Superheated steam drying of porous clay

Similar concepts for wood and other media

Concept of inversion temperature above which steam drying is faster than air drying

MHI Super-efficient steam dryers
(see www.mhi-inc.com)

Clay (alumino-silicates with sliding planes)

- Clay is a term used to describe a group of hydrous aluminium phyllosilicates. Phyllosilicates being a subgroup of silicate minerals that are typically less than 2 μm in diameter.

- Clay consists of a variety of phyllosilicate minerals rich in silicon and aluminium oxides and hydroxides which include variable amounts of structural water.

See picture below of clay heaps and clay-objects after firing

Properties of Clay

- The Clay minerals are fine particle size hydrous aluminosilicates which develop plasticity when mixed with water. A common characteristic of Clay is their layered structure. They all are composed of electrically neutral aluminosilicates layers which move readily over each other, giving rise to such physical properties as softness, soapy feel, and easy cleavage.

- Their plasticity is basic to many of the forming processes commonly used; the ability of clay-water compositions to be formed and to maintain their shape and strength during drying and firing is basic to many ceramic processes.

- They fuse over a temperature range depending on their composition in such a way as to become dense and strong without losing their shape.

Drying of clay bodies is associated with:

- Evaporation of moisture from a body.
- Shrinkage in ceramics.

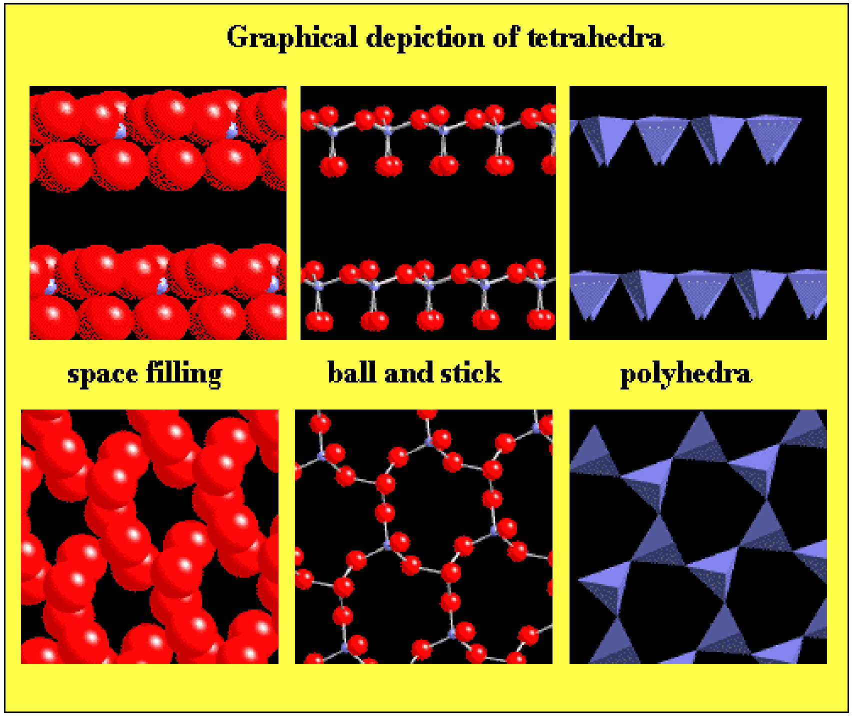
Issues

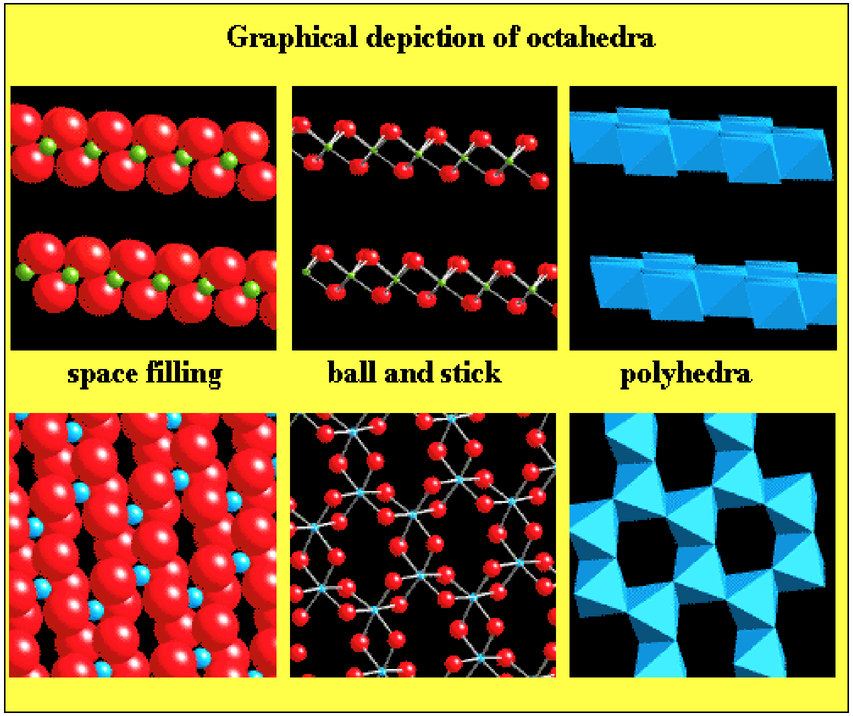
- Drying dependence on shape and size of the ceramic ware.
- The drying gradient.
- Critical moisture content.
- Drying Medium (air, steam etc.)

