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Surface drying of fruit and potatoes

It is evident to dry off surface moist from fruit and potatoes to prevent microbial activities which is a risk for spread of diseases. The process of surface drying is determined by the evaporation cooling effect along the surface. Local flow and transfer effects can be determined. Respecting heat and mass exchange in the boundary, the temperature profile around the surface of the produce can be calculated during drying off moist from the fruit surface. The fruit surface temperature is visualized by image analysis of infrared-thermographic images.

Keywords
Surface moist, surface drying of fruit and potatoes

Abstract
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Moist on surfaces of fruit and potatoes may imply risks in development and spreading of microbial organisms which affect storability and shelf live of the produce. Therefore, it is evident to dry off surface moist prior storage or remove condensed water on the surface. Surface moist exist if a film of liquid water is present on the surface of the produce. The moist should be removed or evaporated to the ambient air as quick as possible (transpiration). The transport mechanisms during transpiration are mass diffusion and heat conduction in air as well as convection in flowing air.

The significant process during drying is the mass transfer, i.e. the transition of water vapour from the surface of the individual fruit passing the boundary layer to the surrounding moving air. The heat transfer is similar to this process.

Important parameters to the drying process are therefore the mass transfer coefficient and the heat transfer coefficient, as well as the parameters for the determination of the thermodynamic condition of the ambient air, like temperature, humidity and air flow velocity.

Transpiration

The ambient conditions (e.g. the storage air conditions) can be easily determined by measurements. An analytic model permits the computation of the mass loss during transpiration. The mass loss E can be determined by weighting and be calculated using equation (1) [1]

$$E = \frac{m_0 - m_1}{A \cdot (t_1 - t_0)} \qquad \text{(Eq. 1)}$$

with A surface area of the produce, m mass of the water film, t time, and index 0 at begin, index 1 at end of experiment. The mass loss E can be identified with the mass flow density j, therefore $j \equiv E$. The fundamental equation to determine the mass flow density is

$$j = -D \text{ grad } Y \qquad \text{(Eq. 2)}$$

with D diffusion coefficient of water vapour in air ($D = 25.6 \cdot 10^{-6}\ m^2 \cdot s^{-1}$), Y absolute humidity of the air, $Y = m_{humid\ air} / m_{dry\ air}$.
The absolute humidity can be read out from a psychrometric chart (Mollier's h-x chart)

Air flow

During convection still the speed of moving air passing the surface is of importance apart from the air temperature, the surface temperature and the humidity. Air speed can be measured e.g. by means of a hot wire anemometer in the proximity of the surface (boundary layer) or be computed by flow simulation by means of numeric fluid mechanics (CFD = Computational Fluid Dynamic).

Dimensionless numbers are used for better comparison of results. Air flow velocity w (in $m \cdot s^{-1}$) is replaced by the Reynolds number ($Re = w \cdot 2R \cdot \nu^{-1}$), with R radius of the spherical produce (R = 35 mm), ν kinematic viscosity of air, $\nu = 15{,}58 \cdot 10^{-6} m^2 \cdot s^{-1}$ at 25 °C, 1 bar.

The Reynolds number is therefore proportional to the air flow velocity but not constant along the path of the air flow. The fruit is assumed as of spherical shape. A „locally variable“ Reynolds number can therefore be defined and illustrated (**figure 1**). With spherical or cylindrical objects the flow profile is symmetrical around the body within an even laminar parallel flow.

At the stagnation point (windward side of the object) the flow velocity is zero, increases around the body, reaches a maximum value close in the zenith and decreases in the leeward side again. In the leeward side either a laminar von Kármán vortex trail or a turbulent flow is developing dependent on the basic flow velocity (or Reynolds number).

In a thermographic temperature image the drying process can be observed (**figure 2**). Windward-laterally the surface-wet fruit dries first. A drying zone is moving with the time from the front (windward) of the fruit to the leeward side.

