© Strojniški vestnik 48(2002)6,318-331
ISSN 0039-2480
UDK 628.83:628.85
Izvirni znanstveni članek (1.01)
© Journal of Mechanical Engineering 48(2002)6,318-331
ISSN 0039-2480
UDC 628.83:628.85
Original scientific paper (1.01)

Prostorska porazdelitev faktorja ugodja na temelju numeričnega modeliranja naravne konvekcije

A Three-Dimensional Factor-of-Comfort Distribution Based on Numerical Modeling of Natural Convection

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Prispevek obravnava prikaz načrtovanja notranjega ugodja v sistemih ogrevanja in klimatizacije. S predstavljenim algoritmom lahko že v fazi načrtovanja notranjega okolja napovemo delež ljudi, ki bodo v območju bivalne cone izražali zadovoljstvo s toplotnim okoljem ter s tem napovemo kakovost notranjega udobja v načrtovani bivalni coni. Takšen način načrtovanja ugodja je pomemben predvsem za inženirsko prakso, saj nam omogoča zagotovitev udobnega notranjega okolja ob majhnem zdravstvenem tveganju ljudi ob hkratnem upoštevanju porabe energije za doseganje tega udobja.

(Ključne besede: klimatizacija, prenos toplote, prenos snovi, konvekcija naravna, dinamika tekočin)

This paper discusses the problem of providing a comfortable indoor environment with heating and air-conditioning systems. With the use of an algorithm the thermal sensation and the degree of discomfort of people can be presented and acceptable thermal environmental conditions for comfort can be specified. The presented method for designing the thermal comfort is important for engineering practise and shows how to provide a comfortable indoor environment with a low health risk for the occupants.

(Keywords: air-conditioning, heat transfer, materials transfer, natural convection, fluid dynamics)

0 UVOD

Načrtovanje ugodja v bivalni coni je z razvojem računalniške tehnologije, krmilnih sistemov in številnih raziskav o vplivu parametrov zraka na človeka v zadnjih letih doživelo silovit napredek. Z računalniškimi simuliranji se razvijajo novi načini prezračevanja z namenom, da bi se po eni strani povečalo ugodje ljudi v prostorih in se s tem zvečala učinkovitost na delovnem mestu, po drugi strani pa se z optimiranjem količine vpihovanega zraka v prostore le-ta zmanjšuje, kar vpliva na izbiro manjših elektromotorjev za pogon ventilatorjev ter skupaj s kakovostno rekuperacijo na zmanjšanje porabe električne energije in toplotnih izgub zaradi prezračevanja.

Namen načrtovanja ogrevanja, hlajenja, prezračevanja in klimatizacije je zagotoviti udobno notranje okolje ob majhnem zdravstvenem tveganju za ljudi, ki so v teh prostorih. Pri tem moramo upoštevati predvsem porabo energije za doseganje tega udobja, saj je bolj priporočljivo zmanjšati vire, ki onesnažujejo zrak, kakor pa povečati izmenjavo zraka v prostoru.

0 INTRODUCTION

Designing to provide comfort in an occupied zone has made a lot of progress with the development of computer design, control systems and considerable research on the influence of air quality. New ways to design a ventilation system with computer-aided design can be developed to increase people's comfort and their efficiency at work. It can have an influence on optimising the quantity of the air inlet, on reducing air comsumption, and the use of smaller electric motors for ventilators, which together with recycling can reduce the consumption of electrical energy and heat resulting from ventilation.

The pupose of heating, cooling, ventilating and air-conditioning is to provide a comfortable indoor environment with a low health risk for the occupants. This environment should be achieved in such a way that the energy consumption is low. As a consequence, the best route is to reduce indoor pollution sources rather then increase the ventilation rate.

Pri načrtovanju se opiramo na standarde, ki določajo, kako kakovost notranjega okolja vpliva na obliko, delovanje in nadzor prezračevanja ter klimatizacijskih sistemov. Tako je za uspešno načrtovanje notranjega okolja treba določiti kriterije in območja, v katerih ti kriteriji še ustrezajo neki odločitvi. Treba je definirati kakovost notranjega okolja in jo primerjalno vrednotiti z raziskanimi vplivi na človekovo počutje. Da pa bi dobili natančne odgovore, je treba določiti kakovost okolja v vseh točkah bivalnega okolja, saj bomo le tako lahko zagotovo že v fazi načrtovanja zagotovili udobje v bivalni coni.

Standardni načini analize primernosti klimatizacije za izbrani prostor in delovne razmere uporabljajo integralni postopek, ki temelji na povprečnih vrednostih vplivnih parametrov. Zaradi resnice, da na počutje ljudi v prostoru v glavnem vplivajo lokalne vrednosti vplivnih parametrov (hitrost in temperatura zraka v določenem delu prostora, kjer se oseba zadržuje), lahko takšen način obravnave problema kaj hitro postane nezadosten.

Pomembno novost pri projektiranju notranjega okolja so v zadnjih letih prinesle metode računalniške dinamike tekočin ([1] in [9]), ki temeljijo na numeričnem reševanju vodilnih enačb toka tekočin in prenosa toplote, katerih rezultat so lokalne vrednosti vplivnih parametrov. Z numerično analizo [7] lahko tako določimo območje v prostoru, kjer se bo določen odstotek ljudi zagotovo počutil udobno, kar je tudi cilj projektiranja klimatizacije prostorov. Prispevek tako podaja nov postopek neposrednega določanja vrednosti parametrov za vrednotenje toplotnega okolja, ki temelji na metodah računalniške dinamike tekočin.

1 OPIS POSTOPKOV OCENITVE PRIMERNOSTI KLIMATIZACIJE

Preden se posvetimo osnovnemu cilju prispevka, si oglejmo na kratko opis parametrov in postopkov ocenitve primernosti klimatizacije. Najpomembnejši dejavnik, dejavnik ugodja, je definiran kot numerična vrednost, ki napoveduje toplotni občutek skupine ljudi na večstopenjski skali ob hkratni napovedi odstotka nezadovoljnih ljudi, ki niso v toplotnem ravnovesju z okolico. Če lahko torej s sistemom ogrevanja in klimatizacije že v fazi načrtovanja zagotovimo ustrezno toplotno okolje za predvideni odstotek zadovoljnih ljudi, lahko govorimo, da tudi dejansko "načrtujemo ugodje" v prostoru. Parametre, ki vplivajo na določitev dejavnika ugodja, podajajo standardi ([3] do [5]). Ti ponujajo v večini primerov tri kategorije kakovosti okolja, ki ga je treba prezračevati: kategorije A, B in C. Za vsak prostor ali stavbo si lahko izberemo različno kategorijo za toplotno okolje, kakovost zraka in akustično okolje.

We use standards to specify how the quality of the indoor environment can be expressed for the design, commissioning, operation and control of ventilation and air-conditioning systems. For the successful design of indoor environment criteria and of occupied zones these standards should be defined to get the appropriate solutions for designing the comfort. The quality of the indoor environment should be defined and compared with researched influences on the human body. To get useful answers the quality of the indoor environment should be defined for every point of the occupied zone and after that we can say that we design the indoor environment.

The standard's access to analyse appropriate air-conditioning systems for a defined room and working conditions uses an integral approach which is based on the average values of influential parameters. Because most influences on indoor comfort have local values of influential parameters (the velocity and temperature of the air in a defined part of the room where people can be expected) standard access can very quickly become insufficient.

In recent years an important novelty in the design of the indoor environment has been introduction of computational fluid dynamics ([1] and [9]), which are based on the numerical solutions of the governing equations of fluid flow and heat trasfer, the solutions of which are local values of the influential parameters. With a numerical analysis [7] we can define a zone in the space where a certain percentage of the occupants feel satisfied, and this is the essence of designing air-conditioning. This paper gives us a new approach to define the values of parameters in order to evaluate the indoor environment, which is based on the methods of computational fluid dynamics.

