欢庆天津科技大 学建校五十年

Recent Developments and R&D Needs in Thermal Drying Technologies

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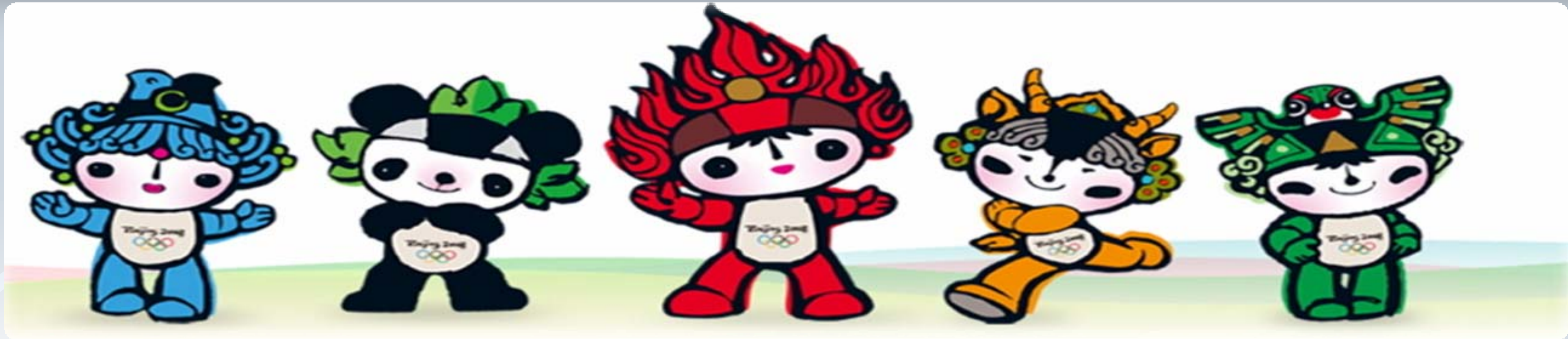


Acknowledgements

I am grateful to my Research Students and Associates who worked with me over more than three decades in drying R&D.

Dr Chung Lim Law , Dr Zhonghua Wu and Dr Xu Peng contributed in various ways to the prepartion of this talk

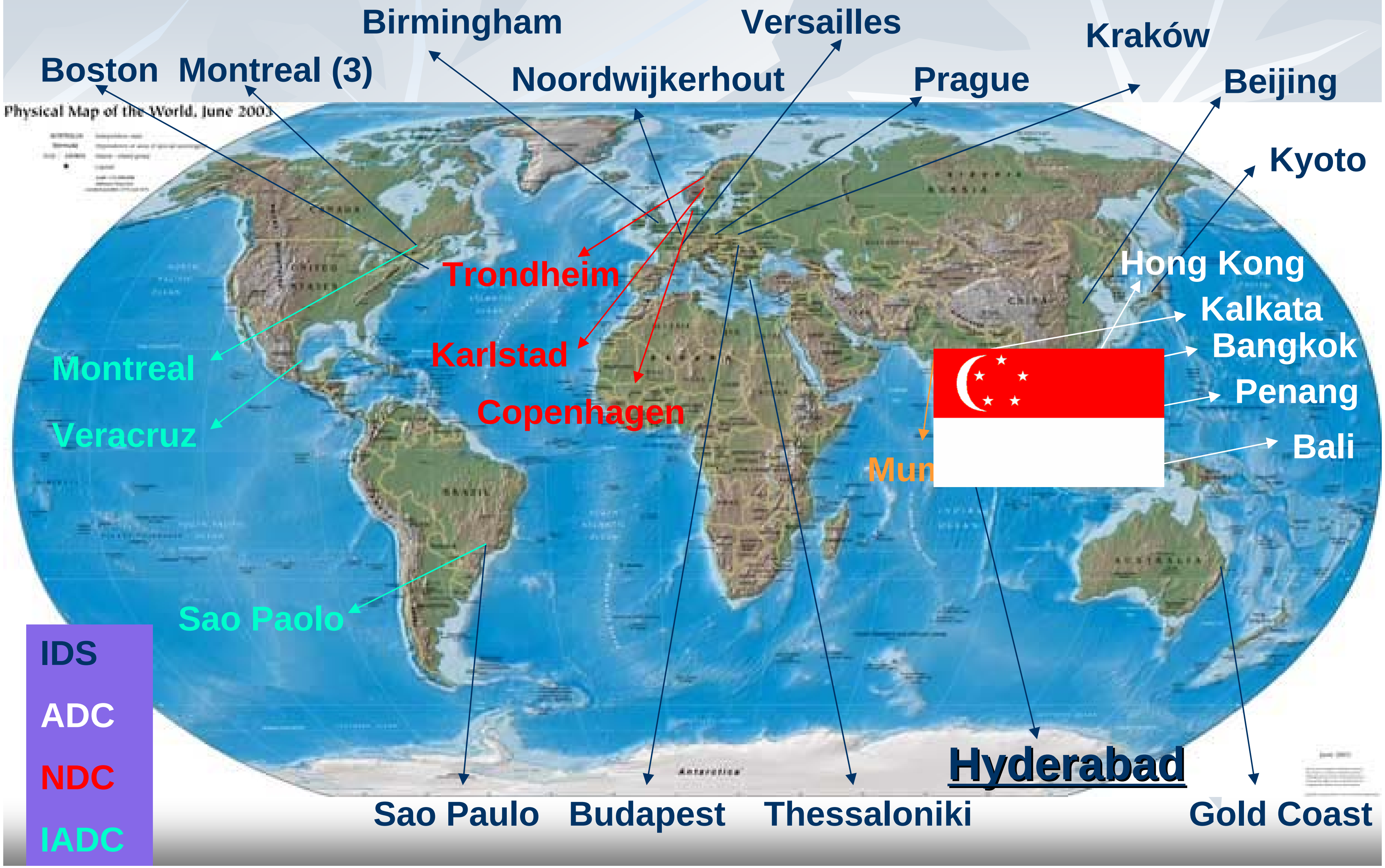
GREETINGS FROM BEIJING OLYMPICS!

Seminar: Danish Technological Institute
October 2008

Introduction to Drying Resources

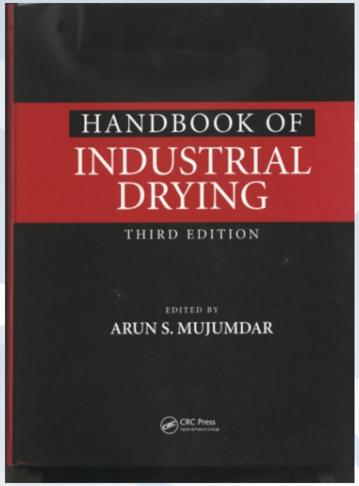
- **Brief chronology**- ASM started in drying R&D in Canada developing steam drying of newsprint-then proceeded to cover grains, foods, ceramics, sludges, coal, dewatering etc etc
- Founded IDS series in 1978 at McGill- 16th IDS to be held in Hyderabad, India in November 2008
- Numerous Drying conferences spawned over the years-in 2009 no fewer than 6 conferences will be held in various parts of the globe- devoted to drying
- ***Covers wide range of topics- necessary to skip some slides or glass over others!***

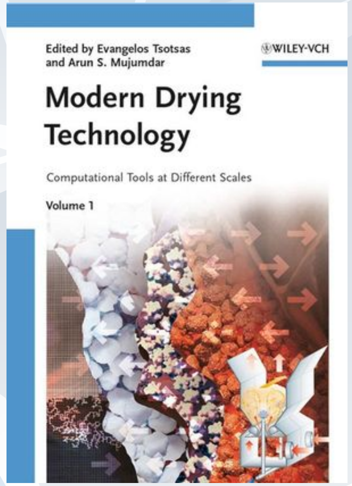
Conferences on Drying Technology

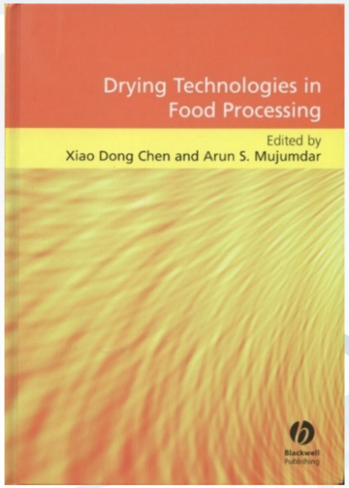


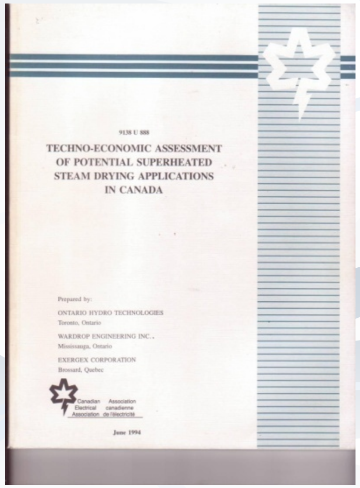
Recent Resources on Drying Technology

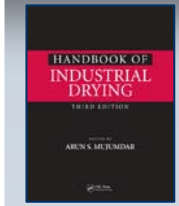
- GUIDE TO INDUSTRIAL DRYING: *PRINCIPLES, EQUIPMENT AND NEW DEVELOPMENTS*
- HANDBOOK OF INDUSTRIAL DRYING (*THIRD EDITION*)
- MODERN DRYING TECHNOLOGY: *COMPUTIONAL TOOLS AT DIFFERENT SCALES, VOLUME 1*
- DRYING TECHNOLOGIES IN FOOD PROCESSING
- TECHNO-ECONOMIC ASSESSMENT OF POTENTIAL SUPERHEATED STEAM DRYING APPLICATIONS IN CANADA
- DRYING TECHNOLOGY: *AN INTERNATIONAL JOURNAL*

