© Strojniški vestnik 45(1999)2, 57-63
ISSN 0039-2480
UDK 697.38:519.61/.64
Strokovni članek (1.04)

© Journal of Mechanical Engineering 45(1999)2, 57-63
ISSN 0039-2480
UDC 697.38:519.61/.64
Speciality paper (1.04)

Tridimenzionalna analiza toplotnega prehodnega pojava v talnih zbirnih sistemih iz betonskih cevi z metodo končnih elementov

Three Dimensional Finite Element Analysis of the Transient Thermal Behavior of Ground-Coupled System Using Concrete Tubes

Igor Tičar

Da bi izboljšali učinkovitost zračnih in vodnih črpalk za ogrevanje tipičnih enodružinskih hiš, vnaprej ogrevamo zrak z uporabo betonskih cevi, vkopanih v zemljo. Članek opisuje toplotni prehodni pojav in s tem obnašanje tovrstnega talnega zbirnega sistema z metodo končnih elementov (MKE).

MKE smo povezali s programsko opremo, ki simulira ogrevalni sistem tipične enodružinske hiše. Simuliranja smo razdelili čez celo leto s časovnim razmikom ene ure, pri čemer je znašal čas računanja za posamezni sistem 25 ur na računalniku DECAlphaStation 5000/500.

Različne geometrijske oblike zbiralnika smo raziskovali z uporabo 20-vozliščnih izoparametričnih končnih elementov. Različna geometrijska izhodišča so dala rezultate o učinkovitosti sistema.

© 1999 Strojniški vestnik. Vse pravice pridržane.

(Ključne besede: ogrevanje hiš, pojavi prehodni, simuliranje sistemov, metode končnih elementov)

To improve the efficiency of air/water heat pumps for the heating of typical one-family houses the air is preheated in an arrangement of concrete tubes embedded in the earth. In this paper, a simulation of the transient thermal behaviour of such earth-collector systems is described using the finite element method (FEM).

The FEM is coupled with a software package simulating the heating system of the house. The simulations are performed during a whole year with a time step of one hour. The calculation time for one system over one year is about 25 hours on a DECAlphaStation 5000/500.

Different collector geometries were investigated using 20 noded isoparametric finite elements. The resulting efficiency numbers of the systems are for different layouts.

© 1999 Journal of Mechanical Engineering. All rights reserved.

(Keywords: heating of houses, transient behaviour, simulations, finite element methods)

0 UVOD

Po uspešni predstavitvi ogrevanja s toplotnimi črpalkami v Avstriji v začetku osemdesetih let, so se začetne težave končale s sesutjem trga. Ponovni začetek še preostalih ponudnikov je bil težaven predvsem zaradi omejitev v zvezi z uporabo talne vode kot toplotnega vira; poleg tega tudi dvodelni sistemi, ki so kot toplotni vir uporabljali okoliški zrak (grelno število - GŠ okoli 2,5), zaradi nizkih cen nafte niso bili več tržno konkurenčni.

To je bil poglavitni razlog za uporabo zemlje kot toplotnega vira in s tem rešitve, ki bo omogočila tudi enodelne sisteme. Uporabili smo vodoravno, 0,8 - 1,2 metra globoko instalirane zbiralnike, jarkaste zbiralnike in navpične sonde. Navkljub vsemu pa je ta izjemno učinkovita tehnologija postala predmet številnih razprav, katerim so botrovale predvsem omejitve v zvezi z odvajanjem toplote iz zemlje.

0 INTRODUCTION

Following the successful introduction of heat pump heating systems in Austria at the beginning of the eighties, initial difficulties resulted in a breakdown of the market. The restart for the remaining vendors was difficult because there were restrictions on using ground water as a heat source, and bivalent systems with ambient air as a heat source with (System Performance Factor) SPFs of about 2.5 were no longer competitive in view of the low oil price.

This was the reason for the introduction of the ground as heat source, a solution also facilitating monovalent systems. Horizontally installed collectors placed at a depth of 0.8 to 1.2 m, ditch collectors and vertical probes are being used. Nevertheless, this highly efficient technology became the subject of extended discussions caused by a regulation on heat extraction from the ground.

