The operation of drying

Some characteristics of drying

• One of the most important operations in industry
  • Reduction of storage and transport needs of products
  • Increase of self life of perishable products (foods,...)

• One of the most energy demanding operations
  • High cost operations
  • Environmental implications (global warming, air pollution,...)
Drying techniques

• Osmotic drying (solid-liquid system)
• Convective drying (solid-gas system)
  • Drum drying
  • Bed drying...
• Sun drying
• Spray drying (liquid-gas system)
• Freeze drying (sublimation, vacuum)
• Atmospheric freeze drying (sublimation)
Convective drying

Main drawbacks
- Energy needs (water phase change)
- Slow kinetics: labor and facilities needs
- Economic cost
- Environmental impact

INTENSIFICATION

Conventional alternatives to increase drying rate

- **Internal resistance: Increase air drying temperature**
  - Thermosensitive food nutrient degradation
  - Undesirable chemical/biochemical reactions
  - Collapse of raw structure

- **External resistance: Increase drying air velocity**
  - Structure could be affected: Case hardening
  - No significant drying rate increase at large air velocities

Search the adequate drying methods for quality preservation (nutrient, structure, ...)

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Drying process intensification

**Process intensification**

The improvement of traditional technologies and at the development of new techniques that will lead to higher production yield, notable reduction in equipment size (both principal and ancillary), lower energy use and waste production, and increase product quality and processing safety, therefore offering more sustainable technologies.

**Drying intensification:** Enhance water removal rate (mass and heat transfer) while simultaneously considering all their constraints.

Combine new alternative sources of energy with convective drying:
- Mechanical
- Thermal
- Hydrodynamic
- Electromagnetic
- Chemical
- ...  
- **ACOUSTIC**

Ultrasound application on convective drying

**How ultrasound can intensify convective drying?**

- **Increasing drying rates**
  - Internal resistance
    - “Sponge effect”
    - Creation of microchannels
  - External resistance
    - Alternating pressures
    - Microstirring at interfaces
- **Small heating effect**: Quality preservation

Could contribute to **drying intensification** affecting
- Kinetics
- Product quality
- Energy consumption
Influence of process variables on ultrasonic effects

Air velocity

The influence of application of ultrasound in drying is high when low air velocities are applied. For some products, this influence disappears at high air velocities. Usually, the effects of ultrasound are significant at air velocities lower than 2 m/s: WHEN DRYING IS SLOWER

![Graph showing influence of air velocity on drying process](image)

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Influence of process variables on ultrasonic effects

Air velocity

The turbulence produced by high air velocities could disrupt the ultrasonic field affecting its effects.

Measures of sound pressure level inside a drying chamber with ultrasound application at different air velocities.

Air velocity

Influence of process variables on ultrasonic effects

Structure of acoustic field inside a cylindrical drying chamber with and without air flow.
Influence of process variables on ultrasonic effects

Power ultrasound applied

The effects of ultrasound depend on the ultrasonic intensity received by the samples: the higher the intensity, the greater the effects.


Influence of process variables on ultrasonic effects

Power ultrasound applied

The power applied affect both internal and external resistance to mass transfer.

Influence of process variables on ultrasonic effects

Power ultrasound applied

There is a threshold of power applied, above it is possible to identify the effects of ultrasound.

Effective diffusivity identified in the drying of carrots and lemon peel at different ultrasonic power. Air temperature 40 °C and air velocity 1 m/s.
Influence of process variables on ultrasonic effects

Power ultrasound applied

At the same ultrasonic intensity applied, the effects depends of the product treated.

Interaction between power ultrasound applied and product

At the same ultrasonic intensity applied, the effects depends of the product treated.

Slope of linear relationship of \( D_W \) and \( UP (SDUP) \): Constitute a measurement of how the product is prone to the effectiveness of ultrasonic assisted drying.
Influence of process variables on ultrasonic effects

Interaction between applied ultrasound power and product

Products studied have different internal structure.


<table>
<thead>
<tr>
<th>Product</th>
<th>Porosity</th>
<th>H (N)</th>
<th>Z (MRayl)</th>
<th>TC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eggplant</td>
<td>0.423±0.020</td>
<td>9.90±2.73</td>
<td>0.143</td>
<td>0.011</td>
</tr>
<tr>
<td>Orange peel</td>
<td>0.330±0.025</td>
<td>9.88±2.09</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lemon peel</td>
<td>0.370±0.017</td>
<td>15.07±1.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Apple</td>
<td>0.233±0.026</td>
<td>25.92±1.63</td>
<td>0.177</td>
<td>0.009</td>
</tr>
<tr>
<td>Cassava</td>
<td>0.029±0.014</td>
<td>30.28±1.01</td>
<td>0.251</td>
<td>0.007</td>
</tr>
<tr>
<td>Potato</td>
<td>0.060±0.010</td>
<td>31.25±1.79</td>
<td>0.660</td>
<td>0.003</td>
</tr>
<tr>
<td>Carrot</td>
<td>0.031±0.016</td>
<td>44.37±1.53</td>
<td>0.286</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Average values and standard deviation.

