UDK: 697.97:66.045

Posredno hlapilno hlajenje energijsko varčne stavbe

Indirect Evaporative Cooling of Energy Efficient Building

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Z dvigovanjem življenjskega standarda se pojavlja tudi zahteva po hlajenju bivalnih prostorov. Premišljena raba energije narekuje uporabo alternativnih načinov hlajenja, saj je poraba energije pri kompresorskih hladilnih napravah velika. V prispevku sta predstavljena nov, cenen kartonski kompaktni prenosnik toplote in posredno hlapilno hlajenje, ki je najprimernejše za hlajenje sodobnih energetsko varčnih poslopij. Prikazano je tudi simuliranje delovanja posrednega hlapilnega hladilnika zraka.

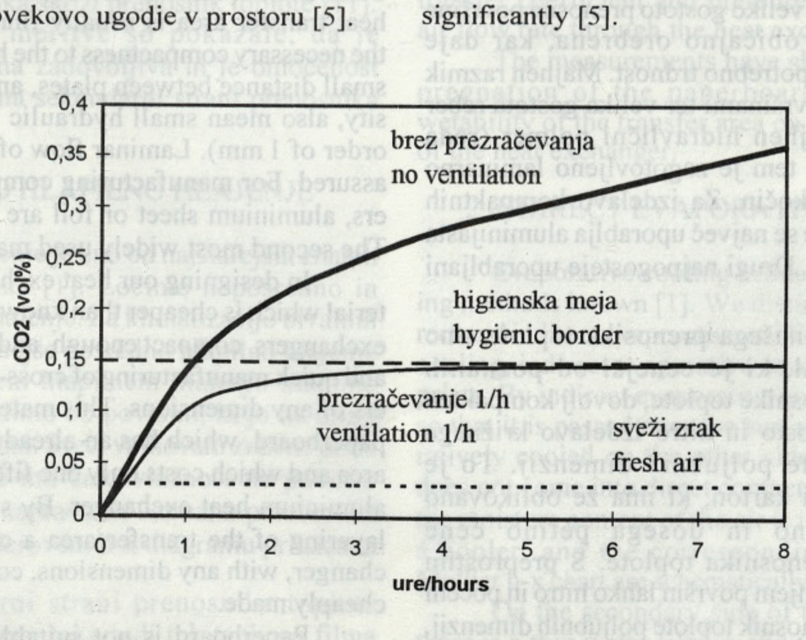
With the growth of living standards, there is an increasing demand for the cooling of living space. Rational energy use demands the use of alternative ways of cooling because the energy consumption of compressor cooling is high. In this paper a new cheap paperboard compact heat exchanger and indirect evaporative cooling are presented. This cooling is the most suitable for energy efficient cooling of buildings. Operation simulation of an indirect evaporative cooler is also shown.

0 UVOD

Sodobne energijsko varčne stavbe so dandanes zasnovane tako, da zaradi svoje oblike, primerne toplotne zaščite, kakovosti oken, pasivnega in aktivnega sprejema sončne energije potrebujejo le še 40 do 60 kWh/m² energije za ogrevanje v ogrevalni sezoni, dajejo pa večje bivalno ugodje. Povečana tesnost stavbe nujno zahteva prezračevanje objekta oziroma vgradnjo sistema za rekuperacijo odpadne toplote. Zmanjšan dotok svežega zraka namreč povzroča problem slabega zraka v prostorih. Poveča se koncentracija škodljivih snovi v zraku (CO_2, vonjave, dim, hlapljive organske spojine) in s tem močno zmanjša človekovo ugodje v prostoru [5].

0 INTRODUCTION

Energy efficient buildings are nowadays designed so that because of their shape, thermal insulation, windows quality, active and passive solar energy use, they need only 40 to 60 kWh/m² of energy for heating in the heating period, but they offer greater living comfort. Enlarged building tightness demands ventilation of the building and installation of a system for vast heat recovery. The decrease in fresh air inflow actually causes the problem of poor indoor air quality. The concentration of pollutants (CO_2, odours, smoke, volatile organic compounds) increases, and so human comfort in the room drops significantly [5].



