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Energetska učinkovitost daljinskega hlajenja za klimatizacijo prostorov

The Energy Efficiency of District Cooling for Space Conditioning

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Oskrba uporabnikov z grelno in hladilno energijo iz daljinskih energetskih sistemov bistveno prispeva k smotrni porabi energije in varovanju okolja. V preteklih nekaj letih se je uporaba daljinskega hlajenja v nekaterih državah pomembno zvečala.

Uporaba absorpcijskih hladilnikov za daljinsko hlajenje se v zadnjem desetletju prav tako povečuje. Te hladilne naprave potrebujejo vir toplote za svoje delovanje. To je lahko plin, kurilno olje, para ali vroča voda. V članku so podani rezultati raziskave vplivnih parametrov na specifične izgube toplote v vročevodnem omrežju in celotni učinek daljinskega hladilnega sistema.

(Ključne besede: hlajenje daljinsko, naprave hladilne, učinkovitost energijska, izgube toplotne)

Supplying customers with heating and cooling energy from district energy systems contributes to the rational use of energy and to environmental protection. In the past few years, the use of district cooling has significantly increased in some countries.

In the last decade, the use of absorption chillers for district cooling has increased. These chillers need a heat source for their operation. It can be gas, fuel oil, steam or hot water. This paper presents the results of research on the parameters which influence the specific heat losses in a district heating network and the overall efficiency of the system.

(Keywords: district cooling, absorption chillers, energy efficiency, heat losses)

0 UVOD

Dvig ravni delovnih in bivalnih pogojev ljudi je nujno povezan s hlajenjem v okviru klimatizacije. V te namene se uporablja različna naključno izbrana oprema različnih proizvajalcev brez ustreznega zagotavljanja učinkovitosti ter tehnične in okoljne neoporečnosti. Posledica tega je povečana poraba elektrike kot najbolj kvalitetne energije.

Rešitev tovrstnih problemov se ponuja z daljinskimi hladilnimi sistemi. Rezultati številnih študij v svetu kažejo, da imajo v primerjavi z lokalnim hlajenjem z uporabo električne energije daljinski hladilni sistem številne prednosti.

Daljinski hladilni sistemi so dokazano okolju bolj prijazni kot posamezne manjše hladilne enote. Z njimi zmanjšujemo oddajo škodljivih snovi, z uporabo sorpcijske tehnike hlajenja pa lahko povsem izločimo ozonu škodljiva hladiva. Kadar so hladilne naprave gnane s toploto iz kogeneracije, neposredno zmanjšu-

0 INTRODUCTION

An increase in the quality of working and living conditions is inevitably connected with cooling as part of air-conditioning systems. Various types of equipment produced by different manufacturers are used for this purpose, they are selected at random and do not provide any assurance as to efficiency and compliance with technical and environmental standards. This has resulted in an increase in the consumption of electrical energy: the energy of the highest quality.

A solution tor such problems is offered by district cooling systems. The results of numerous studies in the world have shown that in comparison with local cooling using electrical energy, district cooling systems have numerous advantages.

District cooling systems have been proven to be more environmentally friendly than individual smaller cooling units. They reduce the emissions of hazardous substances and, with the use of a sorption cooling technique, ozone-unfriendly refrigerants can be eliminated jemo toplotno obremenitev okolja, z uporabo plina za njihov pogon pa odpadejo vmesne pretvorbe energije in dodatne izgube [1].

Odločitev za uporabo absorpcijskih ali kompresorskih hladilnih naprav je odvisna predvsem od investicijskih in obratovalnih stroškov. Investicijski stroški so nekoliko večji za absorpcijske hladilne naprave in so odvisni od tipa hladilnika ter od vrste toplotnega vira. Eden od odločilnih kriterijev izbire vrste hladilnika je lahko tudi ekološka primernost. Absorpcijske hladilne naprave delujejo skoraj neslišno. Uporabljajo tudi hladiva, kot npr. amoniak, litijev bromid in vodo (NH_3 – H_2O, LiBr – H_2O), ki imajo vpliv na nastanek tople grede (GWP) in vpliv na tanjšanjeozonske plasti (ODP) enak nič. Če upoštevamo porabo primarne energije (določeno z ekvivalentom električne energije, ki je potrebna za pogon kompresorskih hladilnih naprav), imajo nekatere absorpcijske hladilne naprave manjšo porabo, kakor prikazuje sl. 1.

