Superheated Steam Drying

An Emerging Drying Technology

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OUTLINE

- **Introduction to Superheated Steam Drying (SSD)**
- **Basic principles**
- **Classification and selection of SSD**
- **Selected applications of SSD**
- **Closure**

Resources

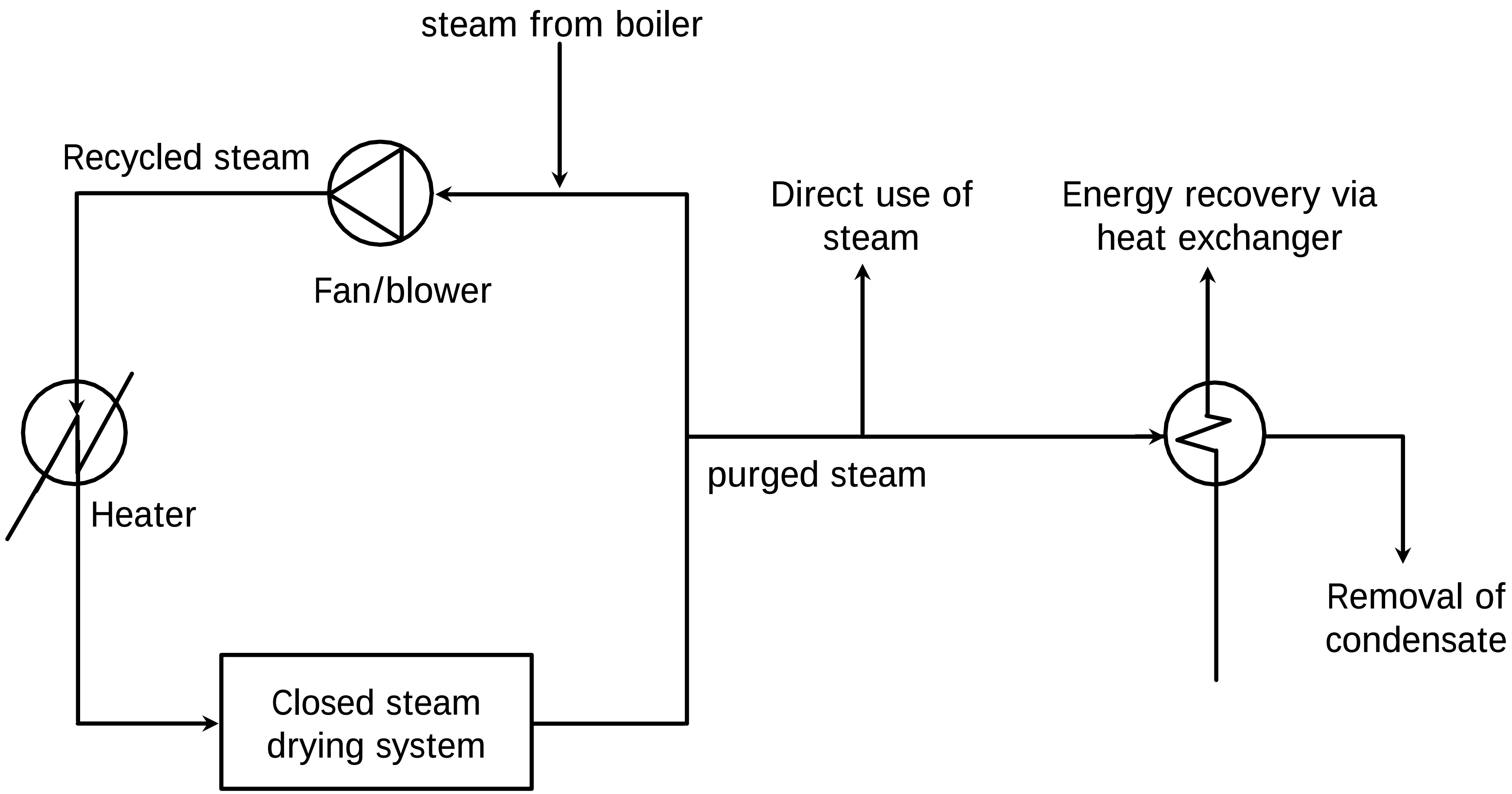
- See chapter on Superheated Steam Drying In handbook of Industrial Drying. Ed. A.S. Mujumdar, CRC Press, USA, 2006, 1280 pp
- See chapter in Guide to Industrial Drying, A.S. Mujumdar, Color Publications, 2004
- Special issues on SHSD of Drying Technology journal, 2007.

SUPERHEATED STEAM DRYING (SSD)

- Proposed over 100 years ago; received serious attention only during the past 20-30 years
- Uses superheated steam instead of hot air or combustion/flue gases in a direct (convection) dryer
- More complex equipment than hot-air drying system;leak-proofing needed; feed/discharge can be difficult
- Lower net energy consumption (if exhausted steam can be used elsewhere in the process and not charged to dryer)
- Better product quality (in most cases);Safe operation, no fire/explosion hazard; no oxidation

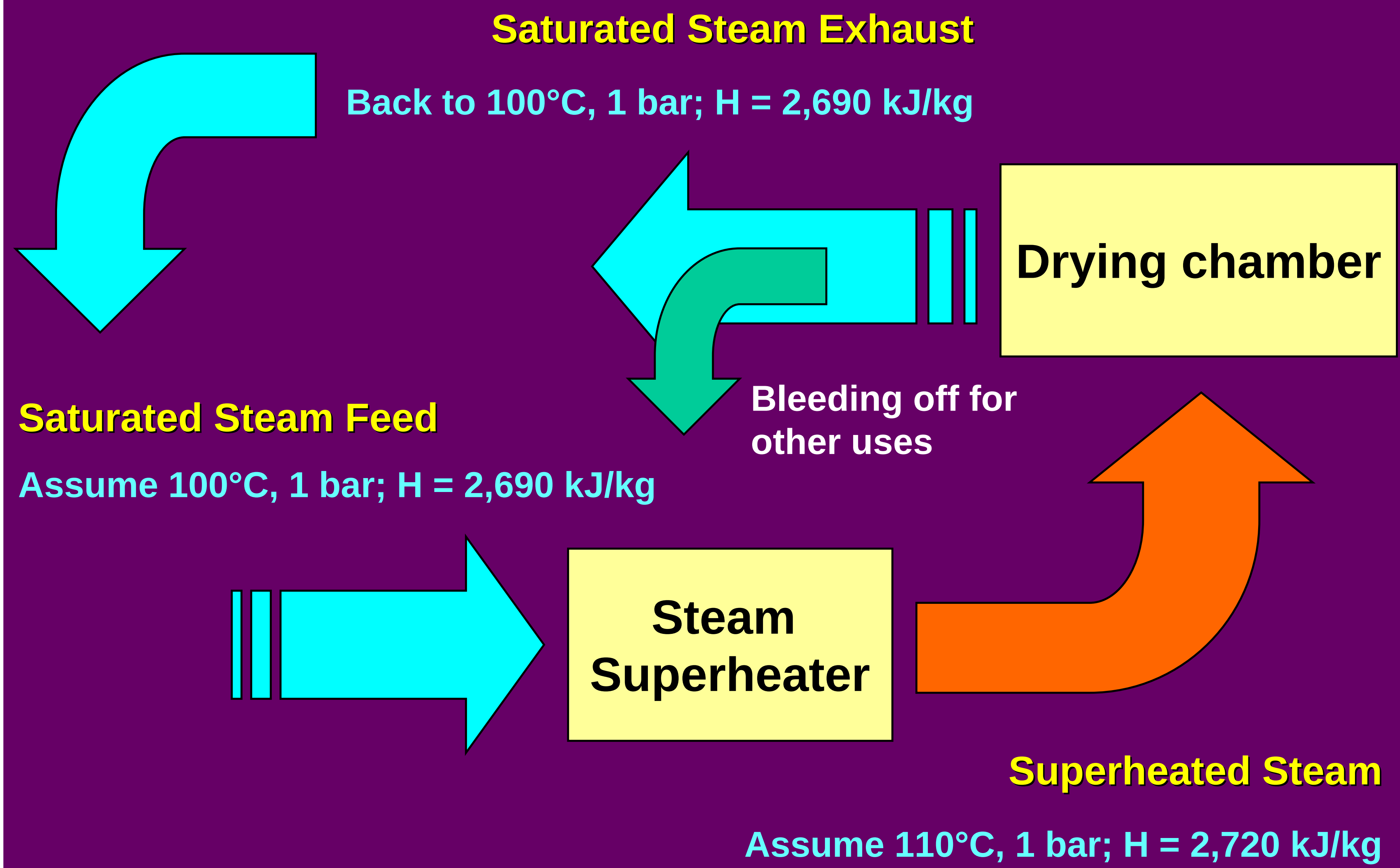
SUPERHEATED STEAM DRYER (Contd)

