Potential Exploitation of Dusty Plasma Physics to PDE small scale MHD

Fred Schauer, AFRL
John Hoke, ISSI
Alan Garscadden, AFIT

Air Force Research Laboratory and Air Force Inst of Technology
Wright-Patterson AFB, Ohio, 45433

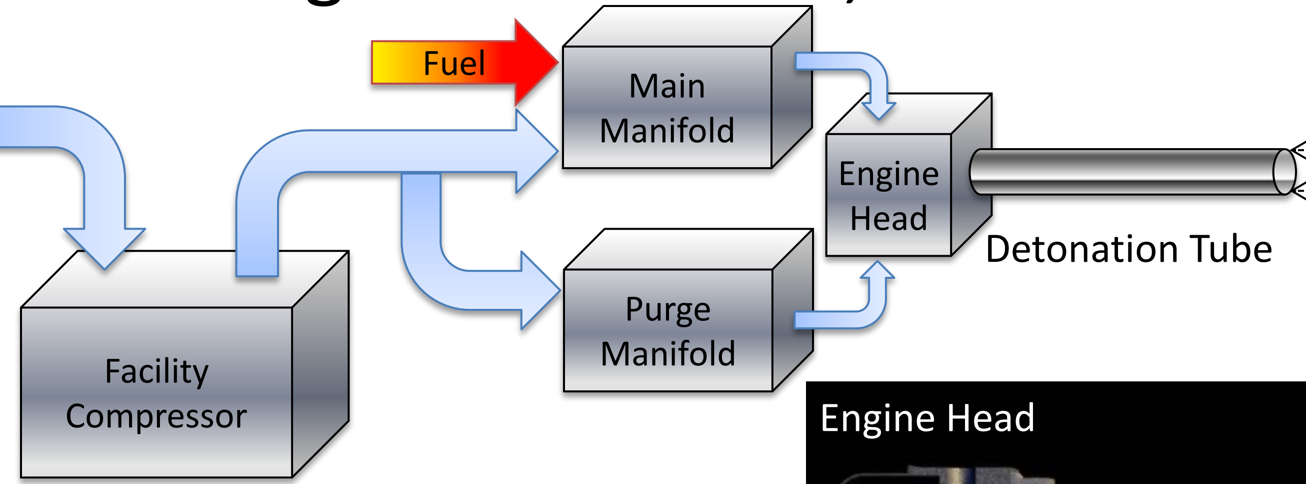
Gordon Conference 1989: Gary Selwyn of IBM reported copious amounts of fine dust in plasma processing reactors.

Early studies by Langmuir, Emeleus, and others had noted the presence of dust in plasmas but that was before laser scattering methods were available.

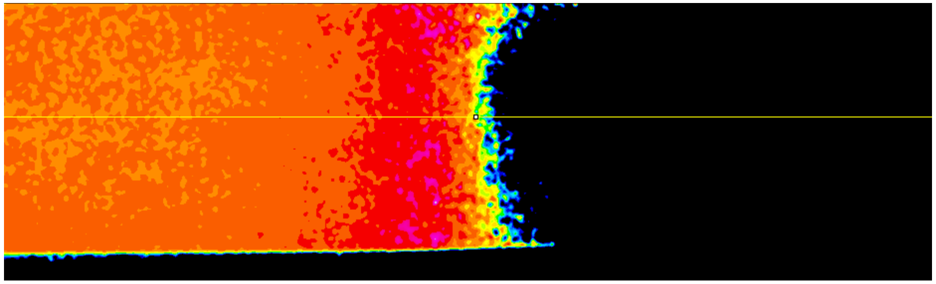
Astronomers including Opik, Whipple, Northrop, Mendis, Goertz had long ago studied the dusty plasmas that exist in space.

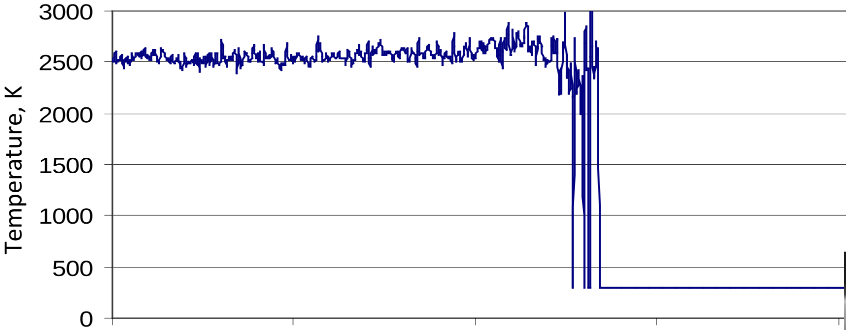
AFRL Detonation Engine Research Facility

