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An experimental study of the local evolution of moist substrates under jet impingement drying

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A R T I C L E I N F O

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A B S T R A C T

Jet impingement can be successfully and efficiently employed in drying or dehydration of moist substrates, like food slices or plates, among other applications. With this intensification technique, a great deal of the available water is removed by applying heat under controlled conditions, but excessive or nonuniform local drying may cause local deterioration (i.e. in case of foods, the eating quality, the nutritional value, the mechanical consistence and so forth).

In this paper the thermal, water activity and moisture depletion histories have been measured in a food substrate, due to localized heating by a turbulent air jet impingement, to infer on the inherent driving forces and transport phenomena. It is evident that strong non-uniformity may exist in the substrate so that a local analysis as the reported one is necessary to help reach optimal processing.

1. Introduction

Water performs a number of important functions in processing and conservation of porous materials such as food substrates. Among these, moisture serves as a medium for the transfer of energy in heating or cooling processes and, in foods, its final content dictates the duration (shelf-life) of the substrate: high moisture substrates are readily spoiled by microorganisms and chemically and enzymatically deteriorated. The total moisture content comprises the bound water (relative to the biochemistry and micro-capillarity) and the free water (kept in place by physical forces only) [1].

The free water can be measured in terms of the ratio of the vapor pressure of water in the sample to the vapor pressure of pure water, or the water activity a_w (an analog of the relative humidity, RH). This concept, along with the usual moisture content U, is commonly employed as a factor that drives keeping and operational quality of the substrate. Therefore a detailed description of such local quality is often needed to avoid poor or excessive treatment, whereas product uniformity is at stake. To this end, the appropriate conditions of design and operation of drying equipment have to be properly analyzed.

Among the available enhanced convection techniques, the jet impingement (JI) of air can be used for its excellent heat and mass transfer characteristics, where localized and rapid surface drying or dehydration of food substrates is desirable [2,3]. Dehydration involves a rather complex combination of application of heat and removal of moisture. In addition to air temperature and humidity, the rate of moisture removal is controlled by the air velocity: when hot air is locally blown over a wet substrate, water vapor from liquid water evaporation diffuses through the boundary layer and is carried away (Fig. 1). A water vapor pressure gradient is therefore established from the moist interior to the external food surfaces.

As in every bulk convection treatment, the boundary layer acts as a barrier to both heat transfer and water vapor removal during drying. But even within its apparent simplicity, JI treatments induce fluid/substrate interaction patterns, in the stagnation and in the wall jet region (Fig. 2) [4]. These patterns contribute to boundary layer destruction, hence in increase of moisture removal but generally in a non-uniform way. Therefore local substrate conditions have to be carefully monitored as well.

Studies on gaseous JI have been performed extensively over the past five decades, nevertheless the coupling and interdependence between simultaneous mass/heat transfer and fluid dynamics still needs to be fully analyzed, with special reference to local moisture removal.

Porous media drying under bulk convection regimes has been long speculated, and a large number of studies are available, following the seminal works by DeVries [5] and Whitaker [6]. However, few contributions have been found only in the available literature, with reference to localized convective porous media

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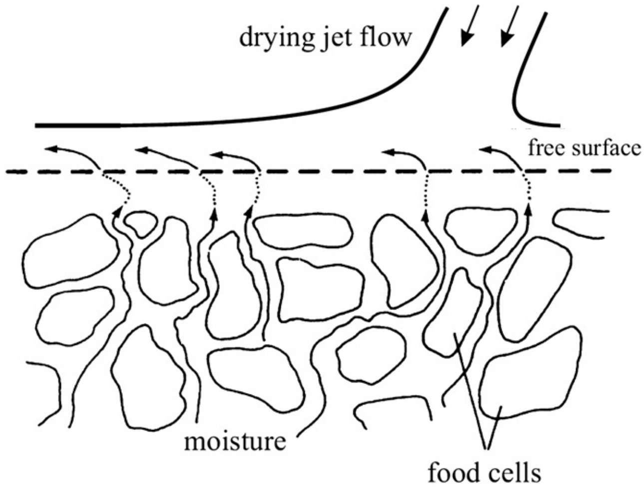

Fig. 1. Moisture transfer in a food substrate.

drying, as recently reviewed by De Bonis and Ruocco [7] and De Bonis [8]. With reference to JI drying, a first contribution was presented by Francis and Wepfer [9] with a transient physical analysis, yet limited as one-dimensional, and later by Moreira [10] and Braud et al. [11] who first applied JI to food drying, with some limitations due to empirical assumptions. Then Cefola et al. [2] presented an experiment on conjugated heat and mass local transport to a food slab due to a moderately turbulent JI, while new modeling approaches were proposed by De Bonis and Ruocco [12,3].

