Periodica Polytechnica
Civil Engineering

60(3), pp. 355–360, 2016
DOI: 10.3311/PPci.8399

RESEARCH ARTICLE

Experimental Increase in the Efficiency of a Cooling Circuit Using a Desuperheater

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Received 09-07-2015, revised 11-02-2016, accepted 24-02-2016

Abstract

Waste heat from cooling circuits can be a useful source of energy for other applications, such as domestic hot water heaters. Furthermore, by removing waste heat from the cooling circuit, its effectiveness can theoretically be enhanced. A number of previous studies have shown that waste heat can be effectively harvested by installing a desuperheater in the cooling circuit between the condenser and compressor. More recently, studies have concentrated on applying heat pumps in conjunction with desuperheaters in low energy houses. In this study, we describe an experimental laboratory-scale cooling circuit with a serially connected desuperheater for heating domestic hot water. We were able to verify that installation of a desuperheater between the compressor and condenser significantly increased the energy efficiency ratio of the experimental cooling circuit, thereby confirming the hypothesis that simultaneous use of waste heat increases the efficiency of cooling circuits.

Keywords

Desuperheater · waste heat · domestic hot water · energy efficiency ratio · heating efficiency

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1 Introduction

Modern buildings often have problems with overheating due to large glazed surfaces and internal gains from people and equipment and therefore it is usually necessary to cool these buildings [1]. Most modern cooling circuits are based on the principle of liquid refrigerant evaporation, with associated isothermal heat supply and heat removal, wherein the heat of evaporation and a considerable part of the circulation approaches that of the Carnot cycle. Cooling circuits based on evaporative compressor cycles, however, produce significant amounts of heat as a by-product of their operation; yet this 'waste' heat could be a useful source of energy for other applications. Furthermore, removal of waste heat from the cooling circuit could enhance the effectiveness of the unit. Some studies have shown that the efficiency of cooling units can be enhanced by installing a desuperheater in the cooling circuit [2]. This article describes the behaviour of the heat pump equipped with a desuperheater. The above-mentioned heat pump was designed for the preparation of Domestic Hot Water (DHW) and space heating. Desuperheater and condenser were connected in series and can only be operated simultaneously. The article does not describe adequately the behaviour of the cooling circuit without the influence of desuperheater. More recently, studies have focussed on the use of desuperheaters in smaller-scale cooling circuits associated with DHW heating units [3], DHW cooling towers [4, 5] or solar-based systems for heating homes or swimming pools [6, 7]. In article [3] the authors deal with the use desuperheater for preparing DHW in zero net energy house. The authors compare the preparation of DHW with desuperheater with other ways of preparing DHW. However, the authors do not evaluate in detail desuperheater impact on the efficiency of the cooling circuit. In Articles [4] and [5] authors compares the the effectiveness of the cooling circuit with desuperheater and reversibly used water cooling tower (RUWCT). In case of using RUWCT desuperheater efficiency is even higher. In our case, we do not use cooling tower. Nevertheless is the comparsion of efficiency of cooling circuits in these articles interesting. It shows that mutual synergy of the RUWCT and desuperheater increases the efficiency of cooling circuits. The authors of article [6] dealing with the use of desuperheater in cooling circuit for pool heating and space heating. The article is used simulations for assessing cooling circuit. It also performed an economic evaluation of the system. Unfortunately it is not in article an assessment of the impact itself desuperheater.