- If steam pressure is kept constant and more energy is added, its temperature increases and saturated steam becomes superheated steam (SHS)
- If extra heat can be transferred to an available heat sink, SHS returns to saturated conditions
- Any convection dryer can be made into SHSD e.g. fluidized bed, flash, rotary, conveyor type, spray, impinging jet; opposing jets (impinging streams) etc. Additional heat sources e.g. radiation, conduction, MW etc can also be added
- Low, near-atmopsheric or high pressure operation possible



Typical SSD schematic

SUPERHEATED STEAM DRYER



SOME ADVANTAGES OF SSD

- ***Dryer exhaust is steam so it is possible to recover all latent heat supplied to SSD- some cost involved in equipment and operation***

- ***No oxidative reactions possible due to lack of O2 Color and some nutrients are better preserved in foods- even silk!***

- ***Higher drying rates possible in both CRP and FRP depending on steam temperature (above the so-called inversion temperature SSD is faster than air drying)- not a decisive factor for selection!***

- ***Toxic or organic liquids can be recovered easily- by condensation (e.g. wood drying)***

SOME ADVANTAGES OF SSD

- Casehardened skin is unlikely to form in SSD- mechanism not known- product dependent

- SSD yields higher product porosity due to evolution of steam within the product ; boiling in interior opens up elastic wet solid- bulk density is thus lower and rehydration behavior is better; also affects color

- Sterilization, deodorization or other heat treatments (e.g. blanching, boiling, cooking) can be performed simultaneously with drying

SOME DISADVANTAGES OF SSD

- SSD system is more complex than its hot-air counterpart
- Initial condensation is inevitable - more time may be required to dry the product –if feed comes below saturation temperature
- Products that may melt, undergo glass transition or be damaged at saturation temperature of steam cannot be dried in SSD e.g silk cacoon (hence can be dried in a low pressure SHSD)
- Limited industrial experience with SSD

BASIC PRINCIPLES OF SSD

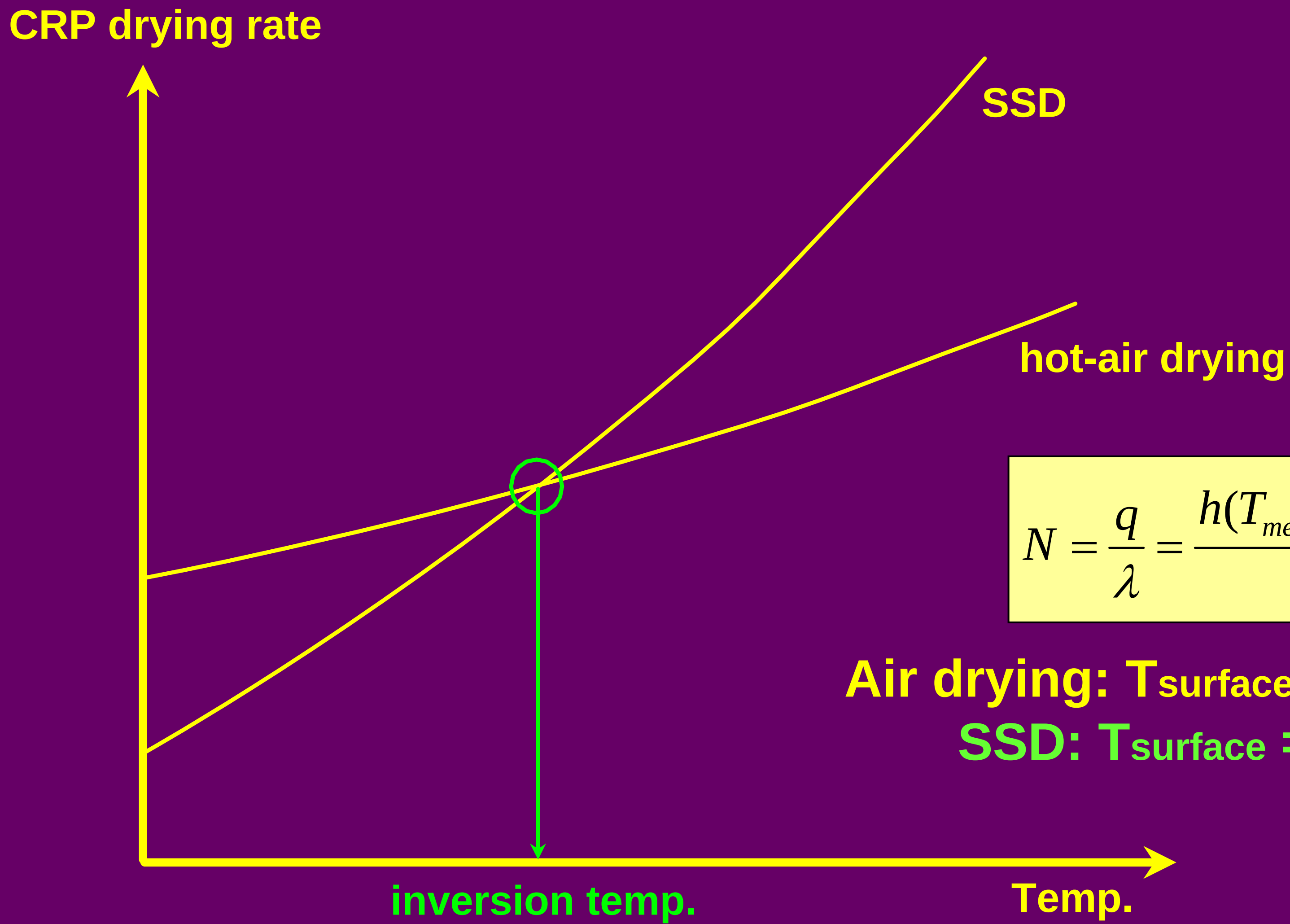
- Drying rate in constant rate period (CRP) depends only on heat transfer rate since there is no resistance to diffusion in its own vapor

- If sensible heat effects, heat losses and other modes of heat transfer are neglected, CRP drying rate is roughly equal to

$$N = \frac{q}{\lambda} = \frac{h(T_{steam} - T_{surface})}{\lambda}$$

BASIC PRINCIPLES OF SSD

- SHS has superior thermal properties to air at the same temperature: ***h is higher!***
- In hot-air drying ΔT is higher at low drying temperatures
- These counter-acting effects lead to phenomenon of inversion; beyond ***inversion temperature*** SSD is faster than hot-air drying
- Over-rated in literature; of fundamental interest as it is a function of geometry and flow configuration as well



$$N = \frac{q}{\lambda} = \frac{h(T_{medium} - T_{surface})}{\lambda}$$

Air drying: $T_{surface} = T_{wet\text{-}bulb}$

SSD: $T_{surface} = T_{saturation}$

The inversion phenomenon

BASIC PRINCIPLES OF SSD

- Inversion temperature depends on flow configurations and flow regimes

- Inversion temperatures of many systems are in the range of 160-200 C (simulations for superheated organic vapors and vaopr-noncondensible gas mixtures show similar behaviour)

- Inversion temperature is defined only for CRP drying - some researchers did not adhere to this limitation!.