Porosity, hardness (H), acoustic impedance (Z) and air/solid transmission coefficient (TC) values measured for the different products tested. Average values and standard deviation.

Impedance (Z): The difference of impedance determine the coupling between solid material and air.

Air/solid transmission coefficient (TC): Constitute a measurement of the fraction of acoustic energy that penetrate in the solid.
Influence of process variables on ultrasonic effects

Interaction between applied ultrasound power and product
The different structure implies that the products have different physical characteristics.

Influence of acoustic impedance (Z, MRayl) of different fruits and vegetables on the ultrasound effectiveness (SDUP, m⁵/kJ) during the drying of different fruits and vegetables (40ºC, 1 m/s) and the air/solid transmission coefficient (TC).

Influence of process variables on ultrasonic effects

Influence of ultrasound treatment in treated products

The ultrasound affected the structure of treated product

- Drying: Spread out of the waxy compound of flavedo (the outside structure of orange peel)
- Application of ultrasound amplify the spread: probably by alternating pressures and the microstirring at the interfaces

\[ \text{Cryo-SEM micrographs of cuticle surface ORANGE PEEL: a (×500); b (40 \, ^\circ \text{C}; 1 \, \text{m/s}; \times 350); c (×2,000); d (40 \, ^\circ \text{C}; 1 \, \text{m/s}; 90 \, \text{W}; \times 2,000). Data from: García-Pérez, J.V., Ortúñio, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012a. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. Food and Bioprocess Technology 5: 2256-2265.} \]

- During conventional air drying:
  - Albedo (inner structure of orange peel) is disrupted
  - Cell tubular shape disappear: water removal collapse the typical cell structure.
- Ultrasonic-assisted drying
  - More intense disruption of the albedo cells than air dried samples
  - High degradation of the cellular structure generating large intercellular space.
  - Ultrasonic stress: sponge effect and the creation of microchannels

\[ \text{Cryo-SEM micrographs of albedo cells from ORANGE PEEL: a fresh (×350); b air dried (40 \, ^\circ \text{C}; 1 \, \text{m/s}; \times 500); c ultrasound-assisted drying (40 \, ^\circ \text{C}; 1 \, \text{m/s}; 90 \, \text{W}; \times 5000). Data from: García-Pérez, J.V., Ortúñio, C., Puig, A., Cárcel, J.A., Pérez-Munuera, I., 2012a. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. Food and Bioprocess Technology 5: 2256-2265.} \]
Influence of process variables on ultrasonic effects

Influence of ultrasound treatment in treated products

The ultrasound affected the structure of treated products

- Conventional convective drying involved microstructural changes in the endocarp: a high degree of degradation and a compacting process.
- In general application of ultrasound reduced the drying changes: increase the mechanical stress but reduce the drying time.
- There is an optimum ultrasonic power: 45W treated samples maintained better the original structure than 90W treated samples.

Cryo-SEM: Endocarp from raw EGGPLANT (A) and dried eggplant samples (40 ºC, 1 m/s) : conventionally (B) and with ultrasound application at 45 W (C) and 90 W (D). Data from: A. Puig, I. Perez-Munuera, J.A. Carcel, I. Hernando, J.V. Garcia-Perez. 2012. Moisture loss kinetics and microstructural changes in eggplant (Solanum melongena L.) during conventional and ultrasonically assisted convective drying. Food and Bioproducts Processing 90, 624-632.

Drying temperature

The increase of drying rate produced by ultrasound is higher at low than at high temperature.

Influence of process variables on ultrasonic effects

Drying temperature

The effects of ultrasound are reduced at temperatures higher than 70 °C, being more intense at lower temperatures when drying kinetics is slower.

\[
\ln D_e = -2811.2 \frac{1}{T} - 13.7
\]

\[R^2 = 0.99\]