The basic principle of an evaporative compressor cycle fitted with a desuperheater (see Figs. 1 and 2) can be described as follows: saturated refrigerant vapour is enters the compressor (state 1), assuming adiabatic compression in the compressor (state 2). The superheated refrigerant partially condenses in the desuperheater (state 2-2'), and completes condensation to a liquid form in the condenser (state 2'-3). Isoenthalpic throttling takes place in an expansion valve, inducing a wet vapor condition (state 3-4). The refrigerant then passes once again to a saturated vapor state following evaporation in the evaporator (state 4-1). Between the condenser and expansion valve is a container with a condensing pressure regulator. The regulator is adjusted according to the desired temperature of the water exiting the desuperheater. Condensing temperature varies proportionally with the temperature of heated water. The thermal cycle represented above includes several consecutive processes that, after execution, return the refrigerant to its initial state. The cycle can be direct, producing work output (e.g. thermal engines; cycle runs clockwise in Fig. 2), or indirect/inverted, where work is consumed (e.g. thermal machines such as refrigeration systems or heat pumps; cycle runs anti-clockwise in Fig. 2). In this study we concentrate only on indirect cycles.

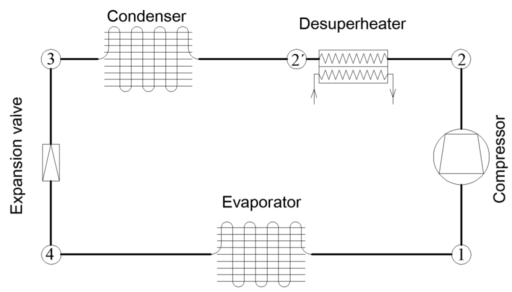

Fig. 1. Schematic functional diagram of a typical cooling circuit with desuperheater. Junction points 1, 2, 2', 3 and 4 are explained in the introduction

The easiest way to make use of the 'waste heat' produced is to fit a heat exchanger and use the collected heat directly. In practice, however, this is rarely appropriate as the need to supply hot and cold water tends to differ over time. A more commonly used solution is to accumulate the heat in an insulated water tank and recover heat as required using a heat exchanger to transfer the accumulated heat to a second tank, where it can then be reheated to the desired temperature.

The cooling/heating cycles outlined above lend themselves to computer-based simulation. The first such simulation focused on cooling/heating systems and DHW production in Hong Kong residential buildings and used the software program HVACSIM+ [8]. The article has been shown that the use of desuperheater for DHW increases the efficiency of the cooling circuit. Since then,

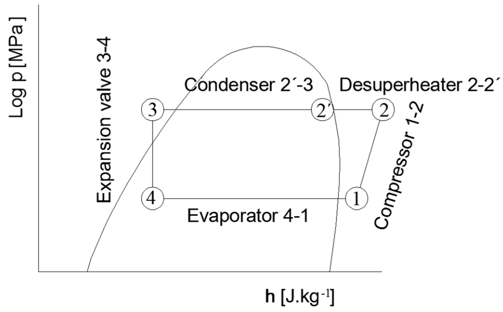

Fig. 2. Log p-h diagram illustrating the principle of an evaporative compressor cycle with a desuperheater

computer simulations have proved an effective tool for evaluating both the effectiveness of desuperheaters in increasing cooling circuit efficiency in low energy houses [9, 10] and the full-year operation of heat pumps with such desuperheaters [11].

In this study, we attempt an experimental verification of the impact of a desuperheater on the coefficient of performance of a small laboratory-based indirect cooling circuit. We believe that the results of such an experiment will provide more conclusive results than numerical simulations alone. As such, the main objectives of our research are to a) demonstrate increased efficiency in a cooling circuit fitted with a desuperheater, and b) demonstrate the use of waste heat from such a small-scale cooling unit for DHW production.