1 DESCRIPTION OF THE PROCEDURES USED TO ESTIMATE THE APPROPRIATE AIR-CONDITION

Before we focus on the main aim of the paper, let us have a look at a description of the parameters and procedures for estimating the appropriate air-condition. The most important index, the factor of comfort, is defined as the numerical mean value of the votes of a large group of people on a many-point scale at the predicted percentage of dissatisfied people, who are not in thermal balance with the surrouding environment. If we can ensure the appropriate indoor enviroment for a known percentage of satisfied people with the heating and air-conditioning system early in the design phase we can say that we actually "design the comfort" in a room. The paramaters that influence and determine the comfort factor are presented in standards ([3] to [5]), which offer, in most cases, three categories of environment quality to be ventilated: categories A, B and C. For each room or building we can choose a different category for the thermal environment, the air quality and the accoustic environment.

Pri načrtovanju klimatizacije prostora je treba vključiti tudi toplotno ravnovesje človeškega telesa, kar pomeni, da moramo zagotoviti takšno toplotno okolje, da bo nastajanje toplote znotraj človekovega telesa ves čas v ravnovesju z izgubami toplote v okolico.

Kakovost notranjega okolja se izraža kot stopnja, do katere ljudje v prostoru še izražajo zadovoljstvo. Kakovost okolja izražamo z odstotkom ljudi, ki v danih razmerah niso zadovoljni z okoljem (gre torej za odstotek nezadovoljnih). Če je delež nezadovoljnih majhen, je kakovost okolja velika in nasprotno.

Za vrednotenje toplotnega okolja je treba definirati naslednje pojme in enote :

– ***NSO (napovedana srednja ocena - PMV)***: vrednost, ki napoveduje toplotni občutek skupine ljudi na večstopenjski lestvici
– ***NON (napovedan odstotek nezadovoljnih - NON)***: to je vrednost, ki napove odstotek nezadovoljnih ljudi z notranjim okoljem (prostorom), ki niso v toplotnem ravnovesju z okolico;
– ***standardna oseba***: oseba s telesno površino A=1,8 m^2 pri metabolizmu 1 met (58,2 W/m^2) (človek, ki počiva).

Odziv ljudi na toplotno okolje se izraža z napovedano srednjo oceno (NSO) in napovedanim odstotkom nezadovoljnih (NON). Prav tako se odziv ljudi na toplotno okolje izraža v napovedanem odstotku nezadovoljnih ob različnih vrstah lokalnega toplotnega neugodja, ki je lahko posledica prepiha (gibanja zraka), prevelike navpične temperaturne razlike v bivalni coni (gleženj - glava), pretoplih ali premrzlih tal ter prevelike sevalne temperaturne nesimetrije [7].

Za kolikostno določanje dejavnika ugodja uporabimo indeks NSO - napovedano srednjo oceno, to je vrednost, ki napoveduje toplotni občutek skupine ljudi na sedemstopenjski lestvici, podani v Preglednici 1.

NSO je odvisen od šestih parametrov: a) stopnje dejavnosti ljudi, b) toplotnih vrednosti oblačil, c) temperature zraka, d) povprečne sevalne temperature, e) hitrosti zraka in f) vlažnosti zraka. Indeks NSO temelji na toplotnem ravnovesju človeškega telesa, kar pomeni, da je proizvodnja toplote znotraj človeškega telesa v ravnovesju z izgubami (oddajo) toplote v okolico. Izračuna se lahko za različne kombinacije stopenj metabolizma, oblačil, temperature prostora, srednje sevalne temperature, hitrosti zraka in vlažnosti zraka.

When we design the air-condition in an indoor space we should also include the thermal balance of the human body, which means that we should ensure an indoor thermal environment such that the internal heat production in the human body is equal to the loss of heat to the environment.

The quality of the indoor environment is expressed as the degree until people in the space still express satisfaction. The quality of the environment is expressed as the percentage of people who are not satisfied with the environment. If the percentage of dissatisfied people is low, the quality of the environment is high and vice versa.

The following notions and units should be defined to evalutate the thermal environment:

– ***PMV (predicted mean vote)***: an index that predicts the mean value of the thermal sensation votes of a large group of people on a many-point scale;
– ***PPD (predicted percentage of dissatisfied)***: an index that predicts the percentage of a large group of people that is likely to feel thermally dissatisfied for the body as a whole;
– ***standard person***: a person with a surface area A=1.8 m^2 and metabolic rate 1 met (58.2 W/m^2) (person at rest)

The human response to the thermal environment is expressed by the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD). The human response is also expressed by the percentages of occupants predicted to feel dissatisfied due to different types of local thermal discomfort, which can be caused by a draught, by an abnormally high vertical temperature difference, by a too warm or too cool floor or too high a radiant temperature asymmetry [7].

To determine the quantity of the factor of comfort we use the PMV index – the predicted mean vote – which predicts the mean value of the thermal sensation votes of a large group of people on a seven-point scale, given in table 1.

The PMV depends on six parameters: a) the occupants' physical activity, b) the thermal resistance of their clothing, c) the air temperature, d) the mean radiant temperature, e) the air velocity and f) air humidity. The PMV index is based on the heat balance of the human body, which means that the internal heat production in the body is equal to the loss of heat to the environment. The PMV can be calculated for different combinations of metabolic rate, clothing, air temperature, mean radiant temperature, air velocity and air humidity.

Preglednica 1. *Vrednosti parametra NSO*
Table 1. *Values of parameter PMV*

+ 3	+2	+1	0	-1	-2	-3
vroče hot	toplo warm	prijetno toplo slightly warm	nevtralno neutral	prijetno hladno slightly cool	hladno cool	mrzlo cold

Kakovost notranjega toplotnega okolja opisuje NON in pomeni vrednost, ki napove odstotek nezadovoljnih ljudi z notranjim toplotnim okoljem (prostorom), ki niso v toplotnem ravnovesju z okolico. Določimo ga po predhodnem izračunu NSO z izkustvenim izrazom 1 [4] :

The quality of the indoor thermal environment describes the PPD and represents a value that predicts the percentage of people dissatisfied with the indoor thermal environment, who are not balanced with the environment. It can be defined after previously calculating the PMV with the empirical expression 1 [4]:

$$\mathrm{PPD} = 100 - 95 \cdot e^{-\left(0{,}03353 \cdot \mathrm{PMV}^4 + 0{,}2179 \cdot \mathrm{PMV}^2\right)} \quad (1).$$

Odstotek ljudi z napovedano oceno toplotnega ugodja se za določene vrednosti lahko prikaže tudi s preglednico 2, v kateri izračunamo vrednosti faktorjev NSO in NON z uporabo enačbe 1.

The percentage of persons predicted to vote on thermal comfort for some values can be expressed with table 2., in which we calculate the values of factors PMV and PPD with the use of equation 1.

Preglednica 2. *Odstotek ljudi z napovedano oceno toplotnega ugodja*
Table 2. *Percentage of persons predicted to vote*

NSO PMV	**NON PPD**	Odstotek ljudi z napovedano oceno Percentage of persons predicted to vote		
		0	-1, 0 ali/or +1	-2, -1, 0, +1, +2
+2	75	5	25	70
+1	25	27	75	95
0	5	55	95	100
-1	25	27	75	95
-2	75	5	25	70

2 FIZIKALNO-MATEMATIČNI MODEL

2 PHYSICAL MATHEMATICAL MODEL

Za numerično reševanje toka realne tekočine je treba postaviti ustrezen fizikalno-matematični model, ki skupaj s predpostavkami in poenostavitvami pomeni temelj za diskretizacijo problema. Dejanske tekočine so viskozne in stisljive ter se gibljejo neustaljeno. Naloga inženirja je, da ob poznavanju teorije in na podlagi praktičnih izkušenj izbere ustrezen fizikalno matematični model, s katerim dosega zadovoljive rezultate v praktičnih preračunih.

Vodilne enačbe so Navier-Stokesove enačbe neustaljenega gibanja newtonske viskozne tekočine [9], pri čemer pa moramo zaradi naravne konvekcije upoštevati še vzgonske sile, ki so v teh primerih mnogo večje od vztrajnostnih. V primeru naravne konvekcije obravnavamo tekočino kot nestisljivo, razen pri spremembi gostote, ki povzroča nastanek vzgonskih sil. Ta poenostavitev se nanaša na znan Boussinesqueov približek:

For numerical calculations of the actual fluid flow an appropriate physical mathematical model should be built, and together with assumptions and simplifications the basis should be defined for the discretisation of the problem. Actual fluids are viscous and compressible, and the flow is unsteady. The engineer's job is to choose the appropriate physical mathematical model with a knowledge of theory and on the basis of experience, which helps him to achieve appropriate sufficient results in practical calculations.