The kind of the process can be interpreted in such a way: air in the boundary layer is saturated almost immediately with water vapour and is not able to dry the body of the fruit along the further air flow path. Only if the surface at the face of the fruit is dried off, the drying zone can move further along the surface toward the leeward flow.

Temperature profile

The processes of the mass transfer are coupled with the thermal processes. The water vapour absorption of flowing air is possible only up to their saturation point at 100 % relative humidity (rH), according to the absolute humidity value Y_s. The saturation limit increases with rising air temperature. Air at the surface of the fruit thus in the boundary layer is always satisfied up to the end of the transpiration.

During the transpiration the surface water is cooling down to a limit temperature (wet bulb temperature). This effect can be used for evaporative cooling and is well recognized e.g. in the temperature image of an infrared thermography camera (**figures 2 and 3**). For the developing of the temperature distribution around the body the heat exchange between body surface and ambient air is decisive.

The wet bulb temperature θ_s can be calculated, e.g. after [3], as

$$\theta_{amb} - \theta_s = \frac{\Delta h_v(\theta_s) \cdot \left(Y_s(\theta_s) - Y_s(\theta_{amb}) \cdot rH\right)}{c_{pg} + Y \cdot c_{pv}} \qquad \text{(Eq. 3)}$$

with θ_{amb} ambient temperature, rH rel. air humidity, c_{pg} and c_{pv} specific heat capacities of air and water vapour and Δh_v evaporation enthalpy. Since equation (3) is implicit related to θ_s, the equation must be solved numerically, for example by using the Regula Falsi method (remark: θ in °C and T in K).

Heat transfer

The methods for the computation of the heat transfer are similar to those of the mass transfer. The dimensionless heat transfer number $Nu = \alpha \cdot \delta_T / \lambda$ (Nusselt number) is similar to the dimensionless mass transfer number Sh (Sherwood number). For a laminar flow around spherical object Nu is valid as [3]

$$Nu = 0.664\, Re^{1/2} \cdot Pr^{1/3} \qquad \text{(Eq. 4)}$$

with λ heat conductivity of air, δ_T temperature boundary layer thickness and Pr Prandtl number. For gas, like air Pr ≈ 0,7 (remark: with the small velocity ranges occurring here laminar flow is assumed).

The heat and mass transfer processes are coupled which is expressed by the Lewis number Le

$$Le = a / D = Sc / Pr \qquad \text{(Eq. 5)}$$

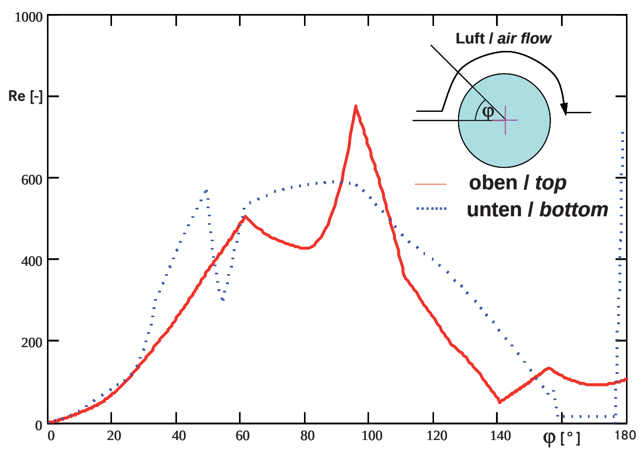
with $a = \lambda_{air} \cdot \rho^{-1} \cdot c_{pg}^{-1}$ thermometric conductivity and D mass diffusion coefficient. The Lewis number for water vapour in air is Le ≈ 0.87 [3].