2 Methods and materials

2.1 Experimental cooling unit with desuperheater

Experimental verification was undertaken using a device comprising an insulated evaporator with a volume of ca. 0.05 m^3, a Danfoss CLX FR 8.5 hermetic compressor with a cooling power of 468 watts, an air condenser, a heat exchanger for heat recovery (desuperheater), an automatic injection valve, solenoids and a control switchboard fitted with a FLICA 110 temperature control (Fig. 3). We used R507 ecological refrigerant throughout the process and the circuit was operated at an evaporating temperature of - 10°C and a condensing temperature of 45°C. All measurements were performed at steady-state with refrigerated space loadings of Q = 70 W, Q = 100 W, Q = 120 W, Q = 140 W and Q = 190 W. Refrigerated space was a thermally insulated box fitted with an evaporator and heating cables. Loading was carried out using resistance heating cables. We tested the circuit using a Testo 556 pressure and temperature monitor (nominal temperature 22°C ± 1 digit; pressure accuracy ± 0.5% fs, range 0 to 5000 kPa). An Instalatest 61557 voltmeter (range 0 to 440 V, accuracy ± 2% fs + 2 digits) and a VA 18B ammeter (range 1 to 6 A, accuracy ± 3% fs + 8 digits) were used for power measurements. The results of the measurement were not absolute values, but had some uncertainties associated with them. Because of the accuracy of instruments used we do not expect significant uncertainty in the results. The biggest influence on the uncertainty can be expected during temperature measurement. More accurate temperature measuring instrument was not available.

We designed the test circuit such that the refrigerant could circulate through the condenser or through either a desuperheater or across the condenser and desuperheater simultaneously (see Fig. 4). For the serial connection, the refrigerant first passed through the desuperheater, where its heat was accumulated, and then flowed on into the condenser. If the water was sufficiently cool, the refrigerant condensed in the desuperheater, otherwise it went on to condense in the condenser. The desuperheater was embedded in crushed ice in a 3 dm^3 open box, the water temperature being measured with an immersion thermometer. The water box itself was insulated with 5 mm natural rubber insulation. Measurements began at the moment when all the ice was melted. The total thermal energy transferred from the desuperheater to the water box being determined according to the volume of water, water temperature, thermal capacity of water and duration of the experiment.

Fig. 3. The experimental cooling unit with attached desuperheater used in this study

During the series connection, solenoid valves A and D were opened and solenoid valves B and C closed (see Fig 4).

Throughout the experiment, temperature and pressure were measured in front of and behind each heat exchanger, while parallel electrical values were recorded at the cooling circuit. Data were collected each second. The temperature and pressure measurements were used to calculate enthalpy and mass flow for each heat exchanger using the Solkane 8 software package [12]. Solkane 8 was also used to determine superheating temperature (7°C) and sub-cooling temperature (2°C).

2.2 Calculation of energy efficiency ratio

The cooling performance of the evaporator is calculated according to the relationship [13]:

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

where Q_e [W] is the cooling performance of the evaporator, which depends on the mass flow of refrigerant $\cdot m$ [$kg.s^{-1}$] and the enthalpy difference between h_1 and h_4 [$J.kg^{-1}$] (see Figs. 1 and 2, junction points 1 and 4).

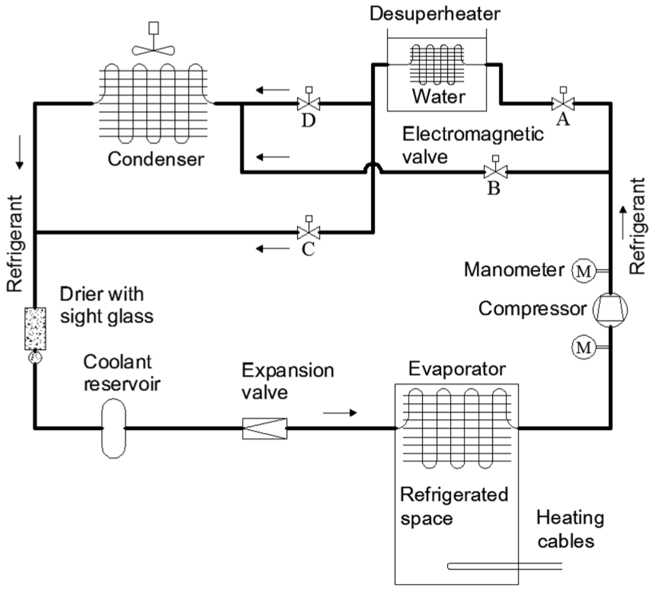

Fig. 4. Schematic test circuit diagram of the experimental cooling unit with desuperheater used in this study

Heating performance of the condenser is calculated in a similar manner using the equation:

$$Q_c = \cdot m.\,(h'_2 - h_3)\,, \tag{2}$$

with heating performance depending on the mass flow of refrigerant $\cdot m$ [$kg.s^{-1}$] and the enthalpy difference between $h_{2'}$ a h_3 [$J.kg^{-1}$] (see Figs. 1 and 2, junction points 2' and 3).

