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Vpliv sreženja uparjalnika na rabo energije za hlajenje

The Effects of Evaporator Frosting on the Energy Consumption for Refrigeration

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Raba energije za hlajenje se je predvsem v zadnjih nekaj letih močno zvečala. To narekuje, da tudi na področju hlajenja skrbimo za učinkovito rabo energije. Prihranke energije lahko dosežemo predvsem v tistih delih hladilnega sistema, kjer je raba največja. Poleg konstrukcijsko ustreznih komponent hladilnega sistema so pri tem bistvenega pomena obratovalni parametri.

V prispevku je analiziran predvsem vpliv temperature hlajenja oziroma temperature uparjanja na rabo energije za hlajenje. Potrjeno je znano dejstvo, da zniževanje temperature uparjanja zmanjšuje hladilno število. Analiza vpliva temperature uparjanja je pokazala, da njeno zniževanje močno pospeši izločanje vlage iz zraka in sreženje uparjalnika, kar močno vpliva na dodatno rabo energije za odtaljevanje sreža.

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(Ključne besede: sreženje, odtaljevanje, število hladilno)

In the last few years the energy consumption for refrigeration has increased rapidly. As a consequence, care should be taken to ensure that these are energy-efficient devices. Energy savings can be achieved most easily in those parts of the refrigerating system where the energy consumption is the largest. In addition to a suitable design of the refrigerating system components, the operating parameters also play a significant role.

This paper analyses the impact of refrigerating temperature or evaporating temperature on the energy consumption. It is well known that decreasing the evaporating temperature reduces the coefficient of performance. An analysis of the impact of evaporating temperature has shown that its reduction is rapidly accelerated by water vapor condensation from the air and frosting of the evaporator, resulting in extra energy consumption for defrosting the evaporator.

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(Keywords: frosting, defrosting, coefficient of performance)

0 UVOD

Raba energije v Slovenskih gospodinjstvih za hlajenje pomeni več ko 20 odstotkov celotne rabe energije. Podobno stanje je tudi po svetu. Ta delež se z dvigom ravni delovnih in bivalnih razmer v gospodinjstvih in tudi na drugih področjih človekovega udejstvovanja stalno povečuje.

Navedena dejstva so razlog, da tudi na področju hlajenja skrbimo za racionalno rabo energije, še predvsem zato, ker za pogon hladilnih naprav v pretežni meri uporabljamo električno energijo, ki je energija največje kakovosti, je čista eksergija.

Možnosti za zmanjšanje rabe energije hladilnih naprav je veliko. V prvi vrsti lahko vplivamo na rabo energije z optimalno izbiro in pravilnim dimenzioniranjem komponent hladilnega sistema. Pri tem moramo posebno

0 INTRODUCTION

In Slovenian households refrigeration represents more than 20 % of the total energy consumption. The situation in the rest of the world is very much the same, and this level of energy consumption is set to rise as a consequence of better working and living conditions.

It is important that the energy for refrigeration is used carefully because refrigerating devices use electricity, the highest form of energy – pure exergy.

There are many possibilities for reducing the energy consumption of refrigerating devices. First of all by choosing refrigeration components of the correct size. Particular attention should be paid to correctly adjusting all the elementary parts and sepozornost posvetiti usklajenosti vseh osnovnih elementov hladilnega sistema. Druga možnost je pravilna izbira obratovalnih parametrov hladilne naprave, s tem pa že vplivamo na tehnologijo hlajenja.

Pravilna oziroma optimalna izbira komponent hladilne naprave je naloga proizvajalca. Pri tem mora biti upoštevana doba trajanja hladilne naprave in tudi zagotavljanje želenih delovnih parametrov. Najmočnejši vpliv na delovanje hladilne naprave ima vsekakor kompresor. Njegova karakteristika mora biti usklajena predvsem s karakteristiko dušilnega elementa. Uparjalnik in kondenzator morata pokrivati območje delovanja kompresorja. Krmilni elementi morajo biti izbrani tako, da prilagajajo delovanje hladilnika trenutnim potrebam po hlajenju. Torej hladilna naprava bo delovala učinkovito z vidika najmanjše porabe energije takrat, ko bodo vsi navedeni elementi med seboj usklajeni, tako da bomo dosegli čim boljše prilagajanje pridobljene hladilne toplote dejanskim potrebam skozi ves čas delovanja [1].

Z obratovalnimi parametri hladilnega sistema, ki so zahteva tehnologije hlajenja, lahko močno vplivamo na rabo energije za hlajenje. Splošno je znano, da povečana razlika med temperaturo kondenzacije in temperaturo uparjanja zmanjšuje hladilno število, kar neposredno pomeni povečano rabo energije na enoto pridobljenega hladu. Zato moramo predvsem poskrbeti za to, da je med obratovanjem temperatura kondenzacije čim nižja in da je temperatura uparjanja čim višja. Znižanje temperature kondenzacije je omejeno s temperaturo ponora toplote. Višanje temperature uparjanja pa je omejeno s temperaturo hlajenja. Zmanjševanje razlike med temperaturo hlajenja in temperaturo uparjanja pomeni sicer dvig druge, vendar obenem pomeni povečevanje površine oziroma velikosti uparjalnika. Nizka temperatura hlajenja in s tem povezana nizka temperatura uparjanja pomeni intenzivno izločanje vlage iz zraka. Posledica tega je povečano sreženje površine uparjalnika, če je njena temperatura nižja od 0 °C. Zaradi tega se skrajša čas obratovanja hladilne naprave in se poveča čas odtaljevanja uparjalnika, s tem pa tudi raba energije za odtaljevanje sreža. Poleg tega je negativni učinek sreženja tudi zmanjšanje toplotne moči uparjalnika in v tem primeru hladilna naprava ne dosega več imenske zmogljivosti. Po podatkih nekaterih raziskav se na začetku sreženja toplotna moč uparjalnika celo začasno nekoliko poveča [2], vendar se kmalu potem začne naglo zmanjševati.

