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**Reducing Evaporation from Cultivated Soils by
Mulching with Crop Residues and Stabilized Soil
Aggregate**

M. Fuchs, J.L. Hatfield, A. Hadas, R. Keren

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Investigators' Names
(Principal listed first)

M. Fuchs

J.L. Hatfield

A. Hadas

R. Keren

Investigators' Institutions

ARO, Volcani Center

USDA-ARS, Nat. Soil Tilth Lab.
Ames

ARO, Volcani Center

ARO, Volcani Center

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M. Fuchs
Signature
Principal Investigator

Comi A.
Signature
Institution's Authorizing Official

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ABSTRACT

Title: Reducing evaporation from cultivated soils by mulching with crop residues and stabilized soil aggregates

Field and laboratory studies of insulating properties of mulches show that the changes they produce on the heat balance and the evaporation depend not only of the intrinsic characteristics of the material but also on the structure of air flow in boundary layer. Field measurements of the radiation balance of corn residue showed a decrease of reflectivity from 0.2 to 0.17 from fall to spring. The aerodynamic properties of the atmospheric surface layer were turbulent, with typical roughness length of 12 to 24 mm. Evaporation from corn residue covered soils in climate chambers simulating the diurnal course of temperature in the field were up to 60% less than bare soil. Wind tunnel studies showed that turbulence in the atmospheric boundary layer added a convective component to the transport of water vapor and heat through the mulches. The decreasing the porosity of the mulch diminished this effect. Factors increasing the resistance to vapor flow lowering the effect of wind. The behavior of wheat straw and stabilized soil aggregates mulches were similar, but the resistance to water of soil aggregate layer with diameter less than 2 mm were very larger, close to the values expected from molecular diffusion.

OBJECTIVES OF ORIGINAL PROPOSAL

The general objective of this proposal was to investigate means of reducing evaporation from the soil surface that can be developed into field scale implementations. Two possible surface treatments will be compared: crop residue cover of the soil surface and combined mechanical and chemical enhancement of self mulching properties. This approach leads to the following specific objectives:

1. Define the conditions for which crop residue mulches significantly promote soil water conservation.
2. Evaluate mechanical and chemical conditioning, including electrolyte composition, of bare soil surface and the relation to evaporation.
3. Evaluate the temporal dynamics of the soil-residue-atmosphere layer to determine the effectiveness of the thermal and hydraulic diffusivities.

After obtaining the first results of the field and laboratory studies of water vapor and heat transport through mulches, showing the importance of convection in the defining the efficacy of mulches to reduce evaporation, the original intent of objectives 2 and 3 was modified. It appeared more promising to shift the research effort on evaluating the interactions between wind, mechanical and geometrical properties of the mulch layer. As the literature review on the subject showed contradictory results, and we suspected insufficient attention to correct methodology to be a problem. Therefore, we enlarged the experimental study of wind effects on mulch properties.

INTRODUCTION

Models predicting soil thermal and moisture regime alterations by mulches rely on experimental values of transport properties (Bristow et al., 1986). The literature survey leading to the preparation of the research proposal revealed inconsistencies in the reported values of vapor diffusion and heat conduction across crop residue and dry soil layers. The first task of the research was to rework literature data to a unified frame of reference compatible with the objectives of the proposal.

The original research plan of the project consisted of the following steps:

1. Laboratory experiments to study vapor transfer through mulches (straw mulch, dry aggregated soil).
2. Laboratory experiments to study heat transfer through mulches.
3. Laboratory experiments to study effect of chemical treatment of soil aggregates on evaporation.
4. Field experiments to evaluate the effect of mulches (straw mulch, dry aggregated soil) on evaporation, soil temperatures and soil water content in the natural environment.
5. Creation of the program (model) for simulating the processes of water and heat exchange into the system "soil-mulch-plant-atmosphere."
6. The verification of the model on the basis of comparison field measurements and numerical calculations.

The report is organized around steps 1 through 4. Issues related to steps 5 and 6 are addressed in the analysis of the field studies. The ARO study at Volcani focused on laboratory measurements, whereas the ARS team in Ames worked in the field.

WATER VAPOR TRANSFER THROUGH MULCHES

G. Feldman, M. Fuchs and A. Hadas

Storage and distribution water in the soils is a major concern in the management of agriculture arid and semiarid regions. To increase the efficiency of soil and water management, it is necessary to evaluate the balance and storage of soil water, to predict quantitatively evaporation rate from soil to atmosphere.

The loss of water by evaporation from soils is controlled mainly (after the initial stage of drying when the uppermost layer is wet) by the vapor transfer in the surface dry layer. This layer may be dry undisturbed soil, a loose aggregate tilled layer, a layer of plant residues, or any combination of these layers. They form the mulch that influences the surface radiation balance, the soil water evaporation rate, the soil water distribution and the soil temperature distribution.

Micrometeorological studies of evaporation from soils make use of the vapor transport properties across the dry surface layer. The parameterization of these properties involves a mechanistic model shown in Figs. 1, 2 and 3. With a bare soil surface (Fig. 1) the dry surface layer functions like a mulch. Evaporation occurs from the water film on the matrix directly below the zone where the moisture content profile remains constant in hygroscopic equilibrium with atmospheric humidity. Here vapor pressure is less than saturation.

Figure 1. Heat and water vapor transport across the surface of a drying soil topped with a fully developed dry surface layer (see list of symbols).

Figure 2. Drying soil with a mulch formed by a layer of plant residues. Liquid water flows to the soil surface (see list of symbols).

Liquid water flow is prevented because the hydraulic conductance is nearly zero. Deeper in the soil the water content increase rapidly. The higher hydraulic conductivity and the steep potential gradient allows liquid flow. Water vapor pressure is at saturation. The temperature gradient controls vapor flow that contributes only to the redistribution of moisture and heat in the soil profile. Figure 2 represents a soil surface towards which liquid water is flowing. The crop residues mulch cover interrupts liquid flow keeping the evaporating front is at the soil surface. Water vapor pressure at the soil surface is saturated. When the moisture content near the soil surface decreases to the point that interrupts liquid flow, the mulch layer combines dry soil and residue layers (Fig. 3).

Figure 3. Drying soil with a mulch formed by a combination of a dry surface layer and a layer of plant residues (see list of symbols).

Steady state evaporation for the model in Figure 1 is:

$$E = \frac{0.622 \rho_a (e_s - e_0)}{p r_s} = \frac{0.622 \rho_a (e_s - e_a)}{p (r_s + r_a)} \quad [1]$$

The same formalism applies to Figures 2 and 3:

$$E = \frac{0.622 \rho_a (e_0 - e_m)}{p r_m} = \frac{0.622 \rho_a (e_0 - e_a)}{p (r_m + r_a)} \quad [2]$$

$$E = \frac{0.622 \rho_a (e_s - e_m)}{p (r_s + r_m)} = \frac{0.622 \rho_a (e_s - e_a)}{p (r_s + r_m + r_a)} \quad [3]$$

with the following symbols' definition:

ρ_a = air density ($\approx 1.18 \text{ kg m}^{-3}$)

c_p = specific heat of air ($\approx 1005 \text{ J kg}^{-1}$)

e_0 = vapor pressure at the soil surface (kPa)

e_a = vapor pressure in the air (kPa)
 e_m = vapor pressure at the mulch surface (kPa)
 e_s = saturated vapor pressure at the top of the wet soil (kPa)
 h_m = mulch thickness (m)
 h_s = thickness of the dry soil layer (m)
 p = barometric pressure (≈ 100 kPa)
 r_a = aerodynamic resistance of air ($s\ m^{-1}$)
 r_m = transport resistance of crop residue mulch ($s\ m^{-1}$)
 r_s = transport resistance of dry soil layer ($s\ m^{-1}$)
 T_a = air temperature ($^{\circ}C$)
 T_m = temperature at the mulch surface ($^{\circ}C$)
 T_s = temperature at the top of the wet soil ($^{\circ}C$)
 U = wind speed ($m\ s^{-1}$)

Literature review of mulch resistance for vapor transfer

Residue mulch

We found few quantitative studies of the effect of crop residue mulches on evaporation from the soil. A first consideration is the amount of crop residue on the soil surface. Cruse et.al. (1980) determined changes of the surface residue dry weight, W , through the year due to decomposition and the amount of the soil surface covered by the residues. The authors suggested an exponential equation to estimate surface residue dry weight through the season.

$$W = W_o \exp(-0.0255t_R) \quad [4]$$

where W is residue dry weight on the soil surface on day t_R , metric tons ha^{-1} , W_o is initial residue dry weight on the soil surface, and t_R is the number of days after residue was applied to the soil.

The fraction of the soil surface covered by residue material, F_R is a function of residue type, weight per unit area and was expressed by the relationship:

$$F_R = 1 - \exp(-J W) \quad [5]$$

where J is a coefficient dependent on residue type (1.32 for oat residue; 0.388 for corn residue; 0.737 for soybean residue).

Adams, Arkin and Ritchie (1976) studied the effect of straw mulch rate on first stage of soil drying under field conditions. The evaporation (from wet soil surface through straw mulch to atmosphere) was measured by means of special metal evaporation plates (100 × 100 mm and 3 mm deep), which were placed on the soil surface. Before each experiment, the soil was wetted sufficiently to comply with the first stage evaporation. Oat straw, cut into 50 mm length, was distributed evenly over the surface of evaporation plates at several mulching rates in the range from 500 to 10,000 kg ha⁻¹.

$$E_m = E_p \exp(-2.2 \times 10^{-4} W); \quad 500 < W < 10,000 \text{ kg ha}^{-1} \quad [6]$$

The evaporation with oat straw mulch E_m , was expressed as a function of potential evaporation from bare soil, E_p and the mulching rate, W in kg ha⁻¹. Relating E_m to potential evaporation hides environmental conditions effects on mulch resistance.

Hares and Novak (1992) suggested to calculate mulch resistance r_m , using the expression

$$r_m = \frac{h_m}{\theta_a D_{air} f C_1} \quad [7]$$

where h_m is straw mulch thickness, D_{air} is molecular diffusivity of water vapor in still air; θ_a is effective (air-filled) porosity of the mulch, f is tortuosity factor, C_1 is a correction factor that accounts for convection within air-filled pores.

The value of the parameter C_1 is chosen by matching measured and modeled daytime average evaporation rate. When straw mulch rate was 20 ton ha⁻¹, $C_1 = 4.5$. One can see that [7] resembles the molecular diffusion equation of a gas in porous materials:

$$r'_m = \frac{h_m}{\theta_a D_{air} f} = \frac{h_m}{D_{eff}} \quad [8]$$

where: r'_m is mulch resistance for molecular diffusion of water vapor; $D_{eff} = \rho D_{air}$ is the effective molecular diffusivity of vapor in the mulch. The parameter C_1 enhances vapor transport accounting for possible convection. Evidently, the value $C_1 = 4.5$ relates only to conditions of the experiments performed by Hares and Novak and does not extrapolated to other conditions.

Tanner and Shen (1990) studied the water vapor transport through crop residues in a wind tunnel (1.5 m wide by 2.1 m high section) to express mulch resistance r_m , as a function of wind speed when mulch thickness is constant ($h_m = 11$ mm). Evaporation rate from saturated vapor source placed under the residue was measured. The mean bulk density of the mulch was $36.4 - 37.4$ kg m⁻³. Tanner and Shen related crop residue mulch resistance r_m to wind speed, $U_{10\text{ mm}}$ in m s⁻¹ measured at height 10 mm above the surface:

$$\frac{1}{r_m} = 2.2 \times 10^{-3} (1 + 2.3 U_{10\text{ mm}}) \quad [9]$$

when $U_{10\text{ mm}} < 1.5$ m s⁻¹. They noted that wind speed $U_{10\text{ mm}}$ was closely related to the wind speed at 1 m ($U_{1\text{ m}}$) and this regression was $U_{10\text{ mm}} = -0.01 + 0.38 U_{1\text{ m}}$. We can rewrite [9] as:

$$r_m = \frac{455}{1 + 2.3 U_{10\text{ mm}}} \quad [10]$$

Equations [9] and [10] allow to determine straw mulch resistance at zero wind as 455 s m⁻¹ and the effective molecular diffusivity, D_{eff} (m² s⁻¹) of water vapor through the mulch:

$$D_{eff} = \frac{11 \times 10^{-3}}{455} = 0.242 \times 10^{-4} \quad [11]$$

that little differs from molecular diffusivity of water vapor in still air ($D_{air} = 0.245 \cdot 10^{-4}$ m² s⁻¹). Equation [10] will allow to compare Tanner and Shen's results with ours for $h_m = 10$ mm and $\rho_m = 37$ kg m⁻³. This result shows the need to develop experimental relationships between mulch resistance as a function of its characteristics, ρ_m , h_m and of wind speed U .

Soil mulch

We divide arbitrarily soil mulches into two groups: (i) dry soil when soil clod size is less $0.5 \div 1$ mm; (ii) dry soil aggregate layer when soil clod size is large $0.5 \div 1$ mm. Sieves with openings

0.5 and 1 mm (diameter), used to prepare soil columns for laboratory experiments set the separating boundary.

Dry soil, clod size < 0.5 - 1 mm

Gardner (1958) calculated the water vapor flux through dry soil E , as molecular diffusion steady state process:

$$E = \frac{0.622 \rho_a}{p} D_{eff} \frac{(e_s - e_0)}{h_s} \quad [12]$$

The driving concentration gradient is expressed as the vapor pressure gradient across the dry layer of thickness h_s shown in Fig. 1. Equation [9] Brisson and Perrier (1991) used [11] to calculate dry soil resistance for water vapor transfer to model evaporation from a bare soil.. Ham and Heilman (1991) also considered that r_s' for dry soil may be calculated using [8]. However, they pointed out that determining the thickness of the dry soil is very difficult under field conditions.

Hillel, van Bavel and Talpaz (1975) accepted that dry soil and dry soil aggregate layer resistance to vapor transfer is the layer thickness divided by effective vapor molecular diffusivity. Hanks (1958) studied experimentally the mechanism of water vapor transfer in three dry soils (silt loam; silty clay loam and fine sandy loam). He found that molecular diffusion is primary mechanism of water vapor movement when thickness of dry soil was in the range from 6.3 to 38 mm, porosity 0.43 - 0.58 and wind speed $\sim 0.75 \text{ m s}^{-1}$.

Hanks and Woodruff (1958) experimentally studied the influence of wind on water vapor transfer through dry soil, gravel and straw mulch. They placed plastic cylinders (44 mm in diameter and with heights ranging from 6.35 to 38 mm) containing dry soil, gravel or straw mulch in a wind tunnel. An aluminum can (44 mm in diameter and 25 mm high) was attached to the bottom of the plastic cylinder and filled with water saturated soil. Wet soil and dry mulch were separated by means of three 16-mesh screens to prevent water capillary movement. Experiments lasted until the soil in the aluminum cans decreased to permanent wilting content. The dry soil mulch (Geary silt loam), treated with a waterproofing agent, was wetted and compacted in the cylinder to a bulk density of 1.45 Mg m^{-3} for all treatments. It was air-dried and then subjected to the wind

(Hanks, Woodruff, 1958). The gravel size ranged from 2 to 6 mm. The mulch was wheat stubble cut into 6.35 mm length, of $\rho_m = 52 \text{ kg m}^{-3}$. Wind speed was measured at 152 mm from the tunnel floor. The vapor pressure at the mulch surface was extrapolated from the vapor pressure at 7.6 and 15.2 cm. At the bottom of the mulch it was calculated as the saturated value at the measured

Figure 4. Mulch resistance to water vapor transport according to Hanks and Woodruff (1958).

temperature. The relation between resistance and layer thickness at different wind speeds (Fig. 4) shows that the resistance increase with layer thickness is not linear. For transport by molecular diffusion the resistance should be proportional to thickness. Resistance decreases with wind speed even for the dry non-aggregated soil. The effect of the wind on resistance is stronger as the size of the voids in the surface layer increases. The decrease of resistance as thickness passes from 24 to 38 mm is most probably an experimental error.