BASIC PRINCIPLES OF SSD

- FRP drying rate of SSD is sometimes higher than that of hot air - mechanisms responsible are different, however! Vapor transfer is faster than liquid diffusion

- FRP drying rate of SSD is sometimes higher than air drying rate since product temperature is higher. Casehardening is unlikely to form and product is likely to be more porous as well

SSD OF FOOD PRODUCTS

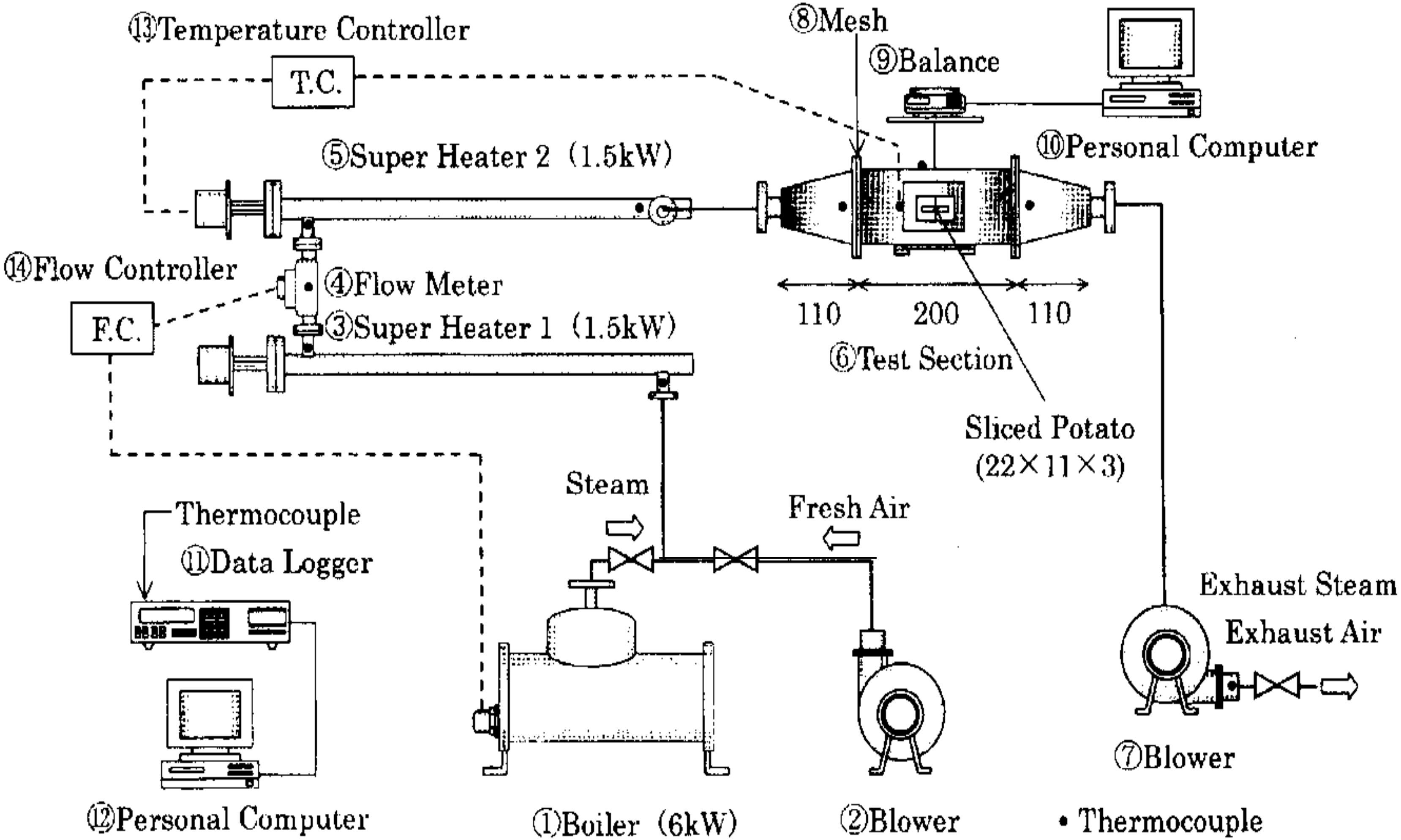
- Received serious attention during the past 10 years
- Possesses several advantages that are of special interest to food processors e.g. lack of oxidative reactions, ability to maintain color, nutrients, yields product of higher porosity
- Ability to inactivate microorganisms; enzymes etc
- Many heat treatments can be performed simultaneously with drying

HIGH-PRESSURE SSD OF FOODS

- Drying of pressed beet pulp after extraction of sugar
- Operates at pressure ~ 5 bar
- Consumes 50% less energy than conventional air dryer
- Product quality i.e. appearance, texture, digestability by cattle is better than air drying
- Pilot tests with spent grain from brewery, alfalfa, fish meal, pulp from citrus, etc.

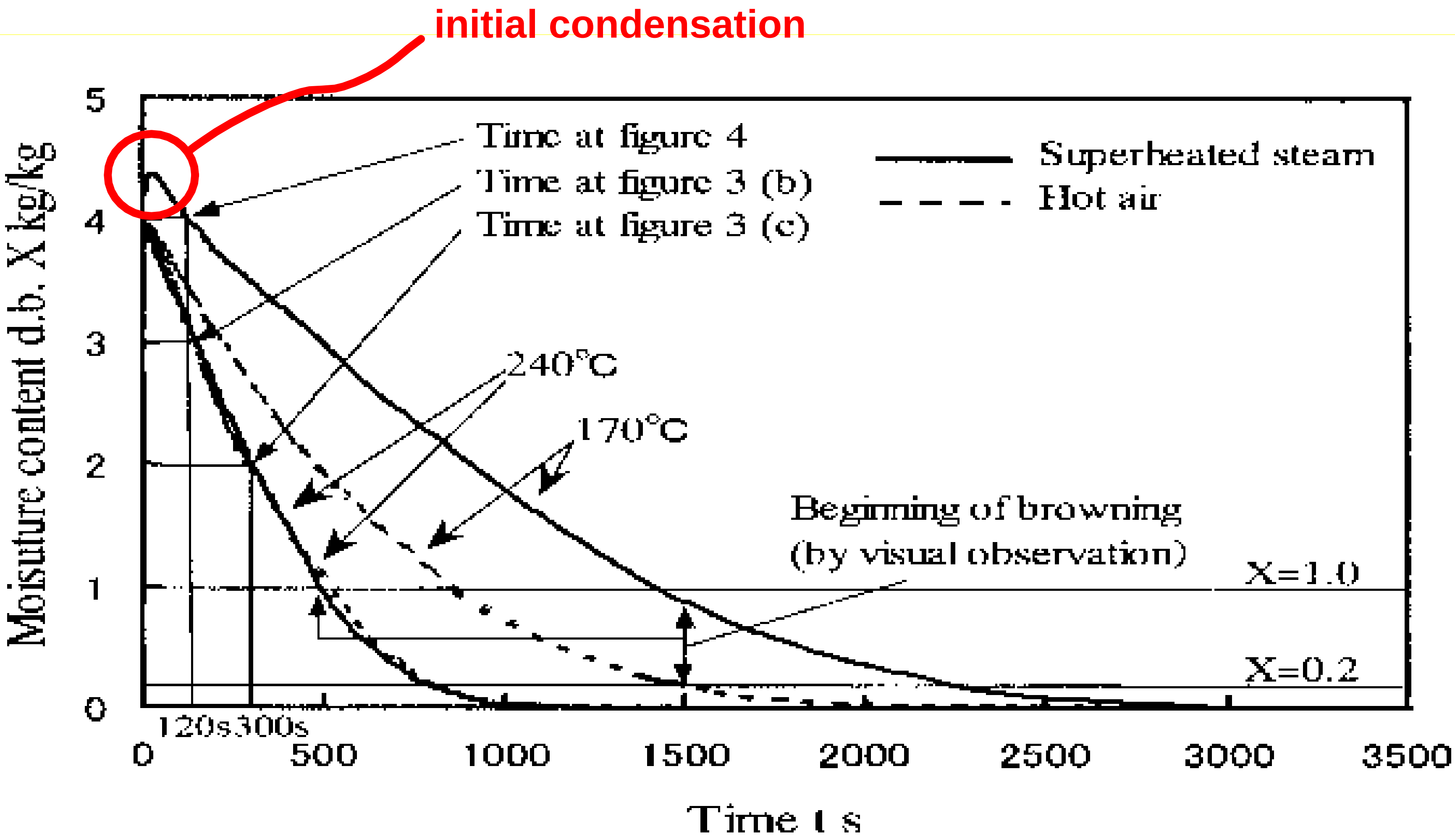
NEAR-ATM PRESSURE SSD OF FOODS

- Most SHSDs operate near-atmospheric condition as equipment cost is lower
- Wide variety of products dried successfully e.g. potato chips, tortilla chip, shrimp, paddy, soybean, noodles etc-
- Better product quality (in some cases) than in air drying