V pričujočem prispevku je prikazan vpliv temperature hlajenja oziroma temperature uparjanja na rabo energije za odtaljevanje sreža ter na celotno energijsko učinkovitost delovanja hladilne naprave.

1 VPLIV OBRATOVALNIH PARAMETROV NA HLADILNO ŠTEVILO

Energijsko učinkovitost kompresorskih hladilnih naprav ocenjujemo s hladilnim številom. Po definiciji je to:

lecting appropriate working parameters for the refrigerator. In this way we can influence the technology of refrigeration.

The correct choice of components for refrigerators is the job of the producers. They must take into consideration the lifetime of the device and the assurance of the desired working parameters. The main component in any refrigerating device is the compressor, its characteristics must be adjusted to those of the expansion element. The evaporator and condenser must cover the area of activity of the compressor. Control elements must be chosen so that we can adjust the working of the refrigerator to the refrigeration requirements. A refrigerating device will work efficiently, with the minimum energy consumption, when all the elements are adjusted to achieve the cooling requirements throughout the whole period of operation [1].

It is possible to lower the energy consumption for refrigeration with the working parameters. A large difference between the temperature of condensation and the temperature of evaporation reduce the coefficient of performance, which means increased energy consumption per unit of acquired cold. For this reason, it is important to ensure that the condensing temperature is as low as possible and that the evaporating temperature is as high as possible. Lowering the condensing temperature is limited by the temperature of the heat sink. Increasing the evaporating temperature is limited by the refrigerating temperature. Reducing the difference between the refrigerating temperature and condensing temperature means a rise in the latter, and at the same time it means a larger evaporator. A low cooling temperature and an associated low evaporating temperature lead to a rapid elimination of humidity from the air. This results in increased evaporator frosting if the temperature is lower than 0 ^{0}C. A consequence of this is a shortening of the operating time for the refrigerating device and an increase in the time for defrosting: the result, a rise in energy consumption. Another negative influence of frosting is the reduced thermal power of the refrigerator and the inability of the device to reach its nominal capacity. Some research has shown that the initial capacity of the evaporator begins to rise for a short period of time [2], but soon after that the capacity starts falling.

This paper looks at the influence of refrigerating temperature or evaporating temperature on the energy consumption for defrosting and on the overall energy efficiency of refrigerating-device operation.

1 INFLUENCE OF WORKING PARAMETERS ON THE COEFFICIENT OF PERFORMANCE

We estimate the energy efficiency of compression refrigerating devices with the coefficient of performance. By definition this is:

$$\varepsilon = \frac{Q_R}{W} \qquad (1).$$

Za idealni ali teoretični proces ga lahko zapišemo tudi z razmerjem temperatur:

For an ideal or theoretical process we can also write it with a temperature ratio:

$$\varepsilon = \frac{T_R}{T_C - T_R} \qquad (2).$$

Ob nespremenljivi temperaturi kondenzacije je hladilno število odvisno predvsem od temperature uparjanja.

Z analizo enačb (1) in (2) ugotovimo zmanjševanje hladilnega števila z nižajočo se temperaturo uparjanja. Zveza med teoretičnim hladilnim številom in temperaturo uparjanja je čista in dana z enačbo (2), medtem ko je dejansko hladilno število odvisno predvsem od izmerjenega izkoristka kompresorja, na katerega poleg temperature uparjanja vplivajo še številni drugi parametri.

At the constant temperature of condensation the coefficient of performance depends first of all on the evaporating temperature.

An analysis of equations (1) and (2) suggests a lower coefficient of performance with decreasing evaporating temperature. The relationship between the theoretical coefficient of performance and the evaporating temperature is given by equation (2), the actual coefficient of performance depends mainly on compressor efficiency, which is influenced by evaporating temperature as well as other parameters.

2 VPLIV TEMPERATURE UPARJANJA NA RABO ENERGIJE ZA ODTALJENJE SREŽA

2 INFLUENCE OF EVAPORATING TEMPERATURE ON ENERGY CONSUMPTION FOR DEFROSTING

Srež na zunanji površini uparjalnika pomeni zaradi svoje razmeroma majhne toplotne prevodnosti znaten upor proti prenosu toplote. Med delovanjem hladilne naprave debelina sreža narašča, kar močno zmanjšuje toplotno moč uparjalnika oziroma celotne hladilne naprave. Zato je treba po določenem času nastali srež odtaliti. To pomeni, da moramo v uparjalnik dovajati dodatno energijo.