Ishihara, Shimojima and Harada (1992) investigated the influence of turbulent surface wind on evaporation in various materials. A uniform porous material was packed in a rectangular box (0.34 m wide, 0.94 m long and 0.64 m deep) placed on top of a balance. The exposed porous material surface was inserted flush with the bottom of a turbulent flow wind tunnel with a cross-section of $0.40 \times 0.40 \text{ m}$. The porous materials were a sand (0.45 mm mean diameter of the particles) and three kinds of glass beads (with diameter 12, 5 and 2 mm). Most experiments were performed with a falling water table, starting with free water at the exposed surface. The temperature of air flow was about 25.5°C , relative humidity 40% and wind speed 2.9 or 1.5 m s^{-1} . The duration of each run ranged from 1 to 3 months. The temperature of the porous material was measured at 5 mm intervals from a depth of 5 to 50 mm. To calculate molecular diffusive resistance, the authors determined the depth of the evaporation front from the location of the temperature minimum. When the evaporation front was less than 30 mm deep, diffusive

resistances were about 1.25 times larger than the experimental values $r_s = 0.622 \rho_a (e_s - e_0) / p E$, proving the contribution of turbulent convection to vapor transport. Yet, the convective enhancement was considerably less than that found by Hanks and Woodruff (1958), possibly because the positioning of the evaporating front was inaccurate (Fuchs and. Tanner, 1967).

Layer of dry soil aggregates

Chung and Horton (1987) used molecular diffusion of water vapor to calculated soil mulch resistance but they pointed out that possible convective transport of vapor between dry soil aggregates would decrease resistance. Farrel, Greacen and Gurr (1966) were the first to investigate the influence of horizontal atmospheric pressure gradients on air movement within a dry soil aggregate layer. Their analysis showed transfer coefficient for coarse mulches (D) as much as 100 times the effective molecular diffusion coefficient (D_{eff}). Scotter and Raats (1969) attempted to estimate the dispersion of water vapor in soil mulch due to air turbulence. The mean vapor "flow is assumed to be caused by trains of pressure fluctuations moving along the soil surface" (Scotter and Raats, 1969). If F_0 is vapor flux due to molecular diffusion only and F is vapor flux due to both convection and molecular diffusion, the ratio (F/F_0) is the dispersion of water vapor in layer of soil aggregates due to air turbulence. The authors calculated (F/F_0) for evaporation from 20 mm below the surface of a semi-infinite porous medium with particles sphere diameter d_p (Table 1).

Table 1: Dispersive enhancement (F/F_0) of vapor flow across a porous medium by surface pressure fluctuations as a function of particle diameter (d_p). (Scotter and Raats, 1969).

d_p , mm	<2	3	4	5	6
F/F_0	1	1.2	1.7	2.5	4.0

The calculations of Scotter and Raats (1969) take into account the atmospheric pressure fluctuations at the soil mulch surface and air permeability of the porous medium. Therefore, value (F/F_0) is the function only of the diameter of soil aggregates d_p (when the train of pressure waves at the mulch surface is given). But these calculations do not take into account kinetic energy of wind entailing direct air penetration into the layer of dry soil aggregates. Therefore, relationship (F/F_0) = $f(d_p)$ underrates influence of wind speed on the water vapor transfer through

soil mulches.

Acharya and Prihar (1969) suggested a simple equation to calculate evaporation (E) from wet soil through soil mulch to atmosphere:

$$E = \frac{E_p}{1 + K_1 h_s} \quad [13]$$

where E_p is potential evaporation; K_1 is a parameter depending on effective porosity (air-filled) of the soil mulch, θ_a and wind speed U . They established the function $K_1 = K_1(\theta_a, U)$ in columns (75 mm diameter and 180 mm high) filled with Hissar sandy loam, saturated by capillarity and allowed to drain. Dry soil mulch of desired thickness and porosity was placed on the wet sandy loam. The soil columns were exposed to 0, 1.6 and 3.3 m s⁻¹ wind speed and irradiated three 300-watt light bulbs. The soil mulch was prepared by treating air-dry Hissar sandy loam with a chemical water repellent to prevent the liquid movement from wet soil to the soil mulch. The thickness of the mulch varied from 10 to 40 mm; soil aggregates ranging in size from 2 to 4 mm; 0.5 to 1 mm and less than 0.5 mm were separated from the treated sandy loam. The total period of experiments was 60 ÷ 84 hours. The results were fitted to:

$$K_1(\theta_a, U) = 12.77 + 16.92 U - 16.93 \theta_a \quad [14]$$

Because U affects E_p this experimental approach does allow to find the contribution of wind on convective transport in the aggregate mulch. In fact the relation between E and E_p depends on the ratio of mulch resistance over aerodynamic resistance to which the linear form of [14] is not suited. The long duration of the drying phase may result in the appearance of a dry layer at the wetted soil surface, adding an additional resistance on the vapor path.

Jalota (1993) studied evaporation through layer of dry soil aggregates on soil contained in columns (0.1 diameter and 0.95m long) under varying wind speed, air temperature and relative humidity. The columns were filled with sandy loam or silt loam soils and then were wetted with the predetermined amount of water required to wet the soil to field capacity water content. The material for the dry soil aggregate layer was prepared by treating air-dry soil with a chemical water repellent. The treated soil was then oven-dried and broken into aggregates. The aggregates ranging from 0.5 to 2 mm were, used as a soil mulch which was placed on the soil columns. The

thickness and porosity of the soil mulch varied from 5 to 75 mm and from 0.53 to 0.63, respectively. The columns were subjected to evaporation in a special wooden chamber where wind speed ranged from 0.56 to 2.2 m/s; air temperature from 17 to 39°C, and relative humidity from 21 to 78%. Prior to the study, potential evaporation (E_p) was determined by the measuring free water loss. The results were fitted to the following regression model:

$$\frac{E}{E_p} = 0.00189 T_a^{2.33} U^{0.29} \theta_a^{3.95} h_m^{-0.65} \quad [15]$$

where T_a , the air temperature is in °C, U , the wind speed is in m s^{-1} , h_m , the thickness of the soil mulch is in mm and θ_a is in $\text{m}^3 \text{m}^{-3}$. The same comments as those following [14] apply here.

A number of investigators have attempted to determine the optimum soil clod size range for maximum evaporation reduction (Hillel and Hadas, 1972; Hillel and Berliner, 1974). Jalota and Prihar (1990) presented the optimum soil clod sizes for maximum evaporation reduction as given by different scientists (Table 2).

Table 2. Optimum clod sizes for evaporation reduction (Jalota and Prihar, 1990).

Reference quoted by Jalota and Prihar (1990)	Clod-size distribution diameter, mm
Wadham, 1944	<10
Ramacharlu, 1957	0.8
Holmes et al., 1960	2.5
Scotter and Raats, 1969	0.3-0.6
Hillel and Hadas, 1972	0.5
Heinonen, 1985	0.5-2.0

The discrepancy in the optimal size of soil aggregates evidently was due to the different conditions of the experiments. So we have to determine the resistance water vapor transfer of the soil aggregate layer to model the optimum combination of soil aggregate sizes and thickness of the layer for maximum evaporation reduction.

Drying soils (Fig. 1)

Experimental researches under field and laboratory conditions were conducted to study resistance of drying soils. Fuchs and Tanner (1967) attempted to determine the resistance to vapor transfer under field conditions of drying Plainfield sand using energy balance measurements of evaporation rate (E) and sensible heat flux density (H). Assuming saturated water vapor at the bottom of the dry surface layer (h_s , Fig. 1), the resistance of the drying soil (r_s) to water vapor transfer is given by:

$$r_s = \frac{0.622 \rho_a (e_s - e_0)}{p E} \quad [16]$$

The resistance of the drying sand obtained in the experiments was far greater than the molecular diffusive resistance. Fuchs and Tanner (1967) suggested to reject the internal resistance models using the resistance of the drying soil because there is no well-defined boundary between dry and wet soil patchiness of the tilled sand surface. Latent heat flux density (E) was far smaller than the other components of the energy balance equation, the error of the resistance estimate was large.

Camillo and Gurney (1986) found a linear relation between drying soil resistance(r_s) and its average soil water content (θ_{av}) by fitting their model of heat and moisture flow in soils to the field experimental data:

$$r_s = 810 - 4140 \theta_{av} \quad [17]$$

for $h_s = 5$ mm and θ_{av} of the upper 5 mm soil layer.

It is interesting to compare values calculated by Equation [17] and [8] for molecular diffusive resistance. Setting the following values for the parameters, $h_m = 0.005$ m, $\theta_a = 0.5$, $f = 0.60$, $\theta_{av} = 0.03$, $D_{air} = 0.245 \times 10^{-4}$ m² s⁻¹. Equation [17] yields $r_s = 810 - 4140 \times 0.03 = 686$ s m⁻¹.

According to equation [5] we obtain:

$$r'_m = \frac{0.005}{0.245 \times 10^{-4} \times 0.5 \times 0.6} = 680 \text{ s m}^{-1}$$

Thus, only molecular diffusion controls water vapor transfer in upper (0.005 m) air-dry ($\theta_a = 0.03$) soil layer.

Several studies attempt to relate the surface layer resistance of dry soil to the average moisture content of the soil. The idea behind this approach is that average moisture content decreases as the thickness of the dry surface layer increases. Van de Griend and Owe (1994) measure the drying resistance of a fine sandy loam in a fast air circulation chamber (1 m long, 0.4 m wide and 0.8 m high). The bottom of the chamber was open to allow the circulating air to be in contact with the soil surface. The authors assumed that vapor pressure in the uppermost pores of the drying soil to be saturated at the observed soil surface temperature:

$$r_s = 10 \exp[35.63 (0.15 - \theta_{av})] \quad [18]$$

where θ_{av} is average volumetric soil water content in an upper soil layer 10 mm, and 0.15 represents the wilting point soil water content.

Kondo, Saigusa and Sato (1990, 1992) suggested a simple expression for drying soil resistance:

$$r_s = \frac{F(\theta_{av})}{D_{air}} \quad [19]$$

where D_{air} is diffusion of water vapor in still air; $F(\theta_{av})$ is parameter depending on soil properties and the soil water content of the top 20 mm soil layer; θ_{av} is the average volumetric soil water content of the top 20 mm soil layer. The function $F(\theta_{av})$ was obtained from experiments with an initially wet layer (20 mm) of soil packed in a pan of 0.3 m diameter. humidity, wind speed at the height of 50 cm above the soil surface; the soil surface temperature. The hourly averaged evaporation rate and soil water content were obtained by weighing the soil every hour. The experimental relationship between $F(\theta_{av})$ and θ_{av} for different soils was expressed as:

$$F(\theta_{av}) = \alpha (\theta_s - \theta_{av})^\beta \quad [20]$$

where θ_s is the volumetric saturation soil water content, and α and β are empirical constants

given in Table 2

Table 2: Constants of $F(\theta_{av})$ (Kondo et al., 1992)

Soil type	α	β	θ_s
Loam	2.16×10^2	10.0	0.49
Sand	8.32×10^5	16.6	0.392
Fine sand	7.0×10^3	11.2	0.397

The authors pointed out that if the drying soil layer (h_s) is thicker than 20 mm then $F(\theta_{av})$ is larger than the value calculated by equation [20], and if $h_s < 20$ mm $F(\theta_{av})$ is smaller.

Shu Fen Sun (1982) proposed that resistance of the drying soil may be estimated by

$$r_s = 33.5 + 3.5 \left(\frac{\theta_s}{\theta_{av}} \right)^{2.3} \quad [21]$$

where θ_{av} is volumetric soil water content into the 0.0 to 5 mm layer.

Passerat de Silans (1986) suggested the following expression for drying soil resistance

$$r_s = 3.8113 \times 10^4 \exp \left(-13.515 \frac{\theta_{av}}{\theta_{f.c.}} \right) \quad [22]$$

where θ_{av} is near-surface soil water content and $\theta_{f.c.}$ is the water content at field capacity.

Vapor transport resistances derived from equations [18] through [22] are shown in Fig. 5. The differences between the empirical regression models are very large. The usefulness of this approach is therefore highly questionable. Furthermore at the low values of the moisture content the calculated resistances exceed the upper limit set by molecular diffusion.

Pikul (1991) suggested to estimate the resistance r_s of the drying soil to an energy flux E_0 related to evaporation:

$$r_s = \frac{0.622 \rho_a \Lambda}{p} \frac{D_e}{E_0} \quad [23]$$

where Λ is the latent heat of vaporization in J kg^{-1} of water and D_e is vapor pressure saturation deficit in the air in kPa. According to Berkowich and Prahm (1982), E_0 decreases with dryness

of the soil which depends mainly on the total net radiation, ΣR_n accumulated from the last rain or irrigation:

$$\Sigma R_n = \int_0^t R_n(t) dt \quad [24]$$

where t is the elapsed time. To justify the correlation between ΣR_n and soil moisture content the authors invoke the energy involve in drying. Considering that E_0 is an estimate of E and ΣR_n is an estimate of current soil moisture content, this approach is very similar to that proposed in Eqs.

[18] through [22]. The resulting resistance could serve as a way to evaluate in the field the long term effect of a mulch on the soil moisture balance. However, the rate of drying depends not only on radiation, but also on temperature, humidity and wind. Therefore, this net radiation based evaluation of the soil surface drying resistance is not universally applicable. On the basis of the review, we can conclude that at present there is no reliable value of mulch resistances as a function of its properties (thickness; porosity or bulk density, diameter of soil aggregates) and wind speed. Therefore, we decided to perform a series of laboratory experiments to determine mulch (straw mulch and soil aggregate layer) resistance as a function of its properties for use in models of soil temperature, water content distribution and evaporation.

Figure 5. Resistance of soil to water vapor transport as a function of the soil moisture content according to van de Griend and Owe (1994), Kondo et al., (1992), Shu Fen Sun (1982), de Silans (1986).

The laboratory experiments on water vapor transfer through mulches

Experimental method

The aerodynamic and diffusion transport properties of the straw mulch and soil aggregate layer were studied in a small wind tunnel (0.25×0.25 m cross-section and 1.30 m long). A blower pushed air into the tunnel. The flow was regulated by means of a series of screens near the air inlet of the tunnel. A side vent diverted excess air from the wind tunnel inlet, to prevent a pressure built-up at the outlet of the blower. Depending on the number of screens the wind speed 125 mm above the mulch surface was 0.5, 1.0, 2.0, 3.0 and 4.2 m s^{-1} . The bottom of the wind tunnel was pierced with a hole fitting the perspex cylinder of 100 mm diameter containing the straw or soil mulch, and the heated water serving as water vapor source (Fig. 6). The cylinder was on a balance to weigh evaporation rate. The height of the cylinder could be modified by adding or removing 10 mm high rings sealed to the cylinder with adhesive tape. The mulch surface was inserted flush with the wind tunnel bottom. Temperature and relative humidity of the air, temperature of the soil, the straw mulch (or the water underlying the mulch) were measured.

Figure 1. Experimental set-up for measuring the resistance of a dry mulch to water vapor transport.

A retaining stainless steel net separated the mulch from the water. A glass tube (diameter 5 mm) controlled the water level in the cylinder. The distance between water surface and steel net was about 2 mm. A heater regulated water temperature measured with a thermocouple near the water surface. Heating was adjusted to maintain temperatures of water surface and air into the wind

tunnel approximately identical (maximum difference $< 1^\circ\text{C}$) to prevent possible condensation vapor on the mulch during the experiment. An experiment lasted about 5 hours until to reach steady state.

Four resistances are on vapor transport path from to water surface to the air in the tunnel: the resistance of the air layer (thickness is about 2 mm) between the water surface and the steel net r_{sp} , the resistance of the steel net r_{net} , the resistance of the mulch r_m , and the resistance from the mulch surface to the air r_a . The three resistances that mask the real value of the mulch resistance formed the r_{set-up} :

$$r_{set-up} = r_{sp} + r_{net} + r_a \quad [25]$$

Placing the water reservoir and the steel net flush with the bottom of the wind tunnel allowed to measure r_{set-up} separately as a function of the wind speed. The set-up resistance r_{set-up} is:

$$r_{set-up} = \frac{0.622 \rho_a}{p} \frac{(e_{ws} - e_a)}{E} \quad [26]$$

where e_{ws} is saturated vapor pressure at T_{ws} measured with a thermocouple near the surface of the water. Results (Table 4) show that the decrease of resistance with wind speed.

