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Analysis of inter-seasonal heat fluxes in soils

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Abstract

Assessment of the practical implementation of systems for subsurface inter-seasonal storage and recovery of solar energy requires a modelling capability which can represent heat transfer processes at the soil surface, at depth in the soil profile, and within the energy collector system itself. This study presents initial findings related to the development of both analytical and numerical tools to represent various components of such inter-seasonal heat storage facilities. In particular two aspects are considered; firstly the use of widely available averaged meteorological data to be employed in an analytical solution of a simplified version of the problem and secondly the use of a more comprehensive finite element solution to explore the detailed thermal response of the ground in terms of seasonal energy storage. Initial comparisons against field measurements from a large scale demonstration project (undertaken by others) are presented and preliminary conclusions related to the key factors affecting the representation of the surface boundary condition made. The analytical approach developed appears to offer a representative and practical way of estimating initial conditions for both initial assessment of potential for energy collection and storage and for use in defining initial conditions in any subsequent numerical analysis of a detailed inter-seasonal heat storage facility.

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1. Introduction

The study and development of devices that store or extract thermal energy from the ground heavily rely on the ability to predict the temperature profile of the soil and the amount of energy stored in it, as well as to accurately describe the heat fluxes occurring on its surface [1].

To investigate such systems two different formulations of heat transfer coefficients [2,3] are used in this study to estimate heat fluxes at the soil surface using experimental meteorological data. The results are compared and the main differences shown. An explanation for these differences is also offered.

An analytical solution for the transient heat diffusion equation using a transform technique is developed and applied to obtain temperature profiles in the soil. Analytical solutions typically have limiting assumptions and can either become difficult to obtain if many physical factors are included or have limited applicability if oversimplified. For this reason analytical solutions, using different techniques, typically tend to focus only on one physical process besides pure conduction in the soil. These processes could be moisture diffusion in the soil or the inclusion of relatively complex boundary conditions at its surface [4,5,6,7]. In the present paper the focus has been put onto the latter with the development of idealised meteorological equations representing solar radiation and air temperature that closely resemble field measurements from a large scale demonstration project [8]. Use of two different approaches to define the boundary conditions allows insights on the physical processes of heat transfer from the soil surface to be made.

2. Formulation of analytical solution

The general form for the one dimensional non-homogeneous transient heat diffusion equation defined in a finite domain of length L has been solved by Ozisik [9] for several boundary conditions using the integral transform technique. In brief, the solution can be summarised as follows:

$$\frac{d^2T}{dx^2}+\frac{g(x,t)}{k}=\frac{1}{\alpha}\frac{dT}{dt} \quad \text{in} \quad 0\le x\le L,\ t>0 \tag{1}$$

where T is the temperature of the soil, k is its thermal conductivity, α is the thermal diffusivity and g represents internal heat generation. The boundary conditions and initial condition are defined as:

$$f_1(t)=-k\frac{dT}{dx}+h_1T \quad \text{at} \quad x=0,\ t>0 \tag{2}$$

$$f_2(t)=k\frac{dT}{dx}+h_2T \quad \text{at} \quad x=L,\ t>0 \tag{3}$$

$$T=F(x) \quad \text{in} \quad 0\le x\le L,\ t=0 \tag{4}$$

where h_1 and h_2 are the heat transfer coefficients at x=0 and x=L respectively. In the case where a robin boundary condition $f_1(t)$ is applied at $x=0$, a homogeneous flux boundary condition is applied at x=L, no heat generation is present and a constant initial condition F_i, is used, the solution has the form:

$$T(x,t)=\sum_{m=1}^{\infty}2\left(\frac{\beta_m^2+H_1^2}{L(\beta_m^2+H_1^2)+H_1}\right)e^{-\alpha\beta_m^2 t}\cos\beta_m(L-x)\left[\frac{F_i\sin(\beta_m L)}{\beta_m}+\frac{\alpha\cos(\beta_m L)}{k_1}\int_{t'=0}^{t}e^{\alpha\beta_m^2 t'}f_1(t')dt'\right] \quad (5)$$

where $H_1=h_1/k$ and β_m being eigenvalues dependant on the combination of boundary conditions [9].

