	83	23
			caused by: CM TV EV mixed	 16 4 8 56	 4 1 2 16
TV	0	0	sum	524	107
			caused by: CD CM EV mixed	 154 -16 403 -17	 32 -3 83 -3
EV	565	334	sum	-58	-34
			caused by: CM TV CD mixed	 -13 8 7 -61	 -8 5 4 -36
Heat pump	1247	415		1383	125

In fact, the outcomes presented in Table 1 are misleading to some extent. For example, the conventional exergetic analysis identifies the compressor and the throttling valve as the most important components on which improvement efforts should focus. However, a more detailed analysis shows that exergy destruction within the compressor depends on its pressure ratio and can be actually reduced by decreasing irreversibilities taking place in the evaporator and the condenser due to temperature differences (Table 2). Moreover, the throttling process is completely irreversible and there are no ways of improving this process with the help of decreasing irreversibilities within it. Also from the conventional analysis of the water-source heat pump it has been found misleading information with respect to relative importance of the condenser and the evaporator. The condenser has a higher exergy destruction without splitting but at the same time compared to the evaporator it can be characterized with a higher exergy destruction which cannot be avoided. As a result, thermodynamic inefficiency, which can be really eliminated in this component, can be lower than in the evaporator. Furthermore, it can be seen from Table 2 that 53% (1383 kWh) of avoidable exergy destruction within the air-source heat pump is due to the component interaction. The highest values of avoidable exogenous exergy destruction belong to the compressor (834 kWh) and the throttling valve (524 kWh). Table 2 also demonstrates the distribution of avoidable exogenous exergy destruction among the components causing this part of exergy destruction. It can be seen that the evaporator is the component which causes the biggest share of exogenous avoidable exergy destruction within the compressor (634 kWh) and the throttling valve (403 kWh). So, improvement of the evaporator plays a pivotal role for possible thermodynamic savings within the compressor and the throttling valve. It can be observed from Table 2 that several parts of avoidable exogenous exergy destruction have negative sign. The avoidable parts of exogenous exergy destruction within the evaporator and the throttling valve caused by compressor are equal respectively to -13 kWh and -16 kWh. It means that increasing the irreversibilities within the compressor leads to some decrease of exergy destruction within the evaporator and the throttling valve.

Some amount of exergy destruction within the air-source heat pump components is mexogenous and caused by the combined interactions of more than two components (see Table 2). The mexogenous avoidable exergy destruction within the compressor and the condenser are equal to 87 kWh and 56 kWh, respectively. The mexogenous avoidable exergy destruction within the evaporator is negative and equal to -61 kWh. Also, -17 kWh of the avoidable exergy destruction within throttling valve also depends on combined interactions of more than two components.

Table 3: Splitted values of avoidable exergy destruction and costs due to exergy destruction for the water-source heat pump

Component	Avoidable endogenous		Avoidable exogenous		
	$E_{D,k}^{AV,EN,year}$, kWh	$C_{D,k}^{AV,EN,year}$, €·year^{-1}		$E_{D,k}^{AV,EX,year}$, kWh	$C_{D,k}^{AV,EX,year}$, €·year^{-1}
CM	207	7	sum	207	7
			caused by:		
			CD	62	2
			TV	1	0
			EV	126	4
			mixed	18	1
CD	174	51	sum	4	1
			caused by:		
			CM	0	0
			TV	9	3
			EV	7	2
			mixed	-13	-4
TV	0	0	sum	194	24
			caused by:		
			CD	104	13
			CM	-7	-1
			EV	103	13
			mixed	-6	-1

EV	243	232	sum	-5	-6
			caused by:		
			CM	-3	-3
			TV	-3	-2
			CD	-3	-2
			mixed	2	2
Heat pump	624	290		400	26

So, the results of Table 2 concerning estimation of avoidable exergy destruction demonstrate that the thermodynamic interconnection between the components of the air-source heat pump is quite strong. In contrast, the results of Table 2 show that, from the point of view of costs due to exergy destruction, the interconnections between the components of the air-source heat pump are weak. 125 €·year^{-1} or 23% of avoidable costs of exergy destruction is due to the component interaction. Such value of cost is mainly caused by irreversibilities within the evaporator, which contributes to 83 €·year^{-1} with respect to the throttling valve.

Similar results are found for the water-source heat pump (see Table 3). 39% (400 kWh) of avoidable exergy destruction within the water-source heat pump is due to the component interaction. Almost all this part of avoidable exogenous exergy destruction belongs to the compressor (207 kWh) and the throttling valve (194 kWh). Improvement in the evaporator will affect not only the avoidable endogenous exergy destruction of this component (243 kWh), but also the exogenous avoidable exergy destruction within the throttling valve (103 kWh) and within the compressor (126 kWh). Similar results are obtained for the condenser with 174kWh of the seasonal avoidable endogenous exergy destruction. With the made assumption of increasing thermodynamic efficiency within the condenser it is possible to decrease 104 kWh and 62 kWh of the annual exogenous avoidable exergy destruction within the throttling valve and the compressor, respectively. Quite small values of avoidable exogenous exergy destruction within the investigated water-source heat pump are negative.

So, the data of Table 3 shows that the thermodynamic interconnection between the components of the water-source heat pump is also quite strong. The results of Table 3 demonstrate that, from the point of view of costs due to exergy destruction, similarly to the air-source heat pump the interconnections between the components of the water-source heat pump are not so strong either. 8% (26 €·year^{-1}) of avoidable costs of exergy destruction is due to the component interaction. The largest share of this value of cost is mainly due to irreversibilities within the evaporator, which contributes to 13 €·year^{-1} with respect to the throttling valve.

