Modeling and Control of an Industrial High Velocity Oxygen-Fuel (HVOF) Thermal Spray Process

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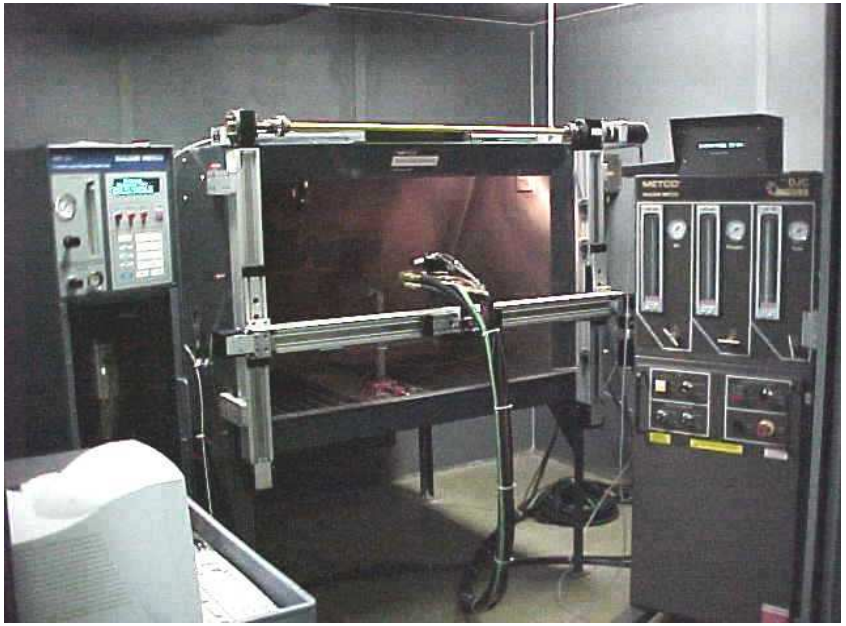
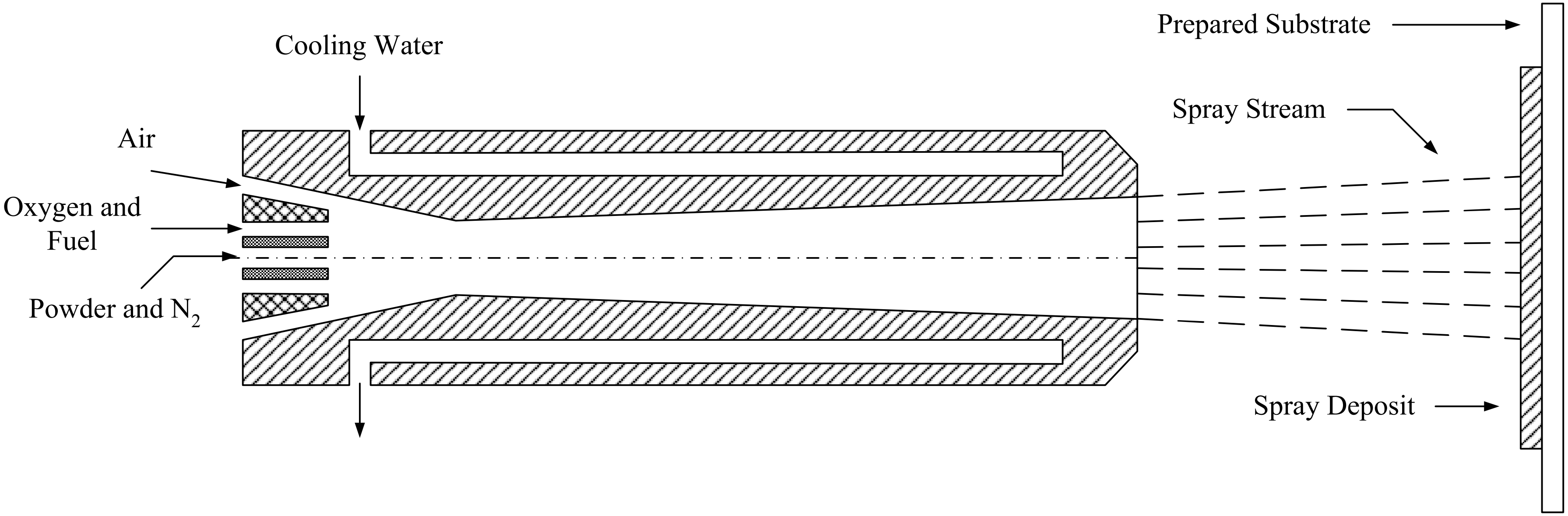
7th Southern California
Nonlinear Control Workshop
Oct. 31 - Nov. 1, 2003