Clay Structure : Tetrahedral and Octahedral Sheets

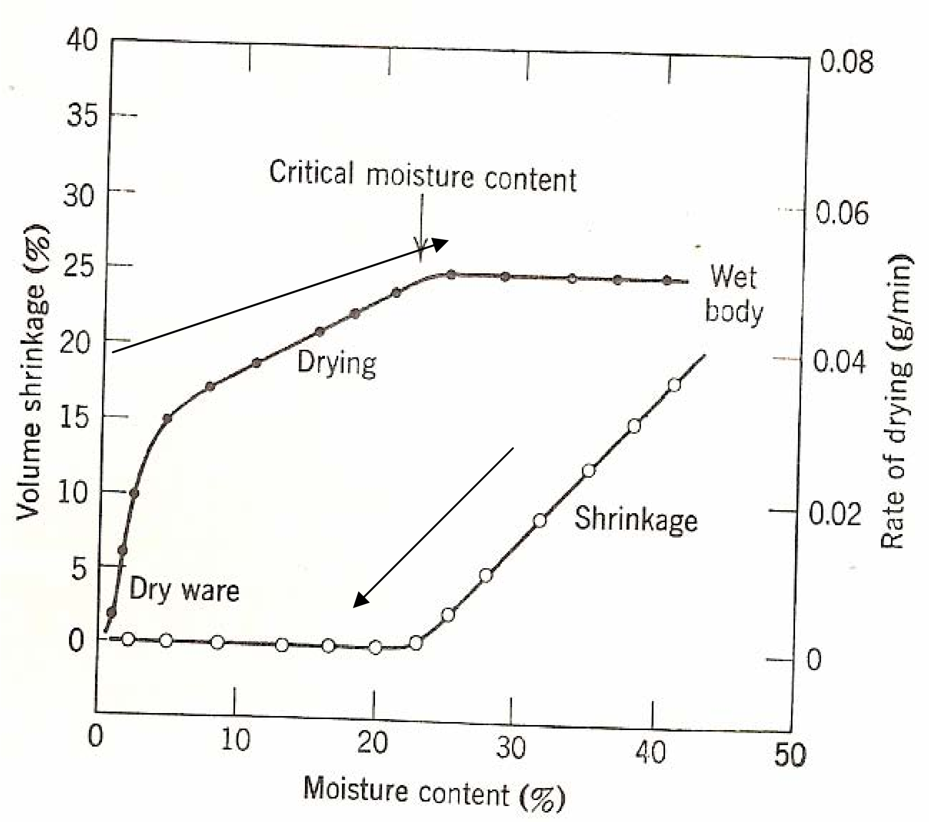
- Tetrahedral sheets are composed of individual tetrahedrons which share 3 of four oxygen Atoms and they are arranged in a Hexagonal pattern. The resultant sheet composition is T_2O_5 where T is the common tetrahedral cations of Si, Al and sometimes Fe^{3+} and B.

- Octahedral sheets are composed of individual octahedrons that share edges composed of oxygen and hydroxyl anion groups with Al, Mg, Fe^{3+} and Fe^{2+} typically serving as the coordinating cation. These octahedrons too, are arranged in a hexagonal pattern.