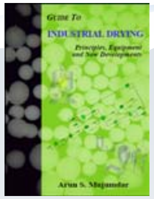


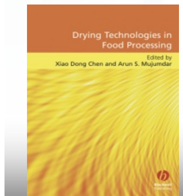






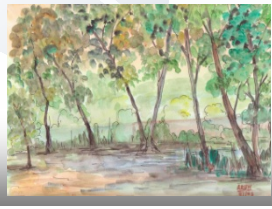
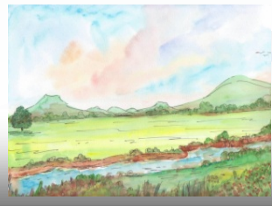


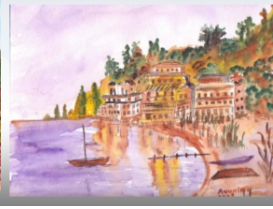
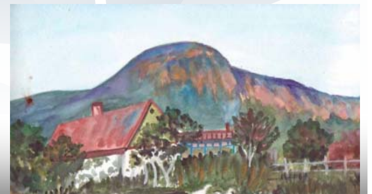




<u>Some *Statistics* and Factoids on Drying</u>

- Product size: µm – ten of cm
- Product porosity: 0 – 99%
- Drying times: 0.25sec (tissue paper) to 5months (hard woods)

INNOVATION AND R&D NEEDS IN INDUSTRIAL DRYING TECHNOLOGIES

- **Introduction**
  - Statistics
  - Significance
  - Complexity
- **Innovation**
  - Definition
  - Characteristics
  - ‘S’ Curve
- **Intensification**
  - Digital Computing
  - Some Observations
- **Selected Innov**
  - Selected Drying Technologies
  - Conventional vs. Innovative
  - Innovative Concepts
- **Selected DrT**
  - Steam
  - Pulse Combustion
  - Heat Pump
  - Spray
  - Impinging Streams
- **Closure**

Outline

- *Introduction to Drying*
- *Some facts and figures, complexity in Drying*
- *Difference between conventional and innovative dryers*
- *What is innovation?*
- *Selected new dryers*
- *Need for R&D in Drying*
- *Closure*

A bit about NUS-National University of Singapore, Singapore

- Joined NUS ME in 2000 after 25 years on Chemical Engg. faculty of McGill Univ., Montreal ,Canada
- NUS; 30,000 students; 9000 postgrad.students
- 9000 students in Engg Faculty; 1/3 postgrads
- Ranked 8 in Science and Technology by London Times- 3rd in Asia as University, 33 overall
- McGill Univ. ranked 12 overall, first in N. America as a Public University, 2007
- Research-intensive university

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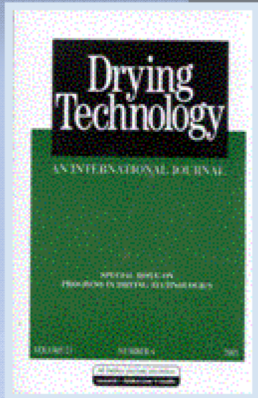
Some *Statistics* and Factoids on Drying

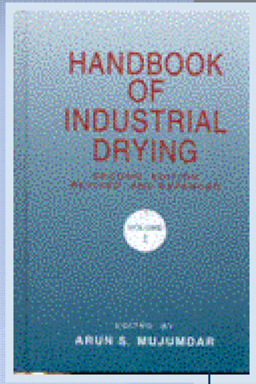
- Product size: µm – tens of cm
- Product porosity: 0 – 99%
- Drying times: 0.25sec (tissue paper) to 5months (hard woods)
- Production capacities: 0.10kg/h - 100t/h
- Product speeds: 0 (stationary) - 2000m/min (tissue paper)
- Drying temperatures: < triple point - > liquid critical point
- Operating pressures: < 1millibar - 25atm
- Heat supply: continuously, intermittently;

  convection, conduction, thermal and microwave radiations
- Patents granted each year: 250 (US), 80 (European)



Some Statistics and ***Factoids*** on Drying

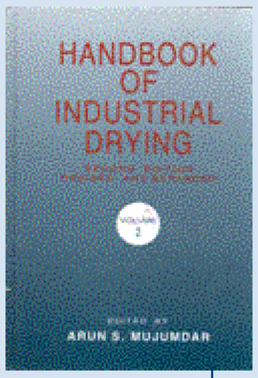
- Industrially developed nations: 12-25% national industrial energy consumption - thermal dehydration
- Excluding petrochemical refining, drying is by far the most energy-intensive
- Improper drying of the most expensive drugs may form polymorphs (no therapeutic value) – mil$$$ of losses
- Most thermal energy comes from combustion of fossil fuels, a major environmental impact
- Important in almost all industries



Significance of Drying: Figures for the U.K

- Approx. 27 million tons water removed / year in drying processes
- An efficient dryer consumes about 1 ton of oil equivalent (TOE) to remove 8 tons of water (inefficient ones are as low as 1:3)
- Assuming average ratio of 1:6, 4.5 million TOE of fossil fuel energy is consumed annually in the U.K. for industrial drying – emitting 13 million tons of CO_2!

Handbook Industrial Drying II



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Significance of Drying: Figures for Canada

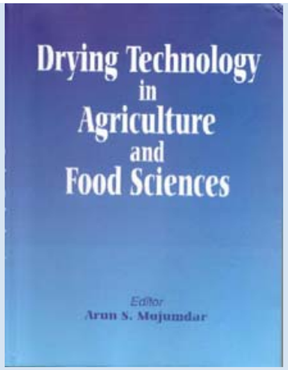
- 230 x 10^{15} J/year used for drying
- 17.1 million tons / year CO_2 emission
- Current efficiency levels 15-35% (EDRL)
- 5% improvement in energy efficiency will decrease CO_2 emission by 3 - 4 million tons / year
- Improving existing dryers and developing new drying technologies have potential to reduce CO_2 emission by 1.2 and 9 million tons / year

Post-Harvest Drying of Grains (source: FAO, 1996)

- World production ~ 2 billion tons
- 35% world's cereal crops need drying (25% to 15% water, w.b.)

Pharmaceutical Industry

- Drying / energy costs negligible component of market price of products
- Over $190 billion worth pharmaceutical products are freeze dried around the world



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Complexity of Drying

Heat and Mass Exchangers – Complicating issues

Material Properties

- Liquid
- Semi-solid
- Solid
- Physical & thermal properties – vary with moisture, temperature

Equipment Characteristics

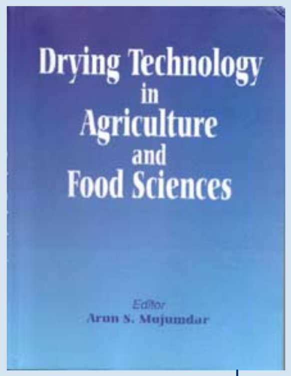
- Enormous variety
- Various modes of heat input
- Various flow configurations
- 2-phase flows; transient, 3-D effects
- Dwell times vary widely

Operating Conditions

- Temperature
- Pressure
- Steady, unsteady
- Affect properties of product
- Affect micro-structure

Bottom line: Total cost of drying per kg product !

Drying Technology
Agriculture Food Sci.



Complexity of Drying

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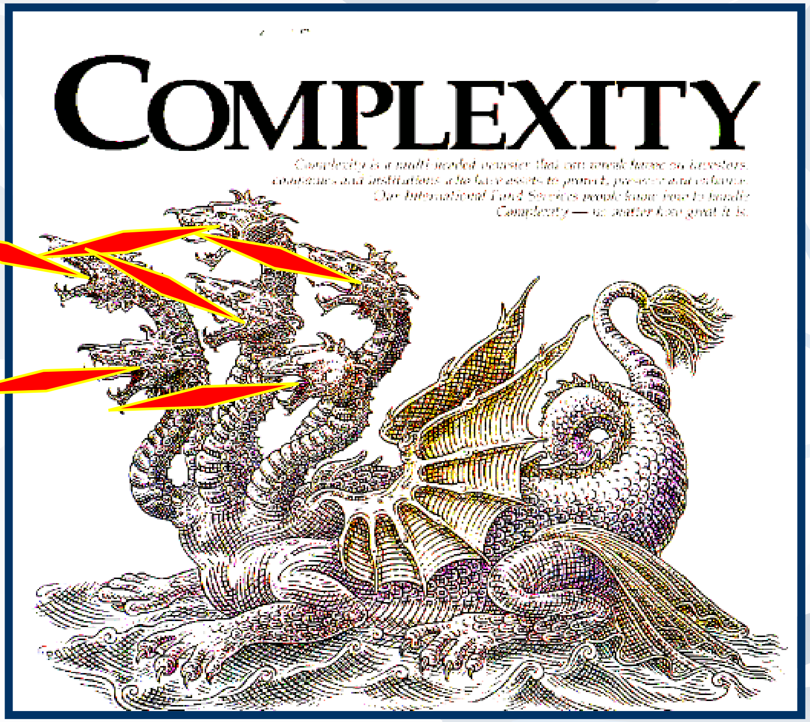
Multi-component transport

Transient transport processes

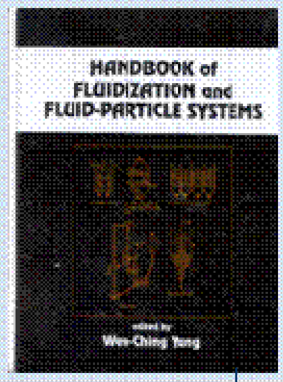
Physical / chemical transformations

Variety of energy sources (continuous, intermittent)



Varying moisture transport mechanisms

Product quality interactions



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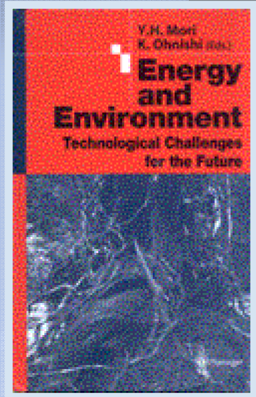
Motivating Factors for Innovation

- New product or process
- Higher capacities than current technology permits
- Better quality than currently feasible
- Reduced cost
- Reduced environmental impact
- Safer operation
- Better efficiency (resulting in low cost)
- Lower cost (overall – i.e. lower investment and running costs)



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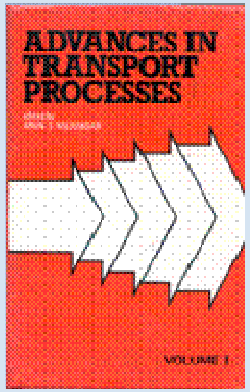
Some Remarks on Innovation

Innovation is crucial in industries with short time scales of products / processes, e.g. a short half life (< 1 year, say).