- Fuel: hydrogen ($\phi = 1.0$) or ethylene ($\phi = 1.2$)
- Frequency: 10, 20, 30 Hz
- Fill fraction: 0.6, 0.75, 0.9
- Purge fraction: 0.5, 0.75

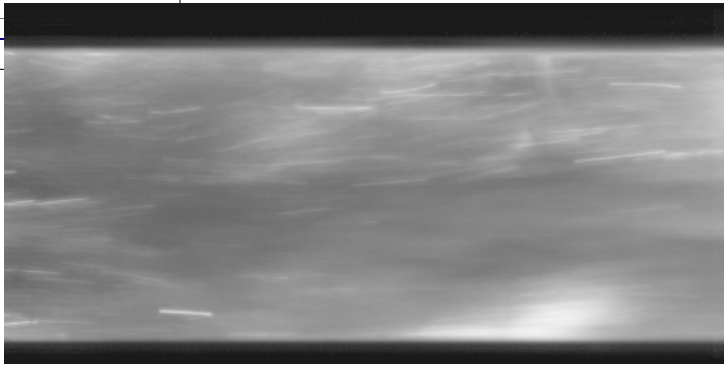



Garrett GT28 Turbo





Thermal emission from PDE shock (left) from which temperatures are obtained and images of particulates in the flow (below) from which velocities can be estimated.

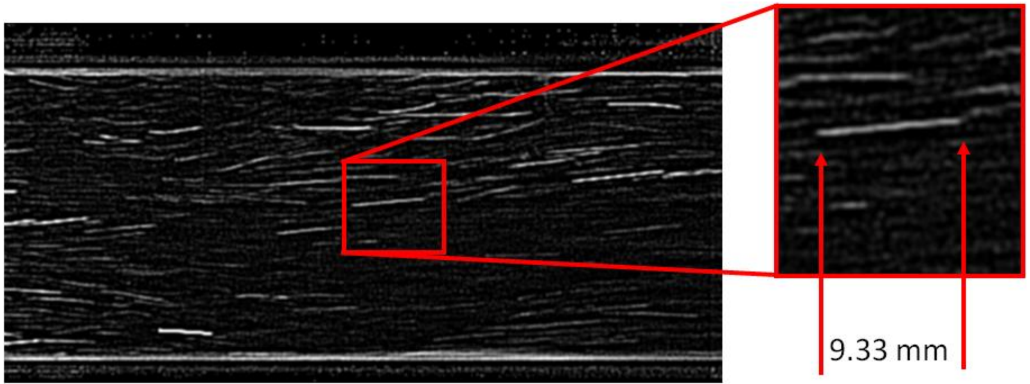


Raw Image

$$u = \frac{\text{streak length}}{\text{exposure time}}$$

$$u = \frac{9.33\ \text{mm}}{0.02\ \text{ms}}$$

$$u = 466.5\ \text{m/s}$$



Processed Image

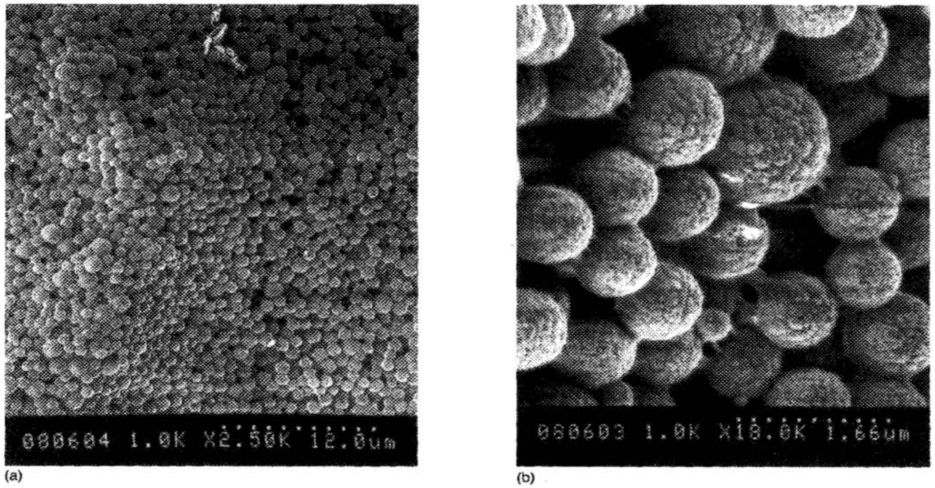


FIG. 4. (a) Low magnification scanning electron micrograph of dust collected with a swab from the walls of a helium plasma tube. Three distinct diameters, 900, 1800, and 450 nm are present in a 90:8:2 ratio. (b) At larger magnification, the cauliflower surface texture and uniform morphology are displayed, as are examples of the larger and smaller grains. The weblike matrix is resin from the conducting paint used to mount the grains for microscopy.