Table 4: Variation of the set-up resistance as a function of the wind speed

U (m s ⁻¹)	0.5	1.0	2.0	3.0	4.2
r_{set-up} (s m ⁻¹)	270	173	98	84.8	72.6

The set-up resistance includes the aerodynamic resistance of the surface air layer which is inversely proportional to the wind speed. Construction characteristics of the wind tunnel determine the nature of convection in this air layer. Yet turbulence may also affect the resistance of the net or of the air space above the water surface. If this effect is significant the measured

Figure 2. Separating the wind speed depend component of the experimental set-up resistance.

set-up resistance does not represent correctly the set-up resistance obtained when mulch covers the net. To check this eventuality, we plotted the measured r_{set-up} against U^{-1} the reciprocal of the wind speed (Fig. 7). The data produced a highly significant linear fit with $r^2 = 0.992$ and a rejection probability of only 2.8×10^{-4} proving that the offset, $r_{sp} + r_{net} = 47.2 \text{ s m}^{-1}$ is independent of wind speed. As the air boundary layers above the free steel net and the mulch surface are similar data in Table 4 provide an adequate correction for the subsequent experiments.

Mulch materials

The straw mulch consisted of dry wheat stalks. The mulch was packed to obtain bulk densities of either 31 or 37 kg m^{-3} . For the study of mulching with soil aggregates, we stabilized aggregates of a sandy loam (*Typic Rhodoxeralf*). We sieved the dry soil in five diameter classes (0.5 - 0.7, 1 - 2, 2 - 4, 4 - 8, 8 - 11.2 mm). The soil aggregates were treated with a 0.5 % solution of Krylium (vinyl acetate maleic acid).

Results

Straw mulch

The experiments examine the effect of three controlled variables on the transport of water vapor through a straw mulch: bulk density, layer thickness and wind speed. Table 5 summarizes the results of the measurements. Figure 8 shows that the relationship between mulch resistance r_m and mulch thickness h_m is positively curvilinear and dependent on wind speed. These two observations strongly suggest convective transport through the mulch.

Table 5: Straw mulch resistance, r_m (s m⁻¹) versus mulch thickness, h_m and wind speed, U at height 125 mm.

$\rho_m = 31 \text{ kg m}^{-3}$							
$U, \text{ m s}^{-1}$	$h_m, \text{ mm}$						
	1	10	20	30	40	60	100
0.5	66.6	305	491	907	1473	2480	4450
1.0	22	90.5	110	308	547	1112	2374
2.0	5	47	77	144	243	565	1387
3.0	2	27	60.5	96.3	160.3	344	949
4.2	1	17.4	62.4	65.1	129.4	252	605

$\rho_m = 37 \text{ kg m}^{-3}$							
$U, \text{ m s}^{-1}$	$h_m, \text{ mm}$						
	1	10	20	30	40	60	100
0.5	101	362	590	1197	1840	3036	4992
1.0	32	121	147	403	765	1411	3004
2.0	7	63	98	188	357	739	1851
3.0	2	38.5	73.5	108.5	207.5	447	1230
4.2	1	24.9	71.4	99.4	174.4	381	908

The dashed lines represent the value of the molecular diffusive resistance of the mulch. For the bulk density of 31 kg m⁻³ the porosity is 0.88 and the tortuosity is 0.83. Corresponding values for the bulk density of 37 kg m⁻³ are 0.85 and 0.80. Measured resistance is lower than the resistance caused by molecular diffusion. The slopes dr_m/dh_m increase with h_m and approach those of the molecular diffusive resistance. To evaluate the respective contribution of convection and diffusion to vapor flow, we fitted the experimental results to a combined linear exponential function forced through the axes' origin:

$$r_m = a(e^{-bh_m} - 1) + ch_m \quad [27]$$

where h_m is the thickness of the mulch.

In the first term is $e^{-bh_m} < 1$. This term evaluates the decrease of resistance caused by convection. For the second term we consider that dh_m/dr_m approaches $D_{eff} = 1/c$ when h_m increases towards infinity. Therefore, it represents the contribution of diffusion to the resistance.

Figure 3. The increase of the straw mulch resistance to water vapor flow with thickness is not linear. The curvature is convex. Resistance grows with bulk density, and decreases with wind speed.

Table 6. Comparison between effective molecular diffusivity calculated for straw mulch and $1/c$ fitted to the experimental data in Fig. 8.

Bulk density, kg m ⁻³	31	37
	Diffusivity m ² s ⁻¹ × 10 ⁵	
D_{eff} calculated	1.79	1.67
Wind speed m s ⁻¹	Derived from $1/c$ of Eq. [27] fitted to experimental points	
0.5	1.94	1.83
1.0	2.78	2.28
2.0	1.96	1.1
3.0	0.90	0.28
4.2	1.2	2.92

Fitting the coefficients of eq. [27] to experimental r_m produced the lines in Fig. 8. Table 6 shows

D_{eff} derived from the fitted values of c . This calculation corresponds to an extrapolation of the experimental results to very large values of h_m . Despite the large difference between measured resistances and those of molecular diffusivity the extrapolation is in fair concordance with the theoretical values. Thus, the experimental results support the asymptotic model assumed to derive eq. [27].

Larger bulk densities produced correspondingly larger values of the resistance (Fig. 8). As the internal surface area generates the drag impeding air flow through the mulch, it should be possible to unify the two panes of Fig. 8 into a single family of curves by using an area parameter in the abscissa. By analogy with the leaf area index for describing foliage, we used here the mulch area index (MAI), i.e., the area of straw per unit ground area to quantify the mulch cover over the evaporating surface. This transformation of the data in Fig. 8 results in a unified representation of the resistances in Fig. 9.

Figure 4. Using the mulch area index to quantify the amount of mulch cover unify the resistance measurements in a single family of curves.

The effect of wind on mulch resistance calculated by Eq. [9] according to Tanner and Shen (1990) is in close agreement with our experimental results (Table 7). Differences between the present experimental set-up and that used by Tanner and Shen can account for the minor discrepancies.

Table 7. Comparison between experimental r_m ($s m^{-1}$) and predictions from Eq. [7] (Tanner, Shen, 1990) for $\rho_m = 37 kg m^{-3}$ and $h_m = 10 mm$.

$r_m, s m^{-1}$	$U, m s^{-1}$	0.5	1.0	2.0	3.0	4.2
	Eq. [9] with U at 10 mm and $h_m = 11 mm$	213	138	81.3	57.6	42.7
	Experimental with U at 125 mm and $h_m = 10 mm$	362	121	63	38.5	24.9

To examine the effect of wind speed on the convective resistance, we looked at the relation

between conductance, i.e., the reciprocal of resistance and wind speed in Fig.9. The results show that conductance increases linearly with wind speed, hinting that the convective transport is turbulent. Higher density and thicker layers diminish the conductance and attenuate the effect of wind. The zero intercept of most lines is

Figure 5. Water vapor conductance increase linearly with wind speed. Layer density and thickness diminish conductance and attenuate the influence of wind.

small and occasionally negative. A physical interpretation of this parameter is not possible because flow in the tunnel is laminar at very low wind speed.

Aggregated soil layer

For the investigation of aggregate mulch resistance we packed soil in columns to measured bulk density (ρ_{ag}) shown in Table 8. Using a specific weight of 2.63 Mg m^{-3} we calculated the porosity p , the tortuosity factor ($f = p^{2/3}$) and effective molecular diffusivity of water vapor D_{eff} . (Table 8).

Table 8. Properties of soil aggregate layer.

Parameter	Diameter of soil aggregates, mm				
	<1	1 to 2	2 to 4	4 to 8	8 to 11.2
Bulk density ρ_{ag} , Mg m^{-3}	1.27	1.08	1.07	1.05	0.99
Porosity, p	0.517	0.589	0.593	0.601	0.624
Tortuosity, f	0.644	0.703	0.706	0.712	0.73
D_{eff} , $\text{m}^2 \text{ s}^{-1} \times 10^6$	8.0	9.9	10.1	10.3	10.9

We varied layer thickness (10, 20, 30, 40, 60 and 100 mm), aggregates diameter ($d_{ag} = 0.5$ to 0.7, 1 to 2, 2 to 4, 4 to 8 and 8 to 11.2 mm) and wind speed (0.5, 1, 2, 3 and 4.2 m s⁻¹). Table 9 summarizes the results of the measurements and Fig. 11 shows the relationship between transport resistance and thickness of the aggregate layer at various wind speeds and for the selected aggregate sizes. As for the straw mulch, the increase of resistance with layer thickness is curvilinear. The measured resistances are less than those calculated from a purely diffusion process. As resistance decreases with wind speed, convective transport by air flow in the pores between particles is the mechanism that lessens resistance. Layer with larger aggregates have a lower resistance. As the influence of aggregate size on D_{eff} is only minor, the decrease of resistance is due to a reduction of the specific drag area and the consequent increase of air flow. At larger values of the resistance, the rate of resistance increase approaches that of a diffusion process.

Figure 6. Water vapor transport resistance of stabilized soil aggregate layers as a function of wind speed and layer thickness.

Table 9. Vapor transport resistance (r_m , s m⁻¹) of aggregated soil layers as a function of layer thickness, h_m , and wind speed U measured at height 125 mm.

aggregate diameter, $d_{ag} = 8$ to 11.2 mm						
U , m s ⁻¹	h_m , mm					
	10	20	30	40	60	100
0.5	265	480	812	1124	2002	4413
1.0	122.7	186.3	303	419	809	1906
2.0	51	90	143	175	355	1011
3.0	18	41.7	65.8	87.2	201	599
4.2	15	33.2	49	70	152	463

aggregate diameter, $d_{ag} = 4$ to 8 mm						
U , m s ⁻¹	h_m , mm					
	10	20	30	40	60	100
0.5	502	1097	1725	2637	4627	8630
1.0	227.8	501	893	1388	2845	6796
2.0	77.4	202.7	421	627	1240	3332
3.0	26.5	90.5	210.2	344	641	1598
4.2	20	52.2	129.2	200.6	398	982

soil aggregate diameter, $d_{ag} = 2$ to 4 mm						
U , m s ⁻¹	h_m , mm					
	10	20	30	40	60	100
0.5	709	1324	2166	3203		
1.0	486	859	1407	2109	4078	
2.0	226.7	453	805	1212	2443	
3.0	111.8	210.4	397	674	1353	3702
4.2	49.7	120.2	230.5	372	736	2125

soil aggregate diameter , $d_{ag} = 1$ to 2 mm

$U, \text{ m s}^{-1}$	$h_m, \text{ mm}$					
	10	20	30	40	60	100
0.5	865	1645				
1.0	751	1219	2092			
2.0	625	962	1498	2486		
3.0	439	753	1114	1826	3827	
4.2	296.2	553	838	1295	3245	

soil aggregate diameter , $d_{ag} = 0.5$ to 0.7 mm

$U, \text{ m s}^{-1}$	$h_m, \text{ mm}$	
	10	20
0.5	1244	2504
1.0	1241	2506
2.0	1250	2533
3.0	1246	2450
4.2	1251	2507

Two layers mulch: straw and soil aggregates

The curvilinearity of the change of transport resistance with layer thickness leads to believe that the combined resistance of a multi-layer mulch is greater than the sum of the resistance of each individual compound. For a simple test of this hypothesis we measured the resistance r_M of mulches composed of equal thickness layers of the straw and soil aggregates and compared them with Σr_m the sum of the separate resistances of straw and soil aggregates.

The controlled variables of this experiment were: compound mulch total thickness (20, 40 and 60 mm), soil aggregate diameter (1 to 2 and 2 to 4 mm) and wind speed (0.5, 1.0, 2.0, 3.0, 4.2 m s^{-1}). For instance, a compound mulch thickness of 20 mm, had a 10 mm straw layer and a 10 mm soil aggregate layer. The bulk density of the straw was 37 kg m^{-3} . The straw layer was placed on top of the aggregate layer.

The compound resistance is larger than the sum of the resistance of the two layers (Table 14). As wind tunnel conditions for the top layer are the same as in the single component experiments resistance enhancement is in the bottom layer. The ratio $r_M(\Sigma r_m)^{-1}$ increases with wind speed and layer thickness. This result suggests that convection in the bottom layer is diminished. The attenuation of convection is stronger with increased resistance of the top layer. Consequently, the resistance of a compound layer will not be the same if the order of the layer is changed. Placing aggregates with diameter less than 8 mm on top of the straw will produce a larger combined resistance than the opposite arrangement. This mechanism explains the lower evaporation rate from soil with straw mulch buried under the surface in comparison with straw on top of the soil (Sembiring et al., 1995).

Table 14. Comparison of summed and compound resistance of a two-layer mulch composed of straw (on top) and soil aggregates.

U, m s ⁻¹	$d_{ag} = 1 \text{ to } 2 \text{ mm}$								
	$h_{ag,soil} = 10 \text{ mm}$			$h_{ag,soil} = 20 \text{ mm}$			$h_{ag,soil} = 30 \text{ mm}$		
	$h_{straw} = 10 \text{ mm}$			$h_{straw} = 20 \text{ mm}$			$h_{straw} = 30 \text{ mm}$		
	$\Sigma r_m,$ s m ⁻¹	$r_M,$ s m ⁻¹	r_M (Σr_m) ⁻¹	$\Sigma r_m,$ s m ⁻¹	$r_M,$ s m ⁻¹	r_M (Σr_m) ⁻¹	$\Sigma r_m,$ s m ⁻¹	$r_M,$ s m ⁻¹	r_M (Σr_m) ⁻¹
0.5	1227	1215	0.99	2235	2334	1.044	3837	4340	1.13
1.0	871.5	887	1.02	1366	1471	1.077	2495	2914	1.168
2.0	688	712	1.035	1060	1215	1.146	1868	2117	1.255
3.0	477.6	531.6	1.11	826.5	1043	1.26	1223	1690	1.382
4.2	321.1	372.7	1.16	624.4	856.6	1.37	937.6	1446	1.542

$d_{ag} = 2 \text{ to } 4 \text{ mm}$

$U,$ m s^{-1}	$h_{aggr. \text{ soil}}, h_{straw \text{ mulch}}, \text{ mm}$								
	$h_{ag,soil} = 10 \text{ mm}$			$h_{ag,soil} = 20 \text{ mm}$			$h_{ag,soil} = 30 \text{ mm}$		
	$h_{straw} = 10 \text{ mm}$			$h_{straw} = 20 \text{ mm}$			$h_{straw} = 30 \text{ mm}$		
	$\Sigma r_m,$ s m^{-1}	$r_M,$ s m^{-1}	r_M $(\Sigma r_m)^{-1}$	$\Sigma r_m,$ s m^{-1}	$r_M,$ s m^{-1}	r_M $(\Sigma r_m)^{-1}$	$\Sigma r_m,$ s m^{-1}	$r_M,$ s m^{-1}	r_M $(\Sigma r_m)^{-1}$
0.5	1071	1072	1.0	1914	2132	1.114	3363	4070	1.21
1.0	607	625	1.03	1006	1176	1.169	1810	2369	1.309
2.0	289.7	314.5	1.086	551	718	1.303	993	1464	1.474
3.0	150.3	173.1	1.152	283.9	406	1.43	505.5	867	1.715
4.2	74.6	94	1.26	191.6	305.6	1.595	329.9	652.7	1.978

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HEAT TRANSFER THROUGH MULCHES

G. Feldman, M. Fuchs and A. Hadas

For given climate conditions, root zone temperature depends greatly on the thermal properties of the soil surface. To predict this temperature it is important to have good estimates of the thermal conductivity of mulches. Yet, because wind and temperature gradient generate forced and free convective heat transport, it is necessary to evaluate the contribution of convection to the energy balance of mulched soils.

This research bears relation to the problem of effective thermal conductivity of the straw mulch and the dry soil aggregates layer. The aim of this investigation is to discuss previous scientific works devoted to the problem and to present our experimental results connected with determination of mulch effective thermal conductivity in the wide range of parameters influencing heat transfer through plant residue mulch and dry soil aggregates layer.

