Recent Innovations in Drying Technologies

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August 2016
Introduction - Role of IDS/LDRT
Innovation - Needs and challenges
Selected innovations
  o SHSD
  o Pulse Combustion Drying
  o DIC/Swell Drying
  o Flame Drying

Closing remarks
Introduction - What is innovation? Novelty, Renovation versus Innovation

Why Innovation? Incremental vs Radical

Technology Development via Industry-University Collaboration

Time scales of Innovation in Drying-Academia-Industry appear to be a mismatch

Innovative dryers-most are at lab and pilot scales
Thinking out of the box

... maybe we should try to think out of the box?
Motivating factors for innovation

- New product or process
- Higher capacities than current technology permits
- Better quality than currently feasible
- Reduced overall cost
- Reduced environmental impact, sustainable
- Safer operation; more flexibility
- Better efficiency
Innovations in drying

Innovative dryers for particulates

Modified Fluid Beds
- Vibrated
- Agitated Mechanically
- Pulsed Air
- Periodic localized Fluidization
- Superheated Steam

Modified spouted beds
- Pulsed
- 2D
- Superheated Steam
- Mechanical fluidization
- SB driven by pulse combustor

Impinging Streams
- 2D
- Complex Geometries
- Superheated steam
- Vortex Type
Classification of Innovations

Based on way heat is supplied
- Steady
- Periodic
- on/off
- Combination of different modes - concurrent or sequential

Cyclic Operation
- Pulsed fluidization or spouting

Multi-staging
- Conventional or innovative dryers in multi-stage arrangement
## Conventional vs Newer developments

<table>
<thead>
<tr>
<th>Conventional</th>
<th>Innovative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Steady thermal energy impact</td>
<td>• Intermittent energy input</td>
</tr>
<tr>
<td>• Constant gas flow</td>
<td>• Variable gas flow</td>
</tr>
<tr>
<td>• Single mode of heat input</td>
<td>• Combines modes of heat input</td>
</tr>
<tr>
<td>• Single dryer type - single stage</td>
<td>• Multi-stage; each stage maybe different dryer type</td>
</tr>
<tr>
<td>• Air/combustion gas as convective medium</td>
<td>• Superheated steam drying medium</td>
</tr>
</tbody>
</table>
Developments in Drying

Developments in Drying Coarse Classification

Empirical (> 90% published work)

Modeling Drying

*Modeling Dryers

- Microscopic
- Macroscopic
- Analysis / scale-up / Control
- Smart dryers

Lab Scale

- > 80%

Pilot Scale

- ~ 10%

** Industrial Scale

- ~ 10%

* Dependent on dryer type and material

** Unpublished; difficult to guestimate
Developments in drying

Industrial Drying - Innovations

Incremental Evolutionary
- Low risk
- Hybrids of known technologies
- More accepted by industries

Radical / *Revolutionary
- High risk
- Not readily accepted
- High R&D cost

* Game changing technologies - few

Long half-life of drying technologies attracts less R&D. ROI on R&D investment not attractive
Developments in drying

Coarse Classification of Innovations in Thermal Dryers

How wet material is handled
- Stationary
- Moving
- Agitated
- Vibrated
- etc

How heat is supplied to dryer
- Convection
- Conduction
- Radiation
- MW/RF
- Combinations / Concurrent / Consecutive
- Intermittent

Miscellaneous
- Hybrids
- Multi-staging
- In-situ heat generation - Remaflam / Flame Drying
- Pulse Combustion Drying
- Superheated Steam Drying
Developments in drying

Some Recent Innovations*

- Inclined Blade Paddle Dryer
  TSK, Japan
- Remaflam / Flame Drying
- Pulse Combustion Dryer
- DIC / Swell Drying

- Sludge
- Pastes
- Textile
- Liquids
- Liquids

* Illustrative only, No commercial endorsement is intended or implied
Enhancement of Drying Rates

- Vibration (e.g. Vibrated bed dryers)
- Pulsations (e.g. Impinging jets)
- Sonic or ultrasonic fields (e.g. pulse combustion dryers)
- Dielectric fields {MW, RF} (e.g. MW-assisted steam drying)
- Superheated steam drying
Superheated Steam Dryers

- **Low Pressure**
  - Vacuum steam dryers for wood*
  - Vacuum steam dryers for silk cocoons**

- **Near Atmospheric Pressure**
  - Fluidized bed dryers for coal*
  - Impingement and/or through dryer for textiles, paper***

- **High Pressure**
  - Flash dryers for peat (25 bar)****
  - Conveyor dryers for beet pulp (5 bar)****
  - Fluidized bed dryers for pulps, sludges*

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* Extensive commercial applications
** Laboratory scale testing
*** Pilot scale testing
**** At least one major installation
Superheated steam drying

Possible Types of SSD

- Flash dryers with or without indirect heating of walls
- FBDs with or without immersed heat exchangers
- Spray dryers
- Impinging jet dryers
- Conveyor dryers
- Rotary dryers
- Impinging stream dryers
Photographs of carrot cubes underwent LPSSD and vacuum drying