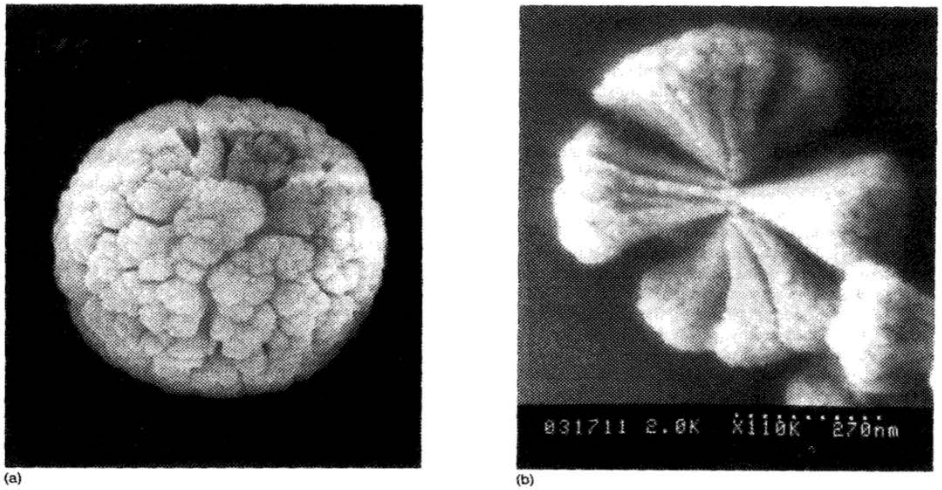


FIG. 5. Uncoated SEM images of grains grown in a 1 Torr Ar plasma. (a) A whole grain is 700 nm in diameter illustrating deep fissures and columnar morphology. (b) Fracturing of the grains can occur during handling, providing a glimpse of the interior morphology. This image shows the radial symmetry and uniform density of the grains.

Some important properties of the low pressure discharge particles are noted:

- There are many thousands of particles formed in seconds in a low current Argon-Carbon Monoxide discharge.
- The particles are almost all of a uniform size.
- The surfaces of the particles are textured.
- The particles are amorphous rather than crystalline (rapid growth does not allow time for optimum site selection).
- If broken, the internal structure has a cauliflower-like fractal structure (this may indicate charged particle growth mechanism).
- The initial seed appears to be smaller than nanometers.
- The particles eventually assemble into structure suspended above electrode sheaths.
- The particles eventually display collective behavior and are in constant motion.

Potential of a dust particle in a plasma

- As the electrons are much more mobile than the ions, the particle will charge negatively in order to balance the charged fluxes.

- The (floating) potential will be V = - 2.5 kT/e

- For a 1 micron radius particle, the dust charge will be Qd = - 8.4 x 10^-17 Coulombs, or about 500 electrons.

- The floating potential, especially at higher temperatures, is subject to statistical fluctuations.

