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Unsteady heat transfer in an aerodisperse system with a dense gravel bed in a soil regenerator channel

The paper investigates the space-time evolution of the temperature field in the aerodisperse system "air–dense gravel bed" realized in the channel of a soil regenerator for greenhouses. Aerodisperse systems with dense granular layers are widely used in heat power units, regenerative heat exchangers, and seasonal thermal energy storage devices, but the physics of unsteady heat transfer between the gas flow and a fixed bed of particles has not been fully clarified. Special attention is paid to the sequential heating of the bed along the channel and to the interaction between the thermal front in the solid phase and the temperature field of the gas phase, which are characteristic features of aerodisperse systems under charging conditions of heat storage units.

The aim of this study is to analyze the temperature field in the channel of a soil regenerator with a dense gravel bed considered as an aerodisperse system and to quantify coupled heat transfer between the gas and solid phases under transient conditions. The physical model is formulated as a two-component quasi-homogeneous medium, where the gas flow and the dense granular layer are treated as interacting components of the aerodisperse system. The governing equations include the heat transfer equation for the solid phase with effective thermal conductivity and a convective energy equation for the gas flow with an intercomponent heat transfer term describing the energy exchange between the gas and dispersed subsystems. The numerical implementation is performed in Matlab using finite-difference schemes: gas temperature along the channel is calculated sequentially in space, while the temperature of the granular bed is obtained by an implicit time-stepping scheme.

The calculations employ thermophysical properties of a gravel bed typical for regenerators with dense granular packing, including porosity, density, specific heat, effective thermal conductivity, and specific particle surface area. The results are presented as two-dimensional temperature fields T(x,t) and Tg(x,t), temperature profiles of the bed and gas along the channel at characteristic times, and time dependences at selected cross-sections. It is shown that a pronounced heating front is formed in the "air–dense gravel bed" aerodisperse system, which gradually propagates from the inlet region of the channel towards the outlet due to gas cooling and heat accumulation in the granular layer. The obtained regularities provide deeper physical insight into heat transfer in aerodisperse systems with dense packing and can be used to optimize geometric and operating parameters of soil regenerators and other regenerative heat exchangers with granular beds.

Keywords: *gas flow, dense granular bed, gravel, soil regenerator, temperature field, heat transfer, two-component model, Matlab.*

Introduction. Problem statement. Energy-efficient heating systems for agricultural greenhouses remain a pressing engineering challenge, particularly in regions with significant diurnal temperature fluctuations. One promising solution is the soil (ground) regenerator – a channel filled with a dense granular bed that accumulates thermal energy during daylight hours by blowing warm greenhouse air through the packed layer and releases this heat to the incoming cold air at night. The working medium of such a device is an aerodisperse system formed by a through airflow and a stationary dense layer of granular particles, in which coupled heat transfer between the gas and solid phases determines the charging and discharging performance of the entire unit. Despite the apparent simplicity of this physical picture, the spatiotemporal evolution of the temperature field in the channel – particularly the propagation of the thermal front along the granular bed – requires rigorous modelling that accounts for the separate energy equations of both phases.

Formulation of the article's aim. Despite the progress described above, the published results for soil regenerators are largely based on either simplified single-phase approaches or analytical solutions that treat the gas temperature as uniform along the channel – an assumption that conceals the physically important phenomenon of gas cooling in the flow direction and the resulting delayed heating of downstream bed sections. The aim of this article is to investigate the spatiotemporal temperature field in the aerodisperse system "air – dense gravel bed" of a soil regenerator channel by means of a two-component numerical model that solves coupled energy equations for both phases, and to demonstrate the formation and propagation of the thermal heating front along the packed-bed channel.

Analysis of recent studies and publications. The heat transfer in dense packed beds with a gas flow has been studied extensively since the classical work of Schumann, who proposed a one-dimensional two-phase (gas–solid) model that forms the theoretical basis for most contemporary approaches [1]. Subsequent analytical and numerical developments confirmed that the Schumann-type model adequately captures the thermocline behaviour in packed-bed thermal energy storage systems when intercomponent heat transfer is correctly parameterised. Reviews of packed-bed sensible heat storage systems highlight that the single most important parameter governing the shape of the thermal front is the intercomponent heat transfer coefficient between the flowing fluid and the granular packing [1, 2]. Practical experiments on soil regenerators with crushed stone and gravel packing showed that this coefficient lies in the range of 4–9 W/(m^2·K) under typical greenhouse operating conditions, and the Biot number remains sufficiently small to justify the lumped-solid assumption for individual particles. Mathematical modelling of the heat transfer process in a dense blown gravel layer demonstrated that the analytical temperature distribution along the channel correlates satisfactorily with experimental data when porosity, density, specific heat, effective thermal conductivity, and specific particle surface area are taken as input parameters [3 – 5]. Development of the soil regenerator design for a greenhouse with an 18 m^2 floor area showed that five 5.75 m channels filled with crushed stone can accumulate enough heat during a six-hour charging period to maintain the temperature for approximately 2.6 hours after sunset under a mean ambient temperature of 7 °C [3, 6]. Effective thermal conductivity of granular beds has been shown to depend strongly on particle shape, packing fraction, and the contact network between particles, and must be treated as an independent model parameter rather than a simple mixture average. The author's earlier dissertation work systematically investigated the intensification of heat and mass transfer in dense granular layers and developed a procedure for thermal design calculations of soil regenerators with granular packing for greenhouses, establishing the empirical dependences for the intercomponent heat exchange factor and verifying the model against pilot-plant measurements[4 – 7].

In addition to classical one-dimensional models, recent research has focused on refining the description of local thermal non-equilibrium effects and on validating more detailed numerical approaches such as CFD–DEM and pore-scale simulations, which resolve the gas flow and temperature fields around individual particles in the packed bed. These studies confirm that, for engineering-scale soil regenerators operating at moderate Reynolds numbers and with relatively large gravel particles, the Schumann-type two-equation macroscopic model remains sufficient for predicting the overall thermal response, provided that the effective transport properties and interphase heat transfer coefficient are carefully calibrated against experimental data [1, 7]. At the same time, the advanced numerical results help to interpret the influence of bed structure, particle shape and size distribution on the effective thermal conductivity and on the spatial heterogeneity of the temperature field, which is particularly important when designing compact regenerators with limited bed length and when assessing the sensitivity of the thermal front propagation to packing irregularities and local channelling of the airflow.

Experimental setup and pilot regenerator. The experimental investigation was carried out using a pilot soil regenerator installed inside an operating greenhouse and a dedicated laboratory channel designed for studying heat transfer in dense granular beds under controlled conditions. The pilot regenerator channel had an inner diameter of 100 mm and a working length of 1 m; the channel was filled with granite gravel with a particle size fraction of 40–60 mm and was buried under the greenhouse floor to ensure thermal contact with the surrounding soil. The channel was thermally insulated with 12 mm milled rubber, which corresponded to an overall heat transfer coefficient of k=2.34 W/(m^2·K) during the pause period.

Air flow through the channel was provided by a fan with a rated volume flow of 105 m^3/h, yielding a filtration velocity in the range 0.3–0.5 m/s in the granular bed. During the daytime charging phase, warm air was taken from the upper (hottest) zone of the greenhouse and blown through the gravel bed; at night, the air circulation direction was reversed and the accumulated heat was released to the cold incoming air. Automatic insulated shutters were installed at both ends of the channel to prevent convective heat loss during the pause period between charging and discharging.

Temperature measurements were performed using five TemPer 2.0 thermocouples positioned along the channel axis at distances of 0.1, 0.3, 0.5, 0.7, and 0.9 m from the inlet, plus additional sensors at the air inlet and outlet and in the ambient environment; data were logged at 3-second intervals via TemPer V27 software. The thermocouple arrangement allowed the full axial temperature distribution in the granular bed to be monitored continuously throughout the charging and discharging cycles.

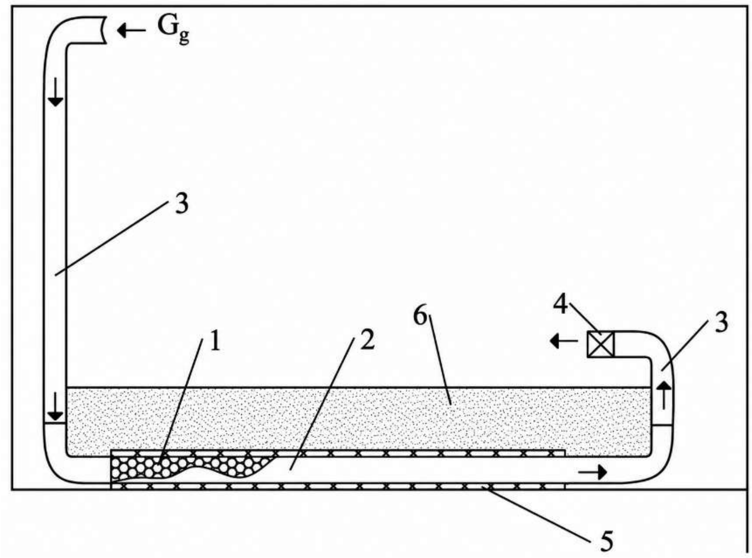

Fig 1. Layout diagram of the ground regenerator in the greenhouse
1 – granulated material, 2 – heat-exchange channel, 3 – air duct, 4 – exhaust fan, 5 – insulation, 6 – soil in the greenhouse.

Table. Thermophysical properties of the gravel bed

Parameter	**Value**	**Unit**
Solid density, ρ_s	1500	kg/m³
Specific heat, c_s	860	J/(kg·K)
Effective thermal conductivity, λ_{eff}	0.25	W/(m·K)
Porosity, ε	0.40	–
Specific particle surface, a_{pit}	800	m²/m³
Intercomponent heat transfer coeff, α	3.8–15.7	W/(m²·K)

The thermophysical properties of the gravel bed used as input data in all calculations are listed in Table 1, and are consistent with values reported in the authors' earlier study.

Physical and mathematical model. The aerodisperse system "air – dense gravel bed" is modelled as a two-component quasi-homogeneous medium consisting of a gas component (air) and a solid component (gravel particles). The dense bed is assumed stationary and the flow is one-dimensional along the channel axis x. Thermal equilibrium between the two components is not assumed; instead, the temperature fields of the gas $T_g(x,t)$ and the solid phase $T(x,t)$ are determined independently and coupled through the intercomponent heat transfer term.

The energy equation for the solid (granular) phase is:

$$\rho_{eff} c_s \frac{\partial T}{\partial t} = \lambda_{eff} \frac{\partial^2 T}{\partial x^2} + \alpha a_{pit}(T_g - T), \qquad 0 \le x \le L, t > 0 \tag{1}$$

Where $\rho_{eff}=(1-\varepsilon)\rho_s$ is the effective density of the solid phase in the bed.

The energy equation for the gas phase is written in the convective quasi-steady form, accounting for the heat exchange with the solid layer:

$$\rho_g c_g \omega \frac{\partial T_g}{\partial x} = -\alpha a_{pit}(T_g - T), \qquad 0 \le x \le L \tag{2}$$

Where w is the filtration velocity of air, and ρ_g=1.2 kg/m^3, c_g=1000 J/(kg·K) are the density and specific heat of air.

Initial and boundary conditions are:

$$T(x,0) = T_0; \qquad T_g(0,t) = T_{g,in}; \qquad \left.\frac{\partial T}{\partial x}\right|_{x=0} = \left.\frac{\partial T}{\partial x}\right|_{x=L} = 0. \tag{3}$$

The initial layer temperature was T_0=20 C and the inlet air temperature was $T_{g,\text{in}}$=36°C, in accordance with the experimental conditions recorded in the pilot tests.

Numerical implementation in Matlab. The mathematical model (1)–(3) was implemented numerically in the Matlab environment using finite-difference schemes. The channel of length L=1 m was discretised into Nx=121 equal spatial intervals (Δx=L/(Nx−1)), and the time domain [0,3600s] was divided into Nt=721 steps (Δt=5s).

At each time step the computation proceeds in two sub-steps. First, the gas temperature distribution $Tg(x)$ is calculated by integrating equation (2) explicitly along the spatial coordinate from the inlet boundary condition:

$$T_g^{(i)} = T_g^{(i-1)} - \Delta x \cdot \frac{\alpha a_{pit}}{\rho_g c_g \omega}\left(T_g^{(i-1)} - T^{(i-1)}\right), \qquad i = 2,\ldots,N_x \tag{4}$$

Second, using the gas temperature field $Tg(x)$ computed in the first sub-step, equation (1) is solved for the solid-phase temperature at the new time level using an implicit (backward-Euler) finite-difference scheme, which yields an unconditionally stable tridiagonal system of linear equations at each time step:

$$-rT_{i-1}^{n+1} + \left(\frac{1}{\Delta t} + 2r + s\right)T_{i+1}^{n+1} - rT_{i+1}^{n+1} = \frac{T_i^n}{\Delta t} + sT_{g,i}^n \tag{5}$$

where $r = \lambda_{\text{eff}}/(\rho_{\text{eff}} c_s \Delta x^2)$ and $s = \alpha a_{\text{pit}}/(\rho_{\text{eff}} c_s)$. The adiabatic wall boundary conditions are enforced using one-sided differences at i =1 and i=N_x.

Results and discussion. The computed two-dimensional temperature field $T(x,t)$ of the gravel bed is shown in Fig. 2, and the gas-phase field $Tg(x,t)$in Fig. 3. Both fields exhibit a pronounced diagonal thermal front propagating from the channel inlet (x=0) toward the outlet (x=L) as time increases.

The physical mechanism is as follows: at the beginning of the heating period the incoming air at 36 °C gives up heat primarily to the inlet section of the gravel bed, where the bed–gas temperature difference is maximal. As the inlet section heats up, the gas arrives at deeper cross-sections with progressively less residual thermal driving force, so these sections begin to heat with a time delay visible as the propagating front in Fig. 1. This sequential layer-by-layer heat absorption is fully consistent with the experimental observations reported in the pilot-regenerator tests, where no abrupt temperature discontinuities were detected along the channel axis.

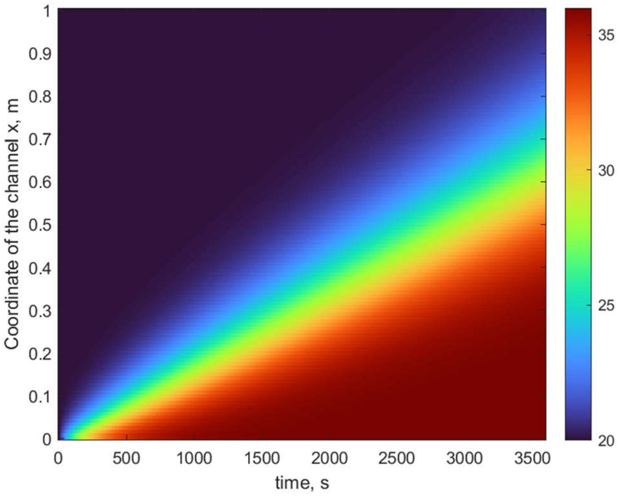

Fig. 2. Temperature field T(x,t) of the dense gravel bed in the soil regenerator channel (Matlab simulation).

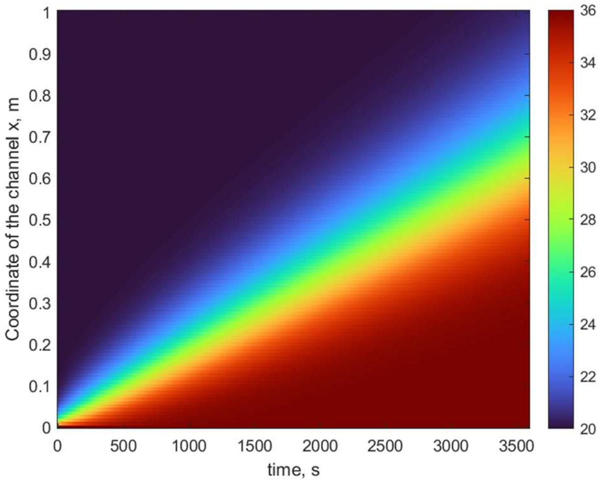

Fig. 3. Temperature field $T_g(x,t)$ of the airflow along the channel (Matlab simulation)

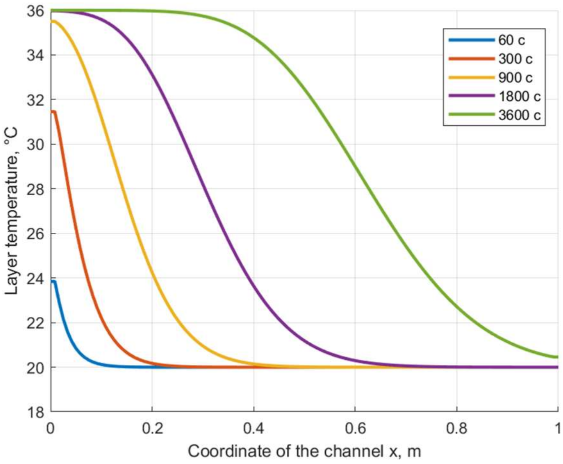

Fig. 4. Temperature profiles of the gravel bed along the channel at selected times.

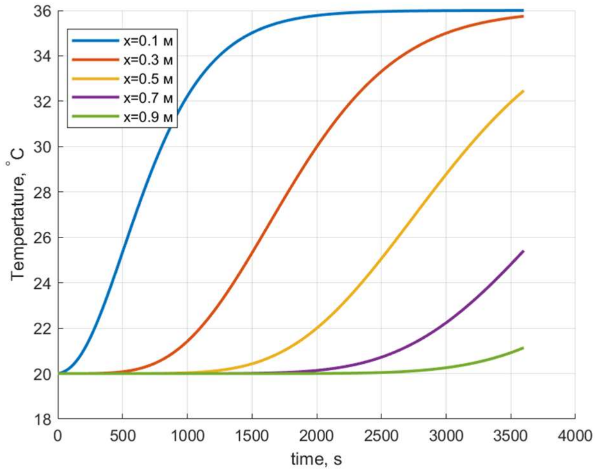

Fig. 5. Time evolution of the gravel bed temperature at selected axial positions.

The axial temperature profiles of the gravel bed at characteristic instants are presented in Fig. 4. After 60 s of heating the temperature elevation is almost entirely confined to the first 0.2 m of the channel; by 900 s the front has advanced to approximately 0.5 m; and at 3600 s a nearly uniform temperature close to the equilibrium value is established along the full channel length.

The time evolution of the bed temperature at five axial positions is shown in Fig. 5. The inlet section (x=0.1 m) reaches near-equilibrium within approximately 600 s, whereas the outlet section (x=0.9 m) does not attain the same temperature even after 3600 s, reflecting the limited heat carried by the cooled air in the downstream region.

The mean cross-sectional bed temperature at t=3600s obtained from the two-component model equals approximately 31–32 °C, which agrees with the experimental value of 32 °C measured in the pilot tests to within the experimental uncertainty. This agreement validates the physical adequacy of the two-component model and the correctness of the adopted thermophysical parameters. The intercomponent heat transfer coefficient α=7 W/(m²·K), used in the present calculation, falls within the experimentally determined range of 3.8–15.7 W/(m²·K) for the gravel bed at a filtration velocity of 0.12 m/s and an inlet air temperature of 36 °C.

The computed gas-phase profiles (Fig. 3) show that at early times the air cools noticeably along the channel – from 36 °C at the inlet to near the initial bed temperature at the outlet – confirming that the assumption of a spatially uniform gas temperature would be physically incorrect for this configuration. As the bed heats up, the driving temperature difference between gas and solid diminishes uniformly, and the axial gradient of Tg flattens progressively, as observed in the experimental temperature records.

Conclusions

1. Based on the analysis of literature and experimental data, a two-component mathematical model of the aerodisperse system "air–dense gravel bed" in a soil regenerator channel has been developed, which accounts for separate energy equations for the gas and solid phases and their intercomponent heat exchange.
2. The numerical implementation of the model in Matlab, using an implicit finite-difference scheme for the solid phase and sequential computation of the gas temperature along the channel, made it possible to obtain spatio-temporal temperature fields $T(x,t)$ and $Tg(x,t)$ with a clearly pronounced heating front propagating from the inlet towards the outlet.
3. It has been shown that, for parameters typical of a gravel bed in a greenhouse soil regenerator (porosity, effective thermal conductivity, specific particle surface area, intercomponent heat transfer coefficient), the most intensive heating occurs in the initial section of the channel, while downstream cross-sections of the bed are heated with a significant time delay, forming a non-stationary thermal front.
4. Comparison of the cross-section-averaged gravel bed temperature predicted by the two-component model with experimental data from the pilot soil regenerator shows satisfactory agreement, with an error of only a few percent, which confirms the adequacy of the adopted thermophysical parameters and the experimentally determined range of the intercomponent heat transfer coefficient.
5. The obtained results can be used for engineering design and optimisation of soil regenerators with dense granular packing, in particular for selecting channel length, particle size and type, airflow filtration velocity, and charging duration, as well as for further development of heat transfer models in aerodisperse systems with dense particle layers.

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Нестаціонарне теплоперенесення в аеродисперсній системі з щільним шаром гравію в каналі ґрунтового регенератора

Анотація

У статті досліджено просторово-часові особливості формування температурного поля в аеродисперсній системі «повітря — щільний шар гравію», що реалізується в каналі ґрунтового регенератора для теплиць. Аеродисперсні системи з щільними шарами гранул широко застосовуються в теплоенергетичних установках, регенеративних теплообмінниках та сезонних акумуляторах теплоти, проте фізика нестаціонарного теплоперенесення між газовим потоком і нерухомим шаром частинок залишається недостатньо вивченою. Особливу увагу приділено послідовному прогріванню шару вздовж каналу та взаємодії фронту нагрівання з полем температур газової фази, що є характерними рисами поведінки аеродисперсних систем у режимах заряджання теплоакумулювальних пристроїв.

Метою роботи є аналіз температурного поля в каналі ґрунтового регенератора з щільним шаром гравію як аеродисперсної системи та кількісна оцінка взаємопов'язаного теплоперенесення між газовою і твердою фазами в нестаціонарних умовах. Фізичну модель побудовано у вигляді двокомпонентного квазігомогенного середовища, де газовий потік і щільний гранульований шар розглядаються як взаємодіючі компоненти аеродисперсної системи. Система рівнянь включає рівняння теплопереносу в твердій фазі з урахуванням ефективної теплопровідності та конвективне рівняння для газового потоку з членом міжкомпонентного теплообміну, який описує енергетичну взаємодію дисперсної та газової підсистем. Чисельну реалізацію виконано в середовищі Matlab за допомогою різницевих схем: температуру газу вздовж каналу обчислювали послідовно за координатою, а температуру щільного шару – за неявною схемою у часі.

У розрахунках враховано теплофізичні характеристики шару гравію, типові для регенераторів з щільною гранульованою насадкою: порозність, густина, питома теплоємність, ефективна теплопровідність та питома поверхня частинок. Отримані результати наведено у вигляді двовимірних температурних полів T(x,t) і Tg(x,t), профілів температури шару і газу вздовж каналу для характерних моментів часу, а також кривих зміни температури в окремих перерізах. Показано, що в аеродисперсній системі «повітря – щільний шар гравію» формується виражений фронт нагрівання, який поступово переміщується від вхідної ділянки каналу до виходу в міру охолодження газового потоку та накопичення теплоти гранульованим шаром. Отримані закономірності дозволяють глибше інтерпретувати фізику теплоперенесення в аеродисперсних системах з щільною насадкою та можуть бути використані для оптимізації геометричних і режимних параметрів ґрунтових регенераторів і інших регенеративних теплообмінників із гранульованими шарами.

Ключові слова: *газовий потік, щільний гранульований шар, гравій, ґрунтовий регенератор, температурне поле, теплоперенесення, двокомпонентна модель, Matlab.*