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Dinamični model nadzora temperature prostora s stropnim hlajenjem

A Dynamic Model for the Control of a Room's Temperature by Means of Ceiling Cooling

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V prispevku je predstavljen model dinamičnega simuliranja toplotnih razmer v prostoru v poletnem času. Analizirali smo dva različna sistema nadzora temperature prostora: stropno hlajenje in dovod hladnega zraka. Predstavljene so primerjave obeh sistemov: primerjava parametrov vpliva in vpliv na spremembo temperature prostora.

(Ključne besede: modeli dinamični, temperature sobne, regulacija temperature, hlajenje stropov)

This paper presents a dynamic-simulation model of a room's thermal behavior during summer conditions. Two different systems for the room's temperature control, i.e. ceiling cooling and cold air supply, were analyzed. A comparison of the influencing parameters and the influence on the operating room temperature variation applying both systems are reported.

(Keywords: dynamic models, room temperature control, ceiling cooling)

0 UVOD

Hladilno obremenitev lahko definiramo kot količino energije, ki jo vnašamo v prostor in hkrati odvzemamo klimatizacijski napravi, da ohranjamo stalno temperaturo v prostoru. To količino energije lahko odvzamemo z vpihovanjem ohlajenega zraka v prostor ali z ohlajanjem katere izmed površin v prostoru, npr. stropno hlajenje. V tem primeru se izmenjava energije večinoma izvaja s prenosom toplote s sevanjem med notranjimi površinami v prostoru. Različna načina ohranjanja sobne temperature v teh dveh primerih predstavljata prav tako različne parametre toplotnega ugodja.

Hladilna obremenitev prostora je toplota, ki jo je treba prenesti iz prostora (s hlajenjem), da ohranimo stalno temperaturo zraka – povprečno sobno temperaturo. Hlajenje izvajamo z zrakom, ki ga hladimo z različnimi sistemi (OPKH – ogrevanje, prezračevanje, klimatizacija, hlajenje - HVAC). Eden izmed načinov nadzora temperature prostora je stropno hlajenje. Pri tem postopku se večina toplote znotraj prostora prenaša s sevanjem med hladnejšim stropom in preostalimi, toplejšimi površinami v prostoru. Različni sistemi za OPKH, ki jih uporabljamo za nadzor temperature v prostoru,

0 INTRODUCTION

The cooling load may be defined as the amount of energy that is transferred to the room air and simultaneously removed by conditioning equipment, to keep a constant temperature in the room. This amount of energy can be removed either by blowing cooled air in to the room or by cooling one of the interior surfaces of the room, for example, ceiling cooling. In this case, the exchange of energy takes place mostly as heat transfer due to radiation between interior surfaces of the room. The different characters of room temperature maintenance in these two cases also mean different thermal comfort parameters.

The room-cooling load is the heat to be transferred out of the room (by cooling) in order to keep a constant air temperature – the mean room temperature. Cooling is carried out by the air, which is cooled in various HVAC (Heating, Ventilation, Airconditioning, Cooling) systems. One of the methods for room temperature control is ceiling cooling. In this procedure, the majority of the heat transferred within the room is a result of radiation between the colder room ceiling and other room surfaces, which are warmer. A different HVAC system used for control of the room's temperature causes a different variapovzročajo različne oblike parametrov, ki določajo posameznikovo ugodje v prostoru. Da bi lahko raziskali medsebojni vpliv parametrov, smo razvili modeliranje in simuliranje toplotnih sprememb določenega prostora. V analiziranem modelu je bila zahtevana temperatura zraka v prostoru ϑ_p = 24°C za obdobje 24 ur. Določili smo hladilno obremenitev prostora in temperature vseh površin za oba obravnavana primera.

tion of the parameters, which determine personal comfort. In order to examine this interaction, modeling and simulation of the thermal behavior specific of the room has been carried out. In the analyzed model, the required air temperature of the room during the 24 hour period was ϑ_p = 24 °C. The cooling load of the room and the temperatures of all the surfaces were determined in both the treated models.