Frost on an external surface of the evaporator represents a high resistance to heat flux because of frost's relatively low heat conductivity. The thickness of the frost increases with operating time and significantly reduces the thermal power of the evaporator and, as a consequence, the refrigerating device. Because of this it is nessesary to defrost periodically the refrigerator and this means that additional energy must be brought into the evaporator.

2.1 Nadomestna toplotna prevodnost sreža

2.1 Effective heat conductivity of frost

Kadar obstaja temperaturni gradient v plasti sreža, poteka prenos toplote z naslednjimi mehanizmi: molekularno prevodnostjo, difuzijo vodne pare, sevanjem in občasno z naravno konvekcijo. Model preračuna je povzet po Auracherju [4].

Posamezne prenosne procese bomo razčlenili in jih skupaj popisali z nadomestno toplotno prevodnostjo:

When there is a temperature gradient in the layer of frost, heat transfer involves the following mechanisms: molecular conductivity, diffusion of water vapor, radiation and sometimes natural convection. The model for the calculation is a simplified model first introduced by Auracher [4].

We will analyse individual transport processes and list them together with substitutional heat conductivity:

$$\lambda = -\frac{\dot{q}}{\mathrm{d}T/\mathrm{d}x} \qquad (3).$$

Difuzija

Gostota toplotnega toka q_D zaradi difuzije vodne pare je:

Diffusion

The density of heat flux q_D because of the diffusion of water vapor is:

$$\dot{q}_\mathrm{D} = \dot{m}_\mathrm{eff} \cdot \Delta h_\mathrm{f} \qquad (4).$$

Glede na splošno definicijsko enačbo za toplotno prevodnost lahko zapišemo nadomestno difuzijsko prevodnost sreža:

Considering the general definition equation for heat conductivity we can write down the effective diffusion conductivity of frost as:

$$\lambda_\mathrm{D} = -\frac{\dot{m}_\mathrm{eff} \cdot \Delta h_\mathrm{f}}{\mathrm{d}T/\mathrm{d}x} \qquad (5).$$

Gostoto difuzijskega masnega toka vodne pare računamo po Fickovem zakonu:

We can calculate the density of the diffusion mass flow of water vapor by Fick‘s law:

$$\dot{m}_{\mathrm{eff}} = -\frac{D}{\mu \cdot R_{\mathrm{w}} \cdot T} \cdot \frac{\mathrm{d}p_{\mathrm{w}}}{\mathrm{d}T} \cdot \frac{\mathrm{d}T}{\mathrm{d}x} \qquad (6).$$

Vrednost difuzijske upornosti μ dobimo iz literature [4].

Difuzijski koeficient izrazimo s temperaturo in tlakom, za tlak nasičenja vodne pare vzamemo temperaturno funkcijo in ob upoštevanju izraza za difuzijsko upornost dobimo naslednjo enačbo:

We can obtain the value of the diffusion resistance μ from the reference [4].

We can express the diffusion coefficient in terms of temperature and pressure. For the saturation pressure of water vapor we take the temperature function and if we then take into consideration the diffusion resistance we get the following equation:

$$\lambda_{\mathrm{D}} = \frac{\rho_{\mathrm{i}} - \rho_{\mathrm{f}}}{\rho_{\mathrm{i}} - C_0 \cdot \rho_{\mathrm{f}}} \cdot \Delta h_{\mathrm{s}} \cdot C_4 \cdot \frac{p_0}{p} \cdot \left(\frac{T}{T_0}\right)^{-1,28} \cdot e^{(\mathrm{C_2} - \mathrm{C_3/T})} \qquad (7),$$

kjer so vrednosti konstant: $C_2 = 24{,}02$, $C_3 = 6145$ K, $C_4 = 1{,}958 \cdot 10^{-9}$ kg/msK.

where the values of the constants are: $C_2 = 24.02$, $C_3 = 6145$ K, $C_4 = 1.958 \cdot 10^{-9}$ kg/msK.

Molekularna prevodnost

Molekularno prevajanje ima največji vpliv na celotni toplotni tok. Toplotna prevodnost sreža ne more biti izračunana zanesljivo s čistim teoretičnim postopkom. Zapleten mehanizem prenosa toplote v porozni snovi zahteva uporabo polempiričnih modelov.

Toplotna prevodnost ni samo funkcija oblike sreža, ampak tudi funkcija gostote in temperature ter tudi notranje zgradbe. To se časovno spreminja s pogoji formiranja sreža in z metamorfnimi procesi.

Celotna molekularna prevodnost sreža je:

Molar conduction

Molar conductivity is by far the most important effect exerted on the total heat flux. The thermal conductivity of frost cannot be calculated reliably using a purely theoretical approach. The complex mechanism of heat transfer in a porous material requires the use of semi-empirical models.

The thermal conductivity of frost is not only a function of the form of the frost, but also a function of density, temperature and internal structure. This in turn varies with time, frost formation conditions and metamorphous processes.

The total molar conductivity of frost is:

$$\lambda_{\mathrm{cd}} = \frac{1}{\frac{\mathrm{c}_1}{\lambda_{\mathrm{v}}} + \frac{1-\mathrm{c}_1}{\lambda_{\mathrm{p}}}} \qquad (8).$$

Prečna λ_{v} in vzporedna toplotna prevodnost λ_{p} sta izračunani po enačbah v [4]. Konstanta c_1 je rezultat meritev molekularne prevodnosti sreža in je dana v [4].