Z vročo vodo in s paro gnani absorpcijski hladilniki lahko uporabljajo toploto odvzeto iz kogeneracijskega sistema. Zaradi odvzema toplote iz parne turbine v kogeneracijskem sistemu se zmanjša pridobljena električna energija.

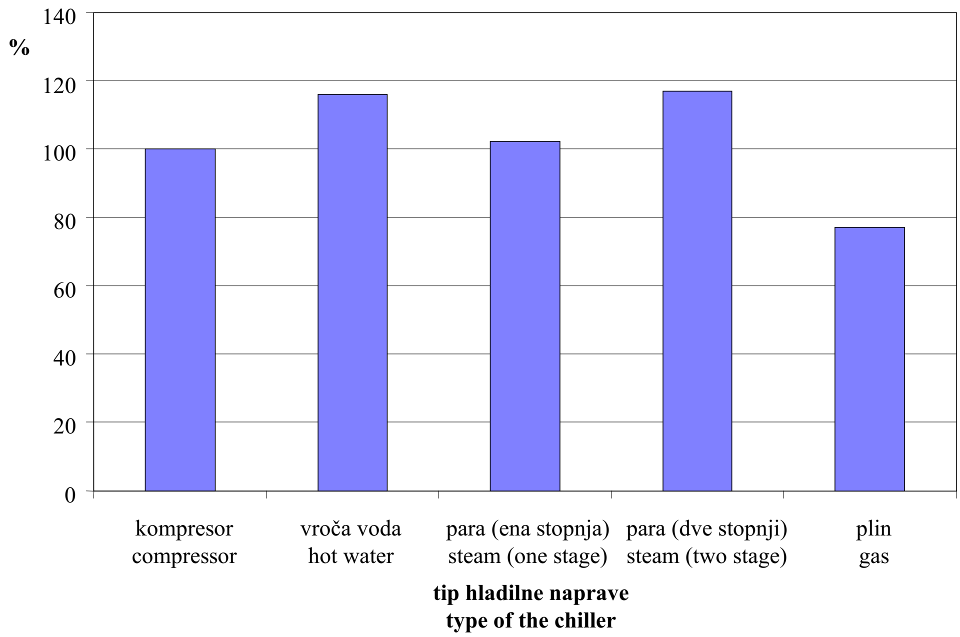
V primeru plinsko gnanih absorpcijskih hladilnih naprav je upoštevana učinkovitost plinsko gnanih turbin, ki je potrebna za določitev ustrezne električne moči. Če primerjavo različne vrste hladilnih naprav, vidimo, da predstavljajo z vročo vodo in s paro gnani dvostopenjski absorpcijski hladilniki najmanjšo porabo ekvivalenta električne energije na enoto hladu, kar je lahko tudi eden izmed načinov zmanjšanja emisij CO_2.

completely. When cooling devices are driven by heat from cogeneration, the thermal burden on the environment is reduced directly, while using gas to drive them means the intermediary stages of energy conversion and additional energy losses are avoided as well [1].

The decision, whether to use absorption chillers or compressor chillers basically depends on the investment and operational costs. The investment costs for absorption chillers can be a little higher, depending on the type of the absorption chiller and the heat source in use. One of the criteria for the decision could be also the ecological aspect. Absorption chillers are almost noiseless during operation. They also use the refrigerants, such as amonia (NH_3 - H_2O) and water (LiBr - H_2O), which have a global warming potential (GWP) and ozone depleting potential (ODP) equal to zero. When the primary energy consumption is considered (defined by the equivalent electrical power which is needed for driving the compressor chillers, and which could be produced by the heat source for absorption chillers), some of the absorption chillers have a reduced consumption as shown in Figure 1.

Hot-water and steam-driven absorption chillers use heat extracted from a cogeneration plant. Because of the heat extracted from a steam turbine in a cogeneration plant, less electrical power will be produced.

In the case of a gas-driven absorption chiller, the efficiency of a gas-driven turbine is considered necessary to determine the equivalent electric power. Comparing different types of chillers, hot-water and two-stage steam-absorption chillers present the lowest equivalent electric power per unit of cold pro-



Sl. 1. *Delna hladilna obremenitev hladilnika na enoto ekvivalenta električne moči [2]*
Fig.1. *Cooling capacity share per unit of equivalent electrical power [2]*

Plinsko gnane absorpcijske hladilne naprave predstavljajo največjo porabo ekvivalenta električne energije na enoto hladu. V primerjavi z drugimi hladilnimi napravami so tudi investicijski stroški največji. Če upoštevamo, da lahko plinsko gnana absorpcijska hladilna naprava nadomesti tudi vročevodni kotel v nekem objektu, je njihova uporaba upravičena.