When comparing the energy performance of an indirect cycle, we use the coefficient of performance for cooling (COP_c), defined as:

$$COP\_c = \frac{Q_e}{Q_c - Q_e}. \tag{3}$$

In the same way, the coefficient of performance for heating (COP_h), can be defined as follows:

$$COP\_h = \frac{Q_c}{Q_c - Q_e}. \tag{4}$$

By definition, however, both the COP_c and COP_h are theoretical calculations that include waste heat at a higher level than actually occurs in the cycle. In order to determine actual (hereinafter real) COP_c and COP_h, it is necessary to include values for compressor and drive efficiency and account for electrical input from other components such as the control unit, fans, etc. To account for these discrepancies, total efficiency of cooling circle can be redefined as maximum proportional energy contribution (COP_tot), which is defined as follows:

$$COP\_tot = COP\_c + COP\_h = \\ = \frac{(h_1 - h_4) + \left(h'_2 - h_3\right)}{\left(h'_2 - h_3\right) - (h_1 - h_4)}. \tag{5}$$

Where h_1 through h_4 represent enthalpy of the refrigerant from the log p-h diagram (see Fig. 2).

In practical applications, Q_c is rarely used during operation of a standard cooling system as the heat from condenser Q_c is usually released into the air. When a desuperheater is connected, however, the proportional energy contribution of the cooling cycle is redefined as η [-]:

$$\eta = \frac{Q_e + Q_d}{P}, \quad (6)$$

where Q_d [W] represents the heat flux from the desuperheater and P [W] is the total electrical (real) input to the cooling device. Q_d is calculated from the equation

$$Q_d = \dot{m}.(h'_2 - h_2). \quad (7)$$

Using only Q_e (i.e. proportional energy contribution without the desuperheater), we obtain the formula for real proportional energy contribution from the cooling cycle (η_e):

$$\eta_e = \frac{\dot{Q}_e}{P}. \quad (8)$$

3 Results and Discussion

This experiment was carried out on a laboratory-scale cooling unit (Fig. 3) under conditions represented in Figure 4. As we used a serial connection, solenoid valves B and C were closed and valves A and D open. Under this set-up, the desuperheater transfers heat to a separate holding-tank where it is used to heat water. As the heat is removed, the refrigerant vapour cools until no further heat is transferred to the tank, whereupon the refrigerant flows into a condenser. This change is not manifested in an increase in energy as the circuit enters into an "only condenser" mode without any additional regulatory element. This dependency is expressed for a range of refrigerated space loadings (70 W, 100 W, 120 W, 140 W, 190 W) in Figs. 5 – 9. When starting the circuit, the default state of the diagrams is at top left. In all cases, as operation proceeds, there is a gradual reduction in COP_c over time. (Note that, were the circuit to be operated under parallel flow conditions (A to D + B), COP_c would be further reduced as increased traffic control would be required, while inclusion of the other electrical elements would further reduce reliability of the circuit.)