OUTLINE OF THE PRESENTATION

- Introduction.
    - ◇ High Velocity Oxygen-Fuel (HVOF) thermal spray process.
    - ◇ Motivation for process control.
    - ◇ Background on the modeling and control of the HVOF thermal spray process.
- Current work.
    - ◇ Modeling of gas and particle behavior in the Metco Diamond Jet Hybrid HVOF thermal spray process.
    - ◇ Stochastic modeling of coating microstructure.
    - ◇ Effect of operating conditions on particle velocity and temperature.
    - ◇ Feedback control of the Metco Diamond Jet hybrid HVOF thermal spray process.

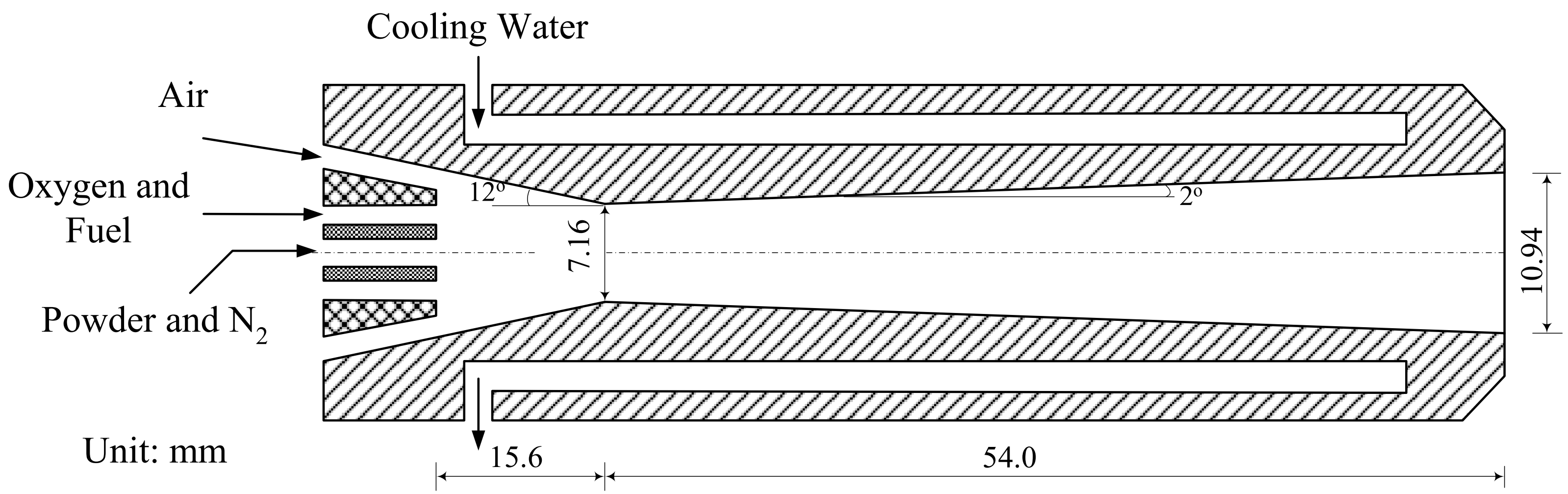
DIAMOND JET HYBRID HVOF THERMAL SPRAY PROCESS





CHARACTERISTICS OF THE DIAMOND JET HYBRID HVOF THERMAL SPRAY PROCESS

- Schematic diagram of the Metco Diamond Jet (DJ) hybrid HVOF gun.