1 RAČUNSKA METODA

1 CALCULATION METHOD

Izračun stropne hladilne obremenitve je mogoč, ko določimo enačbe toplotnega ravnotežja za vse stične površine prostora [1]. Enačbe, ki določajo stopnjo prenosa toplote na katerikoli notranji površini *j* v določenem času *t*, so:

Calculation of the room-cooling load is possible when the equations for thermal equilibrium for all bordering surfaces of the room and for the room air are established [1]. The equations determining the heat transfer rate at any interior surface *j* at a specific time *t* are:

$$q_{j,t} = \alpha_{j,t}\left(\vartheta_p - \vartheta_{j,t}\right) + \sum_{k=1}^{B} G_{j,k}\left(\vartheta_{k,t} - \vartheta_{j,t}\right) + RA_{j,t} \quad (1)$$

kjer je $G_{j,k}$:

where $G_{j,k}$ is:

$$G_{j,k} = 4\,\varepsilon_j\,\varepsilon_k\,\sigma\,T_p^3\,F_{j,k} \quad (2)$$

Toplotni tok na notranjo površino, ki se izvaja s konvekcijo in sevanjem, je enak toplotnemu toku prenesenemu na površino s prevodom.

The heat flux on the inner surface, which is realized through convection and radiation, equals the heat flux transferred to the surface by conduction.

$$q_{j,t} = \sum_{i=0}^{Nj} X_{j,i}\vartheta_{j,t-i} - \sum_{i=0}^{Nj} Y_{j,i}\vartheta_{j,t-i} + R_j q_{j,t-i} \quad (3)$$

Vstopni parametri, ki določajo toplotno obremenitev, so spremembe temperature na zunanji površini zidu *j*, ki hkrati vplivajo na spremembe temperature na notranji površini zidu *j* in nasprotno. Zato je treba določiti enačbe toplotnega ravnotežja na znanji površini *j*. Zunanje površine mejijo na okolico ali na sosednje prostore. Ko določimo vse enačbe toplotnega ravnotežja, oz. toplotne tokove za vse zidove na notranjih in zunanjih površinah, dobimo sistem *n* enačb z *n* neznanimi temperaturami notranjih površin zidov. Izračun hladilne obremenitve prostora je sedaj mogoč s povprečenjem enačbe za toplotno ravnotežje zraka v prostoru.

Input parameters, which determine the heat load, are the temperature changes on the exterior wall surface *j*, which at the same time influence temperature changes on the interior wall surface *j*, and vice versa. It is necessary therefore, to establish the equations of thermal equilibrium on the exterior surface *j*. The exterior surfaces are adjacent either to the environment or to the neighboring rooms. When all the thermal-balance equations, i.e. the heat fluxes for all the walls on the interior and exterior surfaces are established, a system of *n* equations with *n* unknown temperatures for the interior wall surface is obtained. Calculation of the room-cooling load is now possible by means of the equation for thermal equilibrium of the interior air.

$$\Phi_{p,t} = \rho c_p V_{Kl,t}\left(\vartheta_p - \vartheta_{Kl,t}\right) = \sum_{j=1}^{B} A_j \alpha_{j,t}\left(\vartheta_{j,t} - \vartheta_p\right) + \rho c_p V_{In,t}\left(\vartheta_{v,t} - \vartheta_p\right) + RK_{p,t} \quad (4)$$

Sistem enačb, ki določajo temperature notranjih površin in hladilno obremenitev, je v primeru stropnega hlajenja enak. V prvem koraku izračuna določimo temperaturo površine stropa in nato v časovnih korakih vsako uro, ko je hladilna obremenitev enaka nič. Tako lahko nadziramo notranjo temperaturo prostora z nadzorom stropne temperature.

Na temelju opisanega modela, smo razvili lasten računalniški program. Program omogoča simuliranje toplotnega obnašanja določenega prostora.

The system of the equations which determine the interior-surface temperatures and the cooling load is identical to the case of ceiling cooling. The temperature of the ceiling surface is set for the first step of the calculation, and is subsequently determined in hour-by-hour steps for the ceiling temperature at which the cooling load equals zero. In this way, control of the interior temperature is possible by controlling the ceiling temperature.

Based on the described model, an authorized computer program was developed. The program enables simulation of the thermal behavior of one specific room.

