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A METHOD FOR DETERMINATION OF PARAMETERS OF WET SOLIDS IN THE DRYING PROCESS

M. Stefanovic and D. Voronets

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The possibility of determining the moisture and temperature gradients in real wet solids of irregular shape, inhomogeneous composition, etc. by simplified engineering methods is described.

Introduction. The approximate solution of the differential equations of moisture transfer, suggested by A. V. Luikov [1], generalizes the drying kinetics in such a way that the drying rate can be presented as the product of the "drying coefficient" by the difference between the average moisture contents of the material and drying agent in the nondisturbed flow (far from the contact surface) A. V. Luikov assumed that the "drying coefficient" was constant, but all experimental studies of the kinetics show that it changes substantially in the drying process. Therefore, the next step in furthering this research was the suggestion of experiment-based expressions for the drying coefficient, the physical significance of which was not quite clear yet. It is very difficult to determine this coefficient, and the fact is that it describes two physically different processes, namely, convective heat transfer between the material and drying agent and moisture transfer in wet materials.

It is evident from the above that it is impossible to obtain a sufficiently general relation for the drying coefficient in a wide range of parameters of the wet material and drying agent. That these relations do not reveal the physical phenomena occurring in the material during the drying process is especially important because they include both the convection conditions and balance equations for the material and drying agent.

In order to eliminate these contradictions the Institute for Thermal Engineering (ITE) has developed a method for determination of the empirical relation for the drying rate from experimental data on the basis of the known relationships of convective heat transfer and with the assumption of thermodynamic equilibrium between the surface of the material and the drying agent. In this method the difference between the average moisture contents of the bulk of the material and its surface is taken as a mass transfer potential in the material. This approach (ITE method) has given good results.

In [2] it is shown that the relations describing the changes of the temperature and moisture fields (determined by the method developed in [3] in a cylinder of the model material) can be used to investigate the process in real materials (wheat, corn) in terms of both the difference between the average moisture contents of the material bulk and surface and the difference between the temperatures of the material bulk and its surface, determined with the ITE method [4].

In order to find a more reasonable theoretical explanation of the results [2] and to develop new equations for analysis of the drying processes of real materials, the range of validity of the previous results was subjected to experimental and analytical verification. After this verification, it was intended to propose equations relating the drying dynamics and kinetics in various materials. These methods should be physically reasonable and easily realizable. In what follows some results of these studies will be given.

1. Objectives of the Studies. The concrete concept of these studies concerned three objectives. First, we wanted to find experimentally the drying kinetics for a stationary dense bed of spheres of different diameters made of the model materials used in [2, 3] blown by a drying agent and to process the results with the ITE method [4]. The second objective was to determine time changes of the temperature and moisture fields in wet spheres on the

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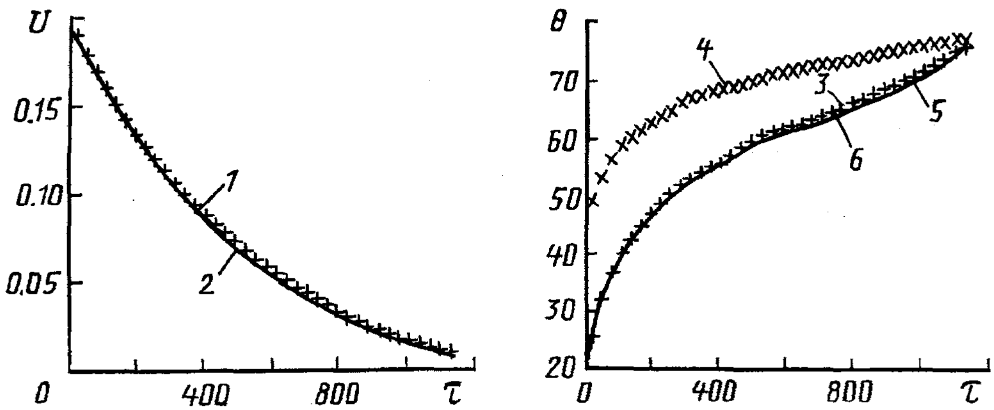

Fig. 1. Time changes of the parameters of a moist body made of the model material: 1) experimental average moisture content; 2) predicted average moisture content; 3) experimental average temperature; 4) surface temperature determined with the ITE method; 5) surface temperature found numerically with boundary conditions of the second-kind; 6) average temperature determined numerically with boundary conditions of the second-kind, U, kg/kg; Θ,^{o}C; τ, sec.

basis of experimentally measured moisture and heat flows on the surface of the material with the method used in [3], taking the geometry into consideration. Third, we intended to compare time-variable parameters of the wet material, which were obtained by the methods of [3] and [4]. Eventually, as a result, it was planned to develop a new engineering method for determination of the relation of the drying kinetics and dynamics for real materials, for which the method of [3] cannot be used because of irregularity of the shape of solids and inhomogeneity of the composition.