The governing equations are the Navier-Stokes equations for unsteady flow for Newtonian viscous fluid [9], where due to the natural convection, bouyancy forces should be taken into consideration, and in many cases these forces can be much greater than the inertial forces. In the case of natural convection the fluid is treated as incompressible, except for the change of density, which causes the body force. This simplification refers to the well-known Boussinesq approximation

$$\frac{\rho}{\rho_o} = 1 - \beta\left(T - T_o\right) \quad (2),$$

kjer je β prostorninski termični razteznostni koeficient. Boussinesqueov približek je uporaben v veliki večini primerov, pri katerih temperaturne razlike niso prevelike. Če poleg tega lahko štejemo, da so lastnosti tekočine nespremenljive znotraj obravnavanega območja, se sistem enačb za laminarni tok tekočine poenostavi v obliko:
– kontinuitetna enačba:

where β is the coefficient of thermal expansion. The Boussinesq approximation can be used in most cases where the temperature differences are not too big. And if we can also assume that the properties of the fluid are constant inside the treated domain, the system of equations for laminar flow can be simplified in the following form:
– continuity equation:

$$\vec{\nabla} \cdot \vec{v} = 0 \quad (3)$$

– gibalna enačba: – momentum equation

$$\rho \frac{D\vec{v}}{Dt} = \rho \left[\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla} \right) \vec{v} \right] = \eta \vec{\nabla}^2 \vec{v} - \vec{\nabla} \left(p - p_o \right) - \rho \beta \left(T - T_o \right) \vec{g} \tag{4}$$

– energijska enačba: – energy equation

$$\rho c_p \frac{DT}{Dt} = \rho c_p \left[\frac{\partial T}{\partial t} + \left(\vec{v} \cdot \vec{\nabla} \right) T \right] = \vec{\nabla} \cdot \left(\lambda \vec{\nabla} T \right) + I = \lambda \vec{\nabla}^2 T + I \tag{5}$$

Te enačbe so osnovne enačbe za obravnavo naravne konvekcije v zaprtih prostorih. Pri reševanju teh enačb za določene začetne in robne pogoje je treba uporabiti numerični način oziroma metode računalniške dinamike tekočin. Za numerično analizo je bil uporabljen programski paket CFX 4.3, ki uporablja metodo končnih prostornin. Problem kontinuuma z neskončno prostostnimi stopnjami se spremeni v diskreten problem s končnim številom prostostnih stopenj, opisan s sistemom algebrskih enačb ([2] in [6]).

Za numerični izračun faktorja ugodja NSO in odstotka nezadovoljnih NON v vsaki točki prostora je treba uporabiti rešitve modela sistema Navier-Stokesovih enačb ter dodatno uporabiti enačbe, ki podajajo odvisnost faktorja ugodja od določenih parametrov, ti temeljijo na vzpostavitvi toplotnega ravnovesja človeškega telesa. V primeru upoštevanja notranjih toplotnih virov in virov vlage je treba sistem Navier-Stokesovih enačb dopolniti še s toplotnimi in snovskimi viri in dodatno prenosno enačbo vlage.

Po razrešitvi sistema Navier-Stokesovih enačb nadaljnji izračun faktorja ugodja v vozliščnih točkah diskretiziranega modela prostora omogoči enačba [4]:

These equations are the basic equations for the treatment of natural convection in closed domains. To solve these equations for a defined start and boundary conditions a numerical treatment should be used or methods of computational fluid dynamics. For the numerical analysis the CFX4.3 program was used, this program uses the method of finite control volumes. The problem of continuum with an infinite degrees of freedom is converted into a discretisied problem with a finite number of degrees of freedom, described with a system of algebraic equtions ([2] and [6]).

For numerical calculations of the factor of comfort (PMV) and the predicted percentage of dissatisfied (PPD) at each point in space we use the solutions of the model of the system of Navier-Stokes equations, and we additionally use equations that give us the dependence of the factor of comfort and defined parameters which are based on the thermal balance of the human body. In the case of the use of internal thermal sources and sources of humidity, the system of Navier-Stokes equations should be completed with heat and material sources as well as the transfer equation of humidity.

After obtaining solutions for the system of Navier-Stokes equations we calculate the factor of comfort in the nodes of the discretisation model with the use of equation [4]:

$$\mathrm{PMV} = \left(0{,}303 \cdot e^{-0{,}036 \cdot M} + 0{,}028\right) \cdot \left\{ \begin{array}{l} (M - W) - \\ -3{,}05 \cdot 10^{-3} \cdot \left[5733 - 6{,}99(M - W) - p_a\right] - \\ -0{,}42 \cdot \left[(M - W) - 58{,}15\right] - \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot \left(5867 - p_a\right) - \\ -0{,}0014 \cdot M \cdot \left(34 - t_a\right) - \\ -3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[\left(t_{cl} + 273\right)^4 - \left(\bar{t}_r + 273\right)^4\right] - \\ -f_{cl} \cdot h_c \cdot \left(t_{cl} - t_a\right) \end{array} \right\} \tag{6}$$

ter enačbe [4]: and equations [4]:

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M - W) - I_{cl} \cdot \left\{ \begin{array}{l} 3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[\left(t_{cl} + 273\right)^4 - \left(\bar{t}_r + 273\right)^4\right] + \\ + f_{cl} \cdot h_c \cdot \left(t_{cl} - t_a\right) \end{array} \right\} \tag{7}$$

$$h_c = \left\{ \begin{array}{ll} 2{,}38 \cdot \left(t_{cl} - t_a\right)^{0{,}25} & \to 2{,}38 \cdot \left(t_{cl} - t_a\right)^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1\sqrt{v_{ar}} & \to 2{,}38 \cdot \left(t_{cl} - t_a\right)^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \end{array} \right\} \tag{8}$$

$$f_{cl} = \left\{ \begin{array}{ll} 1{,}00 + 1{,}290 \cdot I_{cl} & \to I_{cl} \le 0{,}078 \mathrm{m^2K/W} \\ 1{,}05 + 0{,}645 \cdot I_{cl} & \to I_{cl} > 0{,}078 \mathrm{m^2K/W} \end{array} \right\} \tag{9},$$

iz katerih je razvidno, da je treba poprej podati še vrednosti nekaterih spremenljivk, od katerih je določene možno dobiti šele z iteracijo teh enačb. Posamezne

from which we can see that some values are needed and some of them we do not obtain before the iteration of these equations. The variables used in equation spremenljivke v enačbah (6) do (8) imajo naslednji pomen:

M - stopnja metabolizma [1 met = 58,2 W/m^2]

W - zunanje delo (za večino dejavnosti ima vrednost 0) [W/m^2]

I_{cl} - toplotna izolacija (toplotni upor), dosežena z oblačilom [clo][m^{2}K/W]

f_{cl} - razmerje površine oblečenega in slečenega človeškega telesa

t_a - temperatura zraka [°C]

$\bar{t}_r$ - srednja sevalna temperatura [°C]

t_{cl} - površinska temperatura obleke [°C]

v_{ar} - relativna hitrost zraka (glede na človeško telo) [m/s]

p_a - delni tlak vodne pare [Pa]

h_c - toplotna prestopnost [W/m^{2}K]

V splošnem lahko celoten postopek numeričnega določanja faktorja ugodja strnemo v:

Algoritem 1: Numerično določanje faktorja ugodja

1. izbira obravnavanega območja in projektnih parametrov prostora,
2. določitev načina ogrevanja in/ali klimatizacije,
3. določitev robnih in začetnih pogojev za numerični izračun,
4. reševanje sistema enačb (3) do (5) z ustreznim programskim paketom RDT,
5. določitev vrednosti spremenljivk iz enačb (6) do (9),
6. določitev vrednosti faktorja NSO,
7. določitev vrednosti faktorja NON.