Before reviewing some scientific works we have to define concretely two possible systems of heat transfer through mulches: closed and open. Conduction is the molecular transport of heat through the solid fabric and the gases of the porous medium, without involving kinetic energy.

Fig. 19. The mulch thermal conductivity λ_m , is:

$$\lambda_m = \frac{G h_m}{T_3 - T_2} \quad [28]$$

where G is the steady state heat flux density, h_m is mulch thickness, T_2 and T_3 are the temperatures at the mulch boundaries. In this case (when $T_3 - T_2$ is not so great) value of λ_m depends only on dry mulch properties: bulk density, ρ (Mg m^{-3}), sizes of aggregates, diameter (mm), porosity, p , mineralogical composition, texture, particles shape and their space arrangements but doesn't depend on mulch thickness h_m , wind speed, U and temperature differences between the mulch and the atmosphere ($T_m - T_a$). Closed system considers only molecular diffusion (when $T_3 - T_2$ is not too great).

The outline of the open system (for typical situation) is shown in Fig. 20. The open system is characterized by the permeable upper boundary A-A and practically impermeable lower

boundary B-B. In this case, air exchange between mulch and atmosphere is possible. Air exchange between mulch and atmosphere occurs by the forced (wind speed) and free thermal ($T_m > T_a$) convections. The forced convection is generated by the ambient atmosphere air penetration into porous space of the mulch. The depth of such penetration naturally depends on wind speed, penetrability of the porous material and roughness of the mulch surface. The free thermal convection is generated by the difference of the bulk density of air into mulch porous space and atmosphere. This difference of the air bulk density is generated by the difference of the air temperatures between mulch (T_m) and atmosphere (T_{air}).

It is known that intensity of the free thermal convection (open system) into porous material depends mainly on difference of temperature ($T_m - T_a$), thickness of the mulch layer h_m , permeability of the porous material, roughness of the mulch surface. Naturally, forced and free thermal convections exert influence on effective thermal conductivity of the mulch (λ_m) and resistance for heat transfer from mulch surface to atmosphere (r_a).

As a rule, for open systems, when process of heat transfer governs by molecular diffusion, forced and free thermal convections, the effective thermal conductivity λ_m is used and calculated by the Eq. [28]. This effective parameter λ_m takes into account all heat processes: diffusion and convection.

At present, it is impossible to express analytically effective parameter λ_m as a function criterious of Grashoff (Gr); Prandtl (Pr) and permeability coefficient of the porous material. Therefore, we have to determine value of the effective thermal conductivity λ_m by the experimental method. All scientific works devoted to the experimental determination or calculation mulch thermal conductivity do not take into account forced or free convection; in other words, in these works, mainly closed system is considered. But we decided to examine them to receive the order of value λ_m for straw mulch and dry soil aggregates layer.

Review of some works devoted to determination of the mulch thermal conductivity

Straw mulch

Chung Sang-Ok and R. Horton (1987) developed a computer model to study two-dimensional coupled soil heat and water flow with a partial surface mulch cover. The following properties of the crop residue (corn) mulch were taken in the simulation: mulch thickness $h_m = 0.025$ m; mulch tortuosity factor 0.67; wind speed $v = 1.69$ m/s; thermal conductivity of the mulch $\lambda_m = 0.126$ W/m.°C. Unfortunately, the bulk density of the mulch is absent.

Shen Y. and C.B. Tanner (1990) performed some laboratory experiments to determine straw mulch conductivity when wind speed is zero, convection is absent. With a residue layer bulk density of 37.5 kg/m³ and a 0.0025 volumetric fraction of soils in the residue, the thermal conductivity of the residue layer (flail-chopped corn residue) was estimated to be only 2% greater than still air (about 0.025 W/m.°C).

W.R. van Wijk, W.E. Larson and W.C. Burrows (1959) used known solution of the quasi-stationary problem when soil (mulch) surface temperature changes according to the harmonic law. In this case damping depth (for a homogeneous soil or mulch) depends on thermal conductivity (λ_m) and volumetric heat capacity (C_m) of the mulch. After some field experiments and calculations, the authors received the following mulch properties. For an air-dry corn stalk mulch with bulk density $\rho_m = 49.4$ kg/m³, the thickness of 3 tons per acre of mulch is about 1.5 cm; thermal conductivity $\lambda_m = 0.167$ W/m.°C; volumetric heat capacity $C_m = 40$ kkal / m³.°C. Unfortunately, the authors did not present data about wind speed during the experiments.

Bristow, K.L., G.S. Campbell, R.I. Papendick and L.F. Elliott (1986) simulated heat and moisture transfer through a surface residue-soil system. The authors assumed that heat conductance of a straw mulch layer increased linearly with wind speed. Following this conception they modeled thermal conductivity of straw mulch layer as

$$\lambda_m = \lambda_{air} (1 + 0.007 T_m)(1 + 4 V_m) \quad [29]$$

where λ_{air} is thermal conductivity of still air; T_m is averaged temperature of the mulch layer; V

v_m is averaged wind speed within the mulch layer. for thin straw mulch layer wind speed is assumed to decrease linearly with depth approaching a value of zero at the soil surface.

We can notice that effective thermal conductivity of the mulch is governed by the difference of temperatures between mulch (T_m) and atmospheric air (T_{air}), because free thermal convection depends on $(T_m - T_{air})$, h_m and mulch permeability. Therefore, introduction of T_m in Eq. [29] instead $(T_m - T_{air})$; h_m is not correct. Besides, now it is impossible to calculate the averaged wind speed within the straw mulch layer (V_m), because V_m depends not only on V but on h_m , ρ_m , mulch permeability, surface mulch roughness and on position of straw mulch on the soil surface (Smika, 1983). Therefore, at present it is impossible to use Eq. [29]. Thus, after review the values of straw mulch thermal conductivity we can determine the range of this value: $0.025 < \lambda_m < 0.167$ W / m.°C

Dry soil aggregates layer

$$\lambda_m(\Theta) = b_1 + b_2\Theta + b_3\Theta^{0.5} \quad [30]$$

Chung Sang-Ok and R. Horton (1987) used a simple empirical equation to describe a relationship between soil thermal conductivity (λ_m) and volumetric water content (Θ , m³/m³)

We calculated values of λ_m for some dry soils (when $\Theta = \Theta_r$ - residual water content). Values of coefficients b_1 ; b_2 ; b_3 and Θ_r (Chung Sang-Ok and Horton, 1987) and calculated λ_m for dry soils ($\Theta = \Theta_r$) are presented in Table 16.

Table 16: Values of b_1 ; b_2 ; b_3 ; Θ_r (Chung, Horton, 1987) and calculated λ_m for some dry soils.

	Clay	Loam	Sand
b_1	-0.197	0.243	0.228
b_2	-0.962	0.393	-2.406
b_3	2.521	1.534	4.909
Θ_r	0.03	0.01	0.0
λ_m , W/m.°C	0.211	0.40	0.228

$$\lambda_m = A + B\Theta - (A - D)\exp[-C\Theta^E] \quad [31]$$

Bristow, K.L., Campbell, G.S., Papendick, R.I. and Elliot, L.F. (1986) described the function $\lambda_m = f(\Theta)$ by the equation where Θ is mass basis soil water content; A,B,C,D and E are empirical coefficients.

The following values of these coefficients were received for simulation by the authors:

$A = 0.58$; $B = 1.63$; $C = 8,54$; $D = 0.14$; $E = 5.0$. After calculation, the value of dry soil thermal conductivity (when $\Theta = 0$) is $\lambda_m = 0.14$ W / m.°C.

A. Hadas (1977) noticed that in general, two heat transfer processes can be envisaged in a dry aggregated soil: thermal diffusion and heat convection. But all his laboratory experiments were devoted to measuring only thermal diffusivity of dry aggregated soil (closed system). A. Hadas (1977) performed a great number of laboratory experiments to measure the thermal diffusivity of dry soil aggregates. Two soils were used in this study. One was an alluvial clay soil from the Bet Shean Valley, Israel (43% clay, 37% silt and 20% very fine sand). The other soil was a loessial silty loam from Gilat, Israel (18% clay; 27% silt and 55% sand). Natural aggregates were obtained from these soils by sieving field samples through different sieves so as to obtain the following aggregate size groups: <0.25 mm; 0.25-0.50; 0.5 - 1.0 and 1-2 mm (mean diameter of aggregates).

Then the prepared aggregates were uniformly packed into cylinder (diameter 90 mm) where a center heat exchange unit was placed producing two soil sample cells, 200 mm long. The whole

unit was insulated by fiberglass matting 50 mm thick. The bulk density of the aggregated soil was: 0.85 - 0.95 g/cm³ for ϕ 1 - 2 mm; 0.88 - 0.95 for ϕ 0.5 - 1 mm; 0.95 - 0.98 for ϕ 0.25 - 0.50 mm.

Steady state measurements were carried out under conditions of the closed system (without air exchange between aggregated soil and atmosphere). The temperature difference was about 10°C between heated surface of the heat source and the extreme sides of the soil samples. Temperature measurements were taken 72 hours after a constant temperature distribution was obtained. The values of aggregated soils thermal conductivity as a function aggregate size class are shown in Fig. 21. One can see that value λ_m decreases as the size of the dry aggregates and the total and interaggregate porosities increase. This trend (for closed system) may be explained by decrease in the number of contacts between aggregates when diameter of the soil aggregates increases (Hadas, 1977). After analysis of the data presented in Fig. 21 we want to notice the great difference of thermal conductivities between different sizes of soil aggregates. For example: for silty loam (Gilat soil) we have: ϕ 0.125 - 0.25 mm, $\lambda_{m1} = 0.194$ W / m.°C; ϕ 1 - 2 mm, $\lambda_{m2} = 0.0064$ W / m.°C. The ratio is $0.194 / 0.064 = 3.0$. Besides, the function $\lambda_m(\phi)$ is approximately linear. In this case, we can expect very small values of λ_m for aggregates with $\phi > 2$ mm.

Nakshabandi, G.Al. and Kohnke, H. (1965) measured thermal conductivity of soils by means of a thin cylindrical electrically heated probe (closed system). Three soils were used for the study - clay, silt loam and fine sand. Some properties of the soils and values of thermal conductivity for dry soils are presented in Table 17.

There is too great difference between values of thermal conductivities for clay ($\lambda_m = 0.188$) when bulk densities differ not so considerably. The authors (Nakshabandi and Kohnke, 1965) also studied relationship between thermal conductivity of dry

Table 17: Some properties of the soils used for the study (Nakshabandi and Kohnke, 1965).

Properties	Clay	Silt loam	Fine sand
Bulk density, g/cm ³	0.89-1.0	1.15-1.3	1.4-1.43
Gravimetric heat capacity kkal / kg.°C	0.20	0.199	0.168
Thermal conductivity of the dry soil, W / m.°C	0.105	0.188	0.20

aggregated soil and size of the aggregates (closed system). For the study washed sand (diameter of particles 0.5 - 1.0 and 1 - 2 mm) and glass beads (0.1 - 0.25 and 0.25 - 0.50 mm) were used. Values of the thermal conductivities for the dry materials are presented in Table 18.

Table 18: Relation of particle size to thermal conductivity (Nakshabandi and Kohnke, 1965).

Air-dry material	Particle size range mm	Bulk density g/cm ³	Thermal conductivity W / m.°C
Washed sand	0.5-1.0	1.43	0.22
Washed sand	1-2.0	1.43	0.236
Glass beads	0.1-0.25	1.51	0.161
Glass beads	0.25-0.5	1.53	0.165

One can see that thermal conductivity of the dry aggregated material increases with the diameter of aggregates, but size of the individual particles had comparatively small effect upon the thermal conductivity (in the studied range of ϕ).

Hammel, J.E., Papendick, R.I. and Campbell, G.S. (1981) performed the field experiment to compare measured and predicted field soil temperatures and soil water contents. Conventional tillage and no-till fallow treatments were established on two plots (3 x 7 m) on wheat stubble soil (silt loam). Conventional tillage consisted of sweep cultivation to a depth of 15 cm to establish

a loose soil mulch and leaving essentially a smooth, bare surface. With no-till the soil remained partially covered with straw. Porosities of the tilled and untilled soils from field measurements were 0.62 and 0.50, respectively. The experimental site was instrumented for measurement of all necessary parameters.

$$\lambda_m = \lambda_o + \eta\Theta \quad [32]$$

The authors have calculated the thermal conductivities of the soil assuming it is a linear function of water content where λ_o is the oven-dry soil thermal conductivity, W / m. $^{\circ}$ C; η is a proportionality constant; Θ is soil water content, kg/kg. Values of oven-dry and saturated soil thermal conductivities were calculated from De Vries theory. Thermal conductivities for the soil solids, water and air were 2.93; 0.57 and 0.025 W / m. $^{\circ}$ C, respectively. Computed thermal conductivities of oven-dry tilled and untilled soil were 0.17 and 0.20 W / m. $^{\circ}$ C, respectively. For saturated soil the thermal conductivities for the tilled and untilled soils were 1.15 and 1.40 W / m. $^{\circ}$ C, respectively. Finally, the authors suggested the following expressions for thermal conductivities. For tilled soil:

$$\lambda_m = 0.17 + 0.63\Theta \quad [33]$$

For untilled soil:

$$\lambda_m = 0.2 + 2.36\Theta \quad [34]$$

Moench, A.F. and Evans, D.D. (1970) noticed that heat transfer in a dry soil (or mulch) may take place by diffusion, convection and radiation. Thermal conductivity of sandy loam soil was determined using a cylindrical heat source. for dry sandy loam with dry bulk density 1.48 g/cm 3 the thermal conductivity was 0.253 W / m. $^{\circ}$ C.

Ray D. Jackson and D. Kirkham (1958) used alternating source of heat to determine the thermal conductivity of the clay loam (30% sand; 33% silt and 37% clay). For dry clay loam soil with bulk density 1.17 g/cm 3 thermal conductivity was 0.139 W / m. $^{\circ}$ C.

Wierenga, P.J., Nielsen, D.R. and Hagan, R.M. (1969) determined thermal properties of Yolo silt loam on the basis of laboratory and field measurements. Values of the thermal conductivity of the soil were measured as a function of soil water content using aline heat source probe at several

soil depths. Thermal conductivity for dry silt loam was computed from known De Vries equation. In accordance with De Vries values of thermal conductivity for quartz, the other solids, organic matter, water and air were taken as 8.5; 2.9; 0.25; 0.57 and 0.025 W / m.°C, respectively. Calculated values of thermal conductivity for dry Yolo silt loam depend on its dry bulk density:

$$\rho = 1.22 \text{ g/cm}^3, \lambda_m = 0.214 \text{ W / m.}^\circ\text{C}; \rho = 1.30, \lambda_m = 0.255; \rho = 1.42, \lambda_m = 0.29.$$

Taconet, O., Bernard, R. and Vidal-Madiar, D. (1984) suggested the following relationship between thermal conductivity and volumetric soil water content for standard clay soils

$$\lambda_m = 0.209 + 1.46\Theta \quad [35]$$

Then, for oven-dry clay soil $\lambda_m = 0.209 \text{ W / m.}^\circ\text{C}$.

After consideration of the literature, J.R. Garratt (1991) supposes that values of thermal conductivity for dry, natural soils tend to lie in the range of 0.1 - 0.2 W / m.°C and averaged value is 0.15 W / m.°C.

Passerat De Silans et al. (1991) performed some field experiments to compare the numerical results with field data. the plot was equipped with appropriate sensors in order to measure all necessary parameters of atmospheric air and soil (upper layer 0.5 - 30 cm). Soil - silt loam with the following properties: clay content - 27%, silt - 61%, sand - 11%, organic matter - 1%; averaged bulk density 1.32 g/cm³; porosity - 0.5. The thermal conductivity of this upper layer (0.5 - 30 cm) was obtained through the estimation of soil heat capacity and field determination of the soil thermal diffusivity. This was done by analyzing the measured temperature profiles and by solving the linearized heat conduction equation on a daily basis. For the dry silt loam the thermal conductivity was 0.227 W / m.°C.

Now we can present the range of the dry soil thermal conductivities for typical values of bulk density.

