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Dinamična analiza klimatizacijskega sistema s toplotno črpalko

Dynamic Analysis of an Air-Conditioning System with a Heat Pump

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V tem prispevku je predstavljen postopek dinamičnih analiz klimatizacijskega sistema z uporabo toplotne črpalke v odvisnosti od sprememb obratovalnih razmer skozi leto. Za ta namen so razvili nov simulirni model sistema. Model je sestavljen iz dveh povezujočih se delov: izračun toplotnih izgub oziroma toplotnih dobitkov v prostoru in določitev toplotnih in hladilnih obremenitev klimatizacijskega sistema. Na grafih so predstavljeni rezultati urnih in mesečnih porab energije za klimatizacijski sistem s toplotno črpalko, ter primerjava s standardnim osrednjim klimatizacijskim sistemom. Zaradi prilagodljivosti razvitega modela simuliranja lahko analiziramo in primerjamo različne klimatizacijske sisteme, vključno z različnimi rekuperacijskimi sistemi.

(Ključne besede: sistemi klimatizacijski, črpalke toplotne, analize dinamične, porabe energije)

In this paper a dynamic operation analysis of a low-velocity central air-conditioning system with a heat pump in terms of the changing operating conditions during the year is performed. For this purpose an original hour-by-hour simulation model of the system has been developed. The model consists of two integrated parts: calculation of the heat loss or heat gain to the space and determination of the heating and cooling load imposed on the air-conditioning system. The hourly and monthly energy use results for the air-conditioning system with heat pump, also in comparison with the standard central air-conditioning system, are presented in graphical form. Flexibility of the developed simulation model provides the possibility to analyze and compare different air-conditioning systems, including different energy-recovery systems.

(Keywords: air-conditioning systems, heat pumps, dynamic analysis, energy consumption)

0 UVOD

Zahteve po energiji in njeni porabi v klimatizacijskih sistemih imajo neposreden vpliv na obratovalne stroške stavb in posreden vpliv na okolje. Različne energijske ocenjevalne metode omogočajo kolikostne primerjave energije in stroškov različnih energijskih virov. Čeprav se postopki za ocenjevanje zahtev po energiji spreminjajo v stopnjah zahtevnosti, imajo vsi po tri skupne dele izračuna [1]:
– prostorska obremenitev
– obremenitev sekundarne opreme
– energijske zahteve primarne opreme

Sekundarni se nanaša na opremo, ki razdeljuje toploto, hlajenje ali vmesno stanje obojega v klimatizirane prostore, primaren pa se nanaša na opremo, ki spreminja gorivo ali električno energijo v hlajenje ali toploto.

V tem prispevku je poudarjena analiza obremenitve sekundarne opreme. Prvi korak je bil

0 INTRODUCTION

The energy requirements and fuel consumption of HVAC systems have a direct impact on the building operating costs and an indirect impact on the environment. Different energy estimating methods can provide quantitative energy and cost comparisons among design alternatives. Although the procedures for estimating energy requirements vary considerably in their degree of complexity, they all have three common elements of the calculation [1]:
– space load
– secondary equipment load
– primary equipment energy requirements.

Here, secondary refers to the equipment that distributes the heating, cooling or ventilating medium to the conditioned spaces and primary refers to the central plant equipment that converts fuel or electric energy to the heating or cooling effect.

In this paper, the analysis is conducted to the level of the secondary equipment load. The first določitev obremenitve prostora, ta je enak količini energije, ki mora biti dodana ali odvzeta prostoru, da ohranimo toplotno ugodje. Zahtevana energija za ohranitev ugodja je funkcija temperature zunanjega zraka, relativne vlažnosti zunanjega zraka, učinkov sonca, vetra, notranjih toplotnih dobitkov, zadrževanju toplote v elementih gradbene konstrukcije in notranjosti prostora. Naslednji korak je bila sprememba prostorske obremenitve v obremenitev sekundarne opreme. Ta korak vključuje izračun potrebne energije sekundarnega sistema, to je električne energije za delovanje ventilatorjev, črpalk in/ali kompresorjev, pa tudi energije za ogrevanje oziroma hlajenje vode. Dobljeni rezultati so podlaga za izračun zahtev po gorivu in energije primarne opreme ter nadaljnjih ekonomskih analiz klimatizacijskega sistema, ki vključujejo stroške investicije, delovanja in vzdrževanja.