Pri večjih gostotah sreža je temperaturna odvisnost λ_{cd} prav nasprotna kakor pri majhnih gostotah. To je razumljivo, saj se prevodnost ledu zvečuje z nižanjem temperature.

Transverse λ_{p} and parallel λ_{p} thermal conductivities are calculated from equations in [4]. The constant c_1 is the result of measurements of the molar conduction of frost and can be found in [4].

At higher frost densities the temperature dependence λ_{cd} is the opposite to that at low densities. This is quite logical because the conductivity of ice increases with falling temperature.

Nadomestna toplotna prevodnost sreža

Iz raziskav [4] izhaja, da sta prevod in difuzija edina pomembna učinka na prenos toplote v srežu. Celotna toplotna prevodnost je torej:

Effective thermal conductivity of frost

From the research done by Auracher[4] it follows that conduction and diffusion are the only relevant effects on heat transfer in frost. The effective thermal conductivity is thus given by:

$$\lambda = \lambda_{\mathrm{cd}} + \lambda_{\mathrm{d}} \qquad (9).$$

2.2 Gostota sreža

V enačbah za toplotne prevodnosti je navzoča tudi gostota sreža. Analitičnih modelov za izračun gostote sreža v literaturi ne najdemo.

2.2 Density of frost

The density of frost is present in equations for heat conductivities, but in the avaliable literature we could not find any analytical models for the calculation

Obstaja nekaj empiričnih obrazcev, ki so rezultat meritev. V splošnem je znano, da je gostota sreža odvisna od hitrosti in temperature zraka, debeline sreža in gradienta koncentracij vodne pare v zračnem toku.

of frost density. There are some empirical accessories, however, which are the results of measurements. In general it is known that the density of frost depends on air velocity and temperature, frost thickness and on the gradient of concentrations of water vapor in the air flow.

Lotz [2] navaja za gostoto sreža naslednji empirični izraz:

Lotz [2] mentions the following empirical expression for frost density:

$$\rho_{\mathrm{f}} = 343,86 \cdot \ln\left(1 + \frac{13,45}{1+F}\right) \qquad (10).$$

Faktor F zajema vse vplivne veličine na gostoto sreža:

Factor F includes all the influential parameters for frost density:

$$\mathrm{F} = \frac{81,7 \cdot \Delta p_{\mathrm{w}} \cdot c_1 \cdot \left(1 - t_{\mathrm{f}}\right)^{0,5}}{\left[\left(0,225 + \delta_f\right) \cdot c_2 - 0,1 \cdot t_{\mathrm{f}}\right] \cdot v_{\mathrm{a}}^{\mathrm{c}_3}} \qquad (11).$$

Pomožne veličine c_1 do c_3 so odvisne od hitrosti zraka, debeline sreža ter od temperature sreža in jih dobimo v [4].

Auxilliary parameters c_1 to c_3 depend on the air velocity, frost thickness and the frost temperature and can be obtained in [4].

2.3 Toplotna moč osreženega uparjalnika

2.3 Thermal capacity of frosted evaporator

Toplotna moč, ki se prenaša skozi steno uparjalnika, je zmnožek toplotne prehodnosti, zunanje površine uparjalnika in razlike med temperaturo zunanjega zraka ter med temperaturo uparjanja:

The heat flow, which is transfered through the wall of the evaporator, is a product of the thermal conductivity, the external surface of the evaporator and the difference between the temperature of the outer air and the evaporating temperature:

$$\dot{Q} = k \cdot A_{\mathrm{o}} \cdot \left(t_{\mathrm{a}} - t_{\mathrm{R}}\right) \qquad (12).$$

Toplotno prehodnost, ki je sestavljena iz toplotne prestopnosti na notranji strani, toplotne prevodnosti skozi cev, skozi srež ter toplotne prestopnosti na zunanji strani, lahko zapišemo [5]:

The overall heat-transfer coefficient, which comprises the heat-transfer coefficient on the inner side, the heat conductivity through the wall, through the frost and the heat-transfer coefficient on the outer side, can be writen as [5]:

$$k = \frac{1}{\dfrac{A_{\mathrm{o}}}{A_{\mathrm{i}} \cdot \alpha_{\mathrm{i}}} + R_0} \qquad (13),$$

kjer je:

where:

$$R_0 = \left(\frac{1}{\alpha_{\mathrm{a,i}}} + \frac{\delta_{\mathrm{f}}}{\lambda_{\mathrm{f}}}\right) \cdot \frac{A_{\mathrm{o}}}{A_{\mathrm{f}} \cdot (\eta_{\mathrm{R}} - 1) + A_{\mathrm{o}}} + \frac{\delta_{\mathrm{t}}}{\lambda_{\mathrm{t}}} \qquad (14).$$

Pri tem toplotno prestopnost na zunanji strani $\alpha_{\mathrm{a,i}}$ dobimo iz empirične enačbe [3]:

Based on this, the thermal coefficient on the outer side $\alpha_{\mathrm{a,i}}$ can be obtained from the empirical equation [3]:

$$k' = \varphi \cdot \Delta t^{0,5} \cdot S_{\mathrm{f}}^{0,5} \cdot \left(65 \cdot 10^3 \cdot \delta_{\mathrm{f}} + 14\right) \cdot \mathrm{e}^{-1100 \cdot \delta_s} = \frac{1}{\dfrac{1}{\alpha_{\mathrm{a,i}}} + \dfrac{\delta_{\mathrm{f}}}{\lambda_{\mathrm{f}}}} \qquad (15).$$

V enačbah za gostoto sreža in toplotno moč uparjalnika je navzoča tudi debelina sreža δ_{f}. To izračunamo na podlagi masnega toka izločenega sreža in površine uparjalnika.

