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Exergoeconomic evaluation of different types of absorption and compression chillers

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Abstract:

Climatic changes, increasing demands for favourable working and living conditions, better quality of building insulation and increase of heat gains caused by many electronic devices, which are indispensable in our lives nowadays, cause, that cooling of buildings becomes almost as important as heating. In district energy systems primary energy is converted to those products, which are needed to ensure favourable living and working conditions Supplying costumers with cooling energy from district energy systems essentially contributes to the rational use of energy and to environmental protection. Only proper thermodynamic and economic evaluation of energy products provides successful marketing and optimum utilization of primary energy.

In this paper, the exergoeconomic concept is applied to the cold production in district cooling system, using compression or absorption chillers. The objective function is exergy-based cost of final product, which depends on total annual cost of the system which includes cost of input exergy to the system and annualized capital cost of the system. The cost of exergy of chilled water will be calculated for 2 different absorption chillers: single and double effect H_2O/LiBr absorption chiller and for compression chillers with screw and centrifugal compressor and the working fluid R-134a. Input exergy to the system is the electricity consumption of compressor chiller or heat consumption of absorption chiller and the capital costs includes purchase costs of components.

Keywords:

Exergoeconomic Analysis, District Cooling, Absorption Chiller, Compression Chiller.

1. Introduction

In the last few years the energy consumption for refrigeration has increased rapidly. As a consequence, care should be taken to ensure efficient energy consumption and lower CO_2 emissions. In energy systems primary energy is converted into energy products, which are needed to ensure favourable living and working conditions. Only proper thermodynamic and economic evaluation of these products provides successful marketing and optimum utilization of primary energy.

Exergy is the maximum theoretical work (shaft work or electrical work) obtainable from energy conversion system as this is brought into thermodynamic equilibrium with the thermodynamic environment while interacting only with this environment. Exergoeconomic is a branch of engineering which combines the concepts of exergy and economic analysis. For exergoeconomic analysis of energy system all exergy flows and use of exergy of each component has to be known. Economic analysis determines the capital investment and operating costs of each component of energy system. In the next step the exergy and economic analysis are combined and the exergoeconomic variables are calculated. In case of inadequate state, exergoeconomic optimization can be performed in order to find the minimum price of product, in our case, cold.

Exergoeconomic analysis plays an important role in analyzing, planning and optimizing of energy systems. On the field of exergoeconomic of absorption and compression chillers several studies were conducted. Berlitz [1], Kızılkan [2], Misra [3] and Pons [4] were dealing with the exergoeconomic analysis of single- or double-effect $H_2O/LiBr$ absorption refrigeration systems and Sahoo [5] and Farshi [6] with the NH_4/H_2O absorption refrigeration system. Dingeç [7] used exergoeconomic approach to optimize the compression chiller with the artificial working fluid R12, Morozyuk [8] for the compression chiller with the working fluid NH_3 and Rezeyan [9] for the cascade refrigeration system CO_2/NH_3.

Absorption chillers are driven by heat with lower exergy which is relatively cheap. On the other hand, compression chillers are driven by electric energy which is pure exergy and is therefore more expensive. Values of COP ranging around 0.7 for single-effect and 1.2 for double-effect absorption chillers, for compression chillers COP values range between 4 and 6.5; therefore, energy consumption is lower for compression chillers. Investment costs are higher for absorption chillers but maintenance costs are lower.

The objective of this work is to compare results of the exergoeconomic analysis of cold production using different types of absorption and compression chiller in order to calculate the exergy-based cost of final product.

2. Methodology

2.1 Energetic and exergetic evaluation

Chillers can be optimized by minimizing the supplied power or heat flow to the chiller, considering that cooling power $\dot{Q}_C$ is constant. Coefficient of performance COP has to have maximal value. For absorption chiller COP is defined as:

$$COP_{abs} = \frac{\dot{Q}_C}{\dot{Q}_H}, \tag{1}$$

where $\dot{Q}_H$ is heat flow supplied to absorption chiller.