Sl. 1. *Koncentracija CO_2 v prostoru v odvisnosti od prezračevanja*

Fig. 1. *Concentration of CO_2 in the room depending on ventilation*

Za človekovo popolno ugodje je treba zrak v poletnem obdobju tudi hladiti. Kompresorske hladilne naprave, ki se v razvitem svetu največ uporabljajo za klimatizacijo prostorov, so energijsko potratne ter tako ne sodijo v sodobno zasnovano energijsko varčno poslopje. Za energijsko varčne stavbe je predvsem primerno posredno hlapilno hlajenje, ker lahko rekuperator odpadne toplote z majhno dodelavo spremenimo v napravo, ki omogoča tudi hlajenje zunanjega toplega zraka in s tem klimatizacijo bivalnih prostorov. Sistem je energijsko ugoden ter ekološko sprejemljiv, saj porabi manj vode od hladilnih stolpov pri proizvodnji električne energije za pogon kompresorske hladilne naprave [1]. Vendar so take naprave v primerjavi s kompresorsko hladilno napravo večje in dražje. Vzdrževanje teh naprav je zahtevnejše, navzočnost vode pa odpira tudi problem bakterij. Poleg tega hlapilno hlajenje odpove v ekstremnih klimatskih razmerah. Bolj kompaktna in predvsem cenejša izvedba prenosnika toplote bi zmanjšala napravo ter jo naredila cenovno sprejemljivejšo za širšo uporabo. Zato smo naše raziskave usmerili predvsem na problematiko cenenih kompaktnih prenosnikov toplote.

1 KARTONSKI KOMPAKTNI PRENOSNIK TOPLOTE

Za prenos toplote med dvema zračnima tokovoma se največ uporabljajo kompaktni prenosniki toplote z veliko gostoto prenosne površine [4] in [6]. Ta je običajno orebrena, kar daje prenosniku toplote potrebno trdnost. Majhen razmik med prenosnimi površinami ter velika gostota reber pomenita tudi majhen hidravlični polmer (reda velikosti 1 mm). S tem je zagotovljeno laminarno pretakanje obeh tekočin. Za izdelavo kompaktnih prenosnikov toplote se največ uporablja aluminijasta pločevina ali folija. Drugi najpogosteje uporabljani material je plastika.

Pri zasnovi našega prenosika toplote smo uporabili material, ki je cenejši od poznanih materialov za prenosnike toplote, dovolj kompakten in omogoča preprosto in hitro izdelavo križnega prenosnika toplote poljubnih dimenzij. To je dvoplastni valoviti karton, ki ima že oblikovano prenosno površino in dosega petino cene aluminijastega prenosnika toplote. S preprostim lepljenjem ter zlaganjem površin lahko hitro in poceni izdelamo križni prenosnik toplote poljubnih dimenzij.

Karton seveda ni primeren za stik z vodo. Zaradi tega ga je treba prej ustrezno impregnirati in s tem narediti odpornega proti vlagi in bakterijam.

For complete human comfort, air has to be cooled in the summer period. Compressor cooling devices, which are the most widely used for space cooling in the developed countries, are energy consuming and so they are not appropriate for an energy efficient building. For energy efficient buildings indirect evaporative cooling is the most suitable because the recuperator of waste heat recovery system could be adapted, with small supplements, into a device which enables cooling of hot outside air, and hence climatization of the living spaces. Such a system is energy favourable and ecologically acceptable because it needs less water than cooling towers in electricity production for the compressor cooling device [1]. However, in comparison with the compressor cooling devices, indirect evaporative coolers are larger and more expensive. Their maintenance is more demanding, and the presence of water also opens the question of bacteria. Besides this, evaporative cooling fails in extreme climatic conditions. A more compact and, above all, cheaper heat exchanger design would reduce the size of the device and make its price more acceptable for wider use. So we have focused our research especially on the development of cheap compact heat exchangers.

1 PAPERBOARD COMPACT HEAT EXCHANGER

Compact heat exchangers, with a high heat transfer area density, are most widely used for heat transfer between two air streams [4] and [6]. The heat transfer area is usually finned, and this gives the necessary compactness to the heat exchanger. The small distance between plates, and the high fin density, also mean small hydraulic radius (magnitude order of 1 mm). Laminar flow of both fluids is thus assured. For manufacturing compact heat exchangers, aluminium sheet or foil are most widely used. The second most widely used material is plastic.