To je bila začetna točka pri razvoju "zračnega vodnjaka", katerega sestavljajo v zemljo vkopane betonske cevi. Ta vnaprej ogreva okoliški zrak, ki ga kasneje uporabljamo bodisi kot vir toplote za zračne ali vodne toplotne črpalke, bodisi kot svež zrak pri sistemih nadzorovanega prezračevanja, opremljenih s sistemom toplotnega obnavljanja, sestavljenega iz obnovitvenega toplotnega izmenjalnika in zračno - zračne toplotne črpalke. Primeri tovrstnih instalacij so teniški center v Petronellu, Spodnja Avstrija, kjer je posamezne meritve izvedla EVN (Energie Versorgung Niederösterreich - Toplotna oskrba Spodnje Avstrije) in pri katerem lahko preučujemo obe vrsti uporabnosti, kakor tudi drugi objekti, pri katerih so bile kot zbiralnik zraka uporabljene plastične cevi.

V okviru predstavljenega projekta smo razvili simulirne modele za izračun sistema s toplotno črpalko okoliškega zraka, ki jo oskrbuje z uporabo "zračnega vodnjaka" vnaprej ogret zrak. Posamezen "zračni vodnjak" smo z metodo končnih elementov izdelali zelo natančno. Študijo primera za povprečno hišo s toplotno potrebo 9,75 kW smo izvedli s spremenljivimi parametri, to so: dolžina in premer zbiralnika, globina instalacije in podnebne razmere.

1 NUMERIČNO SIMULIRANJE

Programsko opremo za numerično simuliranje "zračnega vodnjaka" sestavljajo trije moduli. Prvi z metodo končnih elementov simulira toplotno prehodno obnašanje v zemljo vkopanih zbiralnikov, drugi modul opisuje toplotno prehodno obnašanje v posamezni cevi, zadnji pa simulira ogrevalni sistem s toplotno črpalko v značilni hiši [1].

1.1 Model končnih elementov

Za natančno obdelavo toplotnega prehodnega pojava ter obnašanja zračnega zbiralnika in zraka, ki ga obdaja, je najprej treba rešiti znano Fourierjevo enačbo, ki opisuje probleme prehoda toplote v tridimenzionalnem prostoru:

This was the starting point for the development of the "air-well", an air collector consisting of concrete tubes buried in the ground. Ambient air is preheated in this collector and used either as a heat source for air-water heat pumps or as fresh air for controlled ventilation systems equipped with a heat recovery system consisting of a regenerative heat exchanger and an air-air heat pump. Examples of such installations are the tennis centre at Petronell, Lower Austria where some measurements by EVN (Energie Versorgung Niederösterreich) have been carried out and which incorporates both kinds of utilisation as well as some residences with plastic tubes also used as air collectors.

Within the project described in this paper, simulation models have been developed for calculating heat pump systems with an ambient-air heat pump supplied by preheated air through an air-well. The air - wells are modelled very accurately by the finite element method. A case study for a standard house with a heating load of 9.75 kW has been carried out with varied parameters such as the length and diameter of the collector, depth of installation and climatic condition.

1 NUMERICAL SIMULATION

The software for the numerical simulation of such air-well systems consists of three modules. In the first module the transient thermal behaviour of the collectors embedded in the earth is simulated by the finite element method. In the second module the transient thermal behaviour of the air flow within the concrete tubes is described, and in the last module the heat pump heating system of the typical house is simulated [1].

1.1 Finite Element Model

An accurate treatment of the transient thermal behaviour of the air collector together with the surrounding air needs the solution of the well known Fourier equation [2] for three dimensional transient heat conduction problems:

$$\nabla \cdot (\lambda \nabla T) + c\rho \frac{\partial T}{\partial t} = 0 \qquad (1),$$

kjer so T temperatura, λ toplotna prevodnost, c specifična toplota, ρ masna gostota t pa neodvisna spremenljivka. Pri numerični rešitvi smo za diskretizacijo geometrijske oblike uporabili metodo končnih elementov, za diskretizacijo časa pa Eulerjevo shemo končnih razlik.

