Heat Transfer Issues and Phenomena for Granular First Walls

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Overview

HEAT TRANSFER ISSUES

a. Peak pebble temperature and temperature gradient
   - to ensure temperature and stress limits can be met

b. Area and volume requirements to transfer heat in the HX (a high-temperature HX is likely to be expensive)

c. Temperature distribution, important for other reasons:
   - *e.g.*, tritium control

PHENOMENA

1. Energy deposition characteristics and temperature evolution in the heated zone *(low-density free-falling medium)*

2. Heat transfer in the HX *(dense confined medium)*

R&D NEEDS

1. Energy Deposition

Key Issue:

Deposition characteristics around and through pebbles determines peak surface temperature and near-surface thermal gradients (stresses)

1. Plasma particle flows:

Depends on plasma contact, CX neutral flux

Complications:

Sheath effects

$\lambda_{Debye} = 743\ T[eV]^{1/2}\ n^{-1/2}$ [cm]

100 eV, 10^{12} /cm^3 $\rightarrow$ 75 μm

(particle separation less than sheath size would result in electrostatic effects)

Larmor radius effect

H Larmor radius = $102\ T^{1/2}$ /B [cm]

100 eV, 50 kG $\rightarrow$ 200 μm

Pebble rotation

Two reasons this may be worth considering:

1. Determine impact of pebble-plasma contact
2. Important for divertor or near-divertor regions

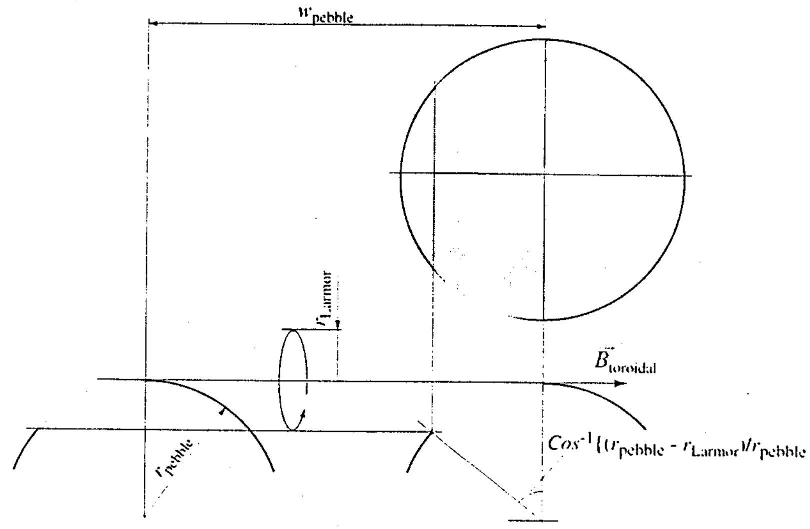


Fig. 1 Larmor radius limited heat load spreading

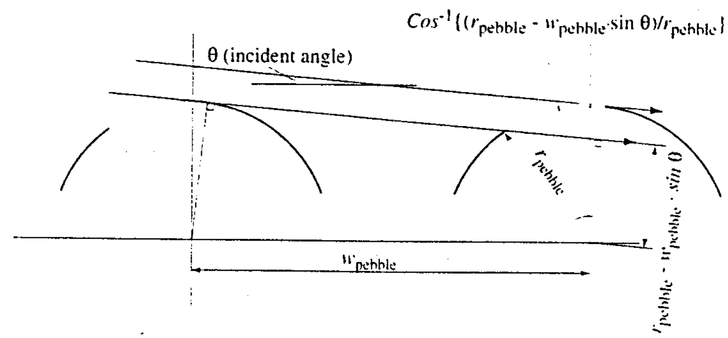


Fig. 2 Incident angle limited heat load spreading

1. Energy Deposition, cont'd.

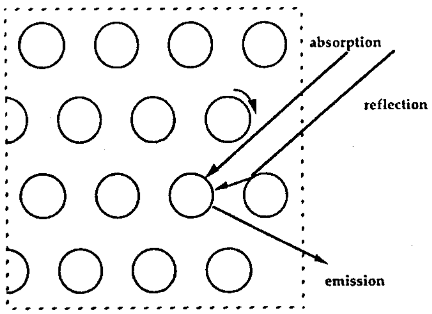
2. Radiation:

Optical properties depend on geometry, pebble directional emissivity/reflectivity, spectra