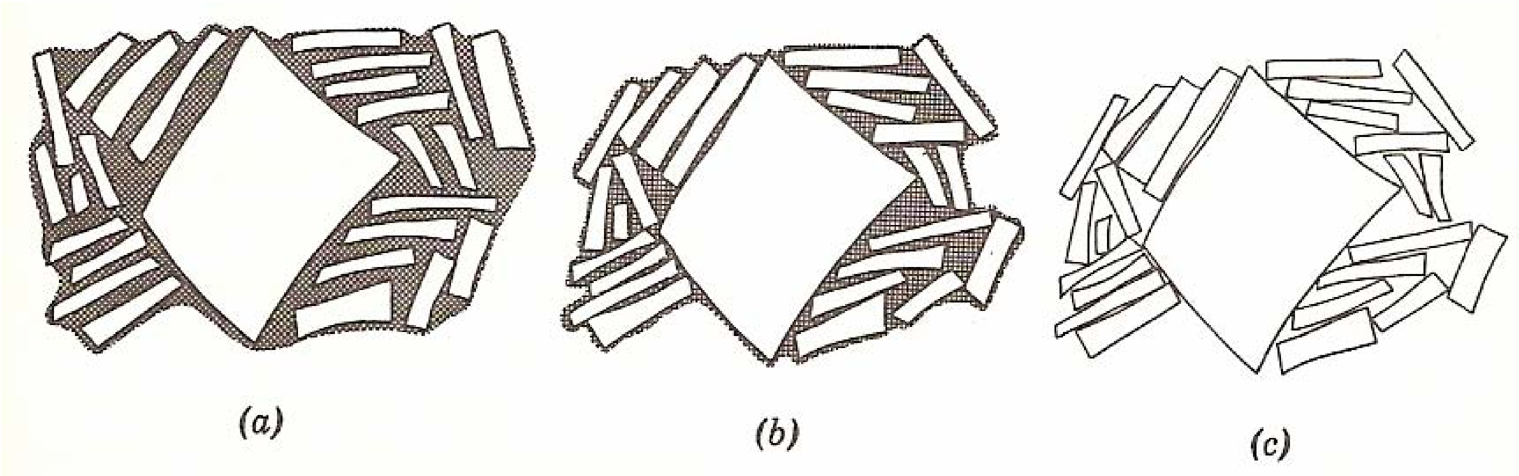
Rate of drying and drying shrinkage for ceramic body



The critical moisture content corresponds to the solid particles coming into contact as shown in the next slide. The rate of drying begins to decrease and the shrinkage stops.

Drying Process (cont…)

Each particle in the body separated by water films at the initial stages of drying. The water films decrease in thickness until at the "critical point "(at which the rate of drying and also the rate of shrinkage sharply change) the particles have just come in contact. This is the end of the shrinkage and the beginning of lower rate of drying.



Drying process for a clay body showing (a) wet body, (b) critical point, (c) dry ware

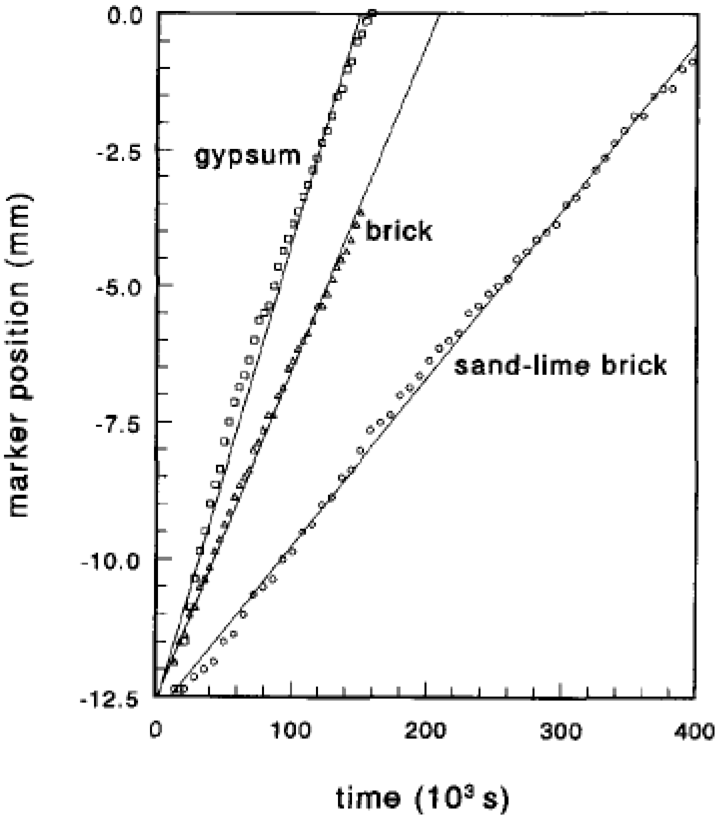
Some physics of the drying process

- Most defects occur in drying in the period of drying shrinkage where partial parts of the ware still have the water films resulting in varying shrinkages.
- As a result, stresses, warping, and possibly cracks develop in the ware. Thus careful rate control is essential.
- Control strategies include humidity control, flow rate control and higher velocities.
- Higher temperature increases the rate of drying by virtue of the increased vapor pressure and the reduced viscosity of the liquid during the falling rate period. Change of drying medium like using superheated steam has a few interesting features such as the inversion temperature.
- In addition to controlling the rate of drying, we can also control the overall shrinkage-mainly by controlling the initial water content during forming, and by controlling the particle size.

