https://doi.org/10.3311/PPme.20262

Periodica Polytechnica Mechanical Engineering, 67(1), pp. 37–43, 2023

Efficiency of Parallel Connected Desuperheater in a Cooling Circuit

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Received: 01 April 2022, Accepted: 19 October 2022, Published online: 27 October 2022

Abstract

Cooling circuits can be improved by using a desuperheater. A series connected desuperheater increases the efficiency of the circuit and allows the waste heat to be used, e.g., for DHW preparation. The study investigates the behavior of a parallel connected desuperheater for DHW preparation in an experimental cooling circuit. The basic parameters of the cooling circuit (efficiency, pressure, temperature and energy consumption) were evaluated when operating 1. with only a condenser and 2. with a condenser and a desuperheater connected in parallel. The results of the study show that a parallel connected condenser and desuperheater reduces the overall efficiency of the cooling circuit.

Keywords

desuperheater, parallel connected, refrigeration, waste heat

1 Introduction

Contemporary modern buildings, mainly those with a large proportion of glazing, quite commonly require mechanical cooling [1, 2]. Although the trend today is to use passive cooling or reduce heat loads, machine cooling is a common part of buildings [3]. Cooling circuits works with using evaporation liquid refrigerant. Isothermal heat input and removal is characteristic for this process. A significant part of the cycle behaves as a Carnot cycle. Compressor refrigeration circuits produce large amounts of waste heat as a by-product of their operation. In well-designed cooling circuits, this waste heat is usually recycled. Removing waste heat also has the benefit of increasing the efficiency of the cooling circuit.

Some studies show an increase in chiller efficiency after application of a desuperheater in the cooling circuit [4, 5]. Some studies have focused on the use of desuperheaters in smaller-scale cooling circuits associated with domestic hot water (DHW) heating units [6–8], DHW cooling towers [9, 10] or solar-based systems for heating homes or swimming pools [11, 12]. An interesting application of the desuperheater is in circuits with multi-temperature heat pumps [13]. Another study focused on the application of a desuperheater in a compression/absorption high-temperature hybrid heat pump using waste heat [14]. Finally, a study that looked at the use of a desuperheater in a monovalent inverter-driven water-to-water heat pump for heating and DHW preparation for low energy houses [15] should be mentioned. A study was carried out focusing on the efficiency of a cooling circuit using a series connected desuperheater circuit [5]. The aim of this work is to verify the efficiency of a cooling circuit with a parallel connected desuperheater.

The basic principle of an evaporative compressor cycle fitted with a parallel connected desuperheater can be described as follows (see Figs. 1 and 2) saturated refrigerant

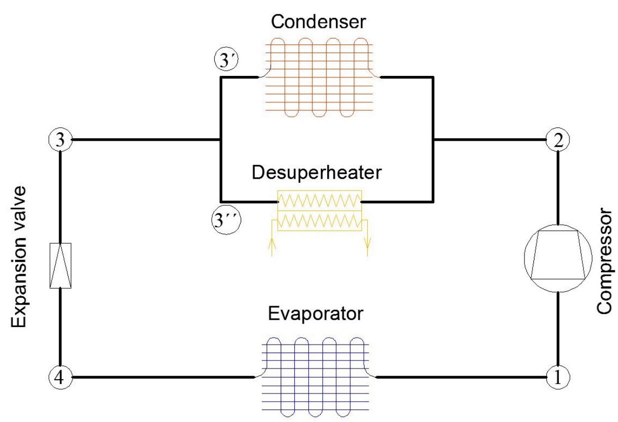

Fig. 1 Schematic of a cooling circuit with a parallel connected desuperheater, including operating points

Cite this article as: Formánek, M., Horák, P. "Efficiency of Parallel Connected Desuperheater in a Cooling Circuit", Periodica Polytechnica Mechanical Engineering, 67(1), pp. 37–43, 2023. https://doi.org/10.3311/PPme.20262