For longer half lives (10 – 20 years) innovations come slowly; are less readily accepted and mature technologies have long survival times, e.g. drying and many unit operations.



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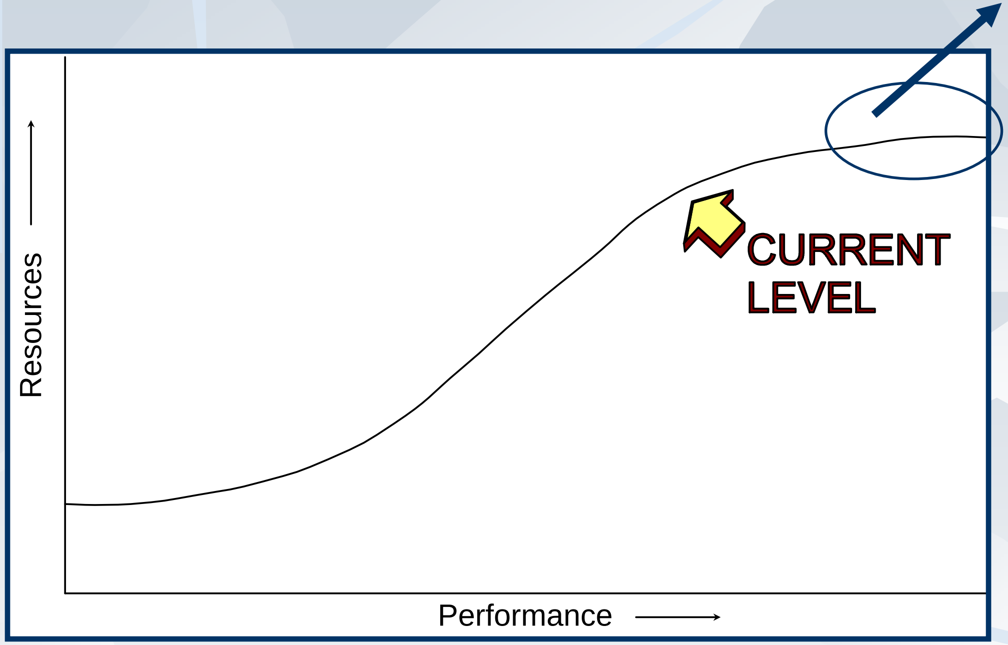
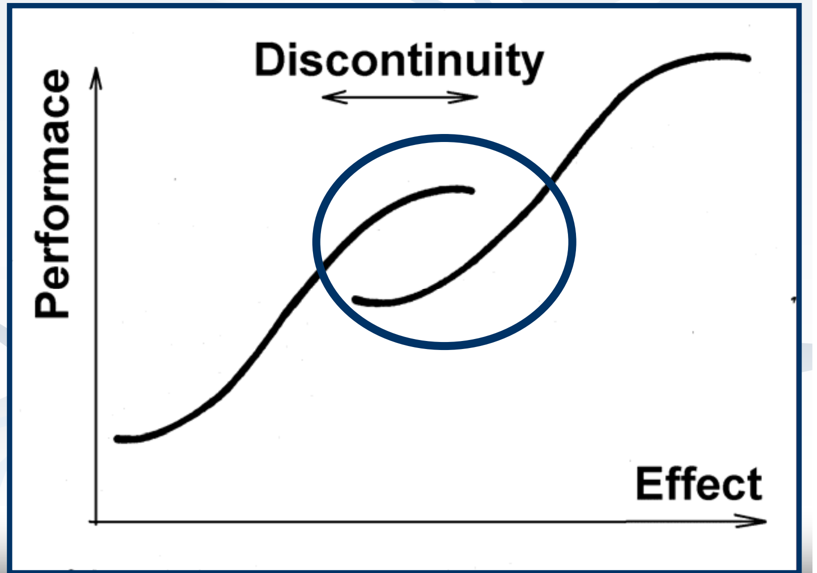
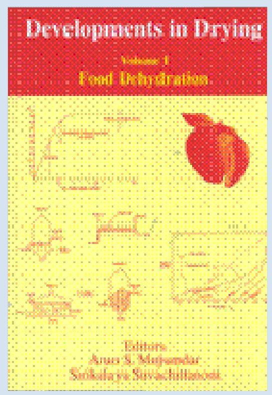
Foster's "S" Curve



Foster's "S" – A valuable tool for estimating the best time when the marketplace requires an innovative tech.

When one technology replaces another, another "S" curve appears.





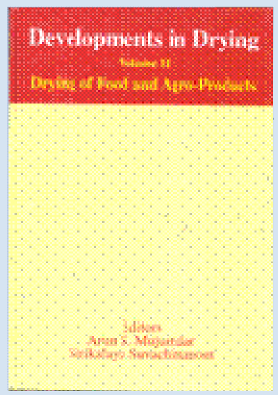
General Observation about innovation in DRT

- Most new dryers are incremental (2/3-stage dryer)
- Based on intelligent combinations of established technologies (2-stage Spray FBD, steam-tube rotary dryer, ultrasonic spray dryer)
- Adoption of truly novel technologies are not readily accepted by industry:

1. **Superheated impinging jet steam [paper],**
2. **Condebelt [liner board],**
3. **Pulse combustion [slurries],**
4. **Bath of liquid metal [paper],**
5. **Remaflam process [textile],**
6. **Impinging streams [sludge]**

Click for more details

Development in Drying II



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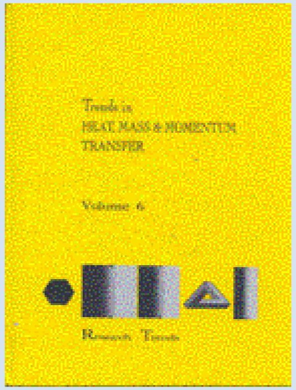
General Observation about innovation in Drying Tech.

- No truly disruptive technologies as yet
- The need for replacement with new equipment is limited (long life cycle, 20-40 years)
- Most drying technologies mature (significant time and effort are needed to make improvement)
- Obtaining and maintaining intellectual rights (IP) is an important and expensive issue, without which innovation cannot be sustained



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Some Selected Innovative Drying Technologies

- **Superheated Steam Drying**

  Pulp; wood; paper etc-commercial

  Foods- low pressure-new

  Waste sludge-industrial

- **Drying of paper-none commercial yet!**

  Impulse drying; high intensity

  Steam drying-new not at mill level yet

- **Miscellaneous**

  Ramaflam process for textiles-old but not common

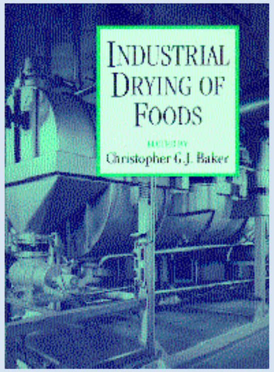
  Sorption drying-new

  Pulse combustion drying-new

Conventional Vs Innovative

(assumes knowledge of common dryer types)

- Most innovative dryers are intelligent combinations of developed technologies
- Incremental innovations succeed more often due to less risk
- Low R&D activity in drying equipment for many reasons
- High energy costs will stimulate new energy efficient, miniaturized dryers



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Comparison of Characteristics

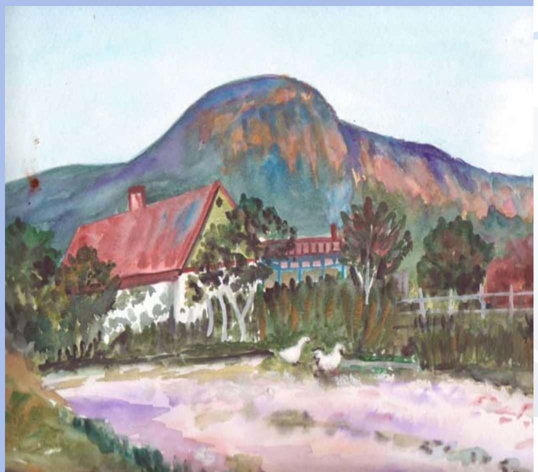
Conventional	*Innovative*
• Steady thermal energy impact	• Intermittent energy input
• Constant gas flow	• Variable gas flow
• Single mode of heat input	• Combines modes of heat input
• Single dryer type – single stage	• Multi-stage; each stage maybe different dryer type
• Air/combustion gas as convective medium	• Superheated steam drying medium

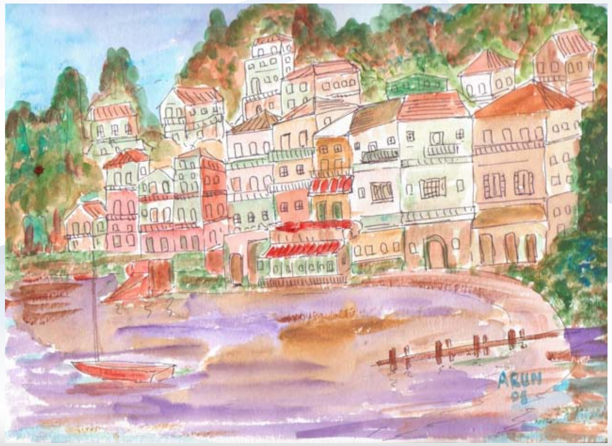
Example: Fluidized Bed Drying

	Conventional	*Innovative*
• Fluidization	• Gas	• Mechanically
• Gas flow	• Vertically upward against gravity	• Rotating to generate 'artificial gravity'
• Materials	• Particles	• Slurries, continuous webs etc.
• Drying medium	• Hot gas fluidizing / drying medium	• Superheated steam as drying medium
• Fluidization mode	• Steady fluidization of whole bed	• Pulsed fluidization

Example: Fluidized Bed Drying

	Conventional	*Innovative*
Heat Transfer	Convection only	Convection + conduction
Temperature	Constant	Variable
Staging	Single/multi-stage fluid beds	Multi-stage with different dryer types