*Devahastin et al., Drying Technol., 22, 1845-1867 (2004)*
Superheated steam drying

SEM photographs of carrot undergoing (a) LPSSD, (b) vacuum drying

SEM photographs showing pore distribution of carrot undergoing (a) LPSSD, (b) vacuum drying

Pulse combustion is intermittent; can be subsonic or supersonic Mach Number >1.0 (supersonic)

<table>
<thead>
<tr>
<th>Features</th>
<th>Steady</th>
<th>Pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion intensity (kW/m³)</td>
<td>100-1000</td>
<td>10000-50000</td>
</tr>
<tr>
<td>Efficiency of burning (%)</td>
<td>80-96</td>
<td>90-99</td>
</tr>
<tr>
<td>Temperature level (K)</td>
<td>2000-2500</td>
<td>1500-2000</td>
</tr>
<tr>
<td>CO concentration in exhaust (%)</td>
<td>0-2</td>
<td>0-1</td>
</tr>
<tr>
<td>NOx concentration in exhaust (mg/m³)</td>
<td>100-7000</td>
<td>20-70</td>
</tr>
<tr>
<td>Convective heat transfer coefficient (W/m²k)</td>
<td>50-100</td>
<td>100-500</td>
</tr>
<tr>
<td>Time of reaction (s)</td>
<td>1-10</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Excess air ratio</td>
<td>1.01-1.2</td>
<td>1.00-1.01</td>
</tr>
</tbody>
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http://blastwavejet.com/pulsejet.htm
Pulse combustion drying (PCD)

- High drying rates
  - Increased turbulence and flow reversal in the drying zone promote gas/materials mixing
  - Decreased boundary layer thickness of materials
  - Increased heat and mass transfer rates
  - High driving force because of high gas temperature

- Short contact time
  - Suitable for some heat sensitive materials

- High energy efficiency and economic use of fuels

- Environmentally friendly operation

- Noise and scale-up issues
<table>
<thead>
<tr>
<th>Dryers</th>
<th>Typical evaporation capacity</th>
<th>Typical consumption (kJ/kgH₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC dryers</td>
<td>250-2000 kg H₂O/h</td>
<td>3000-3500</td>
</tr>
<tr>
<td>Tunnel dryer</td>
<td></td>
<td>5500-6000</td>
</tr>
<tr>
<td>Impingement dryer</td>
<td>50 kg H₂O/hm²</td>
<td>5000-7000</td>
</tr>
<tr>
<td>Rotary dryer</td>
<td>30-80 kg H₂O/hm²</td>
<td>4600-9200</td>
</tr>
<tr>
<td>Fluid bed dryer</td>
<td></td>
<td>4000-6000</td>
</tr>
<tr>
<td>Flash dryer</td>
<td>5-100 kg H₂O/hm³</td>
<td>4500-9000</td>
</tr>
<tr>
<td>Spray dryer</td>
<td>1-30 kg H₂O/hm³</td>
<td>4500-11500</td>
</tr>
<tr>
<td>Drum dryer (pastes)</td>
<td>6-20 kg H₂O/hm²</td>
<td>3200-6500</td>
</tr>
</tbody>
</table>
Pulse combustion spray drying of egg white

PC Spray dryer

PC Atomizer
Product quality - physical properties

Product color

PC spray drying: White

Traditional spray drying: Pale yellow
Product quality - physical properties

Product morphology

PC spray drying
1. Hollow
2. Single
3. Smooth surface

Traditional spray drying
1. Solid
2. Aggregated
3. Coarse surface
Another way - applying step-wise change in operating conditions

Especially final stage of drying - drying rates are sluggish (diffusion controlled) hence effect of external conditions is negligible

Use - stepwise change in operating conditions to save energy

Use - Combinations of modes of heat input

Concept can be applied for different drying methods - tray dryer, FBD, conveyor dryer etc.

Flipping of product?
Energy Savings & Quality Enhancement
Intermittent Drying

Batch - temporal

- Cyclic or time-varying heat input by convection, conduction, radiation, dielectric fields, etc.
- Concurrent or sequential

Continuous - spatial

- Inherent
  - Rotary Dryers
  - Spouted Beds
  - Multi-cylinder paper dryers

- Imposed
  - Freeze Dryers
  - Wood Drying Kilns
  - Pulsed Fluid Beds
Some examples of Intermittent Drying

- Rotating Jet Spouted Bed dryer
- Pulsed bed - intermittent fluidization
- Vibrated bed with tempering periods
- Intermittent IR/MW in a batch heat pump dryer
- Conveyor (Apron) dryer with parts of the dryer unheated

Aside from reduced energy/air consumption, product quality may be better for heat-sensitive and/or fragile solids. Slight increases in drying time are expected.
Controlling freezing