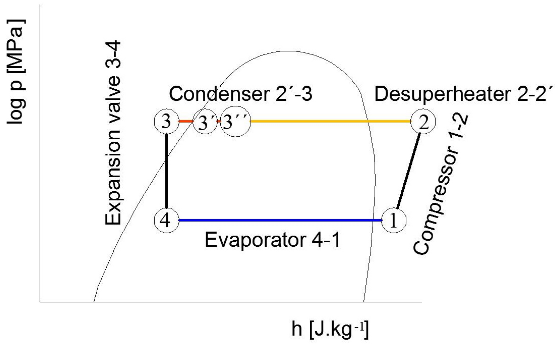

Fig. 2 Schematic of the principle of a cooling circuit operating with a desuperheater in a p-h diagram

vapor is sucked into the compressor (state 1), given that adiabatic compression takes place (state 2). The superheated refrigerant partially condenses in the condenser (states 2-3'), and partially in the desuperheater (states 2–3"). In our case, the refrigerant flow ratio between the condenser and the desuperheater is not a controlled process. Using the expansion valve, isoenthalpic throttling occurs and a wet steam condition is created (states 3–4). The evaporator removes heat and the refrigerant passes into saturated vapor form (states 4–1). The condensing pressure is regulated by an armature located between the condenser (desuperheater) and expansion valve. The temperature of the water coming out of the condenser (desuperheater) is controlled by this regulation armature. During operation of the circuit, the condensing temperature changes depending on the temperature of the heated water. The above-described cycle consists of several processes which, when completed, return the refrigerant to its initial state. The cycle above can operate as direct (produces work) or indirect (consumes work). This laboratory study investigates the indirect cycle.

The waste heat from the refrigeration circuit can be obtained by direct extraction using an exchanger installed on the condenser (desuperheater). In the case of heating HDW using waste heat from the cooling circuit, it is more practical to use a heat exchanger in combination with a storage tank. The secondary heat source in the storage tank then heats the water to the required temperature.

Numerical simulations can be effectively used to study cooling circuits. One study used HVACSIM+ software to simulate cooling/heating and DHW production for residential buildings in Hong Kong [16]. Over time, computer simulations have proven to be a useful tool in optimizing the efficiency of cooling circuit with desuperheater in low-energy construction [15, 17]. Computer simulations were also used to model the year-round operation of heat pumps with desuperheater for low energy houses in Japan [18].

The aim of this study is to verify the performance parameters of a refrigeration circuit operating with a desuperheater connected in parallel to the condenser. For the purpose of the experiments a small laboratory cooling circuit was set up. We believe that the nature of the experiment requires an experimental solution rather than a numerical simulation. The first objective of our research is to verify the efficiency of a cooling circuit with a parallel desuperheater. The second objective is to assess the possibility of using the waste heat from this cooling circuit for preheating HDW

2 Methods and materials

2.1 Description of the experimental cooling device with desuperheater

For the purpose of the experiment, an experimental refrigeration circuit operating with R507 refrigerant was set up (Fig. 3). The drive unit of the circuit is a Danfoss CLX FR 8.5 compressor with an output of 486 watts. An insulated evaporator with a volume of 0.05 m^3, an air condenser, and a desuperheater are installed in the circuit for heat transfer. Other components of the circuit include a control switchboard fitted with a FLICA 110 temperature control, several solenoids and an automatic injection valve. For the experiment, the circuit was operated at a condensing temperature of approximately 45 °C and an evaporation temperature of approximately −10 °C. During the measurements, the evaporator was loaded with heat at Q = 70 watts, Q = 100 watts, Q = 120 watts and Q = 140 watts. The heat source in the evaporator was an electric heating cable.

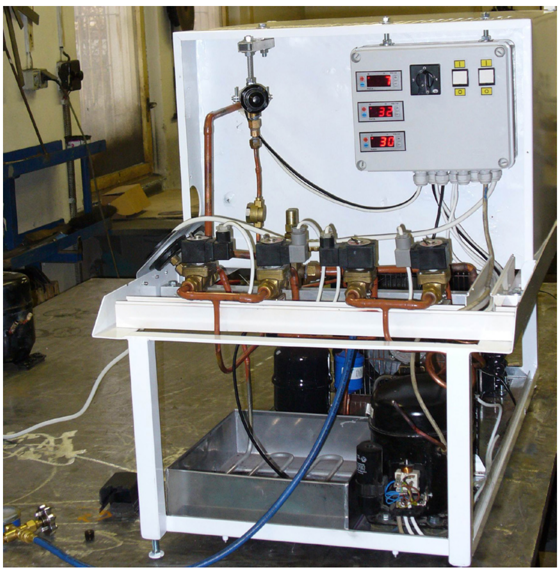

Fig. 3 The experimental cooling circuit equipped with a desuperheater, set up for the study

Different measuring instruments were used to measure the individual variables. Temperature and pressure were measured with a Testo 565 (nominal temperature 22 °C ± 1 digit; pressure accuracy ± 0.5% fs, range 0 to 5,000 kPa). Electrical voltage was measured with Instaltest 61,557 (range 0 to 440 V, accuracy ± 2% fs + digits). The electric current was measured with a VA 18B ammeter (range 1 to 6 A, accuracy ± 3% fs + 8 digits).