Mechanism of Drying in porous media

- Capillary action.
- Pore networks and models
- The receding drying front.
- Moisture concentration profiles.
- The typical drying curve.

- (see list of references provided at the end)



Typical Drying curves

- The various regimes active.
- Drying rate

$$\dot{n} = -\frac{1}{A}\frac{dM}{dt}$$

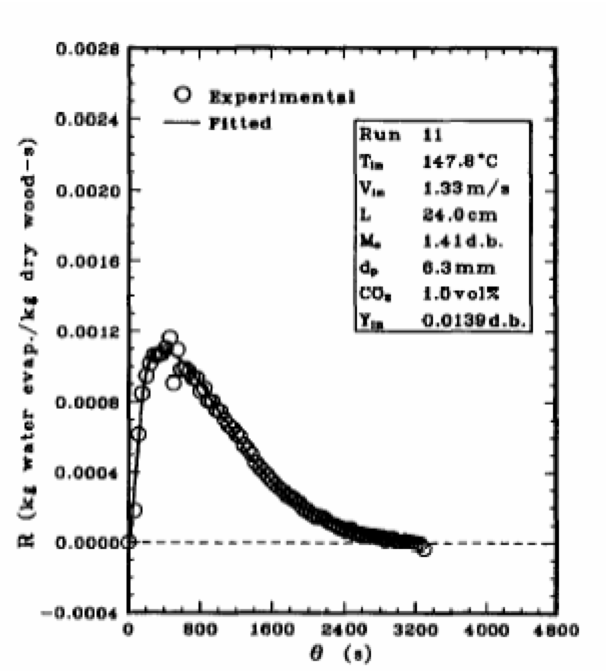
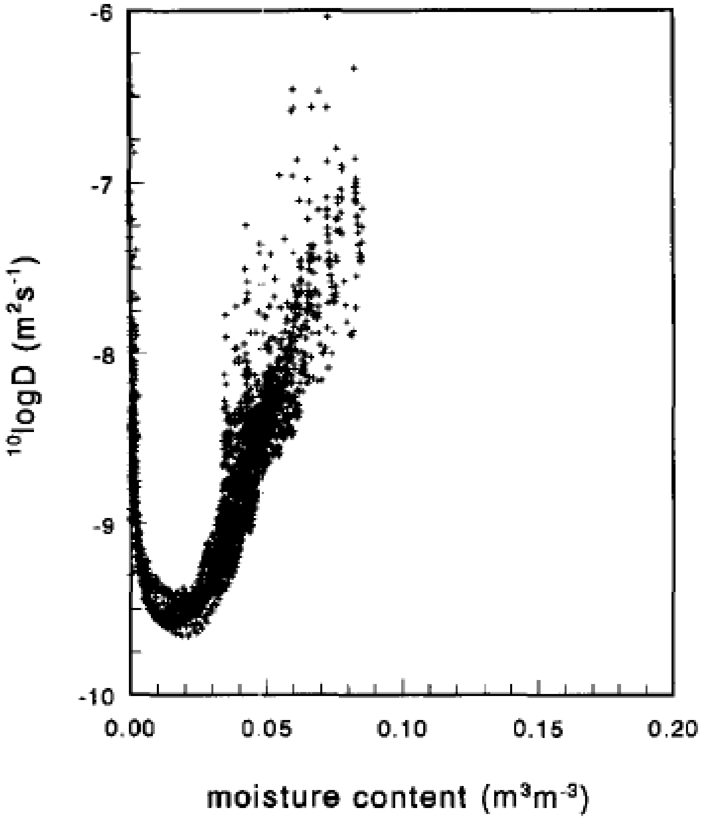


FIG. 1. A typical drying rate curve.

- Moisture diffusivity regimes.
  - High moisture content.
  - Decreasing moisture content
  - Low moisture content.
  - Diffusivity
  - Liquid transport equation for capillary liquid movement (Modified Fickian law)