Dry aggregated soil: Clay soil 0.085 - 0.25 W / m.°C;

silty loam 0.065 - 0.225; sand 0.22 - 0.236.

Dry soil: clay 0.105 - 0.211 W / m.°C; loam 0.17 - 0.29; sand 0.20 - 0.228.

The laboratory experiments on heat transfer through mulches

As stated above, all measurements or calculations of the mulch thermal conductivity (performed before) relates to the conditions of closed system when mulch thermal conductivity corresponded only to molecular diffusion. In contrast with such investigations we study mixed diffusive and convective heat transfer through mulches. As it is known, convective heat transfer through porous material is governed by forced (wind) and free thermal convection (air bulk density difference between mulch and atmosphere). Therefore we used wind tunnel and designed the special device to measure effective (mixed diffusive and convective heat transfer) thermal conductivity of mulches as a function of wind speed; mulch thickness; diameter of aggregates and temperature difference between mulch and atmosphere. Small wind tunnel is described above, the bottom of the wind tunnel is pierced with a hole that fits a 200 mm diameter of the device to measure mulch thermal conductivity (Fig. 22). The device is the plastic cylinder (inner diameter 192 mm; wall thickness is 4 mm) which is mounted on the heater. the height of the upper part of the cylinder can be increased (or decreased) by means of the rings (10 mm thick) which are connected with the cylinder and each other by glue tape. The lower part of the cylinder (30 mm thick) is packed by the very fine sand, and the heat plate (to measure heat flux) is installed at the depth of 10 mm. Three thermocouples are placed to measure temperatures of air (T_1), mulch surface (T_2) and mulch bottom (T_3).

The cylinder is insulated by paralon (50 mm thick) to provide practically one-dimensional heat transport when ratio sum of the cylinder diameter and two-fold insulation thickness ($192 + 2 \cdot 50 = 292$ mm) to mulch thickness (h_m) is less approximately 5.0.

The heater is connected with the transformer to maintain certain predetermined voltage ($\Delta V = 30.6$ v; 25; 20 and 15v); it allows to change values of heat flux and consequently temperature difference between mulch ($T_m = T_3 + T_2 / 2$) and atmospheric air (T_1). Temperature and heat flux measurements were taken one hour after a constant temperature distribution (T_1 ; T_2 and T_3) and

constant heat flux (q) were attained. Under stationary conditions the value of effective thermal conductivity (λ_m) may be calculated by the known Eq. [28].

$$\lambda_m = \frac{q \cdot h_m}{T_3 - T_2} \quad \frac{W}{m \cdot ^\circ C}$$

The aerodynamic resistance (r_a , s/m) to sensible heat transport from the mulch surface to atmosphere can be represented by the known expression

$$r_a = \frac{\rho_{air} \cdot C_{air} \cdot (T_2 - T_1)}{q} \quad [37]$$

where ρ_{air} is air bulk density, $\rho_a = 1.313 \text{ kg/m}^3$; C_{air} is heat capacity of air, $C_{air} = 1005 \text{ J/kg} \cdot ^\circ C$ q is heat flux, W/m^2 . After substitution values of ρ_{air} and C_{air} in expression (31) we have the final formula for calculation value r_a .

$$r_a = \frac{1135(T_2 - T_1)}{q}, s/m$$

Here, it is necessary to notice that accepted scheme in experiments (when $T_3 > T_2$) doesn't exactly correspond to natural real temperature distribution throughout the mulch in the daytime, when in consequence of solar radiation $T_2 > T_3$. But we operate with averaged mulch temperature ($T_m = T_3 + T_2 / 2$), therefore such a scheme doesn't exert great influence on free thermal convection which is governed by parameters ($T_m - T_{air}$), h_m and coefficient of mulch permeability. The conditions of the laboratory experiments ($T_3 > T_2$) and ($T_m > T_{air}$) promote increase of free thermal convection intensity when mulch thickness increases. Therefore, we can expect increase mulch thermal conductivity with parameter h_m .

Straw mulch

The study used wheat straw cut into 4-6 cm lengths. The controlled variables are straw mulch thickness (1;2;3;4 and 6 cm), bulk density $\rho_m = 37 \text{ kg/m}^3$; wind speed (0.5;1;2;3 and 4.2 m/s at height 12.5 cm above mulch surface) and temperature difference between mulch and atmospheric air.

The following experiments were carried out by means of the set-up:

effect of wind speed (V) on mixed diffusive and convective heat transport:

Effect of straw mulch thickness (H_m) at fixed mulch density ($\rho_m = 37 \text{ kg/m}^3$) on mixed diffusive and convective heat transfer;

effect of temperature difference between the mulch (T_m) and atmospheric air (T_1) on heat transport.

We present experimental results in table and graphic forms. the relationship between effective thermal conductivity of the straw mulch (λ_m), mulch thickness (h_m); wind speed (V) and temperature difference (T_m, T_{air}) at $\rho_m = 37 \text{ kg/m}^3$ is shown in Tables 19, 20, 21, 22 and 23.

Table 19: Thermal conductivity of the straw mulch at $\rho = 37 \text{ kg/m}^3$, $h_m = 0.01 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a, \text{s/m}$	$\lambda_m \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
27.3	35.1	49.9	7.8	14.8	15.2	96.7	91.6	0.0653
24.7	29.9	39.8	5.2	9.9	10.15	64.5	91.5	0.0652
$V = 1.0 \text{ m/s}$								
26.5	31.6	48.2	5.1	16.6	13.4	127	45.6	0.0765
26.0	29.4	40.5	3.4	11.1	8.95	84.7	45.6	0.0763
$V = 2.0 \text{ m/s}$								
25.7	28.7	45.2	3.0	16.5	11.25	155	22.0	0.0939
26.0	28.0	39.0	2.0	11.0	7.5	103	22.0	0.0936
$V = 3.0 \text{ m/s}$								
25.3	27.5	43.7	2.2	16.2	10.3	170	14.7	0.1049
26.2	27.7	38.6	1.5	10.9	6.95	114	14.9	0.1046
$V = 4.2 \text{ m/s}$								
26.6	28.2	43.0	1.6	14.8	9.0	175	10.4	0.1182
25.9	27.0	36.9	1.1	9.9	6.05	117	10.7	0.1182

Table 20: Thermal conductivity of the straw mulch at $\rho = 37 \text{ kg/m}^3$; $h_m = 0.02 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a, \frac{\text{m}}{\text{s}}$	$\lambda_m, \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
25.9	31.3	56.2	5.4	24.9	17.58	71.9	85.2	0.0578
22.9	26.5	43.5	3.6	17.0	12.1	47.5	86.0	0.0559
23.7	25.9	36.9	2.2	11.0	7.7	30.3	82.4	0.0551
24.2	25.4	31.4	1.2	6.0	4.2	16.5	82.5	0.0550
$V = 1.0 \text{ m/s}$								
25.6	28.6	53.7	3.0	25.1	15.55	77.8	43.8	0.0620
26.2	28.2	45.1	2.0	16.9	10.45	50.7	44.8	0.0600
24.8	26.1	37.6	1.3	11.5	7.05	34.1	43.3	0.0593
24.5	25.2	31.7	0.7	6.5	3.95	19.2	41.4	0.0591
$V = 2.0 \text{ m/s}$								
22.8	24.5	48.7	1.7	24.2	13.8	88.0	21.9	0.0727
25.0	26.2	43.0	1.2	16.8	9.6	59.4	22.9	0.0707
25.6	26.3	36.9	0.7	10.6	6.0	37.3	21.3	0.0704
23.4	23.8	29.5	0.4	5.7	3.25	20.0	22.7	0.0702

V = 3.0 m/s										
24.9	26.1	49.1	1.2	23.0	12.7	97.3	14.0	0.0846		
24.9	25.3	41.3	0.7	16.0	8.8	65.6	13.8	0.0820		
23.9	24.4	34.5	0.5	10.1	5.55	40.9	13.9	0.0810		
23.4	23.7	29.4	0.3	5.7	3.15	23.1	14.7	0.0810		
V = 4.2 m/s										
24.1	25.0	47.5	0.9	22.5	12.15	107	9.5	0.0951		
24.2	24.8	40.3	0.6	15.5	8.35	71.5	9.5	0.0922		
24.3	24.7	34.7	0.4	10.0	5.4	45.5	10.0	0.0911		
24.3	24.5	30.1	0.2	5.6	2.9	25.3	9.0	0.0904		

Table 21: Thermal conductivity of the straw mulch at $\rho = 37 \text{ kg/m}^3$; $h_m = 0.03 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a, \text{s/m}$	$\lambda_m, \frac{\text{W}}{\text{m}\cdot^\circ\text{C}}$
V = 0.5 m/s								
25.0	28.9	54.6	3.9	25.7	16.75	56.4	78.5	0.0659
25.6	28.3	46.8	2.7	18.5	11.95	37.6	81.5	0.0610
24.9	26.6	38.7	1.7	12.1	7.75	23.7	81.4	0.0588
26.0	27.1	34.4	1.1	7.3	4.75	14.1	88.5	0.0579
V = 1.0 m/s								
23.8	26.3	52.8	2.5	26.5	15.75	68.0	41.7	0.0770
23.3	24.9	42.5	1.6	17.6	10.4	41.9	43.3	0.0714
25.9	26.9	38.2	1.0	11.3	6.65	26.4	43.0	0.0701
25.6	26.2	33.4	0.6	7.2	4.2	16.6	41.0	0.0692
V = 2.0 m/s								
26.0	27.6	54.8	1.6	27.2	15.2	88.8	20.5	0.0980
26.7	27.7	46.2	1.0	18.5	10.25	56.8	20.0	0.0921
25.2	25.9	38.5	0.7	12.6	7.0	36.9	21.5	0.0878
24.8	25.2	32.6	0.4	7.4	4.1	21.1	21.5	0.0855

V = 3.0 m/s										
21.8	23.0	49.3	1.2	26.3	14.35	103	13.2	0.1175		
21.9	22.7	40.6	0.8	17.9	9.75	65.3	13.9	0.1094		
25.3	25.8	37.6	0.5	11.8	6.4	40.9	13.9	0.1040		
26.1	26.4	33.0	0.3	6.6	3.6	22.6	15.1	0.1027		
V = 4.2 m/s										
23.8	24.7	48.6	0.9	23.9	12.85	107	9.5	0.1343		
21.1	21.7	38.6	0.6	16.9	9.05	71.5	9.5	0.1270		
20.6	20.0	32.2	0.4	11.2	6.0	45.5	10.0	0.1220		
23.2	23.4	29.8	0.2	6.4	3.4	25.6	8.9	0.1200		

Table 22: Thermal conductivity of the straw mulch at $\rho = 37 \text{ kg/m}^3$; $h_m = 0.04 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{\text{W}}{\text{m}\cdot^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
22.9	26.1	56.3	3.2	30.2	18.3	52.1	69.7	0.0690
23.7	25.7	46.4	2.0	20.7	12.35	32.2	70.5	0.0622
24.8	26.1	39.8	1.3	13.7	8.15	20.7	71.3	0.0604
23.8	24.5	32.4	0.7	7.9	4.65	11.8	67.3	0.0597
$V = 1.0 \text{ m/s}$								
23.4	25.5	56.2	2.1	30.7	17.45	64.5	37.0	0.0840
22.7	24.1	45.8	1.4	21.7	12.25	42.0	37.8	0.0775
22.2	23.0	37.0	0.8	14.0	7.8	25.6	35.5	0.0732
22.5	23.0	31.0	0.5	8.0	4.5	14.2	39.9	0.0710
$V = 2.0 \text{ m/s}$								
21.4	22.6	52.8	1.2	30.2	16.3	83.1	16.4	0.1101
21.1	21.9	42.6	0.8	20.7	11.15	53.3	17.0	0.103
19.6	20.1	33.8	0.5	13.7	7.35	343.1	16.6	0.0995
19.7	20.0	27.8	0.3	7.8	4.2	19.1	17.8	0.0979

V = 3.0 m/s										
21.3	22.2	49.8	0.9	27.6	14.7	95.2	10.7	0.1380		
21.8	23.4	43.1	0.6	19.7	10.45	64.0	10.6	0.1300		
21.9	22.3	35.8	0.4	13.5	7.15	42.7	10.6	0.1265		
21.9	22.1	29.6	0.2	7.5	3.95	23.3	9.7	0.1243		
V = 4.2 m/s										
22.1	22.8	48.2	0.7	25.4	13.4	103	7.7	0.1620		
22.0	22.5	40.4	0.5	17.9	9.45	68.1	8.3	0.1522		
22.4	22.7	34.5	0.3	11.8	6.2	44.0	7.7	0.1492		
22.5	22.7	29.4	0.2	6.7	3.55	24.7	9.2	0.1475		

Table 23: Thermal conductivity of the straw mulch at $\rho = 37 \text{ kg/m}^3$; $h_m = 0.06 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	r_a, m	$\lambda_m, \frac{\text{W}}{\text{m}\cdot^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
21.8	24.0	56.4	2.2	32.4	18.4	41.3	60.5	0.0765
22.6	23.9	46.2	1.3	22.3	12.45	25.2	58.6	0.0678
24.0	24.8	39.2	0.8	14.4	8.0	15.1	60.1	0.0629
24.2	24.7	33.1	0.5	8.4	4.7	8.5	66.8	0.0607
$V = 1.0 \text{ m/s}$								
23.5	25.0	58.0	1.5	33.0	18.0	55.6	30.6	0.1010
23.3	24.2	46.8	0.9	22.6	12.2	34.2	29.9	0.0908
22.5	23.1	37.5	0.6	14.4	7.4	20.5	33.2	0.0854
22.9	23.2	31.0	0.3	7.8	4.2	10.9	31.2	0.0838
$V = 2.0 \text{ m/s}$								
23.3	24.4	57.4	1.1	33.0	17.6	81.4	15.3	0.1480
20.4	21.1	43.2	0.7	22.1	11.75	50.5	15.7	0.1371
20.9	21.3	35.0	0.4	13.7	7.25	30.2	15.0	0.1323
20.9	21.1	28.8	0.2	7.7	4.05	16.6	13.7	0.1294

V = 3.0 m/s										
21.4	22.2	50.0	0.8	27.8	14.7	91.3	9.9	0.1970		
20.6	21.1	40.5	0.5	19.4	10.2	60.4	9.4	0.1868		
23.1	23.4	36.0	0.3	12.6	6.6	38.1	8.9	0.1815		
20.3	10.5	27.5	0.2	7.0	3.7	20.8	10.9	0.1783		
V = 0.2 m/s										
21.8	22.5	48.3	0.7	25.8	13.6	101	7.9	0.2350		
24.3	24.7	42.6	0.4	17.9	9.35	66.6	6.8	0.2232		
24.6	24.9	36.8	0.3	11.9	6.25	43.1	7.9	0.2173		
24.8	24.9	31.6	0.1	6.7	3.45	23.8	4.8	0.2131		

On the basis of Tables 19-23, the graphic relationships between effective thermal conductivity of the straw mulch (λ_m), thickness (h_m) and wind speed (V) at maximum, voltage $\Delta v = 30.6v$ are shown in Figs. 23 and 24.

One can see that λ_m depends greatly on both h_m and V; value λ_m changes from 0.,06 to 0.235 W / m.°C at accepted range of V, h_m and $9 < (T_m - T_{air}) < 18.4$ °C.

A combination of forced and free thermal convection brings to the minimum values of λ_m at mulch thickness about 2 cm. the graphic relationships between λ_m and $(T_m - T_{air})$ at different mulch thickness (2;3;4 and 6 cm) are shown in Figs. 25, 26, 27 and 28. As it was expected, thermal conductivity of the straw mulch increases with parameter $(T_m - T_{air})$, especially at maximum values of heat fluxes (when maximum voltage $\Delta V = 30.6v$).

It is interesting to calculate parameter $d\lambda / d(T_m - T_{air})$ as a function of mulch thickness (H_m) and wind speed (V). The results of the calculations (based on Tables 19-23) values $d\lambda_m / d(\Delta T_{me})$ are presented in Table 24 and fig. 29, where $\Delta T_{ma} = T_m - T_{air} = T_3 - mT_2 / 2 - T_{air}$.