Kot končne elemente smo uporabili 20-vozliščne, izoparametrične, šeststrane elemente, saj so ti najprimernejši za opisovanje zaobljenih oblik cevi [3]. Slika 1 prikazuje s končnimi elementi dobljeno strukturo raziskovanega zbiralnika v prerezu

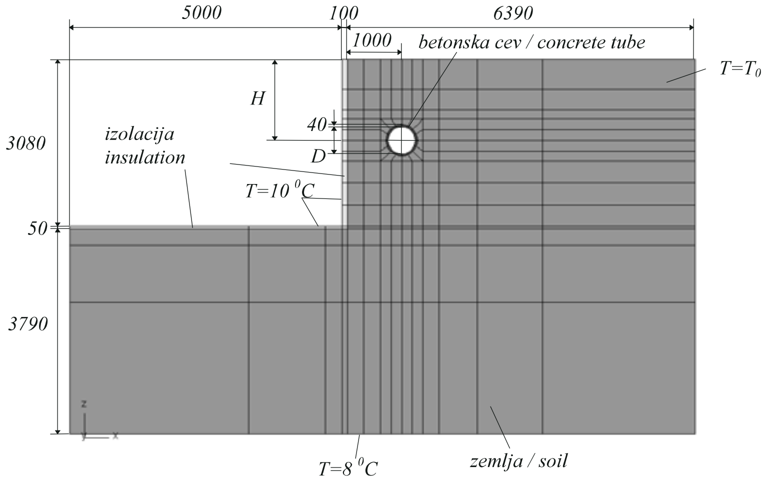
where T is temperature, λ is the heat conductivity, c is the specific heat, ρ is the mass density, and t denotes time. For the numerical solution, the finite element method has been chosen for the discretisation of the geometry, and the Euler backward finite difference scheme for time discretisation.

As finite elements, 20 noded isoparametric brick elements have been used, since these elements are well suited for describing the curved shapes of the tubes [3]. In Figure 1, the finite element structure in the *xz*-plane of one collector arrangement under *xz* skupaj z dimenzijami in pripadajočimi mejnimi razmerami. Dolžina zbiralnika s premerom 0,5 m v smeri *y* znaša 60 metrov. Tridimenzionalno sliko naslednjega raziskanega, zračno-zbirnega sistema, sestavljenega iz dveh ob stavbi vzporedno potekajočih cevi, lahko vidimo na sliki 2. V tem primeru je dolžina zbiralnika s premerom 0,2 m 30 metrov, cevi sta zaporedno med seboj povezani, zračni tok v obeh ceveh pa je nasproten.

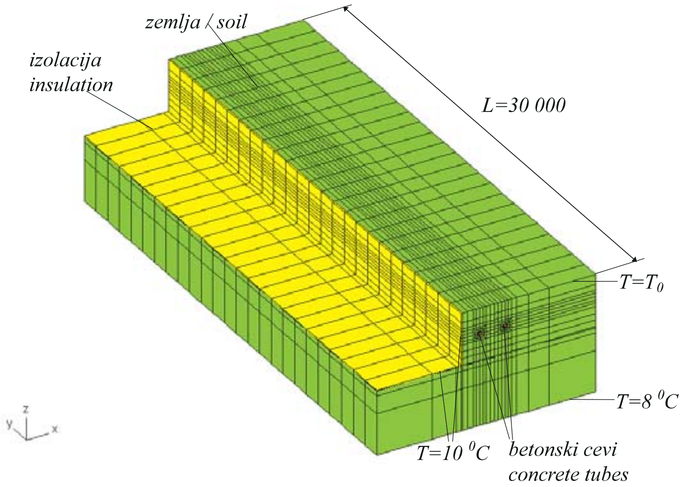
Temperature na površju zemlje so tako imenovane Augsburške vrednosti, ki se objavljajo na uro glede na povprečno leto, skupaj z drugimi značilnimi podatki, npr.: vlažnost. Predpostavljamo, da je temperatura zemlje v globini 6,89 metra stalna in znaša 8 ^{0}C, pod stavbo pa 10 ^{0}C. Zidovi na dnu stavbe imajo 10 oziroma 5 cm debelo toplotno izolacijo.

investigation is shown together with dimensions and appropriate boundary conditions. The length of the collector in the y-direction is 60 m, the diameter of the tube is 0.5 m. A three dimensional plot of another investigated air collector system consisting of two parallel tubes alongside the building can be seen in Figure 2. In this case, the length of the collector is 30 m and the diameter of the tubes 0.2 m. The air flow is anti-parallel in the two tubes, they are connected in series.