▪ What is being controlled?
  ▪ Size of the ice crystals
  ▪ Density of the ice crystals

▪ Why control freezing?
  ▪ Determines bioavailability of products (squishing and intermolecular conc.)
  ▪ Affects final product structure
  ▪ Determines subsequent sublimation rate (freeze drying)
Effect of DC electric field

- Aligns the dipole water molecules

- Implication:
  - Lower level of supercooling
  - Reduces cooling time
  - Larger ice crystals
  - Increases sublimation rate
Effect of magnetic field

- Maintains water in a metastable state (induces molecular electron spin)

- Implications
  - Higher level of supercooling
  - Smaller and more uniform ice crystals
  - Better product preservation
  - Increases freezing time
  - Reduces sublimation rate
Magnetocaloric freezer

- Working principal of a magnetocaloric freezer
Unique feature:

• The liquid material to be dried is first prepared into a frozen material like ice-cream with a certain initial porosity, and then freeze-dried.

• Mannitol was selected as the primary solute in aqueous solution. Liquid nitrogen ice-cream making method was used to prepare the samples.

• More than 30% of drying time was saved.

• Latest publication: Wang W et al. AIChE J. 2015, DOI10.1002/aic.14769
1) LN; 2) stirrer; 3) insulated barrel; 4) solution
SEM images ($S_0=0.28$)
**MW Freeze drying**

- microwave can heat the material volumetrically; thus, greatly improving freeze drying rate is possible
- most promising techniques to accelerate drying and to enhance overall quality
- Examples - Cabbage, marine products, banana chips, potato, skim milk
Images of 400 field of view of samples at different drying stage (1) fresh samples, (2) pre-freezing stage samples, (3) primary drying stage samples of MFD, (4) secondary drying stage samples of MFD, (5) primary drying stage samples of FD and (6) secondary drying stage samples of FD.

Some Hybrid Dryers

Particulate, Granular products
- Flash + Fluid bed
- Fluid bed + Packed bed
- Vacuum + MW
- Well-mixed fluid bed + plug flow fluid bed dryer
- Convection dryer + Vacuum frying

Liquid/Paste
- Spray + Fluid bed
- Spouted bed or fluid bed of inert particles

Sheets (e.g. fruit leather)
- Impingement + IR Radiation
- Fluid bed of inert particles
Instantaneous Controlled Pressure Drop “DIC” method (Détente Instantanée Controlee)

- High température treatment
- Instant Pressure Drop
- Instant cooling
- Expansion

Pressure
MPa

0.1 < P < 1

High température treatment
time

Patm

5 kPa Vacuum

5 kPa Vacuum

5 < t < 60 s
Variable pressure drying

Auto-vaporization

Essential oil Extraction (volatile molecules)

DDS Direct Drying

Stop thermal degradation

De-allergenicity

Cracking/depolymerization of cellulose: 3rd generation bioethanol

DIC

Instant Cooling

Expansion

Swell-Drying

3-stage spray-drying

Decontamination

Solvent Extraction

In-Situ TransEsterification (Biodiesel)
Conventional vs Swell drying

Water content (% DB)

D.I.C.

Post-D.I.C. drying

Standard drying

Time (min)
Variable pressure drying

Structure and Microstructure

Standard Drying

Swell-Drying
Drying comparison

Time (min)

- Conventional Drying
- Swell-drying

- bananas
- kiwis
- apples
Drying is highly energy intensive hence it adversely affects environment, plus good quality is needed to be maintained for foods - need for smart/intelligent dryers

Use mathematical models, advanced sensors and automatic control strategies to design smart dryer

A smart dryer:
- Provides actionable information regarding the performance of the drying system
- Proactively monitors and detects errors or deficiencies in dryer operation
- Incorporates the tools, technologies, resources and practices to contribute to energy conservation and environmental sustainability.

Designed to sense local drying conditions/product properties and adjust them in order to get specified quality at optimized energy consumption.
Industry-academia collaboration with tangible industry collaboration

Global networking - pool human and financial resources. Also promotes innovation and avoids duplication

Develop reliable math models to study innovative concepts before physical testing

Study carefully archival literature and conference papers for ideas and also collaborations
Despite low energy cost - R&D for innovation is needed
- Quality, Carbon footprint are driving forces
- Better models for drying and dryers are still needed.
Handbook of Industrial Drying (CRC Press)

Key contributions to 4th Edition by TPR group

- Principles, Classification, and Selection of Dryers
- Basic Process Calculations and Simulations in Drying
- Indirect Dryers
- Fluidized Bed Dryers
- Industrial Spray Drying Systems
- Impingement Drying
- Pulse Combustion Drying
- Drying in Mineral Processing

- Physicochemical aspects of Sludge drying
- Drying of Proteins
- Product functionality oriented drying process related to pharmaceutical particle engineering
- Drying of Coal
- Use of Simprosys in Drying Flowsheet Calculations
- Life Cycle Assessment of drying systems
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