1 METODA ANALIZ

Energijski izračuni prostorske obremenitve temeljijo na povprečni uporabi in tipičnih vremenskih razmerah. Na splošno najbolj pogosto predstavljeni postopki temeljijo na urnih prikazih klimatskih razmer ter številu značilnih dni v letu ali 8760 ur delovanja na leto. Izbrana metoda za izračun čistih obremenitev prostora je postopek toplotnega ravnovesja v kombinaciji z delovanjem prenosa toplote. Metoda toplotnega ravnovesja temelji na prvem zakonu termodinamike in spada k osnovnim postopkom energijske analize. Enačba toplotnega ravnovesja je napisana za vsako obdajajočo površino (stene, tla, strop in okna) in še ena za zrak prostora. Te enačbe uporabljamo za izračun neznanih temperatur in površin zraka. Ko so temperature znane, jih uporabimo za določitev toplotnega toka iz prostora ali v prostor. Predpostavljeno je, da ima pri vsakem času *t* vsaka od teh površin ter masa zraka v prostoru nespremenljivo temperaturo. V vsakem prostoru se mora vstopajoči toplotni tok izenačiti z izstopnim. Z drugimi besedami to pomeni, da je prevodni tok v ravnovesju s konvekcijo prostorskega zraka, sevanjem notranjih virov (luči, aparatov in ljudi) ter spremembo sevanja med stenami in preostalimi površinami v prostoru. Za zunanjo površino posameznega zidu je prevodni tok v ravnovesju z absorbiranim sončnim sevanjem, dolgovalovnim sevanjem iz okolja in konvekcijo zunanjega zraka. Toplotno ravnovesje mase zraka v prostoru zahteva, da klimatizacijski sistem odstrani toploto, ki je dodana masi zraka s konvekcijo notranjih površin in notranjih virov (luči, aparati in ljudje) in s prenosom snovi zaradi infiltracije.

Toplotno ravnovesje na enoto površine pri *j*-tih notranjih površinah pri času *t*, je:

step was to determine the space load, which is the amount of energy that must be added to or extracted from a space to maintain thermal comfort. The energy required to maintain comfort is a function of the outside air temperature, outside-air relative humidity, solar effects, wind effects, internal heat gains and heat storage in the building construction elements and interiors. The second step was to translate the space load to the load of secondary equipment. This step should include a calculation of the energy required by the secondary system, i.e., the electrical energy to operate fans, pumps and/or compressors as well as the energy in the form of heated or chilled water. The obtained results are prepared for use in the calculation of fuel and energy requirements by the primary equipment and in a subsequent economic analysis of an air-conditioning system, including the investment costs, operating costs and maintenance costs.

1 ANALYSIS METHOD

Energy calculations of the space load are based on average use and typical weather conditions rather than maximum use and worst-case weather. Currently, the most sophisticated procedures are based on hourly profiles for climatic conditions and operational characteristics for a number of typical days of the year or on 8760 hours of operation per year. The selected method for calculating the net-space sensible loads is the heat balance method combined with first-order conduction transfer functions. The heat balance method is based on the first law of thermodynamics and it belongs to the most fundamental energy analysis methods. Heat balance equation is written for each enclosing surface (walls, floor, ceiling and windows), plus one for the room air. This set of equations is used to calculate the unknown surface and air temperatures. Once these temperatures are known, they are used to calculate the heat flow to or from the space air mass. At any time *t*, each of these surfaces and the space air mass are assumed to be of uniform temperature. At any plane boundary, the heat flux entering the boundary must equal the heat flux leaving the boundary. In other words, at the inside surface of any room wall, the conductive flux leaving the surface is balanced by convection from the room air, radiation from interior sources (lights, machines and people) and the net radiant interchange between the wall and all the other surfaces in the room. Similarly, for the outside surface of any exterior wall, the conductive flux leaving the surface toward the room is balanced by the absorbed solar radiation, net longwave radiant flux from the surroundings and the convective flux from the outdoor air. A heat balance on the room air mass requires the air-conditioning system to remove the net heat added to the air mass by convection from interior surfaces and interior sources (lights, machines and people) and by mass transfer due to infiltration.

Thus, the heat balance per unit area at the *j*th inside surface at time *t* is:

$$q_{j,t} = \alpha_{j,t}\left(\vartheta_{a,t} - \vartheta_{SI,j,t}\right) + \sum_{k=1}^{N_S} G_{j,k}\left(\vartheta_{SI,k,t} - \vartheta_{SI,j,t}\right) + q_{RS,j,t} \tag{1}$$

kjer prvi del pomeni dobitke toplote s konvekcijo, drugi del pa spremembo dolgovalovnega sevanja med stenami in preostalimi površinami, zadnji del pa kratkovalovno sevanje luči, opreme in ljudi ter solarne dobitke skozi okna. Leva stran enačbe (1) pomeni prevod toplote homogene površine. To je predstavljeno s prejšnjimi vrednostimi temperatur površin in toplotnega toka z uporabo funkcij prevoda toplote ([2] do [4]). Funkcije prevoda toplote so v povezavi s problemom večplastnih enodimenzijskih površin:

where the first term represents the convection heat gain from the room air, the second term represents the longwave radiative interchange between the wall and all other surfaces and the last term includes shortwave radiation from lights, equipment and people and window solar gain. The left side of Eq. (1) $q_{j,t}$ must match the heat conducted into the solid surface. This is represented with historical values of surface temperatures and heat flux using conduction transfer functions ([2] to [4]). Conduction transfer functions are closely related solutions to the transient one-dimensional, multilayered-slab conduction problem:

$$q_{j,t} = \sum_{i=0}^{N} X_{j,i}\vartheta_{SI,j,t-i} - \sum_{i=0}^{N} Y_{j,i}\vartheta_{SO,j,t-i} + C_{Rj} q_{j,t-1} \tag{2}$$