In equations for the density of frost and the thermal capacity of the evaporator, the thickness of the frost δ_{f} is also present. This can be calculated on the basis of the mass flow of the eliminated frost and the area of the evaporator.

Sreženje je proces izločanja vodne pare iz vlažnega zraka. Masni tok izločenega sreža izračunamo iz masne bilance v zraku in je:

Frosting is a process of desublimation of water vapor from the moist air. We can calculate the mass flow of eliminated frost from the mass balance in the air:

$$\dot{m}_{\mathrm{f}} = \dot{V}_{\mathrm{a}}\, \rho_{\mathrm{a}} (x_{\mathrm{a,i}} - x_{\mathrm{a,o}}) \qquad (16).$$

Absolutne vlažnosti preračunamo iz temperatur in relativnih vlažnosti po znanih enačbah ali pa jih preberemo iz diagrama *h-x*.

Na podlagi poznanega masnega toka sreža, lahko izračunamo možni čas obratovanja hladilnika, v katerem se nabere toliko sreža m_f, da smo ga sposobni odtaliti v predpisanem času 30min:

We can calculate the absolute humidity from the temperature and the relative humidities from known equations or we can read them from the *h-x* diagram.

On the basis of the known mass flow of frost we can calculate the working time of the refrigerator, which has accumulated frost m_f which can be defrosted in 30 min:

$$\tau_o = \frac{m_f}{\dot{m}_f} \tag{17}$$

Toplota, potrebna za odtaljevanje uparjalnika, je sestavljena iz toplote za segrevanje uparjalnika in sreža na 0 °C ter iz toplote za taljenje ledu:

The heat needed for defrosting the evaporator is made up of the heat needed to heat the evaporator and frost to 0 ^{0}C and the heat needed for melting the ice:

$$Q_{m,f} = m_R c_R (0 - t_R) + m_f c_f (0 - t_R) + m_f q_m \tag{18}$$

Dejansko sliko energijske učinkovitosti delovanja hladilne naprave dobimo, če k energiji za pogon kompresorja prištejemo še energijo za odtaljevanje sreža, oziroma če definiramo celotno hladilno število:

We can get a real picture of the energy efficiency of the refrigerating device if the energy neccessary for driving the compressor is added to the energy for defrosting, or if we define the total coefficient of performance as:

$$\varepsilon = \frac{Q_R}{W + Q_{mf}} \tag{19}$$

3 PRIMER PARAMETRIČNE ANALIZE

3 AN EXAMPLE OF PARAMETRIC ANALYSIS

Parametrično analizo porabe energije za hlajenje smo opravili na konkretnem primeru uparjalnika z naslednjimi podatki:

We conducted a parametric analysis of the energy consumption for refrigeration on a real example of an evaporator with the following data:

Zunanji zrak Outer air		Geometrijska oblika uparjalnika Geometrical shape of the evaporator	
vstopna temperatura input temperature	$t_{a,i}$: 5 ^{0}C	zunanja površina external surface	A_o: 7 m^2
vstopna relativna vlažnost input relative humidity	ϕ_i: 80 %	notranja površina inside surface	A_i: 0,66 m^2
izstopna relativna vlažnost output relative humidity	ϕ_o: 95 %	učinkovitost lamel fin efficiency	η_f: 0,8
hitrost velocity	v_a: 3 m/s	razdalja med lamelami distance between fins	S_f : 0,012 m
volumski tok volume flow	$\dot{V}_a$: 0,44 m^3/s	masa uparjalnika mass of the evaporator	m_R: 5,6 kg

Za izvedbo analize smo uporabili že izdelani računalniški program za simuliranje preračun lamelnih hladilnikov zraka [5], v katerega smo dodatno vgradili na podlagi zgoraj predstavljenega modela sreženja izdelani računski modul.

Izkušnje iz podobnih analiz kažejo, da je upor prenosa toplote od hladiva v cevi do zunanje površine uparjalnika praktično zanemarljiv. Zato smo pri preračunu enačili zunanjo temperaturo površine uparjalnika s temperaturo uparjanja.

For the analysis we used an existing computer program for the simulation and calculation of the air cooling coils [5]. Into this program we put an additional calculation module based on the above-described model of frosting.