1 SPECIFIČNE TOPLOTNE IZGUBE

Najboljša izvedba sistemov daljinskega hlajenja je v kombinaciji z absorpcijskimi hladilniki, povezanimi v sistem daljinskega ogrevanja. Ti sistemi morajo delovati tudi v poletnem obdobju zaradi zagotovitve toplote, potrebne za ogrevanje tople sanitarne vode. To pa predstavlja razmeroma velike relativne izgube glede na količino dobavljene toplote.

Z vročo vodo gnani absorpcijski hladilniki potrebujejo za svoje normalno delovanje višje temperature, kot so običajno pri obratovanju sistema daljinskega ogrevanja v poletnem obdobju. S povišanjem temperature dovoda in povratka vroče vode se povečujejo toplotne izgube omrežja, s tem pa tudi specifične toplotne izgube ($kW_{izgube}/MW_{dobava\ toplote}$). S povečanjem odjema za potrebe hlajenja se lahko specifične toplotne izgube zmanjšajo (sl. 2).

Temperaturna razlika med dovodom in povratkom vroče vode v omrežju daljinskega ogrevanja nima vpliva samo na toplotne izgube, ampak tudi na porabo električne energije, ki je potrebna za pogon obtočnih črpalk.

Za dosego večje učinkovitosti z vročo vodo gnanih absorpcijskegih hladilnikov mora biti temperaturna razlika med dovodom in povratkom čim manjša. Povečanje temperature dovoda vroče vode

duced. This could also be a way of introducing state support in a sense of reduced CO_2 emissions.

Gas absorption chillers have the biggest equivalent electrical power consumption. Their investment costs are also higher when compared to the other chillers. As they can also replace the boiler for heat production, there is no doubt about their advantages over compressor chillers.

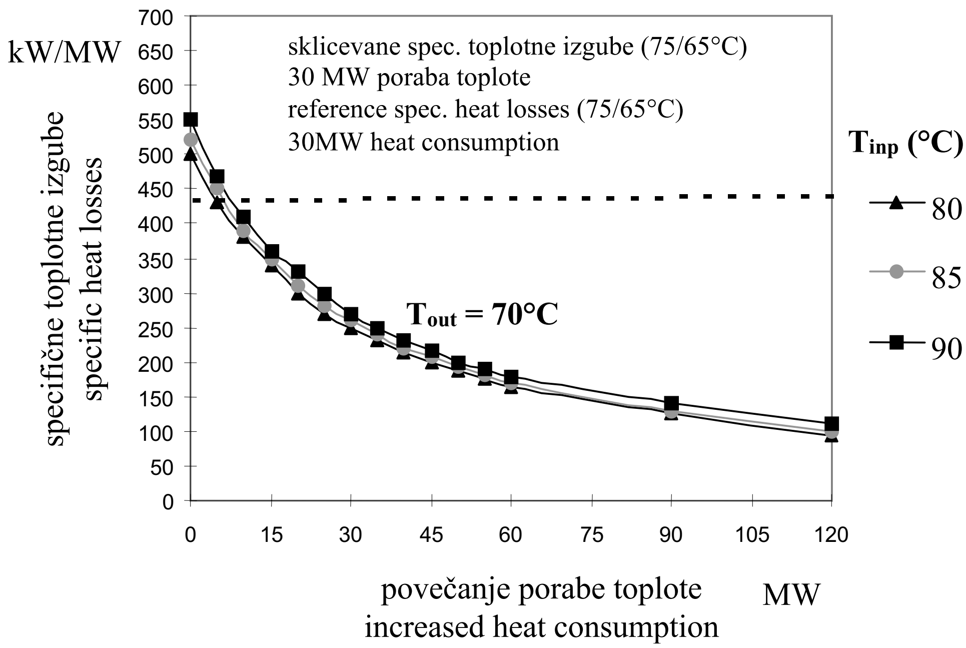
1 SPECIFIC HEAT LOSSES

District cooling systems with sorption chillers are the best when dsigned in combination with district heating systems, the majority of which also have to operate in the summer in order to ensure the supply of sanitary water. But this means a large relative loss with regard to the amount of supplied heat.