For the compression chiller COP is defined as:

$$COP_{comp} = \frac{\dot{Q}_C}{P_{el}}, \tag{2}$$

where P_{el} is electrical power supplied to the compressor.

2.1.1. Exergy of heat

In terms of the thermodynamic average temperature, the exergy transfer rate associated with heat transfer rate $\dot{Q}$ is simply

$$\dot{E}_q = \dot{Q}\left|1 - \frac{T_0}{T_a}\right|. \tag{3}$$

2.1.2. Exergy of work

Exergy rate is equivalent to power:

$$\dot{E}_w = \dot{W}. \tag{4}$$

2.1.3. Exergetic efficiency

For the calculation of the exergetic efficiency both a product and a fuel of the system have to be identified. The product represents the desired result produced by the system and the fuel represents the resources expended to generate the product. The exergetic efficiency ε is the ratio between exergy of product and fuel:

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F}\,. \tag{5}$$

Exergetic efficiency of absorption chiller is calculated as [10]:

$$\varepsilon_{abs} = \frac{\dot{Q}_C\left(\frac{T_0}{T_{a,C}}-1\right)}{\dot{Q}_H\left(1-\frac{T_0}{T_{a,H}}\right)} = COP_{abs}\cdot\left(\frac{T_0-T_{a,C}}{T_{a,C}}\right)\left(\frac{T_{a,H}}{T_{a,H}-T_0}\right), \tag{6}$$

where T_0 is temperature of the environment, $T_{\mathrm{a,C}}$ is average temperature of chilled water and $T_{\mathrm{a,H}}$ is average temperature of hot water.

Exergetic efficiency of compression chiller is calculated as follows [10]:

$$\varepsilon_{comp} = \frac{\dot{Q}_C\left(\frac{T_0}{T_{a,C}}-1\right)}{P_{el}} = COP_{comp}\cdot\left(\frac{T_0-T_{a,C}}{T_{a,C}}\right). \tag{7}$$

2.2 Economic evaluation

The economic analysis conducted in this paper is based on so-called total revenue requirement (TRR) method [11]. By using this method all the costs associated with a project, including minimum required return of investment, are taken into calculation. The total revenue requirement is calculated on year-by-year basis and non-uniform annual costs associated with investment, operating, maintenance and fuel costs of the system have to be levelized in order to convert them to an equivalent series of constant payments.

Annual costs associated with carrying charges ($\mathrm{CC_j}$) and expenses ($\mathrm{FC_j}$ and $\mathrm{OMC_j}$) are not uniform, so the levelized carrying charges ($\mathrm{CC_L}$) have to be calculated as:

$$CC_L = (\text{Total Capital Investment})\cdot CRF\,. \tag{8}$$

CRF is capital recovery factor calculated as

$$CRF = \frac{i_{eff}\left(1+i_{eff}\right)^N}{\left(1+i_{eff}\right)^N-1}, \tag{9}$$

where $\mathrm{i_{eff}}$ is the average annual effective discount rate and N is the economic life of chiller expressed in years.

For the calculation of levelized fuel annual costs ($\mathrm{FC_L}$) the constant escalation levelization factor (CELF) is needed:

$$FC_L = FC_0\cdot CELF = FC_0\cdot CRF\cdot\frac{k_{FC}\left(1-k_{FC}^N\right)}{\left(1-k_{FC}\right)}, \tag{10}$$

where $k_{FC} = \frac{1+r_n}{1+i_{eff}}$ and r_n is a constant.