The test circuit allows several modes of operation (see Fig. 4). The refrigerant can flow either through the condenser or just through the desuperheater. For the parallel connection of the desuperheater, the refrigerant passed through the desuperheater and the condenser at the same time.

In the experimental setup, the desuperheater is stored in an open container with thermal insulation with a volume of 1 dm^3. A container equipped with an immersion thermometer was filled with crushed ice. The measurement of the desuperheater behavior started when the ice in the container melted. In the case of the condenser power measurement, valve B was opened and valves A, C and D were closed (see Fig. 4).

In the case of the performance measurement of the parallel connected desuperheater, valves A, B and C were opened and valve D was closed.

Pressure and temperature sensors were placed ahead and after each heat exchanger. During the experiment, pressure and temperature readings were taken. At the same time, electrical values were read on the cooling circuit. Electrical readings were taken at the compressor and fan on the condenser. Data readings were taken at one-second intervals. Using Solkane 8 software, the enthalpy and mass flow values for each heat exchanger were calculated [19]. The measured values of temperature and pressure were used for this calculation. In Solkane 8 software, the sub-cooling temperature (2 °C) and the superheating temperature (7 °C) for the measured cooling circuit were obtained.

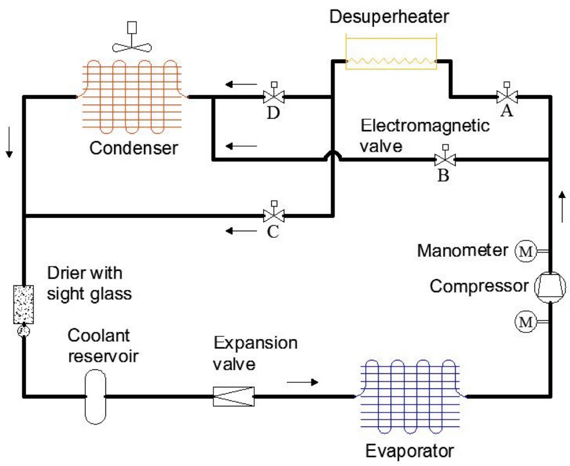

Fig. 4 Diagram of test circuit with marking of control valves

2.2 Computational relationships for experimental evaluation

The cooling performance of the evaporator can be determined according to the well-known equation [20]:

$$Q_e = \dot{m} \cdot (h_1 - h_4), \tag{1}$$

where Q_e [W] is the evaporator performance, $\dot{m}$ [kg s^{-1}] is the refrigerant mass flow, and the values h_1 and h_4 refer the enthalpy (see Figs. 1 and 2).

The heating performance of the condenser can be determined according to the equation:

$$Q_c = \dot{m} \cdot (h_2 - h_3'), \tag{2}$$

where Q_c [W] is the condenser performance, $\dot{m}$ [kg s^{-1}] is the refrigerant mass flow, and the values h_2 and h_3' refer the enthalpy in front and behind condenser (see Figs. 1 and 2).

The Energy Efficiency Ratio (EER [-]) is commonly used to compare the energy efficiency of a refrigeration cycle and is defined as:

$$\text{EER} = \frac{Q_e}{Q_c - Q_e} = \frac{h_1 - h_4}{(h_2 - h_3') - (h_1 - h_4)}. \tag{3}$$

Similarly, the coefficient of performance (COP [-]) can be defined:

$$\text{COP} = \frac{Q_c}{Q_c - Q_e} = \frac{h_2 - h_3'}{(h_2 - h_3') - (h_1 - h_4)}. \tag{4}$$

The EER and COP values are rather theoretical calculations that do not accurately describe the energy balance of the cooling circuit. To obtain real EER and COP values, the compressor efficiency and the power input of other components (control unit, fan, etc.) must be included in the calculation.

If we include EER and COP together, we can define the maximum proportional energy contribution ($\eta_{\max}$ [-]) for the refrigeration circuit, which is defined as follows:

$$\eta_{\max} = \text{EER} + \text{COP} = \frac{(h_1 - h_4) + (h_2 - h_3')}{(h_2 - h_3') - (h_1 - h_4)}. \tag{5}$$

The value $\eta_{\max}$ is a theoretical value, without the influence of the efficiency of the individual components of the cooling circuit.