Conventional Vs. Innovative Drying Techniques

Feed Type	Dryer Type	Innovative
• Liquid suspensions	Drum	Fluid/spout beds of inerts
	Spray	Spray/fluid bed combination
		Vacuum belt dryers
		Pulse combustion dryers
• Pastes/sludge	Spray	Spouted bed of inerts
	Drum	FB (solids backmixing)
	Paddle	Superheated steam dryers

Conventional Vs. Innovative Drying Techniques

Feed Type	Dryer Type	Innovative
• Particles	Rotary Flash Fluidized bed (hot air, combustion) Conveyor dryer	Superheated steam FBD Vibrated bed (variable frequency/amplitude) Ring dryer Pulsated fluid bed Jet-zone dryer Impinging streams Yamato rotary dryer

Comparison of Conventional Vs. Emerging Drying Technologies

	Conventional	Emerging Trends
• Energy (Heat source)	Natural gas, oil biomass, solar/wind electricity (MW/RF) waste heat	No change yet. Renewal energy sources when fossil fuel becomes very expensive
• Fossil fuel combustion	Conventional	Pulse combustion
• Mode of heat transfer	Convection (>85%) Conduction Radiation (<1%) MW/RF	Hybrid modes Non-adiabatic dryer Periodic or on/off heat input

Comparison of Conventional Vs. Emerging Drying Technologies

	Conventional	*Emerging Trends*
• Drying medium	Hot air Flue gases	Superheated steam Hot air + superheated S. Mixture or 2-stage
• Number of stages	One (common) Two @ three (same dryer type)	Multistage with different dryer types
• Dryer control	Manual Automatic	Fuzzy logic, Model based control, Artificial neural nets

Innovative Drying Concepts: Enhancement of Drying Rates

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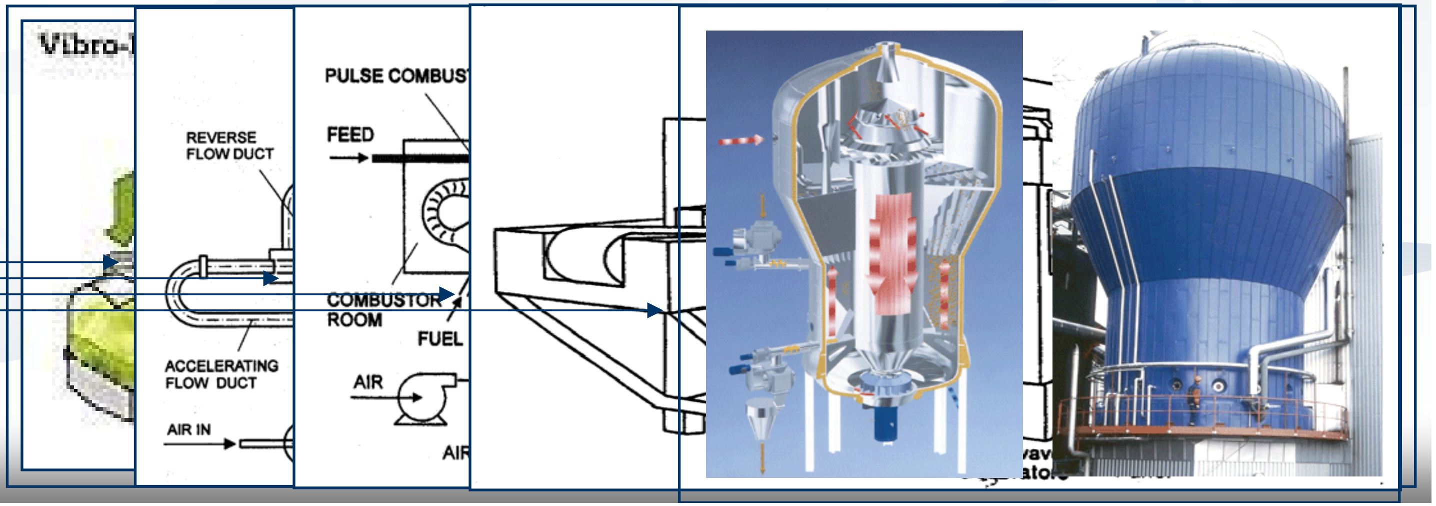
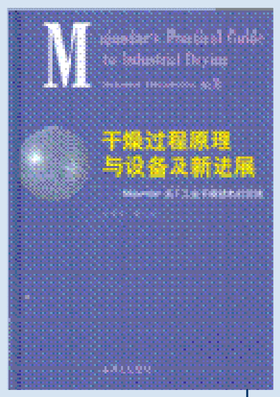
- Vibration (e.g. Vibrated bed dryers)
- Pulsation (e.g. Impinging streams)
- Sonic or ultrasonic fields (e.g. pulse combustion dryers)
- Dielectric fields {MW, RF} (e.g. MW-assisted steam drying)
- Superheated steam drying (future tech.)



New concepts

- Mostly simple and common sense type
- Multi-staging-saves energy; better quality
- Multi-processing capability
- Enhance internal and external drying rates



Mujumdar Guide (Chinese)

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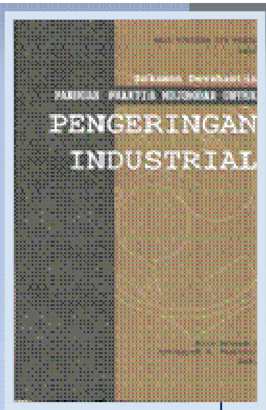
Innovative Drying Concepts: Combination of Optimal Dryers in Stages

- Spray + Fluid bed (Spray Fluidizer)
- Filtermat (Spray + Conveyor)
- Flash + Fluid Bed

Innovative Drying Concepts: Combined Modes of Heat Pump

- Convection + Conduction
- Convection + Radiation (Concurrent or Sequential)
- Convection + (MW / RF)

Mujumdar Guide (Indonesia)



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Innovative Drying Concepts: Combined Unit Operation

- Filter – Dryer
- Dryer – Cooler – Agglomerator etc.

Innovative Drying Concepts: Novel Gas / Particle Contacts

- Spout–fluidized / Rotating spouted bed
- Pulsed Fluid Bed
- Mechanical screw conveyor spouted bed
- Mechanically fluidized bed

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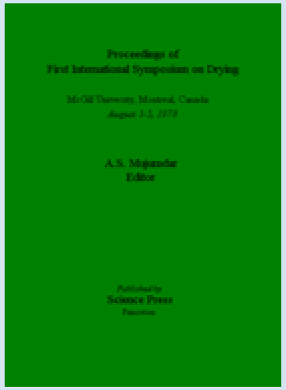
Innovative Drying Concepts: Miscellaneous

- Spray dryer – “engineered” powders
- Ohkawara Kakohiki spray bag dryer
- Condebelt dryer for thick paper grades
- Remaflam (for textiles)
- Supercritical CO_2 extraction (aerogels)
- Spray-freeze drying
- Carver – Greenfield process

Click for more details



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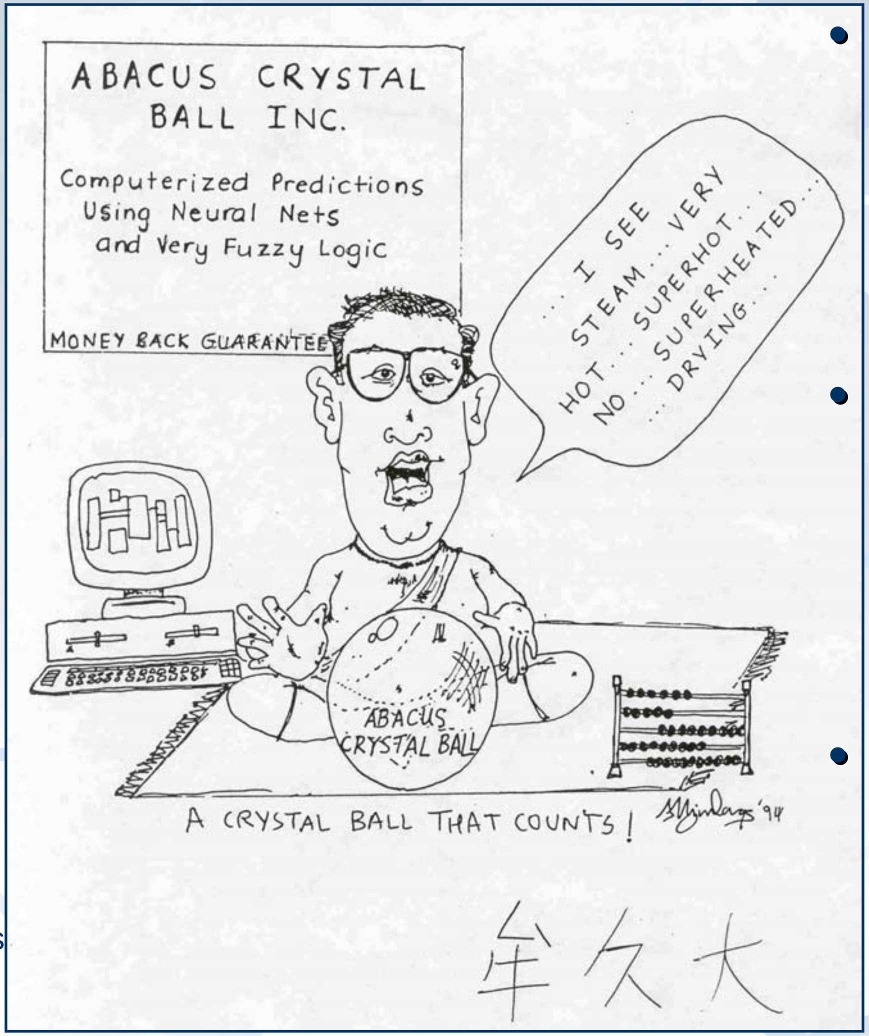
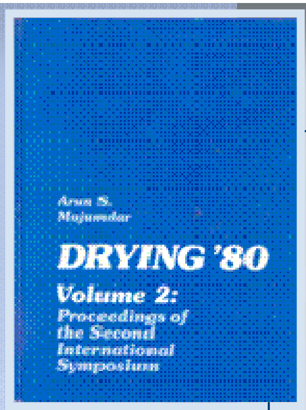
Steam Drying : Advantages



- No oxidative / combustion reactions (no fire/explosion hazard, better quality product)
- Higher drying rates (higher thermal conductivity & heat capacity of SS). Possible
- Suitable for products containing toxic or organic liquids (recovered by condensation)
- Permits pasteurization, sterilization and/or deodorization of food products

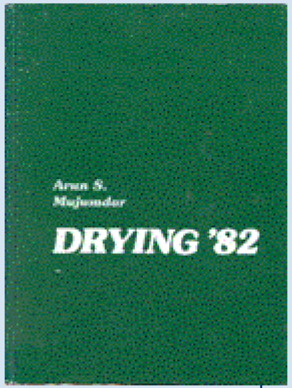
IDS 1980



Steam Drying : Some Advantages

- Low net energy consumption if excess steam - condensed or recycled
- Allows operation of dryer effectively as a multiple effect evaporator!
- In food drying generally avoids “case hardening”; low temperature at low pressure- better quality!
- In some cases produces higher porosity (lower bulk density) products (fluffy product without shrinkage)
- Higher quality product feasible at low pressure (e.g. fibre, pulp, distiller’s dry grain, silk, paper, wood etc.)