The temperature values at the surface of the earth are the so - called Augsburg values, which are given hourly for one standard year together with other significant values, such as humidity etc. At a depth of 6.89 m, the temperature is assumed to be constant at a value of 8 °C and within the building the temperature is 10 °C. The walls and the bottom of the building have a thermal insulation of 10 cm and 5 cm, respectively.



Sl .1. *Samostojna betonska cev (premer D = 500mm) ob stavbi (izmere so v mm)*
Fig. 1. *A single concrete tube (diameter: D=500 mm) near a building. (Dimensions in mm)*



Sl . 2. *Dvocevni sistem (premer = 200mm) ob stavbi (izmere so v mm)*
Fig. 2. *A double tube system (diameter: 200 mm each) near a building. (Dimensions in mm)*

Število končnih elementov strukture, prikazane na sliki 1, je 9100, kar daje v izračun 36440 temperaturnih vrednosti; sistem na sliki 2 pa sestavlja 8200 končnih elementov in 33580 vozlišč.

1.2 Toplotno obnašanje zračnega toka v betonskih ceveh

Model končnih elementov mora biti povezan z modelom, ki opisuje toplotni prehodni pojav obnašanja zračnega toka v cevi. To povezovanje sestoji iz toplotne izmenjave med zrakom in betonsko oblogo, ki poteka po notranji strani cevi. Izmenjava se udejanja prek Cauchyevega mejnega pogoja :

The number of finite elements of the structure shown in Figure 1 is 9100, thus resulting in 36440 unknown temperature values to be calculated. The system shown in Figure 2 consists of about 8200 finite elements with about 33580 nodes.

1.2 Thermal Behaviour of the Air Flow within the Concrete Tubes

The finite element model has to be coupled with a model describing the transient thermal behaviour of the stream of air in the tube. This coupling consists of a heat exchange between air and the surrounding concrete wall along the inner surface of the tube and is realised via a Cauchy boundary condition:

$$\lambda\frac{\partial T}{\partial n}+\alpha(T-T_0)=0 \qquad (2),$$

kjer so n normala na notranjo površino cevi, α toplotni količnik, T_0 pa temperarura zraka v cevi.

Diskretizacijo časa v tem postopku znotraj cevi dosežemo z razdelitvijo cevi v razdelke, dolge približno 1 meter. Tako je čas, v katerem pride do toplotne izmenjave, za posamezni razdelek določen s hitrostjo zraka in dolžino razdelka.

V modelu smo upoštevali tudi od vlažnosti zraka odvisne spremembe med kapljevitim in plinastim agregatnim stanjem. Kakorkoli že, v vseh raziskanih primerih se je njihov vpliv izkazal kot zanemarljiv.

1.3 Model ogrevalnega sistema značilne hiše

Da bi simulirali ogrevalni sistem s toplotno črpalko za povprečno hišo, je bil na TU Graz razvit programski paket, ki ga je mogoče vgraditi v časovno zanko v programu, ki rešuje problem po metodi končnih elementov. Vhod tega modula je izhodna temperatura zbiralnika, ki ga dobimo iz modula MKE skupaj s količino zraka na sekundo. Njegov izhod je potrebni obratovalni čas toplotne črpalke v minutah na posamezno uro. Slednjega uporabljamo za nadzor nad dolžino časovnih korakov v modulu MKE. Če je obratovalni čas črpalke 0 do 60 minut, je časovni interval simuliranja MKE 1 ura. To je glede na toplotne razsežnosti "zračnega vodnjaka" zadovoljivo malo.