In conventional refrigeration circuits, the condensation heat Q_c is not used. This heat is released into the ambient air without being used efficiently. If a desuperheater is connected to the cooling circuit, we can define the proportional energy contribution of the cooling circuit as η [-]:

$$\eta = \frac{Q_e + Q_d}{P}, \tag{6}$$

where Q_d [W] is desuperheater thermal performance and P [W] represents the real electrical input of the cooling circuit. The thermal performance of the desuperheater Q_d can be determined based on the refrigerant mass flow $\dot{m}$ and the difference of the relevant enthalpies h_3'' and h_2' (see Fig. 1):

$$Q_d = \dot{m} \cdot \left(h_3'' - h_2\right). \tag{7}$$

For the purpose of the experimental investigation, the quantity real proportional energy contribution for the cooling circuit was defined (η_e [-]):

$$\eta_e = \frac{Q_e}{P}. \tag{8}$$

3 Results and discussion

The actual experimental work was carried out on the cooling device shown in Fig. 3. Measurements were performed for a parallel connected desuperheater and for a separately connected condenser. The settings of the circuit (control valves) were as described in Section 2.1.

In the case of a parallel connected desuperheater, the desuperheater transferred heat to a separate storage tank where it was used to heat the water. The amount of refrigerant flowing into the condenser and the desuperheater was not a controlled process. Another stage of measurements was carried out only with the involvement of a condenser, solenoid valves A, C and D were closed and solenoid valve B was opened. The dependence of both stages of measurement is expressed for a range of refrigerated space loadings (70 W, 100 W, 120 W, 140 W) in Figs. 5–8.

When the circuit is started, the default values are shown in the diagram on the top left. For both measurement cases, there is a gradual decrease in EER over time. A significant drop in EER is evident for the parallel connected desuperheater. During the experiment, the evaporator pressure was kept constant at 420 kPa at all times. This pressure was kept by an automatic expansion valve with adjustable evaporation pressure.

The relationship between heated water temperature and EER is shown in the graph in Fig. 9. The effect of irregular operation and mechanical losses showed some degree

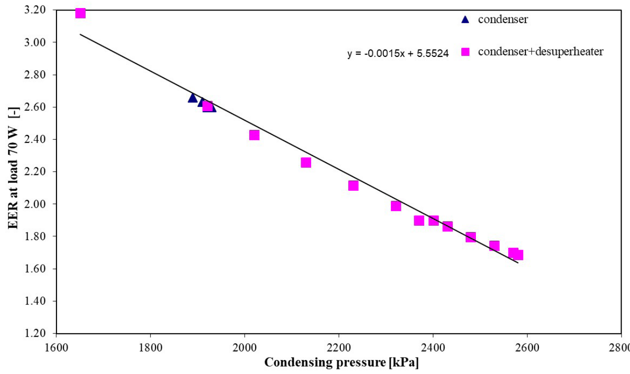

Fig. 5 Relationship between EER and condensing pressure, at a cooling load of 70 watts

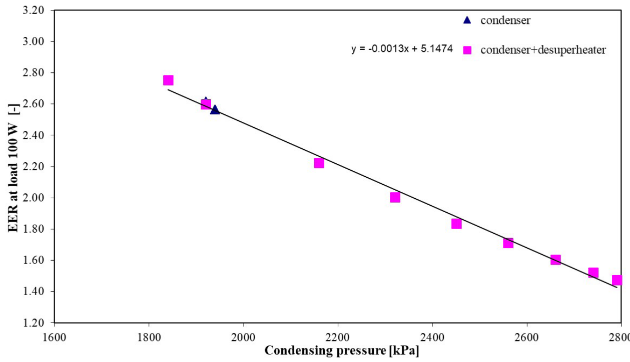

Fig. 6 Relationship between EER and condensing pressure, at a cooling load of 100 watts

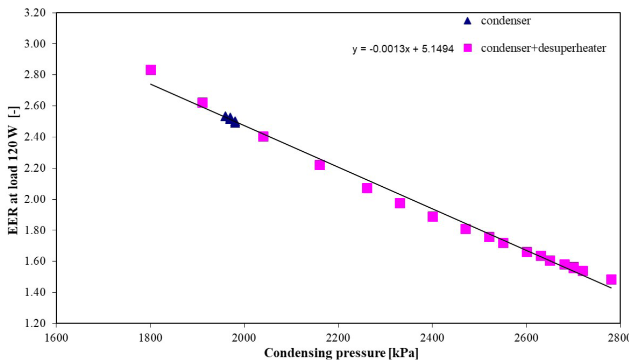

Fig. 7 Relationship between EER and condensing pressure, at a cooling load of 120 watts