The heat transfer coefficient α is defined as

$$\alpha = -\lambda_{air} \cdot (\partial T/\partial r)_{surface} / (T_{s0} - T_{\delta T}) \qquad \text{(Eq. 6)}$$

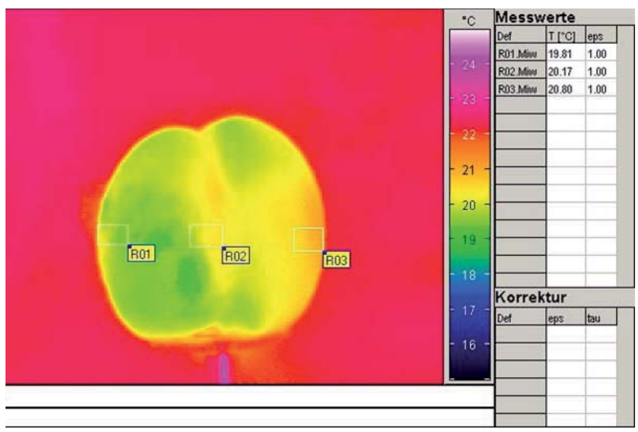
with T_{s0} surface temperature at saturation, $T_{\delta T}$ = temperature at thermal boundary layer thickness, r radial distance and λ heat conductivity. It can be determined from the tangent slope of the temperature shape inside the boundary layer at distance from

Fig. 1



Measured proceed of Reynold's number of the air flow along a peach fruit surface; solid line: along upper half, dashed line: along lower half of fruit

Fig. 2



Temperature distribution on the surface of a peach during drying off surface moisture using infrared thermography, measuring points R01, R02 und R03

the surface. The temperature profile is needed for that but is difficult to obtain.
However, the thermal boundary layer thickness δ_T can be approximated by the boundary layer thickness δ of the mass transfer, thus $\delta_T \approx \delta$. The boundary layer thickness δ can be obtained from the slope of the measured velocity profile at radial distance from the surface.

The dependency of the heat transfer coefficient α from air flow velocity (within the range w = 0.01 to 0.5 m · s^{-1}) can be calculated after [4] as

$$\alpha = 7.8 \cdot \frac{w^{0.6}}{d^{0.4}} \qquad \text{(Eq. 7)}$$

with d = 2 R = fruit diameter.

Mass transfer

The mass transfer coefficient β is similar to the heat transfer coefficient α as

$$\beta = -D \cdot (\partial Y/\partial r)_{surface} / (Y_{s0} - Y_\delta) \qquad \text{(Eq. 8)}$$

with r radial distance from the surface, Y_{s0} = absolute humidity at saturation and Y_δ at boundary layer thickness δ.
The coupling with the heat transfer can again expressed as

$$\beta = Le^m \cdot \frac{D \cdot \alpha}{\lambda} \qquad \text{(Eq. 9)}$$

with m ≈ 1/3 for gases.
The mass flow density j is calculated with (compare equation 2)