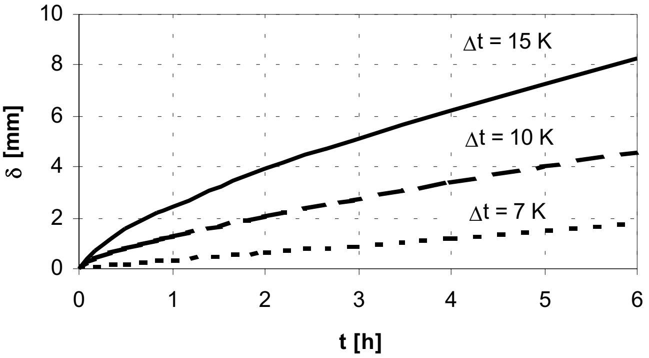
Experiences from a similar analysis have shown that the heat-transfer resistance from the refrigerant in the tube to the external surface of the evaporator is practically negligible. For this reason, in the calculation, the external temperature of the surface of the evaporator was equated with the evaporating temperature.

3.1 Rezultati analize

Za navedene parametre zraka in geometrijsko obliko uparjalnika smo izvajali analizo vpliva različnih vplivnih veličin na rabo energije za odtaljevanje sreža. V prvi vrsti smo ugotovili, da je najpomembnejši vplivni dejavnik debelina sreža. Ta je odvisna predvsem od temperature uparjanja. Zato smo v nadaljevanju vzeli to kot odločujočo veličino rabe energije.

3.1 Results of the analysis

We performed an analysis of the influence of different parameters on the energy consumption for defrosting for the stated conditions of the evaporator, air and geometry. The first point we established was that the most important factor is the thickness of the frost. This thickness depends mainly on the evaporating temperature. In the subsequent steps this was considered as the main factor in terms of energy consumption.



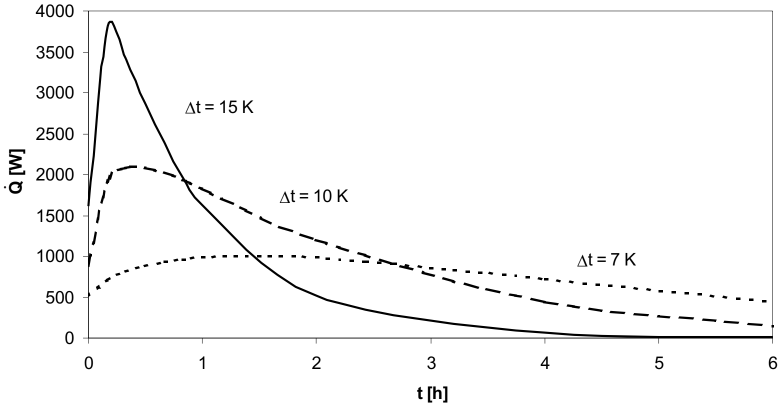
Sl. 1. *Naraščanje debeline sreža s časom*
Fig. 1. *Increase in frost thickness with time*

S slike 1 lahko ugotovimo, da pri večjih temperaturnih razlikah Δt (razlika med temperaturo uparjanja in temperaturo zraka) debelina sreža δ hitreje narašča in je zato treba uparjalnik prej odtaljevati oziroma je potrebnih več odtaljevalnih obdobij.

Primer časovne odvisnosti padanja moči uparjalnika vidimo na sliki 2. Na začetku delovanja lahko opazimo celo delno zvečanje moči uparjalnika in nato naglo zmanjšanje. Vzrok za začetno povečanje moči uparjalnika je v tem, da se na začetku sreženja pojavi močno povečana hrapavost površine, kar povzroči močno turbulenco zraka in s tem povečano toplotno prestopnost. V nadaljevanju delovanja debelina sreža narašča in se močno poveča upornost prenosa toplote.

We can determine from Figure 1, that at higher temperature differences Δt, the difference between evaporating temperature and air temperature, the frost thickness δ increases faster and for this reason the evaporator has to be defrosted first or we need several defrosting periods.

We can see an example of the time dependence of the falling power of the evaporator in Figure 2. At the beginning of the operation there is an increase in the evaporating power and then a sharp fall. The reason for initial sharp rise in the evaporator capacity is that the frost increased the roughness of the surface causing strong air turbulence and an increased heat-transfer coefficient between the air and the frosted area. If the refrigerator continues to work the frost layer thickens and the resistance to heat transfer increase.



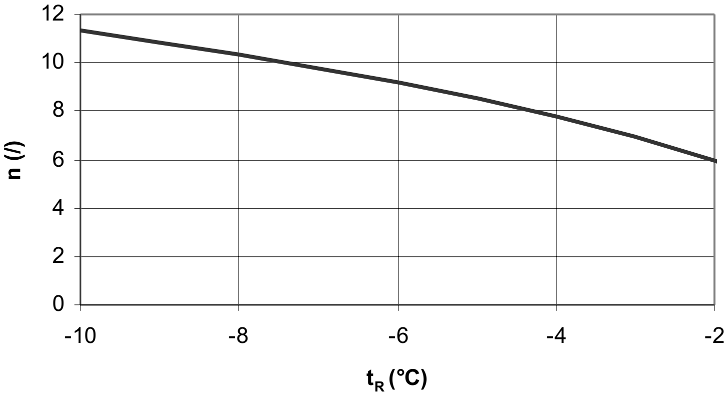
Sl. 2. *Časovni potek spreminjanja toplotne moči uparjalnika zaradi sreženja [2]*
Fig. 2. *Time dependence of evaporator performance due to frosting [2]*

V postavljenem modelu je neposredno ali posredno navzoča temperatura uparjanja. Zato smo poiskali njen vpliv na pomembnejše kazalce učinkovite rabe energije pri hlajenju.