Če vstavimo enačbo (2) v enačbo (1), se $q_{j,t}$ uniči. Enačbo toplotnega ravnovesja prostorskega zraka dobimo z dodatkom N_s za vse površine prostora:

By substituting Eq. (2) into Eq. (1) $q_{j,t}$ is eliminated. In addition to the N_S former equations for all room surfaces, a heat balance equation should be also written for the space air:

$$\sum_{j=1}^{N} \alpha_j A_j\left(\vartheta_{SI,j,t} - \vartheta_{a,t}\right) + m_I c_p\left(\vartheta_{o,t} - \vartheta_{a,t}\right) + \Phi_{C,t} + \Phi_{AC,t} = 0 \tag{3}$$

Prvi del pomeni konvektivni prenos s površin, drugi del prodiranje, $\Phi_{C,t}$ konvektivni prenos notranjih elementov in $\Phi_{AC,t}$ stopnjo dodane oziroma odvzete toplote s klimatizirano napravo.

Enačba (2) vključuje v drugem delu temperature zunanjih površin, ki so izražene s toplotnim ravnovesjem zunanjih površin:

Here, the first term represents the convective transfer from the enclosing surfaces, the second term represents infiltration, $\Phi_{C,t}$ convective transfer from internal objects and $\Phi_{AC,t}$ the rate of heat addition or removal by the air-conditioning equipment.

Eq. (2) in the second term involves the outside surface temperatures, which are expressed by writing a heat balance at the outside surface:

$$\sum_{i=1}^{N} Y_{j,i}\vartheta_{SI,j,t-1} - \sum_{i=0}^{N} Z_{j,i}\vartheta_{SO,j,t-i} + C_{Rj} q_{o,j,t-1} = \alpha_{o,j,t}\left(\vartheta_{SO,j,t} - \vartheta_{e,j,t}\right) \tag{4}$$

in potem vstavljene v enačbo (2). S kombinacijo enačb (2) in (4), z enačbo (1) lahko dobimo N_S+1 enačb z N_S+1 neznanih temperatur (temperature površin in temperature zraka) pri času *t*. Enačbe so urejene tako, da so vse neznanke na levi strani, znane količine pa na desni. Ta problem rešimo z uporabo stolpca - matrike. Prenos toplote na notranji strani stene je združen s prenosom toplote zunanje površine, kar pomeni funkcijo prenosa toplote za steno. Funkcija tudi združuje vse enačbe prenosa toplote notranjih sten in zaradi konvekcijskih vplivov. Tu je treba poudariti, da je za zanesljivo rešitev sistema enačb nujno treba poznati vse prej omenjene temperature in toplotne tokove.

V prejšnjih enačbah so vključene tudi klimatske razmere za območje Zagreba. Statistični algoritem uporabljamo za izbiro najbolj tipičnih mesecev iz desetletnega zapisa. Izbrani meseci pomenijo enoletne podatke o vremenu (8769 h), ki jih imenujemo značilno meteorološko leto (ZML - TMY) ali preskusno referenčno leto (PRL - TRY). Za namen analiz so potrebni naslednji podatki o vremenu: (1) temperatura zunanjega zraka, (2) relativna vlažnost

and then substituted into Eq. (2). Combining Eq. (2) and (4), with Eq. (1) represents N_S + 1 equations with N_S + 1 unknown temperatures (surface temperatures and air temperature) at time *t*. The equations are arranged so that all unknowns are on the left, and all known quantities are on the right. This enables rewriting the problem to be solved in vector-matrix notation. Through these equations, the heat transfer at an inside wall surface is coupled to the heat transfer at the outside surface by means of conduction transfer functions for the wall. It is also coupled to the heat transfer at all other surface through equations of intersurface radiation, and to the room-air volume through the convection. Here it has to be pointed out that for a successful solution of the equation system, all past temperatures and fluxes are assumed to be known.

In previous equations, climatic conditions for the Zagreb area are also included. A statistical algorithm is used to choose the most typical months from the ten–year record. The selected months present a one–year weather data set (8760 h), called a Typical Meteorological Year (TMY) or Test Reference Year (TRY). For the purpose of analysis, the following weather data are used: (1) outside air temperature, (2) zunanjega zraka, (3) sončno sevanje ter podatki o (4) vetru.