$$n_1 = -\rho_s \cdot D(Y,T).\frac{\partial Y}{\partial r}$$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-7
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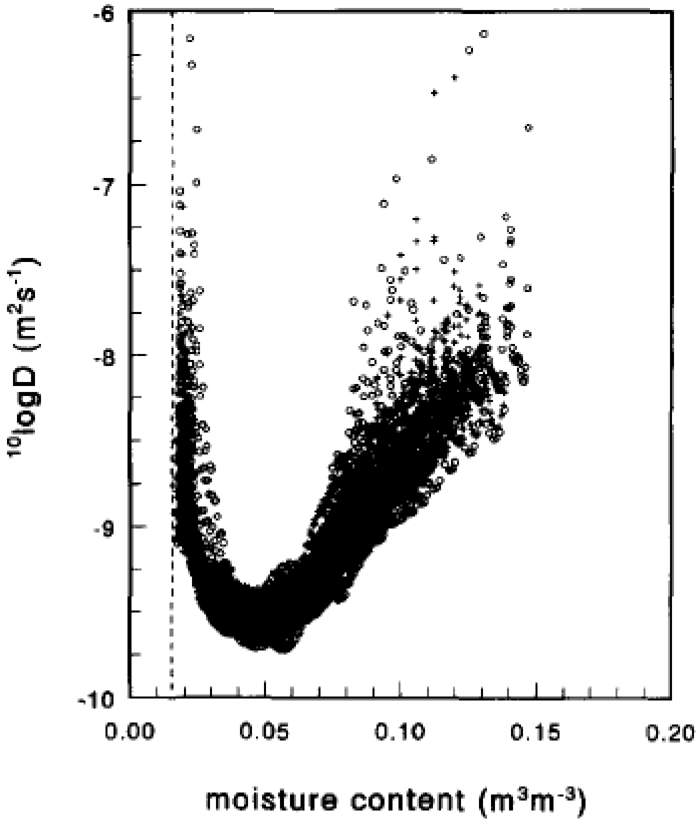
^{10}logD (m^{2}s^{-1})
0.00
0.05
0.10
0.15
0.20
moisture content (m^{3}m^{-3})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Air vs. Steam

- What is superheated steam? Contact MHI web-site or read associated article
- Heat capacity of Steam and Air. Contact mhi or web site www.mhi-inc.com
- How can steam dry? Keep reading this ppt. References at end.
- Concentration gradient.
- Lower Temperature range comparison.
- Higher Temperature range comparison.
- The Inversion Temperature.

The Inversion Temperature

- Definitions. When comparing superheated steam and dry air in a drying process a temperature has been found, at which the drying rates into the gases compared are equal. This temperature is called the inversion temperature.
- Relevance. See inside
- Reason for its existence. Reference 12
- Difficulty in Predicting this temperature.

→ No defined procedure to determine the inversion temperature. Different procedures yield different temperatures.

→ Purely Convective --- 260^{o}C

→ Mass flow 18200 kg m^{-2} h^{-1} --- 170^{o}C

→ Mass flow 9100 kg m^{-2} h^{-1} --- 176^{o}C

- Dependence on Mass flow velocity. Reference 12

- The existence of inversion temperature is due to the existence of opposing effects favoring evaporation in different conditions:

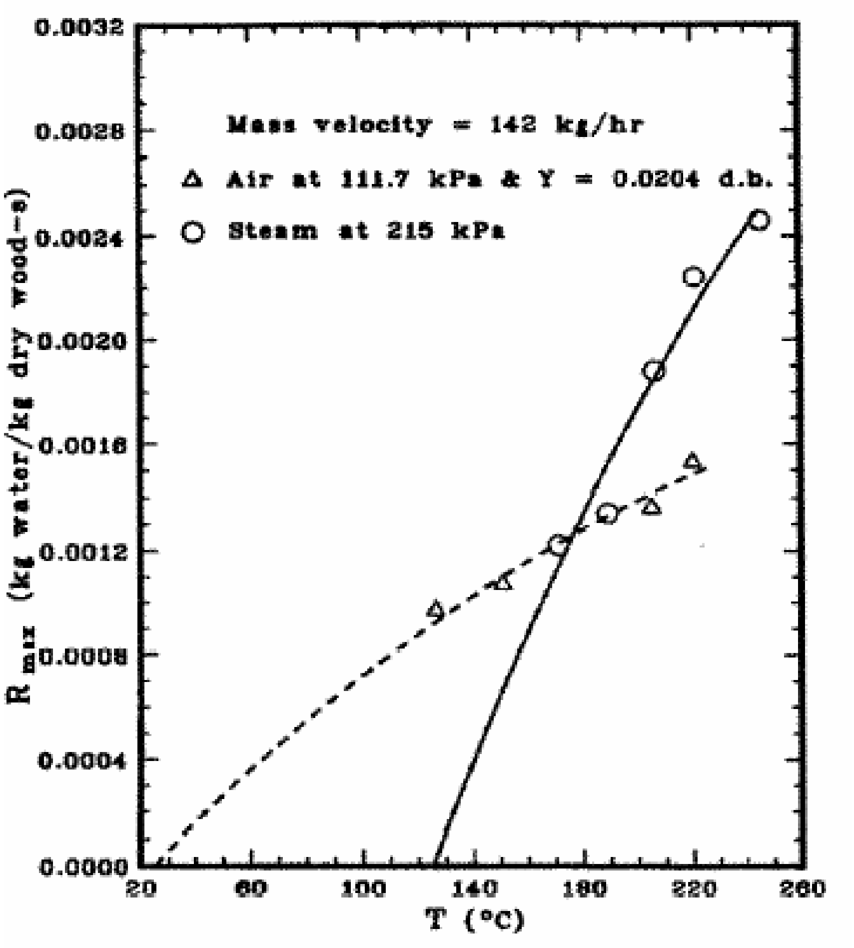
→ Effects decreasing with vapor concentration.

