NOTATION

y, variable concentration of the material retained by the membrane; y_0, initial concentration of the retained material; D, diffusion coefficient of the retained material; β, mass extraction coefficient; x, coordinate; τ, time; R, boundary layer thickness; k, filtration coefficient through the membrane for the retained material; P, pressure; δ, membrane thickness; f and g, coefficients; c, variable permeate concentration; c_0, initial permeate concentration; D_p, β_p, and k_p, corresponding coefficients of diffusion, mass extraction, and filtration for the permeate; a and b, coefficients; n, index number of points on parabola.

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THERMOPHYSICAL PROPERTIES OF GRANULAR—FIBROUS MATERIAL ON THE TEMPERATURE INTERVAL FROM 175 TO 450 K

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The effective thermal conductivity, specific heat and thermal diffusivity of cottonseed on the temperature interval 175-450 K are calculated for fibrosities and moisture contents varying from 0 to 35%.

The use of both fluidization and hydrodynamically active high-temperature jets for drying granular—fibrous materials requires the determination of the thermophysical properties of the material being dried over a broad range of temperatures [1]. The thermal conductivities, thermal diffusivities and specific heats of granular—fibrous materials have not been sufficiently studied [2, 3]. To a large extent, this is due to the complex multilayer structure of such materials, in particular cottonseed which consists of kernel, cortex and cotton fiber. The few published data mainly relate to the thermophysical properties of bulk cottonseed [2, 3] over a narrow temperature range T = 294-359 K [3]. At the same time, the geometric dimensions and thermophysical properties of the layers differ sharply [4, 5], and between the cortex and the kernel there is a layer of air $(0.05\text{-}0.2)\cdot 10^{-3}$ m thick [6].

A feature of cottonseed is the fibrosity of the outer envelope, which varies from 0 to 35%, commercial seed processed in the oil-extracting industry having a fibrosity of between 4 and 12%. Therefore there is much interest in determining the thermophysical properties of cottonseed with different degrees of fibrosity.

Below, we consider a method of calculating the effective thermal conductivity λ_{eff}, specific heat c_{eff} and thermal diffusivity a_{eff} of granular—fibrous material based on the experimental determination of the thermal conductivities and specific heats c of each of the layers, with reference to cottonseed having various fibrosities, moisture contents and temperatures.

The thermal conductivities and specific heats of the kernel and cortex of the cottonseed were determined on standard IT-λ-400 and IT-s-400 instruments at moisture contents U = 0.2-35% and temperatures T = 175-450 K [4, 5].

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Specific Heat

The specific heat is known to be a mass characteristic and in accordance with the first law of thermodynamics can be determined as the fractional sum of the specific heats of the components [7]:

$$c_{\mathrm{ef}} = c_1 m_1 + c_2 m_2 + c_3 m_3 + c_4 m_4. \tag{1}$$

Since the product of the mass fraction m_4 and the specific heat of the air layer c_4 is small, it can be neglected. Then the specific heat of cottonseed can be calculated from the formula

$$c_{\mathrm{ef}} = c_1 m_1 + c_2 m_2 + c_3 m_3. \tag{2}$$

The authors' experimental values of the specific heat of the cortex and kernel of cottonseed and their generalizing relations for calculating c_2 and c_3 on the temperature range 175-450 K and the moisture content range 0.2-35% are presented in [8, 9]. At all moisture contents a monotonic increase in the specific heats of the two materials is observed; however, in the region of 273 and 373 K there is a sharp increase in c_2 and c_3 (except for U = 0.2%). It should be noted that the jump Δc in the region of T = 373 K is greater than that near T = 273 K.