Absorption chillers, driven with hot water, need heat with higher temperatures for their normal operation as the district heating network. By increasing the supply and return temperatures of hot water, the heat losses of the district heating network are higher and so also are the specific heat losses ($kW_{losses}/MW_{heat\ supply}$). But with increasing heat consumption, the specific heat losses decrease (Fig. 2).

The supply- and return-temperature difference for a district heating network does not have an influence only on heat losses, but also on the consumption of electrical energy needed to drive network pumps.

To achieve high chiller efficiencies, the supply and return hot-water temperature difference should be low. Increased hot-water supply tempera-



Sl. 2. *Specifične toplotne izgube vročevodnega omrežja[3]*
Fig. 2. *Specific heat losses of a district heating network [3]*

in zmanjšanje temperaturne razlike pa poveča toplotne izgube v omrežju daljinskega ogrevanja.

2 UČINKOVITOST ABSORPCIJSKE HLADILNE NAPRAVE

Analiza posameznih učinkovitosti je temeljila na obratovalnih parametrih vročevodnega absorpcijskega hladilnika Carrier (16 JB 032 /036) z enojnim efektom in delovno snovjo Li-Br. Parametri obratovanja so bili:

a) temperatura hlajene vode (6/12°C)
b) temperatura hladilne vode (27/32°C)

Rezultati kažejo, da se hladilno število hladilnika povečuje z višanjem temperature dovoda vroče vode in z manjšanjem temperaturne razlike med dovodom in povratkom. Iz slike 3 je razvidno, da je razlika med največjo in najmanjšo vrednostjo hladilnega števila samo okrog 5%.

Temperatura dovedene vroče vode je omejena z najnižjo temperaturo. Pri nižji temperaturi dovoda (< 85 °C), je učinkovitost absorpcijskih hladilnikov zelo majhna in so zato specifični investicijski stroški previsoki. Pri teh pogojih se pojavijo tudi problemi v samem delovanju absorpcijskega hladilnika.

Bistvo naše analize je bila določitev temperaturnega območja obratovanja omrežja daljinskega ogrevanja, v katerem dosežemo ustrezno učinkovitost tako absorpcijskega hladilnika kot tudi celotnega omrežja daljinskega ogrevanja.

tures and a small temperature difference, however, increase the heat losses of a district heating network.

2 ABSORPTION-CHILLER EFFICIENCY

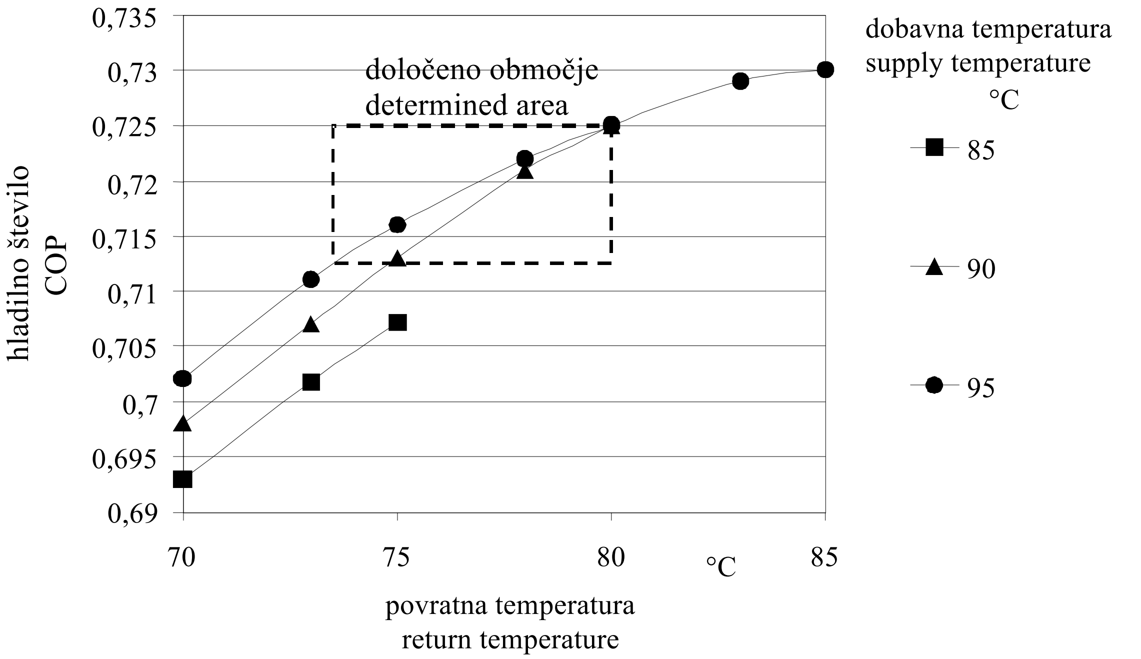
An analysis of individual efficiencies using the data from a commercially available Carrier's single-effect Li-Br absorption chiller, which is arranged for use with hot water (16 JB 032 / 036) was made. We chose further parameters:

a) chilled water temperatures (6/12°C)
b) cooling water temperatures (27/32°C)

The COP (coefficient of preformance) increases by increasing the hot-water supply temperatures and by decreasing the differences between the hot-water supply and return temperatures. Referring to Fig. 3, the difference between the highest and the lowest COP is only about 5%.

The hot-water supply temperatures were limited by the lowest temperature. At lower supply temperatures (<85°C), the efficiencies of absorption chillers are very low and the specific investment costs are too high. Besides this, the operational problems at lower hot-water supply temperatures occur.

The return hot-water temperatures were also limited by the determined temperature range. The purpose of our analysis was to determine the temperature range of a district heating network operation, at which the corresponding efficiency of both an absorption chiller and the district heating network could be achieved.



Sl. 3. *Hladilno število absorpcijskega hladilnika v odvisnosti od temperatur dovoda in povratka vroče vode [4]*
Fig. 3. *COP of the absorption chiller depending on different hot-water supply and return temperatures [4]*

3 UČINKOVITOST OMREŽJA DALJINSKEGA OGREVANJA

Izkoristek vročevodnega sistema smo definirali kot razmerje med odjemnim toplotnim tokom na strani odjemalca, ter celotnim transportiranim toplotnim tokom in električno močjo črpalk (za transport vroče vode). Toplotni ekvivalent električne moči smo definirali kot trikratno vrednost električne moči.

$$\eta = \frac{\dot{Q}_{absorpcija}}{\dot{Q}_{absorpcija} + \dot{Q}_{izgub} + 3 \cdot P_{električna}} \tag{1}$$

$\dot{Q}_{absorpcija}$ - toplotni tok, doveden v absorpcijski hladilnik
$\dot{Q}_{izgub}$ - izgube toplotnega toka pri transportu skozi vročevod
$P_{električna}$ - električna moč črpalk za transport vroče vode

Izkoristek vročevodnega sistema smo opazovali pri različnih izgubah toplotnega toka ter različnih toplotnih močeh na strani odjemalca. Slika 4 prikazuje izkoristek vročevodnega sistema pri izgubah toplotnega toka 0,04 MW/K in odjemni toplotni moči 30 MW. Temperatura okolice je bila izbrana kot povpreček srednje dnevne temperature za Ljubljano v mesecih junij, julij, avgust in znaša 18,8°C.
Izgube v MW/K predstavljajo v enačbi :

$$\dot{Q}_{izgub} = k \cdot A \cdot \Delta T \tag{2}$$

3 DISTRICT-HEATING-NETWORK EFFICIENCY

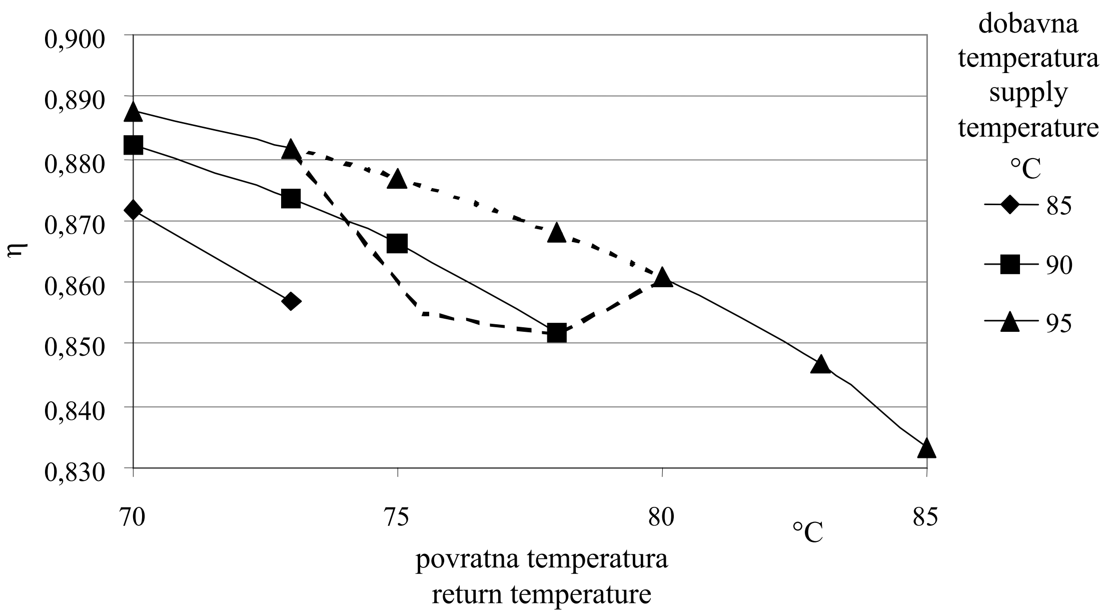
We determined the overall district-heating-network efficiency as the ratio of consumed heat, and the heat transported through the network, added to the electrical power of the network pumps (used to transport the hot water). The heat equivalent of the electrical power was defined by the three times increased value of the electrical power.