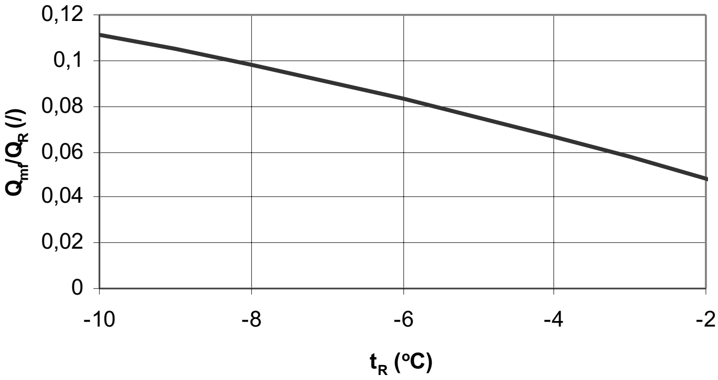
S slike 3 lahko vidimo, da se z nižanjem temperature uparjanja močno povečuje število odtaljevalnih obdobij, s tem pa se zmanjšuje čas obratovanja, v katerem se odtaljeni srež obnovi. Vzroka za to sta dva. Prvi vzrok je v tem, da se del dodatne energije porabi za segrevanje sreža in uparjalnika in se ta količina energije ne more uporabiti za taljenje, drugi in poglavitni vzrok za to pa je, da se z zniževanjem temperature uparjanja znižuje temperatura površine uparjalnika, ki povzroči močno povečanje izločanja vlage iz zraka in večji masni tok nastalega sreža, s tem pa krajši čas za obnovo sreža.

In the model the evaporating temperature is present either explicitly or implicitly. For this reason we have investigated its influence on the important indicators for the effective use of energy in refrigeration.

From Figure 3 we can see that with decreasing evaporating temperature the number of defrosting periods increases, and the woking time for the melted frost to be restored is reduced. There are two reasons for this. First reason is that an additional amount of energy is spent for heating the frost and the evaporator, and this energy cannot be used for defrosting, the second and most important reason is that with a falling evaporating temperature the surface temperature of the evaporator is falling too. This causes a large rise in the moisture elimination from the air and a higher mass flow of the created frost and with that a shorter time for the renewal of the frost.



Sl. 3. *Število odtaljevalnih obdobij na dan v odvisnosti od temperature uparjanja*
Fig. 3. *Number of defrosting periods per day versus the temperature of evaporation*



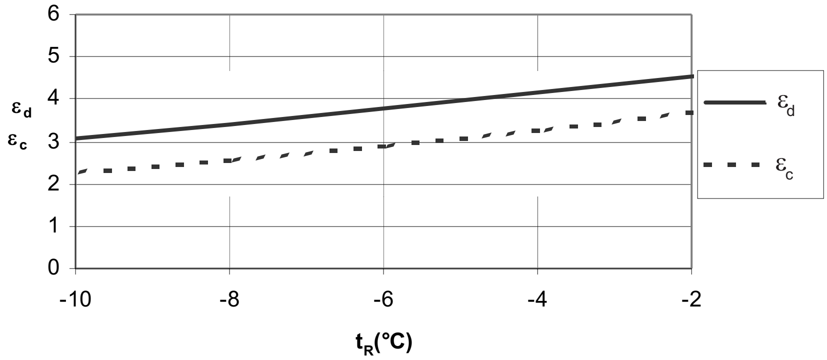
Sl. 4. *Razmerje energije za odtaljevanje in hladilne energije v odvisnosti od temperature uparjanja*
Fig. 4. *Ratio of energy for defrosting and refrigeration capacity versus the temperature of evaporation*

Slika 4 prikazuje, da pri temperaturi uparjanja 0 °C pomeni raba energije za odtaljevanje nekaj manj ko 3% energije, potrebne za pogon hladilne naprave, in da se ta odstotek pri temperaturi uparjanja –10 °C poveča na nekaj več ko 11%.

S primerjavo običajno definiranega hladilnega števila po (1) in hladilnega števila z upoštevanjem energije za odtaljevanje uparjalnika

Figure 4 shows that at an evaporating temperature of 0°C the energy consumption for defrosting accounts for less than 3% of the energy needed for driving the refrigerating device and that at the temperature of evaporation –10°C it rises to more than 11%.

By comparing the traditionally defined coefficient of performance according to (1) with the coefficient of performance defined by taking into consideration the energy needed for the defrosting of the evapo-



Sl. 5. *Dejansko in celotno hladilno število v odvisnosti od temperature uparjanja*
Fig. 5. *Actual and total coefficient of performance versus evaporation temperature*

po en. (19) s slike 5 vidimo, da je celotno hladilno število manjše za okrog 20% pri temperaturi uparjanja –2 °C in da ta razlika znaša več ko 30% pri –10 °C.