In designing our heat exchanger we used material which is cheaper than known materials for heat exchangers, compact enough, and enables the simple and quick manufacturing of cross-flow heat exchangers of any dimensions. This material is double layer paperboard, which has an already designed transfer area and which costs only one fifth of the price of an aluminium heat exchanger. By simple sticking and layering of the transfer area a cross-flow heat exchanger, with any dimensions, could be quickly and cheaply made.

Paperboard is not suitable for contact with water. Therefore it must previously be adequately impregnated and so made resistant to moisture and bacteria.

S poskušanjem smo našli optimalno impregnacijsko sredstvo, ki omogoča tudi dobro omočljivost prenosne površine [11].

Na tržišču obstajata dva tipa dvoplastnega valovitega kartona, primerna za izdelavo kompaktnega prenosnika toplote. Iz njiju smo naredili dva različna prenosnika toplote.

Preglednica 1 prikazuje geometrijske parametre obeh tipov uporabljenega dvoplastnega valovitega kartona ter izračunane vrednosti hidravličnega premera D_h in gostote prenosne površine *A/V*.

Preglednica 1. *Geometrijska oblika prenosnih površin*

Table 1. *Transfer area geometry*

parameter	enota unit	označba kartona paperboard type	
		val B wave B	val C wave C
b	mm	3,73	2,78
δ_p	mm	0,15	0,15
δ_r	mm	0,1	0,1
D_h	mm	2,81	2,16
A/V	m^2/m^3	659	835

Z meritvami smo določili značilnice obeh kartonskih prenosnikov toplote, ki omogočajo določitev toplotne prestopnosti in tlačnega padca ob znanem pretoku zraka skozi prenosnik toplote [11].

Opravljene meritve so pokazale, da je impregnacija kartona zadovoljiva in je omočenost prenosne površine na sekundarni strani prenosnika toplote zelo dobra.

2 POSREDNO HLAPILNO HLAJENJE

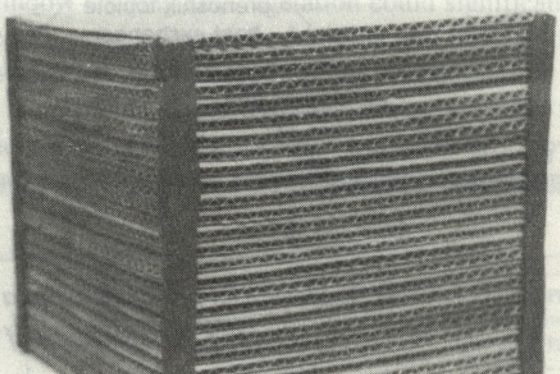
Hlapilno hlajenje je eno od najstarejših znanih metod hlajenja zraka [1]. Ločimo neposredno in posredno hlapilno hlajenje. Za klimatizacijo bivalnih prostorov je primernejše posredno hlapilno hlajenje zraka. Pri posrednem hlapilnem hlajenju hladimo zrak tako, da ga vodimo ob površini, ki jo na drugi strani hlapilno hladimo. Sveži vpihovani zrak ne pride v stik z vodo in se mu zato vlažnost ne poveča. Shematsko je taka naprava in ustrezna preobrazba stanja zraka v Mollierovem h-x diagramu prikazana na sliki 3.

Na sekundarni strani prenosnika toplote imamo poleg zračnega toka tudi tok tankega filma vode na prenosni površini, ki ga razdeljujejo razprševalne šobe. Zaradi razlike delnih tlakov vodne pare na vodni površini in v zračnem toku prihaja do

Through experiment we found the optimal impregnating material, which also enables good wetability of the transfer area [11].

Two types of double layer paperboard suitable for a compact heat exchanger exist on the market. From these we have made two different heat exchangers.

Table 1 shows the parameters of both types of double layer paperboard used, and computed values for the hydraulic diameter D_h and heat transfer area density *A/V*.



Sl 2. *Kartonski križni prenosnik toplote*

Fig. 2. *Cross-flow paperboard heat exchanger*

The characteristics for both paperboard heat exchangers have been determined by measurement. These characteristics enable determination of the heat transfer coefficient and pressure drop for a known air flow rate through the heat exchanger [11].