The levelized operation and maintenance costs (OMC_L) are given by:

$$OMC_L = OMC_0 \cdot CELF\,. \tag{11}$$

Finally, the total revenue requirement (TRR_L) is obtained from

$$TRR_L = CC_L + FC_L + OMC_L\,. \tag{12}$$

For the exergoeconomic analysis, capital investment (CI) and operating and maintenance (OM) costs are calculated as follows:

$$\dot{Z}^{CI} = \frac{CC_L}{n}, \tag{13}$$

$$\dot{Z}^{OM} = \frac{OMC_L}{n} \tag{14}$$

and

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM}\,. \tag{15}$$

The levelized cost rate of the expenditures for fuel supplied to the system is given by

$$c_F = \frac{FC_L}{n}\,. \tag{16}$$

Levelized costs, such as $\dot{Z}^{\mathrm{CI}}$, $\dot{Z}^{OM}$ and c_{F}, are used as input data for the exergoeconomic analysis.

The value of $\dot{Z}^{\mathrm{CI}}$ is a function of total capital investment of chiller. It is obtained from the graph of a total capital investment of chiller as a function of cooling capacity. It differs according to different types of chillers.

The following assumptions have been used for the economic analysis:

- According to [12] and heat suppliers experiences the operational and maintenance costs for absorption chiller represent 0.3% of total investment and for compression chiller 1.5 % of total investment.
- Data for the economic analysis
  - The average cost of money is i_{eff}=10 %.
  - The economic life of absorption chiller is n=20 years for and n=15 years for compression chiller.
- The average general inflation rate is r_{n}=2.5 %.

2.3 – Exergoeconomic model

The exergoeconomic analysis of energy system [11] consists of cost balance written as

$$\sum_{out} \dot{C}_{out,k} = \sum_{in} \dot{C}_{in,k} + \dot{Z}_k \tag{17}$$

or

$$\sum_{out} \left(c_{out,k} \cdot \dot{E}_{out,k}\right) = \sum_{in} \left(c_{in,k} \cdot \dot{E}_{in,k}\right) + \dot{Z}_k\,. \tag{18}$$

Using the definitions of fuel and exergy flow of product the equation can be re-arranged as

$$\dot{C}_P = \dot{C}_F + \dot{Z} \tag{19}$$

or

$$c_P \cdot \dot{E}_P = c_F \cdot \dot{E}_F + \dot{Z}\ . \tag{20}$$

Cost rates associated with product and fuel are $\dot{C}_\mathrm{P}$ and $\dot{C}_F$ and c_P and c_F are the cost per unit of exergy of the product and fuel.

3. Case study

A study was performed on district cooling system in Municipality Velenje, Slovenia. This project started in 2008. It was planned that 8 buildings will be connected to district cooling network with total cooling demand of 888 kW. For those conditions absorption chiller BROAD BDH84 X-87/1005-35/28-10 with cooling capacity 980 kW was installed.

In the first phase only two buildings out of 8 were connected to the network. It was assumed that cooling demand of those two buildings is 240 kW. In second phase all other buildings should be connected to network but this phase has been never accomplished.

Table 2 shows average monthly temperatures of environment T_0 and cooling demand Q_C in Municipality Velenje in cooling season from April to September 2011, [12]. Real cooling demand $Q_\mathrm{C,Case1}$ in 2011 was obtained from the operator. Data of cooling demand for the provided scenario with 8 connected buildings $Q_\mathrm{C,Case2}$ was given from [12]. Using equation (3), exergy of cooling demand E_C for Case 1 and 2 was calculated.

Table 1. Temperature of environment, cooling demand and exergy demand in 2011 in Municipality of Velenje, Slovenia [12]

Month	T_0, °C	$Q_\mathrm{C,Case1}$, kWh	$E_\mathrm{C,Case1}$, kWh	$Q_\mathrm{C,Case2}$, kWh	$E_\mathrm{C,Case2}$, kWh
APR	11.7	5587	43.5	20460	159.3
MAY	14.6	13650	246.3	50589	912.8
JUN	19.1	29631	1006.4	109757	3727.8
JUL	22.9	35722	1693.5	132561	6284.5
AUG	21.6	16758	717.4	61645	2639
SEP	15.6	11948	257.9	44382	957.8

In Table 2 the operating conditions for different types of chillers are displayed. Chiller operates with 1296 h/y; data are taken from district cooling system in municipality Velenje in 2011.