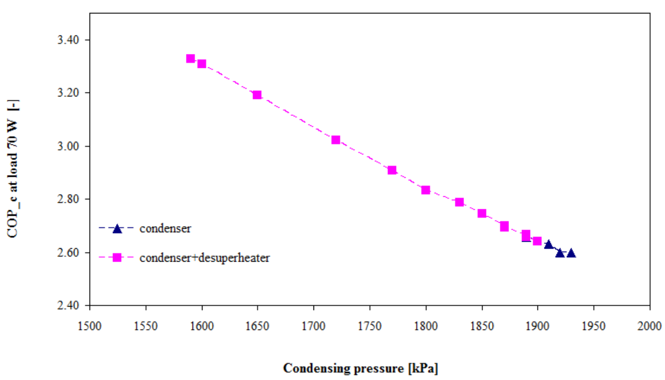

Fig. 5. Relationship between energy efficiency ratio (COP_c) and condensing pressure (kPa) for a serially connected condenser and desuperheater circuit with a refrigerated space loading of 70 watts

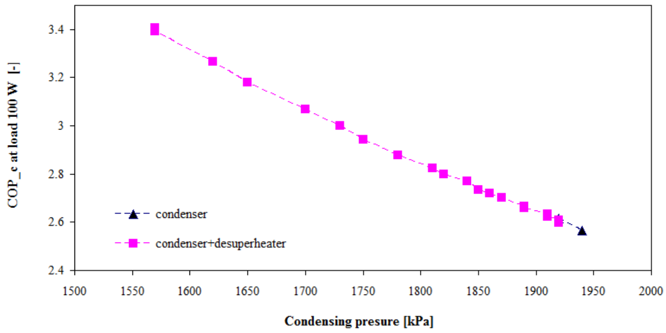

Fig. 6. Relationship between energy efficiency ratio (COP_c) and condensing pressure (kPa) for a serially connected condenser and desuperheater circuit with a refrigerated space loading of 100 watts

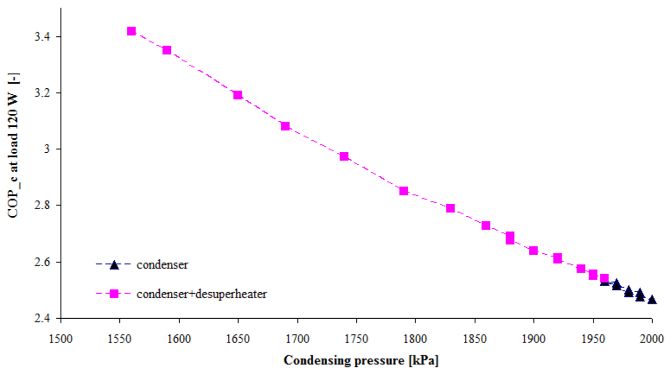

Fig. 7. Relationship between energy efficiency ratio (COP_c) and condensing pressure (kPa) for a serially connected condenser and desuperheater circuit with a refrigerated space loading of 120 watts

Evaporator pressure remained constant at 420 kPa throughout the experiment (range 70 to 190 watts) as pressure was controlled via an automatic expansion valve with adjustable evaporation pressure.

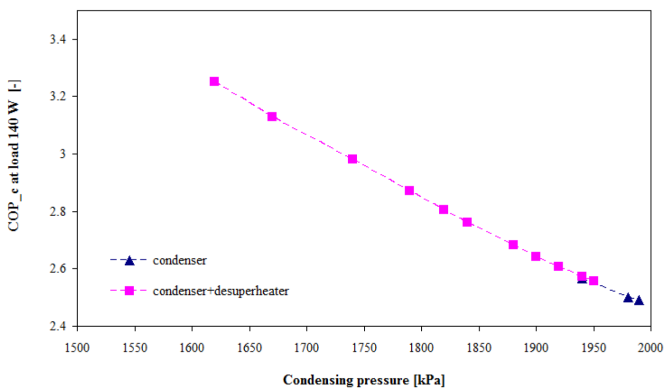

Fig. 8. Relationship between energy efficiency ratio (COP_c) and condensing pressure (kPa) for a serially connected condenser and desuperheater circuit with a refrigerated space loading of 140 watts

The relationship between water temperature and COP_c showed a relatively high degree of variation due to mechanical losses and irregular running of the test circuit (Fig. 10). In general, however, as thermal load increased so electricity consumption also increased. In other words, when levels of available cold water are high then COP_c remains high. It follows,

