# HEAT TRANSFER COEFFICIENTS OF CITRUS FRUITS

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Coefficients of heat and moisture transfer have been determined, on the basis of which the optimum mode of transporting citrus fruit can then be established.

The transport and the storage of fruit results in considerable spoilage because of the varying heat and moisture conditions. The purpose of this study was to determine the coefficients of heat and moisture transfer, in order to discover the best method of storing citrus fruit. Published data on the specific heat of fruit represent average-weighted values for water and dry substance: $c_q = 0.90$-$0.92$ kcal/kg · deg C (3.77-3.86 J/kg · deg C). For dry fruit and vegetables one uses the value $c_d = 1.26$-$1.68$ J/kg · deg C. No data on the effect of pomological factors on the specific heat nor on other thermal characteristics of fruit are available [1, 4, 5].

The authors examined oranges and lemons of seven grades from early and late 1967-1969 crops grown in the Mediterranean countries. The specific heat ($c_q$), the thermal conductivity ($\lambda_q$), and the thermal diffusivity ($\alpha_q$) were determined by the Maksimov method, on the basis of an analytical solution to the problem of heating two bodies (one of finite size and one semiinfinite), as proposed by Lykov. As the reference standard, a semiinfinite body with known thermal properties, we used paraffin [2, 3].

The quasisteady thermal characteristics of all the grades of fruit are the same and do not depend on pomological factors. The specific heat of fruit is higher than had been calculated. The transient time for fresh uncut fruit is 4 h. With the Biot number $Bi \ll 1$, the lead point is far under the surface and this allows us to disregard in subsequent practical calculations the temperature drop inside a fruit, as compared to the heat load, and to omit space coordinates from further considerations. The Lykov number is $Lu \ll 1$, which indicates that the moisture field is much more inert than the temperature field. The internal heat source $w_{max} = 20\ W/m^3$ is attentuated exponentially: $w = w_0 \exp(-0.02\tau)$ when fruit at a 25°C temperature is stored in a 0°C chamber with natural convection at a Reynolds number $Re < 20$.

The transient thermal conductivity and specific heat of fruit, as functions of the Fourier number Fo, increase up to a certain constant value, while the thermal diffusivity curve has its peculiar wave (moisture content) with the relaxation ending at $Fo = 0.5$. This wave shape is explained by an unstable initial moisture distribution in specimens with the temperature (dimensionless)-dependence of the Fourier number remaining unchanged throughout this heating period [2, 3].

The heat transfer coefficients are functions of the moisture content in the various grades of fruit, typical of colloidal capillary-porous materials, with characteristic maxima and singular values corresponding to transitions from one to another form of bond (Fig. 1). It is well known that the specific heat, an extensive property, is an additive quantity for many moist materials. The specific heat of several moist materials (e.g., wood), however, varies with increasing moisture content along a curve which dips toward the $c_q$-axis [3]. The specific heat curve for citrus fruit is analogous to an isotherm, with a straight line between two curved segments. The trend at the lower end is explained by the impossibility of making the material perfectly dry, the trend at the upper end is explained by the weight reduction (loss of moisture) in an almost constant volume during the first few days after the harvest. Throughout this period the density of the fruit substance also varies nonlinearly, while $\lambda_q$ and $\alpha_q$ remain constant within the 6.68-6.0 kg/kg range of moisture content. Thus, the fruit begins to shrink and its specific heat $c_q$ decreases after the moisture content has dropped to 6 kg/kg, i.e., by 10% from its initial level, and this

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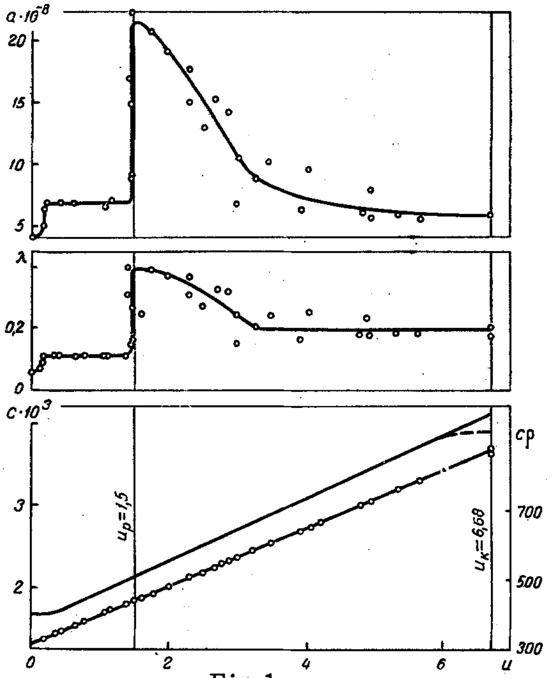

Fig. 1

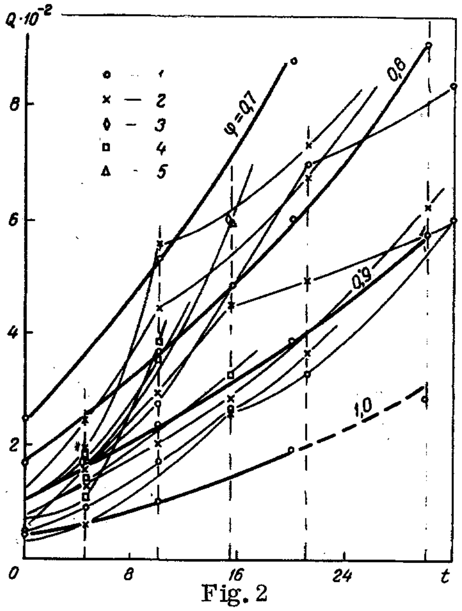

Fig. 2

Fig. 1. Heat transfer coefficients of citrus fruit as functions of the moisture content: $a$ ($m^2$ sec), $\lambda$ (W/m • deg C), c (J/kg • deg C), u (kg/kg).

Fig. 2. Heat released from fruit, as a function of the temperature and the relative humidity of air, based on published data: 1) International Refrigeration Institute; 2) Rath Eric; 3) L. V. Metlitskii; 4) V. G. Speranskii; 5) Transzheldorizdat Handbook. Heat $Q \cdot 10^{-2}$ J/kg • sec, temperature, °C.

confirms the conclusions drawn by other authors concerning the ability of fruit to retain its initial turgor [1, 4, 5]. The heat released from a fruit mass has been plotted as a function of the storage temperature $Q = f(T)$, on the basis of data from various sources, but the authors do not reveal their methods of calculation and their curves differ widely. Our respective curves are based on the law of energy conservation and they provide a needed correction to published data, including those by the International Refrigeration Institute. Apparently, when calculating the heat released from a fruit mass, those other authors have not accurately enough accounted for the transpiration rate as depending not only on the temperature but also on the relative air humidity and, therefore, being determined by the difference between the moisture-transfer potentials of the fruit and the ambient air: $Q = f(j, \varphi, T)$ (Fig. 2).

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