Table 2. Operating conditions for different types of chillers

Type of chiller	Cooling capacity, kW	COP	Temperature regime of chilled water, °C	Temperature regime of hot water, °C	Temperature regime of cooling water, °C
Absorption chiller, single-effect	980	0.775	7/12	105/87	32/28
Absorption chiller, double-effect	980	1.2	7/12	140/90	32/28
Compression chiller, screw compressor	980	6.05	7/12	/	32/28
Compression chiller, centrifugal compressor	980	6.18	7/12	/	32/28

The cost of heat is 0.011 €/kWh [12] and the cost of electricity is 0.132 €/kWh [12].

4. Results and discussion

Exergoeconomic model of cold production was used to calculate price of chilled water. Several different chillers were covered in this analysis: screw and centrifugal compression chillers with the working fluid R-134a and LiBr/H_2O absorption chillers with single and double-effect.

4.1 Investment costs of chillers and cooling towers

Investment cost of absorption chiller was obtained from the company BROAD, which produces single and double-effect LiBr/H_2O absorption chillers. From the given data for single-effect LiBr/H_2O absorption chiller the trend line is drawn and the following equation is developed:

$$\dot{Z}^{\mathrm{CI}} = 1273 \cdot \dot{Q}_{\mathrm{C}}^{0.7267}. \tag{21}$$

The trend line of investment cost of the single-effect LiBr/H_2O absorption chiller depending on cooling capacity is shown on Fig. 1.

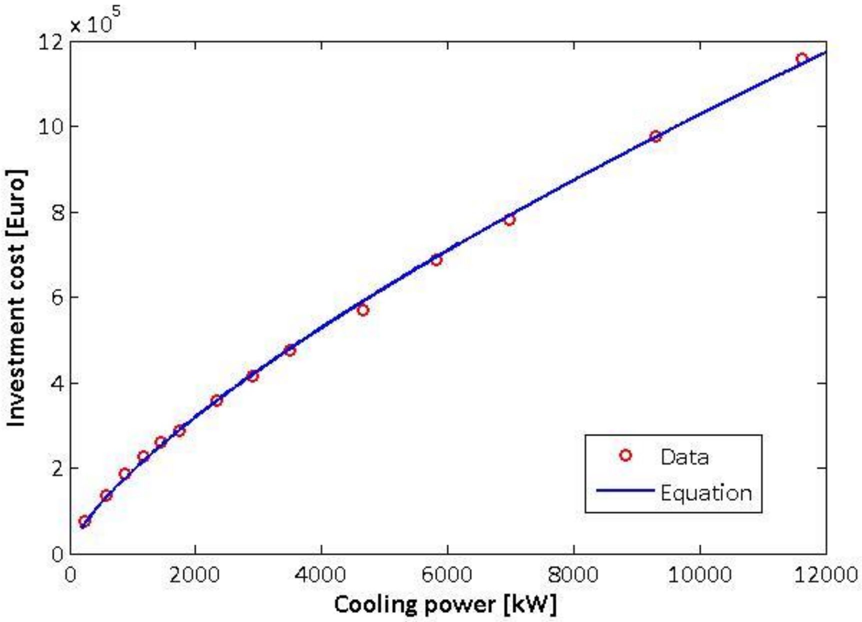

Fig. 1. Investment cost of single-effect absorption chiller as a function of cooling capacity [13]