2. Results and Analysis. Attempts to partially solve the problems stated in the previous section were made in [5], where experiments were carried out with spheres of three diameters (d = 8, 12, and 16 mm), made of the model material, using the ITE method. Sixteen experiments were conducted, in which the temperature, moisture content, and the flow velocity of the drying agent were varied. The method of [3] was used to construct a model of heat and moisture transfer in spheres of a model material with the boundary conditions of the second kind. Time changes of the temperature and moisture fields in the drying process were calculated numerically with experimentally found parameters. Some results of these studies will be presented in the following.

As was be expected, the predicted U_{sr} differs slightly from the experimental values (Fig. 1), except for the final drying stage, where the heat flux values were determined with a lower accuracy.

Time changes of the moisture and temperature distributions are shown in Fig. 2 for experiment 4. For the other experiments the shape of the curves are similar. Local temperature values across the sphere differ slightly, i.e., the bulk of the material is heated rapidly, while the moisture-content distributions show that the evaporation front moves rather slowly toward the center of the sphere.

The difference between the predicted surface temperature Θ_s of the sphere (Fig. 1) and that obtained in the drying kinetics experiment processed by the ITE method is too large to be acceptable. It is necessary to analyze the reason for the difference between the predictions and experimental results processed with the ITE method with the assumption that the set of equations with the boundary and initial conditions describes the heat and mass transfer in the sphere with sufficient accuracy.

First, attention should be paid to the fact that heat and mass flows (the boundary conditions for τ = 0) were not found experimentally but determined by numerical calculations, which give the highest errors in this region. Second, only 0.1-0.5% of the heat supplied to the moist body is used to heat the material (except for the start of drying). Therefore, with errors of the order of 1% in the determination of the heat flow on the material surface and the moisture flow, the balance method can produce the same errors.

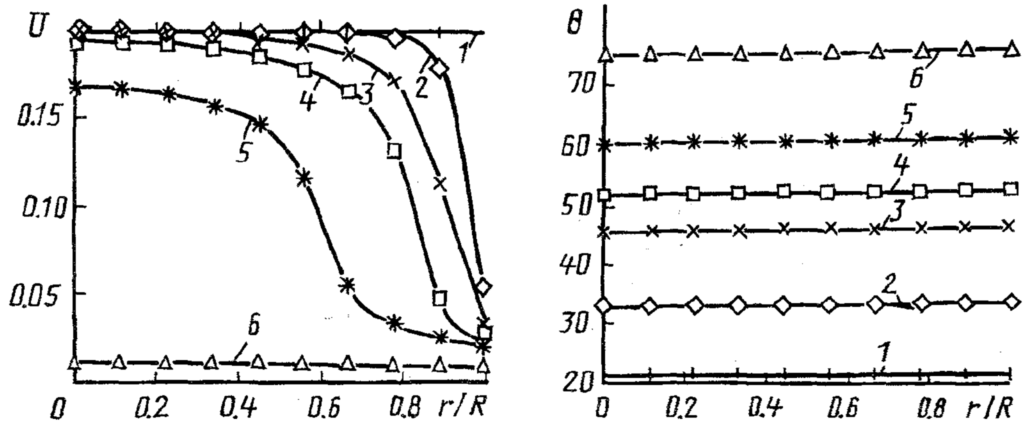

Fig. 2. Changes of moisture and temperature fields in the drying process, obtained numerically with boundary conditions of the second kind: 1) $\tau = 0$; 2) 60, 3) 180, 4) 300, 5) 600, 6) 1100 sec.

Since there are no data on the time dependence of the phase transition coefficient, a linear relation applied to the experimental data of [2, 3] was used in the calculation. This means that the error due to different particle shapes was anticipated.