Time-dependencies: pebble rotation, bed geometry evolution

Re-emission could reduce temperature peaking factors:

T (C)	$5.7x10^{-8}\ T^4$
878	0.1 MW/m^2
1000	0.15
1448	0.5
1774	1



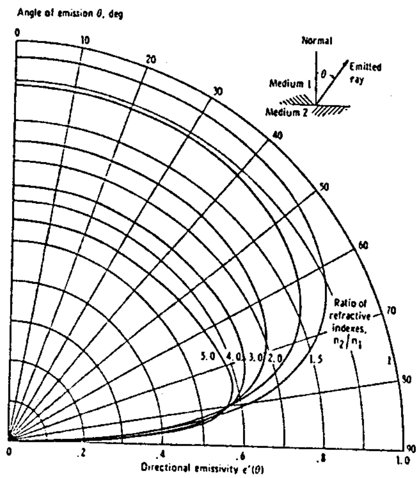


Figure 4-6 Directional emissivity predicted from electromagnetic theory.

2. Heat Transfer in the Heat Exchanger

h	=	h_{pc}	+	h_{gc}	+	h_r
		particle convection*		gas convection		radiation

* includes gas-phase conduction at contact points

J. S. M. Botterill, "Fluid-Bed Heat Transfer," Academic Press, London 1975.

- In vacuum, $h_{gc} = 0$
- h_{pc} is highly dependent on the flow field – empirical data typically is used, and can not be extrapolated easily

Key Questions:

1. How is h_{pc} affected by gas pressure?
2. At what point does h_r become dominant?
3. How does h_r reduce h_{pc}?

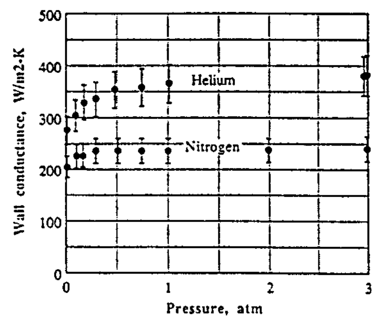


Fig. 8. Wall conductance for 4.3 mm balls with He and N_2 fill gas.

2. Heat Transfer in the Heat Exchanger, cont'd.

$$h_r = \frac{\sigma\, \varepsilon_r\, (T_{bed}^4 - T_{surface}^4)}{T_{bed} - T_{surface}}$$

for 1000 C bed, 800 C surface, ε~1
h_r ~ 400 W/m^2-K

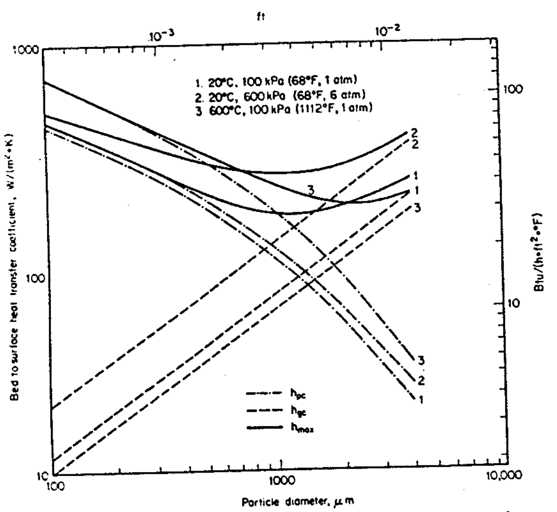


FIG. 9 Effect of particle size on maximum bed-to-surface heat transfer coefficient h_{max} for operation at (1) 20°C and 100 kPa, (2) 20°C and 600 kPa, and (3) 600°C and 100 kPa. Interphase gas convective component of heat transfer h_{gc} taken as that for quiescent bed; particle convective component h_{pc} estimated by difference [26].

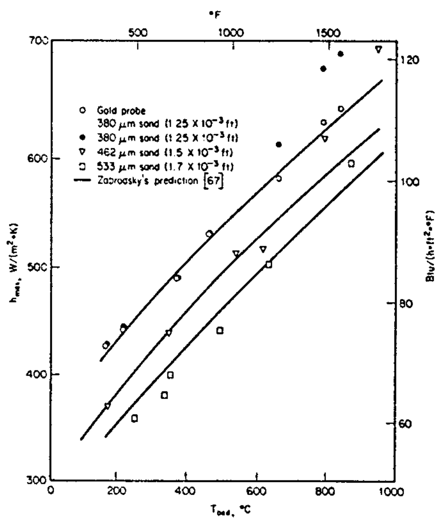


FIG. 10 Variation in maximum bed-to-surface heat transfer coefficient h_{max} with operating temperature compared with the prediction of the Zabrodsky correlation, Eq. (57), for beds of sand of different mean particle size [26]. Note that $h_{max} \approx h_{pmax} + h_r$