According to BROAD, double-effect LiBr/H_2O absorption chillers are more expensive. Equation for investment cost depending on cooling capacity will result in the following form:

$$\dot{Z}^{\mathrm{CI}} = 1448 \cdot \dot{Q}_{\mathrm{C}}^{0.7252}. \tag{22}$$

The same approach to determine equation for investment cost of chiller is also used for compression chillers with the working fluid R134a. Data were given by authorized Slovenian representative for the company TRANE. With the use of MATLAB tool, the following equation for compression chiller with screw compressor is developed:

$$\dot{Z}^{\mathrm{CI}} = 887.5 \cdot \dot{Q}_{\mathrm{C}}^{0.6742}. \tag{23}$$

For centrifugal compression chiller the following equation for price of chiller is developed:

$$\dot{Z}^{\mathrm{CI}} = 22590 \cdot \dot{Q}_{\mathrm{C}}^{0.2583}. \tag{24}$$

Fig. 2 shows investment costs of different chillers depending on cooling capacity. Cooling capacity is ranging from 500 kW to 3000 kW for absorption chillers, from 500 to 1500 kW for compression chillers with screw compressor and from 1000 to 3000 kW for compression chillers with centrifugal compressor.

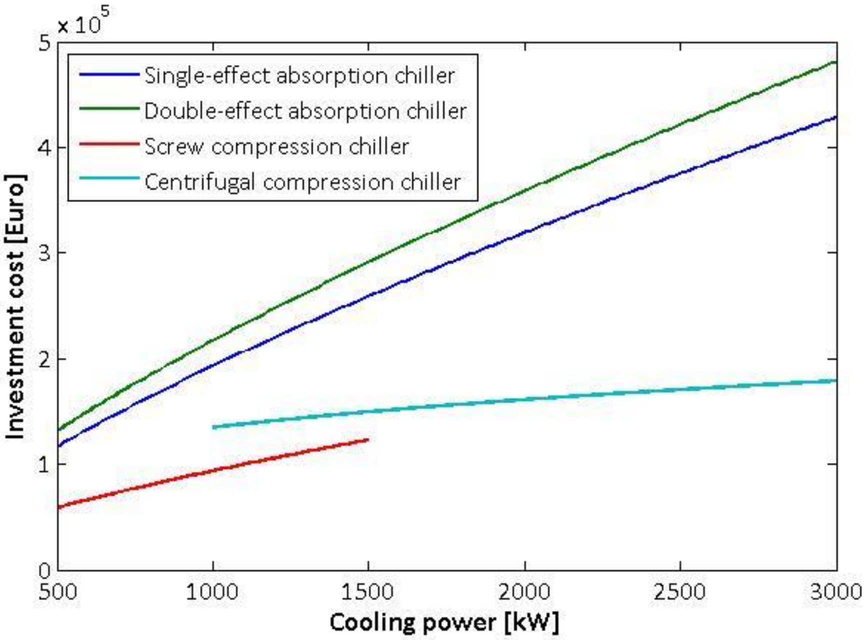

Fig. 2. Investment costs of different chillers [13, 14]

As it is seen from Fig. 2, double-effect absorption chiller is the most expensive. With increasing of cooling capacity the difference between single and double-effect absorption chiller is increasing. Compression chillers with screw compressor are only used for cooling capacities up to 1500 kW. For higher cooling capacities compression chillers with centrifugal compressor are used.

For calculation of the cost of exergy of chilled water the investment costs of cooling towers have to be included. In district cooling system in Velenje two cooling towers ESOT EWK 900/09 with required thermal power 1133 kW each. The price of each cooling tower is 19000 €, temperature regime of this cooling tower is 35/28 °C. [12]

For compression chillers only one cooling tower has to be installed because less heat has to be transferred to the environment.

In Table 3 investment cost of chillers with cooling capacity 990 kW, heat flow of condensation and investment cost of cooling tower are displayed.

Table 3. Investment cost of chillers with cooling capacity of 990 kW, *heat flow of condensation and investment cost of cooling tower [12]*

Type of chiller	Investment cost of chiller with cooling capacity 990 kW, €	Heat flow of condensation, kW	Investment cost of cooling tower, €
Absorption chiller, single-effect	191350	2245	38000
Absorption chiller, double-effect	215270	1797	25000
Compression chiller, screw compressor	92865	1142	19000
Compression chiller, centrifugal compressor	138000	1139	19000

4.2 Exergoeconomic analysis

The main results obtained through the exergoeconomic analysis are presented in Table 4. Cost of the exergy of chilled water c_C, was calculated using equation (20).

