Thermal diffusivity of peat-sand mixtures

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Abstract. Thermal diffusivity of peat, quartz sand, and their mixtures was studied at different water contents using the unsteady-state method. Quartz content in studied samples was 0.00 m³m⁻³ (pure peat), 0.05, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.55, and 0.62 m³m⁻³ (pure sand). Thermal diffusivity of air-dry samples varied from 0.6×10⁻⁷ m²s⁻¹ for pure peat to 7.0×10⁻⁷ m²s⁻¹ for pure sand. Thermal diffusivity of moist samples grew by two-four times as compared to dry samples. Small amounts of quartz material with separate sand particles distributed within the peat didn’t contribute much to the heat transfer through the studied media, and the thermal diffusivity of mixtures with quartz contents of 0.05 and 0.10 m³m⁻³ was practically the same as that for pure peat. Vice versa, there were pronounced differences in thermal diffusivities between the samples with quartz contents of 0.55 and 0.62 m³m⁻³. It means that addition of small amounts of peat to the sand material results in significant lessening of thermal diffusivity. We assume that there is a kind of threshold between the quartz contents of 0.10 and 0.15 m³m⁻¹, after which the continuous sandy chains are formed within the peat, which can serve as preferential paths of heat transport.

1. Introduction
Thermal diffusivity is a parameter of the diffusion equation, which describes the temperature dynamics in soil profile. Thermal diffusivity is responsible for the rate of soil heating and cooling. When thermal diffusivity is great enough, the temperatures at the surface and in the depth are comparable – and this is the case of sandy soils. And when thermal diffusivity is small, the heat flux into the depth is also small and hence the temperatures at the surface are much greater than those in the depth. This is the case of peat soils. Therefore the peat layers behave like thermal insulators. They prevent the underlying soil horizons from heating in summer and cooling in winter. As a result, the surface peat layers are overheated in summer which constitutes a serious environmental problem.

Soil temperature strongly influences the rate of organic matter decomposition, and sand admixture is often used to protect cultivated peat soils from rapid destruction and degradation [1, 2]. Peat-sand mixtures are also used to optimize the topsoil quality and to create the artificial soils in metropolitan areas [3]. In this case sand also protects the upper layer from overheating and contributes to lowering the CO₂ emission rates.

Soil thermal properties are highly dependent on soil moisture [4], and so it is a common practice to measure the thermal diffusivity of peat-sand mixtures across a range of water contents [5].

The purpose of this study was to investigate the thermal diffusivity of peat-sand mixtures for different proportions of organic and mineral components in the mix and for different water contents: from the capillary-moistened samples to the air-dry ones.
2. Objects and methods
We used the peat material from the upper horizon of the arable peat soil which was formed from the naturally accumulated woody peat underlain by the sedge-peat layer, and the quartz sand sieved through a 1-mm sieve. The peat was mixed with the sand in different proportions, and then the obtained mixtures were packed with equal effort into the thin-walled steel cylinders 100 mm in height and 38 mm in diameter, two replicates for each mixture. The quartz content in obtained samples varied from 0.00 m$^{-3}$ for pure peat to 0.62 m$^{-3}$ for pure sand as presented in table 1. The bulk densities were different and grew almost 4 times from pure peat to pure sand. The organic carbon content was measured for pure peat and for pure sand using the dry combustion method [6]. The organic carbon contents in peat-sand mixtures were estimated from data for pure materials.

![Table 1. Properties of studied samples.](image)

| Quartz content (m$^{-3}$) | Bulk density (kg m$^{-3}$)     | Organic carbon content (%) |
|--------------------------|--------------------------------|----------------------------|
|                          | Series 1 | Series 2 |                          |
| 0.00                     | 440      | 440      | 30.5                      |
| 0.05                     | 590      | 530      | 23.5                      |
| 0.10                     | 670      | 650      | 18.5                      |
| 0.15                     | 780      | 740      | 14.7                      |
| 0.20                     | 860      | 780      | 11.8                      |
| 0.30                     | 1010     | 1010     | 6.9                       |
| 0.40                     | 1300     | 1220     | 4.0                       |
| 0.50                     | 1430     | 1320     | 2.0                       |
| 0.55                     | 1440     | 1410     | 1.1                       |
| 0.62                     | 1670     | 1710     | 0.0                       |