In order to solve equation (5) it is necessary to define a suitable expression for $f_1(t)$. The next section presents the formulation for this boundary term.

3. Boundary condition at the soil surface

The boundary condition at $x=0$ is the heat energy balance at the surface of the soil and can be defined by:

$$-k\frac{dT}{dx}=(1-\alpha_S)R+4\sigma\overline{T}^3\varepsilon_G\varepsilon_{sky}^{0.25}T_a-4\sigma\overline{T}^3\varepsilon_G T+h_E(q_G-q_a)+h_C T_a-h_C T \quad (6)$$

where α_s is the soil albedo, R is solar radiation, σ is the Steffan-Boltzmann constant, $\overline{T}^3$ is an average temperature that arises from the linearization of the infrared heat transfer equation [10], ε_G and ε_{sky} are the emissivities of the soil surface and sky respectively, T_a is air temperature, q_G and q_a is the specific humidity for the ground and air respectively. The heat transfer coefficients for evaporative (h_E) and convective (h_C) heat flux as well as the values for the previous variables can be defined following the approaches of Jansson et al [2] and Herb [11]. Herb provides a formulation for heat transfer coefficients for the soil surface based on the work of Edinger et al [3]. The main difference between these two formulations is a natural convective term in Edinger's formulation that is not present in Jansson's formulation - most probably because the latter is developed for turbulent heat transfer processes. Jansson's heat transfer coefficients for convection and evaporation are given by:

$$h_E=\frac{\rho_a L_V}{r_a} \quad (7)$$

$$h_C=\frac{\rho_a c_p}{r_a} \quad (8)$$

where ρ_a is the air density, c_p is air specific heat capacity, L_v is latent heat of vaporization of water and r_a is the aerodynamic resistance, a term inversely proportional to the wind speed u. Edinger's heat transfer coefficients are given by:

$$h_E=\rho_a L_V(C_{fc}C_{sh}u+C_{nc}\Delta\theta_v^{0.33}) \quad (9)$$

$$h_C=\rho_a c_p(C_{fc}C_{sh}u+C_{nc}\Delta\theta_v^{0.33}) \quad (10)$$

θ_v in equations (9) and (10) is the difference in virtual temperature between the air and the soil surface. The concept of virtual temperature arises in meteorology and is introduced when working with moist air as it allows use of the ideal gas law for dry air [12]. Cnc, Cfc and Csh are coefficients that weight the natural and forced convective processes and the sheltering caused by surrounding objects respectively. However, the implementation this term in Edinger's coefficients make equation (5) difficult to solve in an analytical manner.

In general equation (6) can be rewritten in the form of equation (2) and subsequently be used in the solution of equation (5).

$$\begin{aligned} f_1(t) &= -k\frac{dT}{dx} + \left(h_C + 4\sigma\overline{T}^3\varepsilon_G\right)T \\ &= (1-\alpha_S)R + h_E(q_G - q_a) + \left(h_C + 4\sigma\overline{T}^3\varepsilon_G\varepsilon_{sky}^{0.25}\right)T_a \end{aligned} \tag{11}$$

4. Formulation of analytical expressions for idealised meteorological variables

In order to solve equation (5) using equation (11) as boundary conditions it is necessary to formulate expressions for the meteorological variables required. Analytical expressions for solar radiation and air temperature are available in the literature [10]. In general these expressions are functions of geographical parameters. In this paper, in turn, we offer two simplified analytical expressions for idealised variations of solar radiation and air temperature constructed using widely available averaged meteorological data and from onsite data recordings. The meteorological data is taken from averaged climate recordings from the British Meteorological Office [13]. Onsite recordings were reported by the Transport Research Laboratory (TRL) [8].

