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Using earth to air heat exchangers for space cooling

Utilisation d'un échangeur enterré pour le refroidissement de l'espace

Die Erd-zu-Luft Thermoaustauschbenutzung zur Raumkuehlung

G. Mihalakakou, M. Santamouris, D. Asimakopoulos

Summary

This paper deals with the thermal performance of an earth to air heat exchanger for cooling and heating purposes. The cooling system consists of an earth tube buried in the ground through which ambient air is propelled and cooled by the bulk temperature of the natural ground. Fresh or indoor air can be circulated inside the tube. A new, more accurate, transient, implicit, numerical model based on the coupled and simultaneous transfer of heat and mass into the soil and the pipe has been developed. The proposed model was validated against experimental data and it was found that predicts accurately the temperature of the air along the tube and the temperature distribution of the ground at any point in the pipe vicinity.

Résumé

Ce travail s'agit de l'exécution thermique d'un échangeur enterré qui sert pour le refroidissement et le chauffage de l'espace. Le système de refroidsissement se compose d'un tube enterré dans la terre, à travers duquel l'air ambiant se pousse en avant et se refroidit par la température de masse du sol naturel. L'air frais ou bien l'air d'un espace intérieur peut être circulé dans le tube. Un nouveau modèle, plus exacte, transitoire, implicite, numérique, qui est basé sur le transfert couplé et simultané de chaleur et de masse dans le sol et le tube a été développé. Le modèle proposé a été validé contre des données expérimentales et il a été trouvé qu'il prévoit avec exactitude la température de l'air au long du tube ainsi que la distribution de la température de la terre sur n'importe quel point à la proximité du tube.

Zusammenfassung

Diese Studie beschaeftigt sich mit der thermischen Leitung eines Erd-zu einem Luft-Waermeaustauscher zu Kuehlungs- und Heizzwecken. Das Kuehlungssystem besteht aus einem im Erdboden vergrabenen Rohr durch welches die Umweltluft mittels eines Propellers gefuehrt und durch die Temperatur der Erdmasse des Naturgrundes gekuehlt wird. Frisch- oder Innenluft kann in dem Rohr zirkulieren. Es wurde ein neues, genaueres, durchgehendes, vollstaendiges, numerisches Modell, basierend auf gepaarter und gleichzeitiger Leitung von Waerme und Masse in den Boden und in das Rohr, entwickelt. Das vorgeschlagene Modell war den Testdaten gegenueber bestaending und es wurde nachgewiesen, dass die Lufttemperatur entlang des Rohres und die Temperaturverteilung des Bodens an jedem Punkt in der Rohrumgebung genau angezeigt werden.

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1. Introduction

The use of earth-to-air heat exchangers for heating and cooling of buildings and agricultural greenhouses has gained ground during the last few years (1,2). Recent evaluation of eight different models to predict the performance of earth-to-air heat exchangers (3-10), leads to the conclusion that almost all the proposed models can predict accurately the temperature of the circulated air inside the pipe. However ,these models are characterized by a limited applicability because they do not take into account the simultaneous movement of heat and moisture in soils under .temperature gradient as well as the vertical thermal stratification in the soil which breaks down the axial symmetry of the heat flow from the pipe.

The main objective of this research was to develop a more accurate numerical model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe. This model includes a complete mathematical description of moisture migration through the soil under a thermal gradient from the higher to lower temperature regions, while simultaneously tending to redistribute itself in reverse under the created moisture gradient.

The natural thermal stratification was taken into account while soil boundary conditions were applied at ground surface.