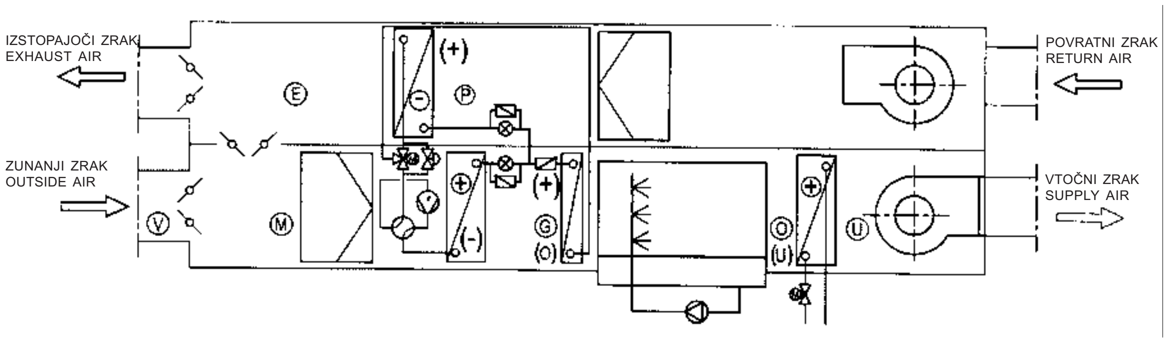
2 KLIMATIZACIJSKI SISTEM S TOPLOTNO ČRPALKO

Področni v celoti zračni osrednji sistem s toplotno črpalko (sl. 1) je sestavljen iz naslednjih delov: (1) ventilator izstopajočega zraka, (2) filter izstopajočega zraka, (3) glušna komora, (4) dušilnik povratnega zraka, (5) dotok zunanjega zraka, (6) filter vtočnega zraka, (7) toplotna črpalka z ločenim kondenzatorjem, (8) ovlaževalnik, (9) predgrevalnik, (10) ventilator vtočnega zraka. Izbrana toplotna črpalka s spiralnim predgrevalnikom zraka lahko zamenja proces hlajenja z ogrevanjem s spreminjanjem lege ventila. V ogrevalni sezoni ima prvi prenosnik toplote vlogo kondenzatorja medtem ko ima prenosnik toplote v povratnem vodu vlogo uparjalnika. V času hlajenja prostora se stanje obrne. Prvi prenosnik deluje kot uparjalnik (hladilno navitje), drugi pa kot kondenzator. Drugi prenosnik v oskrbovalnem toku zraka ima vlogo ogrevanja zraka v hladilnem obdobju samo, ko se pojavlja kondenzacija v uparjalniku.

outside air relative humidity, (3) solar radiation, (4) wind data.

2 AIR-CONDITIONING SYSTEM WITH HEAT PUMP

A single-zone, all-air, central system with heat pump (Fig. 1) is arranged with the following components: (1) return-air fan, (2) return-air filter section, (3) relief-air damper, (4) return-air damper, (5) outdoor-air intake, (6) supply-air filter section, (7) heat pump with split condenser, (8) humidifier, (9) reheat coil, (10) supply-air fan. The selected heat pump with refrigerant-to-air coils can change the cycle from the cooling to the heating mode by means of a reversing valve. So, during the heating season, the first heat exchanger in the supply air stream operates as a condenser (heater), while the heat exchanger in the return air stream operates as an evaporator. During the cooling season, the situation is reversed.The first heat exchanger in the supply air stream operates as an evaporator (cooling coil), while the heat exchanger in the return air stream operates as a condenser. The second exchanger in the air supply stream has to reheat air in the cooling season to the supply temperature, only when air dehumidification on the evaporator occurs.



Sl. 1. *Osrednji klimatizacijski sistem s toplotno črpalko*
Fig. 1. *Central air-conditioning system with heat pump*

Znaki v oklepajih na sliki 1 se nanašajo na hlajenje. Izračun za doseganje želenega termodinamičnega stanja vstopajočega zraka (določeni iz toplotnih dobitkov) sloni na tipičnem klimatizacijskem procesu: (1) ogrevanje, (2) hlajenje (z izločevalnikom vlage ali brez njega), (3) mešanje, (4) ovlaževanje.

Dodatek toplote na kondenzatorju v ogrevalni sezoni se mora ujemati s stopnjo toplote med sistemoma *M* in *G* (sl. 1) v času *t*:

In Fig. 1, the signs in brackets refer to the cooling operation mode. The calculation procedure used to achieve the desired thermodynamic condition of the supply air (determined from the net space load) is based on typical air-conditioning processes: (1) heating, (2) cooling (with or without moisture separation), (3) mixing, (4) moisture addition.