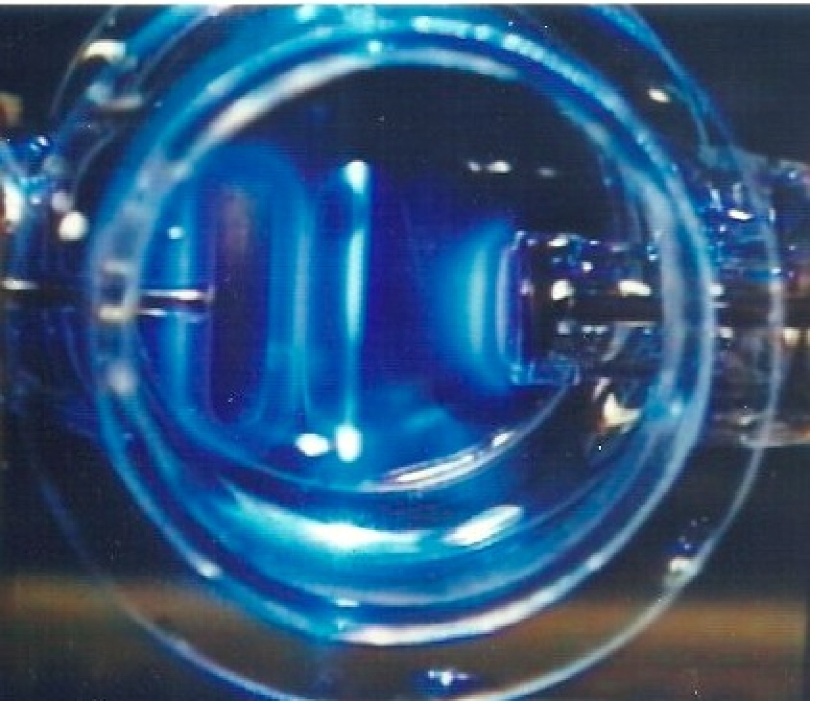


Figure 2. Sheaths formed around the discharge electrodes and trapped dust in RF excited reactor, Ganguly et al. Dust is suspended for long periods by electric fields in the plasma.

The sizes of the particles range from tens of Angstroms to several microns and under some conditions to several mm.

A typical 500nm particle immersed in plasma will contain 10^8 to 10^{10} atoms.
The particles can be formed by homogeneous nucleation, by clustering, sputtered atoms, by ion collection or by ablation from the boundaries.

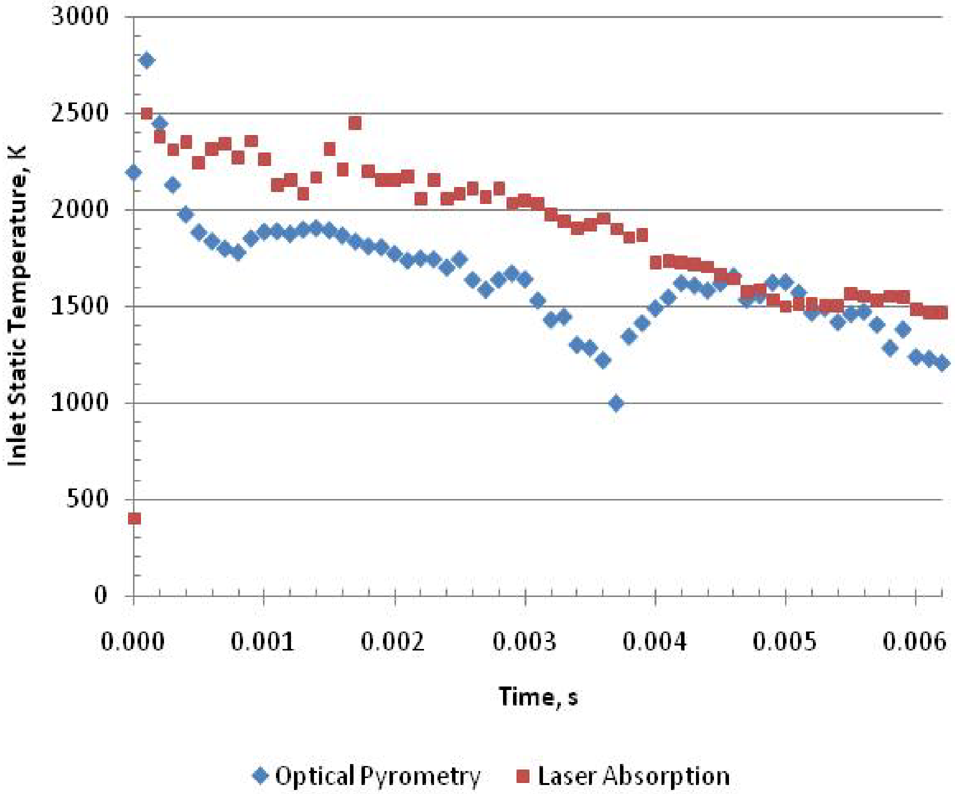
The particles in carbon monoxide-argon plasmas are formed almost instantaneously even at 0.1 torr carbon monoxide pressure.
If the discharge is operated for some hours at the particles become larger and then tend to concentrate just outside the discharge sheaths. (photograph)

These are low pressure results:-
there are many more examples of dust in plasmas from the semiconductor processing literature, from astrophysics and even from fusion studies.
The observation of copious amounts of dust in IBM ultra-high vacuum quality processing reactors by Gary Selwyn et al (1989) came as a surprise.