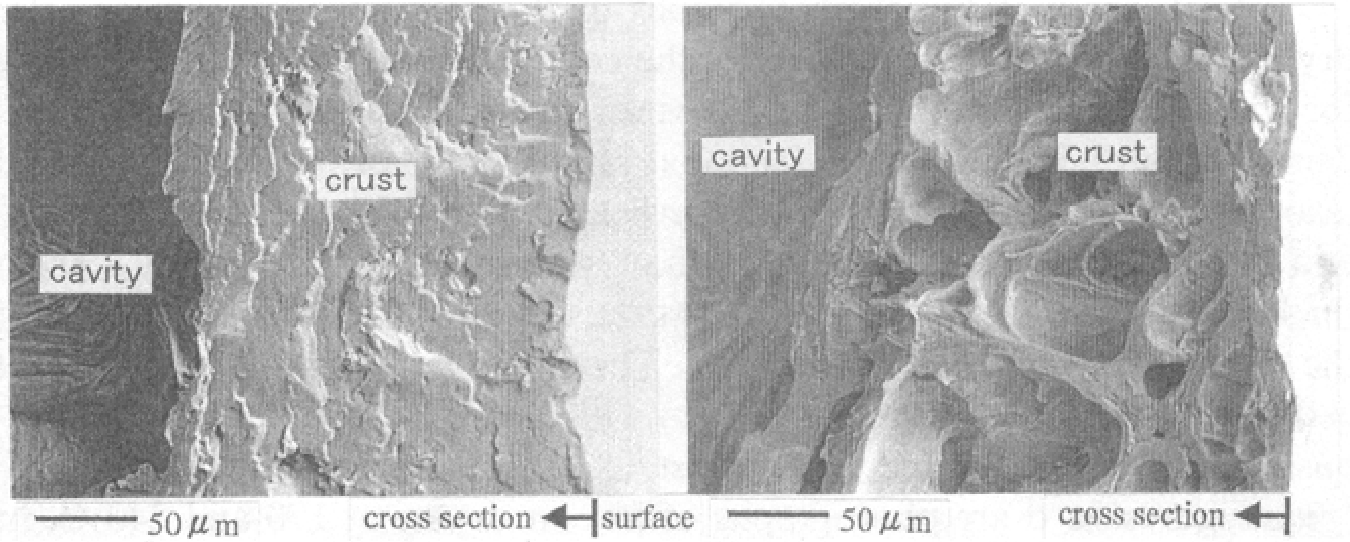
Experimental set up of Iyota et al. (2001)

Iyota et al., Drying Technol., 19, 1411-1424 (2001)



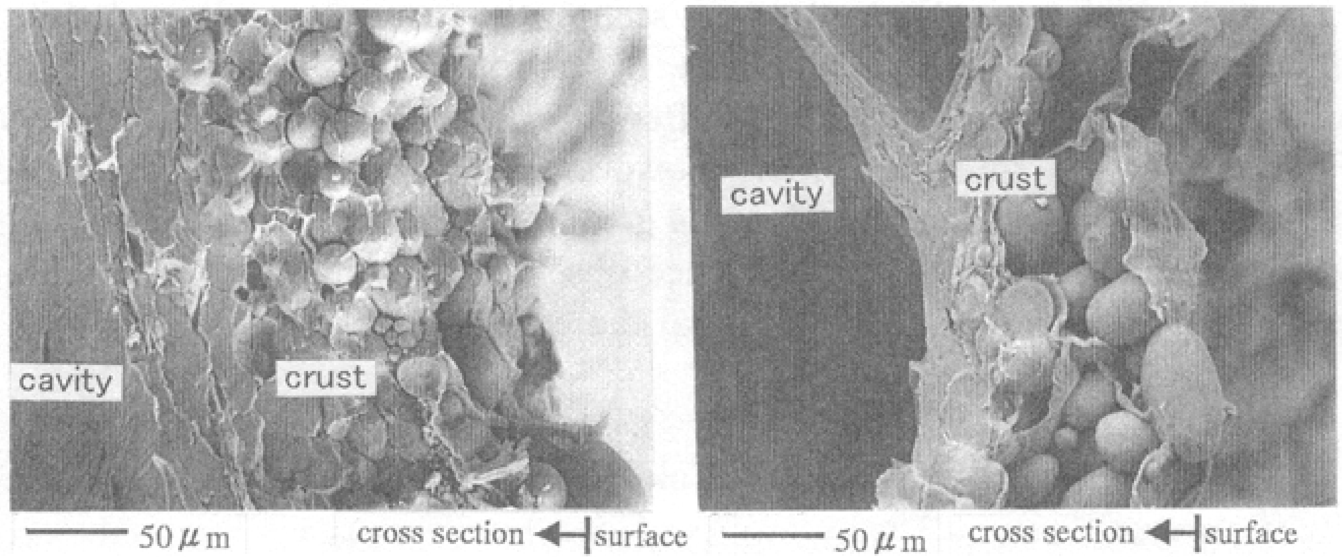
Drying curves for both SSD and hot air drying of potato slices

Iyota et al., Drying Technol., 19, 1411-1424 (2001)



(a)Superheated steam, T_g=170°C, t=5400s (b) Superheated steam, T_g=240°C, t=3000s

