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Exergy analysis of a reversible chiller

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***Abstract* — The work presents the results of exergetic analysis of a reversible chiller providing both cooling and space heating in varying operational modes. The year values of avoidable parts of exergy destruction occurring in each system component are used for the analysis. The outcomes obtained showed that the both inside and outside heat exchangers have the highest priority for improvement revealing more than 718 kW-hr avoidable year exergy destruction within the system.**

***Keywords* — reversible chiller; avoidable exergy destruction; irreversibilities.**

I. INTRODUCTION

Today, a large offer of reversible units is proposed, with investment costs comparable to the nonreversible units. The air-cooled chiller is the most present technology on the European air-conditioning market, representing 85% of chillers sold in the commercial sector. The chiller can be reversed by means of a refrigerant change-over, which inverses the flow passage into the two exchangers: – in cooling mode, the air exchanger (outside heat exchanger) works as condenser, rejecting heat to outdoor air, while the water-exchanger (inside heat exchanger) works as evaporator, transferring cooling power to the distribution system; - in heating mode, the air exchanger works as evaporator, extracting heat from outdoor air, while the water exchanger works as condenser, transferring heating power to the distribution system. Reversible air-cooled units are installed in most of the case in combination with a backup boiler [1–3]. Typically, the air-cooled chillers have a limiting outdoor temperature (generally around –10° C), below which they cannot be operated. In addition, at very low outdoor temperature, the chiller COP degrades dramatically, and using the boiler could become preferable. The scope of the paper is to demonstrate the application of exergetic analysis for finding annual exergy destruction within an air-cooled reversible chiller providing both cooling and space heating in varying operational modes, which is typical for built environment and caused by fluctuating in outdoor conditions.

II. METHODOLOGY

Taking into account that the investigators need to focus only on the reduction in avoidable parts of exergy destruction occurring in each system component, this work is based uniquely on these irreversibilities and proposes application of a new calculation method to compute them [4]. According to the novel method the avoidable exergy destruction rate ($\dot{E}_{D,k}^{AV,INT}$), being internally caused, can be computed as the difference between the total exergy destruction of the investigated component ($\dot{E}_{D,k}$), i.e. calculated under real operation conditions, and its exergy destruction ($\dot{E}_{D,k}^{MIN,k}$) evaluated under conditions at which its irreversibilities are reduced by improving its efficiency taking into account that the remaining components are operating under real conditions

$$\dot{E}_{D,k}^{AV,INT} = \dot{E}_{D,k} - \dot{E}_{D,k}^{MIN,k} . \qquad (1)$$

The avoidable exergy destruction within the k-th component, being caused by the avoidable irreversibilities occurring within the r-th component (i.e. externally caused) ($\dot{E}_{D,k}^{AV,EXT,r}$), can be computed by subtracting the exergy destruction rate ($\dot{E}_{D,k}^{MIN,r}$) within the k-th component under conditions at which the r-th component is working with reduced irreversibilities and the remaining components are operated with their real conditions from the exergy destruction rate ($\dot{E}_{D,k}$) taking place within the k-th component under its real operation

$$\dot{E}_{D,k}^{AV,EXT,r} = \dot{E}_{D,k} - \dot{E}_{D,k}^{MIN,r} . \qquad (2)$$

The importance of the components from the thermodynamic viewpoint and priorities for improving the k-th components are identified on the base of the sum of the internally caused avoidable exergy destruction ($\dot{E}_{D,k}^{AV,INT}$) and the externally caused avoidable exergy destruction within the remaining components ($\dot{E}_{D,r}^{AV,EXT,k}$)

$$\dot{E}_{D,k}^{AV,\Sigma,INT,EXT} = \dot{E}_{D,k}^{AV,INT} + \sum_{\substack{r=1\\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EXT,k} . \qquad (3)$$

For exergetic assesment of the reversible air-to-water unit it is proposed to consider annual values of parameters.

The reversible unit is connected to a two-pipe water distribution system, in parallel with the backup boiler. In this case no simultaneous heating and cooling loads are expected. The switch between operating modes is regulated by a central change-over located in the outdoor unit.