Among these effects, are temperature potential (T_i - T_0) effect (T_i increases with vapor concentration and consequently (T_i - T_0) decreases). These effects dominate when the ambient temperature is below to the inversion temperature.

→ Effects increasing with vapor concentration

The latent heat effect (the latent heat requirement Lv decreases with vapor concentration). These effects dominate when the ambient temperature is higher than the inversion temperature.

The Heat transfer potential – Reynold’s number and Prandtl number contribution to inversion temperature



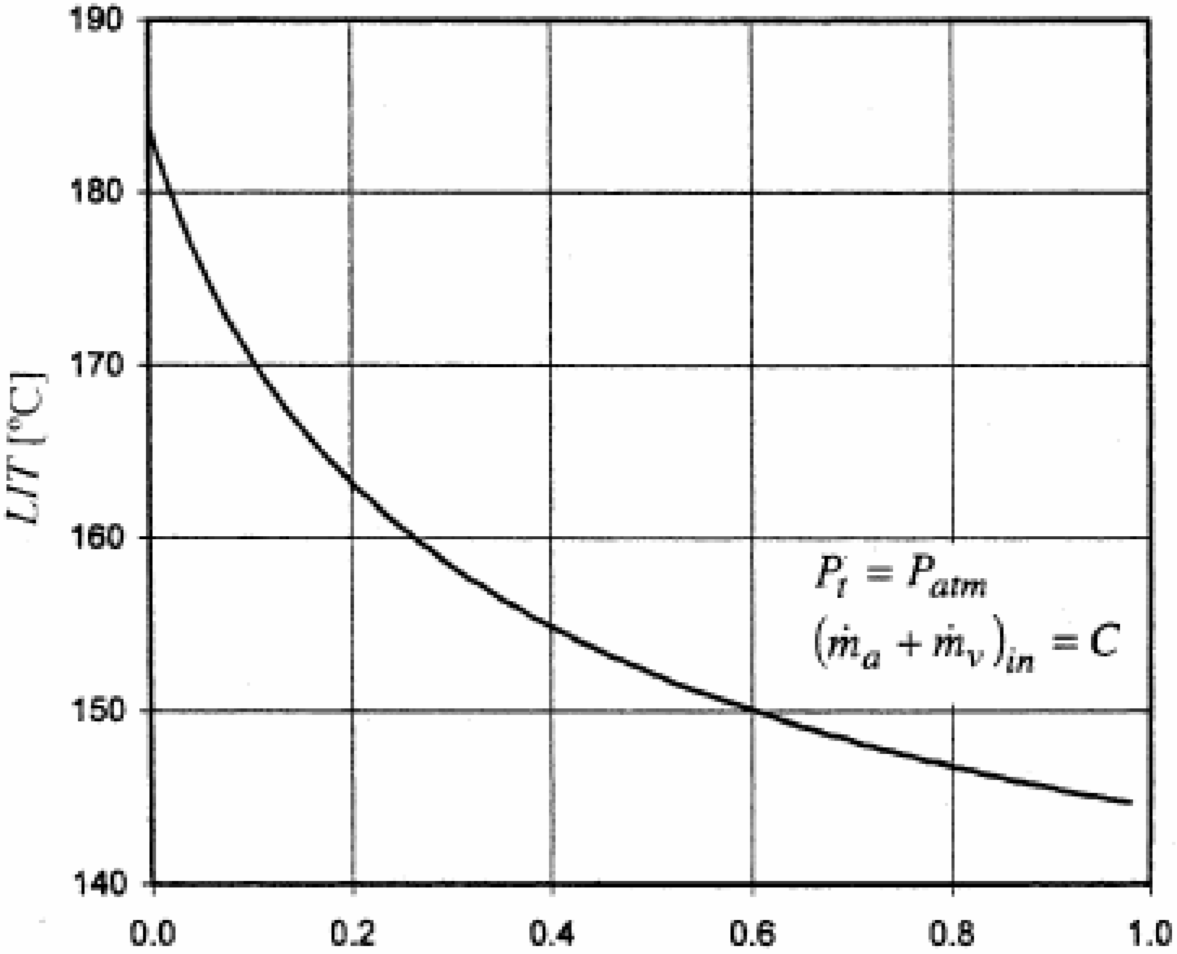
Drying Rates of Air and steam showing an Inversion temperature