2. Modelling of Earth-to-Air heat exchangers

The conservation equation for energy can be written as follows :

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) - l_g\,\rho_m\,\frac{1}{r}\frac{\partial}{\partial r}\left(D_{u,vap}\,r\frac{\partial h}{\partial r}\right) - l_g\rho_m\,\frac{\partial}{\partial y}\left(D_{u,vap}\,\frac{\partial h}{\partial y}\right) \qquad (1)$$

while the conservation equation for mass can be written as follows:

$$\frac{\partial h}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(D_T\,r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_T\,\frac{\partial T}{\partial y}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(D_u r\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_u\frac{\partial h}{\partial y}\right) \qquad (2)$$

where

$$\frac{1}{r}\frac{\partial}{\partial r}\left(D_T r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_T\frac{\partial T}{\partial y}\right)$$

is the component of moisture flux due to the temperature gradient and

$$\frac{1}{r}\frac{\partial}{\partial r}\left(D_u r\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_u\frac{\partial h}{\partial y}\right)$$

is the component of moisture flux due to the moisture gradient.

The initial conditions are:
$T(r,y,t=0)=T_0(r)$
$h(r,y,t=0)=h_0(r)$

The programme has been developed inside TRNSYS environment .TRNSYS is a transient system simulation programme with a modular structure which facilitates the addition to the programme of mathematical models not included in the standard TRNSYS library.

3. Model Validation

Experiments were performed during Summer and lasted fifteen days. A plastic pipe of 150mm in diameter and 14.8m in length was buried in the soil at about 1.10m in depth. The air velocity in the pipe was 10.5 m/sec. Temperature values of the air along the pipe as well as of the soil below and above the pipe were recorded at 10 minutes intervals.
The results of the experiment were compared with the theoretical calculations ,and it was found that the proposed model predicts accurately the temperature of the air and the temperature distribution of the ground at any point in the pipe vicinity. Fig.1 shows the variation of the measured and calculated air temperature at the pipe outlet. As shown in this figure there is a very great agreement between the theoretical and measured data. In Fig.2 the variation of the soil temperature as recorded at a depth of 90cm below the ground surface and 20cm above the pipe was compared with the theoretical predictions. As shown there is also for the soil temperature a very good agreement between predicted and measured values. The same agreement between the predicted and observed temperature values was obtained in Fig.3 for a point located at a depth of 30cm below the earth surface and at a distance from the pipe of 80cm.

Concluding Remarks

A new, accurate,implicit numerical model based on coupled and simultaneous heat and mass transfer has been developed to describe the earth tube system thermal performance . The proposed model was validated against experimental data and it was found to be accurate.

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K : soil thermal conductivity (W/m*C)
K_p : pipe thermal conductivity (W/m*C)
l : pipe length (m)
l_g : moisture heat of vaporization (J/Kgr)
m_a : mass flow rate of ambient air through pipe (Kgr/sec)
r : radial polar coordinate (m)
R_l : an arbitrarily taken large radial distance from pipe axis (m)
r_{in} : inner pipe radius(m)
R_p : outer pipe radius (m)
T : soil temperature (C)
T_a (y) : temperature of air flowing along the pipe (C)
$T(R_p, y, t)$: temperature of pipe (C)
T_m : mean annual ground temperature (C)
T_s (r) : undisturbed soil temperature which is not influenced by the earth tube system (C)
T_u (z,t) : ground temperature at time t and depth z (C)
t : time (sec)
t_0 : phase constant
y : axial polar coordinate (m)
y_A : a large axial distance from pipe inlet (m)
y_B : a large axial distance from pipe outlet (m)
z : depth below earth surface (m)

Greek characters

ρ : soil density (Kgr/m ^{3})