Without ultrasound

With ultrasound


Influence of process variables on ultrasonic effects

Drying temperature

The application of ultrasound during drying reduce drying time and can contribute to reduce the energy consumption.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>US</th>
<th>AIR</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective diffusivity (10⁻⁹ m²/s)</td>
<td>6.13</td>
<td>4.04</td>
<td>51.7</td>
</tr>
<tr>
<td>Mass transfer coefficient (10⁻³ kg water/m²s)</td>
<td>2.43</td>
<td>1.17</td>
<td>107.7</td>
</tr>
<tr>
<td>Drying time (h)</td>
<td>5.0</td>
<td>9.7</td>
<td>-48.4</td>
</tr>
<tr>
<td>Energy consumption (kWh)</td>
<td>1.20</td>
<td>1.65</td>
<td>-37.5</td>
</tr>
</tbody>
</table>

Effective diffusivity and mass transfer coefficient identified for the drying of ORANGE PEEL (40 °C; 1 m/s) with (US: 90 W; 21.8 kHz) and without (AIR) application of ultrasound. Drying process extended until achieve the lose of the 80 % of initial weight. Data from: García-Pérez, J. V., Ortuño, C., Peig, A., Cárcel, J.A., Pérez-Munuzuri, I., 2012. Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. Food and Bioprocess Technology 5: 2256-2265.
Influence of process variables on ultrasonic effects

Drying at low temperature

Removal of solvents at low temperature (below or close to freezing point) is a slow process used in different industrial areas (food, chemical, pharmaceutical or cosmetic) to preserve quality attributes.

Main example Vacuum Freeze Drying
- Provide high quality products
- Very expensive process: batch production (vacuum)
- Only applied to obtain high added value products (special foods, chemical or pharmaceutical products,...)

Alternative: Atmospheric Freeze Drying
- High quality products as vacuum freeze drying
- Continuous production: lower cost than vacuum freeze drying
- Very slow process: need of intensification

Drying at low temperature assisted by ultrasound

1. Fan
2. Pt 100
3. Temperature and relative humidity sensor
4. Anemometer
5. Ultrasonic transducer
6. Vibrating cylinder
7. Sample load device
8. Retreating pipe
9. Slide actuator
10. Weighing module
11. Heat exchanger
12. Heating elements
13. Desiccant tray chamber
Drying at low temperature assisted by ultrasound

Equipment

**PROCESS SETTINGS**

- Temperature (-15 to 80 °C)
- Air velocity (0.1 to 20 m/s)
- Parallel or through air flow
- Solids and semisolids
- HPU Devices: tube and plates
- HPU Powers: until 40 kW/m³ (160 dB)

Drying at low temperature assisted by ultrasound

From modelling

<table>
<thead>
<tr>
<th>Material</th>
<th>( D_e ) (10(^{-11}) m(^2)/s)</th>
<th>Increment (%)</th>
<th>( k ) (10(^{-5}) kg water/m(^2)s)</th>
<th>Increment (%)</th>
<th>Explained variance(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>AIR 0.8(\pm)0.1</td>
<td>+425</td>
<td>3.3(\pm)1.5</td>
<td>+152</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>AIR+US 4.2(\pm)0.4</td>
<td></td>
<td>8.3(\pm)2.3</td>
<td></td>
<td>99.8</td>
</tr>
<tr>
<td>Apple</td>
<td>AIR 1.4(\pm)0.7</td>
<td>+428</td>
<td>4.8(\pm)0.2</td>
<td>+96</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td>AIR+US 7.4(\pm)2.1</td>
<td></td>
<td>9.4(\pm)0.9</td>
<td></td>
<td>99.9</td>
</tr>
<tr>
<td>Eggplant</td>
<td>AIR 4.4(\pm)1.7</td>
<td>+407</td>
<td>23.7(\pm)4.3</td>
<td>+170</td>
<td>99.9</td>
</tr>
<tr>
<td></td>
<td>AIR+US 22.3(\pm)4.7</td>
<td></td>
<td>64.1(\pm)10.4</td>
<td></td>
<td>99.9</td>
</tr>
</tbody>
</table>

- Ultrasound increased the mass transfer coefficient
- Ultrasound increased the diffusion coefficient:

**REDUCTION OF EXTERNAL RESISTANCE**

**REDUCTION OF INTERNAL RESISTANCE**


Drying at low temperature assisted by ultrasound

Ultrasound can be used to enhance mass transfer in the removal solvents process at low temperatures

CONCLUSIONS

• Ultrasound, adequately applied (design of efficient equipment), enhances the moisture transport during drying.

• The effects of ultrasound depended mainly of the actual acoustic energy applied that is influenced by process variables such as air velocity (turbulence), power applied, mass load density or product treated.

• Therefore, each particular application needs a previous study to determine the optimum process variables to achieve the maximum effects of ultrasound.

• The effectiveness of ultrasound increases when lower energy are available in the medium: at low temperatures and air velocities.

• Thus, the ultrasonically assisted drying at low temperature can be an interesting alternative to an expensive and high demanding energy process such as freeze-drying.