Dust in the form of soot is usually observed in combustion studies. Dust in a PDE is not a surprise.

Inlet Temperature and Velocity Validation

- Inlet temperatures from pyrometry & laser absorption
  - Pyrometry emission threshold: 1300 K (6 ms of blowdown)
  - Differences attributed to emissivity of soot particles



Possible ways to increase the plasma conductivity via the dust

UV irradiation to produce pre-ionization electrons by photoemission (as used in high pressure CO2 lasers), and we have the possibility of thermionic emission.

Seed with low work function additives that with shock gas heating will enhance thermionic emission and then locally apply a short duration, very high field to enhance ionization growth and perhaps also give field emission of electrons.

Strongly Coupled Plasmas

At high dust densities the dust interactions are described by the Coulomb Coupling Parameter

CCP = ratio of the potential Coulomb energy to the mean thermal energy of the particles

Under conditions of high electron density and low temperature, CCP can approach values considerably greater than unity. These conditions result in the charged dust formation of Coulomb liquids and even a solid if CCP > 170.

It may be possible to suddenly disrupt this condition by means of lasers or microwaves or another gas shock and release the attached electrons.

Thermal Plasmas a la Fortov

The seeded particles in a Meeker burner were interrogated by laser scattering and the particle radial correlation function was measured by laser (Mie) scattering.

At T = 1700K and $N_{dust} = 10^7$, $n_e = 7.2 \times 10^{10}$; $n_i = 4.2 \times 10^{10}$, giving CCP = 120.

This condition gives rise to coupled motions of the dust.

Pre-ionization schemes

- In the Saha equation, the ♐ in the exponential is the ionization potential whereas in thermionic emission equation, ♐ is the work function which is considerably lower in value.
- However, eventually the thermionic emission will reach plasma potential and stop the emission.
- There was a comment at the workshop that the dust can never be positively charged. There is not universal agreement on this point. Wu and Xie (2005) argue that the dust will become positively charged whenever the thermionic emission becomes so large that the available electron collection cannot balance it, admittedly an unusual situation.
- The net particle charge (sum of the the induced charge and the collected charge) will always be negative. Near an electrode the net positive space charge will induce negative surface charges on the particles, thus causing increased positive ion collection and in some cases, a positively charged particle (Abolmasov et al).

- Analogous to high pressure laser techniques, the pre-ionization electrons can be energized by RF or microwave excitation; a poster paper at the workshop by M. N. Schneider et al proposed similar nsec high voltage pulses and electron beam ionization schemes.

Planned studies

Laser and SEM analysis of dust from PDE (size, morphology, amounts and distribution).

Synchronize additional pulsed excitation with arrival of detonation in MHD interaction zone.

Improved solid state magnets

Arrange for ionization growth without arcing in a similar way to Jay Palmer’s TEA (transverse electric atmospheric) CO2 laser.

Examination of effects of different seeded dusts (e.g. Bismuth compounds) on plasma conductivity.

Notable prior study

R. J. Litchford, NASA/TP-2001-210801
“Integrated Pulse Detonation Propulsion and Magnetohydrodynamic Power”

References

Aneurin Evans, “The Dusty Universe”, Ellis Horwood (1993)
G. S. Selwyn, J. Singh, and R.S.Bennett, J. Vac. Sci. Technol. **A7**, 2758 (1989)
M. Rosenberg, D. A. Mendis and D.P. Sheehan, IEEE Trans Plasma Science, **24,**1422 (1996)
K. Rouser, PhD Thesis, Air Force Inst Technology (2011)
H. J. J. Seguin, J. Tulip and D. McKen, Appl. Phys. Lett., **23,** 344 (1973)
B. N. Ganguly, P. D. Haaland and A. Garscadden, J. Vac. Sci. Technol. **A11,** 1120 (1993)
Hai-Cheng Wu and Bai-Song Xie, Physics of Plasmas, **12**, 064503 (2005)
S. N. Abolmasov, E. V. Romashchenko and P. Roca Cabarrocas, arxiv.org/pdf/1307.1969
V. E. Fortov, A. P. Nefedov, A.A. Samarian and A. V. Chernyschev, Phys. Lett. A, **219,** 89 (1996); also Phys. Rev. E. **54, 1** (1996)
A. J. Palmer, Appl. Phys. Lett. **25,**138 (1974)