Table 24: Values $d\lambda_m / d(\Delta T_{ma})$ for straw mulch at $10 < \Delta T_{ma} < 18$ °C.

V m/s	h_m , cm			
	2	3	4	6
0.5	$3.3 \cdot 10^{-4}$	$10 \cdot 10^{-4}$	$11.4 \cdot 10^{-4}$	$14.6 \cdot 10^{-4}$
1.0	$3.9 \cdot 10^{-4}$	$10 \cdot 10^{-4}$	$12.4 \cdot 10^{-4}$	$17.6 \cdot 10^{-4}$
2.0	$4.8 \cdot 10^{-4}$	$12 \cdot 10^{-4}$	$13.8 \cdot 10^{-4}$	$18.6 \cdot 10^{-4}$
3.0	$6.7 \cdot 10^{-4}$	$18 \cdot 10^{-4}$	$18.4 \cdot 10^{-4}$	$22.7 \cdot 10^{-4}$
4.2	$7.6 \cdot 10^{-4}$	$19 \cdot 10^{-4}$	$24.8 \cdot 10^{-4}$	$27.8 \cdot 10^{-4}$

One can see from Fig. 29 that parameter $d\lambda_m / d(\Delta T_{ma})$ depends greatly on both wind speed and mulch thickness at maximum value of heat flux.

It is known that an aerodynamic resistance (r_a , s/m) to sensible heat transport from the mulch surface to atmosphere (when mulch surface is impenetrable boundary) depends on wind speed, roughness of mulch surface and character of air temperature distribution (stability correction determined by richardson number). But in general case (when mulch surface is penetrable boundary) value r_a depends also on intensity of air exchange between dry mulch and atmosphere (when $\Delta T_{ma} > 0$). therefore, we have calculated values r_a using expression (32) and presented graphic relationship $r_a = f(h_m; V)$ in Fig. 30.

One can see that value r_a depends essentially on h_m at small wind speed. Dependence $r_a = f(h_m)$ is not essential at great wind speed and it is comparable with experimental error. It is obvious, function $r_a = f(h_m, V)$ takes into account the temperature difference ($T_2 - T_{air}$), but we couldn't calculate Richard number because wind speed distribution throughout the wind tunnel section doesn't correspond to the natural law - logarithmic function.

Layer of soil aggregates

The soil aggregates properties depending on diameter of soil aggregates are shown in Table 8. The controlled variables are soil aggregates layer thickness (1,2,3 and 4 cm), diameter of soil aggregates (8-11.2 mm, 4-8, 2-4 and 1-2 mm), wind speed (0.5, 1.0, 2.0. 3.0 and 4.2 m/s) and temperature difference between the mulch ($T_m = T_3 + T_2/2$) and atmospheric air (T_1).

The following experiments were carried out by means of the set-up.

- effect of soil aggregates layer thickness (H_m) on mixed diffusive and convective heat transport
- effect of wind speed on heat transport
- effect of soil aggregates diameter (ϕ) on heat transport
- effect of temperature difference ΔT_{ma} on heat transport.

We present experimental results in table and graphic forms.

Diameter of aggregates 1-2 mm

The relationship between λ_m , h_m , V and ΔT_{ma} at $\rho_m = 1080 \text{ kg/m}^3$ is shown in Tables 25,26,27 and

Figs. 31, 32. Value of λ_m changes from 0.188 to 0.225 W / m.°C at accepted range of V , h_m and ΔT_{ma} . One can see from Figs. 31 and 32 and Tables 25-27 that effective thermal conductivity doesn't depend essentially on mulch thickness, wind speed and temperature difference ΔT_{ma} . It may be explained by comparatively low permeability of the aggregated soil with diameter of aggregates 1-2 mm. The calculated parameter $d\lambda_m / d(\Delta T_{ma})$ as a function of h_m and V are presented in Table 28 and Fig. 33. the graphic relationship $r_a = f(h_m, V)$ is presented in Fig. 34.

Table 25: Thermal conductivity of the soil aggregates layer at $\phi 1 / 2$ mm; $\rho = 1080 \text{ kg/m}^3$, $h_m = 0.02 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{\text{W}}{\text{m}^\circ\text{C}}$
V = 0.5 m/s								
23.0	34.7	49.4	11.7	14.7	19.05	138	96.2	0.1878
22.7	30.6	40.5	7.9	9.9	12.85	92.7	96.7	0.1873
V = 1.0 m/s								
21.9	28.1	43.3	6.2	15.2	13.8	148	48.5	0.1908
22.9	27.0	37.0	4.1	10.0	9.75	95.1	48.9	0.1902
V = 2.0 m/s								
23.2	26.5	42.2	3.3	15.7	11.15	154	24.3	0.1969
23.8	26.0	36.6	2.2	10.6	7.5	104	24.0	0.1962
V = 3.0 m/s								
23.1	25.4	41.8	2.3	16.4	0.5	163	16.0	0.1988
23.0	24.6	35.6	1.6	11.0	7.1	109	16.7	0.1982
V = 4.2 m/s								
23.2	24.9	41.9	1.7	17.0	10.2	171	11.3	0.2012
23.0	24.1	35.1	1.1	11.3	6.6	111	11.0	0.2000

Table 26: Thermal conductivity of the soil aggregates layer at $\phi 1 / 2$ mm; $\rho = 1080 \text{ kg/m}^3$, $h_m = 0.03 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
23.1	33.6	52.6	10.5	19.0	20.0	126	94.6	0.1989
23.0	30.0	42.8	7.0	12.8	13.4	84.5	94.0	0.1980
$V = 1.0 \text{ m/s}$								
22.9	28.3	47.7	5.4	19.4	15.1	131	46.8	0.2026
23.2	26.8	39.6	3.6	12.8	10.0	86.1	47.5	0.2018
$V = 2.0 \text{ m/s}$								
23.1	26.0	46.4	2.9	20.4	13.1	141	23.3	0.2074
23.3	25.3	38.9	2.0	13.6	8.8	93.6	24.3	0.2065
$V = 3.0 \text{ m/s}$								
23.0	25.0	46.1	2.0	21.1	12.55	148	15.3	0.2104
23.2	24.5	38.6	1.3	14.1	8.35	98.3	15.0	0.2091
$V = 4.2 \text{ m/s}$								
23.1	24.6	46.1	1.5	21.5	12.25	153	11.1	0.2135
23.0	24.0	38.3	1.0	14.3	8.15	101	11.2	0.2119

Table 27: Thermal conductivity of the soil aggregates layer at $\phi 1 / 2$ mm; $\rho = 1080 \text{ kg/m}^3$, $h_m = 0.04 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{\text{W}}{\text{m}\cdot^\circ\text{C}}$
V = 0.5 m/s								
23.1	32.1	52.8	9.0	20.7	19.35	109	93.7	0.2106
23.2	29.2	43.0	6.0	13.8	12.9	72.3	94.2	0.2095
V = 1.0 m/s								
23.4	28.1	49.3	4.7	21.2	15.3	114	46.8	0.2151
22.9	26.0	40.2	3.1	14.2	10.2	75.9	46.4	0.2138
V = 2.0 m/s								
22.6	25.0	46.5	2.4	21.5	13.15	118	23.1	0.2195
22.7	24.3	38.8	1.6	14.5	8.85	79	23.0	0.2179
V = 3.0 m/s								
22.9	24.6	46.5	1.7	21.9	12.65	122	15.8	0.2228
23.0	24.2	38.9	1.2	14.7	8.55	81.2	16.8	0.2210
V = 4.2 m/s								
22.6	23.8	46.0	1.2	22.2	12.3	125	10.9	0.2252
22.5	23.3	38.2	0.8	14.9	8.25	83.1	10.9	0.2231

Table 28: Values $d\lambda/d(\Delta T_{ma})$ for dry aggregated soil with sizes of aggregates 1-2 mm and $8 < \Delta T_{ma} < 20^\circ\text{C}$.

V, m/s	h_m , cm		
	2	3	4
0.5	$0.81 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$
1.0	$1.5 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$
2.0	0.0	$2.1 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$
3.0	$1.8 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$
4.2	$3.3 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$

Diameter of aggregates 2-4 mm

The relationship between λ , h_m , V and ΔT_{ma} at $\rho_m = 1070 \text{ kg/m}^3$ is shown in Tables 29,30,31,32 and Figs. 35 and 36. The value of λ_m changes from 0.19 to $0.258 \text{ W / m}^\circ\text{C}$ at accepted range of V; h_m ; ΔT_{ma} . The relationship $\lambda_m = f(V)$ is approximately linear for this diameter of aggregates (2-4 mm).

The relationships between λ_m and ΔT_{ma} at different mulch thickness (1,2,3 and 4 cm) are shown in Figs. 37-40. The calculated parameters $d\lambda_m / d(\Delta T_{ma})$ (at range $7 < \Delta T_{ma} < 15^\circ\text{C}$) as a function of the mulch thickness (h_m) and wind speed (V) are presented in Table 33 and Fig. 41.

The graphic relationship $r_a = f(h_m; v)$ is presented in Fig. 42.

Table 29: Thermal conductivity of the soil aggregates layer at $\phi 2 / 4 \text{ mm}$; $\rho = 1070 \text{ kg/m}^3$, $h_m = 0.01 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
23.4	36.7	45.3	13.3	8.6	14.1	164	92	0.1907
23.6	32.5	38.1	8.9	5.6	9.3	106	95.3	0.1893
24.3	29.7	33.2	5.4	3.5	5.85	66.2	92.6	0.1891
24.1	27.2	29.2	3.1	2.0	3.3	37.8	93.1	0.1890
$V = 1.0 \text{ m/s}$								
23.1	30.3	39.5	7.2	9.2	13.4	177	46.2	0.1924
23.3	28.1	34.1	4.8	6.0	7.8	115	47.4	0.1917
24.0	27.1	30.9	3.1	3.8	5.0	72.7	48.4	0.1914
24.1	25.89	27.9	1.7	2.15	2.75	40.2	48.0	0.1914
$V = 2.0 \text{ m/s}$								
24.5	28.5	38.2	4.0	9.7	8.85	192	23.6	0.1979
24.6	27.3	33.9	2.7	6.6	6.0	130	23.6	0.1970
24.2	26.1	30.3	1.7	4.2	3.8	82.5	23.4	0.1964
24.5	25.5	27.9	1.0	2.4	2.2	47.1	24.1	0.1963

V = 3.0 m/s										
25.4	28.3	38.6	2.9	10.3	8.05	207	15.9	0.2010		
25.5	27.5	34.6	2.0	7.1	5.55	142	16.0	0.2000		
24.8	26.1	30.5	1.3	4.4	3.5	87.8	16.8	0.1995		
24.9	25.6	28.1	0.7	2.5	1.95	49.8	16.0	0.1992		
V = 4.2 m/s										
24.8	27.1	37.5	2.3	10.4	7.5	214	12.2	0.2058		
24.9	26.4	33.4	1.5	7.0	5.0	143	11.9	0.2043		
24.8	25.8	30.3	1.0	4.5	3.25	91.7	12.4	0.2038		
24.8	25.4	27.9	0.6	2.5	1.85	50.9	13.4	0.2036		

Table 30: Thermal conductivity of the soil aggregates layer at $\phi 2 / 4 \text{ mm}$; $\rho = 1070 \text{ kg/m}^3$, $h_m = 0.02 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
23.6	34.1	47.8	10.5	13.7	17.35	134	88.9	0.1956
23.7	30.9	40.4	7.2	9.5	11.95	92.4	88.4	0.1945
24.0	28.3	34.0	4.3	5.7	7.15	55.3	88.3	0.1940
24.2	26.8	30.2	2.6	3.4	4.3	32.9	89.7	0.1935
$V = 1.0 \text{ m/s}$								
24.5	30.2	44.8	5.7	14.6	13.0	146	44.3	0.200
24.6	28.3	37.9	3.7	9.6	8.5	95.5	44.0	0.1990
24.8	27.2	33.4	2.4	6.2	5.5	61.5	44.3	0.1984
24.9	26.3	29.8	1.4	3.5	3.15	34.6	45.9	0.1977
$V = 2.0 \text{ m/s}$								
24.8	27.9	43.3	3.1	15.4	10.8	158	22.3	0.2052
24.6	26.7	37.0	2.1	10.3	7.23	105	22.7	0.2039
24.9	26.3	33.0	1.4	6.7	4.75	68.1	23.3	0.2033
24.4	25.2	28.9	0.8	3.7	2.65	37.6	24.1	0.2032

V = 3.0 m/s										
25.1	27.3	42.9	2.2	15.6	10.0	164	15.2	0.2103		
25.3	26.7	37.1	1.4	10.4	6.6	109	14.6	0.2096		
25.4	26.3	32.5	0.9	6.2	4.0	64.6	15.8	0.2084		
25.8	26.3	29.9	0.5	3.3	2.3	34.3	16.5	0.2079		
V = 4.2 m/s										
26.1	27.8	43.6	1.7	15.8	9.6	171	11.3	0.2165		
26.2	27.3	37.9	1.1	10.6	6.4	114	11.0	0.2150		
26.0	26.7	33.5	0.7	6.8	4.1	72.3	11.0	0.2126		
26.3	26.7	30.5	0.4	3.8	2.3	40.3	11.3	0.2121		

Table 31: Thermal conductivity of the soil aggregates layer at $\phi 2 / 4 \text{ mm}$; $\rho = 1070 \text{ kg/m}^3$, $h_m = 0.03 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a, \frac{\text{s}}{\text{m}}$	$\lambda_m, \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
25.6	34.3	51.0	8.7	16.7	17.05	115	85.9	0.2066
25.5	31.4	42.7	5.9	11.3	11.55	77.3	86.6	0.2052
25.4	29.1	36.3	3.7	7.2	7.3	49.1	85.5	0.2046
25.4	27.5	31.6	2.1	4.1	4.15	27.9	85.4	0.2041
$V = 1.0 \text{ m/s}$								
25.5	30.3	48.2	4.8	17.9	13.75	127	42.9	0.2128
25.7	28.9	40.9	3.2	12.0	9.2	84.4	43.0	0.2110
25.7	27.7	35.3	2.0	7.6	5.8	53.3	42.6	0.2104
25.6	26.8	31.3	1.2	4.3	3.35	30.1	45.2	0.2100
$V = 2.0 \text{ m/s}$								
25.5	28.1	47.1	2.6	19.0	12.1	139	21.2	0.2195
25.3	27.1	39.9	1.8	12.8	8.2	92.9	22.0	0.2177
25.2	26.3	34.5	1.1	8.2	5.2	59.2	21.1	0.2166
25.3	26.0	30.6	0.7	4.6	3.0	33.1	24.0	0.2159

V = 3.0 m/s										
25.0	26.9	46.3	1.9	19.4	11.6	146	14.8	0.2258		
25.2	26.4	39.4	1.2	13.0	7.7	96.5	14.1	0.2227		
25.2	26.3	34.6	0.8	8.3	4.95	61.5	14.8	0.2223		
25.3	25.8	30.4	0.5	4.6	2.8	34.0	16.7	0.2217		
V = 4.2 m/s										
25.8	27.2	46.7	1.4	19.5	11.2	153	10.5	0.2354		
25.6	26.5	39.7	0.9	13.2	7.5	102	10.0	0.2318		
25.6	26.2	34.6	0.6	8.4	4.8	64.8	10.5	0.2314		
25.5	25.9	30.6	0.4	4.7	2.75	36.1	12.6	0.2304		

Table 32: Thermal conductivity of the soil aggregates layer at $\phi 2 / 4$ mm; $\rho = 1070 \text{ kg/m}^3$, $h_m = 0.04 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	$r_a, \frac{s}{m}$	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
V = 0.5								
25.3	33.2	53.1	7.9	19.9	17.85	10.9	82.3	0.2191
25.4	30.7	44.1	5.3	13.4	12.0	72.8	82.6	0.2173
25.5	28.9	37.5	3.4	8.6	7.7	46.5	83.0	0.2163
25.4	27.3	32.1	1.9	4.8	4.3	25.9	83.3	0.2158
V = 1.0 m/s								
25.4	29.6	49.9	4.2	20.3	14.35	115	41.5	0.2266
25.5	28.3	42.0	2.8	13.7	9.65	76.7	41.4	0.2239
25.5	27.4	36.3	1.9	8.9	6.35	49.5	43.6	0.2225
25.5	26.6	31.6	1.1	5.0	3.6	27.7	45.1	0.2216
V = 2.0 m/s								
25.6	27.8	48.5	2.2	20.7	12.55	122	20.5	0.2357
25.6	27.1	41.1	1.5	14.0	8.5	81.4	20.9	0.2326
25.5	26.5	35.5	1.0	9.0	5.5	52.0	21.8	0.2311
25.5	26.1	31.2	0.6	5.1	3.15	29.3	23.2	0.2298

V = 3.0 m/s										
25.7	27.2	47.9	1.5	20.7	11.85	127	13.4	0.2454		
25.4	26.4	40.5	1.0	14.1	8.05	84.8	13.4	0.2406		
25.2	25.9	35.0	0.7	9.1	5.25	54.2	14.7	0.2382		
21.1	25.5	30.6	0.4	5.1	2.95	30.2	15.0	0.2369		
V = 4.2 m/s										
25.4	26.5	47.0	1.1	20.5	11.35	132	9.5	0.2576		
25.6	26.7	40.4	0.8	14.0	7.8	88.2	10.3	0.2520		
25.3	25.8	34.8	0.5	9.0	5.0	56.2	10.1	0.2498		
25.7	26.0	31.1	0.3	5.1	2.85	31.7	10.7	0.2486		

Table 33: Values $d\lambda/d(\Delta T_{ma})$ for dry aggregated soil with sizes of aggregates 2-4 mm and $7 < \Delta T_{ma} < 15^\circ\text{C}$.