Literature

- A huge literature exists on fluidized beds

  Limited heat transfer studies in vacuum, vertical free-flow

  Some particle-particle and particle-wall radiation results

- 3D numerical simulations and experimental work has been done very recently on the mechanics of granular materials, which is identical under vacuum conditions

  *X. Zhuang, A.K. Didwania, J.D. Goddard, "Simulation of the quasi-static mechanics and scalar transport properties of ideal granular assemblages," J. Computational Physics, **121** (2), Oct. 1995.*

  V.V.R. Natarajan, M.L. Hunt, E.D. Taylor, "Local measurements of velocity fluctuations and diffusion coefficients for a granular material flow," J. Fluid Mechanics 304, Dec. 1995. p.1-25.

  C.S. Campbell, "Self-diffusion in granular shear flows," J. Fluid Mechanics, 348, 10 Oct. 1997. p.85-101.

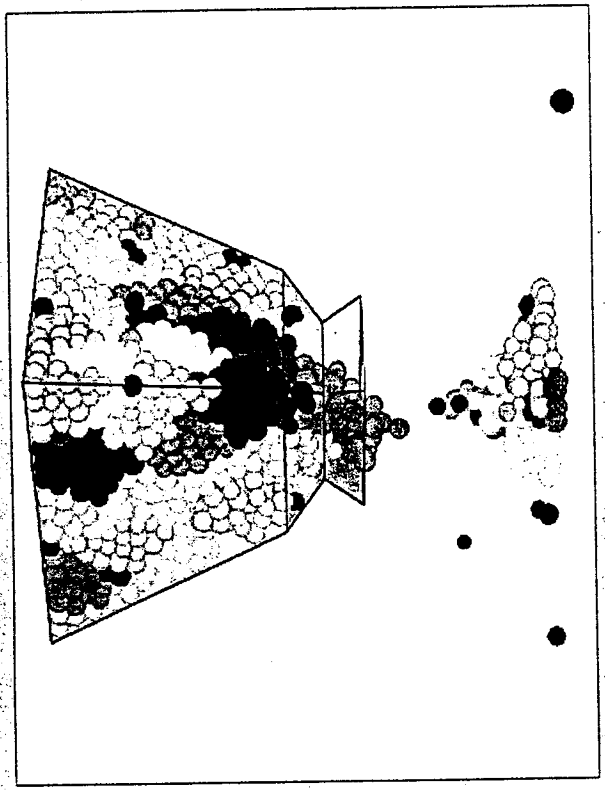
- "The heat transfer area seems to be very lightly traveled."
  I have yet to find an article on vacuum heat transfer in falling beds.

  *V.V.R. Natarajan, M.L. Hunt, "Heat transfer in vertical granular flows," Experimental Heat Trans., **10** (2), Taylor & Francis, April-June 1997. p.89-107.*

  R.E. Nietert, S.I. Abdelk-Khalik, "Thermal hydraulics of flowing particle-bed-type fusion reactor blankets," Nuclear Eng. & Design, 68 (3), 1981. p.293-300.

NSF ENGINEERING RESEARCH CENTER on
Particle Science and Technology ($60M/11 yr, 1994)
http://www.erc.ufl.edu/

Particle Flow Code in 3 Dimensions



A three-dimensional distinct element program to simulate the true 3D behavior of particulate materials. *PFC3D* is the 3D extension of *PFC2D*.

Recommendations

Near-term

- Approximate single-sphere heat transfer and stresses
- 2D (cylinder) model for scoping calculations.
  Explore critical issues, develop physics models.
- Plan empirical verification in table-top experiments

Medium-term

- Develop and/or extend an existing 3D code to model energy deposition, heat transfer and stresses.
- Perform table-top experiments

Longer-term

- System development
- Experiments in a plasma device

Collaborations

Japanese activities on granular media for fusion:

Masahiro Nishikawa, Osaka University

Akihiko Shimizu, Kyushu Univbersity

Tomoaki Kunugi, Tokai University

US/J meeting on PMI, Yokohama, Oct. 1998