The purpose of this work is to describe experimentally, with proper data reduction and uncertainty analysis, a_w and U distributions during round, turbulent JI drying depending on relative position (distance from stagnation), system geometry (jet height) and operational parameters (inlet velocity and temperature, and process duration).

2. Material and methods

2.1. Experimental set-up and measurement procedure

Moist corn flour dough is selected as the target substrate. In order to study the spatial progress and evolution of its water activity and moisture content, subject to an air JI, target samples are prepared and cast as circular segments, and weighted by a precision balance (PLS 360-3, Kern & Sohn GmbH, Balingen, Germany), with initial water activity a_w of 95% $\pm$ 3 and initial moisture content (wet basis) U of 44% $\pm$ 3. This is consistent to the procedure reported by Moreira [10] and Braud et al. [11].

Air is drawn from the outdoor by a blower (Robust, Leister Process Technologies, Sarnen, Switzerland), while its velocity is monitored by an anemometer (AF 210, Digitron Instrumentation Ltd, Torquay, England), and its temperature and RH are detected by a probe (AW-DIO, Rotronic Ag, Bassersdorf, Switzerland). The flow is ducted to an electric heater (Labo, Leister Process Technologies, Sarnen, Switzerland) and through a pipe having an internal diameter d_j of 26.14 mm. The pipe is insulated and long enough for full hydrodynamical and thermal development, necessary to characterize the jet velocity and thermal profile. Then temperature and humidity are detected again, and the flow is directed perpendicularly into a 0.8 m $\times$ 0.8 m $\times$ 0.4 m thermally insulated enclosure (Fig. 3).

The enclosure is provided with a large number of small exit slots to ensure exit flow uniformity and no recirculation. The jet impinges on a Teflon 0.6 m $\times$ 0.6 m target tray, whose distance to the nozzle, H (Fig. 2), can be varied continuously in a 0.0–0.40 m range. The dough segment samples are inserted in 3 circular slots (shown in Figs. 2 and 3) on the target tray, numbered with distance from jet stagnation. The slots have semi-circular sections of 1 cm dia., in the y direction normal to r, starting at 1.5 cm from stagnation (sample nr. 1) and spaced by about 4 cm, in the r direction (Fig. 2). These slots are provided with K-type thermocouples (Labfacility Ltd, Dinnington, England) that are immersed at a uniform depths within the samples, carefully avoiding parasitic conductances (i.e. contact with holding Teflon tray). Their signals are acquired and converted by a datalogger (Pico Technology Ltd, St. Neots, England).

The process is initiated by turning on the blower and the heater. Upon flow and temperature adjustment and stabilization, the temperature signals are acquired. The target tray, initially maintained at outdoor temperature T_o, is then readily exposed to the JI as that the dough samples (that were kneaded at the same temperature) were inserted in it. At each given process duration, the samples are removed from the tray, vacuum-packaged to avoid further moisture loss and let cool off until equilibrium with the ambient.

At each given process duration the bulk a_w is analyzed (Hygropalm 3, Rotronic Ag, Bassersdorf, Switzerland) for a portion of each sample. This measurement is based on the water vapor that leaves the sample: during the measurement, this vapor saturates the available space in the container, yielding a constant RH increment

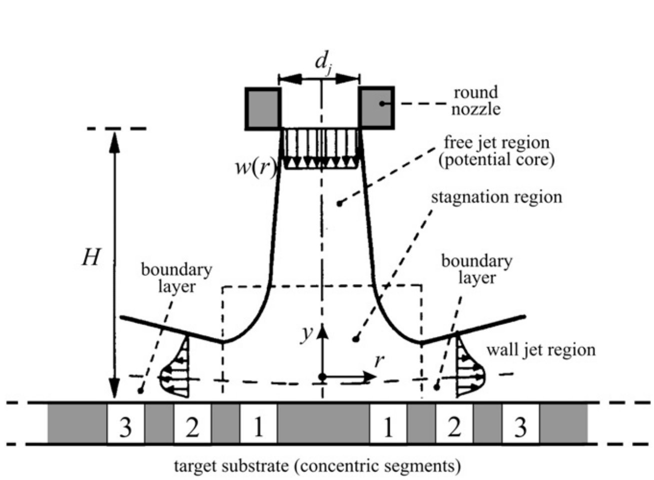

Fig. 2. The round JI configuration at hand, with geometry and flow field regions nomenclature.

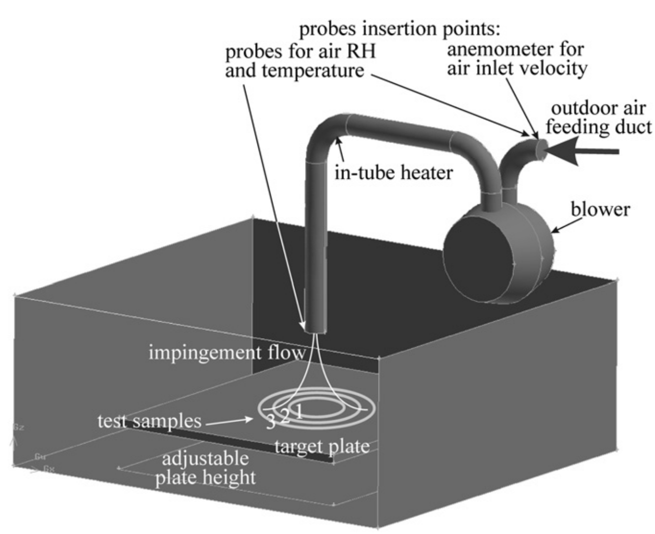

Fig. 3. The test rig. The ceiling and front aperture are removed for sake of visibility.

until the equilibrium is reached. Moreover, at the same process duration, the samples are also evaluated for the residual moisture content. This measurement is carried out by drying the samples according to AOAC [13] in a convection oven (UFE 400, Memmert GmbH, Schwabach, Germany).

2.2. Data reduction

As mentioned earlier, upon application of surface heat transfer by JI on a wet medium, water vapor is produced at and removed from the substrate surface. On the same account, as heat is diffused within the substrate, the liquid water is depleted into additional water vapor. The process at hand then results in combining surface and volumetric heat/mass transfer mechanisms.

In this paper, the local water activity moisture content evolutions due to round JI drying are experimentally addressed. In a preliminary paper [2], the driving forces to steady-state a_w variation were described in terms of local “internal” interface transfer phenomena. Heat transfer was referred to by a local Nusselt number, dependent on Reynolds and Prandtl numbers and related to the heat Biot number. Similarly, mass transfer was referred to by a local Sherwood number, dependent on Reynolds and Schmidt numbers and related to the mass Biot number [14,15]. In the present framework, a different approach is proposed instead, emphasizing on the following 4 “external” driving factors:

- the fluid dynamic regime, through the jet Reynolds number, Re;
- the thermal regime, through the jet temperature, T_j;
- the geometry configuration, through the dimensionless jet height, $H^* = H/d_j$, and the dimensionless the distance from stagnation, $r^* = r/d_j$;
- the process duration, Δt.

As the working air temperature is significantly high and the measurements are carried out at about normal conditions, no variation of the relative humidity of the environmental air is taken into account.

The injected flow rate and ultimately Re is evaluated upon measurement of the air flow at inlet outdoor conditions, upstream from heater, based on mass conservation. For turbulent fully-developed flows (with a feeding duct longer than 20 internal diameters), a polynomial progress of velocity w is adequate; for axisymmetric flow, from measuring the maximum velocity $w_{o,\max}$ at the feeding duct centerline, the mass flow rate $\dot{m}_o$ can be approximately evaluated with the following [15,16]:

$$\dot{m}_o = \rho_o w_{o,\max} \pi d_o \int_0^{d_o/2} \left(1 - \frac{r}{d_o/2}\right)^{1/n} \mathrm{d}r,$$
$$\text{with } n = 6 \text{ or } 7, \text{ as appropriate} \quad (1)$$

The mass flow rate can be also given based on the average velocity $\overline{w}$ and, due to conservation, we have:

$$\dot{m}_o = \dot{m}_j = \rho_j \overline{w}_j \frac{\pi d_j^2}{4} \quad (2)$$

The value of the average jet velocity $\overline{w}_j$ is therefore resumed:

$$\overline{w}_j = 4 w_{o,\max} \frac{\rho_o d_o}{\rho_j d_j^2} \int_0^{d_o/2} \left(1 - \frac{2r}{d_o}\right)^{1/n} \mathrm{d}r \quad (3)$$

and with it, Re:

$$\mathrm{Re} = \frac{\overline{w}_j d_j}{\nu_j} \quad (4)$$

The integral in Eq. (3) is calculated through a Simpson polynomial [18] for an adequate number of intervals. The air properties in Eqs. (3) and (4) are evaluated at the bulk temperature T_j through common temperature-dependent interpolating polynomials for air.

3. Results and discussion

3.1. Temperature distribution and progress

To help describe the thermal regime, the temperature evolution in the substrate samples during the process are first presented in Fig. 4: as expected, the temperature depends on the sample distance from jet stagnation, and on interaction of typical JI flow field regions (stagnation and wall jet) with underlying samples. In the sample 1, just within the stagnation region, the temperature increases logarithmically with time, until reaching a linear progress for $\Delta t > 300$ s. The evolution of temperature is linear instead, for the samples affected by the wall jet region, but the on-set of an approximate steady-state for $\Delta t > 900$ s. Depending on these temperature progresses, it is expected that a_w and U will performed similarly.

3.2. Uncertainty analysis

An uncertainty analysis for the water activity and moisture measurements is performed by following the ISO’s Guide to the Expression of Uncertainty in Measurement [17]. For a confidence level of 95%, the uncertainties for the water activity and moisture are 0.0316 and 0.00566, respectively. Moreover, for the same confidence level, the combined uncertainty due the propagation of uncertainties on the measurement of all independent variables (Re, T_j, H and r) is 0.132 or 0.11, depending on the operating regime (jet Reynolds number and temperature). All uncertainties are provided as error bars in each plot.

3.3. Water activity distribution and progress

In Figs. 5 and 6 the water activity progress with dimensionless distance from stagnation, $a_w(r^*)$ are reported, for one value of the jet height (H), four values of the jet Reynolds number (Re) and two process durations (Δt), corresponding to 8 Data Sets (Table 1). An interpolating line is provided in each plot.

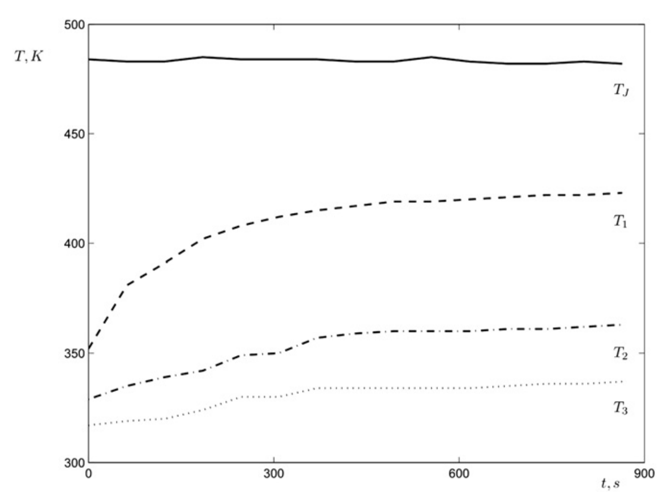

Fig. 4. Typical temperature evolutions for the jet j and the substrate samples 1 to 3.

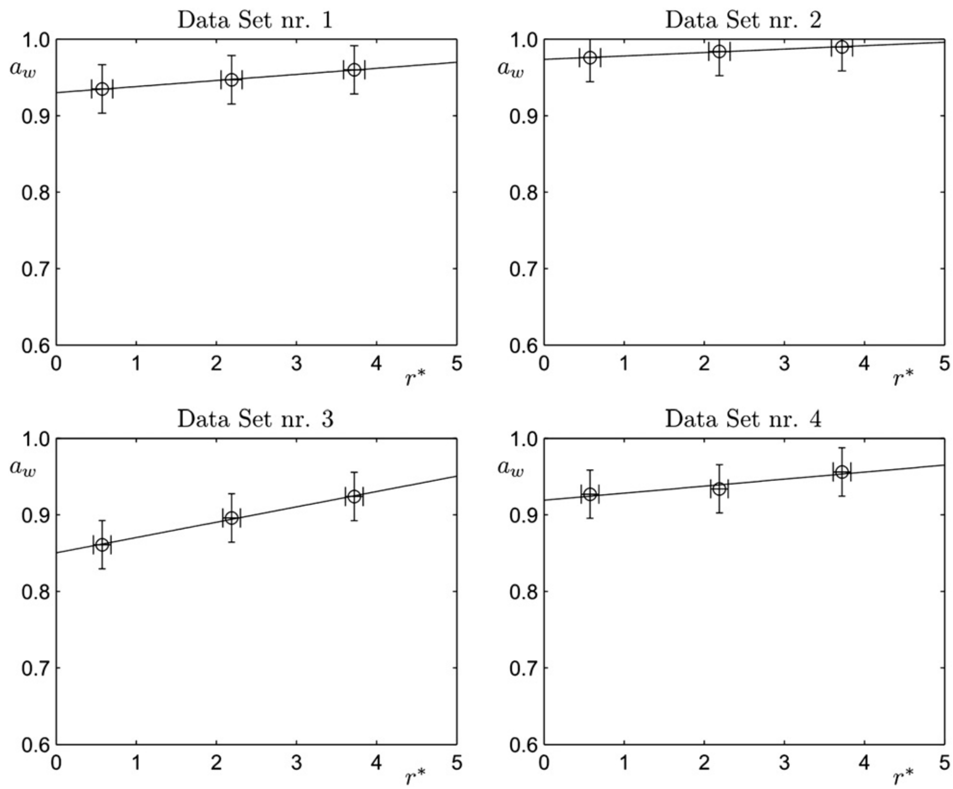

Fig. 5. $a_w(r^*)$ progress for Data Set 1 to 4 (Table 1).

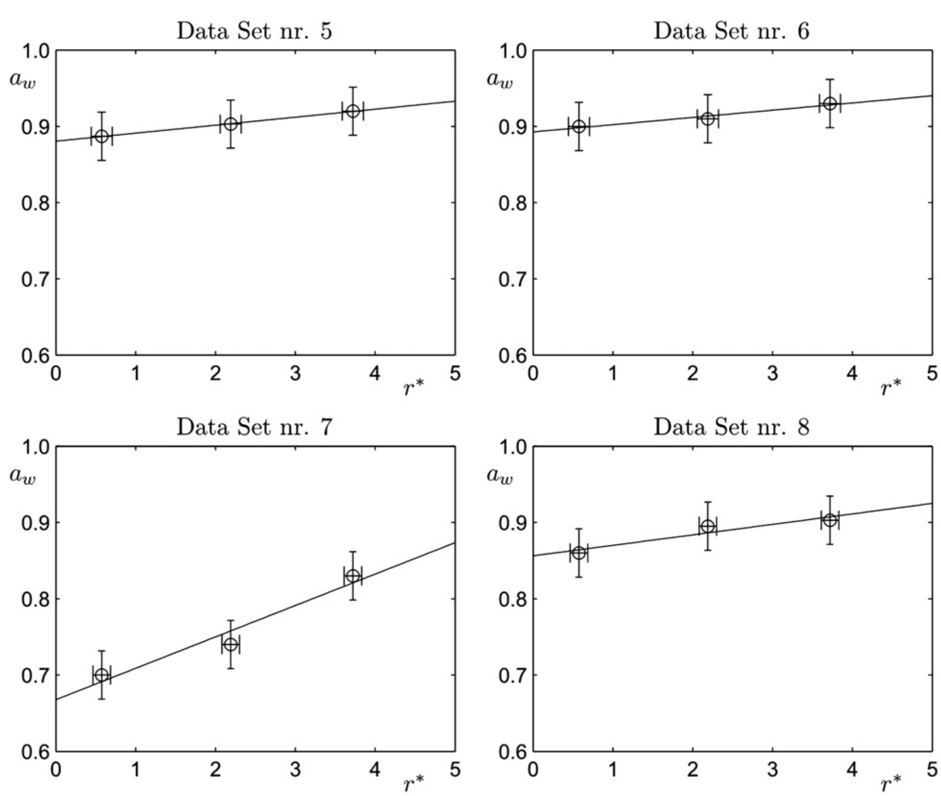

Fig. 6. $a_w(r^*)$ progress for Data Set 5 to 8 (Table 1).

Table 1
Data sets.

Data Set	Re	T_j (K)	Δt (s)
1	6950	483	300
2	7640	423	300
3	9910	483	300
4	10,900	423	300
5	6950	483	900
6	7640	423	900
7	9910	483	900
8	10,900	423	900

In Fig. 5 the results for short height ($H = 5.22$ cm) and duration ($\Delta t = 300$ s) are first presented. The drying is more efficient with decreasing distance from stagnation, as expected, due to the aforementioned temperature progress. In the wall jet region the sample (position nr. 3, Fig. 2) is being dried less efficiently, therefore the velocity at the boundary layer is less important in convecting water vapor away from the substrate surface. Then, by inspecting the plots for different Data Set couplings (Table 1), one would also expect that with increasing Re (i.e. with larger flow rate and higher turbulence at substrate surface due to JI mixing and fluctuations), a higher surface heat and mass transfer would result, specially in the stagnation region (position nr. 1). The water activity decrement, instead, appears to depend monotonically on T rather than on the Re.

This is exactly the situation depicted in Fig. 5, for Data Set nr. 3 and 4: the Re in the latter plot is higher then in the former, nevertheless with a lower T_j (Data Set nr. 4) the water activity decrement is lower. A similar, confirming effect is found by comparing the Data Sets nr. 1 and 2 in Fig. 5.

It is evident, then, that for the lowest T_j the drying proceeds less effectively, compared to the other cases. The contribution of the thermal driving force is therefore stronger than the fluid dynamic driving force.

A longer drying exposure is then presented in Fig. 6. The dependence of $a_w(r^*)$ on T_j is confirmed and, additionally, it is evident that a longer exposure dries much further the substrates (by comparing the Data Set nr. 3 and 7 plots of Figs. 5 and 6). However, by comparing all data ranges, it is confirmed that the cumulative effect of longer process duration exists, though non-linearly. In Figs. 5 and 6 runs, however, highly non-uniform substrates result for the combination of the highest T_j and a higher mass flow rate (Re = 9910), whereas the increasing Re is felt for the farthest sample, only, at the longer exposure (Data Set nr. 8 plot in Fig. 6): here the relatively high turbulence rate contributes comparatively to fetch more water from the substrate.

The same runs than in Figs. 5 and 6 have been conducted by doubling the value of H, but are not reported here as this configuration proved unfavorable. The effect of longer duration prevails uniformly, as mass transfer depends less on JI fluid structures. An even progress of $a_w(r^*)$ results for all thermal and fluid dynamics regimes, and therefore it is concluded (for the specific nozzle design employed in so far) that the increase of jet height is detrimental to the net result of the drying process, without added uniformity to the local progress of water activity, nor the increase of Re in the explored range, can improve the treatment.

3.4. Moisture content distribution and progress

The analysis on the local drying is complemented by reporting the moisture content progress, U with distance from stagnation, in Figs. 7 and 8. The same Data Sets have been enforced (Table 1). The moisture content progress is similar to the water activity distribution earlier discussed. It is evidenced, therefore, that the processing is again rather non-uniform, with an effect of drying increment for the substrate closer to the jet stagnation.

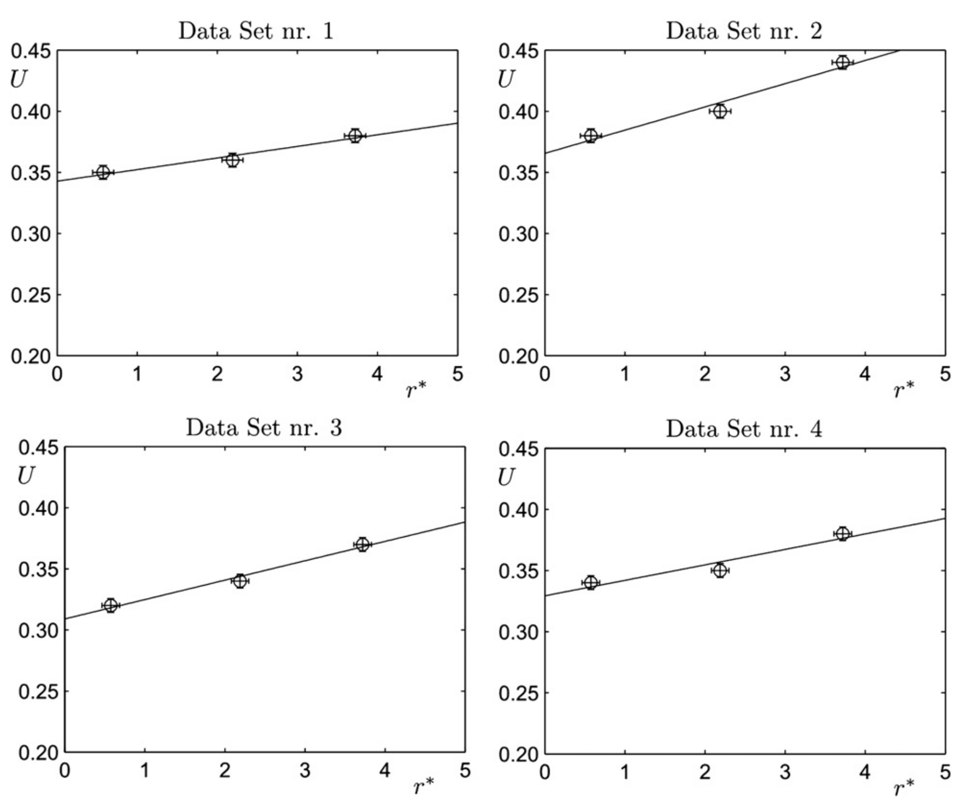

Fig. 7. $U(r^*)$ progress for Data Set 1 to 4 (Table 1).

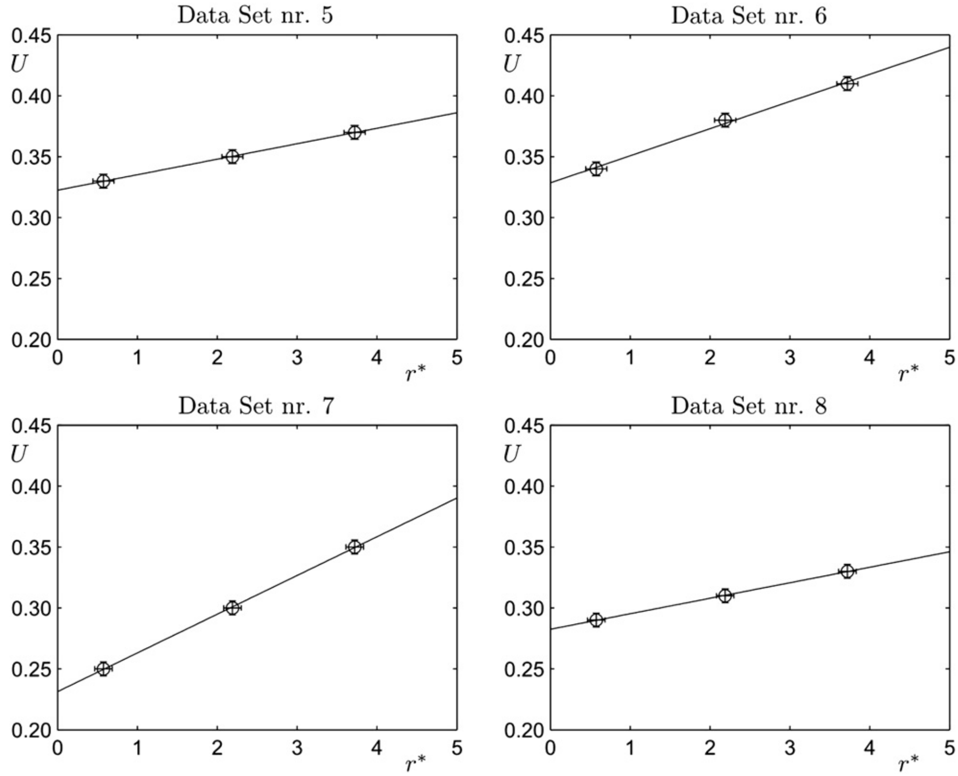

Fig. 8. $U(r^*)$ progress for Data Set 5 to 8 (Table 1).

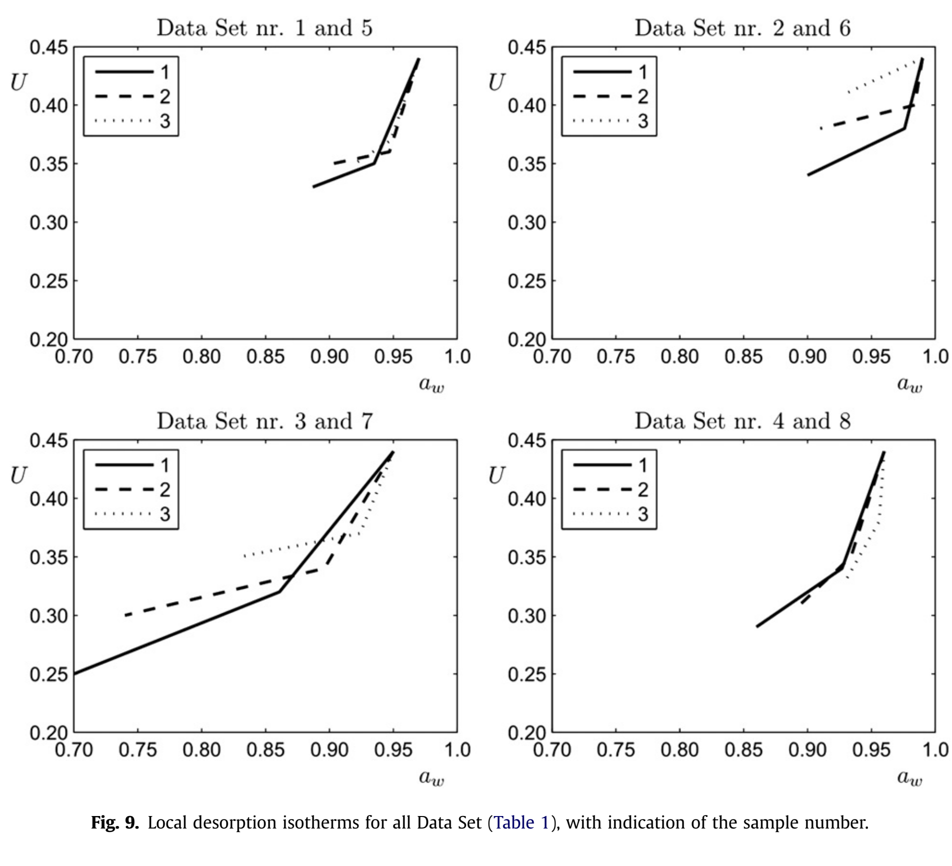

Fig. 9. Local desorption isotherms for all Data Set (Table 1), with indication of the sample number.

3.5. Local desorption isotherms

In Fig. 9 the desorption isotherms for all employed Data Sets are finally reported. The knowledge of the desorption properties of foods is of great importance in modeling food dehydration [1], as commonly performed for example by De Temmerman et al. [19]. Nevertheless in this study for the first time the concept of "local" isotherm is proposed: in Fig. 9 such isotherms are reported for each sample, under the same operating conditions. The most efficient treatments, already evidenced earlier, are those described by Data Sets nr. 3 and 7. But in these cases strong non-uniformities exist along the substrate, under the same conditions: i.e. the sample in the position nr. 3 the moisture content is much higher than in the position nr. 1 and 2. More uniform treatments result, instead, from applying Data Sets nr. 1, 4, 5 and 8: these combination of thermal and fluid dynamics driving forces are exemplary to help avoid local under- or over-processing, with every implications in the safety and quality of the food substrate. It is clear then that the present local approach should be employed when the determination of the uniformity of treatment is at stake, which simply cannot be ascertained when the usual "substrate-average" (time-dependent only) approach is enforced.

4. Conclusions

In the present work, turbulent round air jet impingement has been fundamentally characterized during a dehydration process of a moist food substrate. Four driving factors (namely, flow rate, thermal regime, process duration and geometry) have been found to influence the progress of the water activity and moisture content in the substrate.

The residual water is found varying substantially along the distance to stagnation, specially for different values of operating thermal regime. The fluid dynamic regime in the explored configurations is less effective in determining the drying strength, instead. The treatment is always rather non-uniform, and appears to depend linearly upon the exposure time and the jet height.

The "local" desorption isotherms are introduced: this concept is needful when the uniformity of the treatment is being assessed, together with usual food stability and quality considerations. Based on the present parametric analysis, the present procedure can help design drying process by air jet impingement, while evaluating a given set of governing system parameter instead of using empirical transfer coefficients.

Nomenclature

a_w	water activity, or relative humidity of substrate (−)
d	diameter (m)
H	jet height (m)
$\dot{m}$	mass flow rate (kg/s)
n	power law exponent, Eq. (1)
r	radial coordinate (m)
Re	Reynolds number (−)
T	temperature (K)
U	moisture content, wet basis (kg liquid water/kg substrate)
y	height coordinate (m)
w	air velocity (m/s)

Greek

Δt	process duration (s)
ν	kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)

Subscripts

j	jet
max	maximum
o	at outdoor inlet

Superscripts

*	dimensionless

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