IDS 1982



Steam Dryer : Classification

Superheated Steam Dryers

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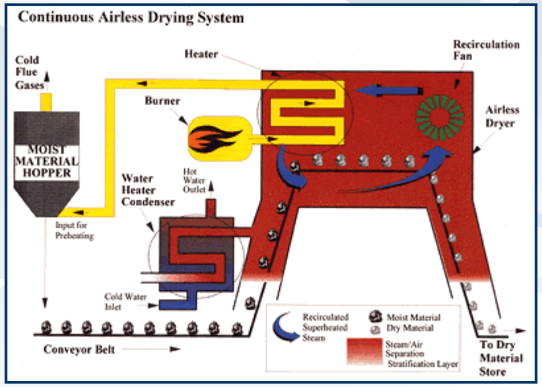
- Intensification
- Selected Innov.
- **Selected DrT**
  - Steam
  - Pulse Combustion
  - Heat Pump
  - Spray
  - Impinging Streams
- Closing
- End

Low Pressure

- Vacuum steam dryer (wood)
- Vacuum steam dryers (silk cocoons)

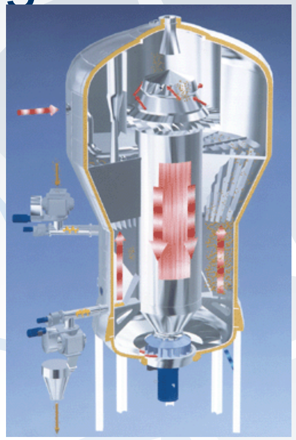
Near Atmospheric Pressure



Source: Stubbing, 2003

- Fluidized bed dryers (coal)
- Impingement and/or through dryer (textiles, paper)

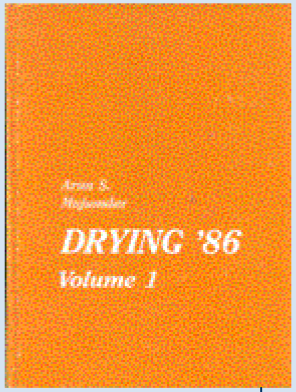
High Pressure



Source: GEA Niro, 2003

- Flash dryers (peat, 25 bar)
- Conveyor dryers (beet pulp, 5 bar)
- Fluidized bed dryers (pulps, sludge)

IDS 1986



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Steam Dryer : Applicable if

- Energy cost high; product value low (coal, peat, newsprint, tissue paper, waste sludge)
- Product quality is superior if dried in steam (newsprint, silk)
- Risk of fire/explosion, oxidative damage is high if dried in heated air (coal, peat, pulp) - low insurance rate offset high investment cost
- Large quantity of water to be removed
- High production capacity

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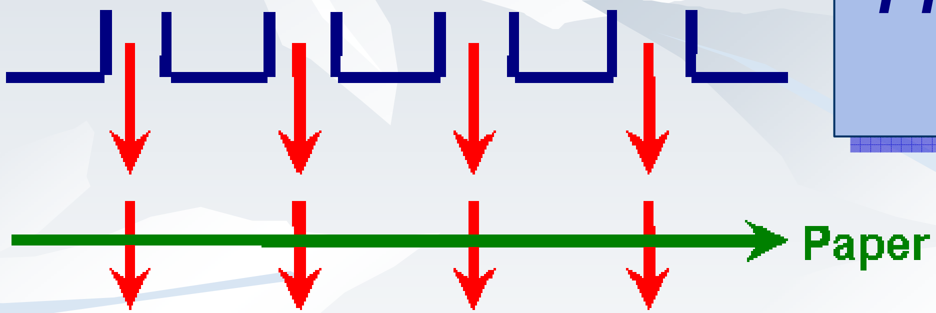
Novel Solution

- Use superheated steam impingement + throughflow

Pilot testing at VTT, Finland



***Advantages*:**

- **High drying rate**
- **Better strength**
- **Better efficiency**

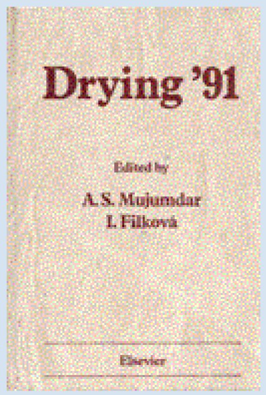
***Disadvantages*:**

- **Air infiltration**
- **Condensation**
- **COST!!**
- **New Technology**

More about SHSD

- *This will be covered in a separate PPT to follow this presentation- time permitting*
- *Refer to chapter on SHSD from Guide – available to participants along with chapter on fundamentals and classification/selection of dryers*

IDS 1991



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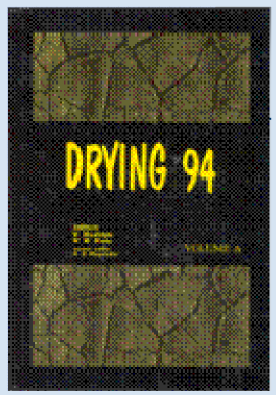
Pulse Combustion: Advantages over Conventional

- Increases heat and mass transfer rates (2x to 5x)
- Increases combustion intensity (up to 10x)
- Higher combustion efficiency with low excess air values
- Reduced pollutant emissions {NO_x, CO, and soot} (up to 3x) and lower volume discharge
- Reduced air consumption (3% - 40%), thus reducing space requirement for the combustion equipment
- Lower gas and product temperatures during processing
- Eliminate temperature, concentration, MC distribution, thus improves product quality
- Eliminate air blower from the system
- Handles sticky materials without mechanically mixing
- Handles dispersed liquids, slurries without atomizer

IDS 1994



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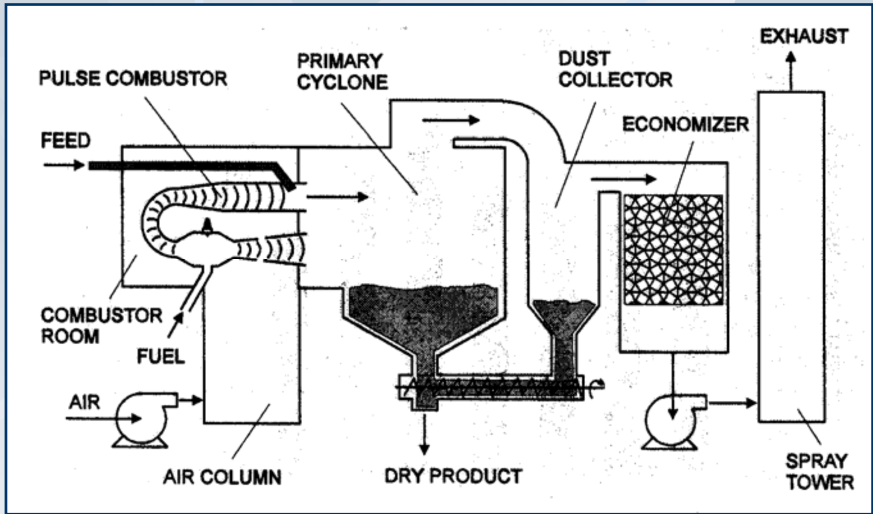
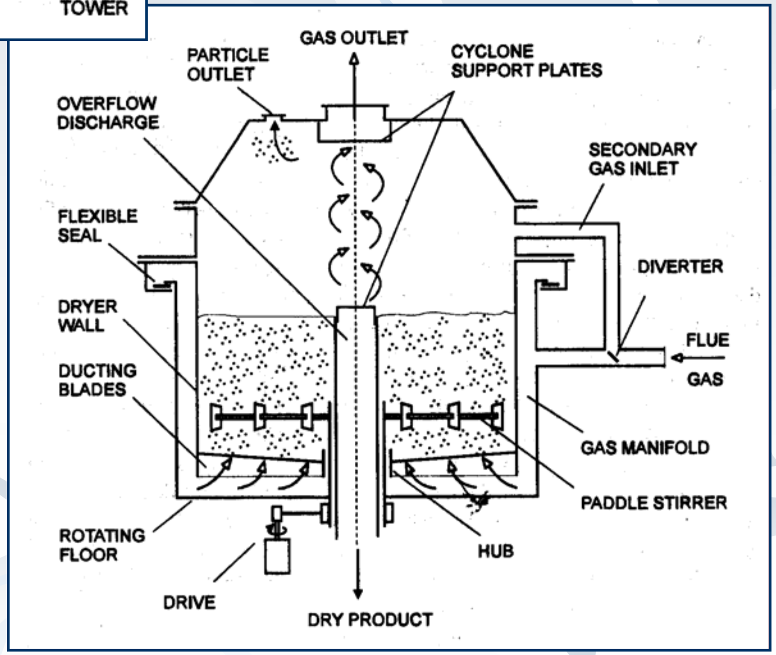
Pulse Combustion Dryer: Some Examples