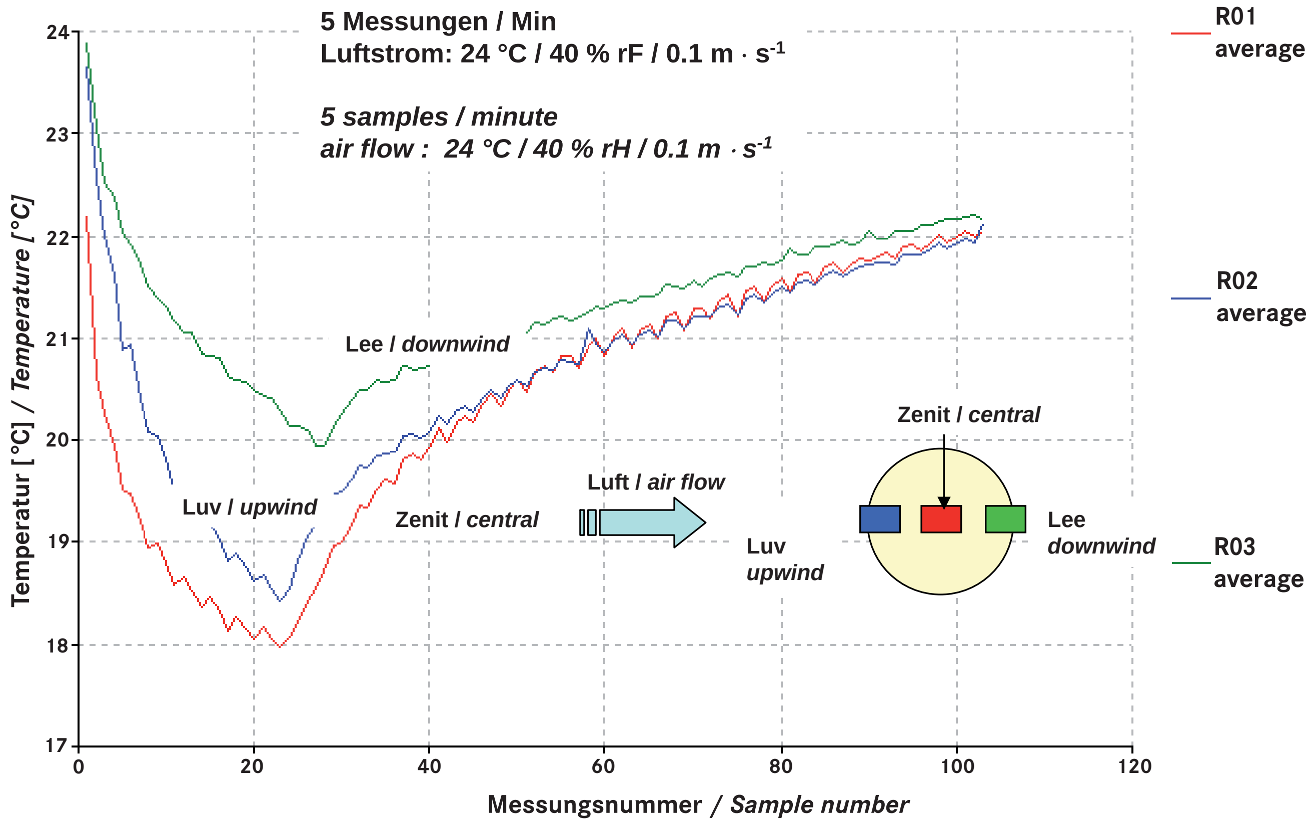
$$j = \beta \cdot \rho_{Luft} \cdot (Y_{s0} - Y_\delta) \qquad \text{(Eq. 10)}$$

The humidity Y_δ at the boundary layer thickness can be approximated with the humidity Y_{amb} at a sufficient high distance from the surface (thus in the ambience). This value can be determined from a psychrometric chart (Mollier's h-x chart) for water vapour in air by using the temperature and the relative humidity, which can be easily measured.

Results

At adiabatic evaporation cooling the wet bulb temperature can be reached on the surface. A thermographically measured curve (**figure 3**) shows, however, that this temperature is not reached but remains at a higher value. The explanation is that heat is diffusing from inside the fruit to the surface and therefore the real process is not adiabatic. Heat diffusion inside the fruit can be calculated with the classical Fourier's method for spheres [3]. Additionally, a heat transport takes place within the boundary layer, whereby the temperature can

Fig. 3



Thermographic measurement of temperature at three local points on the surface of a peach during drying off surface moisture only remain within the range of the minimum attainable wet bulb temperature θ_s in proximity of the surface (i.e. on the water film) and of the maximal attainable ambient temperature $\theta_{amb} \approx \theta_{\delta T}$. Due to the heat exchange processes with the body a measurable temperature is reached in the range of between θ_s und θ_{amb}. The heat transfer is dependent on the air flow velocity according to equation (7), and therefore variant along the surface because the air flow velocity (or Reynolds number) is variant. The calculation of the surface temperature by the method explained above, especially after equation (3), combined with the Fourier's method for spheres, results for this example (**figure 3**) in an acceptable accordance (**figure 4**).