2 REZULTATI

Značilni raziskani primeri so prikazani v preglednici 1 skupaj z njihovimi GŠ.

Slika 3 prikazuje razporeditev temperature treh prerezov zbiralnika, za postavke s slike 1 v času, ko je temperatura okolja zelo nizka (19. december, opoldan - 3.vrsta v preglednici 1). Izbrani prerezi so

where n is the direction normal to the inner surface of the tube, α is the heat exchange number and T_0 is the air temperature in the tube.

The time discretisation of this process inside the tube is realised by subdividing the tube into segments of about 1 m. Therefore, the heat exchange time for each segment is given by the velocity of the air and the length of the segments.

In this model, the phase transition between liquid and gaseous due to the humidity of the air has also been taken into account. However, it turned out that in all cases investigated, this effect is negligible.

1.3 Model of Heating System of Standard House

To simulate the heat pump heating system of a standard house (a typical Austrian one family house), a software package developed at the Technical University Graz had to be implemented into the time loop of the finite element code. The input for this module is the output temperature of the collector obtained by the FEM-module together with the volume of air per second. Its output is the necessary running time of the heat pump in minutes for each hour. This time is used to control the length of the time steps in the FEM-module. If the running time of the heat pump is 0 to 60 minutes, the default time step length of the FEM simulation is one hour. This is sufficiently small in view of the thermal properties of the air-well.

2 RESULTS

Some typical cases investigated are listed in Table 1 together with the SPFs obtained.

In Figure 3 the temperature distribution in three planes perpendicular to the collector is shown for the configuration of Figure 1 at a time instant when the ambient temperature is very low (December 19, 12 a.m., third row in Table 1). The three planes

Preglednica 1. *Nekaj raziskanih primerov (podano je GŠ)*
Table 1. *Some investigated cases (with SPFs attained)*

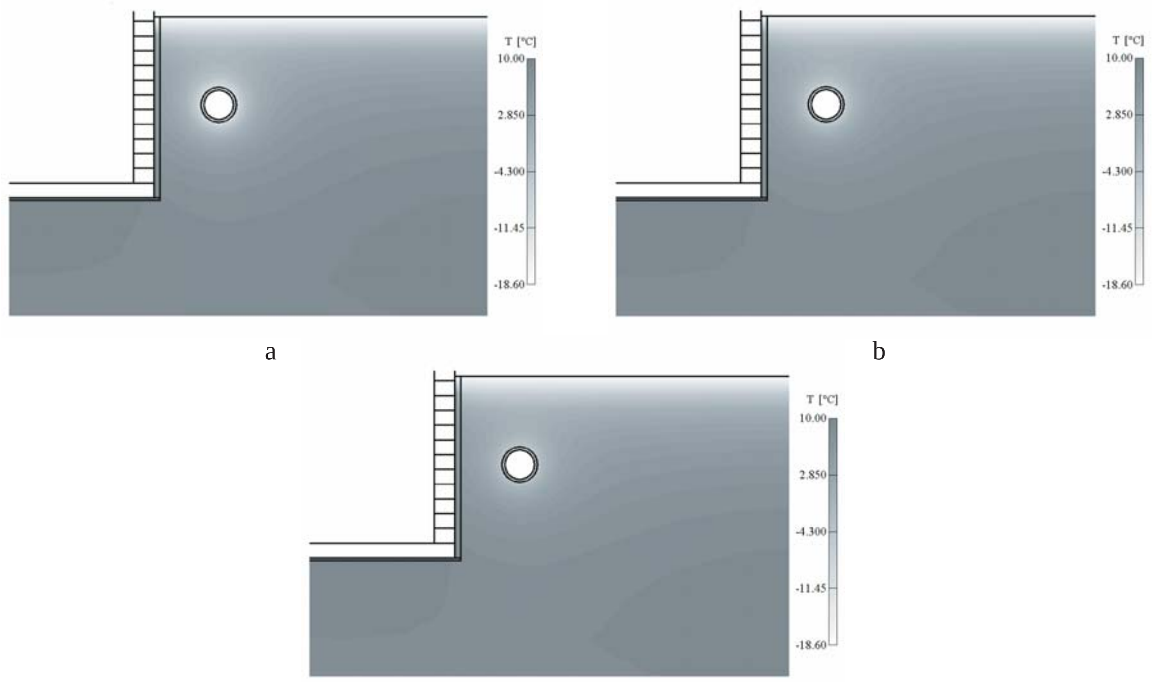
Ena cev pod stavbo: Single tube under a building:	H=1,5 m, D=50 cm, L=50 m	GŠ=3,377=SPF
Ena cev - zunaj stavbe: Single tube, outdoors:	H=1,5 m, D=50 cm, L=60 m	GŠ=2,880=SPF
Ena cev ob stavbi: Single tube beside a building:	H=1,5 m, D=50 cm, L=60 m	GŠ=2,894=SPF
Dve cevi ob stavbi: Double tube beside a building:	H=1,5 m, D=20 cm, L=2×30 m	GŠ=2,895=SPF
Ena cev ob stavbi: Single tube beside a building:	H=2,0 m, D=50 cm, L=60 m	GŠ=2,900=SPF
Ena cev - zunaj stavbe, izboljšana toplotna črpalka: Single tube, outdoors, improved heat pump:	H=1,5 m, D=50 cm, L=60 m	GŠ=3,466=SPF