That the value of the heat transfer coefficient α_{sl} for a stationary bed of material is determined inaccurately in the ITE method seems to be the most important factor resulting in large differences between the predicted temperatures on the material surface and the values obtained with the ITE method. The following information about the determination of α_{sl} is available [6, 7]: most of the published results are expressed by empirical or semiempirical relations; these relations cannot be extrapolated beyond the experiment with sufficient accuracy.

The following conclusions can be drawn from analysis of published results for experiments with spheres (d is about 8 mm) in a stationary racked bed:

It is shown in [8] that for the dependence of α_{sl} on the Reynolds number in the range of Re used in the experiment [6] (Re = 192), substantial scatter of experimental points about the correlation curve for the Prandtl number of 0.7 (Pr = 0.7) is observed.

It is shown in [7] that the ratio of the Nusselt numbers for spheres in a stationary bed and for a single sphere in a flow is $1 + 1.5(1 - \varepsilon)$. With the use of this ratio for calculation of α_{sl} in the experiment [6] with τ = 45 α_{sl} = 65.45 was obtained.

It should be emphasized here that calculation by the ITE method (using the expression from [8]) gives $\alpha_{sl} = 94.06$.

In [6] from experiments with spheres heated by microwaves (to obtain a gradientless bed of heated spheres, i.e., to provide conditions for investigation of convective heat transfer from heated air to the bed without heat transfer between the spheres) a correlation was obtained for the convective heat transfer coefficient as a function of Colburn's heat transfer factor of the Archimedes number Ar and Reynolds number Re. The correlation gives α_{sl} = 42.5.

To this short analysis of the reasons for the difference between the predictions of [3] and the results obtained by the ITE method it is necessary to add that the phase transition coefficient determined numerically varies in a wide range, while no substantial variation of the surface temperature was found. This seems unusual, but taking into consideration the errors in the evaluation of fluxes and the fraction of heat spent on heating the material, these results seem reasonable.

From the above said it can be concluded that comparison of the predictions performed with the boundary conditions of the second kind and the results obtained by the ITE method is not sufficiently adequate. The prediction method can be extended to the region with the boundary conditions of the third kind in order, that under natural coincidence with the ITE results, the corresponding relations are chosen for transfer coefficients to be used both in the former and in the latter methods. Only then can the phase transition coefficient and particularly

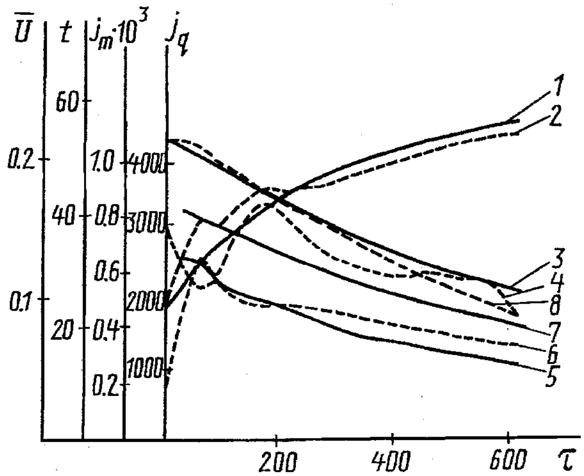

Fig. 3. Time changes of the parameters of the material: 1) experimental average temperature processed with the ITE method; 2) average temperature determined numerically with boundary conditions of the third kind; 3) experimental average moisture content processed with the ITE method; 4) average moisture content obtained numerically with boundary conditions of the third kind; 5) experimental heat flux through the body surface processed with the ITE method; 6) heat flux through the body surface found numerically with boundary conditions of the third kind; 7) experimental mass flux through the body surface processed with the ITE method; 8) mass flux through the body surface determined numerically with boundary conditions of the third kind. $\overline{U}$, kg/kg; t, °C; j_m, kg/(m^2·sec); j_q, W/m^2.