From equation (7) to (9) $\beta \approx 6.4 \cdot 10^{-3}$ m · s^{-1} at w = 0.15 m · s^{-1}, D = 26.6 · 10^{-6} m^2 · s^{-1}, λ_{air} = 0.026 W · m^{-1} · K^{-1} was determined. By measuring the air velocity profile using a hot wire anemometer the ratio $D_{air}/\beta = \delta/Sh \approx (1.20 \text{ to } 1.22) \cdot R$ with R fruit radius. The Sherwood number is similar to the Nusselt number

$$Sh = 0.644 \, Re^{1/2} \cdot Sc^{1/3} \quad \text{(Eq. 11)}$$

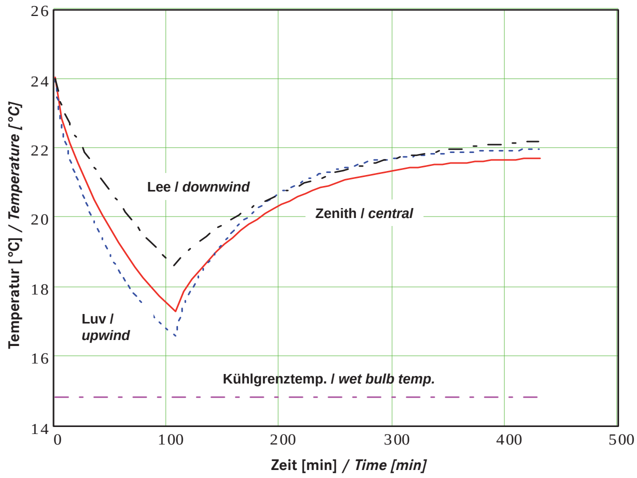
for spherical bodies. The Schmidt number is $Sc = \nu/D$.

In the example (**figures 3 and 4**) the surface of a fruit covered with a water film of 80 µm thickness was dried within half an hour using air at 24 °C, 40 % rH. The mass loss caused by transpiration was E = 2.2 · 10^{-5} kg · s^{-1} · m^{-2} (equation (1)). The calculation using equation (10) resulted in j = 2.4 · 10^{-5} kg · s^{-1} · m^{-2}, which is in good accordance to the experiment (E) after assumption of $\beta \approx 6.4 \cdot 10^{-3}$ m · s^{-1}.

Conclusions

The main effect during the transpiration is the mass and heat transfer within the fruit and its boundary layer as well as the mass and heat transition of the boundary layer to the flowing air. This process is non-adiabatic. Therefore, the theoretical wet bulb temperature is not reached during the evaporation of surface water, as long as heat is diffusing from the inside of the fruit. The simple analysis of the heat and mass transfer processes in connection with the thermal conduction inside the fruit respecting the transfer coefficients results in good agreement of the computation of the surface temperature compared with the thermographically determined surface temperature distribution.

Fig. 4



Calculated proceed of temperature at three local points on the surface of a peach during drying off surface moisture

Literature

[1] Linke, M. (1997): Modelling and predicting the postharvest behaviour of fresh vegetables. Mathematical and Control Applications in Agriculture and Horticulture, Eds. Munack and Tantau, Oxford, Pergamon Press, UK, pp. 283-288

[2] Gottschalk, K.; Linke, M.; Mészáros, C.; Farkas, I. (2007): Modelling condensation and evapouration on fruit surface. Drying Technology 25, pp. 1237-1242

[3] Baehr H. D., Stephan, K. (1996): Heat and Mass Transfer. Springer-Verlag, Berlin Heidelberg

[4] Rastovski, A (1987): Storage of Potatoes. Eds. Rastovski, A., van Es, A. et al, Wageningen, Pudoc

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