$$h = 0.027\frac{k}{D}Re_D^{0.8}Pr^{1/3}\left[1+\left(\frac{D}{x}\right)^{2/3}\right]$$

$$Nu_x = \frac{hx}{k} = 0.332Re_x^{1/2}\,Pr^{1/3}.$$

$$\mathrm{LIT}_W = T_{\mathrm{s,v}} + \left(\frac{V_W}{V_\mathrm{v}}\right)^m \left(\frac{\mathrm{RM}}{\mathrm{Ac_v}}\right)\left(\frac{h_{\mathrm{fg}(T_\mathrm{s})}}{c_{\mathrm{P,v}}}\right)\left(\frac{\rho_W}{\rho_\mathrm{v}}\right) \times \left(\frac{Pr_\mathrm{v}}{Sc_W}\right)^{(1-n)}\left(\frac{Sc_W}{Sc_\mathrm{v}}\right)^{(1-m)}\ln\left(\frac{W_\mathrm{s}+\mathrm{RM}}{W+\mathrm{RM}}\right)$$

Proposed formula for Local Inversion Temperature



Variation of Inversion temperature with specific humidity

IN MHI RECIRK-UNITS

- Air and excess steam vented away (Heat and condensed steam can be reused).
- Max efficiency achieved as steam is vented (flows).