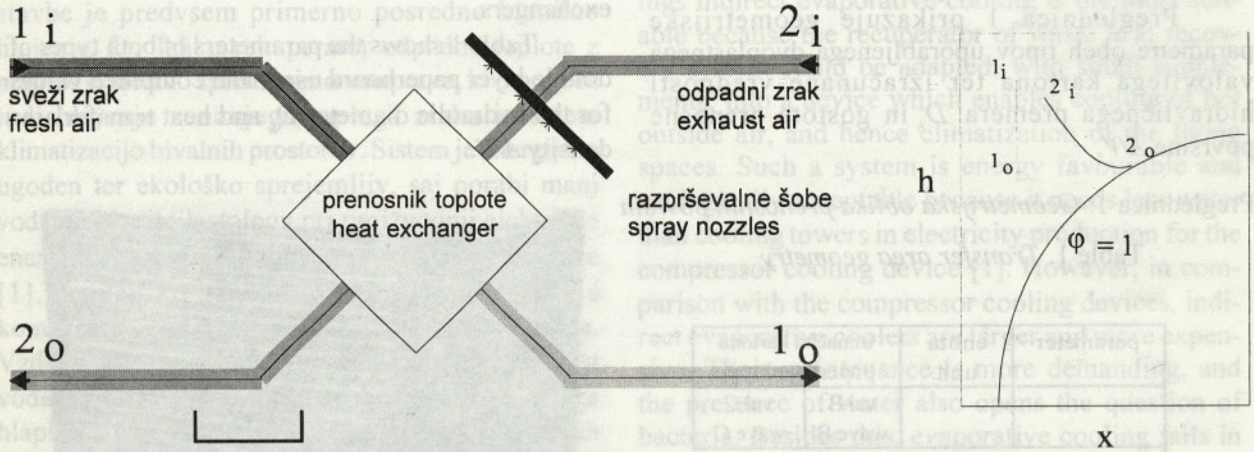
The measurements have shown adequate impregnation of the paperboard and very good wetability of the transfer area on the secondary side of the heat exchanger.

2 INDIRECT EVAPORATIVE COOLING

Evaporative cooling is one of the oldest cooling methods known [1]. We distinguish between direct and indirect evaporative cooling. For living space cooling, indirect evaporative cooling is more appropriate. By indirect evaporative cooling, air is cooled so that it is passed over the surface which is evaporatively cooled on the other side. Fresh cooled air does not come into direct contact with water, and so the moisture content of the air is not increased. Such a cooler, and the corresponding psychrometric Mollier h-x chart are schematically shown in Figure 3.

On the secondary side of the heat exchanger there is a thin water film in addition to the air flow. The water is distributed by spray nozzles. Because of the difference between water steam partial pressure on the water surface and in the air stream, water hlapenja vode. Temperatura zraka se zniža, prav tako pa se ohladi tudi film vode. Temperatura, na katero je teoretično mogoče ohladiti film vode in tudi primarni zračni tok, je enaka temperaturi vlažnega termometra sekundarnega zračnega toka na vstopu v prenosnik toplote [2] in [3].

evaporation occurs. The air temperature drops, and the water film also cools down. The temperature at which it is theoretically possible to cool down the water film and also the primary air flow equals the secondary air wet bulb temperature at the heat exchanger inlet [2] and [3].



Sl. 3. *Shematski prikaz delovanja posrednega hlapilnega hladilnika zraka*

Fig. 3. *Operation of indirect evaporative cooler*

Za študijo dejanskih razmer v prenosniku toplote ter za potrebe dimenzioniranja smo naredili matematični model prenosa toplote in snovi v posrednem hlapilnem hladilniku zraka [11] ter računalniški program, ki omogoča izračun izstopnih parametrov ob danih vstopnih parametrih zraka in vode glede na izbrane dimenzije križnega kartonskega prenosnika toplote. Program omogoča tudi preračun za primer rekuperacije odpadne toplote. Z meritvami smo verificirali tako matematični model kakor tudi računalniški program.

3 ENERGIJSKA ANALIZA POSLOPJA

Hladilna moč posrednega hlapilnega hladilnika zraka je odvisna od velikosti prenosnika toplote in od stanja zraka v prostorih. Naprava, ki bi pokrila celotno hladilno obremenitev poslopja, bi bila velika in draga. Zato smo naredili energijsko analizo enodružinske stavbe, hlajene z dvema različno velikima, dimenzijsko in cenovno sprejemljivima, posrednima hlapilnima hladilnikoma zraka [11], [12].