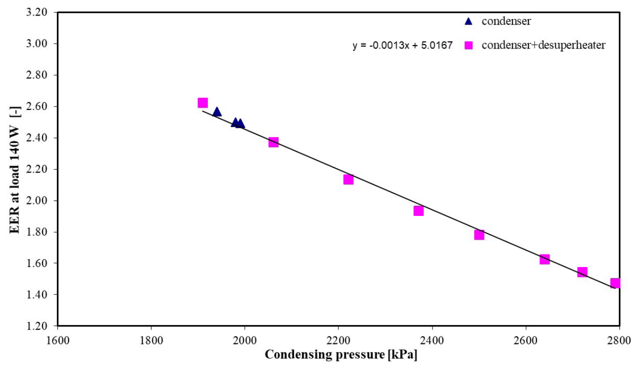

Fig. 8 Relationship between EER and condensing pressure, at a cooling load of 140 watts

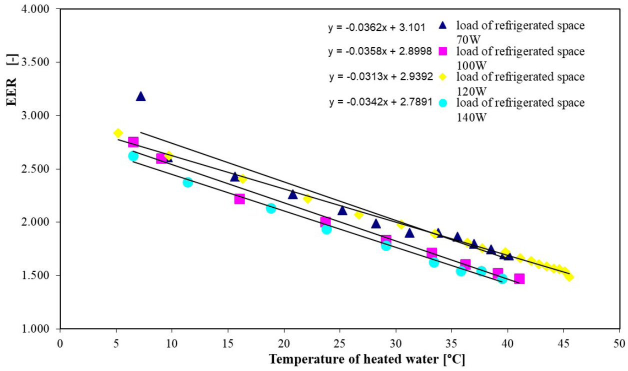

Fig. 9 Relationship between EER and temperature of heated water for the parallel connected condenser and desuperheater

of fluctuation. In general, as heat load increases, EER decreases and electricity consumption increases. In other words, the colder the water the higher the EER of the cooling circuit. If waste heat is not removed through the desuperheater as the cooling load increases, the condenser temperature and power consumption increase. By using a desuperheater, higher EER values can be achieved at lower water temperatures.

Similar behavior can also be seen for the η_{max} variable in Fig. 10, where higher values are at lower water temperature. The η_{max} and EER values show a similar trend, the only difference is in the magnitude of the values. The calculations for EER and η_{max} are based only on the theoretical power input of the compressor.

The influence of the real power input of the compressor, including other electrical components of the circuit (control unit, fan, etc.) is expressed by the values η and η_e (Figs. 11 and 12).

The experimentally obtained dependence of the real proportional energy contribution on the heated water temperature is shown in Fig. 12.

The comparison of the η values (involvement with desuperheater) with the η_e values (involvement without desuperheater) shows small difference. This small difference is due to the use of heat from the desuperheater. The energy gain of a parallel connected desuperheater cannot compensate for the low EER efficiency.

On the other hand, the total electricity consumption (kW h day^{-1}) increases when a desuperheater is used at different refrigerated space loadings over a 24-hour period for the test unit with the desuperheater connected (Table 1).

In general, the lowest power consumption (16.74 kW h day^{-1}) of the parallel connected desuperheater was at a load of (70 W). The highest power consumption (17.42 kW h day^{-1}) was at load (120 W), while most of the excess heat (60.64 kW h day^{-1}) was produced at loadings (140 W).

Table 2 shows the results of the serially connected desuperheater for comparison.

When comparing Table 1 and Table 2, a higher electricity consumption of the parallel connected desuperheater is evident. A parallel connected desuperheater, on the other hand, produces more heat than a serially connected one.