Our experimental data coincide to within ±5.6% with the values of c_2 and c_3 found by calculation from the expression

$$c = c_{\mathrm{ads}} m_{\mathrm{ads}} + c_{\mathrm{w}} m_{\mathrm{w}} \tag{3}$$

The specific heat of cotton fiber can be found from the formula given in [10]. Then, using the generalizing relations for c_2 and c_3 [8, 9] we obtain an expression for calculating the effective specific heat of multilayer cottonseed in the form:

$$c_{\mathrm{ef}} = m_1 \left[c_{\mathrm{ads}} \left(1 - \frac{U}{100} \right) + \frac{c_{\mathrm{w}} U}{100} \right] + m_2 \left[60 + 4 (T - 50) \exp \cdot 0{,}028 U \right] + \\ + m_3 \left[540 + (3{,}56\, U^{0,83} + 0{,}73)(T - 110{,}5) \right]. \tag{4}$$

From Table 1 it follows that with increase in temperature c_{eff} increase considerably (by up to four times), while with increase in fibrosity it decreases. Only at low temperatures (T < 200 K), starting from a fibrosity $0_f > 5\%$, is a certain increase observed.

A comparison of the values of c_{eff} calculated from (4) and the data calculated from (2) using (3) reveals agreement to within ±12% on the intervals U = 0.2-35%, 0_f = 0-35%, and T = 175-450 K.

Thermal Conductivity

As the experiments have shown, the existing models [11, 12] are unsuitable for determining the effective thermal conductivity of cottonseed because of the varying structure of its components. Thus, for example, the kernel is a capillary-porous colloidal body, the cortex a capillary-porous body, and the envelope has a fibrous structure.

In accordance with the model of alternating layers of solid skeleton and fluid-filled voids [11], the calculated thermal conductivities have a maximum and a minimum, since the formulas describe the extreme case of pore distribution in the material.

There is also the model of a capillary-porous body consisting of stacks of spherical particles. However, the relation proposed in [12] describes only homogeneous porous materials.

In industrial processes, cottonseed is dried at various temperatures and moisture contents, and accordingly the thermal conductivity of the material may vary over a wide range [13]. In carrying out engineering calculations it is convenient to have a formula for determining the thermal conductivity as a function of temperature and moisture content, but, considering the fibrosity of the outer envelope, it is also important to know the effect of that characteristic of cottonseed as well.

On the basis of experiments it has been established that at the center of the seed there is an embryo 0.1-0.15 mm in diameter [14]; therefore in solving the heat conduction equation for cottonseed it is possible to treat it as a system of hollow spheres. Then the effective thermal conductivity of cottonseed, as a body of irregular shape, can be determined from the equation $\lambda_{\mathrm{eff}} = f\lambda_{\mathrm{eff}1}$.

TABLE 1. Effective Specific Heat of Cottonseed c_{eff}, J/(kg·K), on the Temperature Interval 175-450 K and the Fibrosity Interval 0-35% at a Moisture Content of 21.8%

T, K	O_f							
	0	5	10	15	20	25	30	35
175	1067	1028	900	919	941	962	984	1003
200	1299	1212	1202	1191	1181	1170	1161	1150
250	1610	1584	1550	1521	1492	1461	1440	1402
275	1980	1947	1895	1855	1820	1782	1750	1709
300	1998	1949	1900	1848	1802	1749	1703	1655
350	2385	2317	2250	2180	2111	2044	1975	1906
375	3142	3062	2985	2905	2826	2752	2668	2588
400	2773	2685	2597	2510	2420	2340	2240	2156
450	3161	3053	2946	2840	2732	2625	2520	2410

TABLE 2. Effective Thermal Conductivity of Cottonseed λ_{eff}, W/(m·K), on the Temperature Interval 175-450 K and the Fibrosity Interval 0-35% at a Moisture Content of 21.8%