It has been found above that for both air-source and water-source heat pumps (see Table 1) the most important cost source is the purchase cost of the compressor. Also, finding possibilities of reducing this part of cost with the help of reducing the inefficiencies caused by component interaction is of high priority. For this purpose it is proposed to split the capital investment cost into endogenous/exogenous (see Tables 4). The evaluation of the results presented in Table 4 shows that for the air-source heat pump some amount of investment expenditures of the most expensive component (compressor) can be decreased by increasing the thermodynamic efficiency of the evaporator and condenser. This can be explained with a more detailed evaluation of the exogenous part of the capital investments for the compressor (Table 4). It can be seen that endogenous capital investment costs of the compressor are equal to 1205 €·year^{-1}. Furthermore, this is the largest share of capital investment for the heat pump. However, 426 €·year^{-1} belong to the exogenous part of the capital investment costs and refer to the irreversibilities distributed within other components: 116 €·year^{-1} due to the condenser, 236 €·year^{-1} due to the evaporator and 74 €·year^{-1} due to the mixed influence of more than one component. According to the methodology of advanced exergoeconomic analysis [19], if the exogenous capital investment cost of the compressor caused by irreversibilities taking place within some component is positive, it means that investment cost of the compressor can be decreased by reducing the irreversibilities within the other components (i.e. evaporator and the condenser). On the other hand, if the exogenous part of capital investment cost is negative, it means that in order to decrease the investment cost of the considered component the irreversibilities within the other components needs to be increased. The latter refers to the case of application of water-source heat pump (see Table 4). Despite the fact that almost all capital investment of the heat pump in belong to the endogenous one

(1304 €·year^{-1} or 97%) the exogenous part can play some role for decision making in simultaneous thermodynamic and economic enhancement of this unit especially concerning the compressor. From Table 5 it can be observed that 42 €·year^{-1} of investment cost within the compressor belongs to the exogenous part. However, the distribution of this cost among the irreversibilities within other components is different as compared to the air-source heat pump. 63 €·year^{-1} of exogenous investment cost is due to the condenser, -62 €·year^{-1} – due to the evaporator and 74 €·year^{-1} – due to the mixed influence of more than one component. It means that investment expenditures for the compressor can be decreased with increasing thermodynamic efficiency of the condenser. Nevertheless, thermodynamic improvement of the evaporator can increase investment costs of the compressor and cannot be recommended.

Table 4: Splitting the capital investment cost for the air-source and water-source heat pumps

Component	Endogenous		Exogenous		
	$Z_{D,k}^{EN,year}$, €·year^{-1}		$Z_{D,k}^{EX,year}$, €·year^{-1}		
	air-source	water-source		air-source	water-source
CM	1205	1071	sum	426	42
			caused by:		
			CD	116	63
			TV	0	0
			EV	236	-62
			mixed	74	41
CD	119	124	sum	12	11
			caused by:		
			CM	9	8
			TV	0	0
			EV	4	2
			mixed	-1	1
EV	150	109	sum	-22	-9
			caused by:		
			CM	-10	-3
			TV	0	0
			CD	-1	-1
			mixed	-11	-5
Heat pump	1474	1304		416	44

4 Conclusions

The paper presents evaluation of component interactions in air-source and water-source heat pumps applied in space heating using exogenous parts of exergy-based parameters. Possible ways for simultaneous thermodynamic and economic enhancement of these energy conversion systems are provided:

it has been shown that 53% of avoidable exergy destruction within the air-source heat pump and 39 % of avoidable exergy destruction within the water-source heat pump is due to the component interaction. The highest values of avoidable exogenous exergy destruction belong to the compressor and the throttling valve;

in contrast to the thermodynamic interconnections the obtained results have shown that from the point of view of costs due to exergy destruction the interconnections between the components of the air-source and water-source heat pumps are not so strong;

for both air-source and water-source heat pumps the most important cost source is the purchase cost of the compressor;

splitting the capital investment cost of the compressor into endogenous/exogenous has shown that for the air-source heat pump some share of this cost can be decreased by reducing the irreversibilities within the evaporator and the condenser. For the water-source heat pump thermodynamic improvement of the condenser can decrease investment costs of the compressor, but decreasing irreversibilities within the evaporator cannot be recommended because it contributes to increases of the compressor investment costs.

Nomenclature

A	heat transfer area (m^2)
c	cost per unit of exergy (€·kWh^{-1})
C	cost associated with an exergy stream (€)
GHG	greenhouse gas
$\dot{E}$	exergy rate (kW)
E	amount of exergy (kWh)
f	exergoeconomic factor (%)
m	mass (kg)
N	total number of time steps within the heating season (day)
p	pressure (Pa)
τ	time step (day)
Z	cost associated with capital investment (€)
Greek symbols	
η	isentropic efficiency (-)
Subscripts and superscripts	
AV	avoidable
UN	unavoidable
UN, EN	unavoidable endogenous
UN, EX	unavoidable exogenous
AV, EN	avoidable endogenous
AV, EX	avoidable exogenous
D	exergy destruction
F	exergy of fuel
k	k-th component
n	number of time steps within the heating season
year	annual
tot	overall system
Abbreviations	
CM	compressor
CD	condenser
PEC	purchase equipment costs
EV	evaporator
TV	throttling valve

Acknowledgements

This work was supported by Ministry of Education and Science of Ukraine, project number 0120U102168.

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