Heat addition from a condenser in the heating season must match the required heat rate between air conditions *M* and *G* (Fig. 1) at time *t*:

$$\Phi_{Co,H,t} = V_{AC,t}\,\rho \quad (h_{G,t} - h_{M,t}) \qquad (5),$$

kjer je entalpija zmesi $h_{M,t}$ neznana. Vrednost entalpije za standardno toplotno črpalko lahko določimo iz povezave med kapacitetama kondenzatorja in uparjalnika:

where the mixture enthalpy $h_{M,t}$ is unknown. Its value can be determined by means of the standard heat pump relation for a connection between the condenser and evaporator capacity:

$$\Phi_E = \Phi_{Co}\left(1-\frac{\eta_a}{\varepsilon_H}\right) \tag{6},$$

kjer je:

where:

$$\varepsilon_H = \frac{\Phi_{Co}}{P_{KP}} \tag{7}.$$

Kombinacija enačb (5) in (6), skupaj z enačbo za mešanje zračnih tokov, da rešitev:

Combining Eq. (5) and Eq. (6) together with an equation for mixing of the air streams, gives the solution:

$$h_M = \frac{g_o h_V + (1-g_o)h_P - (1-g_o)\left(1-\frac{\eta_a}{\varepsilon_H}\right)h_G}{1-(1-g_o)\left(1-\frac{\eta_a}{\varepsilon_H}\right)} \tag{8}.$$

Po ovlaževanju je končno želeno toplotno razmerje doseženo z ogrevalnim navitjem (če je potrebno), s tem dosežemo primerno termodinamično stanje vstopajočega zraka:

Rest of the required heat rate is supplied by the reheat coil (if necessary), after humidification, in order to achieve an adequate thermodynamic condition of the supply air:

$$\Phi_{RH,t} = V_{AC,t}\rho \quad (h_{U,t} - h_{O,t}) \tag{9}.$$

V prehodnem obdobju med ogrevanjem in hlajenjem je primerno termodinamično stanje zraka doseženo s spreminjanjem razmerja mešanice vstopajočega in izstopajočega zračnega toka.

Če je potrebno hlajenje z ločevanjem vlage, se pojavi sprememba na toplotni črpalki. Tako prvi prenosnik vstopajočega zraka deluje kot uparjalnik, pogosto s 100% uporabo zunanjega zraka. V danem primeru je hladilna zmogljivost uparjalnika pri času t podana:

In the transitive period between heating and cooling seasons, adequate thermodynamic condition of the supply air is achieved by changing the mixing ratio of the return- and outside-air streams.

If air cooling is necessary, with possible moisture separation, the changeover in heat pump cycle occurs. So, the first heat exchanger in supply air stream operates as an evaporator, most often with 100% of outside air. In the former case, the cooling capacity of an evaporator at time t is given by:

$$\Phi_{E,t} = V_{AC,t}\rho \quad (h_{V,t} - h_{O,t}) \tag{10}.$$

Potrebna količina toplote, ki omogoča ustrezno termodinamično stanje vstopnega zraka, je lahko uporaba drugega menjalnika, ki deluje kot kondenzator. Njegova ogrevalna zmožnost se določi z enačbo (9).

The possibly required heat rate, to achieve an adequate thermodynamic condition of the supply air is supplied by a second exchanger in the supply-air stream that operates as a condenser. Its heating capacity is calculated by the term in Eq. (9).