Table 4. Cost of the exergy of chilled water

Month	$c_{\mathrm{C,abs,single,1}}$, €/kWh$_\mathrm{C}$	$c_{\mathrm{C,abs,single,2}}$, €/kWh$_\mathrm{C}$	$c_{\mathrm{C,abs,double,2}}$, €/kWh$_\mathrm{C}$	$c_{\mathrm{C,comp,screw,2}}$, €/kWh$_\mathrm{C}$	$c_{\mathrm{C,comp,cent.,2}}$, €/kWh$_\mathrm{C}$
APR	48.37	13.43	13.93	12.12	14.11
MAY	18.78	5.16	5.36	4.81	5.56
JUN	6.74	1.88	1.94	1.97	2.24
JUL	4.04	1.13	1.17	1.27	1.42
AUG	8.10	2.25	2.34	2.08	2.41
SEP	8.94	2.46	2.53	2.75	3.09

Costs of exergy of chilled water for different types of chillers are shown in Fig. 3. There are 4 different costs displayed on graph: cost of exergy in case of LiBr/H_2O single-effect absorption chiller for real case scenario in Velenje 2011 (Case 1) and cost of exergy of chilled water in case of LiBr/H_2O single and double-effect absorption chiller and compression chiller with the working fluid R-134a in case of ideal scenario where all planned buildings are connected to the network (Case 2).

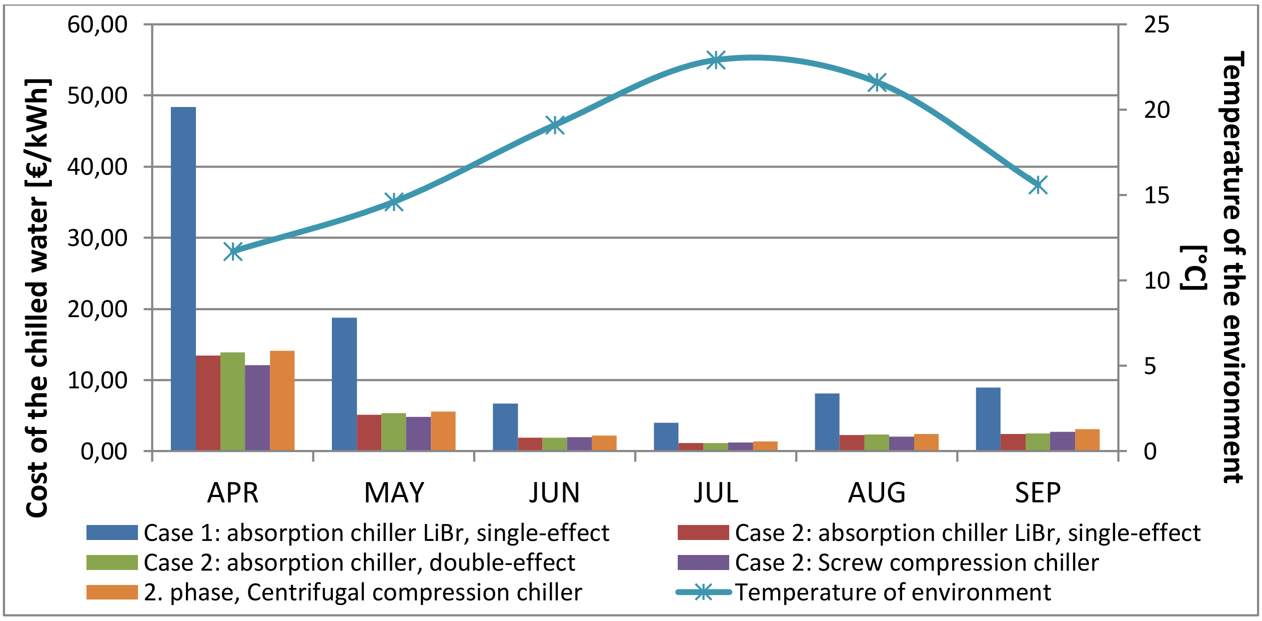

Fig. 3. Cost of exergy of cooled water for different chillers

Cost of the exergy of chilled water is the highest in real case scenario (Case 1). In this case only two buildings are connected to the network, absorption chiller is working at 25 % of nominal power and COP of the chiller is low, from 0.29 in September to 0.53 in July [12], because absorption chillers achieve the highest COP at peak operation conditions.