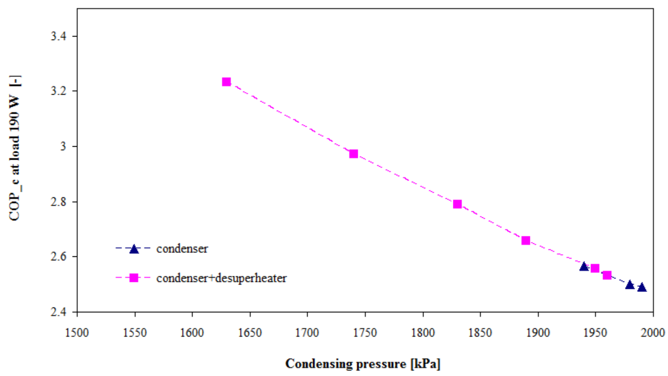

Fig. 9. Relationship between energy efficiency ratio (COP_c) and condensing pressure (kPa) for a serially connected condenser and desuperheater circuit with a refrigerated space loading of 190 watts

therefore, that 1) if waste heat is not removed via the desuperheater while increasing refrigerated space loading, both condenser temperature and electricity consumption increases, and that 2) higher COP_c values can be achieved at lower water temperatures when using the desuperheater. This is also reflected by COP_tot (Fig. 11), which also shows highest values at lowest water temperatures. Both COP_c and COP_tot values show a similar trend, differing only in the higher values for COP_tot. Note, however, that the calculations for both COP_c and COP_tot rely on theoretical compressor power input only.

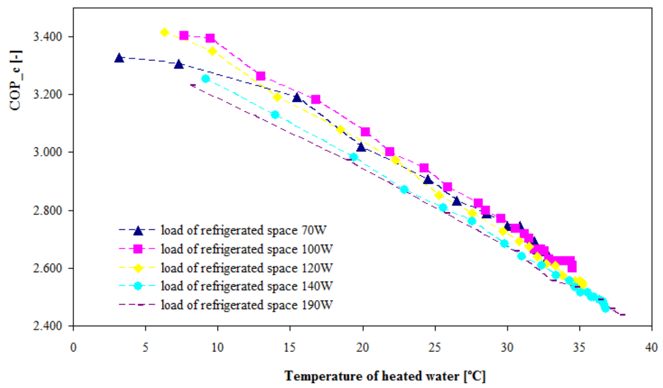

Fig. 10. Relationship between energy efficiency ratio (COP_c) and water temperature (°C) for the serially connected condenser and desuperheater circuit used in this study

Compared to COP_c and COP_tot, values for η and η_e (Figs. 12 and 13) are relatively low due to the inclusion of the actual (real) power input from the compressor and other electrical cycle components, such as solenoid valves, controls, fans, etc. Overall, the real efficiency (η_e) of the cooling circuit was almost half that of the theoretical efficiency (COP_c). (Note that, total power input to the test circuit was relatively high due to the low cooling output and high number of regulatory elements involved.)

A comparison of the values for η (with desuperheater; Fig. 12) and η_e (without desuperheater; Fig. 13) indicate that inclusion of a desuperheater increases overall circuit efficiency. Not only does the desuperheater improve cooling circuit efficiency, it also

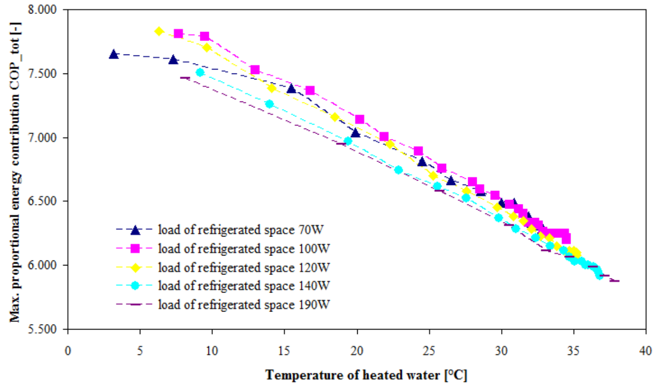

Fig. 11. Relationship between maximum proportional energy contribution (COP_tot) and water temperature (°C) for the serially connected condenser and desuperheater circuit used in this study