An equation for solar radiation is proposed here as:

$$R(t) = \frac{2\pi e_R}{3\pi+4}\left(\cos^2(\phi t) - \cos(\phi t) + \frac{4-\pi}{2\pi}\right)\left(A\cos(\varphi t) + B\right) \tag{12}$$

where t is given in seconds with origin at midyear (July 1st), φ is an annual period defined as π divided by six months in seconds, and ϕ is a daily period defined as π divided by twelve hours in seconds. A and B are variables calculated from the average solar radiation for July (R_s) and January (R_w) recorded onsite by TRL during a 2005-2006 demonstration project [8]. e_R is a normalization parameter defined as the ratio of average total energy recorded by TRL to the average total energy estimated from the un-normalized form of equation (12) and is included to ensure that eq. (12) delivers the same amount of energy as recorded by TRL.

$$A = \frac{R_s - R_w}{2} = 314.5\ \text{W/m}^2 \tag{13}$$

$$B = \frac{R_s + R_w}{2} = 475\ \text{W/m}^2 \tag{14}$$

$$e_R = \left(\frac{3\pi+4}{2}\right)\left(\frac{134.6}{R_s + R_w}\right) = 0.951 \tag{15}$$

The equation for air temperature is given as:

$$T_a(t) = e_{T_a}\left\{\left[T_{amp,ave}\left(\cos(\varphi t)+0.5\sin(\varphi t)\right)+T_{ave,ave}\right] - \cos(\phi t)\left[T_{amp,amp}\left(\cos(\phi t)+0.5\sin(\phi t)\right)+T_{ave,amp})\right]\right\} \tag{16}$$

where t is given in seconds with origin at midyear (July 1st). $T_{amp,ave}$, $T_{ave,ave}$, $T_{amp,amp}$, $T_{ave,amp}$ are variables calculated from the last 30 years minimums and maximums averages air temperatures for July ($T_{s,max}$,$T_{s,min}$) and January ($T_{w,max}$, $T_{w,min}$) provided by the Met Office [13]. e_{Ta} is a normalization parameter defined as the ratio of 30 year average air temperature provided by the Met Office to the average air temperature predicted by the un-normalized equation (16) and is included to ensure that (16) predicts the same average temperature as the Met Office recordings.

$$T_{amp,ave} = 0.25\left[\left(T_{s,\max}+T_{s,\min}\right)-\left(T_{w,\max}+T_{w,\min}\right)\right] = 6.075\ °\text{C} \tag{17}$$

$$T_{ave,ave} = 0.25\left[\left(T_{s,\max}+T_{s,\min}\right)+\left(T_{w,\max}+T_{w,\min}\right)\right] = 10.175\ °\text{C} \tag{18}$$

$$T_{amp,amp} = 0.25\left[\left(T_{s,\max}-T_{s,\min}\right)-\left(T_{w,\max}-T_{w,\min}\right)\right] = 0.925\ °\text{C} \tag{19}$$

$$T_{ave,amp} = 0.25\left[\left(T_{s,\max}-T_{s,\min}\right)+\left(T_{w,\max}-T_{w,\min}\right)\right] = 3.725\ °\text{C} \tag{20}$$

$$e_{T_a} = \frac{9.7}{T_{ave,ave}} \tag{21}$$

Due to the random nature of relative humidity and wind speed, analytical expressions for these variables haven't been developed and instead annual averages values from TRL recordings for 2005-2006 were used.

5. Description of experimental data

The experimental data used to compare the analytical solution given by equation (5) proposed in this work was measured and reported by the Transport Research Laboratory [8] and is part of a two year-long demonstration project commissioned by the British Highways Agency in order to assess the feasibility of use of inter-seasonal heat storage systems aimed to provide thermal maintenance to highways and heating for buildings. The project was carried out during 2005 - 2007 at Toddington, UK. Boreholes up to 12.875 m depth were drilled and temperature sensors distributed inside. Two of these boreholes were located far from the experimental site and served as control boreholes, the remaining boreholes were distributed on a highway section and recorded the ground temperature evolution through time while the system was active. The specific data used for this work corresponds to one of the control boreholes. No details regarding regular surface maintenance on this borehole (e.g. grass cutting) are provided in [8]. However after visiting the site, it appears reasonable to assume that the surface was subject to a natural cycle of plant growth (mainly grass). Heat transfer coefficients for bare soil have been used to model the surface in this preliminary analysis of the problem as the main aim here, is to explore possible solution strategies, more detailed analysis of surface cover is on-going and will be published at a later stage.