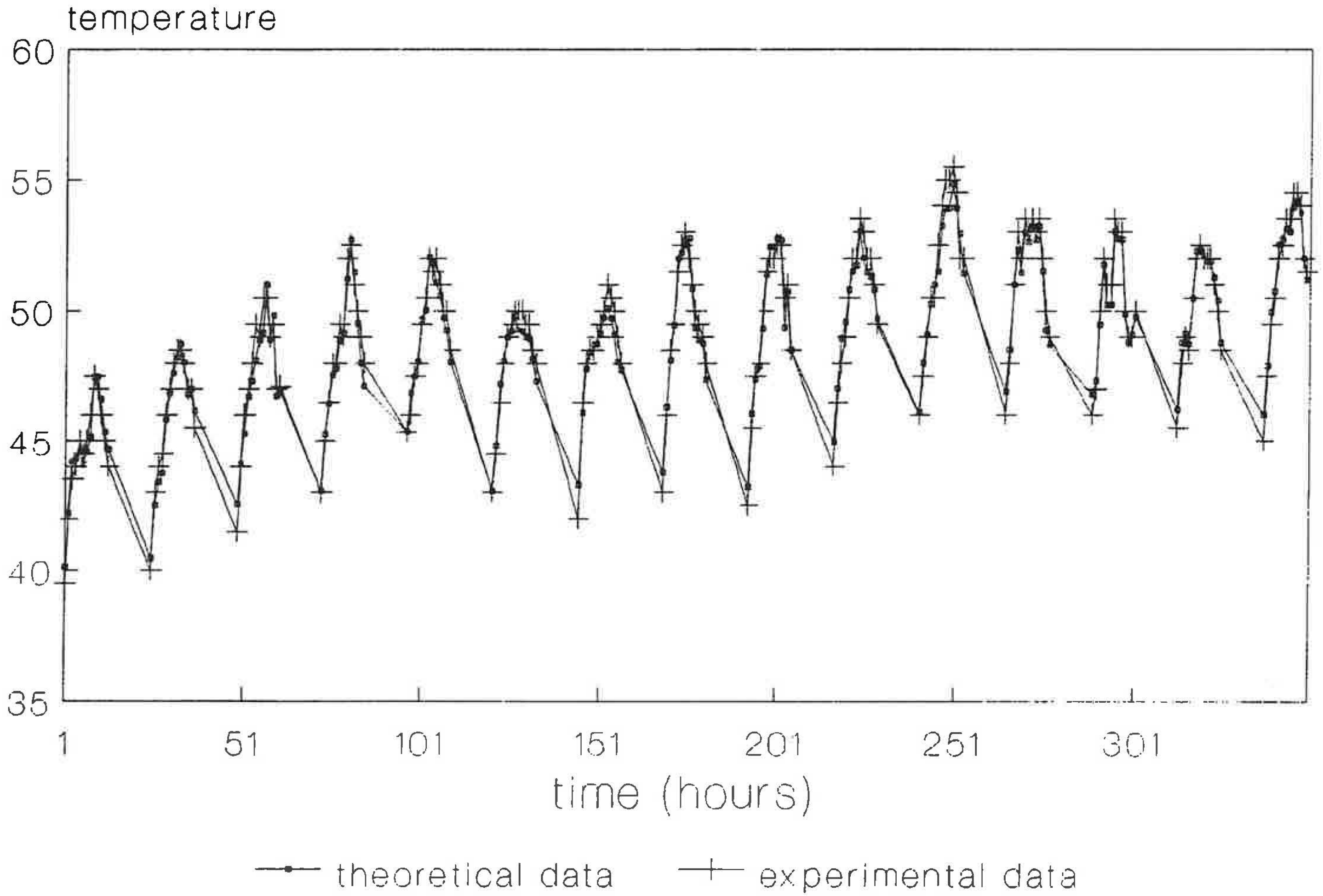
ρ_m : density of moisture (Kgr/m ^{3})

Figure Captions

Figure 1 : Measured and predicted values of the air temperature at the outlet of the pipe during the experiment.

Figure 2 : Measured and predicted soil temperature at 20cm distance above the pipe, and at a depth of 90 cm , during the experiment.