Pulse-dryer (Courtesy, Oregon)

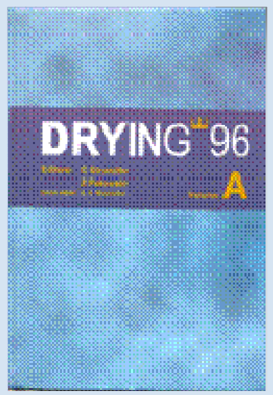
Combines dispersion / drying in the combustor and finish drying / separation in a primary cyclone

Flue gases from a pulse combustor enter the FB just above the solid floor to avoid attenuation of the pulsating gas stream by a perforated gas distributor



Pulse combustion FBD (Lockwood, 1983)

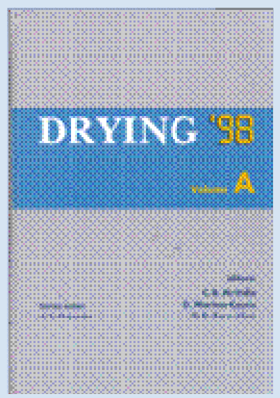
IDS 1996



Heat Pump Dryer: Advantages

- High energy efficiency with improved heat recovery
- Better product quality with controlled temperature
- Wide range of drying conditions (-20^{o}C – 100^{o}C)
- Excellent control of the environment for high-value products
- Aseptic processing is possible

IDS 1998



Heat Pump Dryer: Classification

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Classification

Batch

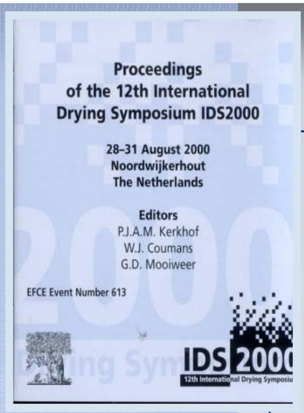
- Steady Conditions
- Time-varying temperature, velocity, humidity
- Different heat transfer modes (auxiliary heating) – Multi-mode operation

Intermittent HP Operation

- HP used only when most effective
- With/without auxiliary heating by radiation, conduction, convection

Continuous

- With supplementary heat input (RF, MW, radiation and etc.)
- Low or medium temperature
- Single or multi-stage



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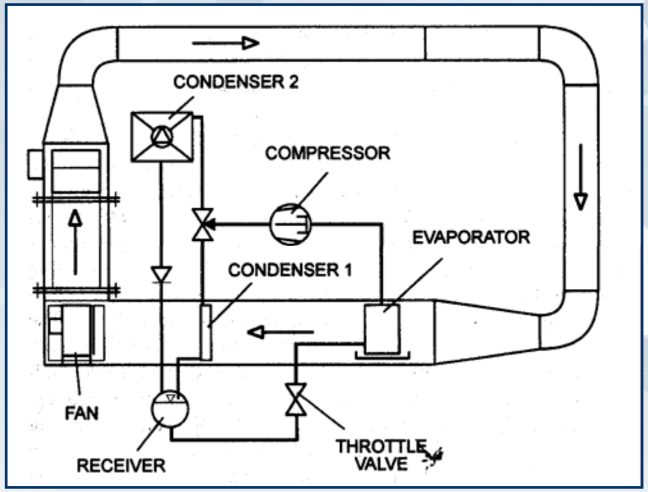
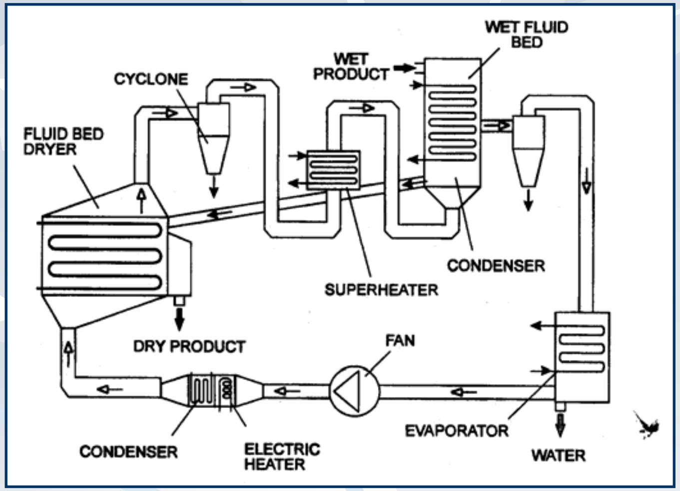
Heat Pump Dryer: Various types

Low Temperature Heat Pump Drying

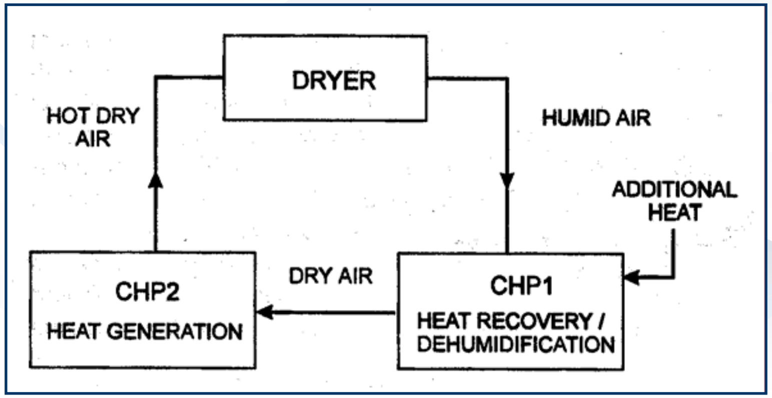


Lab Scale HPD (Stromen & Kramer, '94)



HP FBD (Stromen & Jonassen, '96)

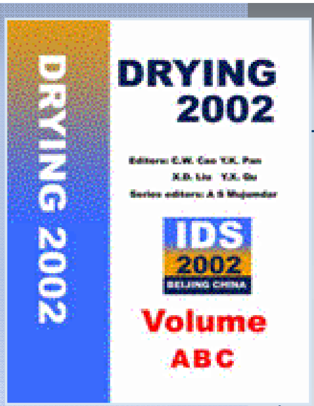
Chemical Heat Pump Drying



Concept of Chemical HPD

Chemical HPDs operate using only thermal energy and do not release contaminant gases.

Numerous chemical reaction has been validated for heat storage and cold/hot heat generation



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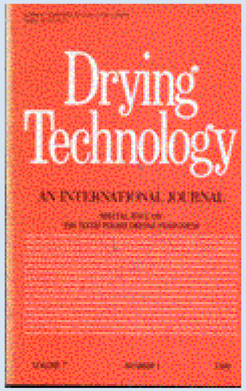
Heat Pump Dryer: Various types

How to make Heat Pump Dryer **cost-effective?**

- **Cyclic, batch drying using Heat Pump only when it is most effective**
- **Use model-based control**
- **Use smaller Heat Pump to service 2 – 3 drying chambers in sequence; use only ambient or heated air for major part of drying cycle**
- **Multi-product, multi-chamber Heat Pump Dryer can be optimized with a simple mathematical model based switching – run blower, heater and heat Pump continuously!**
- **Multi-stage Heat Pump may be better …**



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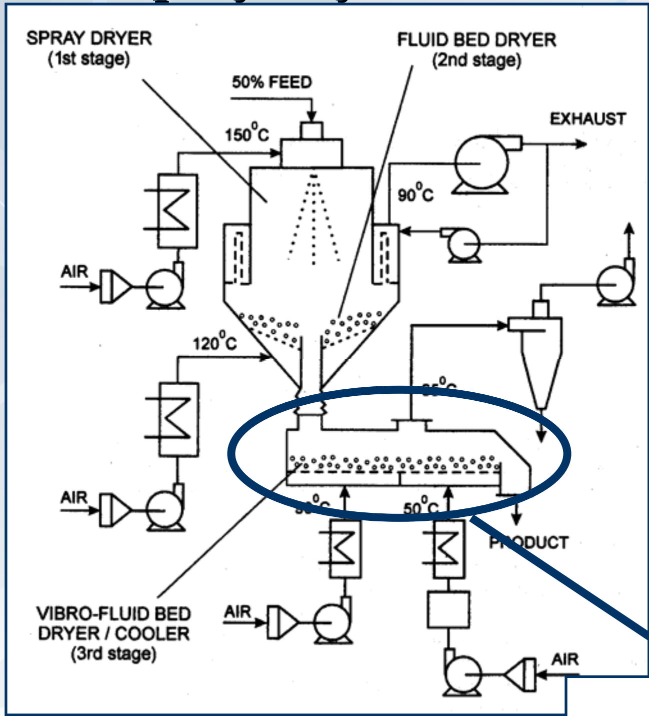
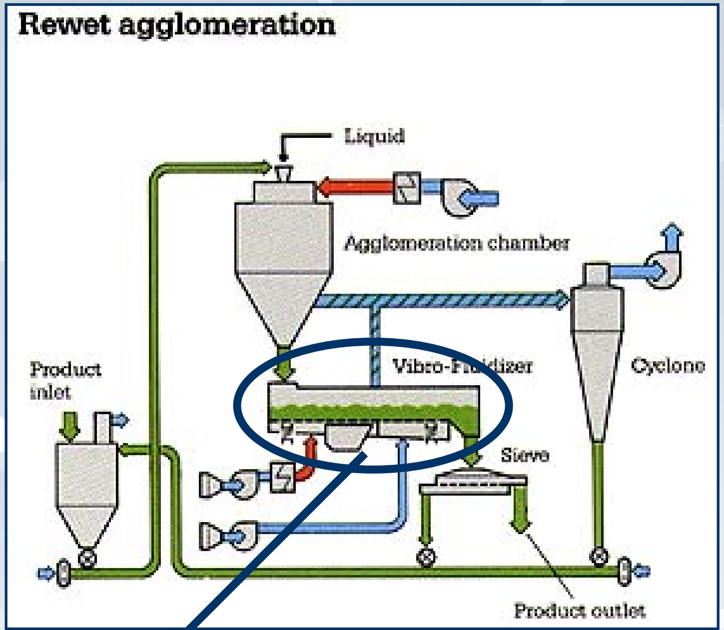
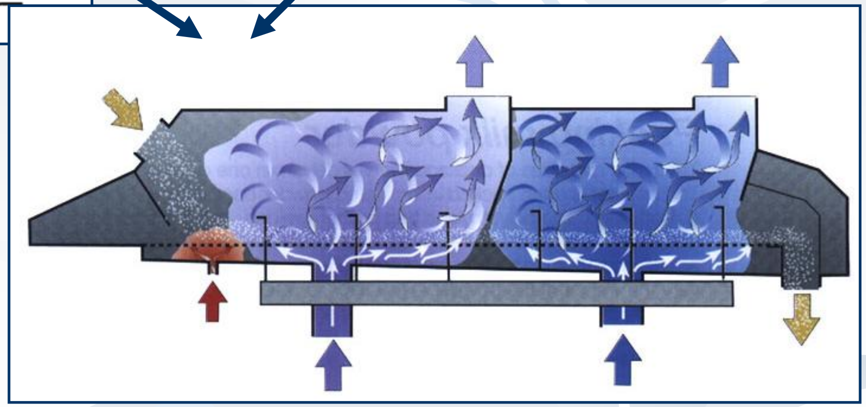
Spray Dryer