Analizirali smo temperaturne razmere v stavbi in doseženo stopnjo ugodja. Za primerjavo smo naredili tudi analizi za primer naravnega prezračevanja stavbe, in sicer za štirikratno izmenjavo zraka na uro.

Za analizo smo izbrali eksperimentalno stavbo Moškon, izdelovalca Marles iz Maribora, ki je bila zasnovana v okviru projekta Sončna vas Kamnica.

A mathematical model of heat and mass transfer in the indirect evaporative cooler has been developed for study of conditions in the heat exchanger and for dimensioning [11]. A computer program has also been made to enable calculation of the outlet parameters from the known inlet parameters of air and water for the chosen dimensions of the cross-flow heat exchanger. The computer program also allows for calculations of heat recovery. The mathematical model and computer program have been verified by measurements.

3 BUILDING ENERGY ANALYSIS

Indirect evaporative cooler cooling-power depends on the heat exchanger dimensions and on the air-condition in the rooms. Cooler which would cover the complete building cooling load would be big and expensive. Therefore we made energy analysis of one family house cooled by two differently sized indirect evaporative coolers, of suitable dimensions and at an acceptable price [11], [12].

We analysed the temperatures in the building and the comfort level attained. For comparison, simple ventilation of the building with four air changes per hour was also analysed.

The experimental building Moškon, produced by Marles from Maribor, was chosen. The building has been designed for the Sunny Village Kamnica project. Simulations were made using the TRNSYS

Objekt smo popisali v programskem paketu TRNSYS [10] in [7], ki je med drugim namenjen tudi za računalniško simuliranje toplotnega odziva stavbe. Dodali smo modul za izračun ugodja v prostoru, ki smo ga naredili po standardu ISO 7730 [8].

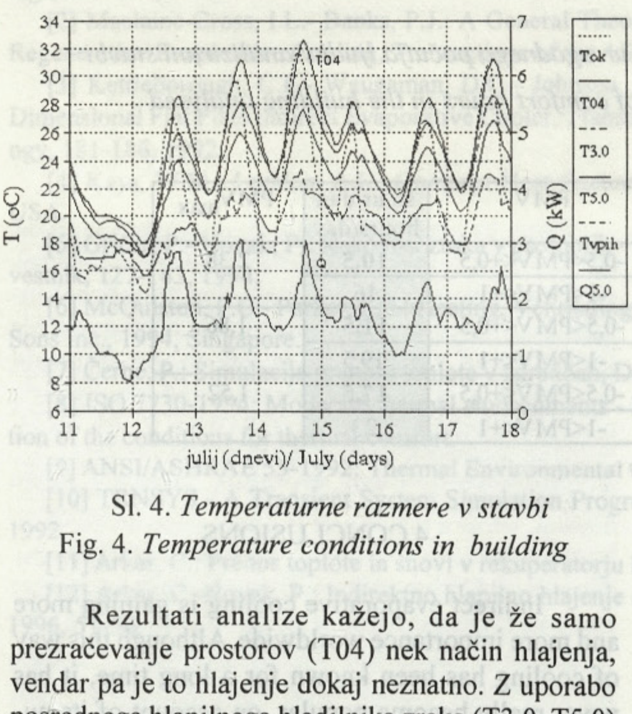
Toplotne dobitke stavbe sestavljajo solarni in notranji dobitki stavbe, ki smo jih definirali s toplotno oddajo svetil in ljudi. Pri popisu objekta nismo upoštevali možnega senčenja oken. Tako so solarni dobitki upoštevani v celoti. Opravljena analiza tako prikazuje skrajne bivalne razmere. V dejanskih razmerah lahko nadstreški, okenska senčila in zunanja vegetacija bistveno zmanjšajo solarne dobitke stavbe ter s tem temperaturne ekstreme v njej.

Na slikah 4 in 5 so prikazani rezultati opravljenih analiz za mesec julij. Zaradi slabše preglednosti grafa, ki prikazuje rezultate analize za celoten mesec, je prikazan le graf, ki zajema podatke za teden dni.

simulation program [10] and[7], which is also used for computer simulation of building heat response. A module for comfort analysis, made according to the ISO 7730 standard [8], has been added.