4 SKLEP

S pričujočim prispevkom smo želeli prikazati, kakšen vpliv ima temperatura uparjanja na rabo energije za delovanje hladilne naprave. Iz parametrične analize lahko ugotovimo, kje so možnosti za zmanjšanje porabe energije za hlajenje. Neizogibno dejstvo je negativni vpliv zniževanja te temperature na hladilno število.

Pogoji za začetek nastajanja sreža na uparjalniku se vzpostavijo v odvisnosti od geometrijske oblike uparjalnika ter parametrov zraka. Parametrično analizo vpliva sreža na porabo energije smo opravili pri temperaturi uparjanja pod –2 °C, ker smo ugotovili, da se pri tej temperaturi uparjanja zagotovo pojavijo pogoji za začetek sreženja.

Rezultati analize kažejo, da pri temperaturi uparjanja malo pod 0 ^{0}C srež le malo vpliva na nadomestno toplotno prevodnost in posledično na toplotno moč uparjalnika. Medtem je pri nižjih temperaturah uparjanja (–10 ^{0}C) vpliv sreža zelo velik, saj po določenem času močno zmanjša toplotno moč uparjalnika. Kakor je razvidno s slik 1 in 2, bi lahko srež po določenem času zapolnil prostor med rebri in bi se toplotna moč uparjalnika zmanjšala na 0.

Poleg tega smo z analizo ugotovili, da zniževanje temperature uparjanja močno skrajša morebitni čas obratovanja hladilne naprave, v katerem se odtaljeni srež obnovi. To pomeni večjo porabo energije za odtaljevanje, kar bistveno zmanjšuje celotno hladilno število.

Dejanska raba energije za odtaljevanje sreža je v bistvu še večja, ker pri odtaljevanju voda odteka pri nekaj višji temperaturi od 0 °C (naša predpostavka).

Iz rezultatov analize lahko povzamemo, da ima zniževanje temperature hlajenja večkraten negativni učinek na rabo energije. Zato moramo biti

rator, see equation (19), we can see that the total coefficient of performance is lower by around 20% at the temperature of evaporation -2°C and that this difference rises to more than 30% at –10°C, see Figure 5.

4 CONCLUSION

The purpose of the paper was to show what kind of effect the evaporating temperature has on the energy consumption of a refrigeranting device. From a parametric analysis we can find the possibilities for reducing the energy consumption. An inevitable fact is the negative influence a drop in the evaporating temperature has on the coefficient of performance.

The conditions for frost formation on the evaporator depend on the evaporator geometrical shape and air parameters. We conducted a parametric analysis of the influence of frost on the energy consumption at an evaporating temperature under –2°C, because at this temperature the conditions are suitable for frost formation.

The results of the analysis show that at an evaporating temperature under 0 ^{0}C frost has only a minor influence on effective thermal conductivity, and as a result, on the evaporator's thermal power. On the other hand, at lower temperatures of evaporation (–10 ^{0}C) the influence of frost is very strong, because after a certain time it greatly reduces the evaporator's thermal power. From Figures 1 and 2 it is clear that after a certain time frost could fill the space between the fins and the evaporator's thermal power would vanish.

This analysis has also established that lowering the evaporating temperature significantly reduces the time avaliable for defrosting, which effectively reduces the total coefficient of performance.

The real energy consumption for defrosting is, in reality, even bigger, because in the process of defrosting, the water flows away at a slightly higher temperature than 0°C (our presumption).

On the basis of the results we can conclude, that lowering the refrigerating temperature has a negative effect on energy consumption. Because of this pri izbiri temperature hlajenja zelo pazljivi in izbirajmo najvišjo mogočo, ki jo dopuščata tehnologija hlajenja in dimenzioniranje prenosnikov toplote.

we must be very careful in choosing the refrigerating temperature. We should choose the maximum possible temperature that is allowed by the refrigerating technology and the heat exchanger's dimensions.

5 OZNAKE VELIČIN
5 SYMBOLS USED

površina	A	m^2	surface
specifična toplota	c	J/kgK	thermal capacity
difuzijski koeficient	D	-	diffusion coefficient
entalpija	h	J/kg	enthalpy
masa	m	kg	mass
tlak	p	Pa	pressure
gostota toplotnega toka	$\dot{q}$	W/m^2	density of heat flow
toplotni tok	$\dot{Q}$	W	heat flow
plinska konstanta	R_v	J/kgK	gas constant
temperatura	T	K	temperature
temperatura	t	^{0}C	temperature
hitrost	v	m/s	velocity
volumski tok	$\dot{V}$	m^3/s	volume flow
delo	W	W	work
absolutna vlažnost	x	kg/kg	absolute humidity
debelina	δ	mm	thickness
toplotna prevodnost	λ	W/mK	thermal conductivity
učinkovitost	η	-	efficiency
difuzijska upornost	μ	-	diffusion resistance
gostota	ρ	kg/m^3	density

Indeksi	**Index**	
zrak	a	air
kondenzacija	C	condensation
srež, rebro	f	frost, fin
notranji, vstop	i	inside, input
talilni	m	melt
zunanji, izstop	o	outside, output
vzporedno	p	parallel
uparjanje, uparjalnik	R	evaporation, evaporator
sublimacijski	s	sublimative
cev	t	tube
para	v	vapour
voda	w	water

6 LITERATURA
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