na vhodu, sredini in izhodu zbiralnika. Ogrevalni učinek "zračnega vodnjaka" je jasno razviden.

Slika 4 je izdelana za podobne postavke, le da je zbiralnik sestavljen iz dveh vzporedno potekajočih cevi, ki sta zaporedno med seboj povezani (4.vrsta v preglednici 1). Trije prerezi, izbrani v tem primeru, so: skupni vhodno-izhodni, sredinski in prerez mesta, na katerem sta obe cevi povezani. Temperaturne razlike na skupnem vhodno-izhodnem prerezu zelo dobro ponazarjajo učinek "zračnega vodnjaka".

selected are at the input, at the middle and at the output of the collector. The heating effect of the air-well is easy to see.

Figure 4 shows a similar configuration, but the collector is made up of two parallel tubes connected in series (fourth row in Table 1). The three planes selected now are the common plane of the input and output, the middle plane and the plane where the two tubes are connected. The sharp temperature gradients in the common plane of the input and output illustrate the effect of the air-well.

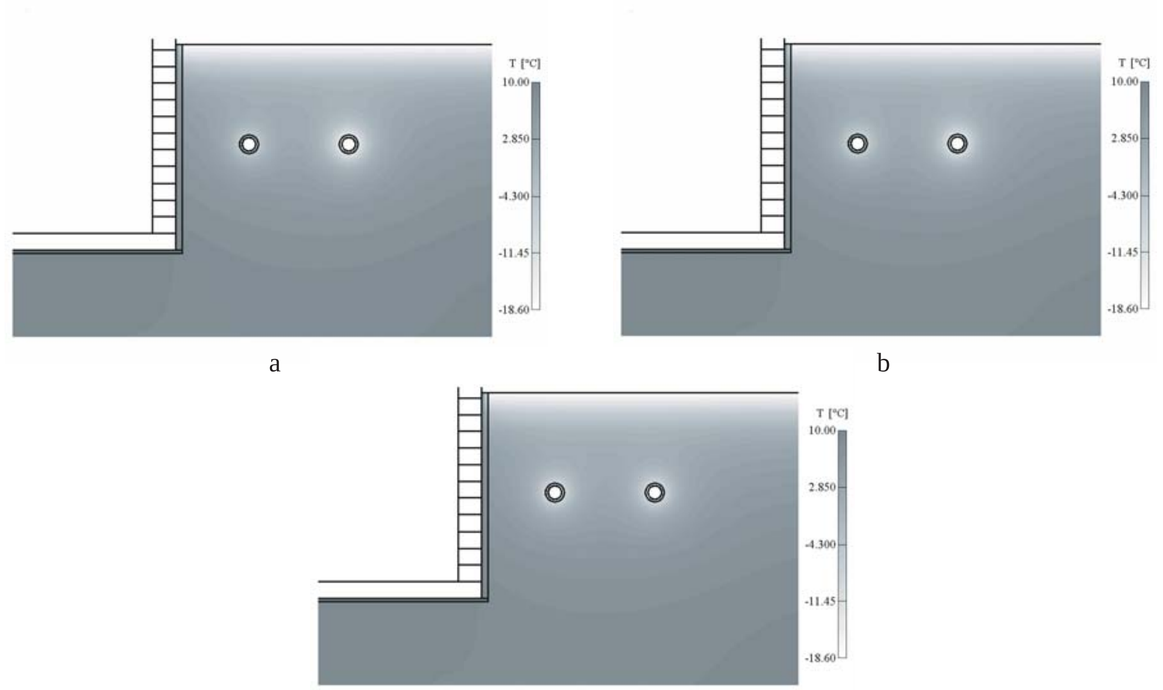


a

b

c

Sl. 3. *Razporeditev temperature v treh prerezih prečno na betonsko cev ob stavbi (L=60 m, D=50 cm, H=1,5 m) 19. decembra ob 12h. a - vhod v zbiralnik; b - sredina zbiralnika; c - izhod iz zbiralnika*
Fig. 3. *Temperature distribution in three planes perpendicular to the concrete tube near a building (L=60 m, D=50 cm, H=1,5 m) at December 19, 12 a.m. a - Collector input, b - Middle of collector, c - Collector output*