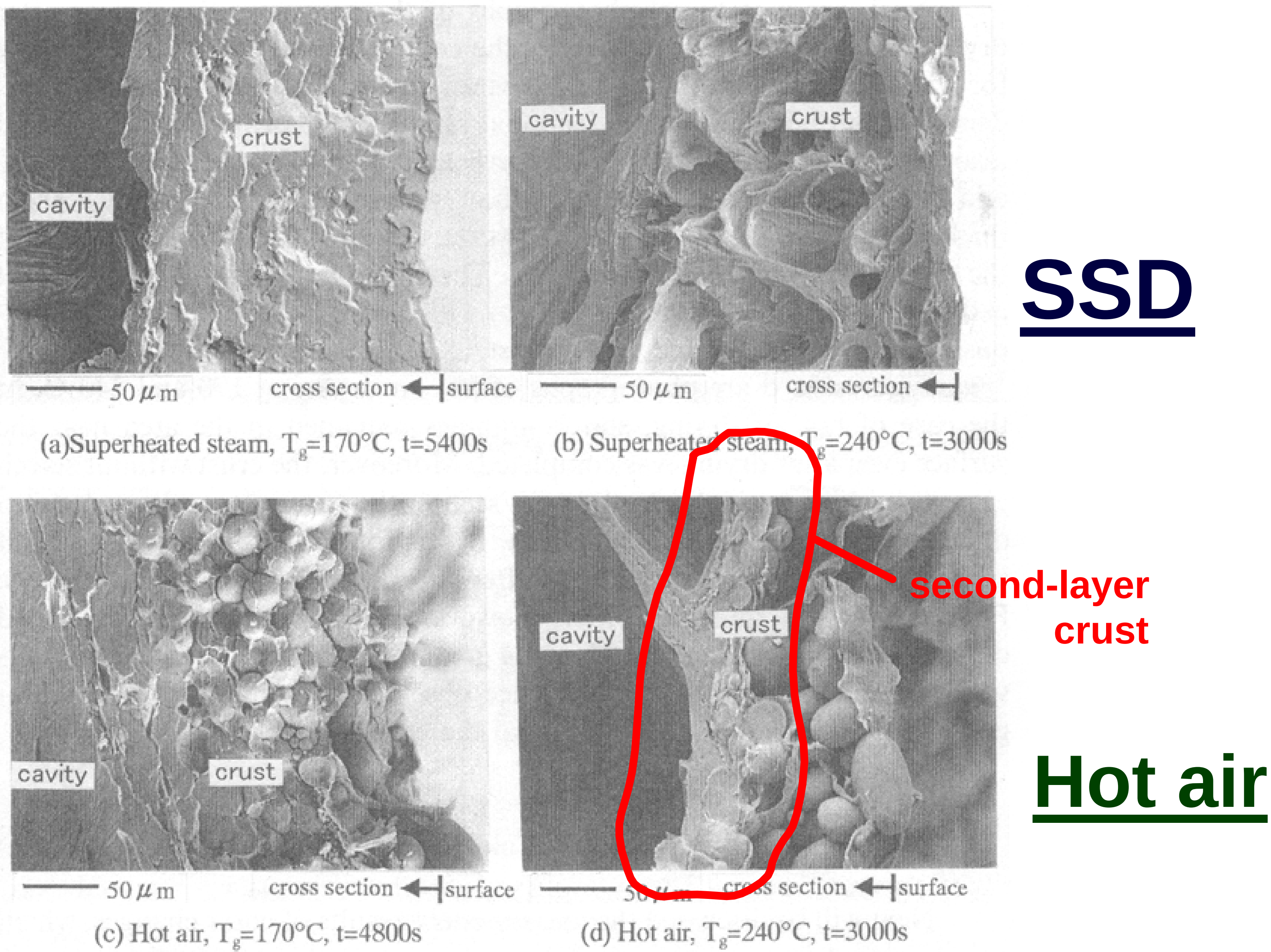
SSD



(c) Hot air, T_g=170°C, t=4800s (d) Hot air, T_g=240°C, t=3000s

Hot air

SEM photos of cross section near the surface of potato slices



SEM photos of cross section near the surface of potato slices

<u>SOME PRODUCTS DRIED IN SSD</u>

- Potato chips, tortilla chips
- Shrimp, pork, chicken, fermented fish
- Sugar beet pulp, spent grain from brewery, okara
- Paddy, soybean, sunflower seed, cacao bean
- Asian noodles
- Vegetables, fruits, herbs - *problems here! Must lower pressure*

- Products that may melt, undergo glass transition or be damaged at saturation temperature of steam cannot be dried in SSD
- First reported study and application was by Chen & Mujumdar (1985) to dry silk caccoons in low pressure SHS;enhanced brightness and strength of silk fibre produced (China)
- Vacuum SHSD kiln for wood is now popular technology for wood drying.

LPSHSD for heat-sensitive products

LOW-PRESSURE SSD (LPSSD)

- Combines the ability to dry product at low temperature with some advantages of SSD
- Dryer is operated at reduced pressure (5-10 kPa)
- Steam becomes saturated (and superheated) at lower temperature
- Suitable for highly heat-sensitive products e.g. herbs, fruits and vegetables and other bio-active materials

- Taken

Following works on LPSHSD are from Dr. S. Devahastin, KMUTT, Thailand

Devahastin et al., Drying Technol., 22, 1845-1867 (2004)

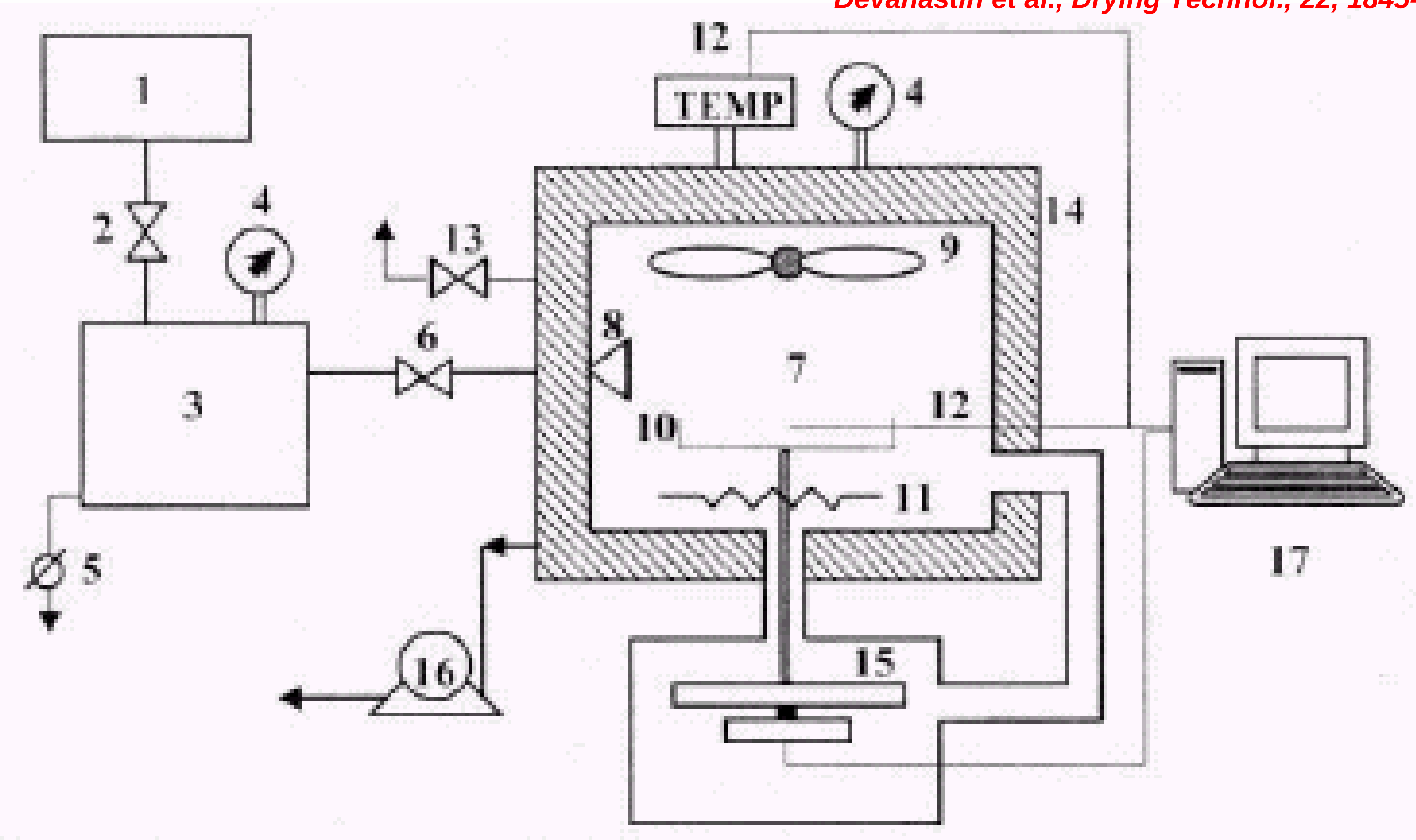
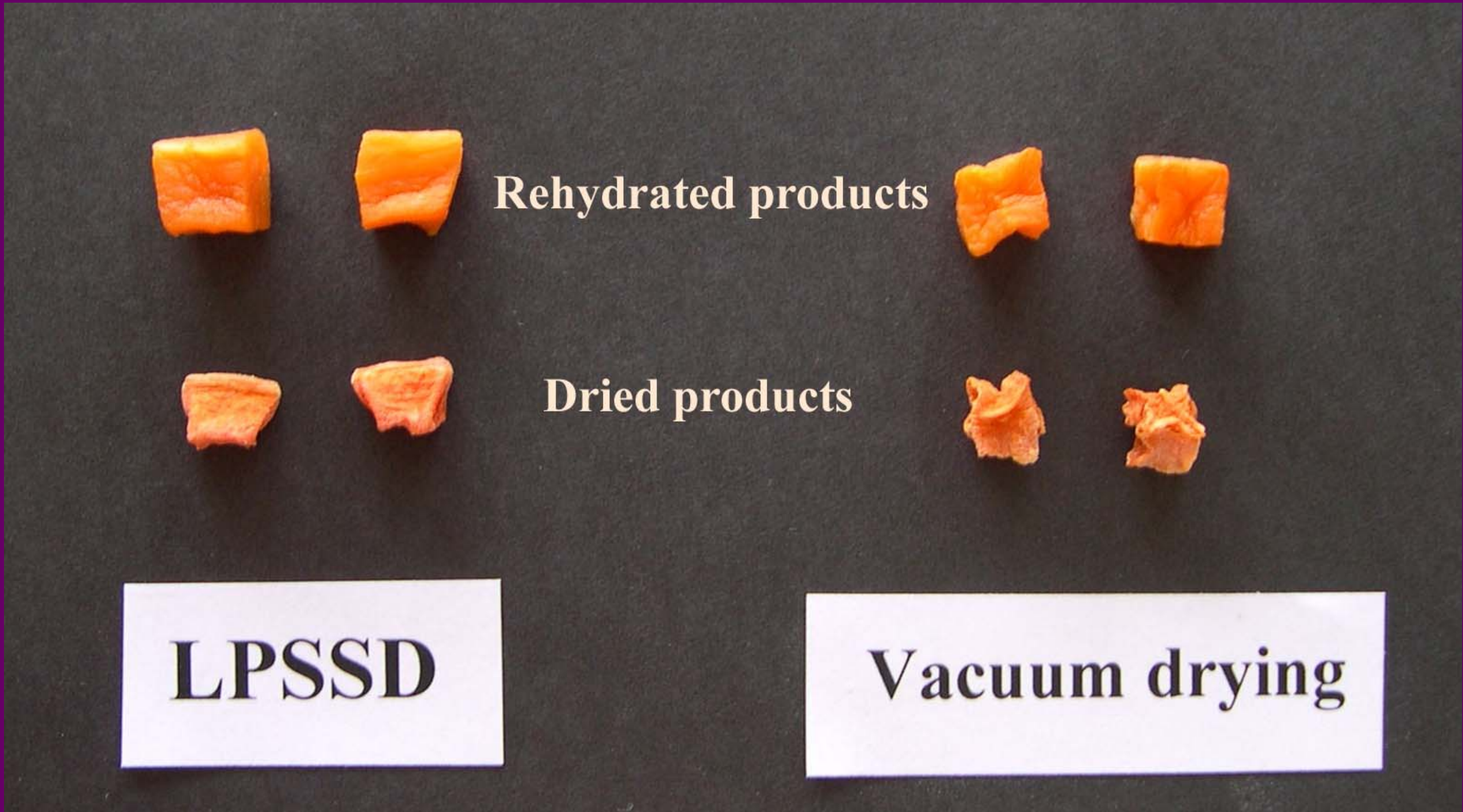