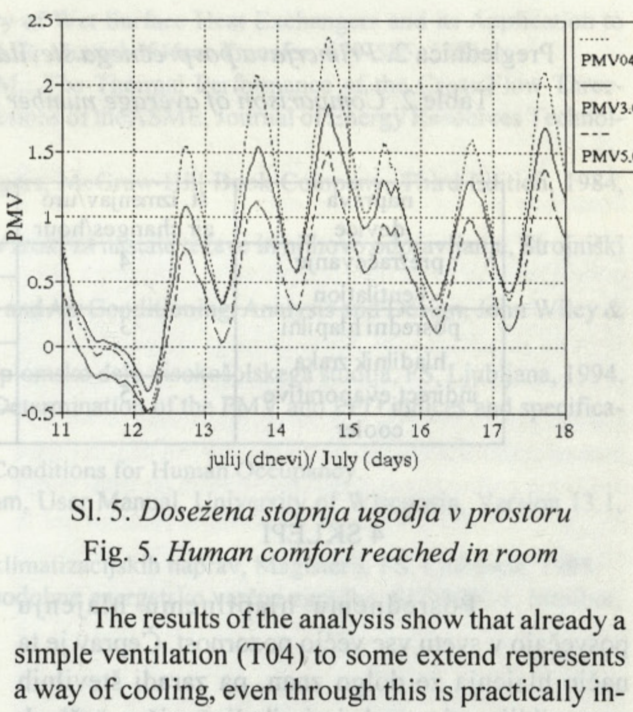
Building heat gains consist of solar gains and internal building gains which are defined by heat gains from human bodies and from lights. Possible window shading was ignored. The complete solar gains are obtained by simulation. The analysis which has been made thus represents extreme living conditions. In real living conditions architectural shading, window shading and vegetation could significantly reduce solar gains of the building and through this the maximum temperature of the building.

Figures 4 and 5 shows analysis results for month of July. Data for only one week are shown because of the better readability of the graph.



Sl. 4. *Temperaturne razmere v stavbi*

Fig. 4. *Temperature conditions in building*



Sl. 5. *Dosežena stopnja ugodja v prostoru*

Fig. 5. *Human comfort reached in room*

Rezultati analize kažejo, da je že samo prezračevanje prostorov (T04) nek način hlajenja, vendar pa je to hlajenje dokaj neznatno. Z uporabo posrednega hlapilnega hladilnika zraka (T3.0, T5.0) lahko temperaturo v prostoru, v primerjavi s prezračevanjem, znižamo tudi do 5 °C, seveda odvisno od velikosti oziroma moči hladilne naprave.

Temperaturi vpihovanega zraka (Tvpih) se bistveno ne razlikujeta med seboj. Tako lahko povečamo hladilno moč oziroma znižamo temperaturo v prostoru le s povečevanjem pretoka vpihovanega zraka oziroma števila izmenjav zraka na uro. Ker je temperatura vlažnega termometra prostorskega zraka ponoči približno enaka ali celo višja od temperature zunanjega zraka (Tok), je bolj primerno, da ponoči uporabimo naravno prezračevanje. S tem lahko v nočnem času bolj ohladimo prostorski zrak.

The results of the analysis show that already a simple ventilation (T04) to some extend represents a way of cooling, even through this is practically insignificant. With indirect evaporative cooling (T3.0, T5.0) temperatures in the building could be dropped to 5 °C, comparing to a simple ventilation, depending on the cooling device used and it's cooling power.

The temperatures of the air supply (Tvpih) do not differ much between each other. So cooling power or room temperature could be regulated only by increasing air supply flow rate or air changes per hour. The wet bulb temperature of room air is equal to or even higher than the ambient temperature (Tok) during the night, so it is more suitable to use ventilation instead of indirect evaporative cooling at night time. The room air could in this way be significantly cooled during the night.

Najpomembnejša je seveda analiza dosežene stopnje ugodja v prostoru. Stopnja ugodja je izražena z indeksom PMV, ki pomeni s številom izraženo počutje ljudi. Število se giblje v mejah +3 (vroče) do -3 (mrzlo). Analizo ugodja smo naredili za osebo, ki je oblečena v lahko delovno obleko in opravlja lahka domača dela. Gibanje indeksa PMV v mesecu juliju je razvidno s slike 5. Vsekakor zanimivejša je morda primerjava, koliko ur na dan je stanje zraka v bivalnem delu analizirane stavbe v območju ugodja. To območje je po standardu [9] definirano kot stanje zraka, v katerem se ugodno počuti več ko 90 odstotkov ljudi, kar ustreza vrednostim indeksa PMV med -0,5 in +0,5. V preglednici 2 smo dodali tudi primerjavo števila ur, ko je indeks PMV v območju -1 do +1, to je v območju prijetno toplega do prijetno hladnega počutja. Prikazana pa je tudi največja vrednost indeksa PMV (PMVmax), dosežena v mesecu juliju.