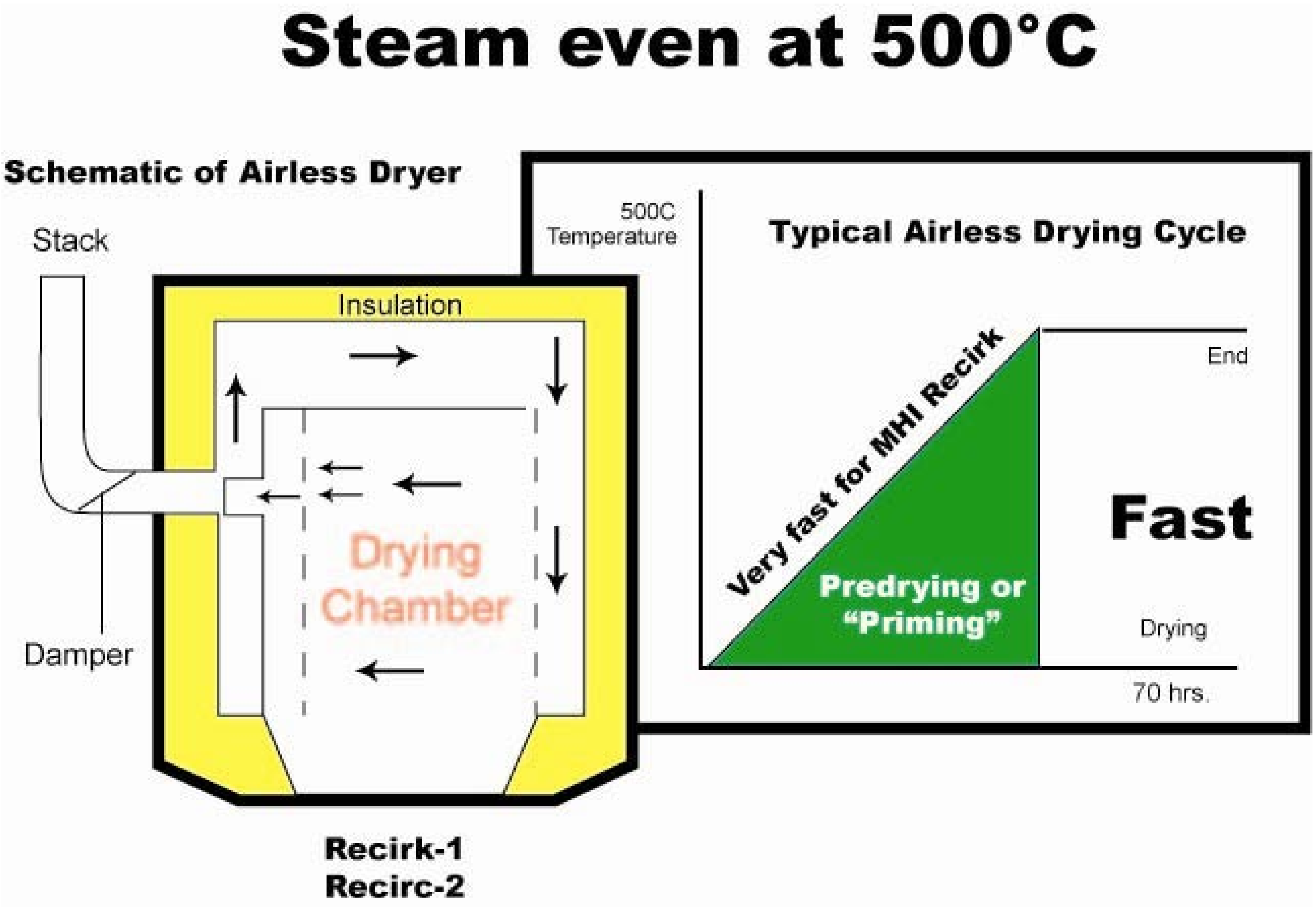
Micropyretics
Heaters
International

Thermodynamic Aspects

- Steam has higher Specific Capacity
- Higher Heat Transfer Potential
- Enthalpy losses reduced – Large part of heat is recoverable!
- Entropy change reduced – Precise control of water evaporation and drying rates ensure reduced shrinkage related stresses and cracks.

MHI Micropyretics Heaters International

Schematic for the superheated steam drying process. For very, very large chambers. Contact MHI for your specific condition. Trials available at company test units. Just contact us at sales@mhi-inc.com



Steam even at 500°C

MHI
Micropyretics
Heaters
International

Some Advantages of using MHI superheated Steam for Drying (patents applied)

- In the process of steam drying superheated steam is brought in direct contact with the product to be dried. The superheated steam at a significantly high temperature transfers heat to the wet product which then starts to dry. The steam remains superheated and does not condense. As a result the evaporated water comes out of the drying process as steam.
- **Energy savings:** The evaporated water is released as pure steam and its energy can be recovered by condensation. The energy consumption thus can be reduced even by 80% compared to drying with hot air.
- **Product Quality:** Drying in a steam environment can lead to a higher product quality.
- **Emission abatement:** Since Steam drying is a closed system no contaminants can leave the system so any emission of environmentally hazardous components is prevented.
- **Patented:** Recirculation for huge energy benefits. MHI has several patents and patents applied for.
- **Productivity**: Steam drying as noted in this presentation can often lead to **faster drying** with less defects.
- **Low Risk**: TEST YOUR PART FOR A SMALL FEE. Contact MHI at sales@mhi-inc.com.

REFERENCES

- (1) Denis A. Brosnan and Gilbert C. Robinson, Introduction to Drying of Ceramics: With Laboratory Exercises, The American Ceramic Society, Westerville, Ohio, 2003.
- (2) Kenneth G. Budinski, Engineering Materials: Properties and Selection, Second Edition, Reston Publishing Company, Inc., Reston, VA, 1985.
- (3) David J. Green, An Introduction to the Mechanical Properties of Ceramics, Camridge University Press, Cambridge, 1998.
- (4) W. D. Kingery, H. K. Bowen and D. R. Uhlmann, Introduction to Ceramics, Second Edition, John Wiley & Sons, Inc., New York. 1976.
- (5) Merle C. Potter and Craig W. Somerton, Schaum's Outline of Thermodynamics For Engineers, Second Edition, McGraw Hill, New York, 2006.
- (6) James S. Reed, Principles of Ceramics Processing, Second Edition, John Wiley & Sons, Inc., New York, 1995.
- (7) Christopher W. Sinton, Raw Materials for Glass and Ceramics: Sources, Processes, and Quality Control, John Wiley & Sons, Inc., New York, 2006.
- (8) Lawrence H. Van Vlack, Elements of Materials Science and Engineering, Fourth Edition, Addison-Wesley Publishing Company Inc., Reading, Mass., 1980.
- (9) W. E. Worrall, Clays and Ceramic Raw Materials, Halsted Press, New York, 1975.
- (10)R. SHEIKHOLESLAMI and A. P. WATKINSON, Rate of evaporation of water into superheated steam and humidified air, ht. J. Heat Mass Transfer. Vol. 35, No. 7, pp. 1743-1751, 1992
- (11)C. Debbissi a, J. Orfi b,*, S. Ben Nasrallah, Evaporation of water by free or mixed convection into humid air and superheated steam, International Journal of Heat and Mass Transfer 46 (2003) 4703–4715
- (12) Schwartze JP, Brocker S Chemical Engineering Journal, Vol.86, No.1-2, 61-67, 2002 A theoretical explanation for the inversion temperature
- (13) Vítor António Ferreira da Costa A1, Fernando Neto da Silva A1, Celestino Rodrigues Ruivo A2 An Alternative Approach to the Inversion Temperature. Drying Technology Publisher: Taylor & Francis Issue: Volume 23, Number 9-11 / 2005 Pages: 1783 - 1796

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