Figure 1. A schematic diagram of the overall experimental set-up. 1, boiler; 2, steam valve; 3, steam reservoir; 4, pressure gauge; 5, steam trap; 6, steam regulator; 7, drying chamber; 8, steam inlet and distributor; 9, electric fan; 10, sample holder; 11, electric heater; 12, on-line temperature sensor and logger; 13, vacuum break-up valve; 14, insulator; 15, on-line weight indicator and logger; 16, vacuum pump; 17, PC with installed data acquisition card.

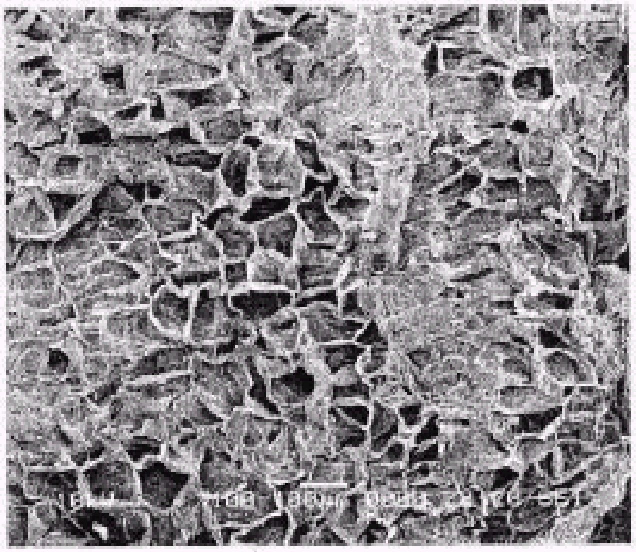
Low-Pressure Superheated Steam Dryer Prototype

Devahastin et al., Drying Technol., 22, 1845-1867 (2004)

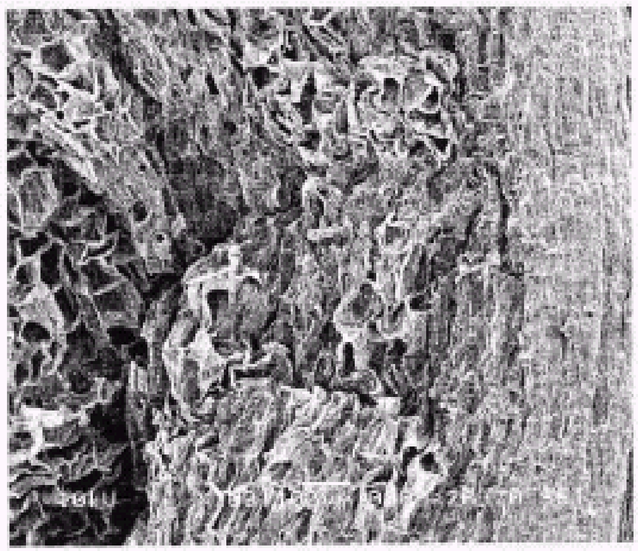


Devahastin et al., Drying Technol., 22, 1845-1867 (2004)

Photographs of carrot cubes underwent LPSSD and vacuum drying

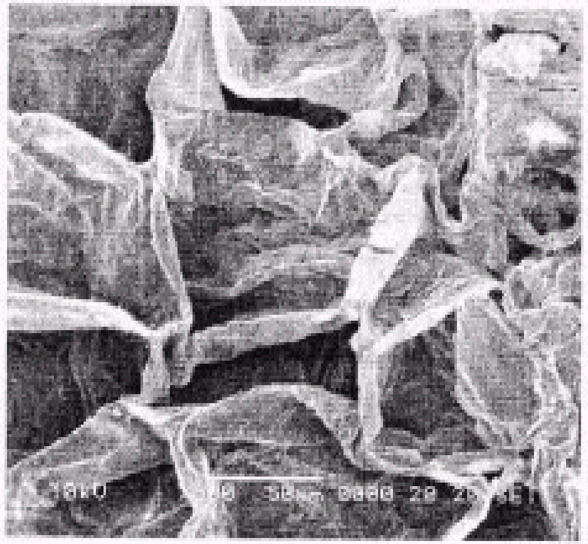


(a)

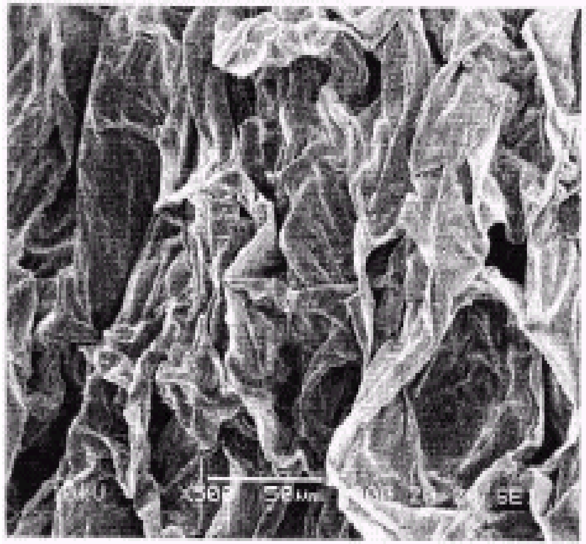


(b)

Figure 7 — *Figure 7.* SEM photographs of carrot undergoing (a) LPSSD, (b) vacu drying.



(a)



(b)

Devahastin et al., Drying Technol., 22, 1845-1867 (2004)

Figure 8. SEM photographs showing pore distribution of carrot undergoing (a) LPSSD, (b) vacuum drying.