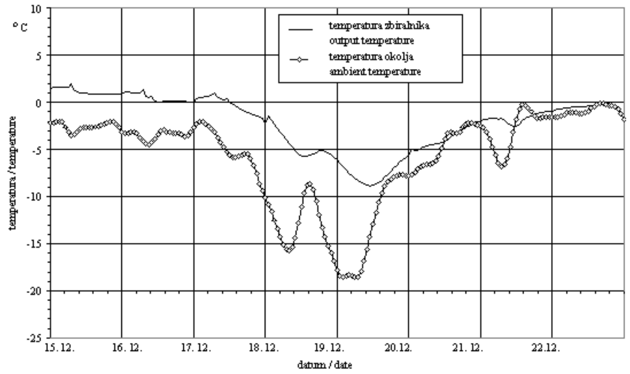


a

b

c

Sl. 4. *Razporeditev temperature v treh prerezih prečno na dvoje betonskih cevi ob stavbi (L=2× 30 m, D=20 cm, H=1,5 m) 19. decembra ob 12h. a - vhod / izhod v zbiralnik; b - y=15m c - y=30m*
Fig. 4. *Temperature distribution in three planes perpendicular to the two concrete tubes in series near a building (L=2× 30 m, D=20 cm, H=1,5 m), on 19 December, at 12 a.m. a - Collector input and output (y=0), b - y=15 m, c - y=30 m*



Sl. 5. *Gibanje temperature okolja in izhodne temperature zbiralnika v tednu med 15. in 22. decembrom*
Fig. 5. *Evolutions of ambient and collector output temperature from 15th to 22nd December*

Slika 5 prikazuje gibanje izhodne temperature "zračnega vodnjaka" v primerjavi s temperaturo okolja med hladnim razdobjem od 15. do 22.12. Ogrevalni učinek je še posebej očiten v izjemno mrzli noči 18. decembra.

3 SKLEP

Razvili smo simulirni model za izračunavanje ogrevalnih sistemov s toplotno črpalko, ki jo oskrbuje okoliški zrak, katerega vnaprej ogrejemo v "zračnem vodnjaku". Geometrijsko obliko in toplotni prehodni pojav in obnašanje "zračnega vodnjaka" smo z MKE izdelali zelo natančno. Študijo primera za povprečno enodružin-

The evolution of the output temperature of the air-well is compared to the ambient temperature during a cold period from December 15 to December 22 in Figure 5. The heating effect is especially pronounced during the extremely cold night of December 18.