- Typical operating conditions.
  - ◇ Gas flow rate $\approx 18\ g/s$ $(12\ l/s)$.
  - ◇ Powder feed rate 20-80 g/min.
  - ◇ Powder size 5-45 μm.
  - ◇ Coating thickness 100-300 μm.
  - ◇ Spray distance 150-300 mm.

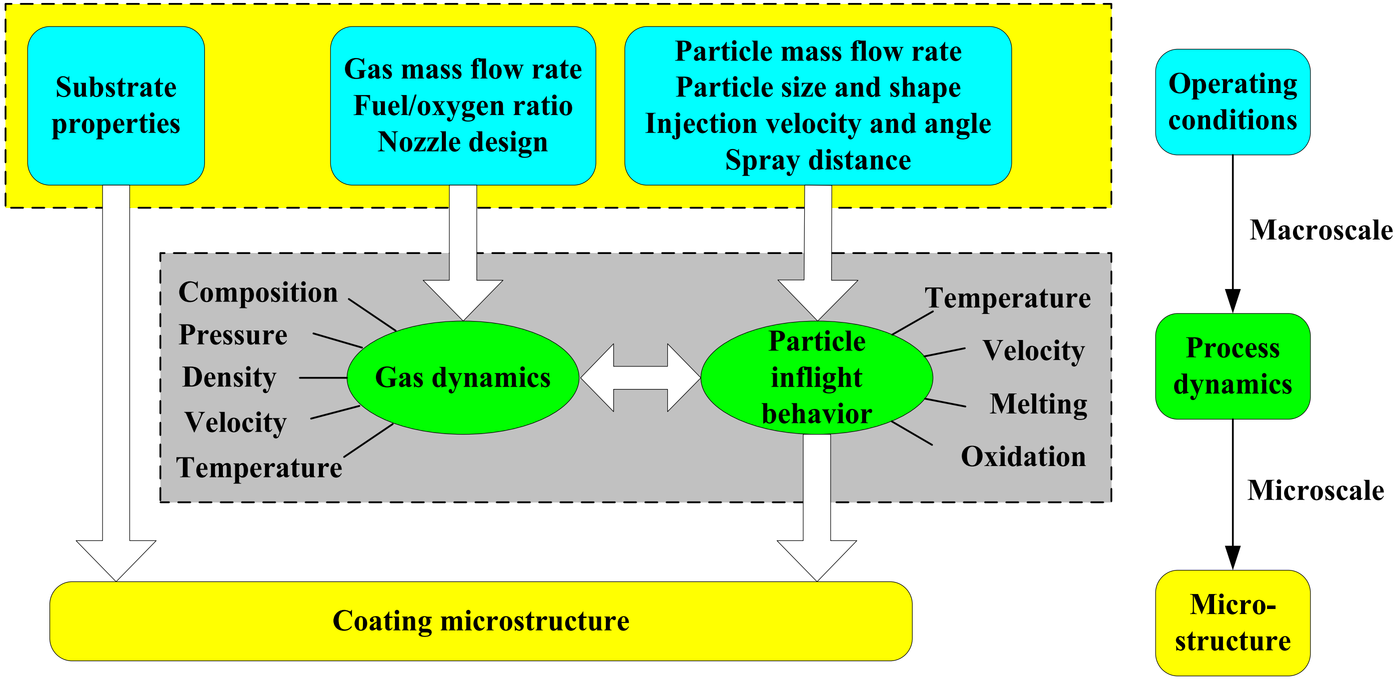
- Process characteristics.
  - ◇ Flame temperature $\approx 2800\ ^oC$.
  - ◇ Exit Mach number ≈ 2.
  - ◇ Exit gas velocity $\approx 2000\ m/s$.
  - ◇ Deposition efficiency $\approx 70\%$.
  - ◇ Coating porosity $\approx$ 1-2%.