2 OPIS MODELA IN REZULTATI

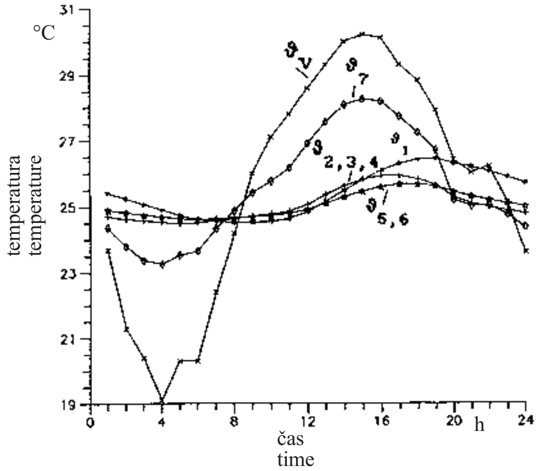
Izmere izbranega prostora so 4 × 5 × 3 m z eno zunanjo steno (1) in enim oknom (7), velikosti 3,2 × 1,25 m. Vmesni zidovi (2,3,4), tla (5) in strop (6) mejijo na prostore z enakimi toplotnimi razmerami, kakršne ima analiziran prostor. Prostor je usmerjen na jug in postavljen v zagrebški regiji, z vsemi potrebnimi podatki za značilen poletni dan, 21. julij. Notranji viri toplote so tri osebe in naprave z močjo 100 W. Temperatura v prostoru je ϑ_p = 24°C.

Analize rezultatov so prikazane v diagramih, Sl. 1-4.

2 MODEL DESCRIPTION AND RESULTS

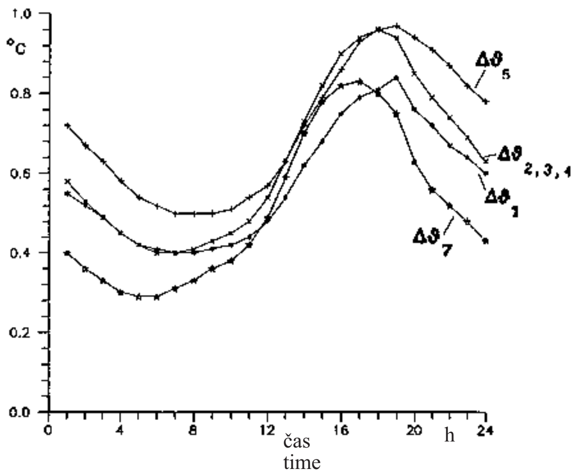
The dimensions of the chosen room are 4 × 5 × 3 m with one external wall (1) having one window (7) of size 3.2 × 1.25 m. Partitioning walls (2,3,4), floor (5) and ceiling (6) are adjacent to the rooms having thermal conditions identical to the conditions in the analyzed room. The room orientation is south, the location is the Zagreb region, with all relevant data characteristic for a summer's day i.e. July 21. The internal heat sources are three persons and equipment of 100 W power. The room temperature is ϑ_p = 24 °C.

Analysis of the results are shown in diagrams, Fig.1 - 4.



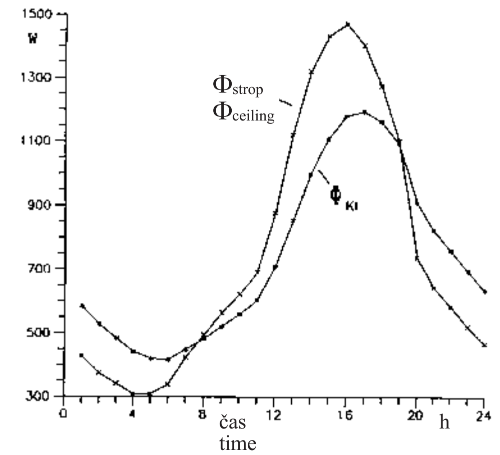
Sl.1. *Potek zunanje temperature in notranjih temperatur površin v prostoru*

Fig. 1. *Variation of enviroment temperature and room surface interior temperature*



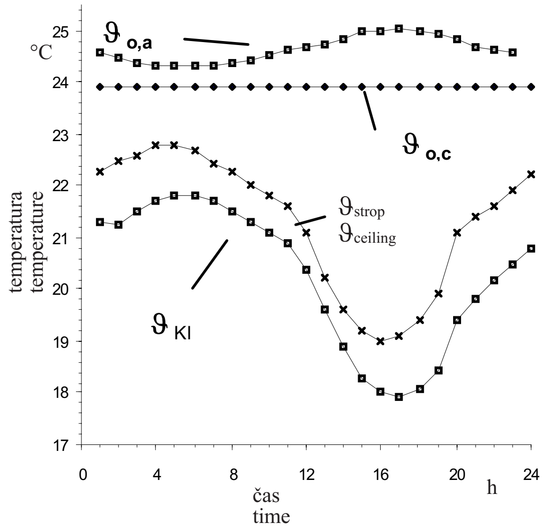
Sl.2. *Razlika med temperaturami površin v prostoru z upoštevanjem in brez upoštevanja hladilne obremenitve*