Multi-stage spray dryer

- Spray + FBD/C
- Spray + VFBD/C
- Spray + Conveyor Dryer



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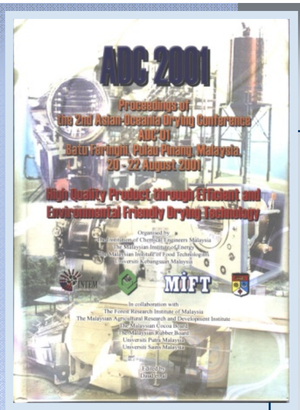
Spray Dryer: Some new developments

Development	Key Features
Built in filters	Powder confined to spray dryer chambers
SS spray dryer	High efficiency; quality adjustment
Low rpm rotary disk atomizer	Reduced power consumption; narrower size distribution
Multi-stage operation	Reduces chamber size; internal water removed in small FBD/VFBD or through circulation conveyor dryer
Low pressure operation	Ultrasonic atomizer for monodisperse particles of heat sensitive materials. E.g. biotech, pharmaceutical products

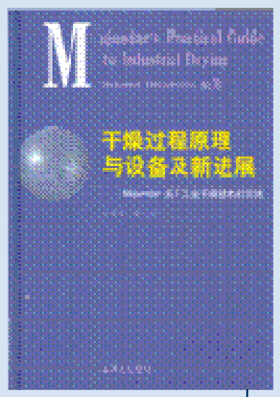


Impinging Streams Dryers

Main features of impinging configuration:

- High intensity of drying
- High product quality
- Simple design and operation
- Compactness
- Possibility of combining drying with other operations (granulation, disintegration, heating, cooling, chemical reactions, etc)

Mujumdar Guide
(Chinese)



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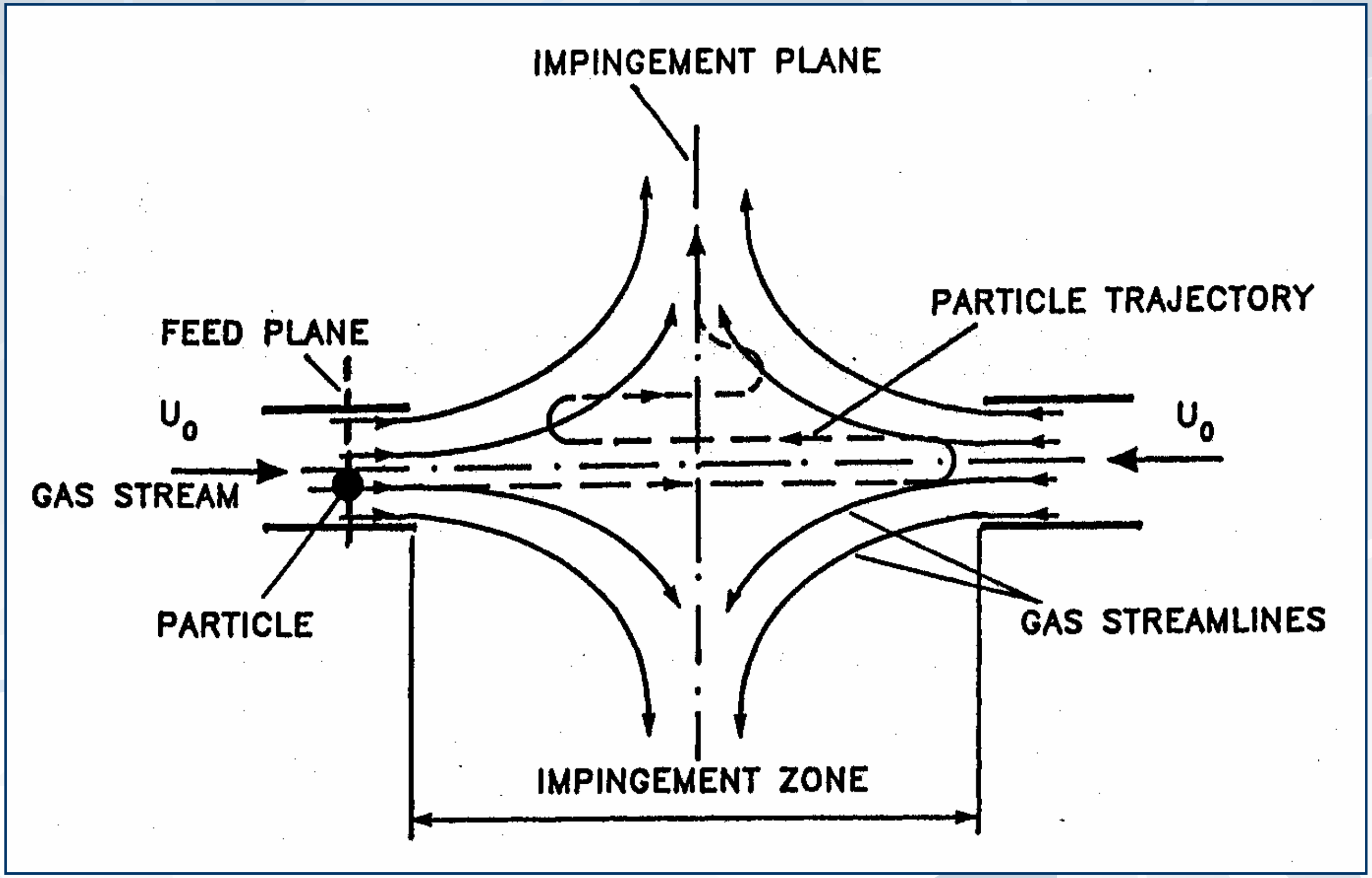
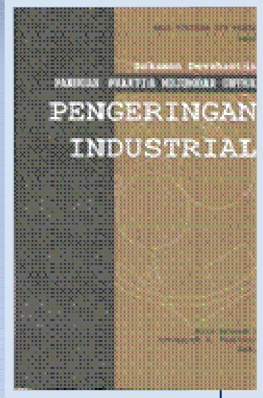
Impinging Streams Dryers



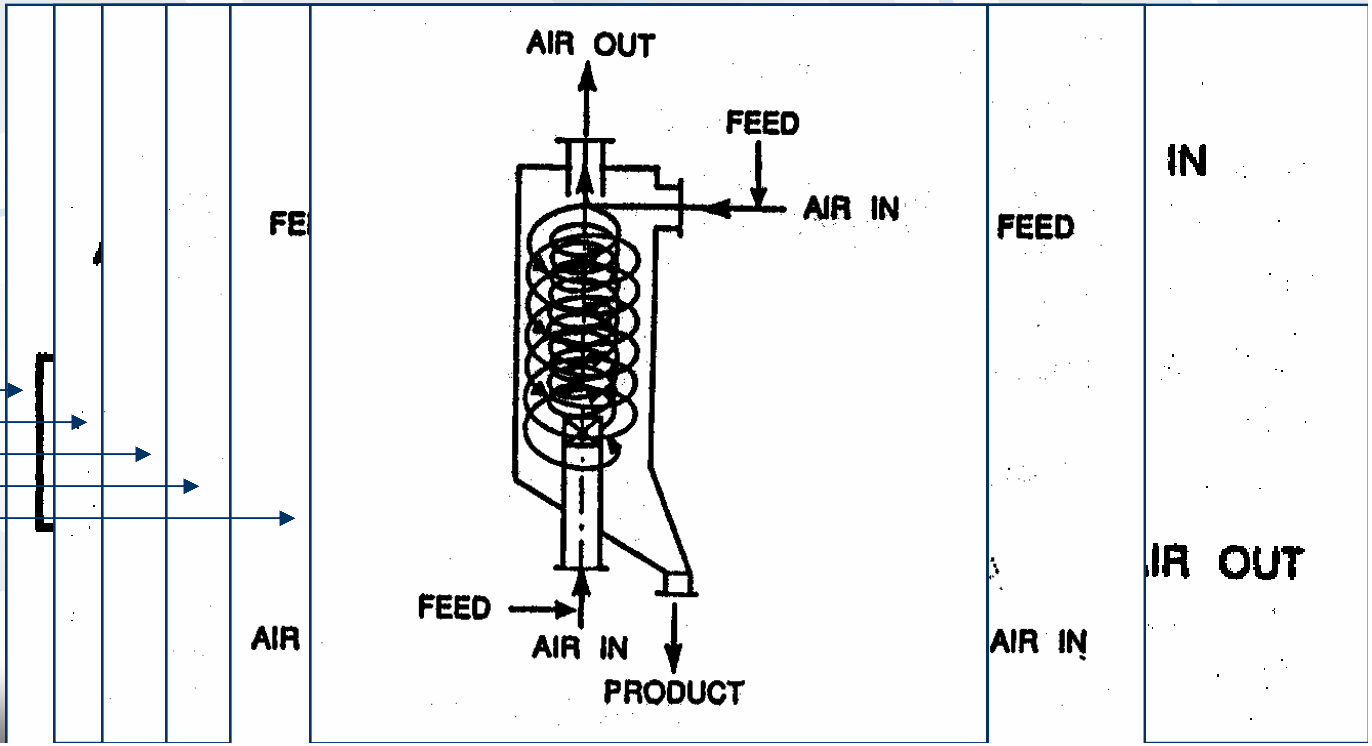
Moisture evaporation occurs in an impingement zone that develops as a result of “collision” of 2 oppositely directed high velocity gas streams