V, m/s	h_m , cm		
	2	3	4
0.5	$2.04 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$
1.0	$2.2 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$	$5.75 \cdot 10^{-4}$
2.0	$3.7 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$
3.0	$2.1 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$12.6 \cdot 10^{-4}$
4.2	$4.7 \cdot 10^{-4}$	$9.7 \cdot 10^{-4}$	$15.8 \cdot 10^{-4}$

Diameter of aggregates 2-4 mm

The relationship between λ , h_m , V and ΔT_{ma} at $\rho_m = 1050 \text{ kg/m}^3$ is shown in Tables 34-37 and Figs. 43, 44. The value of λ_m changes from 0.19 to $0.313 \text{ W / m}^\circ\text{C}$ at accepted range of V; h_m ; ΔT_{ma} . The relationship $\lambda_m = f(V)$ is approximately linear for this diameter of aggregates (4-8 mm).

The graphic relationships between λ_m and ΔT_{ma} at different mulch thickness (1,2,3 and 4 cm) are shown in Figs. 45-48. The calculated parameters $d\lambda_m / d(\Delta T_{ma})$ (at range $7 < \Delta T_{ma} < 15^\circ\text{C}$) as a function of the mulch thickness (h_m) and wind speed (V) are presented in Table 38 and Fig. 49.

The graphic relationship $r_a = f(h_m; v)$ is presented in Fig. 50.

Table 34: Thermal conductivity of the soil aggregates layer at $\phi 4 / 8$ mm; $\rho = 1050 \text{ kg/m}^3$, $h_m = 0.01 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{\text{W}}{\text{m}^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
25.9	36.7	44.6	10.8	7.9	14.75	150	81.7	0.1899
26.0	33.2	38.5	7.2	5.3	9.85	99.6	82.0	0.1879
26.2	30.0	32.8	3.8	2.8	5.3	52.3	82.5	0.1868
26.3	28.5	30.1	2.2	1.6	3.1	29.8	83.8	0.1863
$V = 1.0 \text{ m/s}$								
26.9	33.2	42.1	6.3	8.9	10.75	173	41.3	0.1944
26.8	31.0	37.0	4.2	6.0	7.2	115	41.5	0.1917
26.8	29.5	33.3	2.7	3.8	4.6	72.5	42.3	0.1908
26.7	28.2	30.3	1.5	2.1	2.65	40.0	42.6	0.1905
$V = 2.0 \text{ m/s}$								
26.8	30.6	40.6	3.8	10.0	8.8	197	21.9	0.1970
26.7	29.3	36.1	2.6	6.8	6.0	132	22.4	0.1941
26.7	28.4	32.8	1.7	4.4	3.9	85.0	22.7	0.1932
26.7	27.7	30.2	1.0	2.5	2.25	48.2	23.5	0.1928

V = 3.0 m/s										
26.7	29.6	39.9	2.9	10.3	8.05	211	15.6	0.2049		
26.8	28.7	35.7	1.9	7.0	5.4	141	15.3	0.2014		
26.8	28.1	32.6	1.3	4.5	3.55	89.5	16.5	0.1989		
26.7	27.4	29.9	0.7	2.5	1.95	49.6	16.0	0.1984		
V = 4.2 m/s										
26.8	29.1	39.3	2.3	10.2	7.4	214	12.2	0.2098		
26.9	28.4	35.4	1.5	7.0	5.0	143	11.9	0.2043		
26.8	27.8	32.4	1.0	4.6	3.3	92.4	12.3	0.2009		
26.7	27.3	29.9	0.6	2.6	1.9	52.0	13.1	0.2000		

Table 35: Thermal conductivity of the soil aggregates layer at $\phi 4 / 8 \text{ mm}$; $\rho = 1050 \text{ kg/m}^3$, $h_m = 0.02 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
25.4	34.4	47.6	9.0	13.2	15.6	137	74.6	0.2080
25.6	31.7	40.6	6.1	8.9	10.55	91.3	75.8	0.2052
25.6	29.5	35.2	3.9	5.7	6.75	58.2	76.1	0.2042
25.8	28.0	31.2	2.2	3.2	3.8	32.5	76.8	0.2031
$V = 1.0 \text{ m/s}$								
27.0	32.1	46.3	5.1	14.2	12.2	151	38.3	0.2127
26.9	30.3	39.8	3.4	9.5	8.15	100	38.6	0.2105
26.8	29.0	35.1	2.2	6.1	5.25	63.9	39.1	0.2095
26.7	28.0	31.4	1.3	3.4	3.0	35.5	41.6	0.2088
$V = 2.0 \text{ m/s}$								
26.8	29.8	45.2	3.0	15.4	10.7	170	20.0	0.2280
26.8	28.8	39.2	2.0	10.4	7.2	113	20.1	0.2173
26.9	28.2	34.9	1.3	6.7	4.65	72.3	20.4	0.2158
26.9	27.7	31.5	0.8	3.8	2.7	40.9	22.2	0.2153

V = 3.0 m/s									
26.9	29.2	44.9	2.3	15.7	10.15	180	14.5	0.2293	
26.8	28.3	39.0	1.5	10.7	6.85	120	14.2	0.2243	
26.7	27.7	34.6	1.0	6.9	4.45	76.8	14.8	0.2226	
26.8	27.4	31.3	0.6	3.9	2.55	43.2	15.8	0.2215	
V = 4.2 m/s									
27.0	28.8	44.2	1.8	15.4	9.5	184	11.1	0.2390	
26.9	28.1	38.7	1.2	10.6	6.5	123	11.1	0.2321	
26.8	27.6	34.4	0.8	6.8	4.2	78.2	11.6	0.2300	
26.9	27.4	31.2	0.5	3.8	2.4	43.5	13.0	0.2289	

Table 36: Thermal conductivity of the soil aggregates layer at $\phi 4 / 8$ mm; $\rho = 1050 \text{ kg/m}^3$, $h_m = 0.03 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	$r_a \text{ s/m}$	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
V = 0.5 m/s								
25.8	33.6	50.2	7.8	16.6	16.1	130	68.1	0.2349
25.9	31.2	42.4	5.3	11.2	10.9	86.4	69.6	0.2314
26.1	29.5	36.7	3.4	7.2	7.0	55.1	70.0	0.2296
26.4	28.4	32.5	2.0	4.1	4.05	31.2	72.8	0.2283
V = 1.0 m/s								
27.2	31.5	48.4	4.3	16.9	12.75	138	35.8	0.2450
26.8	28.8	36.2	1.9	7.4	5.6	58.9	36.6	0.2388
26.9	28.8	36.2	1.9	7.4	5.6	58.9	36.6	0.2388
27.0	28.1	32.3	1.1	4.2	3.2	33.3	37.5	0.2379
V = 2.0 m/s								
27.0	29.4	47.2	2.4	17.8	11.3	151	18.0	0.2545
26.9	28.5	40.6	1.6	12.1	7.65	101	18.0	0.2504
26.8	27.9	35.7	1.1	7.8	5.0	64.5	19.4	0.2481
26.9	27.5	31.9	0.6	4.4	2.8	36.2	18.8	0.2468

V = 3.0 m/s										
26.9	28.8	46.9	1.9	18.1	10.95	159	13.6	0.2635		
27.0	28.3	40.0	1.3	12.1	7.35	104	14.2	0.2579		
27.0	27.8	35.6	0.8	7.8	4.7	66.2	13.7	0.2546		
26.8	27.3	31.7	0.5	4.4	2.7	37.1	15.3	0.2530		
V = 4.2 m/s										
27.0	28.5	46.7	1.5	18.2	10.6	166	10.3	0.2736		
27.0	28.0	40.4	1.0	12.4	7.2	110	10.3	0.2662		
26.9	27.6	35.7	0.7	8.1	4.75	70.6	11.3	0.2615		
26.9	27.3	31.9	0.4	4.6	2.7	39.9	11.4	0.2602		

Table 37: Thermal conductivity of the soil aggregates layer at $\phi 4 / 8 \text{ mm}$; $\rho = 1050 \text{ kg/m}^3$, $h_m = 0.04 \text{ m}$.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	r_a, m	$\lambda_m, \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5 \text{ m/s}$								
26.3	32.8	51.1	6.5	18.3	15.65	120	61.5	0.2623
26.5	31.0	43.4	4.5	12.4	10.7	79.8	64.0	0.2574
26.7	29.7	37.7	3.0	8.0	7.0	51.0	66.8	0.2550
26.8	28.5	33.0	1.7	4.5	3.95	28.6	67.5	0.2542
$V = 1.0 \text{ m/s}$								
27.1	30.8	50.1	3.7	19.3	13.35	132	31.8	0.2736
27.0	29.5	42.7	2.5	13.2	9.1	88.2	32.2	0.2673
27.0	28.7	37.2	1.7	8.5	5.95	56.3	34.3	0.2649
26.9	27.9	32.7	1.0	4.8	3.4	31.6	35.9	0.2633
$V = 2.0 \text{ m/s}$								
26.7	28.8	48.6	2.1	19.8	12.0	142	16.8	0.2869
26.6	28.1	41.6	1.5	13.5	8.25	94.5	18.0	0.2800
26.5	27.5	36.2	1.0	8.7	5.35	60.3	18.8	0.2772
26.4	27.0	31.9	0.6	4.9	3.05	33.8	20.1	0.2759

V = 3.0 m/s										
26.4	28.1	48.0	1.7	19.9	11.65	148	13.0	0.2975		
26.5	27.7	41.4	1.2	13.7	8.05	98.6	13.8	0.2879		
26.5	27.3	36.2	0.7	8.9	5.25	63.3	14.3	0.2845		
26.4	26.9	31.9	0.5	5.0	3.0	35.3	16.1	0.2824		
V = 4.2 m/s										
26.4	27.7	47.4	1.3	19.7	11.15	154	9.6	0.3127		
26.5	27.4	41.1	0.9	13.7	7.75	103	9.9	0.3007		
26.5	27.1	36.0	0.6	8.9	5.05	66.0	10.3	0.2966		
26.6	27.0	32.0	0.4	5.0	2.9	36.8	12.3	0.2944		

Table 38: Values $d\lambda/d(\Delta T_{ma})$ for dry aggregated soil with sizes of aggregates 4-8 mm and $7 < \Delta T_{ma} < 15^\circ\text{C}$.

V, m/s	h_m , cm			
	1	2	3	4
0.5	$4.1 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	$6.7 \cdot 10^{-4}$	$10.9 \cdot 10^{-4}$
1.0	$7.6 \cdot 10^{-4}$	$5.4 \cdot 10^{-4}$	$8.2 \cdot 10^{-4}$	$14.8 \cdot 10^{-4}$
2.0	$10.4 \cdot 10^{-4}$	$10 \cdot 10^{-4}$	$11.2 \cdot 10^{-4}$	$18.4 \cdot 10^{-4}$
3.0	$13.2 \cdot 10^{-4}$	$15.2 \cdot 10^{-4}$	$15.6 \cdot 10^{-4}$	$26.7 \cdot 10^{-4}$
4.2	$22.9 \cdot 10^{-4}$	$23 \cdot 10^{-4}$	$21.8 \cdot 10^{-4}$	$35.3 \cdot 10^{-4}$

Diameter of aggregates 8-11.2 mm

The relationship between λ , h_m , V and ΔT_{ma} at $\rho_m = 1070 \text{ kg/m}^3$ is shown in Tables 39-41 and Figs. 51 and 52. The value of λ_m changes from 0.19 to $0.258 \text{ W / m}^\circ\text{C}$ at accepted range of V; h_m ; ΔT_{ma} . The relationship $\lambda_m = f(V)$ is not linear for this diameter of aggregates (8-11.2 mm) in all ranges of wind speed (0.5-4.2 m/s).

The relationships between λ_m and ΔT_{ma} at different dry soil aggregate layers (2,3 and 4 cm) are shown in Figs. 53-55. The calculated parameters $d\lambda_m / d(\Delta T_{ma})$ as a function of the dry aggregated soil thickness (h_m) and wind speed (V) are presented in Table 42 and Fig. 56.

The graphic relationship $r_a = f(h_m, v)$ at $\Delta V = 30.6$ is presented in Fig. 57.

Table 39: Thermal conductivity of the soil aggregates layer at $\phi 8 / 11.2$ mm; $\rho = 990$ kg/m³, $h_m = 0.02$ m.

T_1 , °C	T_2 , °C	T_3 , °C	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	r_a s/m	$\lambda_m, \frac{W}{m \cdot ^\circ C}$
V = 0.5 m/s								
25.1	34.6	48.7	9.5	14.1	16.65	163	66.2	0.2312
25.3	31.5	40.8	6.2	9.3	10.88	105	67.0	0.2258
25.7	29.9	36.1	4.2	6.2	7.3	69.2	68.9	0.2232
25.9	28.3	31.8	2.4	3.5	4.15	38.8	70.2	0.2217
V = 1.0 m/s								
26.6	31.8	45.3	5.2	13.5	11.95	171	34.5	0.2533
26.6	30.1	39.1	3.5	9.0	8.0	111	35.8	0.2467
26.5	28.9	34.9	2.4	6.0	5.4	73.0	37.3	0.2433
26.7	28.1	31.5	1.4	3.4	3.1	41.0	38.8	0.2412
V = 2.0 m/s								
26.7	29.8	43.5	3.1	13.7	9.95	190	18.5	0.2774
26.6	28.7	38.1	2.1	9.4	6.8	127	18.8	0.2702
26.5	27.9	34.0	1.4	6.1	4.45	81.1	19.6	0.2659
26.5	27.3	30.8	0.8	3.5	2.55	46.1	19.7	0.2634

V = 3.0 m/s										
26.4	28.7	41.9	2.3	13.2	8.9	198	13.2		0.3000	
26.6	28.2	37.2	1.6	9.0	6.1	131	13.9		0.2911	
26.6	27.7	33.6	1.1	5.9	4.05	84.7	14.7		0.2871	
26.3	26.9	30.2	0.6	3.3	2.25	47.0	14.5		0.2848	
V = 4.2 m/s										
25.8	27.6	40.5	1.8	12.9	8.25	207	9.8		0.3209	
26.0	27.2	36.1	1.2	8.9	5.65	138	9.9		0.3101	
26.3	27.1	32.9	0.8	5.8	3.7	88.3	10.3		0.3045	
26.2	26.7	30.0	0.5	3.3	2.15	49.7	11.4		0.3012	

Table 40: Thermal conductivity of the soil aggregates layer at $\phi 8 / 11.2$ mm; $\rho = 990$ kg/m³, $h_m = 0.03$ m.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{\text{W}}{\text{m}^2}$	$r_a, \text{s/m}$	$\lambda_m, \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$
$V = 0.5$ m/s								
26.4	23.0	48.0	6.6	15.0	14.1	130	57.6	0.2600
26.5	31.0	41.3	4.5	10.3	9.65	86.7	58.9	0.2525
26.6	29.6	36.3	3.0	6.7	6.35	55.6	61.2	0.2490
26.8	28.6	32.4	1.8	3.8	3.7	31.3	65.3	0.2471
$V = 1.0$ m/s								
26.9	30.6	45.8	3.7	15.2	11.3	143	29.4	0.2822
26.8	29.4	39.8	2.6	10.4	7.8	94.9	31.1	0.2737
26.9	28.7	35.5	1.8	6.8	5.2	61.1	33.4	0.2696
26.8	27.8	31.7	1.0	3.9	2.95	34.7	36.0	0.2669
$V = 2.0$ m/s								
26.9	29.0	44.0	2.1	15.0	9.6	153	15.6	0.3060
26.7	28.2	38.3	1.5	10.1	6.55	99.7	17.1	0.2961
26.8	27.8	34.5	1.0	6.7	4.35	65.0	17.5	0.2910
26.8	27.4	31.2	0.6	3.8	2.5	36.5	18.7	0.2881

V = 3.0 m/s										
26.8	28.3	43.1	1.5	14.8	8.9	161	10.6	0.3264		
26.7	27.8	38.2	1.1	10.4	6.3	109	11.4	0.3144		
26.7	27.4	34.1	0.70	6.7	4.05	68.9	11.5	0.3080		
26.8	27.2	31.0	0.4	3.8	2.3	38.6	11.8	0.3047		
V = 4.2 m/s										
26.7	27.9	42.4	1.2	14.5	8.48	168	8.1	0.3476		
26.9	27.7	37.8	0.8	10.1	5.85	112	8.1	0.3327		
27.1	27.2	34.3	0.6	6.6	3.9	71.5	9.5	0.3250		
27.4	27.7	31.5	0.3	3.8	2.2	40.7	8.4	0.3213		

Table 41: Thermal conductivity of the soil aggregates layer at $\phi 8 / 11.2$ mm; $\rho = 990$ kg/m³, $h_m = 0.04$ m.