This phenomenon is due to the fact that the refrigerant flow is not evenly distributed between the condenser and the desuperheater. The experimental circuit does not allow for an even distribution of the refrigerant between

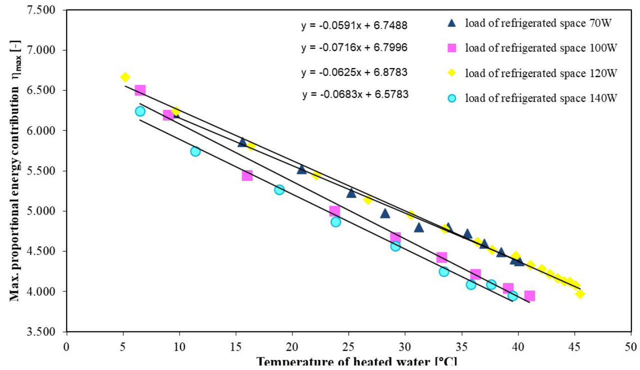

Fig. 10 Relationship between η_{max} max and temperature of heated water for the parallel connected condenser and desuperheater

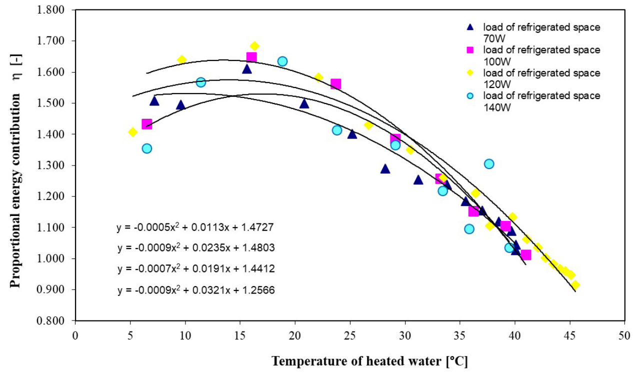

Fig. 11 Relationship between η and temperature of heated water for the parallel connected condenser and desuperheater

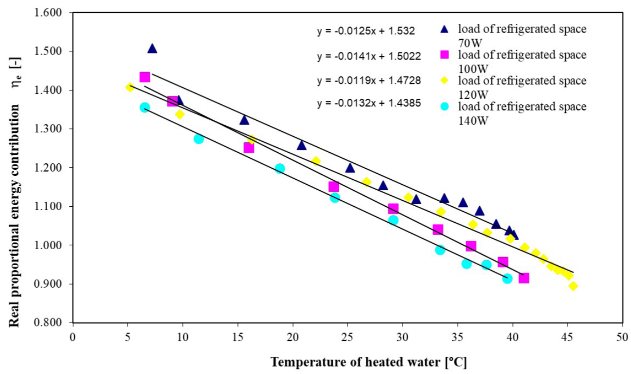

Fig. 12 Relationship between η_e and temperature of heated water for the condenser only

Table 1 Total electricity consumption at different refrigerated space loadings over 24 hours using the condenser only, and parallel connected desuperheater

	Condenser only	Parallel connection between condenser and desuperheater	
Refrigerated space load [W]	Total electricity consumption [kW h day^{-1}]	Total electricity consumption [kW h day^{-1}]	Heat produced by desuperheater [kW h day^{-1}]
70	7.218	16.74	17.51
100	8.269	16.85	52.60
120	8.892	17.42	28.12
140	11.647	17.17	60.64

Table 2 Total electricity consumption at different refrigerated space loadings over 24 hours using serially connected desuperheater

	Serially connection between condenser and desuperheater	
Refrigerated space load [W]	Total electricity consumption [kW h day^{-1}]	Heat produced by desuperheater [kW h day^{-1}]
70	5.723	6.7
100	5.815	13.1
120	8.290	21.2
140	8.541	13.4

the condenser and the desuperheater. A parallel connected desuperheater causes higher condensing pressures and lower EER values than a separately connected condenser (Figs. 5–8).

When the desuperheater is connected in series, there is a small heat production through the desuperheater and at the same time a lower electricity consumption than without desuperheater. When the desuperheater is connected in parallel, the heat production through the desuperheater is higher but at the same time the electricity consumption is also higher than without the desuperheater. At the same time, the EER parameter is lower compared to a separately connected condenser.

4 Conclusion

Our result indicates a higher electricity consumption when operating an experimental cooling circuit with a desuperheater and a condenser connected in parallel. This state is caused by uncontrolled refrigerant flow between the condenser and the desuperheater.

EER values are generally worse for a parallel connected desuperheater than for a separately connected condenser.

Based on the above, it can be concluded that a parallel connected desuperheater worsens the energy balance of the cooling circuit.

However, a series connected desuperheater positively affects the energy balance. A parallel connected desuperheater also increases the condensing pressure, thus negatively affecting the circuit lifetime.

Acknowledgment

This paper is supported by research project FAST-S-22-7788.

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