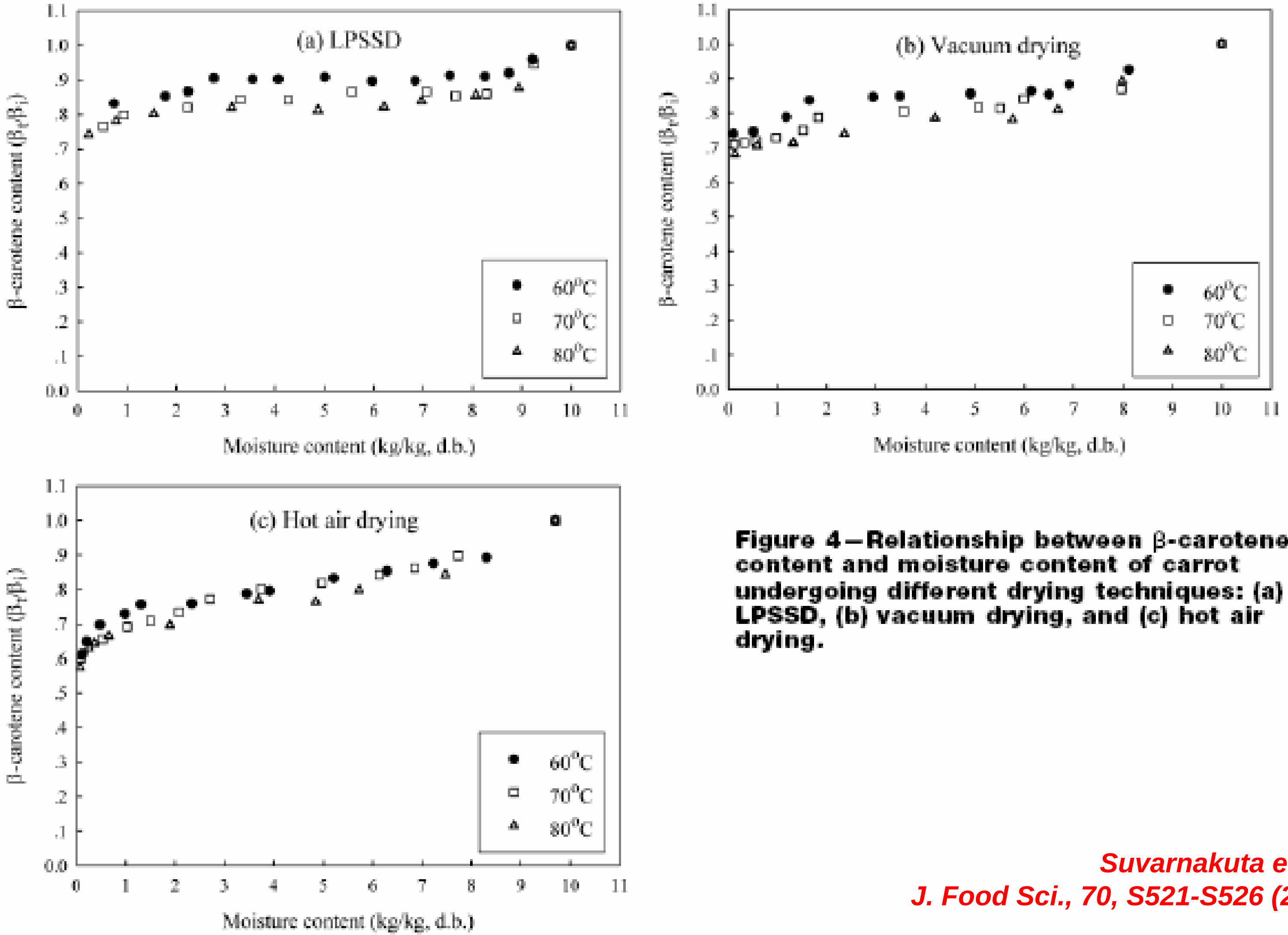


Figure 4—Relationship between β-carotene content and moisture content of carrot undergoing different drying techniques: (a) LPSSD, (b) vacuum drying, and (c) hot air drying.

Suvarnakuta et al., J. Food Sci., 70, S521-S526 (2005)

Relationship between β-carotene content and MC of carrot during drying

Table 2
Total ascorbic acid content of fresh and dried samples[a]

Drying method	Conditions		Ascorbic acid (g/100g)		% Retention
	T (°C)	P_{abs} (kPa)	Fresh	Dried	
VD[b]	65	7	1.08 ± 0.07	3.67 ± 0.13	71.52[ab] ± 1.97
		10	1.06 ± 0.09	3.50 ± 0.25	66.89[a] ± 2.51
		13	0.94 ± 0.05	3.07 ± 0.30	64.84[a] ± 6.01
	75	7	0.96 ± 0.02	3.84 ± 0.18	94.46[cd] ± 2.57
		10	0.99 ± 0.02	3.72 ± 0.11	89.46[c] ± 2.78
		13	0.98 ± 0.11	3.34 ± 0.03	78.13[b] ± 2.83
LPSSD[c]	65	7	1.05 ± 0.06	3.99 ± 0.22	93.46[cd] ± 1.58
		10	—	—	—
		13	—	—	—
	75	7	1.06 ± 0.04	4.04 ± 0.08	95.35[d] ± 3.49
		10	1.09 ± 0.08	4.03 ± 0.11	95.67[d] ± 2.10
		13	1.04 ± 0.08	3.99 ± 0.11	94.96[cd] ± 2.14

[a] Mean ± SD ($n = 2$). Means in the same column having the same letter are not significantly different ($\alpha < 0.05$).
[b] VD stands for vacuum drying.
[c] LPSSD stands for low-pressure superheated steam drying.

Methakhup et al., Lebensm.-Wiss. u.-Technol., 38, 579-587 (2005)

Table 3
Hunter parameters and total color difference (ΔE) of dried samples[a]

Drying method	Conditions T (°C)	P_{abs} (kPa)	$\Delta L/L_0$	$\Delta a/a_0$	$\Delta b/b_0$	ΔE
VD[b]	65	7	0.06 ± 0.00	−0.91 ± 0.01	0.01 ± 0.01	3.83[b] ± 0.09
		10	0.08 ± 0.00	−1.39 ± 0.07	0.02 ± 0.02	5.40[cd] ± 0.10
		13	0.07 ± 0.01	−0.98 ± 0.22	0.00 ± 0.04	4.99[c] ± 1.04
	75	7	0.08 ± 0.00	−0.71 ± 0.01	−0.02 ± 0.01	5.61[cd] ± 0.28
		10	0.09 ± 0.00	−1.11 ± 0.01	−0.02 ± 0.00	6.42d ± 0.26
		13	0.07 ± 0.01	−1.56 ± 0.58	0.03 ± 0.02	5.38[cd] ± 0.66
LPSSD[c]	65	7	0.04 ± 0.00	−0.88 ± 0.97	0.04 ± 0.01	3.09[ab] ± 0.19
		10	—	—	—	—
		13	—	—	—	—
	75	7	0.03 ± 0.01	−0.64 ± 0.04	0.04 ± 0.02	2.48[a] ± 0.44
		10	0.04 ± 0.00	−0.49 ± 0.18	0.04 ± 0.01	2.88[ab] ± 0.18
		13	0.04 ± 0.04	−0.64 ± 0.23	0.02 ± 0.04	2.93[ab] ± 0.39

[a]Mean ± SD ($n = 2$). Means in the same column having a same letter are not significantly different ($\alpha < 0.05$).
[b]VD stands for vacuum drying.
[c]LPSSD stands for low-pressure superheated steam drying.