3 REZULTATI

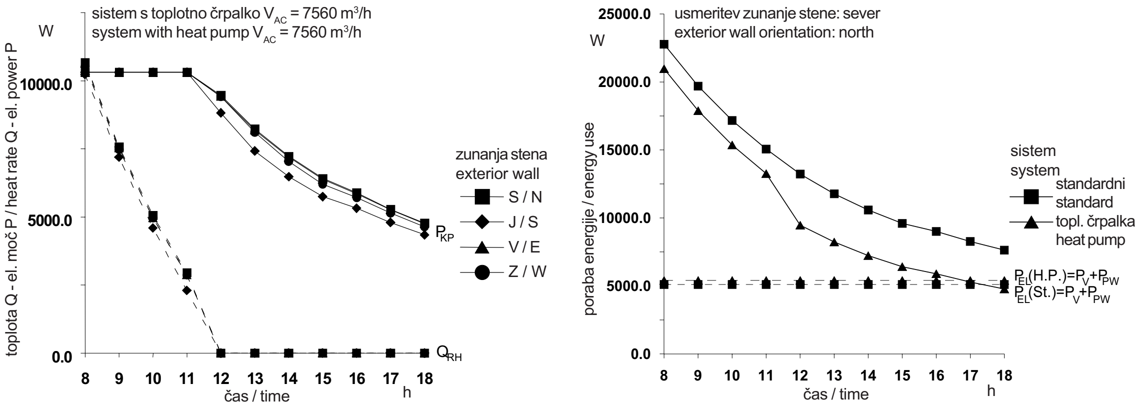
3 RESULTS

Doseženi rezultati so sestavljeni iz podatkov za 8760 h ZML. Podatki so oblikovani za vsako uro obremenitve prostora ter porabe energije posameznih komponent sistema, ki ga sestavljajo navitja, kompresor, ventilator in vodna črpalka. Poleg tega je analiziran tudi standardni osrednji klimatizacijski sistem, kjer je zahtevano ogrevanje oziroma hlajenje doseženo z ogrevanjem vode in zraka, dogrevalnim in hladilnim navitjem. Pri predstavljenih rezultatih v tem prispevku so vrednost naslednjim parametrom ne spreminja: (1) celotna prostornina prostora – 24 m x 15 m x 3,5 m, (2) celotna površina oken – 16 m^2, (3) prostornina kondenziranega zraka – 7560 m^3/h. (4) celotna notranja senzibilna toplota – 8000 W, (5) obdobje klimatizacje – 8:00 do 18:00 h.

The obtained results consist of the data sets for 8760 h of the TMY. The data sets are created for hourly net space load, and the energy use of the system components including coils, compressor, fans and water pump. In addition, analysis is also conducted for the standard central air-conditioning system, where the required heating, i.e. cooling rate is achieved by means of the water-to-air heat, reheat and cooling coils. For the results presented in this paper the following parameters are held constant: (1) total room volume – 24 m x 15 m x 3.5 m, (2) total window area – 16 m^2, (3) air-conditioning volume rate – 7560 m^3/h, (4) total internal sensible load – 8000 W, (5) system operation period – 8:00 to 18:00 h.

Na sliki 2 (levo) so rezultati urne porabe energije na karakteristični dan v ogrevalni sezoni, za sistem s toplotno črpalko. Rezultati so prikazani za vse štiri osnovne usmeritve sten skupaj. Na desni strani slike je primerjava s toplotno črpalko in standardnim sistemom, v tem primeru je uporabljena samo severna usmeritev stene.

Hourly energy use results for a characteristic day in a heating season for the system with heat pump are shown in Fig. 2 (left). The results are presented for four main exterior wall orientations, together with a comparison between the system with a heat pump and a standard system for the north-oriented room (right).



Sl. 2. *Urna poraba energije v ogrevalni sezoni*
Fig. 2. *Hourly energy use in a heating season*

Na levem diagramu (slika 2) je moč opaziti, da je najmanjša poraba energije na južni strani, najbolj neugodna pa je severna stran. To je posledica manjšega sončnega sevanja skozi steno in okna, to prispeva tudi k toplotnim dobitkom v ogrevalni sezoni. Prihranek energije pri sistemu s toplotno črpalko je pomemben v primerjavi s standardnim sistemom (sl. 2 – desni diagram). V določenih razmerah lahko razlike dosegajo tudi do 30%. Omeniti je treba, da je zaradi večjega števila navitij poraba električne energije ventilatorjev večja za sisteme s toplotno črpalko, čeprav te razlike niso tako očitne.

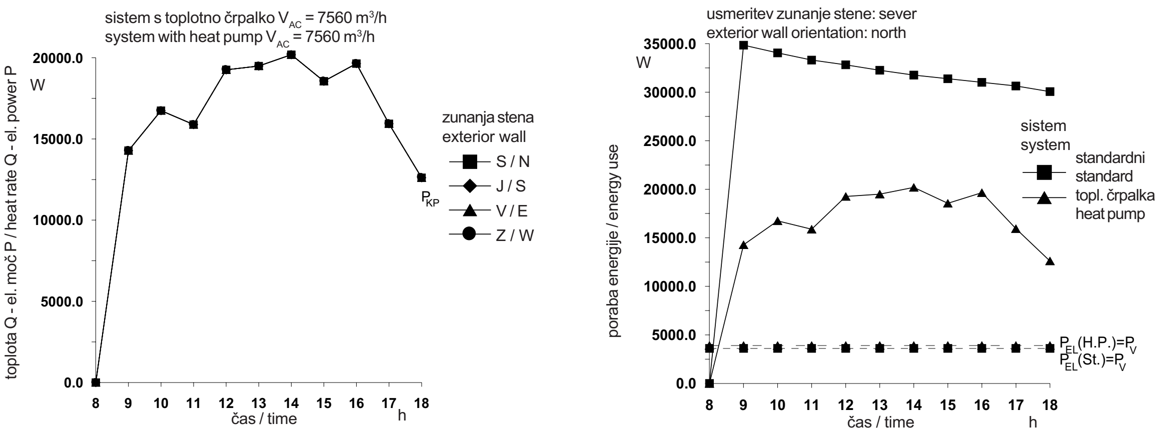
Rezultati urne porabe energije na značilni dan v hladilni sezoni, skupaj s primerjavo sistema s toplotno črpalko in običajnega sistema za severno usmeritev stene, so prikazani na sliki 3.