T, K	O_f							
	0	5	10	15	20	25	30	35
175	0,371	0,361	0,356	0,344	0,336	0,327	0,318	0,309
200	0,377	0,367	0,362	0,350	0,342	0,333	0,323	0,314
250	0,395	0,384	0,379	0,367	0,358	0,348	0,339	0,329
275	0,275	0,267	0,264	0,255	0,249	0,242	0,236	0,229
300	0,295	0,287	0,283	0,274	0,268	0,260	0,253	0,246
350	0,318	0,309	0,305	0,294	0,288	0,280	0,272	0,264
375	0,347	0,337	0,333	0,322	0,314	0,306	0,297	0,289
400	0,287	0,279	0,275	0,266	0,260	0,253	0,246	0,239
450	0,257	0,250	0,247	0,239	0,233	0,227	0,221	0,214

The shape factor f is variously estimated by different investigators [7, 15], but is best determined from the expression $f = 1/\varphi$. Experiments have shown that the cottonseed shape factor depends on the fibrosity and varies over the interval f = 0.89-0.93.

In view of the fact that in the present case the temperature varies only in the direction of the radius of the sphere, we assume that the heat transfer process is steady, i.e., the same amount of heat passes through all the layers: $Q_1 = Q_2 = Q_3 = Q_4 = Q$. Then, in accordance with Fourier's law, after simple manipulation [11], we obtain an expression for calculating the effective thermal conductivity of a body of irregular shape in the form:

$$\lambda_{ef} = \left\{f\left(\frac{1}{r_1} - \frac{1}{r_5}\right)\right\}\left\{\frac{1}{\lambda_1}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) + \frac{1}{\lambda_2}\left(\frac{1}{r_2} - \frac{1}{r_3}\right) + \frac{1}{\lambda_3}\left(\frac{1}{r_3} - \frac{1}{r_4}\right) + \frac{1}{\lambda_4}\left(\frac{1}{r_4} - \frac{1}{r_5}\right)\right\}^{-1}. \quad (5)$$

In calculating the effective thermal conductivity of cottonseed we used empirical values of the thermal conductivities of the cortex λ_2 and the kernel λ_3, which we obtained on the moisture content and fibrosity intervals U = 0.2-35% and O_f = 0-345% [9], the values of the thermal conductivities of cotton fiber λ_1 and air λ_4 being taken from [10, 16].

Calculating the effective thermal conductivity of cottonseed from (5) revealed anomalies on the curves in the region of 273 and 373 K, which on the temperature interval T = 175-450 K form three zones of variation of λ_{eff}. In the first (T < 273 K) and second (T < 373 K) zones λ_{eff} increases for all moisture contents, while in the third (T > 373 K) the variation of λ_{eff} is complex, which is evidently attributable to the biochemical changes taking place in the oily cottonseed at temperatures above 388-395 K.

Table 2 shows that for bare cottonseed (O_f = 0%) the coefficient λ_{eff} has the highest value and that as O_f increases the value of λ_{eff} falls. This behavior is observed at all cottonseed moisture contents.

On the temperature interval corresponding to a change in the state of aggregation of the moisture contained in the material there is a sudden fall in λ_{eff}. Beyond these critical

TABLE 3. Effective Thermal Diffusivity of Cottonseed $a_{eff} \cdot 10^7$, m^2/sec, on the Temperature Interval 175-450 K and the Fibrosity Interval 0-35% at a Moisture Content of 21.8%

T, K	O_f							
	0	5	10	15	20	25	30	35
175	3,30	3,50	3,63	3,70	3,83	3,96	4,09	4,26
200	2,67	2,92	3,05	3,14	3,27	3,41	3,56	3,73
250	2,29	2,38	2,52	2,62	2,76	2,96	3,06	3,26
275	1,30	1,35	1,44	1,50	1,57	1,66	1,75	1,86
300	1,38	1,44	1,54	1,61	1,71	1,81	1,93	2,06
350	1,25	1,31	1,40	1,47	1,57	1,67	1,79	1,92
375	1,03	1,08	1,14	1,20	1,27	1,31	1,42	1,53
400	0,97	1,02	1,09	1,15	1,23	1,32	1,43	1,54
450	0,76	0,80	0,86	0,91	0,98	1,05	1,14	1,23

temperatures λ_{eff} is observed to increase with temperature over the entire range of fibrosities.