MODELING AND CONTROL: MOTIVATION AND BACKGROUND

- Motivation for process control.
  - ◇ To suppress the influence of external disturbances and to reduce coating variability.
  - ◇ To produce coatings with desired microstructure and resulting thermal and mechanical properties.
- Fundamental modeling of the HVOF process.
  - ◇ Modeling of thermal/fluid field in HVOF process using CFD technology (e.g. Power *et al.*, 1991, Dolatabadi *et al.*, 2002) or semi-empirical method (e.g. Tawfik and Zimmerman, 1997).
  - ◇ Modeling of coating microstructure evolution and porosity (e.g. Cai and Lavernia, 1997, Ghafouri-Azar *et al.*, 2003).
- Control of thermal spray process.
  - ◇ Advances in on-line particle temperature and velocity measurement.
  - ◇ PID control in plasma thermal spray process (Fincke *et al.*, 2002).

CONTROL PROBLEM FOR THE HVOF PROCESS

- Multiscale feature of the HVOF process.



- Main control objectives.
  - ◇ Velocity, temperature and molten state of particles at impact.

- Manipulated inputs:

  Total gas flow rate

  Fuel/oxygen ratio

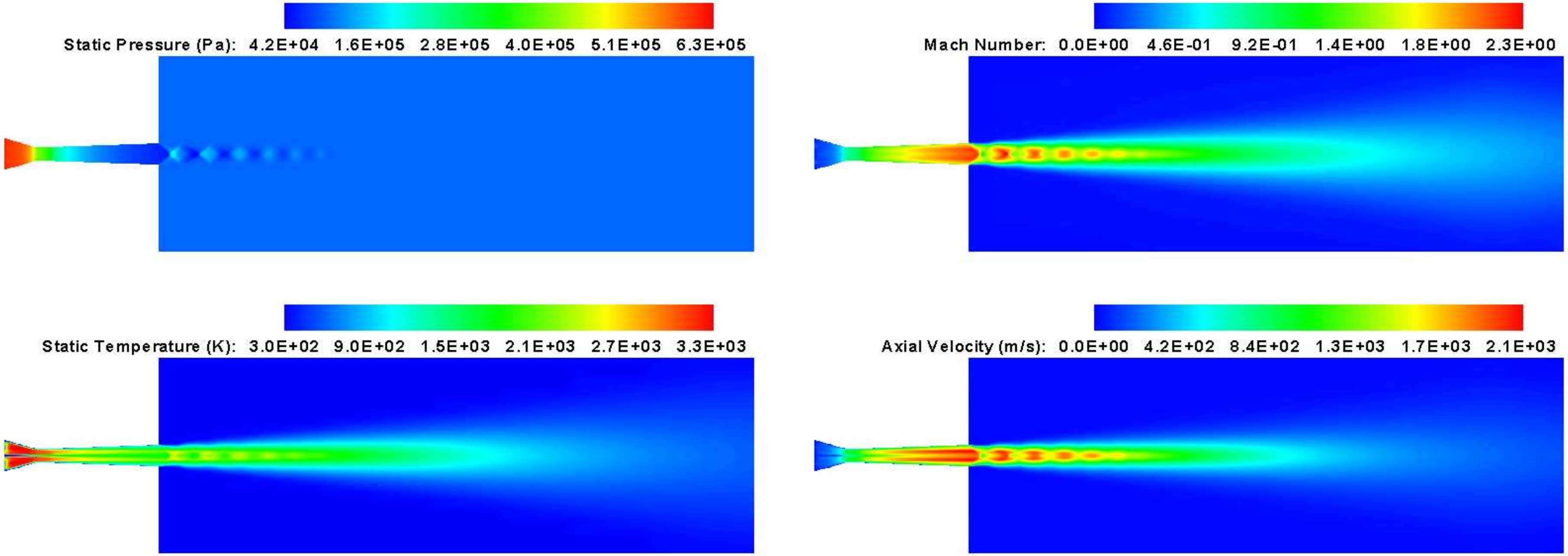
On-line measurements:

  Particle velocity

  Particle temperature

MODELING OF THE DJH HVOF PROCESS - CFD
(Li, Shi and Christofides, CES, 2004)

- Contours of pressure, mach number, temperature and velocity.