provides excess heat for preheating domestic hot water. This is further backed up by figures for total electricity consumption (kW.h.day^{-1}) at different refrigerated space loadings over 24 hours for the test unit with and without the desuperheater connected (Table 1). In general, electricity consumption was reduced most at lowest (70 W) and highest (190 W) refrigerator loadings.

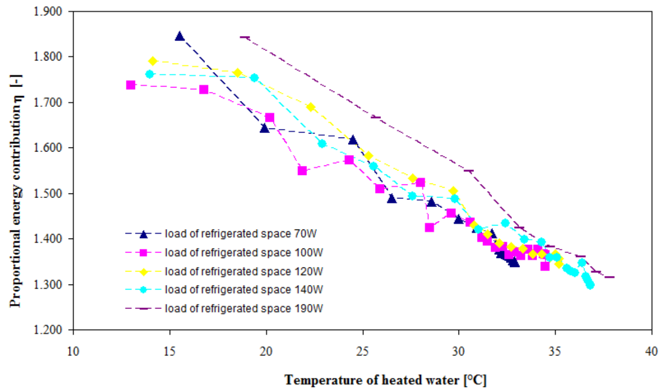

Fig. 12. Relationship between proportional energy contribution (η) and water temperature (°C) for the serially connected condenser and desuperheater circuit used in this study

4 Conclusion

Our results indicate a clear improvement in electricity consumption when operating the experimental cooling circuit with a desuperheater and condenser serially connected, with total electricity consumption reduced by between 10 and 34% depending on cooling performance and pre-heated water temperature. In general, cooling circuit efficiency decreased as the temperature of the water leaving the desuperheater increased (see Fig. 12). In theory, maximum efficiency is achieved at the lowest temperatures. This is unrealistic for practical DHW applications; however, hence the most efficient option is to maintain the desuperheater temperature at a few degrees above ambient air temperature and to then reheat the water to the desired temperature in a secondary tank. Note that final costs should be balanced against the secondary costs of reheating the water to the required

Tab. 1. Comparison of total electricity consumption (kW.h.day-1) at different refrigerated space loadings (W) over 24 hours using a) the condenser only, and b) serial connection of the condenser and desuperheater

	Condenser only	Serial 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	5.703	6.8
100	8.269	5.965	13
120	8.892	8.013	13,3
140	11.647	8.671	13.5
190	15.757	13.198	13.8

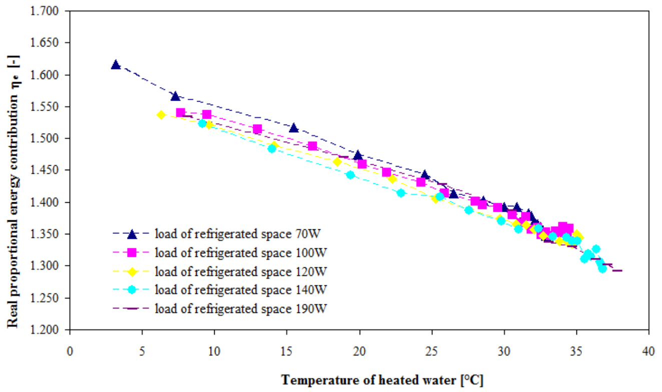

Fig. 13. Relationship between real proportional energy contribution (η_e) and water temperature (°C) for the cooling circuit used in this study without the desuperheater unit

temperature from a secondary heat source.

Savings from heat recovery were considerable and came from a number of sources, including savings in heat transmitted for use in preheating water and in total electricity consumption due to an increase in cooling efficiency. Secondary savings were also obtained through reductions in condensing pressure and operation time, which subsequently reduced overall wear and tear of the cooling device and increased operating lifetime.