3 TESTNI PRIMER

Za računalniško simuliranje testnega primera smo izbrali kombinacijo talnega ogrevanja za ustaljeno pokrivanje toplotnih izgub in klimatizacijo za doseganje optimalnih pogojev udobja v prostoru. Testni primer je zasnovan za zimski režim obratovanja, kjer je mogoče vključiti tudi talno ogrevanje. Klimatizacija je izvedena z izpodrivnim načinom prezračevanja, pri katerem je dovod zraka pri tleh ob zunanji steni, odvod pa v notranjosti prostora v stropnem delu. V praksi se takšen način ogrevanja in klimatizacije uporablja v novejših poslovnih stavbah in stanovanjskih hišah, kjer želi investitor zagotavljati veliko ugodje ob majhni porabi energije. Investicija v takšne sisteme je nekoliko večja kakor na primer pri radiatorskem ogrevanju, se pa kmalu povrne zaradi nižjih temperatur ogrevalnega medija (kondenzacijski kotli) in nadzorovane ventilacije, ki praktično več ne ustvarjata toplotnih izgub.

Kot testni prostor je rabil običajni pisarniški prostor z izmerami širina/dolžina/višina = 3,0/5,0/3,0 metrov, z enim oknom (sl. 1). V prostoru zaradi poenostavitve geometrijskega modela ni zajeto pisarniško pohištvo, vsekakor pa je moč v pisarniškem prostoru dodatno modelirati tako pasivne ovire (pisarniško pohištvo) kakor grelne elemente (generacija toplote pri električnih napravah, npr. računalnikih in monitorjih).

(6) to (8) are as follows:

M - the metabolic rate [1 met = 58,2 W/m^2]

W - the external work (equal to 0 for most activities) [W/m^2]

I_{cl} - the thermal resistance of clothing [clo][m^{2}K/W]

f_{cl} - the ratio of a man's surface area while clothed, to a man's surface area while naked

t_a - the air temperature [°C]

$\bar{t}_r$ - the mean radiant temperature [°C]

t_{cl} - the surface temperature of clothing [°C]

v_{ar} - the relative air velocity (relative to the human body) [m/s]

p_a - the partial water-vapour pressure [Pa]

h_c - the convective heat-transfer coefficient [W/m^{2}K]

The whole procedure to numerically define a factor of comfort we can generally merge in:

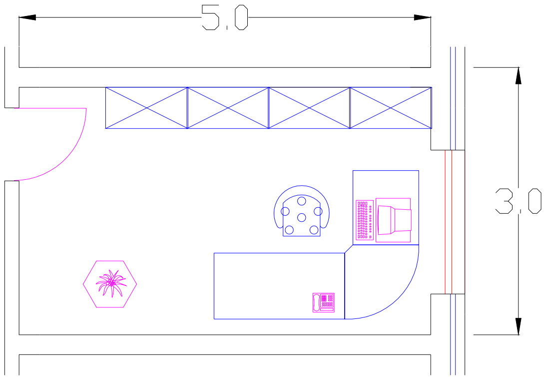
Algorithm 1: Numerically defining the factor of comfort

1. Selection of the treated area and the project parameters of the space,
2. defining the system of heating and/or air-conditioning,
3. defining boundary and start conditions for numerical calculations,
4. solving the system of equations (3) to (5) with an appropriate computer program,
5. defining values of the variables from equations (6) to (9),
6. defining the values of the index PMV,
7. defining the values of the index PPD.

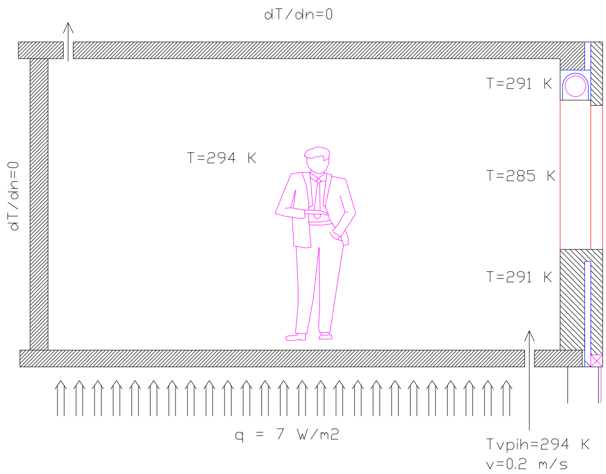
3 TEST EXAMPLE

For numerical simulations of the test example we selected the combination of floor heating to cover the steady heating losses and an air-conditioning system to reach the optimum conditions for the comfort in the space. The test example is designed for a winter mode of work, where we can include floor heating. Air-conditioning is executed in the mode of under-pushing ventilation, where the air inlet is at the floor of an outer wall, but the air outlet is in the inside of the space in the part of the ceiling. In practice we use such heating and air-conditioning systems in new business or residential buildings, where investors want to have comfort with a low consumption of energy. The investment in such systems is higher than, for example, just heating with radiators, but it is repaid early because of the lower temperatures of the heating medium (condense boilers) and controlled ventilation, which does not present any practical heating loss.

As the test example we have used a typical office space with dimensions width/length/height = 3.0/5.0/3.0 meters, with one window, as shown in Figure1. Because of rationalizing the geometry model of the space we did not include office furniture, but it can be added in any case to moderate as passive obstructions (office furniture) or active elements (heating with electrical devices, i.e. computers, monitors).



Sl. 1. *Gradbeni tloris testnega primera*
Fig. 1. *Architectural plane of test example*



Sl. 2. *Robni pogoji testnega primera*
Fig. 2. *Boundary conditions of test example*

Sredstvo v prostoru je zrak s fizikalnimi lastnostmi pri projektni temperaturi v prostoru T = 294 K, atmosferskem tlaku v prostoru p_{atm} = 101,325 kPa, gostoto ρ = 1,1774 kg/m^3, specifično toploto c_p = 1005,7 J/kgK, toplotno prevodnostjo λ = 0,02624 W/mK, dinamično viskoznostjo η = 1,846·10^5 kg/ms in koeficientom prostorninskega temperaturnega raztezka β = 1/T = 1/294 K.

Robni pogoji za numerični izračun so bili (grafično predstavljeni na sliki 2): toplotni tok iz tal q_{TLA} = 7 W/m^2, notranja površinska temperatura okna T_{OK} = 285 K = 12°C, notranja površinska temperatura zunanjega zidu T_{ZZ} = 291 K = 18°C, potreben dovod svežega zraka $\dot{V}_{DOVOD}$ = 400 m^3/h ter vpihovalna hitrost iz talnega elementa v_N = 0,2 m/s s temperaturo 294 K. Pri izračunu faktorja udobja NSO v prostoru so bile upoštevane vrednosti parametrov, podanih v preglednici 3.

Na slikah 3 do 12 so za določene posamezne prostorske prereze prikazana hitrostna in temperaturna polja v izbranih prerezih skozi obravnavani prostor. Slike 10 do 16 prikazujejo prostorsko porazdelitev relativne vlažnosti, vrednosti faktorja ugodja NSO in odstotka nezadovoljnih NON.

Analiza rezultatov osnovnega testnega primera temelji predvsem na preučevanju območja bivalne cone, ki je odločujoča za počutje ljudi. Pri tem nismo dajali bistvenega poudarka območjem zunaj bivalne cone, torej nad višino 180 cm in do 20 cm od sten. Ne glede na to so rezultati predstavljeni za celotni prostor in razberemo lahko, da je zelo pomembno, kakšno območje si izberemo za bivalno cono, saj širitev tega območja neposredno vpliva na način porazdelitve zraka ter na način ogrevanja, kar lahko zelo hitro bistveno podraži celotni sistem klimatizacije in ogrevanja.

Iz rezultatov preračuna je razvidno, da so relativne hitrosti v bivalni coni med 0,01 in 0,05 m/s, kar je daleč pod največjimi dopustnimi za namembnost pisarne in nimajo negativnega vpliva na počutje ljudi v prostoru. Razen v neposredni

The medium in the space is air, with physical properties at the project temperature in the space T = 294 K, atmospheric pressure in the space p_{atm} = 101.325 kPa, density ρ = 1.1774 kg/m^3, heat capacity c_p = 1005.7 J/kgK, heat conductivity λ = 0.02624 W/mK, dynamic viscosity η = 1.846·10^5 kg/ms and coefficient of thermal expansion β = 1/T = 1/294 K.