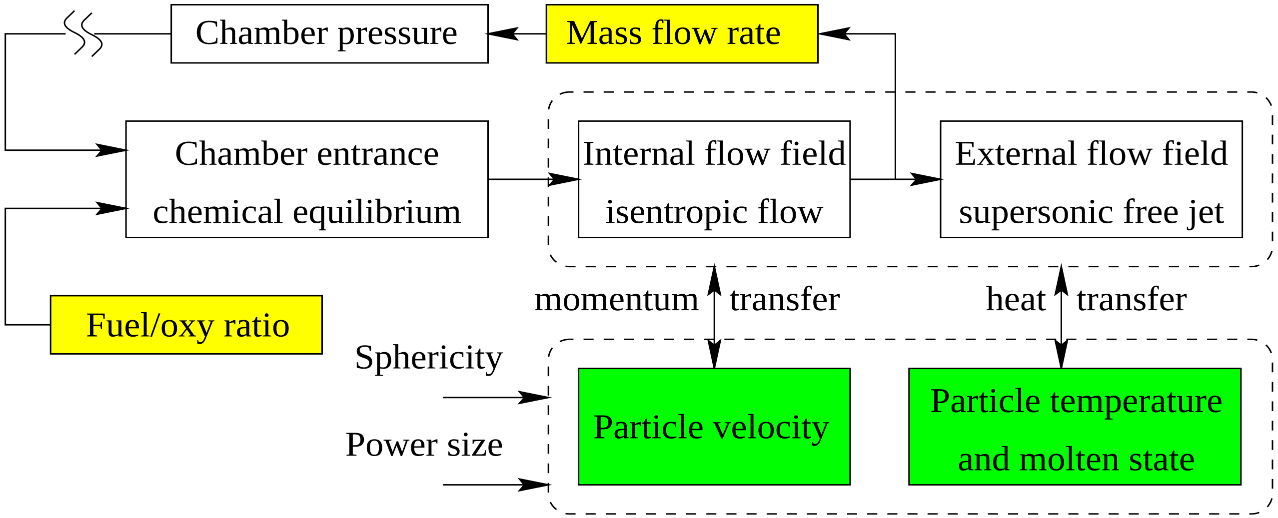


- Flow/thermal field characteristics.
  - ◇ Overexpanded flow at the exit of the torch ($P_e < P_b$).
  - ◇ Compression and Expansion waves (shock diamonds) alternatively occur along the centerline in the external flow field.

MODELING OF THE HVOF PROCESS - SIMPLIFIED MODEL

(Li, Shi and Christofides, IECR, 2003)

- Main assumptions.
  - ◇ One way coupling of the two-phase flow due to small particle loading.
  - ◇ Steady gas fluid/thermal field.
  - ◇ Chemical equilibrium at the entrance of the combustion chamber.
  - ◇ Isentropic frozen flow during passage of the Laval nozzle.
- Modeling procedure.



- Simulated pressure under four different operating conditions are all within 6% of the experimentally measured values provided by the manufacturer.

MODEL OF GAS PHASE BEHAVIOR

- Chemical equilibrium is solved by minimization of Gibbs energy (Gordon and McBride, 1994).
- Internal flow field is solved by laws governing isentropic compressible flow (Roberson and Crowe, 1997)

$$\frac{T_2}{T_1} = \frac{1+[(\gamma-1)/2]\mathbf{M}_1^2}{1+[(\gamma-1)/2]\mathbf{M}_2^2}, \qquad \frac{P_2}{P_1} = \left\{\frac{1+[(\gamma-1)/2]\mathbf{M}_1^2}{1+[(\gamma-1)/2]\mathbf{M}_2^2}\right\}^{\frac{\gamma}{(\gamma-1)}},$$