Thermal Diffusivity

The thermal diffusivity enters into the thermal and diffusion similarity criteria. Consequently, the true values of the thermal diffusivity make it possible to carry out accurate heat and mass transfer calculations. The experimental determination of the thermal diffusivity of multilayer particles of the cottonseed type involves considerable difficulties; accordingly, we determined the effective thermal diffusivity of cottonseed for various fibrosities and moisture contents on the basis of c_{eff} and λ_{eff} for a known density [17] from the formula $a = \lambda/c\rho$.

It is clear from Table 3 that over the entire temperature interval the a_{eff} of cottonseed with different fibrosities and moisture contents falls, and only when $O_f = 0\%$ and $T > 475$ K is an increase in a_{eff} to $(2.4\text{-}2.8) \cdot 10^{-7}$ m^2/sec observed. An increase in fibrosity leads to an increase in a_{eff}, and this holds true over the entire range of temperatures and moisture contents. It follows from the table that, like the specific heat, the effective thermal diffusivity has peaks at 273 and 373 K, but in the present case a sudden decrease is observed as the moisture passes from the solid to the liquid and from the liquid to the vapor states.

On the temperature range 175-350 K there is a sharper decrease in a_{eff} for $U = 7.3\%$, $O_f = 10\%$ from $4.2 \cdot 10^{-7}$ to $1.65 \cdot 10^{-7}$ m^2/sec. A similar dependence is also typical for all other cottonseed fibrosities. With further increase in temperature ($T > 350$ K) the fall in a_{eff} stabilizes and the difference over the interval from 350 to 450 K is only 25%. It should also be noted that at low temperatures an unusually strong moisture content effect was recorded.

An analysis of the relations obtained shows that the effective thermal diffusivity of cottonseed depends only slightly on the moisture content. As the temperature increases, a_{eff} always falls. On the basis of the thermal diffusivity data we achieved a generalization by dividing the $a_{eff} = f(T)$ curve into two zones and obtained empirical relations of the form:

$$\text{for} \quad T < 250K \quad a_{ef} = (428{,}2 + 1{,}71 O_f) U^{0,1} T^{-1}, \tag{6}$$

$$\text{for} \quad 250 < T < 450K \quad a_{ef} = (556{,}7 + 2{,}31 O_f) U^{-0,05} T^{-1}. \tag{7}$$

Relation (6) has an accuracy of ±9.7% and relation (7) an accuracy of ±9.92%. Relations (6) and (7) are valid for various varieties of cottonseed with a fibrosity $O_f = 0\text{-}35\%$ and a moisture content $U = 0.2\text{-}35\%$ on the temperature interval $T = 175\text{-}450$ K.

Thus, we have experimentally investigated the thermophysical properties of cottonseed with various fibrosities over a broad range of variation of moisture content and temperature. It has been found that the fibrosity of the seeds has an important influence on a_{eff}.

On the basis of our investigation of the thermophysical properties of the components of multilayer cottonseed and their generalization we have obtained formulas for calculating the effective specific heat c_{eff} (4), thermal conductivity λ_{eff} (5), and thermal diffusivity a_{eff} (6) on the temperature interval $T = 175\text{-}450$ K, the moisture content interval $U = 0.2\text{-}35\%$ and the fibrosity interval $O_f = 0\text{-}35\%$.

By a similar method it is possible to calculate the thermophysical properties of multilayer oilseeds and other materials.

NOTATION

T, absolute temperature, K; U, moisture content, %; λ, thermal conductivity, W/(m·K); c, specific heat, J/(kg·K); ρ, density, kg/m^3; a, thermal diffusivity, m^2/sec; m, mass fraction of the i-th component; φ, sphericity factor; f, shape factor; r, radius of the particle, m. Indices: ads, absolutely dry substance; 1, cotton fiber; 2, cortex; 3, kernel; 4, air; 5, embryo; w, water; eff, effective; eff1, effective sphere.

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