Mujumdar Guide (Indonesia)



Impinging Streams Dryers: Various types

- Coaxial
- Mutually perpendicular X configuration
- Curvilinear countercurrent
- 4 impinging streams
- Counter-rotating countercurrent
- Co-rotating countercurrent



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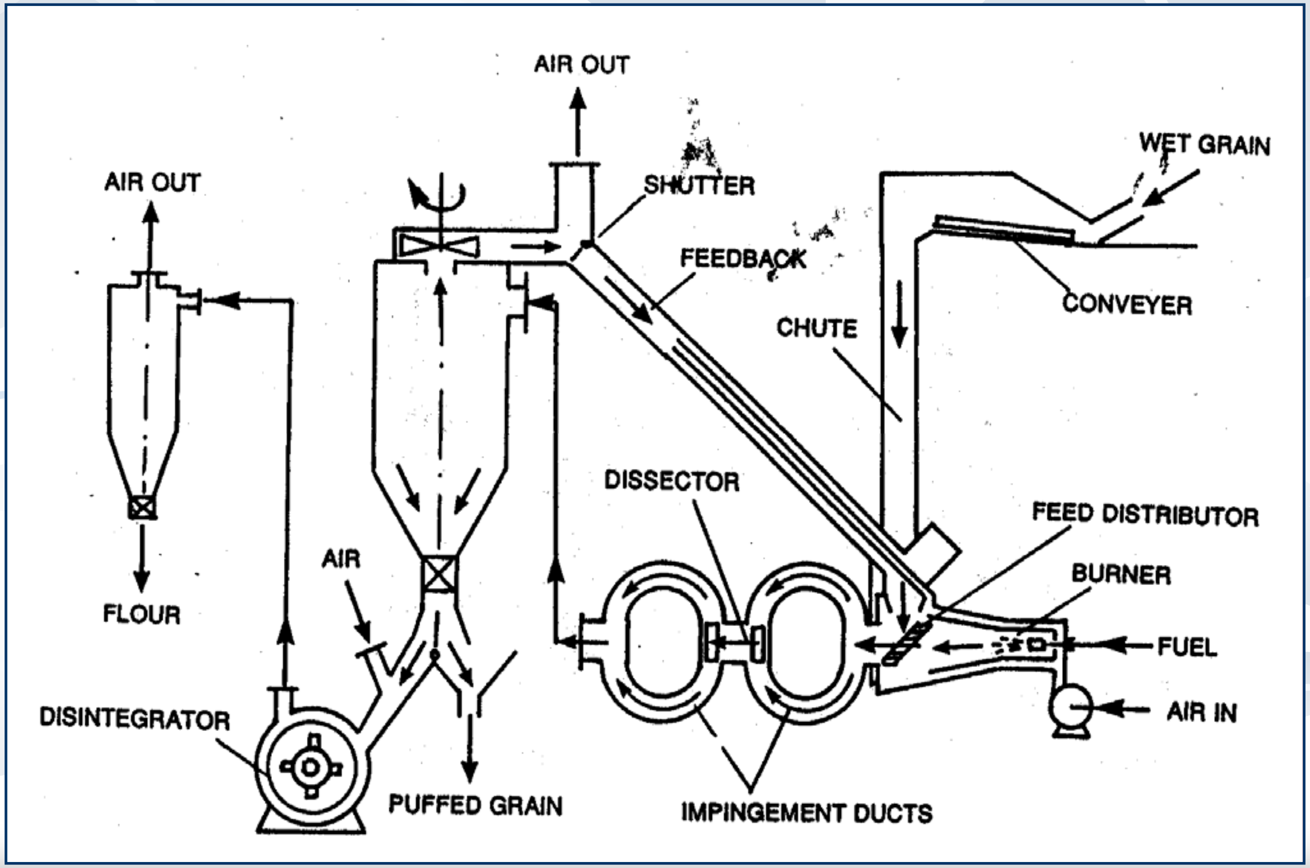
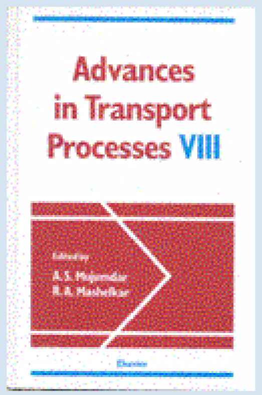
Impinging Streams Dryers: Various types

Industrial setup with semicircular impinging streams ducts for thermal processing of grains (drying, puffing, certain thermally induced biochemical reactions)





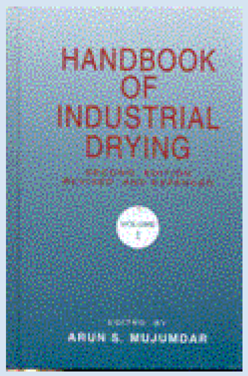
Closing Remarks: R&D Needs and Opportunities

Fundamental Research

- Modelling microscopic transport of moisture (liquid / vapour form) in solids; multi-component transport
- Combined modes of heat transfer – steady / unsteady
- Transport phenomena including drying-induced deformation; changes in transport mechanisms; quality changes

Applied R&D

- Improve drying efficiency, quality of product
- “Miniaturization” of industrial dryers
- Dynamic optimization of hybrid dryers
- Development of scale-up criteria for various dryers types; multi-stage dryers
- Design of “smart” dryers
- Model-based control of dryers
- New dryers – steam drying, supercritical drying, freeze drying etc.



Closing Remarks: R&D Needs and Opportunities

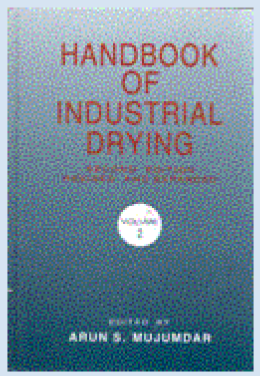
Category A: Math Modelling of Drying

- Micro-scale description of transport phenomena including mechanical deformation, change in structure and allowing for chemical reactions, glass transitions, crystallization etc.

Category B: Math Modelling of Dryer

- Equipment / product specific
- Some easy to model – most very difficult
- Complex models need more information which is harder to obtain
- Valuable scale-up tool – even design
- Useful tool to develop new dryer design concepts

Handbook Industrial Drying II



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Category C: Special Drying Problems

- Product-specific: gel-drying
- Equipment specific: spray dryers – aroma retention
- "smart" dryers – need sensors
- Pulse combustion dryers
- Novel design concepts: impinging sprays, impinging stream

Interesting but unlikely to succeed

- Supercritical CO_2 extraction drying of coal
- Drying of herbs in high electric fields (~500kV/m)
- Drying in ultrasonic or sonic field
- Impulse drying of paper (extremely high temperature and high pressure)

Advanced Drying Technologies

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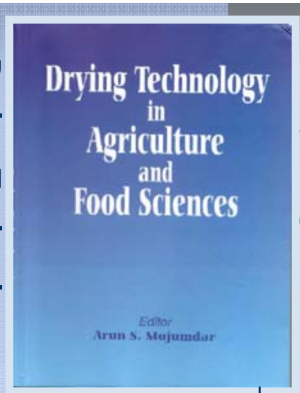
Closing Remarks

- Improve and design **intelligent combinations** of current technologies - better quality product, smaller equipment size, greater reliability, safer operation, lower energy consumption, and reduced environmental impact while reducing the overall cost
- Further R&D is needed - **close interaction among industry - university researchers** – to better design, optimise, and operate the wide assortment of dryers
- Evolution of **fuzzy logic, neural networks and genetic algorithms** has opened new exciting opportunities for applications involving complex drying system



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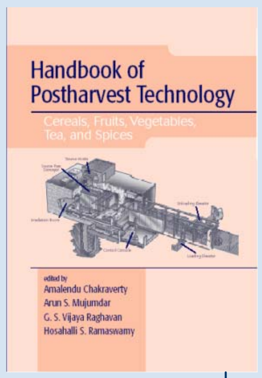
Closing Remarks

- **On-line sensing** of the colour, the texture, moisture content and temperature of the product and use this information to control the dryer operating conditions locally to yield high value product
- Complexity in **microscopic understanding** of drying remains a major deterrent. Micro-level understanding still at rudimentary level
- There is a need to develop and operate **environmentally friendly** drying processes
- Employing **model-based control or fuzzy control strategies** will probably become commonplace within the decade

Handbook of Postharvest Tech.



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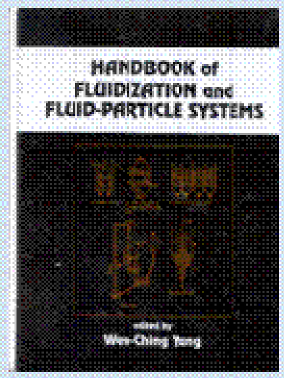
Closing Remarks

- Development of **“smart”** or **“intelligent” dryers** will help improve quality of products as well as enhance the energy efficiency to assure desired product quality
- There is need to devise more **efficient combustors** as well as drying equipment to obtain high-quality products with the least consumption of resources
- **Heat pump** drying will become more accepted technology - chemical heat pump-assisted direct and indirect dryers still need to be evaluated carefully

Handbook of Fluidization



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Closing Remarks

- With advances in computer technology, material science, and understanding of the underlying transport phenomena in drying of solids, there is scope for rapid development of more efficient drying technologies
- **Micro-scale dryers** could be useful for pharmaceutical applications where “scale-up by replication” has distinct advantages
- **Superheated steam** at near atmospheric or low pressures will become more popular for a host of industrial products (foods and agro-products to paper to wood and waste sludge)

Closing Remarks

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- **Closing**
- End

Knowledge is proud it knows so much
Wisdom is humble it knows no more

Thank you

谢谢！