$$\frac{\rho_2}{\rho_1} = \left\{\frac{1+[(\gamma-1)/2]\mathbf{M}_1^2}{1+[(\gamma-1)/2]\mathbf{M}_2^2}\right\}^{\frac{1}{(\gamma-1)}}, \qquad \frac{A_2}{A_1} = \frac{\mathbf{M}_1}{\mathbf{M}_2}\left\{\frac{1+[(\gamma-1)/2]\mathbf{M}_2^2}{1+[(\gamma-1)/2]\mathbf{M}_1^2}\right\}^{\frac{(\gamma+1)}{2(\gamma-1)}},$$

$$\dot{m}_g = \rho_t v_t A_t = \frac{P_0}{\sqrt{T_0}} A_t \left[\frac{\gamma \bar{M}_{pr}}{R}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\right]^{1/2}$$

- External flow field is correlated by empirical formulas (Tawfik and Zimmerman, 1997).

$$\left.\begin{array}{c} v/v_e \\ \\ (T-T_a)/(T_e-T_a) \end{array}\right\} = 1-\exp\left(\frac{\alpha}{1-\bar{x}/\beta}\right)$$

MODEL OF PARTICLE INFLIGHT BEHAVIOR

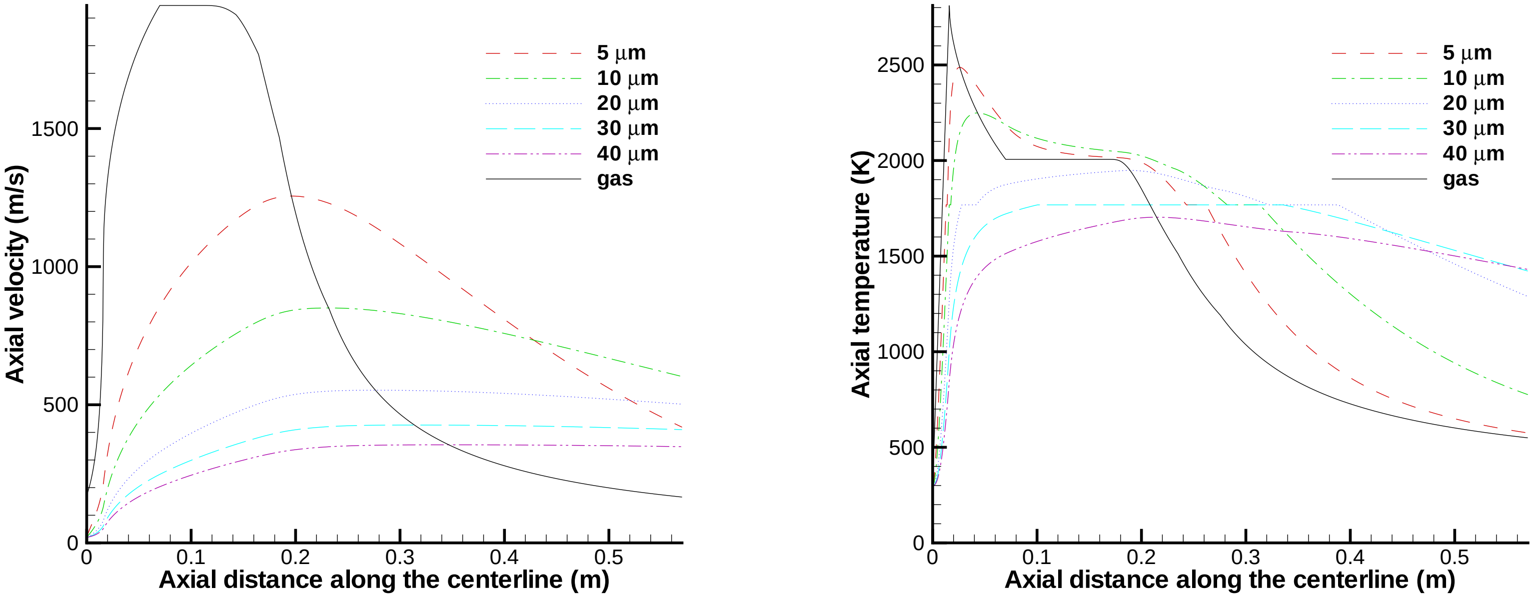
- Model for particle velocity, temperature and degree of melting in the gas flow field.