The most important analysis is that of the comfort attained. Comfort is expressed by the PMV (predicted mean vote) index which represents human comfort expressed by numbers. PMV moves from +3 (hot) to -3 (cold). A comfort analysis was made for a person dressed in light working clothes and carrying out light household activity. Figure 5 shows the PMV index for month of July. More interesting might be a comparison of hours per day when air conditions reach the comfort zone. The comfort zone is defined according to standard [9] as a state of air with which more than 90% of people are satisfied and this corresponds to the values of PMV index at between -0,5 and +0,5. Table 2 also shows hours per day when the PMV index is between -1 and +1, which equals the range between slightly cold and slightly warm. The maximum value of the PMV index (PMVmax) reached in July is also shown.

Preglednica 2. *Primerjava povprečnega števila ur ugodnega počutja ljudi v analizirani stavbi*

Table 2. *Comparison of average number of comfort hours in the building analysed*

naprava device	št. izmenjav/uro air changes/hour	PMV	št. ur/dan hours/day	PMV_{max}
prezračevanje ventilation	4	-0,5<PMV<+0,5	10,5	2,38
		-1<PMV<+1	16	
posredni hlapilni hladilnik zraka indirect evaporative cooler	3	-0,5<PMV<+0,5	11,5	1,86
		-1<PMV<+1	19.5	
	5	-0,5<PMV<+0,5	17,5	1,52
		-1<PMV<+1	23	

4 SKLEPI

Posrednemu hlapilnemu hlajenju posvečajo v svetu vse večjo pozornost. Čeprav je ta način hlajenja že dolgo znan, pa zaradi številnih pomanjkljivosti v praksi ni nikoli resnično zaživel. Z razvojem kompaktnih prenosnikov toplote so posredni hlapilni hladilniki zraka postajali vse manjši, kar je bila do sedaj ena od njihovih glavnih pomanjkljivosti. Tudi energijska kriza, spoznanje o škodljivosti freonov in novi materiali so prispevali k novemu zagonu pri razvoju in uporabi posrednih hlapilnih hladilnikov zraka.

V individualnih stavbah ta naprava postane ekonomična, če jo kombiniramo s prezračevalno napravo. Kakor je pokazala opravljena energijska analiza stavbe, se temperatura vpihovanega zraka prek dneva giblje med 18 °C in

4 CONCLUSIONS

Indirect evaporative cooling is gaining more and more importance worldwide. Although this way of cooling has been known for a long time, it has never really become popular, on account of its numerous disadvantages. With development of heat exchangers indirect evaporative coolers are becoming smaller and smaller, their size being until now one of their main disadvantages. The energy crisis, knowledge about the harmfulness of CFC's and new materials have also helped towards a new thrust in the development and use of indirect evaporative coolers.

In individual buildings this device becomes economical if it is combined with a heat recovery unit. As the energy analysis of energy efficient building shows, the supply temperatures range between 18 °C and 22 °C. These are high temperatures for

22 °C. Za klimatizacijo so to visoke temperature. Za optimalno počutje ljudi je tako potrebno zagotoviti ustrezno senčenje stavbe. S tem zmanjšamo solarne dobitke stavbe in potrebno velikost hladilne naprave. Tako ta postane dimenzijsko in cenovno sprejemljiva.

Naše raziskave kartonskih prenosnikov toplote so pokazale, da je karton primeren material za prenosnike toplote; je lahek, cenovno ugoden, uporabljena impregnacija pa zagotavlja primerno dobo trajanja.

climatisation. So for optimum comfort conditions, appropriate building shading has to be assured. Solar energy gains are thus reduced, and hence also the necessary size of the cooling device. The cooling device thus becomes acceptable both in size and in price.

Our research work on paperboard heat exchangers shows that paperboard is an appropriate material for heat exchangers. It is light and cheap, and the impregnation used ensures a suitable working life.

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Prejeto: 9.5.1996
Received:

Sprejeto: 28.6.1996
Accepted: