OPERATIONAL CONDITIONS AFFECTING LOW-TEMPERATURE DRYING ASSISTED BY POWER ULTRASOUND

J.V. Santacatalina, J.A. Carcel, S. Simal, A. Mulet, J.V. Garcia-Perez
WHY EXPLORING THE USE OF LOW-TEMPERATURE DRYING in Solids and Pastes

HOT AIR DRYING:

PROS:
+ Low cost
+ Simple unit operation

CONS:
- High energy consuming
- Quality loss in biomaterials (high stress)
  Structural damage
  Nutritional damage (vitamins, etc…)

FREEZE DRYING OR LYOPHILIZATION

From http://www.arakawa-mfg.co.jp/
WHY EXPLORING THE USE OF LOW-TEMPERATURE DRYING in Liquids

SPRAY DRYING (ATOMIZATION):

**PROS:**
- Good quality
- High productivity (Simple operation)

**CONS:**
- Nozzles
- High viscosity liquids

From [www.bete.co.uk](http://www.bete.co.uk)
FREEZE-DRIYING OR LYOPHILIZATION

PROS:
+ Excellent quality
+ Liquids, solids and pastes
+ Market: Pharmaceutics and Biotechnology

CONS:
- Vacuum
- Batch operation
- High investment
- High operational costs
- Food industry: High added value products

From www.cci-icc.gc.ca/
LOW-TEMPERATURE CONVECTIVE DRYING

Use of air temperatures below standard room conditions (T<15-20 °C):

\( T > T_{\text{freezing}} \) (Evaporation)

\( T < T_{\text{freezing}} \) (Sublimation, Atmospheric Freeze drying)

PROS:
- No Vacuum (Continuous processing)
- Low investment
- Liquids, solids and pastes
- Similar quality than freeze-drying
- Chemical, pharmaceutical,.....

CONS: VERY SLOW!!!!
**ALTERNATIVES FOR LOW-TEMPERATURE DRYING INTENSIFICATION:**

**Thermal energy:**
- Direct increase of drying air temperature
- Thermal technologies: Microwave, Infrared radiation
- High risk of product overheating

**Mechanical energy:**
- Power ultrasound (US)
- Higher cost
- Not developed technology
Recent advances in the design of efficient air-borne ultrasonic devices have been carried by the Power Ultrasonics Group (CSIC, Spain and PUSONICS) and their feasibility for hot air drying intensification has been tested in collaboration with the ASPA Group (Universitat Politecnica de València, UPV, Spain).
Table. Compendium of previous works carried out by UPV and CSIC groups addressing the application of power ultrasound on convective drying.

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>PROCESS VARIABLE UNDER STUDY</th>
<th>MATERIAL BEING TESTED</th>
<th>ULTRASONIC DEVICE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallego-Juarez et al., 1999</td>
<td>Air temperature and ultrasonic power</td>
<td>Carrot</td>
<td>SPR</td>
</tr>
<tr>
<td>Gallego-Juarez et al., 2007</td>
<td>Air temperature and velocity and ultrasonic power</td>
<td>Carrot and apple</td>
<td>SPR</td>
</tr>
<tr>
<td>Mulet et al., 2003</td>
<td>Ultrasonic power</td>
<td>Carrot</td>
<td>SPR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2011</td>
<td>Ultrasonic power</td>
<td>Eggplant</td>
<td>CR</td>
</tr>
<tr>
<td>Ozuna et al., 2011a</td>
<td>Ultrasonic power</td>
<td>Potato</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2012a</td>
<td>Product structure and ultrasonic power</td>
<td>Orange peel</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2009</td>
<td>Product structure and ultrasonic power</td>
<td>Lemon peel and carrot</td>
<td>CR</td>
</tr>
<tr>
<td>Puig et al., 2012</td>
<td>Product structure and ultrasonic power</td>
<td>Eggplant</td>
<td>CR</td>
</tr>
<tr>
<td>Carcel et al., 2010</td>
<td>Mass load density</td>
<td>Carrot</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2006b</td>
<td>Air velocity, mass load and ultrasonic power</td>
<td>Carrot</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2007</td>
<td>Air velocity</td>
<td>Lemon peel, persimmon and carrot</td>
<td>CR</td>
</tr>
<tr>
<td>Carcel et al., 2007</td>
<td>Air velocity</td>
<td>Persimmon</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2012b</td>
<td>Air temperature</td>
<td>Eggplant, carrot and apple</td>
<td>CR</td>
</tr>
<tr>
<td>Garcia-Perez et al., 2006a</td>
<td>Air temperature</td>
<td>Carrot</td>
<td>CR</td>
</tr>
</tbody>
</table>

* CYLINDRICAL RADIATOR (CR), STEPPED PLATE RADIATOR (SPR)
“Thereby, this work aims to show the influence of air velocity and temperature, two of the most important operational parameters, on Low-Temperature Drying assisted by power ultrasound.”
**Materials and Methods**

**RAW MATERIAL:**

- Materials with very different internal structure have been used.
- Structure has been characterized by macroscopic and microscopic analysis:
  - Density and porosity measurements
  - SEM and Cryo-SEM observations
  - Instrumental texture tests have been performed.

EGGPLANT  
APPLE  
CARROT
Materials and Methods

Scheme of the convective drier with the cylindrical radiator:

- Cylindrical radiator
- Piezoelectric transducer
Materials and Methods

DRYING TESTS:

PROCESS VARIABLES:

- Air velocity (from 1 to 6 m/s)
- Air temperature (from -14 to 10 °C)

DIFFUSION MODELS were used to describe the water transport mechanisms during drying, as well as to quantify the influence of power ultrasound on kinetic parameters.

![Diagram of food particle with labels for effective diffusivity and external coefficient.]

EFFECTIVE DIFFUSIVITY, $D_e$

EXTERNAL COEFFICIENT, $K$
Results and Discussion

**Influence of raw material:**

<table>
<thead>
<tr>
<th>Material</th>
<th>AIR</th>
<th>AIR+US</th>
<th>Increment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>1.6±0.4</td>
<td>5.5±1.1</td>
<td>244</td>
</tr>
<tr>
<td>Apple</td>
<td>1.1±0.1</td>
<td>3.1±0.3</td>
<td>182</td>
</tr>
<tr>
<td>Eggplant</td>
<td>4.8±1.3</td>
<td>15.8±3.3</td>
<td>229</td>
</tr>
</tbody>
</table>

Table. Influence of ultrasonic application on effective moisture diffusivity for low-temperature drying (-14 ºC) (Garcia-Perez et al., 2012).

Figure. Influence of acoustic impedance on TC and ultrasonic performance for hot air drying operations (Ozuna et al., 2014a).
Results and Discussion

Influence of raw material

- Uniform Retreating Ice Front (URIF) models for freeze drying ($T \leq T_{\text{freezing}}$)

- FROZEN CORE + EXTERNAL POROUS LAYER $\rightarrow$ Low acoustic impedance ($Z$)

- It is being reduced the influence of internal structure $\rightarrow$ Similar behavior
Influence of air temperature

- Drying at -10 °C involves a more porous structure.
- Any remarkable effect of US was observed on product structure.
Results and Discussion

Influence of air temperature

- Larger effects of US at temperatures below freezing point (-10 °C, more porous structure)

Figure. Drying kinetics of apple cubes at 10 °C (Santacatalina et al., 2014).

Figure. Drying kinetics of apple cubes at -10 °C (Santacatalina et al., 2014).
Results and Discussion

Influence of air temperature

Figure. Drying kinetics of eggplant cubes (8.5 mm) at different air velocities and temperatures.
Results and Discussion

Influence of air velocity

- The higher the air velocity, the faster the drying.
- The same effect is observed at the different temperatures.
- The increase of air velocity reduces the external resistance to mass transfer (greater turbulence in the air/product interface).

Figure. Drying kinetics of eggplant cubes (8.5 mm) at different air velocities and temperatures.
Results and Discussion

Influence of air velocity

The typical effect is observed at 10 and -10 °C (the higher the air velocity, the faster the drying).

At 0°C, the opposite behavior was found (the higher the air velocity, the slower the drying)

WHY???

- Water removal causes the temperature reduction (close to product freezing)
- Ultrasound could contribute to the product freezing
- A portion of the energy is employed for nucleation and less amount of energy is assigned for mass transport improvement.

Figure. Drying kinetics of eggplant cubes (8.5 mm) at different air velocities and temperatures.
Results and Discussion

Influence of air velocity

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Air velocity (m/s)</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_e ) (10^{-10} \text{m}^2/\text{s})</td>
<td>1.44_a</td>
<td>1.20_a</td>
<td>1.34_a</td>
<td>1.48_a</td>
</tr>
<tr>
<td>AIR</td>
<td>( K ) (10^{-3} \text{kg w/m}^2/\text{s})</td>
<td>0.44_a</td>
<td>0.52_a</td>
<td>0.74_ab</td>
<td>0.95_b</td>
</tr>
<tr>
<td>-10</td>
<td>VAR (%)</td>
<td>99.8</td>
<td>99.5</td>
<td>99.6</td>
<td>99.7</td>
</tr>
<tr>
<td></td>
<td>EMR (%)</td>
<td>4.1</td>
<td>6.4</td>
<td>7.6</td>
<td>4.1</td>
</tr>
<tr>
<td>AIR+US</td>
<td>( D_e ) (10^{-10} \text{m}^2/\text{s})</td>
<td>8.40_b</td>
<td>11.05_b</td>
<td>10.01_b</td>
<td>10.85_b</td>
</tr>
<tr>
<td></td>
<td>( K ) (10^{-3} \text{kg w/m}^2/\text{s})</td>
<td>1.46_c</td>
<td>2.22_d</td>
<td>3.07_e</td>
<td>3.55_f</td>
</tr>
<tr>
<td></td>
<td>VAR (%)</td>
<td>99.1</td>
<td>99.5</td>
<td>99.9</td>
<td>99.7</td>
</tr>
<tr>
<td></td>
<td>EMR (%)</td>
<td>7.6</td>
<td>4.6</td>
<td>3.8</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>( \Delta D_e ) (%)</td>
<td>485</td>
<td>824</td>
<td>645</td>
<td>631</td>
</tr>
<tr>
<td></td>
<td>( \Delta K ) (%)</td>
<td>227</td>
<td>322</td>
<td>313</td>
<td>271</td>
</tr>
</tbody>
</table>

Table. Modeling of drying kinetics of eggplant cubes (8.5 mm) at -10 °C and different air velocities.

- US improved both internal \((D_e)\) than the external \((K)\) mass transport.
- The increased was more marked on \(D_e\) (up to 824%) than \(K\) (up to 313%).
- The influence of air velocity on US performance was negligible at -10 °C (FLUIDIZED BED DRYING OPERATION)
The feasibility of power ultrasound to improve low-temperature convective drying of foodstuffs has been confirmed.

Ultrasound was able to speed-up both internal and external water transport, but the effect was more marked in internal transport.

Air velocity and temperature are significant variables affecting the low-temperature drying assisted by power ultrasound.

Although, the effect was different to that found in hot air drying operations.

The scaling-up of ultrasound technology for drying operations is still a challenge ahead.


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