The boundary conditions for the numerical calculation were (graphically presented in Figure 2): heat flux from the floor q_{TLA} = 7 W/m^2, internal surface temperature of a window T_{OK} = 285 K = 12°C, internal surface temperature of an outer wall T_{ZZ} = 291 K = 18°C, required inlet of fresh air $\dot{V}_{DOVOD}$ = 400 m^3/h and the inlet velocity from the floor element v_N = 0.2 m/s with temperature 294K. For calculating the factor of comfort (PMV) in the space the values presented in table 3 were used.

In Figures 3 to 12 are the speed and temperature fields for some specific space cross-sections in selected cross-sections through the treated space. Figures 10 to 16 show in the space divided relative humidity, the values of the factor of comfort (PMV) and the percentage of dissatisfied PPD.

The analysis of the results of the test example is based mainly on a study of the occupied zone, which is suitable for people's feeling. In the calculations we did not specially study unoccupied zones, that is the height over 180 cm and distances up to 20 cm from the walls. Nevertheless, the results are presented for the whole space and we can see how very important it is to choose where the occupied zone is, because extending that space has an influence on the way the air is distributed and on the heating system, which can significantly raise the price of heating and air-conditioning.

From the results of the calculations we can see that the relative speeds in the occupied zone are between 0.01 and 0.05 m/s, which is much less than the maximum allowed for space use in offices, and does not have any negative influence on people's

Preglednica 3. *Parametri za izračun ugodja*
Tabel 3: *Parameters for calculating the comfort*

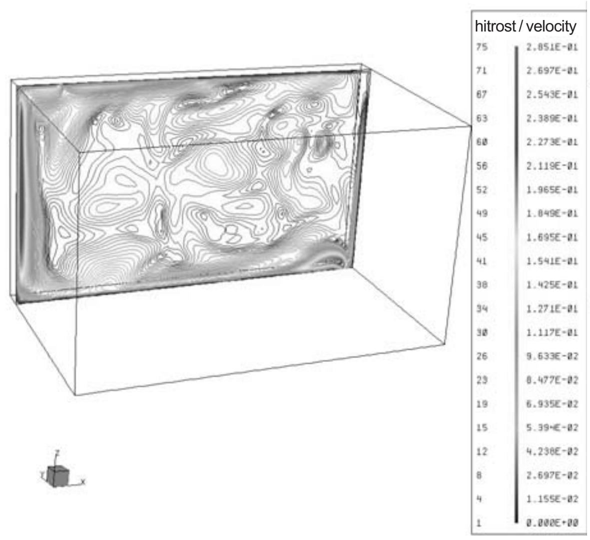
	Parameter	*Oznaka* *Label*	*Vrednost* *Value*	*Enota* *Unit*
1.	Stopnja metabolizma Metabolic rate	M	1,2 69,744	met W/m^2
2.	Zunanje delo External work	W	0	met
3.	Toplotna izolacija, ki jo dosežemo z oblačilom Thermal resistance of clothing	I_{cl}	1,0 0,155	clo m^{2}K/W
4.	Razmerje površine oblečenega in nepokritega človeškega telesa Ratio of person's surface area while clothed, to person's surface area while naked	f_{cl}	1,15	---
5.	Srednja sevalna temperatura Mean radiant temperature	$\overline{t_r}$	18	°C
6.	Prevodnostni koeficient obleke Convective heat-transfer coefficient	h_c	3,56	W/m^{2}K
7.	Površinska temperatura obleke, dobljena z 2. iteracijo enačbe (7) Surface temperature of clothing from 2. iteration of equation (7)	t_{cl}	25	°C
8.	Temperatura zraka v prostoru Air temperature	t_a	**rezultati preračuna results of the calculation**	°C
9.	Relativna hitrost zraka (glede na človeško telo) Relative air velocity (relative to the human body)	v_{ar}	**rezultati preračuna results of the calculation**	m/s
10.	Delni tlak vodne pare [8] Partial water-vapour pressure [8]	p_D	**dobljeno iz rezultatov preračuna results from the calculation**	Pa
11.	Nasičeni parni tlak vode [8] Saturated water-vapour pressure [8]	p''_D	**dobljeno iz rezultatov preračuna results from the calculation**	Pa
12.	Relativna vlažnost [8] Relative humidity [8]	φ	**dobljeno iz rezultatov preračuna results from the calculation**	%
13.	NSO - napovedana srednja ocena PMV – predicted mean vote	PMV	**dobljeno iz rezultatov preračuna results from the calculation**	---
14.	NON - napovedan odstotek nezadovoljnih PPD - predicted percentage of dissatisfied $PPD = 100 - 95 \cdot e^{-\left(0,03353 \cdot PMV^4 + 0,2179 \cdot PMV^2\right)}$	PPD	**dobljeno iz rezultatov preračuna results from the calculation**	%

bližini vpihovanja oz. sesanja zraka, so relativne hitrosti ugodne.

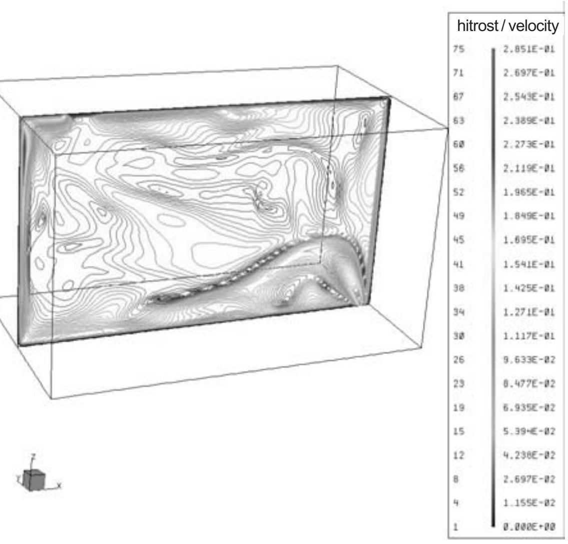
Temperatura in občutena temperatura sta zelo bistveni pri pojmovanju udobja, saj večina ljudi izraža nezadovoljstvo prav z izrazi, ki so povezani s temperaturo v prostoru : prevroče, premrzlo, prenizka temperatura in podobno. S slike 9 so razvidne izoterme med 21°C in 21.5°C. Vidimo lahko, da so v bivalni coni višje temperature opazne v območjih, kjer so manjše hitrosti zraka, kar seveda vpliva na končni izračun faktorja ugodja oz. na počutje ljudi, saj nekoliko višje temperature ob manjših hitrostih zraka in nasprotno ugodno vplivajo na počutje.

feelings in the space. Except for areas very close to the air inlet or air outlet, they are very suitable.

Temperature and extensive temperature are very important for an understanding of comfort because most people express dissatisfaction with words connected with a temperature in the space: too hot, too cold, too low a temperature, and so on. In Fig. 9 are the isotherms between 21°C and 21.5°C, and we can see that the space over the occupied zone has higher temperatures and a lower speed of air, which has an influence on calculating the factor of comfort on people's feelings, because a slightly higher temperature at a lower speed of air and vice versa have a positive influence on people's feelings.