The system is cooling-driven. That means that the priority is given to cold generation. The boiler is used when the heating demand is too large to be covered by the chiller or when the reversible chiller cannot operate or has too bad performance due to low outdoor temperature. The system is designed for the following cooling design conditions: cooling capacity 10.5 kW; the water is cooled in evaporator (inside heat exchanger) from 12 to 7° C and the outside air is heated in condenser (outside heat exchanger) from 30 to 35° C; the pinch point temperature differences in the inside unit and in the outside unit was 5 K and 12 K, respectively; the calculated value of the real isentropic efficiency of the compressor was equal to 0.86. For evaluating the internally and externally caused avoidable exergy destruction the following parameter values were assumed: the pinch point temperature differences in the condenser (outside unit) and the evaporator (inside unit) were equal to 3 K and 1 K, respectively, whereas the unavoidable compressor efficiency was equal to 0.96.

A set of non-linear algebraic equations involving the heat and mass balances as well as the heat transfer equations were utilized. CoolProp was employed for providing the thermo-physical properties of the working fluids, while the simulation model of the heat pump was implemented in MathCad math environment. R134a was selected as the refrigerant. The ambient (outdoor air) temperature was chosen as the reference state for the exergy analysis.

Daily weather data of a typical meteorological year for the city of Kyiv located in the central part of Ukraine were used for the analyses. So, 24-hour time step τ_k was assumed for quasi-steady state modelling.

III. RESULTS AND DISCUSSION

The year values of the internally caused and the externally caused avoidable exergy destruction $E_{D,k}^{AV,\Sigma,INT,EXT,year}$ in the components of the investigated reversible chiller are presented in Fig. 1. It could be observed that 594 kW-hr of avoidable exergy destruction in the compressor can be reduced by improving this component. Another part of avoidable exergy destruction in the compressor was caused by the irreversibilities that occur in the remaining components: outside unit (146 kW-hr) and inside unit (152 kW-hr). Also, 397 kW-hr of avoidable exergy destruction within the inside unit can be reduced by decreasing the irreversibilities within the inside unit. Another part of avoidable exergy destruction within the inside unit (47 kW-hr) could be avoided by improving the remaining components: compressor and outside unit. The outside unit was found to be responsible for 162 kW-hr of avoidable exergy destruction within the throttling valve. In addition, 222 kW-hr of avoidable exergy destruction within the throttling valve were caused by irreversibilities within the inside unit. Furthermore, -52 kW-hr of avoidable exergy destruction within the throttling valve depended on irreversibilities taking place in the compressor. According to the results presented in Fig. 1 the largest share of avoidable exergy destruction in the outside unit was internally caused (405 kW-hr). -31 kW-hr and -36 kW-hr of avoidable exergy destruction within the outside unit could be reduced by improving the inside unit and the compressor, respectively.

The proposed approach for evaluation of avoidable exergy destruction (see the pie chart in Fig. 1) identified priorities for improving the overall system. The outcomes obtained showed that the inside unit has the highest priority for improvement – it revealed 739 kW-hr avoidable exergy destruction within the system. Also, the outside unit was the second component on which it was needed to focus, as it offers the potential to reduce 718 kW-hr of year exergy destruction. Thirdly, the compressor enhancement was found to lead to a potential decrease of 540 kW-hr of year exergy destruction.

It should be noted that in case of design and operation of a separate air-source heat pump for heating with similar parameters the biggest share of avoidable exergy destruction (about 65%) can be removed by improving outside block (evaporator). The inside block (condenser) accounts only about 20% of avoidable exergy destruction within such heat pump [5].

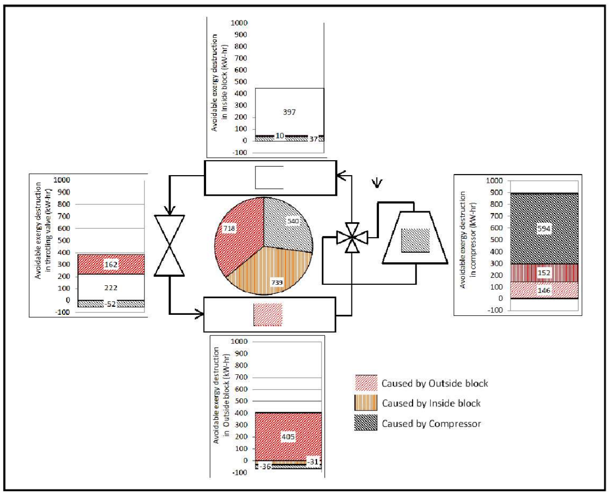

Figure 1. Year values of the internally caused and the externally caused avoidable exergy destruction $E_{D,k}^{AV,\Sigma,INT,EXT,year}$ in the components of the investigated reversible chiller

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