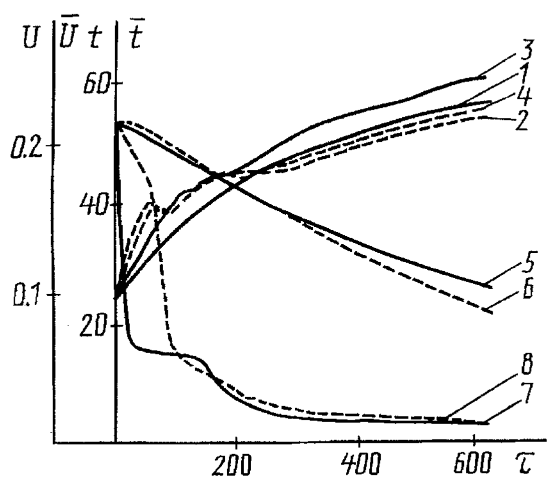

Fig. 4. Time changes of the parameters of the material: 1) experimental average temperature processed with the ITE method; 2) average temperature determined numerically with boundary conditions of the third kind; 3) surface temperature determined with the ITE method; 4) surface temperature determined numerically with boundary conditions of the third kind; 5) experimental average moisture content processed with the ITE method; 6) average moisture content determined numerically with boundary conditions of the third kind; 7) experimental surface moisture content processed with the ITE method; 8) surface moisture content determined numerically with boundary conditions of the third kind.

the heat and mass transfer coefficients be studied thoroughly. At present, we have only to agree that the choice of precise relations is virtually impossible.

The obtained solution should be checked by measurements of the surface temperature and the average temperatures of the material in a high-accuracy experiment.

With the above conclusions in mind, additional experimental investigations were carried out and a set of differential equations with the boundary conditions of the third kind was developed and solved numerically in [9]. Numerical solution of this set of equations and processing of the experimental results by the ITE method were carried out with parametrically changed heat and mass transfer coefficients. The coefficients were changed until a pair of coefficients was found that provided good agreement between numerical solutions obtained with the ordinary methods and the ITE method, i.e., until good agreement between the changes of the average moisture content and the average temperatures in the drying process was obtained. This was done for all experiments in this study and for some of the experiments reported in [3]. It should be stressed that this procedure is a good precondition for agreement of solutions obtained by the two methods. This was not observed when the ITE results were compared with the numerical solution with the boundary conditions of the second kind, i.e., when the comparison was made in terms of experimental heat and mass fluxes. The transfer coefficients that gave good agreement between the results were analyzed. The analysis shows that they are in good agreement with Barker's dimensionless criterial relation for heat transfer with half as large a constant and Treiball's relation for mass transfer also with a decreased constant. This result has a physical ground which is not considered in this study. The use of the transfer coefficients obtained with the method described above gives good agreement of the solutions. As an example, Fig. 3 gives typical results of one of the experiments, where time changes of heat and mass fluxes, average temperatures of the material, and its average moisture content in the drying process obtained with the two methods described. In Fig. 4 the changes of the temperatures and moisture content of the material surface obtained with the two methods are shown. The results presented in Figs. 3 and 4 are typical and describe well all the results obtained in [9], which will be analyzed briefly in what follows.

Changes in the average moisture contents and temperatures of the material obtained by the two methods agree well. The same holds for heat and mass fluxes through the surface of solid particles. Characteristically, the heat and mass fluxes obtained numerically for the initial period of 130-150 sec are smaller, and after that period they are larger than the actual fluxes (which are determined experimentally and used in the ITE method). This fact allows us to conclude that the empirical relations for transfer coefficients which, on the average, generalize well the initial data, fail to describe these relatively small systematic differences. The same differences in all the experiments show that the actual transfer coefficients are larger at the start of experiments when the vapor flow through the material surface is the largest. All differences in the average parameters of material can be explained reasonably by the effect of the values of the transfer coefficients. As regard the comparison of the "gradient measures" (the difference between the average moisture content and temperature of the bulk of material and the moisture content and temperature of the material surface), it can be concluded that agreement of the moisture content "gradient measure" is very good, whereas the temperature gradients show only fair agreement. It should be recalled that the measured difference of the surface and average temperatures (2-4°C, such measurements show that the accuracy of the experiment is inadequate) was always between the values obtained numerically (1-3°C) and by the ITE method (5-8°C).

Conclusion. Analysis of all the reports available confirms that the ITE method is a good engineering technique. Comparison of the relations obtained with this method with the known relations for the transfer coefficients shows good agreement both in processing of the drying dynamic results and in determination of the initial parameters (the average temperature, moisture content of the material, and the moisture content and temperature "gradient measure" in the material), which are necessary for choosing drying technology [10]. The resources of this method have not been fully exhausted. It can also be extended to similarity theory analysis and the first attempt to do it has been already made in [2], where Luikov's basic equation of the drying kinetics is analyzed. With this approach the ITE method can be used more effectively in determining the actual potentials of the simultaneous heat and mass transfer observed in convective drying.

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