Figure 3 : Comparison of the measured and predicted soil temperature at 30 distance from the soil surface and 80 cm above the pipe.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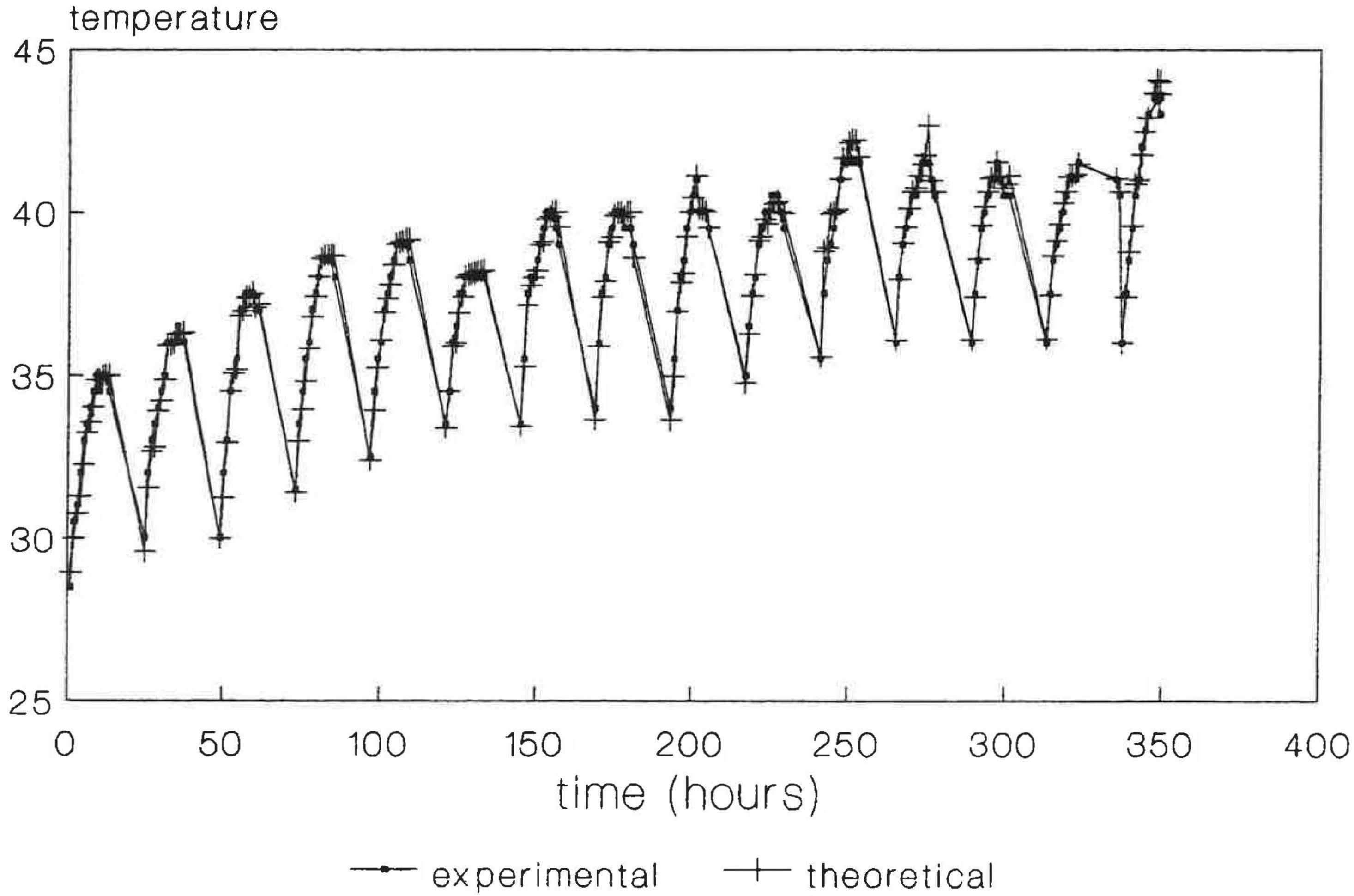
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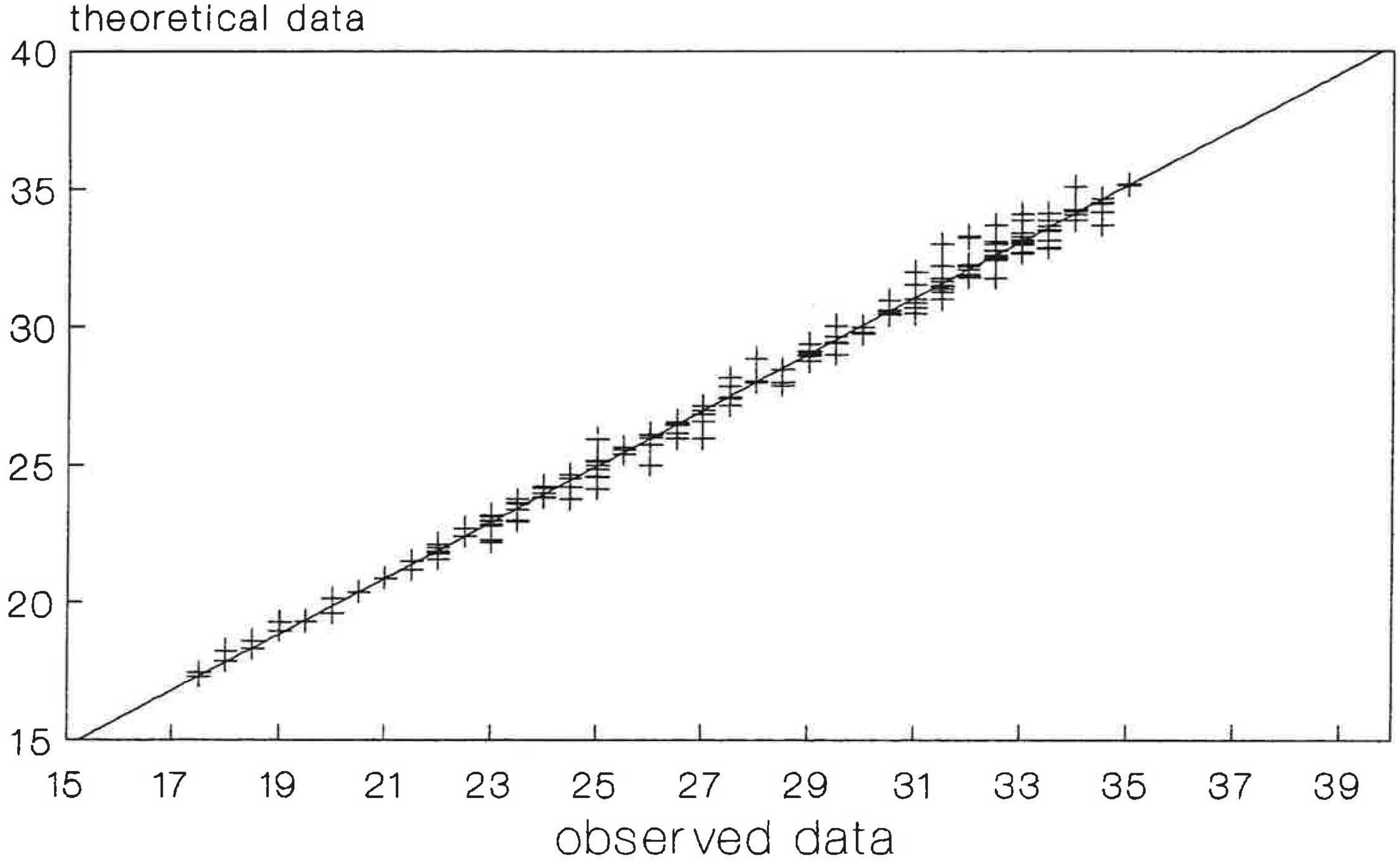
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Keyword cooling space_cooling heat_exchangers performance heating pipes underground models calculating validating temperature accuracy

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Mot-clé rafraîchissement rafraîchissement_des_locaux échangeurs_de_chaleur performance chauffage tuyaux modèles_de_simulation calculer valider température température_d'air précision enterré

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