6. Results

Figure 1 shows the averaged values for the different heat fluxes that compose equation (6) using Jansson's formulations given in equations (7) and (8), and Edinger's equations (9) and (10) for heat transfer coefficients. The heat fluxes are divided and averaged by season and period of day. Each season corresponds to three months: March, April and May for spring; September, October and November for Autumn; December, January and February for winter; and due to data availability Summer is composed only with June and July. For the purposes of this study the 'day' has been defined as the period between 7:30 am and 6:30 pm. The 'night' is defined as the remaining hours. Figure 1 also compares the estimated heat fluxes generated using both TRL's experimental meteorological data and analytical meteorological data derived from equations (12) and (16). Where required surface temperature has been set equal to that recorded at a depth of 0.025 m.

It can be seen in figure 1 that the main differences between formulations lie in the contribution of the evaporative and convective terms. This may be due to the fact that Jansson's formulation assumes a turbulent scenario [2] commonly related with relatively high wind speeds and high heat transfer coefficients. However, this formulation, may fail in periods when wind speeds drops near the surface of the soil. On the other hand, evaporation and convection have a relatively lower contribution in Edinger's formulation. This formulation includes a term for natural convective effects, this might suggest that it is meant for scenarios with relatively low wind speed and low heat transfer coefficients. This formulation may fail, in turn, when high wind speeds are prevalent near the surface.

Figure 1 also shows the effect of using analytical meteorological data. The first difference observed is in the evaporative term. This term, in general, is negative contributing to the cooling of the soil surface. In both formulations, for the idealised meteorological data its contribution is consistently overestimated during night and underestimated by day. This may be related to a drying effect of solar radiation over the soil surface during the day. This effect is not observed when using idealised meteorological expressions because equation (12) is based on annual averages, resulting in a loss of information, specifically, peak values with higher energy fluxes into the surface. The second difference is directly related to the previous one. It can be observed, for both formulations, that solar radiation is overestimated during winter and autumn whereas it is underestimated during spring and summer. This is because, as explained above, equation (12) is based on annual averages that cannot predict peak values observed during spring and summer, while during autumn and winter the reason is mainly the lack of a cloud cover factor in equation (12). The last difference is more subtle and can be observed again in the solar radiation term. For spring and summer, a small contribution can be observed during the night periods using the experimental data while this contribution is smaller and evenly distributed using analytical data. The reason for this is that equation (12) does not take into account the change in the length of daytime through the year.

Figure 2 shows the experimental soil temperature profile with depth compared against the temperature profile generated with the analytical solution given by equation (5) using equation (11) as boundary condition and Jansson's heat transfer coefficients given by equations (7) and (8). Edinger's formulation given by equations (9) and (10) has not been included due to its non-linear relation to the soil temperature. The experimental profile corresponds to the recordings of a control borehole for September 1st 2005. The analytical profile corresponds to an equivalent date after a 400 years period to ensure that the analytical solution has reached a stable state. It can be seen that the analytical solution describes well the experimental variation of temperature with depth except for the zone close to the surface. The best match is obtained in the middle region and then a slight drift is observed with depth. These observations, and the considerations that the boundary condition at the bottom is set as homogeneous free flux (insulated) and the relatively large number of cycles (400 years), is an indicator that the heat fluxes predicted by Jansson's formulation in combination with (5) are correct in the average. However, the discrepancies at the surface suggest that this formulation might not be completely suitable to describe this scenario. Further tests have shown that this behaviour is closely related with the magnitude of wind speed.

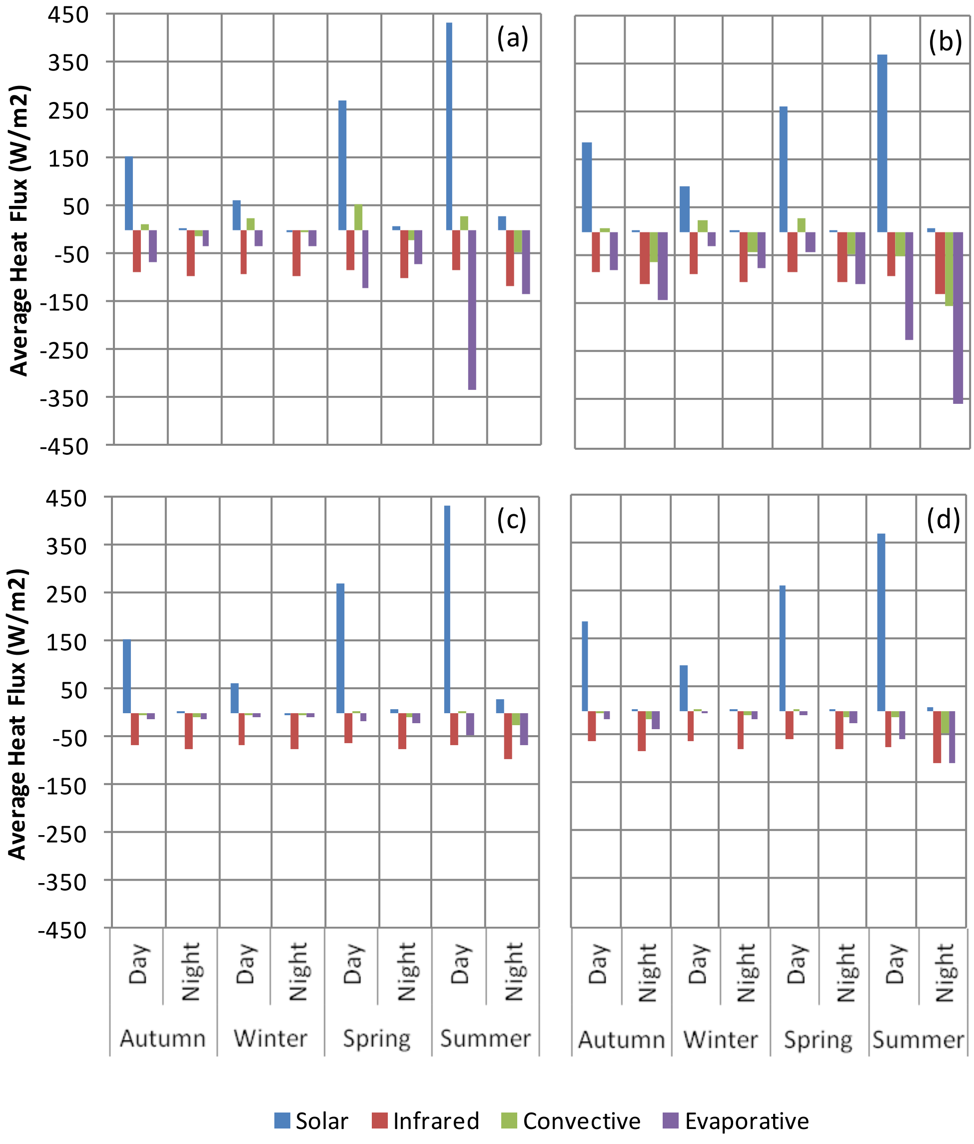

Fig. 1 - Averaged values for different components of the heat flux equation (6). (a) Jansson's formulation using experimental data. (b) Jansson's formulation using idealized data. (c) Edinger's formulations using experimental data. (d) Edinger's formulations using idealized data. Heat fluxes are divided and averaged by season and period of day.

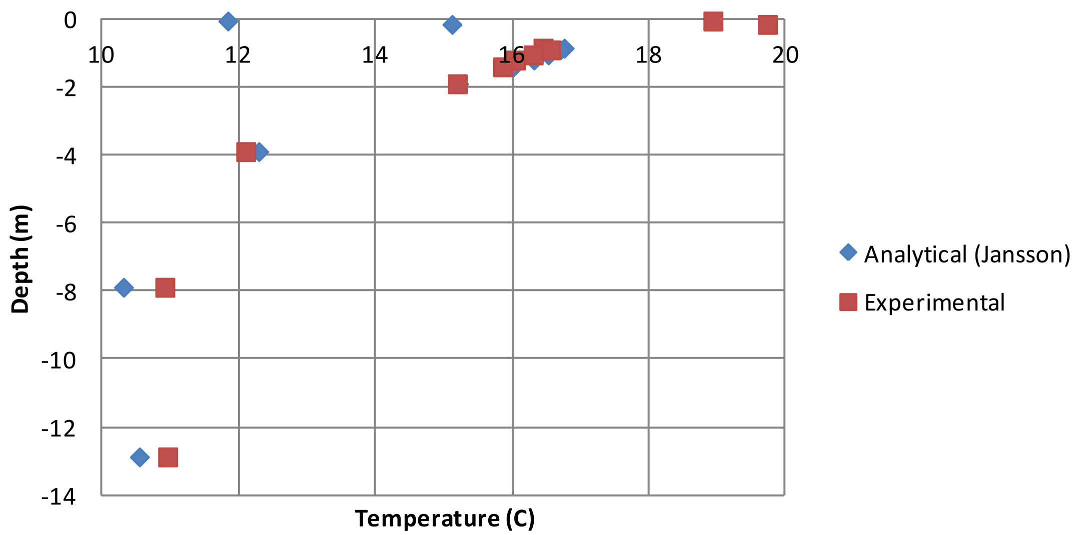

Fig. 2 - Experimental soil temperature profile with depth for September 1st 2005 compared against the temperature profile generated with the analytical solution (5) using (11) as boundary condition and Jansson's heat transfer coefficients (7), (8) for an equivalent date.

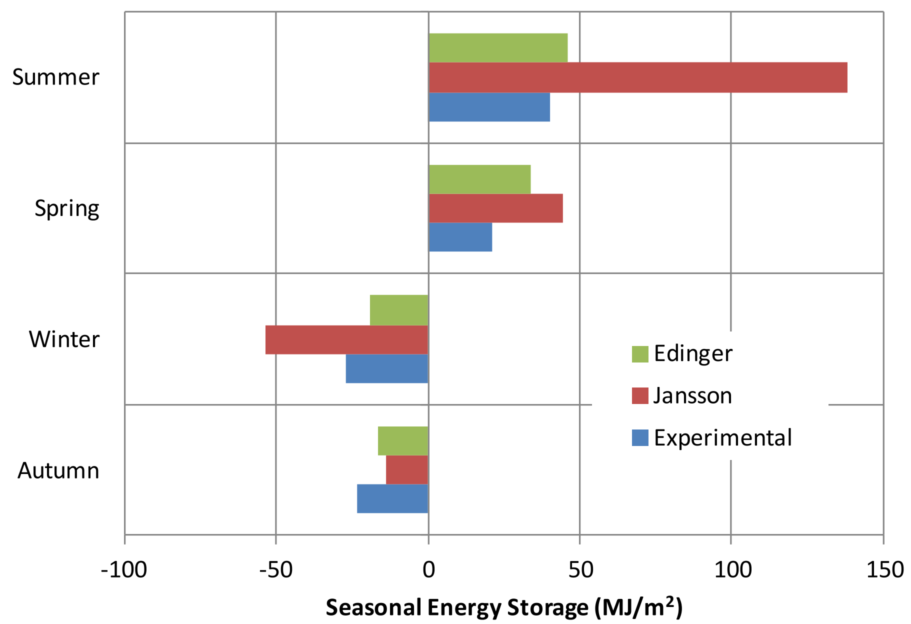

Fig 3. Energy stored per season in a column of soil 12.875 m deep calculated from experimental data and estimated numerically using Jansson's and Edinger's heat transfer coefficients formulations.

7. Conclusions

Two formulations for heat transfer coefficients for the soil surface have been presented. There are evident differences between both formulations, even though they are developed to be applied for the same physical process (heat exchange between the atmosphere and the soil surface). These differences arise from assumptions related with the behaviour of meteorological variables like wind speed and may lead to inaccurate estimates of heat fluxes at the soil surface impacting the prediction of performance of any system dependent on them.

Two simple analytical expressions to describe variations in solar radiation and air temperature were introduced and applied to calculate heat fluxes at the soil surface and were compared with corresponding heat fluxes approximated from experimental data. The differences observed between both approaches are due to the simplicity of the expressions and meteorological events that are difficult to predict (e.g. clouds) or which have a random pattern of behaviour (e.g. wind speed). However, it was shown that the magnitude of the heat fluxes calculated with the analytical approach are comparable to those calculated with experimental data. These analytical meteorological expressions were used together with one formulation for heat transfer coefficients as boundary conditions to solve the transient heat diffusion equation. A particular date was chosen and the analytical temperature profile was shown to have good correspondence with the experimental measurements except for the region close to the surface. This analytical solution with realistic boundary conditions can be used as a simple and quick assessment tool for preliminary feasibility studies of devices that rely on the amount of energy stored into the ground.

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