Thermal diffusivity of peat, sand, and peat-sand mixtures was measured using the unsteady-state method [4, 7, 8]. Thermal diffusivity at certain moisture content was determined from the heating curve of sample packed in the waterproof measuring cell and placed into a water bath with a constant temperature which was higher than the initial temperature of the sample. The heating rate was considered to be proportional to the thermal diffusivity of the sample. At the beginning of our experiments the studied samples were saturated with water; the initial water contents in the samples varied from 0.38 m$^{-3}$ in the sand to 0.73 m$^{-3}$ in the peat. Then the samples were dried step-by-step and their thermal diffusivity was measured at different water contents until the air-dry state was reached.

3. Results
Thermal diffusivity of air-dry samples varied from 0.6×10$^{-7}$ m$^{2}$s$^{-1}$ for pure peat to 7.0×10$^{-7}$ m$^{2}$s$^{-1}$ for pure sand. The bulk density of mixture with sand content of 0.05 m$^{-3}$ was much greater than that of the pure air-dry peat (table 1), but the thermal diffusivity of studied mixture was practically the same as that of the peat (figure 1). Increasing the quartz content up to 0.10 m$^{-3}$ resulted in slight growth of thermal diffusivity, and mixture with quartz content of 0.15 m$^{-3}$ demonstrated significant increase in thermal diffusivity by about 1.5 times compared with that of the pure peat. It means that small amounts of sand with separate sand particles distributed within the peat don’t contribute much to the heat transfer through the studied media. And there is a kind of threshold between the quartz contents of 0.10 and 0.15 m$^{-3}$, after which the continuous sandy chains are formed within the peat, which can serve as preferential ways of heat transport. The increase in sand content up to 0.20 m$^{-3}$ of sand resulted in further increase in thermal diffusivity, which became almost two times greater than the initial value for pure peat. Further increase in sand contents was accompanied by further growth of
both bulk density and thermal diffusivity and by diminishment of organic carbon content in the studied samples (table 1 and figure 1).

Thermal diffusivity of moist samples grew by two-four times as compared to dry samples. Thermal diffusivity vs. moisture content dependencies had different shapes. Some were almost linear; some had a pronounced S-shape, some had peaks. Generally for quartz contents lower than 0.40 m³m⁻³ the thermal diffusivity increased with water content in the whole studied range of water contents from the air-dry samples to the capillary-moistened ones. For quartz contents of 0.50 m³m⁻³ and greater the thermal diffusivity vs. moisture content curves had a pronounced maximum within the range of water contents between 0.10 and 0.25 m³m⁻³ and then decreased.

![Figure 1](image_url)

**Figure 1.** Thermal diffusivity vs. water content dependencies for peat, sand and peat-sand mixtures with different quartz sand volumetric contents: series 1 – circles, series 2 – triangles.

Figure 2 presents the sand content – thermal diffusivity dependencies for the minimal and maximal values of thermal diffusivity. It is clearly seen that these dependencies are non-linear: the greater sand content is, the greater is the growth rate of thermal diffusivity with sand percentage. And besides, the maximal thermal diffusivities are more sensitive to sand percentage than the minimal ones in the whole range of sand contents. For example, minimal thermal diffusivities of mixtures with 0, 5 and 10% of sand contents are almost equal, whereas the maximal thermal diffusivities demonstrate the linear growth trend within the same sand contents range. And the difference between maximal thermal diffusivities for 55 and 62% of sand content is much greater than that between the minimal ones.
The obtained non-linear impact of quartz sand additions on the thermal diffusivity of peat-sand mixtures is quite consistent with the data reported in [1] and [10]. In these studies the peat-sand mixtures were investigated as model systems of peat soils enriched with mineral matter. Both water-air properties and water retention characteristics of peat-sand mixtures demonstrated similar trends: the addition up to 60% of sand into peat didn’t cause significant changes in the conditions of oxygen availability for plant roots [1], and the greatest changes in bulk density, total porosity, water retention and differential water capacity were observed within the range of 0.1-23% of organic matter content in the systems, i.e. within the range of high sand contents [10]. We can conclude that the small amounts of sand added into the peat material don’t contribute much to the physical properties of peat-sand mixtures.