Sl. 3. *Absolutne hitrosti v prerezu y = 270 cm*
Fig. 3. *Absolute speed in section y = 270 cm*



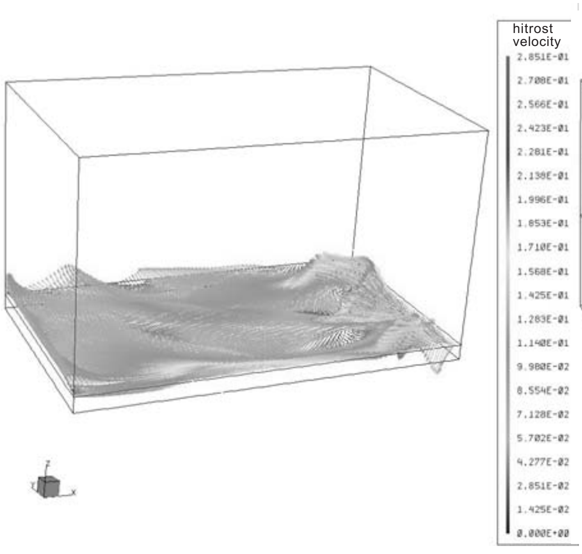
Sl. 4. *Absolutne hitrosti v prerezu y = 150 cm*
Fig. 4. *Absolute speed in section y = 150 cm*

Zaradi potrebnega izračunavanja delnega tlaka vodne pare in nasičenega parnega tlaka je mogoče vzporedno z izračunavanjem faktorja ugodja izračunati še relativno vlažnost v prostoru. Iz rezultatov razberemo, da je relativna vlažnost skoraj povsod po prostoru enakomerna in se giblje v testnem primeru med 48% in 49% v bivalni coni. V mejni plasti zunanjega zidu in okna je opazno povečanje relativne vlažnosti celo do 85%, vendar do kondenzacije ne prihaja.

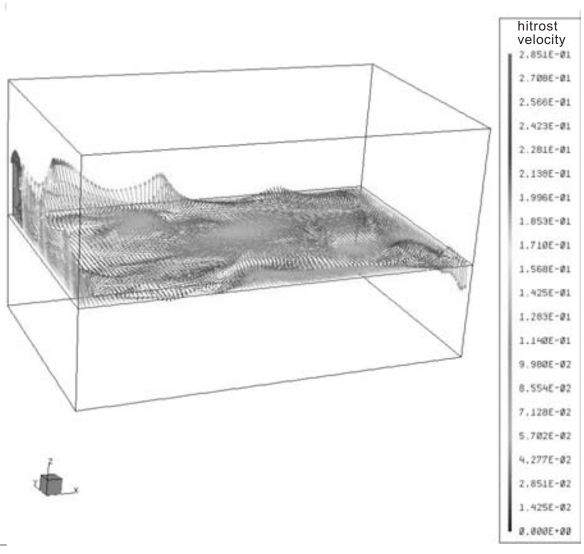
Glavni del analize je analiza faktorja ugodja in njegova prostorska porazdelitev. Največje vrednosti so skoraj povsod v prostoru v mejah med –0,8 in –0,5, kar pomeni, da je testni primer prikaz velikega ugodja v prostoru. Zelo zanimiva je slika 11, ki prikazuje območje faktorja ugodja NSO za ozko območje –0,7 do –0,6 in v večini zapolnjuje prostor v bivalni coni. Prostor je torej projektiran za ljudi

Because we have to calculate partial water-vapour pressure and saturated water-vapour pressure we can, in parallel with calculating the factor of comfort, also calculate the relative humidity in the space. From the results we can see that the relative humidity is uniform almost everywhere in the space and reaches values in the test example between 48% and 49% in the occupied zone. In the border zone of the outer wall and the window an increase in the relative humidity can be seen, up to 85%, but there is still no condensation.

The main part of the analysis is the analysis of the factor of comfort in this space distribution. The maximum values almost everywhere in the space are between –0.8 and –0.5, which means that the test example is an example of high comfort in the space. Figure 11 is very interesting, it shows the range of the factor of comfort (PMV) between –0.7 and –0.6 and almost everywhere fills the space in the occupied zone. The space is designed



Sl. 5. *Vektorji hitrosti v prerezu z = 20 cm*
Fig. 5. *Velocity vectors in section z = 20 cm*



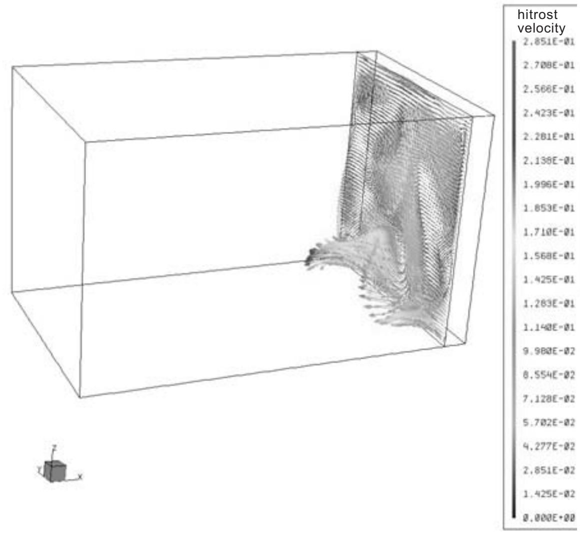
Sl. 6. *Vektorji hitrosti v prerezu z = 150 cm*
Fig. 6. *Velocity vectors in section z = 150 cm*

kategorije B. V primeru, da bi želeli doseči udobje za skupino ljudi A, bi moral biti faktor ugodja NSO v bivalni coni v mejah med –0,2<NSO<+0,2, kar pa je v praksi povezano z visokimi stroški izvedbe.

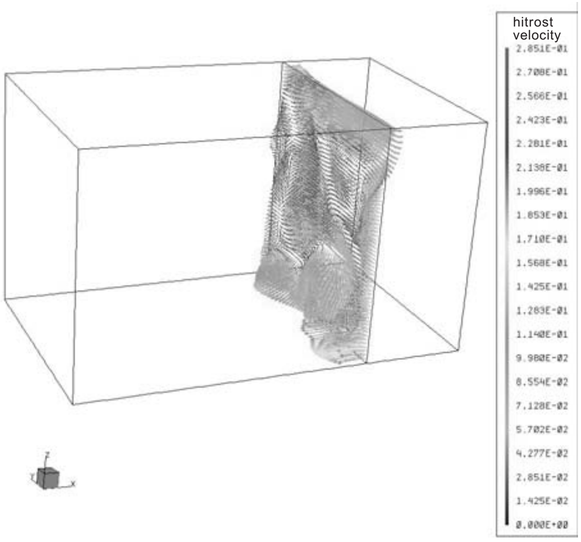
Z uporabo enačbe (1) lahko ob znanem faktorju ugodja v vsaki točki prostora dobimo tudi napovedan odstotek nezadovoljnih NON. Iz rezultatov je razvidno, da ni bistvenih razlik v celotnem območju bivalne cone in da je napovedan odstotek nezadovoljnih NON povsod nekje med 12% do 17%. V celotnem območju bivalne cone torej lahko napovedujemo, da bo vedno nekje med 83% in 88% ljudi s projektiranimi pogoji zadovoljnih, drugi bodo nezadovoljni.

for B-category people. If we want to reach the comfort for the A group of people, the values of the factor of comfort should be between –0.2<PMV<+0.2, but this means more expensive systems and higher costs.

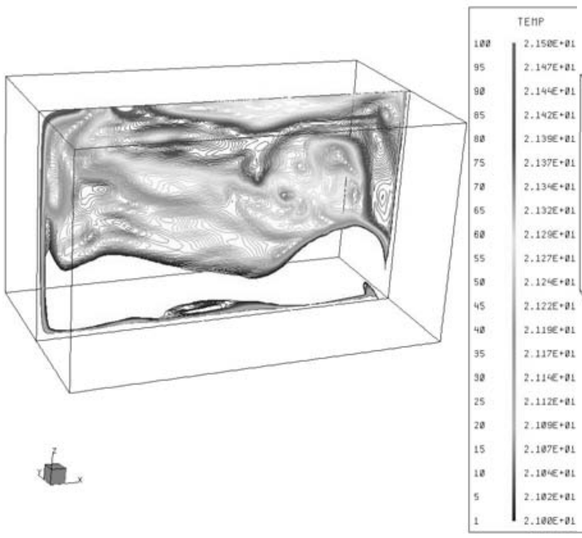
With the use of equation (1) and known values of the factor of comfort we can calculate the index PPD for each point in the space. We can see from the results that there are no essential differences in the whole space of the occupied zone and that the values of the predicted percentge of dissatisfied PPD is always between 12% and 17%. In the whole space of the occupied zone we can predict that there will always be between 83% and 88% of people satisfied with the designed conditions, the rest will be dissatisfied.