3 CONCLUSION

A simulation model has been developed for calculating heat pump systems with an ambient-air heat pump supplied by preheated air through an air-well. The geometry and the transient thermal behaviour of the air-wells have been modelled very accurately using FEM. A case study for a standard one - family house with a heating load of 9.75 kW sko hišo z ogrevalno potrebo 9,75kW smo izvedli za različne dolžine, premere in globine betonskih cevi. Poleg tega smo raziskali primere z vzporednimi cevmi in primere, pri katerih so cevi bodisi ob stavbi, ali pod njo.

Analize so temelj za načrtovanje smernic za gradnjo tovrstnih sistemov. Določene težave povzroča odsotnost jasno določenih mej: brez "zračnega vodnjaka" deluje sistem kot toplotna črpalka okoliškega zraka, medtem ko z "zračnim vodnjakom", predvsem zaradi nizkih izgub, deluje kot dobro načrtovana talna toplotna črpalka.

Izkazalo se je, da je optimalen sistem za povprečno hišo sestavljen iz zbiralnika zraka s premerom 0,3 metra, dolžino 60 metrov pri globini 1,5 metra. V tem primeru ima lahko nova toplotna črpalka razsežnosti za 60% moči siceršnje toplotne črpalke okoliškega zraka, pa vendarle zlahka dosežemo vrednosti GŠ, ki se gibljejo okoli 3,6.

Nadaljnje raziskave se bodo osredotočale predvsem na uporabo "zračnega vodnjaka" za predgretje okoliškega zraka v sistemih z nadzorovanim prezračevanjem; v prihodnje bodo naša posebna zanimanja vperjena predvsem k rešitvi tega problema.

has been carried out for different lengths, diameters and depths of the concrete tubes as well. Cases with parallel tubes as well as installations beside and under a building have been investigated.

These analyses constitute the basis for design guidelines for such systems. A certain difficulty is caused by the lack of clearly defined limits: without the air-well, the system operates as a mere ambient-air heat pump whereas with the air-well it works as a correctly designed ground heat pump at the best due to thaw losses.

The optimum for the standard house turned out to consist of an air collector with a diameter of 0.3 m, a length of 60 m and a depth of installation at 1.5 m. In this case, the heat pump can be dimensioned for 60 % of the power of a usual ambient-air heat pump, and SPF values of about 3.6 can be attained.

Further investigations should concern the utilisation of the air-well for preheating ambient air in controlled ventilation systems, a solution of special interest for the future.

4 LITERATURA
4 REFERENCES

[1] Biro, O., Halozan, H., Preis, K., Renhart, W., K. Richter (1997) Numerische Simulation der Erwärmenutzung mittels Betonkollektoren. *Schriftenreihe der Energieforschungsgemeinschaft im Verband der E-Werke Österreichs.*

[2] Preis, K., Biro, O., Dyczij-Edlinger, R., Richter, K.R., Badics, Zs., H. Riedler (1994) *Stögner, Application of FEM to Coupled Electric, Thermal and Mechanical Problems, IEEE Trans. Magn., Vol. 30, No. 5, 3316-3319.*

[3] Stögner, H., K. Preis (1982) Application of Higher Order Isoparametric Finite Elements in 3D Magnetic Field Calculation. *Journal of Applied Physics, 53 (11), 8411-8413.*

Avtor se zahvaljuje za sodelovanje I. Bárdi, O. Biró, H. Halozan, K. Preis, W. Renhart, K.R. Richter (Technische Universität Graz, Avstrija) in H. Mandl, W. Ritter, H. Stögner (Verband der Elektrizitätswerke Österreichs, Avstrija).

Author thanks to the following I. Bárdi, O. Biró, H. Halozan, K. Preis, W. Renhart, K.R. Richter (Technische Universität Graz, Austria) and H. Mandl, W. Ritter, H. Stögner (Verband der Elektrizitätswerke Österreichs, Austria) for cooperation.

Avtorjev naslov: Igor Tičar
Fakulteta za elektrotehniko,
računalništvo in informatiko
Univerze v Mariboru,
Smetanova 17
2000 Maribor

Author's Address: Igor Tičar
Faculty of Electrical Eng. and
Computer Science
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

Prejeto:
Received: 25.8.1998

Sprejeto:
Accepted: 26.2.1999

Ticar-1.p65 63 22.3.99, 15:46