Acknowledgement

This paper has been worked out under the project No. LO1408 "AdMaS UP – Advanced Materials, Structures and Technologies," supported by Ministry of Education, youth and Sports under the "national Sustainability Programme I". We would like to thank Dr. Kevin Roche for his help with English language and for valuable comments on an earlier version of the manuscript.

References

1 **Szabó L**, *Effect of Architectural Glazing Parameters, Shading, Thermal Mass and Night Ventilation on Public Building Energy Consumption under Hungarian Climate*, Periodica Polytechnica Civil Engineering, **59**(2), (2015), 209–223, DOI 10.3311/PPci.7091.

2 **Fernández-Seara J, Pereiro A, Bastos S, Dopazo J A**, *Experimental evaluation of a geothermal heat pump for space heating and domestic hot water simultaneous production*, Renewable Energy, **48**, (2012), 482–488, DOI 10.1016/j.renene.2012.05.019.

3 **Biaou A L, Bernier M A**, *Achieving total domestic hot water production with renewable energy*, Building and Environment, **43**(4), (2008), 651–660, DOI 10.1016/j.buildenv.2006.06.032.

4 **Tan K, Deng S**, *A simulation study on a water chiller complete with a desuperheater and a reversibly used water cooling tower (RUWCT) for service hot water generation*, Building and Environment, **37**(7), (2002), 741–751, DOI 10.1016/S0360-1323(01)00069-5.

5 **Tan K, Deng S**, *A method for evaluating the heat and mass transfer characteristics in a reversibly used water cooling tower (RUWCT) for heat recovery*, International Journal of Refrigeration, **25**(5), (2002), 552–561, DOI 10.1016/S0140-7007(01)00044-5.

6 **Chow T T, Bai Y, Fong K F, Lin Z**, *Analysis of a solar assisted heat pump system for indoor swimming pool water and space heating*, Applied Energy, **100**, (2012), 309–317, DOI 10.1016/j.apenergy.2012.05.058.

7 **Kuang Y H, Wang R Z**, *Performance of a multi-functional direct-expansion solar assisted heat pump system*, Solar Energy, **80**(7), (2006), 795–803, DOI 10.1016/j.solener.2005.06.003.

8 **Cui P, Yang H, Spitler J D, Fang Z**, *Simulation of hybrid ground-coupled heat pump with domestic hot water heating systems using HVACSIM+*, Energy and Buildings, **40**(9), (2008), 1731–1736, DOI 10.1016/j.enbuild.2008.03.001.

9 **Blanco D L, Nagano K, Morimoto M**, *Steady state vapor compression refrigeration cycle simulation for a monovalent inverter-driven water-to-water heat pump with a desuperheater for low energy houses*, International Journal of Refrigeration, **35**(7), (2012), 1833–1847, DOI 10.1016/j.ijrefrig.2012.07.005.

10 **Blanco D L, Nagano K, Morimoto M**, *Experimental study on a monovalent inverter-driven water-to-water heat pump with a desuperheater for low energy houses*, Applied Thermal Engineering, **50**(1), (2013), 826–836, DOI 10.1016/j.applthermaleng.2012.07.008.

11 **Blanco DL, Nagano K, Morimoto M**, *Impact of control schemes of a monovalent inverter-driven water-to-water heat pump with a desuperheater in continental and subtropical climates through simulation*, Applied Energy, **109**, (2013), 374–386, DOI 10.1016/j.apenergy.2012.12.047.

12 *Solkane 8 software:*, `http://www.solvaychemicals.com/EN/products/Fluor/Software.aspx`.

13 **Madhawa Hettiarachchi H D, Golubovic M, Worek W M, Ikegami Y**, *Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources*, Energy, **32**(9), (2007), 1698–1706, DOI 10.1016/j.energy.2007.01.005.