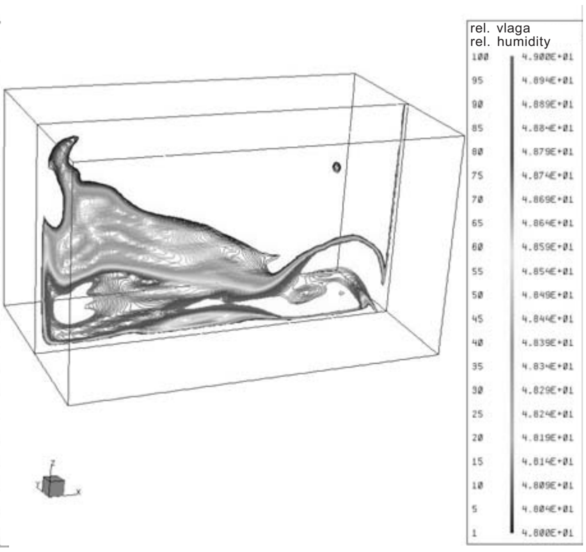
Sl. 7. *Vektorji hitrosti v prerezu x = 450 cm*
Fig. 7. *Velocity vectors in section x = 450 cm*



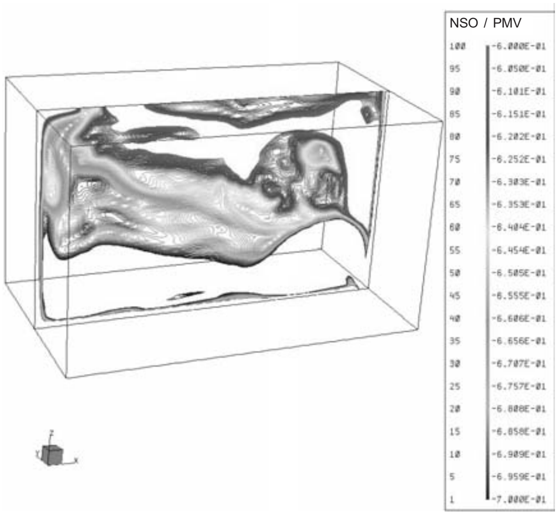
Sl. 8. *Vektorji hitrosti v prerezu x = 350 cm*
Fig. 8. *Velocity vectors in section x = 350 cm*



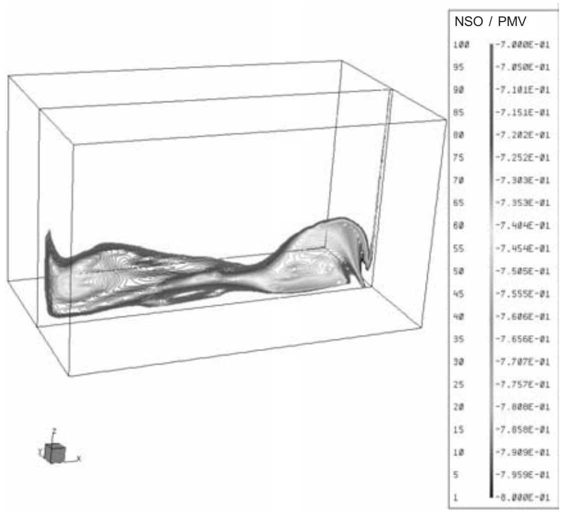
Sl. 9. *Izoterme med 21°C in 21,5°C*
Fig. 9. *Isotherms between 21°C and 21.5°C*



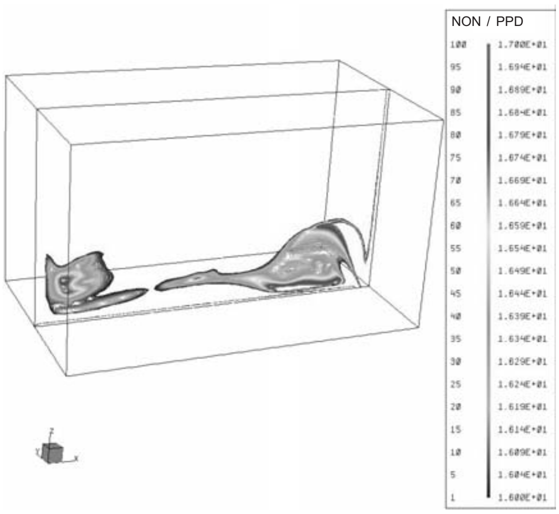
Sl. 10. *Izolinije relativne vlage od 48% do 49%*
Fig. 10. *Isolines of relative humidity from 48% to 49%*



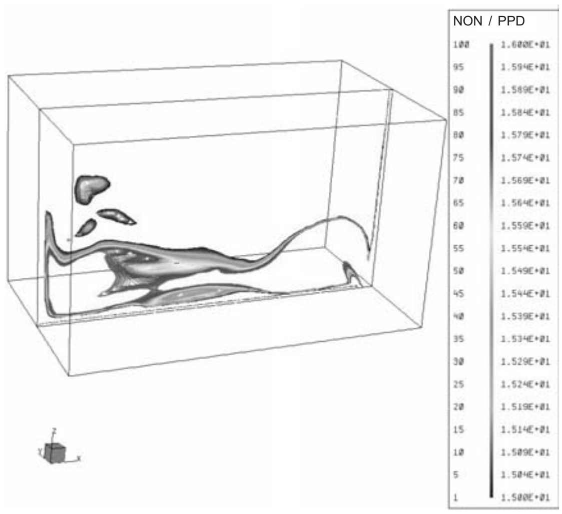
Slika 11. *Izolinije faktorja NSO od –0,7 do -0,6*
Fig. 11. *Isolines of factor PMV from –0.7 to -0.6*



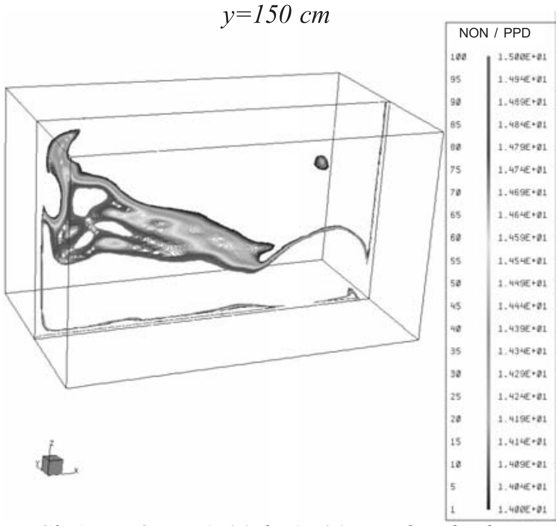
Slika 12. *Izolinije faktorja NSO od –0,8 do -0,7*
Fig. 12. *Isolines of factor PMV from –0.8 to -0.7*



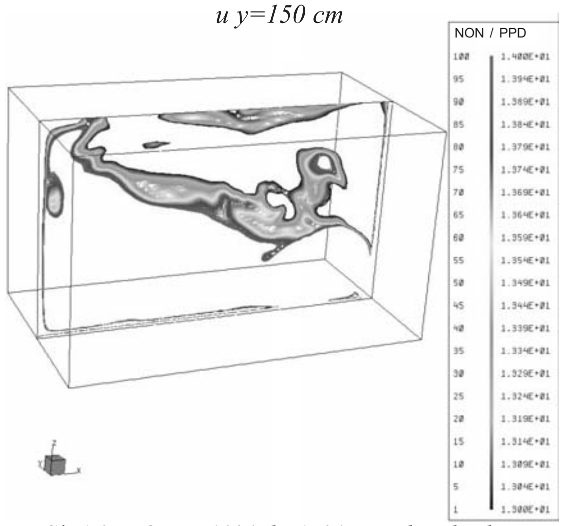
Sl. 13. *NON = 16% do 17% nezadovoljnih v prerezu y=150 cm*
Fig. 13. *PPD = 16% to 17% dissatisfied in section y=150 cm*



Sl. 14. *NON = 15% do 16% nezadovoljnih v prerezu y=150 cm*
Fig. 14. *PPD = 15% to 16% dissatisfied in section u y=150 cm*



Sl. 15. *NON = 14% do 15 % nezadovoljnih v prerezu y=150 cm*
Fig. 15. *PPD = 14% to 15 % dissatisfied in section y=150 cm*



Sl. 16. *NON = 13% do 14% nezadovoljnih v prerezu y=150 cm*
Fig. 16. *PPD = 13% to 14% dissatisfied in section y=150 cm*

4 PRIKAZ VPLIVA SPREMEMB ROBNIH POGOJEV

Za prikaz vpliva sprememb robnih pogojev na rezultate in s tem na udobje ter odstotek nezadovoljnih smo uporabili dodatno k osnovnemu primeru še dve kombinaciji robnih pogojev, prikazanih v preglednici 4.