V urah, ko potrebujemo večje hlajenje, kompresor deluje ne glede na usmeritev prostora, ker je hlajenje naravnano na strani oddajanja toplote (sl. 3 – levo). Delovanje ogrevalnega navitja prevzema drugi prenosnik toplote v oskrbovalnem toku zraka, ki deluje kot kondenzator. Ko je potrebno manjše hlajenje, se pojavijo razlike med različno usmerjenimi površinami, posebno v zgodnjih in poznih urah delovanja sistema. Slika 3 (desno) prikazuje večje spremembe med obema analiziranima sistemoma, kakor so se pojavile med ogrevalno sezono (v določenih razmerah dosega razlika tudi vrednost 55%). Na splošno je razvidno, da so prihranki energije pri toplotni črpalki višji v obdobjih, ko je potrebno največje hlajenje. Kljub vsemu pa se le redko pojavijo tako visoke zahteve po obremenjevanju toplotne črpalke.

In the left diagram (Fig. 2) it is clear that the lowest energy use is achieved for the south orientation of a space, and the most inconvenient was the north orientation. This is the consequence of solar irradiation on the exterior wall and through the windows, which also influences the heat gain in a heating season. Energy saving with the system with a heat pump is significant compared to the standard system (Fig. 2 – right diagram). The differences can be up to 30% under certain operating conditions. Here it has to be pointed out that the electricity consumption of fans is higher for the system with a heat pump because of the higher pressure drop in the system, although this difference is not significant.

Hourly energy use results for a characteristic day in a cooling season, together with comparison between the system with a heat pump and a standard system for the north-oriented room, are presented on Fig. 3.

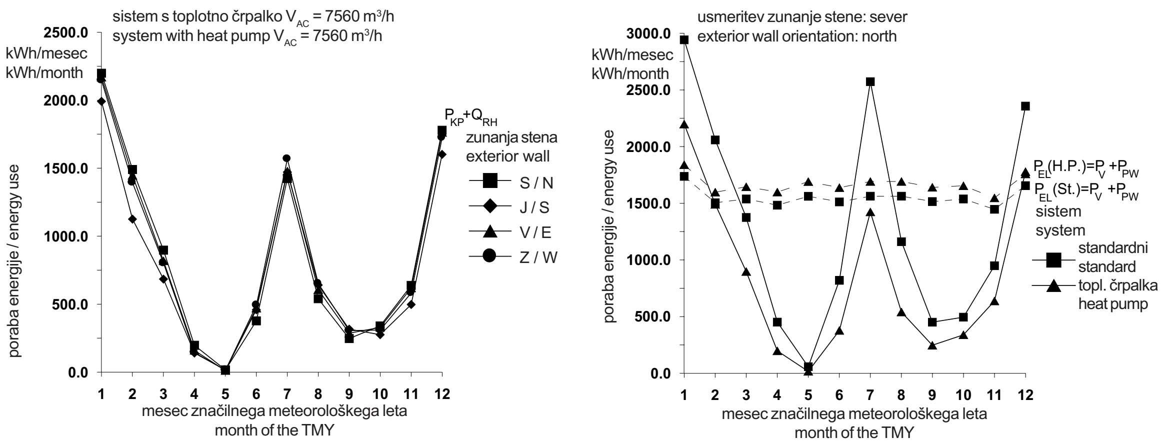
In the hours with higher required cooling rates the compressor operated regardless of the room orientation because the capacity control is done on the reheat side (Fig. 3 – left). Function of the reheat coil is taken over by the second heat pump exchanger in the supply-air stream, which operates as a condenser. When a lower cooling rate is required, there appeared some differences between the orientations, especially in the early and late operation hours. A comparison (Fig. 3 – right) showed even greater differences between the two analyzed systems than during a heating season (up to 55% under some operating conditions). Generally, it is observed that the energy saving with a heat pump is highest in the hours with maximum cooling rates. However, there are not many hours in a cooling season with such high demands on the equipment.



Sl. 3. *Urna poraba energije v hladilni sezoni*
Fig. 3. *Hourly energy use in a cooling season*

Rezultati porabe energije po posameznih mesecih skozi značilno meteorološko leto so predstavljeni na sliki 4.

Results for the energy consumption in the form of the monthly sums during the Typical Meteorological Year are presented in Fig. 4.