Fig. 2. *Difference between room-surface temperatures with and without applied ceiling cooling load*



Sl.3. *Pretok stropne hladilne obremenitve*

Fig. 3. *Ceiling cooling load flow*



Sl.4. *Sprememba temperature stropa in občutene temperature z upoštevanjem hladilne obremenitve na sliki 3*

Fig. 4. *Variation of ceiling temperature and operating temperature with applied cooling load in figure 3*

Sprememba zunanje temperature ϑ_v in ustreznih temperatur vseh notranjih površin prostora so prikazane na sliki 1. Ustrezna hladilna obremenitev Φ_{Kl} je prikazana na sliki 3. Na temelju največje hladilne obremenitve smo izračunali pretok zraka, ki je potreben za pokritje potreb hladilne obremenitve, V_{kl} = 600 m^3/h. Izračunali smo tudi ustrezno temperaturo zraka ϑ_{Kl}, ki je prikazana na sliki 4. Diagram na sliki 2 prikazuje razliko med temperaturami na površinah v prostoru v skladu s sliko 1 in temperaturami istih površin ob upoštevanju stropnega hlajenja. Sprememba hladilne obremenitve za ta primer je prikazana na sliki 3, ustrezna temperatura stropa, ϑ_{strop}, pa na sliki 4. Ustrezni občuteni temperaturi prostora $\vartheta_{0,a}$ in $\vartheta_{0,c}$ sta prav tako prikazani na sliki 4.

Na temelju izračuna temperatur notranjih površin smo za oba analizirana modela določili srednjo sevalno temperaturo in občuteno temperaturo [4]. V primeru, ko vzdržujemo temperaturo prostora s "pokrivanjem" hladilne obremenitve s cirkulacijo hladnega zraka, se srednja temperatura sevanja spreminja od 24,3°C (ob 5h) do 25,9°C (ob 17h) in občutena temperatura prostora od 24,3°C do 25°C. Sprememba teh parametrov ustreza spremembi hladilne obremenitve prostora. Kadar uporabljamo stropno hlajenje, sta srednja temperatura sevanja in občutena temperatura prostora stabilni in sta enaki 23,8°C oziroma 23,9°C.

The variation of the environment temperature, ϑ_v, and the corresponding temperatures of all the room's interior surfaces are shown in Fig. 1. The adequate cooling load, Φ_{Kl}, is shown in Fig. 3. Based on the maximal cooling load, the air volume needed to cover the cooling load is calculated, it is V_{kl} = 600 m^3/h. The corresponding air temperature, ϑ_{Kl}, is also calculated and is shown in Fig. 4. The diagram in Fig. 2 shows the difference between the room-surface temperatures according to Fig. 1 and the temperatures of the same surfaces when ceiling cooling is applied. The cooling-load variation in this case is shown in Fig.3 and the corresponding ceiling temperature, $\vartheta_{ceiling}$, is shown in Fig. 4. The corresponding operating room temperatures $\vartheta_{0,a}$ and $\vartheta_{0,c}$ are also shown in Fig. 4.

Based on the calculation of interior-surface temperatures in the room, in both analyzed models the mean temperature of radiation and the operating room temperature are determined [4]. In the case when the room temperature is maintained by covering of the cooling load by means of cold air circulation, the mean temperature of radiation varies from 24.5 °C (5 A.M.) to 25.9 °C (5 P.M.), and the operating room temperature varies from 24.3 °C to 25 °C. The variation in these parameters corresponds with the variation in the room-cooling load. When ceiling cooling is used, the mean temperature of radiation and operating room temperature are stable, i.e. 23.8 °C and 23.9 °C, respectively.

3 SKLEP

Krmiljenje temperature prostora z uporabo zračnega sistema je v primerjavi s stropnim hlajenjem pokazal zmanjšanje časovne zakasnitve in povečanje amplitude največje hladilne obremenitve. Z upoštevanjem kriterija posameznikovega ugodja v določenem prostoru, to je z upoštevanjem srednje sevalne temperature in dejanske temperature v prostoru, stropno hlajenje zagotovi izjemno stabilnost teh temperatur. Hkrati pa je njihova vrednost zelo blizu temperaturi zraka v prostoru, kar ustreza sobni temperaturi.