4 PRESENTATION OF THE INFLUENCE OF CHANGES TO THE BOUNDARY CONDITIONS

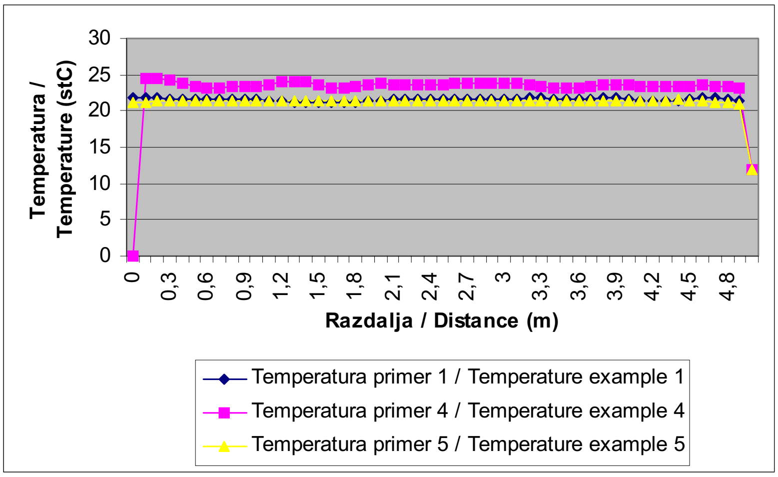
To present the influence of changes to the boundary conditions on results, and consequently on comfort, and the percentage of dissatisfied, we have, in addition to the base example, used two more combinations of boundary conditions, presented in table 4.

Preglednica 4. *Tri kombinacije robnih pogojev za numerično analizo faktorja ugodja*
Table 4. *Three combinations of boundary conditions for the numerical analysis of the factor of comfort*

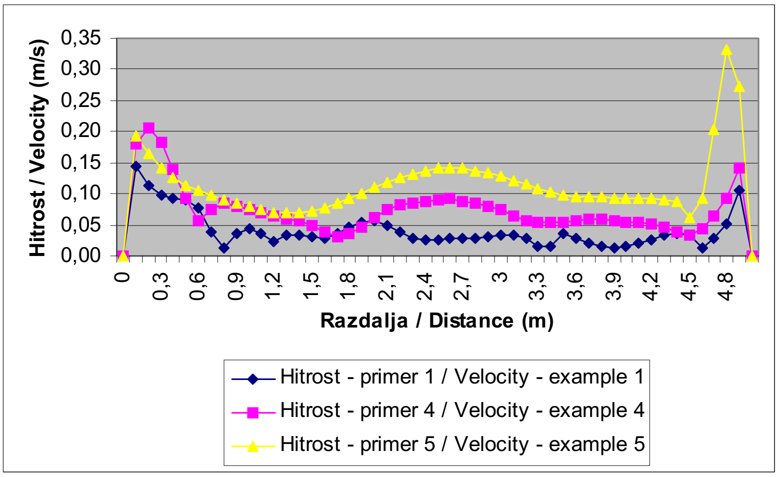
Primer numerične analize / *Example of numerical analysis*	*Toplotni tok iz tal* / *Heat flux from the floor* W/m^2	*Hitrost vpihovanega zraka* / *Speed of inlet air* m/s	*Temperatura vpihovanega zraka* / *Temperature of inlet air* °C
Primer 1 / Example 1	7	0,2	21
Primer 4 / Example 4	20	0,2	21
Primer 5 / Example 5	7	0,6	21

Spreminjali smo moč toplotnega toka v kombinaciji s hitrostjo vpihovanega zraka, medtem ko je temperatura vpihovanega zraka ostajala ves čas nespremenjena, saj v klimatizaciji lahko temperaturo krmilimo centralno v klimatizirani napravi.

The heat flux in combination with the speed of the inlet air were varied, but the temperature of the inlet air was constant in all examples, because the temperature in an air-conditioning system can be easily controlled in the central air-conditioning device.



Sl. 17. *Primerjava rešitev temperature za primere 1, 4 in 5 glede na vpliv sprememb robnih pogojev*
Fig. 17. *Comparison of results for temperature for examples 1, 4 and 5 because of the changing boundary conditions*



Sl. 18. *Primerjava rešitev absolutne hitrosti za primere 1, 4 in 5 glede na vpliv sprememb robnih pogojev*
Fig. 18. *Comparison of results for absolute speed for examples 1, 4 and 5 because of the changing boundary conditions*

Na slikah 17 do 19 je prikazan vpliv spremembe robnih pogojev na temperaturno polje v prerezu po sredini dolžine prostora na višini 1,5 metra od tal.

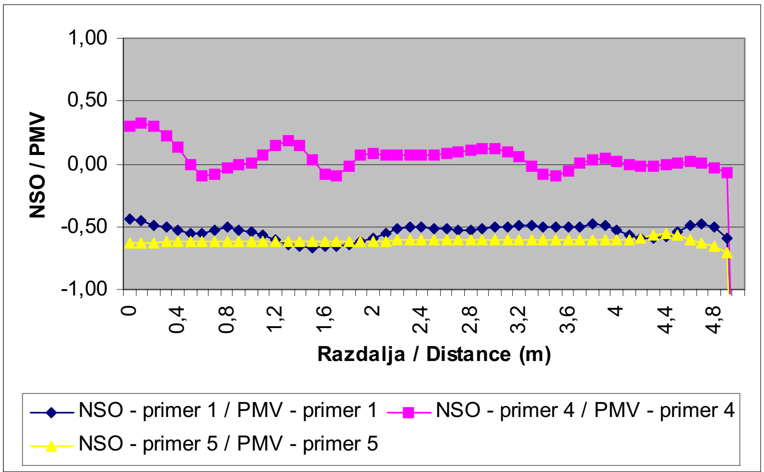
Spremeni se tudi hitrostno polje, kar je razvidno iz slike 18.

Največjo spremembo opazimo v spremembi faktorja ugodja NSO, razvidno s slike 19.

In Figures 17 to 19 the influence on the temperature field because of the changing boundary conditions is shown in the cross-section in the middle of the length of the room at a height 1.5 metres from the floor.

Also, the speed field has changed, presented in Figure 18.

The biggest change can be seen in the change of the factor of comfort (PMV), presented in Figure 19.



Sl. 19. *Primerjava rešitev NSO za primere 1, 4 in 5 glede na vpliv sprememb robnih pogojev*
Fig. 19. *Comparison of results for PMV for examples 1, 4 and 5 because of the changing boundary conditions*

5 SKLEP

Iz predstavitve rezultatov testnih primerov je razvidna praktična uporabnost novega postopka načrtovanja notranjega okolja.

Prikazani način novega načrtovanja notranjega okolja tako omogoča, da že v fazi načrtovanja napovemo delež ljudi, ki bodo v območju bivalne cone izražali zadovoljstvo s toplotnim okoljem ter s tem podati doseženo kakovost notranjega udobja v načrtovani bivalni coni.

5 CONCLUSION

From the presented results of the test examples the practical use of a new approach to the design of an indoor environment has been demonstrated.

The presented method of the new approach to designing an indoor environment allows us to predict early in the design phase the percentage of people who will be satisfied with the thermal environment in the space of the occupied zone and with the use of this approach it enables us to reach the desired quality of indoor environment in the occupied zone.

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6 REFERENCES

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Prejeto:
Received: 27.2.2002

Sprejeto:
Accepted: 20.9.2002