Methakhup et al., Lebensm.-Wiss. u.-Technol., 38, 579-587 (2005)

RECENT USES OF LPSSD

- **Production of fat-free potato chips**
  - **Effects of physical pretreatments of chips prior to LPSSD**
  - **Combined blanching and freezing is the best pretreatment method (due to starch gelatinization and retrogradation leading to better mouth feel)**
  - **Next step – comparing quality of pretreated chips baked by LPSSD and SSD (instrumental & sensory evaluation)**

RECENT USES OF LPSSD

- **Production of edible films for active packaging/controlled release applications**
  - **Edible chitosan films dried by LPSSD have higher mechanical strength than air dried and vacuum dried films due to enhanced crystallinity and thermal cross-linkage**
  - **Work is underway to study effects of different drying methods on antioxidant and antimicrobial properties as well as controlled release behavior of films**
  - **Next step – testing with real food system**

ENHANCEMENT OF LPSSD

- **Combined LPSSD with FIR**
  - **Enhanced drying rates**
  - **Enhanced some physical qualities of dried products (banana chips) e.g. hardness and crispness***
  - **Potential for production of fat-free snacks or instant foods requiring fast rehydration**

Table 4
Effects of drying methods, drying temperature and pressure on maximum force and number of peaks of dried banana slices

Drying method	Drying temperature (°C)	Drying pressure (kPa)	Maximum force (N)	Number of peaks
LPSSD–FIR	70	7	N/A	N/A
		10	N/A	N/A
	80	7	17.09 ± 3.15^{a}	37 ± 3^{d}
		10	17.30 ± 3.60^{a}	36 ± 4^{d}
	90	7	16.39 ± 3.57^{a}	38 ± 4^{d}
		10	16.89 ± 4.58^{a}	38 ± 5^{d}
VACUUM–FIR	70	7	18.44 ± 3.80^{a}	22 ± 4^{ab}
		10	19.12 ± 4.07^{a}	21 ± 5^{a}
	80	7	19.95 ± 3.55^{a}	25 ± 5^{bc}
		10	18.16 ± 4.51^{a}	26 ± 5^{c}
	90	7	16.72 ± 3.19^{a}	36 ± 3^{d}
		10	17.81 ± 3.63^{a}	36 ± 4^{d}
LPSSD[a]	70	7	N/A	N/A
	80	7	21.52 ± 2.23	27 ± 3
	90	7	24.09 ± 1.26	28 ± 6

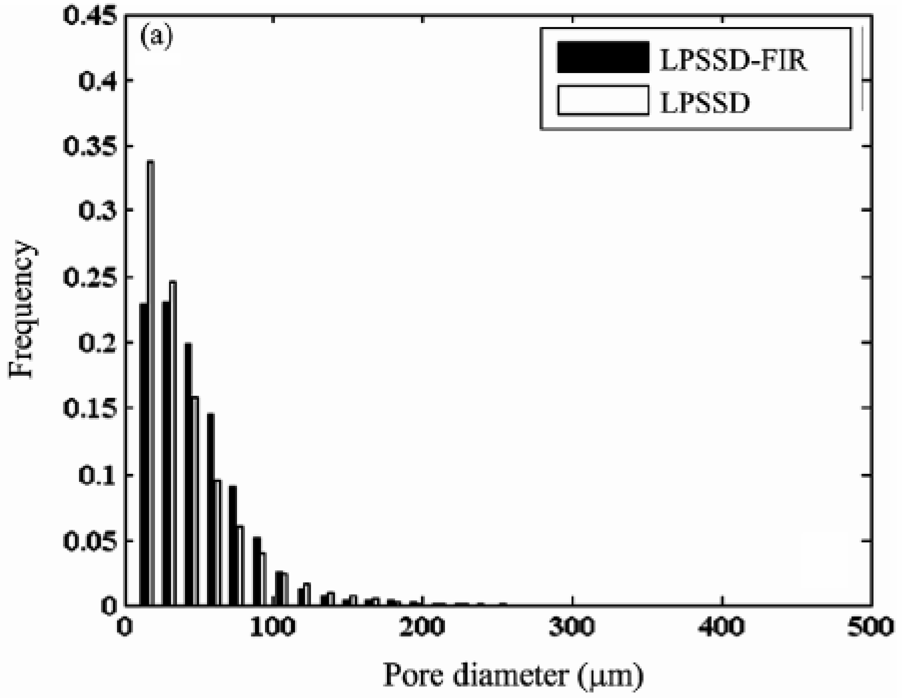
N/A implies that the final moisture content of 0.035 kg/kg (d.b.) was not obtainable at this condition.Values in the same column with different superscripts mean that the values are significantly different ($p < 0.05$).

[a] Data obtained from Thomkapanish (2006).

Nimmol et al., J. Food Eng., 81, 624-633 (2007)

Table 1
Total porosity of banana slices undergoing various drying methods at different drying conditions

Drying method	Drying temperature (°C)	Porosity
LPSSD	80	0.42 ± 0.05
	90	0.53 ± 0.06
LPSSD–FIR	80	0.55 ± 0.06
	90	0.70 ± 0.08
VACUUM	80	0.54 ± 0.05
	90	0.46 ± 0.05
VACUUM–FIR	80	0.57 ± 0.06
	90	0.63 ± 0.07



Leonard et al., J. Food Eng., 85, 154-162 (2008)

FUTURE WORK ON LPSSD-KMUTT

- **Use of LPSSD to produce functional foods and ingredients (from carrot, spring onion and mangosteen peel)**
  - **Retention of antioxidant/antimicrobial activities of active compounds (β-carotene, vitamin C and xanthones)**
  - **Long-term storage stability of products (physical qualities and active compounds)**
  - **Release properties or extractability of active compounds**
  - **Bioavailability of active compounds**
  - **Related also to microstructure (so more works on this are needed!)**

Techno-economic Assessment of SHSD Applications

- CEA Report 9138 U 888, June 1994 by B. Woods, H. Husain and A.S. Mujumdar, Montreal, Canada
- Results /costs are for 1994- must be modified e.g. payback periods etc will change as cost of energy has sky-rocketed
- For Canada, HHSD of lumber, DDG(distiller's dry grain) and coal upgrading were considered as potentially most relevant
- Paper drying (Mujumdar, McGill, 1982-95) using SHS impinging jets) is attractive in terms of energy savings and enhanced quality of paper but equipment needed is radically different and hence not yet commercialized.

Some interesting results from literature on SHSD

- Energy savings- for sugar beet pulp and lumber drying : 30% savings; quality improved; complex feeding and discharge valves; acidic extraction causes materials problems
- V/SS Drying of Lumber (IWOTECH, Denmark). SHSD drying rates 3-7 times faster, no discoloration; recovery of terpenes from exhaust by condensation; not much effect on shrinkage
- Capital costs higher for V/SSD but has higher throughput to compensate.

Lumber drying

- Many case studies reported in CEA Report
- Payback is immediate if drying rate is 4 times higher
- For replacement of air drying kils, payback time can be long
- Payback time is very sensitive to enhancement of drying time, quality and cost of energy
- Probably best to use V/SS for wood …

DDG Drying in SHS

- Ethanol fermentation processing produces large volumes of DDG- used for cattle feed after drying
- Ready use exists for steam produced by SHSD in ethanol plants
- Tests done in Canada (1993) show 30& protein content(depends on grain used); lighter color in SHSD; no mal odor (burnt smell due to oxidation)
- Tests show 1 bar pressure SHSD gives best product quality; higher pressures yield darker product-probably protein denaturation

DDG SHSD_ Dryer Types

- Many options: Rotary, Fluid bed; rotary with steam tube, flash; high pressure SHSD
- To obtain energy efficiency, must find use for excess steam produced by dryer
- Reheat or compress or condense- all involve extra capital and operating costs
- Frequent start-up and shut-down is not desirable for SHSD

Coal Upgrading using SHSD

- Reduction in MC of LRC (lignites) gives better C.V., better flowability in hoppers, better grindability; reduced flue has volumes due to reduced water vapor content (hence lower fan power)
- Reduction in sulfur content if steam-rated at 300-400 C.
- Reduction in Na content of coal. Reduced fouling/slagging. Na has positive effect on electrostatic precipitator performance due to better resistivity of fly ash

More on Coal Drying

- Many competing processes
- Fluid bed with intenal heat exchanger is used in large coal-fired power plants in Germany
- Many engineering problems remain and are not discussed in open literature
- Case study for Brown Coal-CEA Report

Other Products

- Biosolids, sludges-includes sterilization
- Soil remediation-steam stripping of volatiles
- Pulp, hog fuel, bark etc-MoDo Chemetics/Exergy Dryer- flash dryer with heating jacket
- Paper Drying- feasible technically but not commercial yet
- Peat Drying-Finland. Pressured gasification reactor preceded by high pressure SHSD.
- Textile drying-not commercial yet; drying of salts

Closing Remarks

- SHSD- drying technology of the future
- Although attractive on paper, not many suppliers of SHSD exist
- Considered revolutionary or game-changing and hence finds much resistance in market
- High energy costs favor SHSD but better quality may provide better incentive
- Typically increases electricity consumption!

Thank you!