Sl. 4. *Poraba energije v značilnem meteorološkem letu*
Fig. 4. *Energy use during the Typical Meteorological Year*

Na levem diagramu (sl. 4) so predstavljene spremembe porabe energije za ogrevanje, hlajenje in razvlaževanje zraka v obratovalnih razmerah in za zunanjo steno. Severno usmerjeni prostori imajo večjo porabo energije v ogrevalni sezoni in manjšo v hladilni sezoni. Južno usmerjeni prostori imajo manjšo energijsko porabo v ogrevalni sezoni, zahodno usmerjeni prostori imajo večjo porabo energije v hladilni sezoni. Vsota celotne porabe energije za vse leto je največja v zahodno usmerjenih prostorih in najmanjša v južno usmerjenih prostorih. Primerjava za severno usmerjene prostore, prikazana na sliki 4 (desno), prikazuje razliko med obema analiziranima sistemoma skozi vse leto. Iz celotne vsote porabljene energije skozi vse leto je razvidno, da sistem s toplotno črpalko porabi 20% manj energije (severna stena) v primerjavi z običajnim sistemom. V določenih obdobjih hladilne sezone pa ta vrednost lahko doseže 30 odstotkov.

In the left diagram (Fig. 4) are presented the changes in energy use for heating, cooling and dehumidification of the air with operating conditions and with exterior wall orientation. The north-oriented space had the highest energy use in a heating season and the lowest energy use in a cooling season. The south-oriented space had the lowest energy use in a heating season and the west-oriented space had highest energy use in a cooling season. Total sum of the energy use for a whole year is determined to be the highest for the west-oriented space and the lowest for the south-oriented space. A comparison for the north-oriented space (Fig. 4 – right) showed differences between the two analyzed systems during a whole-year operation. The total sum for a whole year showed that the system with a heat pump consumed up to 20% less energy (north orientation), compared to the standard system. However, in some months of a cooling season this difference increased up to 30%.

4 SKLEP

Razvit vsakourni simulirni model osrednjega klimatizacijskega sistema s toplotno črpalko omogoča analizo delovanja sistema skozi različna obdobja in razmere, ki se pojavljajo med letom. Dobljeni rezultati kažejo, da ima sistem s toplotno črpalko opazno manjšo porabo energije v primerjavi z običajnim sistemom (20 do 25%, odvisno od usmeritve prostora). Zaradi navedenega je uporaba ekonomsko upravičena, vendar bi pred dejansko odločitvijo o uporabi bilo pametno upoštevati tudi stroške investicije in vzdrževanja.

Toplotna ravnovesna metoda, uporabljena za izračun ocenjenih energijskih obremenitev, je odvisna od modela, uporabljenega za oblikovanje ali izbiranje opreme, ker temelji na tipičnih vremenskih podatkih. Zaradi njenih velikih zmožnosti avtorji predpostavljajo, da se bo uporaba metode v klimatizacijskih sistemih v prihodnosti povečala. V tem trenutku je največja omejitev metode njena zapletenost, toda z razvojem in uporabo vse hitrejših računalnikov je moč upati, da bo tudi ta omejitev odpravljena.

4 CONCLUSION

The developed hour-by-hour simulation model for a central air-conditioning system with heat pump enabled a system operation analysis under different operating conditions during the year. The results showed that the system with a heat pump had significantly lower energy use compared to the standard system (20 to 25%, depending on the space orientation). Therefore, its application seems to be economically justified, although for the complete evaluation, investment and maintenance costs should be also included.

The heat balance method used for calculating the load aspects of energy estimating is different from the model used to design or select the equipment because it is based on typical weather conditions. Because of its great possibilities the authors presume that its use for the HVAC system operation analysis will increase in the future. The most limiting factor at the moment is its complexity, but fast computer development could create the prerequisite conditions to simplify its exploitation.

5 OZNAČBE
5 SYMBOLS

površina	A	m^2	area
specifična toplota	c_p	J/kgK	specific heat capacity
količnik toplotnega toka	C_R	-	heat flux factor
masni tok zunanjega zraka	g_o	-	outside air mass ratio
količnik kota	G	-	angle factor
specifična entalpija	h	J/kg	specific enthalpy
masni tok infiltracije	m_I	kg/s	infiltration mass flow rate
električna moč kompresorja	P_{KP}	W	compressor electrical power
gostota toplotnega toka	q	W/m^2	heat flux density
prostorninski tok sistema	V_{AC}	m^3/s	system volume flow rate
prenosne funkcije	X, Y, Z	W/m^2K	conduction transfer functions
količnik toplotne prestopnosti	α	W/m^2K	heat transfer coefficient
hladilno število	ε_H	-	COP - coefficient of preformance
toplotni tok	Φ	W	heat flux
količnik pretvorbe električne energije kompresorja	η_a	-	conversion factor to electrical power of compressor
temperatura	ϑ	°C	temperature
gostota	ρ	kg/m^3	density

6 LITERATURA
6 REFERENCES

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