$$\eta = \frac{\dot{Q}_{absorption}}{\dot{Q}_{absorption} + \dot{Q}_{losses} + 3 \cdot P_{electric}} \tag{1}$$

$\dot{Q}_{absorption}$ - heat flow, supplied to the absorption chiller
Q_{losses} - heat flow losses due to hot-water transport through district heating pipes
$P_{electric}$ - electric power for the pumps, which are used for transporting the hot water through the district heating network

The efficiencies of a district heating system at different heat losses and for different heat consumptions of the customers were observed. Figure 4 shows the efficiency of the district heating system at heat flow losses of 0,04 MW/K and at 30 MW of heat consumption. An ambient temperature of 18,8°C was defined as an average of the medium daily temperatures in Ljubljana in June, July and August.
In the equation:

$$\dot{Q}_{losses} = k \cdot A \cdot \Delta T \tag{2}$$



Sl. 4. *Učinkovitost omrežja daljinskega ogrevanja v odvisnosti od različnih temperatur dovoda in povratka vroče vode pri toplotnih izgubah 0,04 MW/K in odjemu 30 MW [5]*
Fig. 4. *The efficiency of the district heating system depending on different hot-water supply and return temperatures at heat flow losses of 0.04 MW/K and the 30 MW of heat consumption [5]*

člen $k{\cdot}A$. Temperaturna razlika predstavlja razliko med temperaturo vroče vode v vročevodu in temperaturo okolice.

Ker izkoristek vročevodnega sistema z naraščanjem temperature povratka vroče vode pada (slika 4), je skoraj nemogoče določiti točko optimalnega obratovanja, saj so v interesu odjemalca vroče vode čim nižji investicijski ter obratovalni stroški absorpcijskega hladilnika, interes distributerja vroče vode pa čim nižji obratovalni stroški vročevodnega sistema.

Pri visokih temperaturah povratka vroče vode se investicijski stroški absorpcijskega hladilnika znižajo, vendar prične v tem območju izkoristek vročevodnega sistema naglo padati, kot je to prikazano na sliki 4.

Iz slike 4 je razvidno, da dosegamo najboljše izkoristke vročevodnega sistema ob čim višjih temperaturah dovoda vroče vode in čim večjih temperaturnih razlikah med temperaturama dovoda in povratka vroče vode (pri določeni temperaturi povratka). Velike temperaturne razlike omogočajo manjše pretoke vroče vode, to pa zmanjša električno moč črpalk.

Na sliki 4 je črtkano označeno področje, v katerem naj bi vročevodni sistem obratoval.

Krivulje, ki predstavljajo temperature dovoda vroče vode, se pri večjih temperaturnih razlikah približujejo neki skupni vrednosti. Iz tega lahko sklepamo, da je izbrano področje ustrezno, saj je padec izkoristka med temperaturama povratka 73 do 80°C veliko manjši v primerjavi z desno stranjo diagrama. Če povečujemo toplotno moč na strani odjemalca, se tudi izkoristek vročevodnega sistema povečuje, tendenca in razvrstitev krivulj pa ostajata zelo podobna.