$T_1, ^\circ\text{C}$	$T_2, ^\circ\text{C}$	$T_3, ^\circ\text{C}$	$T_2 - T_1$	$T_3 - T_2$	$\frac{T_2 + T_3 - T_1}{2}$	$q, \frac{W}{m^2}$	r_a s/m	$\lambda_m, \frac{W}{m \cdot ^\circ\text{C}}$
$V = 0.5$ m/s								
27.5	33.0	50.7	5.5	17.7	14.35	125	49.9	0.2825
27.5	31.5	43.7	4.0	12.2	10.1	83.4	54.4	0.2734
27.6	30.2	38.1	2.6	7.9	6.55	53.1	55.6	0.2689
27.6	29.1	33.6	1.5	4.5	3.75	30.0	56.8	0.2667
$V = 1.0$ m/s								
27.7	30.8	48.6	3.1	17.8	12.0	135	26.1	0.3034
27.5	29.8	42.0	2.3	12.2	8.4	89.7	29.1	0.2941
27.6	29.2	37.2	1.6	8.0	5.6	57.7	29.5	0.2885
27.5	28.4	32.9	0.9	4.5	3.15	32.1	31.8	0.8253
$V = 2.0$ m/s								
27.6	29.4	47.0	1.8	17.6	10.6	144	14.2	0.3273
27.3	28.6	40.8	1.3	12.2	7.4	96.2	15.3	0.3154
27.1	28.0	35.9	0.9	7.9	4.85	61.1	16.7	0.3094
26.8	27.3	31.8	0.5	4.5	2.75	34.4	16.5	0.3058

V = 3.0 m/s										
26.8	28.1	45.3	1.3	17.2	9.9	149	9.9	0.3465		
26.7	27.6	39.5	0.9	11.9	6.85	98.9	10.3	0.3324		
25.6	27.1	34.9	0.6	7.8	4.5	63.5	10.7	0.3256		
26.5	26.9	31.3	0.4	4.4	2.6	35.4	12.8	0.3218		
V = 4.2 m/s										
26.4	27.5	44.8	1.1	17.3	9.75	158	7.9	0.3653		
26.5	27.3	39.4	0.8	12.1	6.85	105	8.6	0.3471		
26.6	27.1	35.1	0.5	8.0	4.5	67.6	8.4	0.3380		
26.7	27.0	31.5	0.3	4.5	2.55	37.5	9.1	0.3333		

Table 42: Values $d\lambda/d(\Delta T_{ma})$ for dry aggregated soil with sizes of aggregates 8-11.2 mm and $7 < \Delta T_{ma} < 17^\circ\text{C}$.

V, m/s	h_m , cm		
	2	3	4
0.5	$9.5 \cdot 10^{-4}$	$16.9 \cdot 10^{-4}$	$21.4 \cdot 10^{-4}$
1.0	$16.7 \cdot 10^{-4}$	$24.3 \cdot 10^{-4}$	$25.8 \cdot 10^{-4}$
2.0	$22.9 \cdot 10^{-4}$	$32.5 \cdot 10^{-4}$	$27.2 \cdot 10^{-4}$
3.0	$31.8 \cdot 10^{-4}$	$46.2 \cdot 10^{-4}$	$46.2 \cdot 10^{-4}$
4.2	$41.5 \cdot 10^{-4}$	$57.3 \cdot 10^{-4}$	$62.8 \cdot 10^{-4}$

Now we can obtain graphic dependence effective thermal conductivity of the dry aggregated soil on (i) mean diameter of aggregates (ϕ) in form $\lambda_m = f(\phi; V)$ and (ii) differences of temperatures $\Delta T_{ma} = T_m - T_{air}$ in form $d\lambda_m / d(\lambda T_{ma}) = f(\phi)$.

The relationships $\lambda_m = f(\phi, V)$ are obtained on the basis of Tables 25-27; 29-32; 34-37; 39-41 and presented in Fig. 58-60. One can see that thermal (λ_m) increases when mean diameter of aggregates (ϕ) increases under conditions of the open system where heat transport through porous material is governed by forced convection, free thermal convection and molecular diffusion. But such augmentation of λ_m decreases with mulch thickness h_m . Let us introduce the following designation: $\Delta\lambda_m$ is augmentation of λ_m when mean diameter of aggregates (ϕ) changes from 4-8 mm to 8-11.2 mm. Values of $\Delta\lambda_m$ were calculated on the basis of Figs. 58-60 and presented in Table 43 and Fig. 61.

Table 43: Values of $\Delta\lambda_m \cdot 10^2$ (W / m.°C) when mean diameter of aggregates change from 4-8 mm to 8-11.2 mm.

V, m/s	h_m , cm		
	2	3	4
0.5	2.35	2.45	2.0
1.0	4.1	3.7	3.0
2.0	5.7	4.6	4.0
3.0	7.1	6.3	4.9
4.2	8.2	7.4	5.3

One can see from Fig. 61 that $\Delta\lambda_m$ decreases with mulch thickness (h_m) at the range $h_m < 4$ cm. The fact is that air penetration into porous material under influence of forced convection is limited, therefore at comparatively great mulch thickness its thermal conductivity (when wind speed is constant) depends only on free thermal convection - parameters ΔT_{ma} , h_m and coefficient of mulch permeability. In principle, we have to express mulch thermal conductivity as a function of filtration coefficient air through aggregated soil. But, unfortunately, we don't know dependence of mulch filtration coefficient as a function of mean diameter of soil aggregates.

The graphic relationships $d\lambda_m / d(\Delta T_{ma}) = f(\phi; V)$ at different mulch thickness (h_m) are obtained on the basis of Tables 28, 33, 38, 42 and presented in Fig. 62-64. One can see that influence ΔT_{me} on λ_m increases when diameter of soil aggregates increase. It may be accounted for by influence of permeability of aggregated soil on free thermal convection.

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$$T_1 = T_2$$

A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

much

A 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

B 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

Schedule of the closed system

Fig 18

Fig. 20 Scheme of the open system

5-11-58
X-10

- 1- Glat soil (control < 1 in.)
- 2- Bet. shear soil (control < 0.25 in.)

Mean aggregate diameter ϕ , mm

control	0.25-0.25	0.25-0.25	0.25-0.25
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Fig. 2. The effect of aggregate size on the rate of erosion of aggregate size (cm/s) (H. H. G. S. 1977)

Fig 22

The scheme of the laboratory experiment
(heat transfer through mulch)

Fig. 33 Relationship between y and x at 100°C , $10 \leq T_{\text{max}} \leq 20^\circ\text{C}$

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	2096	2097	2098	2099	2100
1990	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100

for 42 Polystyrene $L_a = f(V, h_{max})$

$\phi = 2-4 \mu m$ $0.2-10 \mu m$ $1 \mu m$ $h_{max} = 50.6 \mu m$

Fig. 4.3 Relationship $\lambda_m = f(T, D)$ at $D = 10$ mm, 5 mm, 2 mm, 1 mm, 0.5 mm

Fig. 117

Результаты

испытания

сварочных

швов

сварочных

швов

сварочных

швов

сварочных

швов

Fig. 50. Relationship $p = f(Ca, V)$

$p_1 = 8.22, p_2 = 10.50, V_1 = 30.69$

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Fig. 57. Rotations $\chi_1 = A(\chi_2, \chi_3)$ at $\chi_2 = 0.018$, $\chi_3 = 0.018$, $\chi_1 = 0.018$

Fig. 52. Relationship between λ_m and λ at $\lambda = 0.01, 0.02, 0.03$. $V = 0.01, 0.02, 0.03$.

Fig 5f Relationship $V_a(f, V)$ at

$\phi = 8.112 \text{ mm}$, $\rho = 990 \frac{\text{g}}{\text{cm}^3}$, $\pi V = 30.16 \text{ v}$
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CHEMICAL EFFECTS ON EVAPORATION FROM THE SOIL

G. Feldman and R. Keren

The study consisted of an evaluation of salinity effects on the evaporation from the soil surface, and on possible chemical treatments to control evaporation.

The effect of exchangeable sodium percentage (ESP) and salt concentration on evaporation from two sandy loam soils (hamra and loess) was studied under laboratory conditions using the wind tunnel. Air dry aggregates < 2 mm, were packed in cylinders of 50 mm in diameter and 170 mm long at a given bulk density. Solutions with appropriate sodium adsorption ratios (SAR) at total concentrations of 50 me L^{-1} (NaCl and CaCl_2) and distilled water were prepared. Soil columns were initially wetted slowly from the top (using the 50 me L^{-1} solution at the appropriate SAR or distilled water) until reaching a saturation level. The wetted soils were placed in the wind tunnel and exposed to wind velocity of 1.9 m s^{-1} . The air temperature and the relative humidity were 22°C and 56%, respectively.

The water evaporation rate for the hamra soil at ESP 1.3 was relatively constant (around 1.2 mm h^{-1}) during the first 14 hours, regardless of the electrolyte concentration of the soil solution. The effect of electrolyte concentration on water evaporation was more pronounced for the soil with the higher ESP level. Whereas the water evaporation was relatively high and constant for the 50 me L^{-1} solution, a sharp drop was observed for distilled water. This sharp drop began after 3 hours from the beginning of evaporation. This significant

Figure 1. Effect of salinity on evaporation from soil column heated by lamp, wind speed 1.9 m s^{-1} , air temperature 22°C , relative humidity 56%.

effect was probably due to the hydraulic conductivity reduction of the soil at high ESP and low electrolyte concentration. A similar effect was observed for the loess soil for high electrolyte concentration with the exception that the evaporation rate dropped with time at much higher rate. The electrolyte concentration in the extract solution (soil to water ratio of 1) in the end of the evaporation process was extremely high at the soil surface. These results may indicate that significant fraction of the soil solution moved upward as a liquid and the conductivity of the loess soil to water (liquid and vapors) is lower than that of the hamra soil under similar conditions.

We investigated the possible effect of PMA (poly maleic acid) on the evaporation and moisture distribution in the soil. The experiments were carried out on a loess soil Bet Kama with E.S.P. = 3, sieved to aggregate size < 2 mm. The following treatments were made:

1. Control, soil only

Figure 2. Residual soil moisture content profile following 18 hours of evaporation of a soil column topped with a 20 mm layer of aggregates 2 to 4 mm in diameter.

Figure 3. Residual moisture content profile following 50 hours of evaporation of a soil column topped with a 40 mm layer of aggregates 2 to 4 mm in diameter.

2. Soil topped with a 20 mm layer of untreated aggregates, 2 - 4 mm diameter
3. Soil topped with a 20 mm layer of PMA (poly maleic acid, technical grade, 30% concentration) treated aggregates, 2 - 4 mm diameter

PMA treatment: mechanical mixing of 1 volume of 30% PMA solution with 2 volume of aggregated soil.

Soil wetting: drip wetted from top until saturation, sealed and left to drain.

Evaporation: in the laboratory, temperature 23 °C, fan producing wind speed of 1.9 m s⁻¹, 1000 W electric radiator coil 0.4 m above the soil.

The same experiment was repeated with a 40 mm layer aggregated soil.

Results:

Table 1. Effect of aggregated top layer and PMA treatment on the evaporation from a bare soil.

Treatment	20 mm layer, after 18 hours, g	40 mm layer, after 50 hours, g
Control	39.5	68.3
Aggregates only	30.1	54.9
PMA treated aggregates	25.6	33.

The results show that the aggregate layer loses the water it holds, but that the resulting dry layer acts as an effective barrier to further moisture loss. The PMA treatment improves significantly the water conservation effect of the aggregate layer. Comparison of Figure 1 and 2 shows that the short term effect of the treatment is to lower the rate of evaporation in the top layer of the soil, but the more significant water conservation effects are in the deeper layers of the soil.

EVALUATION OF THE RESEARCH ACHIEVEMENTS

The field studies of the crop residue mulches provided data on the changes in the energy balance and the aerodynamic structure of the atmospheric surface layer. Climate chamber experiments simulating natural field conditions showed that residues could reduce substantially water vapor flow through the soil surface. These results show that tillage operations that maintain a residue cover on the ground conserve soil water. Reduced soil heat flux observed in the climate chamber is a factor that may delay soil warming in the spring, yet this possible negative effect may not be significant in field conditions. The dependence of water vapor transport resistance and thermal insulation properties found in the wind tunnel studies explains many discrepancies found in the literature about mulch effects. The data provide a good dataset for evaluating the efficacy of mulches. The study also establishes that chemical treatment of the soil surface will conserve soil moisture.

DESCRIPTION OF COOPERATION

The importance of tillage operations in the management of corn production in Iowa influenced the research program by emphasizing the study of residues in both countries. In Israel the study considered wheat straw. After establishing that the properties of the wheat and corn residues were similar, it was possible to divide the effort between the two research teams. The US team conducted the field studies of the aerodynamic and radiative transport in and above the mulch. The Israeli research concentrated on wind tunnel characterization of the mulches. The wind tunnel constructed for the project served to characterization of aggregate layers. This study had more relevance to Israeli conditions, because of the possible evaporation reduction with stabilized aggregates in bare cultivated soils both in dryland and irrigated farming. Cooperation involved multiple exchange of research results and two exchanges visits of the principal investigators.

CONCLUSION

We obtained numerical values of r_m and λ_m in comparatively wide range of different parameters - wind speed; mulch thickness; difference temperatures between mulch and ambient air; materials (straw mulch and dry aggregated soil); mulch properties (bulk density, sizes of aggregates) and studied the effect of chemical treatment of aggregates on evaporation. These results of our laboratory experiments will be useful to simulate the processes of water and heat exchange between soils and atmosphere for reducing evaporation from cultivated soils by mulching. In combination with the field studies showing a reduction of the net radiation and a lowering of the water vapor flux, the research shows that soil water conservation depends on the properties of the mulch and the climate. Loosely packed mulches allow convective transport. They provide effective protection only when the wind speed is low. With dense and thick mulches transport is insensitive to wind regime, and evaporation reduction is more effective.

LIST OF PUBLICATIONS

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