Comparison between the costs of the exergy of chilled water for single and double-effect absorption chiller shows us that even though the single-effect absorption chiller has lower COP, the investment costs of double-effect chiller are significantly higher; therefore the price for double-effect absorption chiller is higher.

When we compare cost of the exergy of chilled water between compression and absorption chiller we can see that cost chilled water produced by single effect absorption chiller is lower than the one produced by compression chiller with screw or centrifugal compressor. Cost of chilled water produced by centrifugal compression chiller is the highest because the investment cost is high.

The lowest cost of exergy of chilled water is in both cases, for absorption and compression chillers, when the temperature of the environment is the highest.

4. Conclusions

In the article, the exergoeconomic evaluation of different types of compressor and absorption chillers is presented. Several different chillers have been considered in this analysis: screw and centrifugal compression chillers with the working fluid R-134a and LiBr/H_2O absorption chillers with single and double-effect.

Cost rate of chilled water supplied to the consumers consists of cost rate of fuel, cost rate associated with capital investment expenditures and cost rate associated with operational and maintenance expenditures. Cost of chilled water is usually given in Euros per kWh of energy of consumed cold. However, energy specifies only the amount of energy and not its quality. Compression chillers are driven by electrical energy which is the best quality form of energy, while for the production of cold with absorption chillers the low quality heat is used, which depends on the ambient temperature and the temperature of cooled water. Therefore it is reasonable to consider quality and the amount of energy, in order to compare the cost rate of chilled water supplied to the consumers. These two factors have been included in the exergy analysis.

In the exergoeconomic evaluation of cold production, four different types of chillers were analysed. Screw compressor chillers have the lowest capital investment costs, followed by turbo compressor chillers, which are used for larger cooling capacities. Absorption chillers are more expensive, the highest investment costs have double effect absorption chillers. Investment costs of cooling towers depend on quantity of heat rejected from the condenser (and absorber) and are higher for absorption chillers than for compression chillers. In exergoeconomic analysis the cost of fuel is defined in Euros per kWh of exergy supplied to the chiller. The results of this study reveal, that this cost is significantly higher in case of cold production with compression chillers, compared to absorption ones. Despite of the fact, that COP of compression chillers is substantially higher than that of absorption chillers, one has to bear in mind that the electricity represents pure exergy, whereas heat in sorption chillers represents poor exergy.

The exergoeconomic evaluation of cold production, as conducted here, allows us to compare costs of chilled water per unit of exergy in case of different types of cold production, with absorption and compression chillers. The results obtained for compression and absorption chillers demonstrate that new, interesting and useful insights can be gained from this approach.

Nomenclature

c	cost per unit of exergy, €/kWh
$\dot{C}$	cost rate associated with an exergy stream, €/h
COP	coefficient of performance
$\dot{E}$	exergy rate, kW
$\dot{Q}$	heat rate, kW
T	temperature, °C
P	power, kW
$\dot{Z}$	cost rate associated with investment expenditures, €/h

Greek symbols

ε	exergy efficiency

Subscripts and superscripts

a	average
abs	absorption chiller
C	cold water

cent.	centrifugal compressor
CI	capital investment
comp	compression chiller
el	electrical
F	exergy of fuel
H	hot water
in	inlet
k	k-th component
OM	operation and maintenance
out	outlet
P	exergy of product
screw.	screw compressor
0	reference state for the exergy analysis

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