Iz primerjave dveh režimov obratovanja pri enakem odjemu (30MW) in različnih izgubah (0,04 MW/K in 0,12 MW/K), dobimo razlike v hladilnih številih le okrog 3%, razlike v hladilnih močeh pa tudi največ 3%. Ta padec hladilne moči ter hladilnega števila bi lahko korigirali, če bi npr. povišali temperaturo hlajene vode absorpcijskega hladilnika s sistema 6/12°C na sistem 7/13°C.

4 SKLEPI

Sistemi daljinskega hlajenja omogočajo možnost sistematične in nadzorovane uvedbe hlajenja. Omenjena možnost je izražena predvsem na področjih, na katerih že obstajajo ti sistemi daljinskega ogrevanja, ki omogočajo povezavo daljinskega hlajenja z lokalnim generiranjem hladu s pomočjo absorpcijskih hladilnikov, ki so gnani z vročo vodo iz vročevodnega omrežja.

Če se količina toplote iz sistema daljinskega

the factor $k{\cdot}A$ represents determined values in MW/K. The temperature difference (ΔT) represents the difference between the temperature of the hot water in the pipe and of the ambient temperature.

By increasing the hot-water return temperature, the efficiency of the district heating network decreases (Fig.4), as a result, it is almost impossible to determine the optimum temperatures for the operation of a district heating network. The customer demands the lowest investment and operating costs for the absorption chiller, and the hot-water distributor demands the lowest operating costs for the district heating network.

At very high hot-water return temperatures the specific investment costs of an absorption chiller are lower, but the efficiency of the district heating network is rapidly decreasing (Fig. 4).

At the highest hot-water supply temperatures and at the highest temperature differences between the hot-water supply and return temperatures (at the determined return temperature), the highest efficiency of the district heating system can be achieved. Higher temperature differences enable smaller hot-water mass flow through the district heating network and therefore reduced electrical power consumption for the network pumps.

In Figure 4 the temperature range in which the district heating system should operate is marked (dashed line).

At higher hot-water temperature differences, the curves in Figure 4 approach a determined value. The decrease in the efficiency is much lower at hot-water return temperatures between 73 and 80°C when compared to the right side of the chart. Therefore, we can make a conclusion, that the selected temperature range is suitable. By increasing the heat consumption, the efficiency of the district heating system is increasing and the trend and arrangement of the curves remain very similar.

A comparison of the operation of two district heating sytems at the same consumption (30 MW) but with different heat losses (0,04 MW/k and 0,12 MW/K), shows a decrease in the COP and cooling capacities of the absorption chiller by approximately 3%. The drop in the cooling capacity can be compensated for by increasing (for instance) the chilled-water temperature from 6/12°C to 7/13°C.

4 CONCLUSIONS

District cooling systems offer the possibility of a systematic and controlled introduction of cooling. This is particularly true for areas in which district heating systems already exist and can be used to generate cooling with refrigerators driven by heat from the hot-water supply system.

If the amount of heat supplied by a district heating system for sanitary water preparation in the summer was increased to drive cooling devices with ogrevanja, ki je v poletnem obdobju potrebna za pripravo tople sanitarne vode, poveča zaradi pogona absorpcijskih hladilnikov, bi se relativne izgube toplote znatno zmanjšale, prav tako pa tudi poraba elektrike za potrebe hlajenja.

Rezultati analize učinkovitosti absorpcijskega hladilnika prikazujejo, da lahko dosežejo ti hladilniki največjo učinkovitost pri čim višjih temperaturah dovoda vroče vode in čim manjših temperaturnih razlikah med temperaturama dovoda in povratka. Učinkovitost sistema daljinskega ogrevanja s povečanjem odjema vroče vode ter zmanjšuje z višanjem temperatur dovoda in povratka. Primeren odgovor o optimalnih temperaturah obratovanja absorpcijskega hladilnika dobimo z upoštevanjem investicije in obratovalnih stroškov celotnega sistema daljinskega hlajenja.

absorption chillers, the relative heat loss would be reduced considerably and the consumption of electricity for cooling would be reduced.

The results of the presented efficiency of an absorption chiller depending on different hot-water supply and return temperature show that at the highest hot-water supply temperatures and temperature differences, the best efficiencies for the absorption chiller can be achieved. On the other hand, with higher hot-water supply and return temperatures, the efficiency of the district heating and also district cooling system decreases.

The answer to the question of the optimum temperature for the absorption chiller supplying heat can be achieved by taking into account the investment and operating costs of the complete district cooling system.

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