3 CONCLUSION

Control of the temperature of the room by means of the air system shows a decrease in the time delay and an increase of the amplitude of the maximum cooling load, in comparison with ceiling cooling. When considering the criteria for personal comfort in a specific room, i.e. the mean radiation temperature and the actual room temperature, ceiling cooling provides remarkable stability of these temperatures. At the same time, their value is very close to the temperature of the room air, which corresponds to the room temperature.

4 OZNAČBE
4 NOMENCLATURE

količina toplote prenešena z notranje površine j v času t, W/m^2	$q_{j,t}$	rate of heat conducted out of interior surface j at time t, W/m^2
koeficient prestopa toplote notranje površine j v času t, W/m^{2}K	$\alpha_{j,t}$	convective heat transfer coefficient at the interior surface j at time t, W/m^{2}K
temperatura notranjega zraka, °C	ϑ_p	inside-air temperature, °C
povprečna temperatura notranje površine j v času t, °C	$\vartheta_{j,t}$	uniform temperature of interior surface j at time t, °C
število površin (j = 1, 2,.... B, k = 1,2,.... B)	B	number of surfaces (j = 1, 2,.... B, k = 1,2,.... B)
emisijski faktor površin j in k	ε_j, ε_k	emission factor of the j and k surface
Boltzmannova sevalna konstanta, 5,67·10^{-8} W/(m^2 K^4)	σ	Boltzmann radiation constant, 5.67·10^{-8} W/(m^2 K^4)

faktor oblike sevanja med notranjima površinama *j* in *k*	$F_{j,k}$	radiation shape factor between interior surfaces *j* and *k*
povprečna temperatura notranje površine *k* v času *t*, °C	$\vartheta_{k,t}$	uniform temperature of interior surface *k* at time *t*, °C
količina sončnega sevanja in sevalne toplote opreme, razsvetljave in ljudi v prostoru, ki jo absorbira notranja površina *j* v času *t*, W/m²	$RA_{j,t}$	rate of solar heat and rate of heat radiated from equipment, lights and occupants absorbed by interior surface *j* at time *t*, W/m²
funkciji prevoda, [2], [3]	$X_{j,i}$,$Y_{j,i}$,(R_j)	conduction transfer functions, [2], [3]
število členov funkcije prevoda (i = 0,1,.....Nj)	Nj	number of conduction transfer function terms (i = 0,1,.....Nj)
povprečna temperatura notranje površine *j* v času *t*-1, *t*-2, ..., *t-Nj* (ure) pred časom *t*, °C	$\vartheta_{j,t-i}$	uniform temperature of interior surface *j* at time *t*-1, *t*-2, ..., *t-Nj* (hours) before time *t*, °C
hladilna obremenitev prostora v času *t*, W	$\Phi_{p,t}$	room-cooling load at time *t*, W
gostota zraka, kg/m³	ρ	air density, kg/m³
specifična toplota zraka, J/kgK	c_p	air specific heat capacity, J/kgK
masni pretok ventilacijskega zraka v času *t*, kg/s	$V_{Kl,t}$	mass flow rate of conditioning air at time *t*, kg/s
temperatura ventilacijskega zraka v času *t*, °C	$\vartheta_{Kl,t}$	conditioning air temperature at time *t*, °C
masni pretok zunanjega zraka, ki prehaja v prostor v času *t*, kg/s	$V_{In,t}$	mass flow rate of outdoor air infiltrating into room at time *t*, kg/s
temperatura zunanjega zraka v času *t*, °C	$\vartheta_{v,t}$	outdoor air temperature at time *t*, °C
količina toplote,ki jo oddajajo oprema, ljudje v prostoru in zrak, ki prehaja v prostor v času *t*, W	$RK_{p,t}$	rate of heat obtained from equipment, occupants and convected into room air at time *t*, W
občutena temperatura v prostoru, ko je hlajenje zraka upoštevano, °C	$\vartheta_{0,a}$	operating room temperature when air cooling is applied, °C
občutena temperatura v prostoru, ko je stropno hlajenje upoštevano, °C	$\vartheta_{0,c}$	operating room temperature when ceiling cooling is applied, °C

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