To compare $\kappa(\theta)$ curves, where $\kappa$ is thermal diffusivity and $\theta$ is water content, and to analyze them formally, we used a four-parameter parameterization [9]:

$$\kappa = \kappa_0 + a \exp\left(-0.5 \left(\frac{\ln\left(\frac{\theta}{\theta_0}\right)}{b}\right)^2\right).$$

The suggested parameterization has an advantage of clear physical interpretation: $\kappa_0$ is the thermal diffusivity of dry soil, $a$ is the difference between the highest thermal diffusivity and the thermal diffusivity of dry soil, $\theta_0$ and $b$ are shape parameters.

Table 2. Parameters of the thermal diffusivity vs. water content function for studied peat and peat-sand mixtures with different quartz sand volumetric contents.

| Material          | $\kappa_0$, m$^2$ s$^{-1}$ | $a$, m$^2$ s$^{-1}$ | $\theta_0$, m$^3$ m$^{-3}$ | $b$   |
|-------------------|---------------------------|---------------------|---------------------------|------|
| Pure peat         | 0.675×10$^{-7}$           | 0.758×10$^{-7}$     | 0.703                     | 0.367|
| Sand 5%           | 0.701×10$^{-7}$           | 1.361×10$^{-7}$     | 0.951                     | 0.477|
| Sand 10%          | 0.877×10$^{-7}$           | 1.165×10$^{-7}$     | 0.603                     | 0.320|
| Sand 15%          | 1.081×10$^{-7}$           | 1.522×10$^{-7}$     | 0.570                     | 0.346|
| Sand 20%          | 1.372×10$^{-7}$           | 1.911×10$^{-7}$     | 0.751                     | 0.685|
| Sand 30%          | 1.926×10$^{-7}$           | 2.223×10$^{-7}$     | 0.450                     | 0.465|
| Sand 40%          | 1.852×10$^{-7}$           | 3.470×10$^{-7}$     | 0.395                     | 1.028|
| Sand 50%          | 2.665×10$^{-7}$           | 4.781×10$^{-7}$     | 0.223                     | 0.685|
| Sand 55%          | 2.482×10$^{-7}$           | 6.751×10$^{-7}$     | 0.199                     | 0.709|
The parameters of function (1) for peat and peat-sand mixtures are listed in table 2. It is clearly seen that both $k_0$ and $a$ parameters grow with sand percentage, and the growth rate of $k_0$ parameter is smaller than that of $a$ parameter. The difference in the growth rates of $k_0$ and $a$ parameters can be interpreted as follows. Thermal diffusivity of dry soil ($k_0$) is determined entirely by the conductive heat transfer, and maximal thermal diffusivity of moist soil ($k_0+a$) depends both on the conductive and convective heat fluxes. So $a$ parameter reflects the input of convective heat transfer to the resulting apparent thermal diffusivity. We can conclude from data presented in table 2 that the addition of the quartz particles to the peat material results rather in the growth of the convective heat transfer than in the growth of the conductive heat transfer. This probably means that the apparent thermal diffusivity is more sensitive to changes in pore architecture than to the quality and number of contacts between the solid-phase particles.

Some examples of parameterization of the $k(\theta)$ curves with function (1) are presented in figure 3. One can see that the suggested parameterization describes quite well both the S-shaped curves and the curves with a pronounced maximum.

**Conclusions**

Thermal diffusivity of peat-sand mixtures depends on the proportion between the organic and mineral parts. The increase of sand content in the mixtures resulted in the non-linear increase of thermal diffusivity. The greatest changes in the thermal diffusivity were observed in the range of 40–62% of sand contents. The parameterization was suggested to estimate the thermal diffusivities of peat-sand mixtures with certain sand and water contents.

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