$$\boxed{\begin{aligned}
m_p \frac{dv_p}{dt} &= \frac{1}{2} C_D \rho_g A_p (v_g - v_p)|v_g - v_p|,\ v_p(0) = v_{p_0} \\
\frac{dx_p}{dt} &= v_p,\ x_p(0) = 0 \\
m_p c_{p_p} \frac{dT_p}{dt} &= \left\{ \begin{array}{l} hA'_p(T_g - T_p) + S_h, \quad (T_p \neq T_m) \\ 0, \quad (T_p = T_m) \end{array} \right. ,\ T_p(0) = T_{p_0} \\
\Delta H_m m_p \frac{df_p}{dt} &= \left\{ \begin{array}{l} hA'_p(T_g - T_p) + S_h, \quad (T_p(0) = T_m) \\ 0, \quad (T_p \neq T_m) \end{array} \right. ,\ f_p(0) = 0
\end{aligned}}$$

- 4th Runge-Kutta method is used to solve the above differential equations together with the gas dynamics.

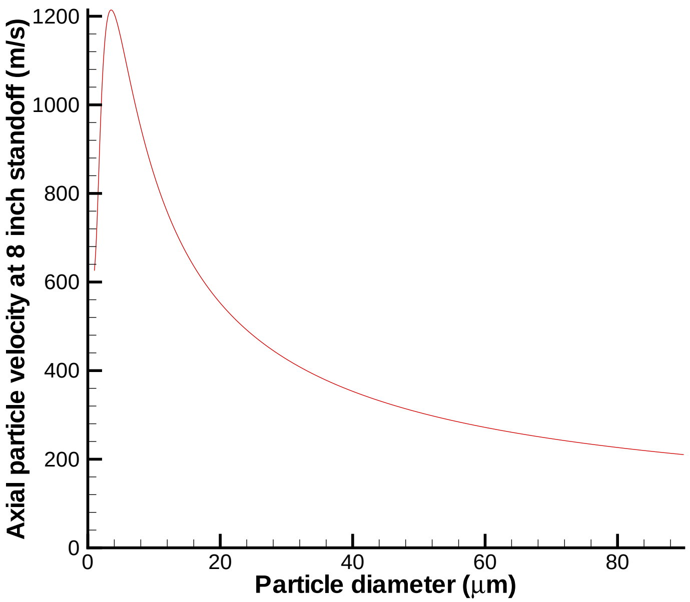
GAS AND PARTICLE INFLIGHT BEHAVIOR

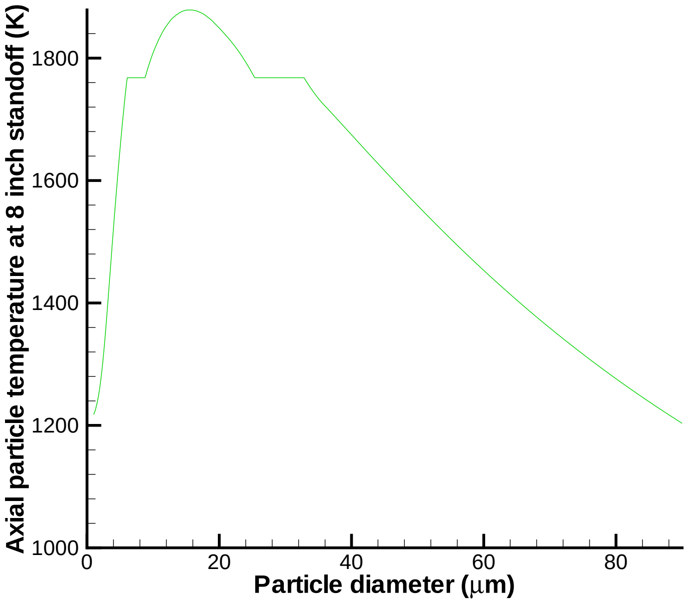
- Axial velocity & temperature profiles of gas and particles of different sizes.

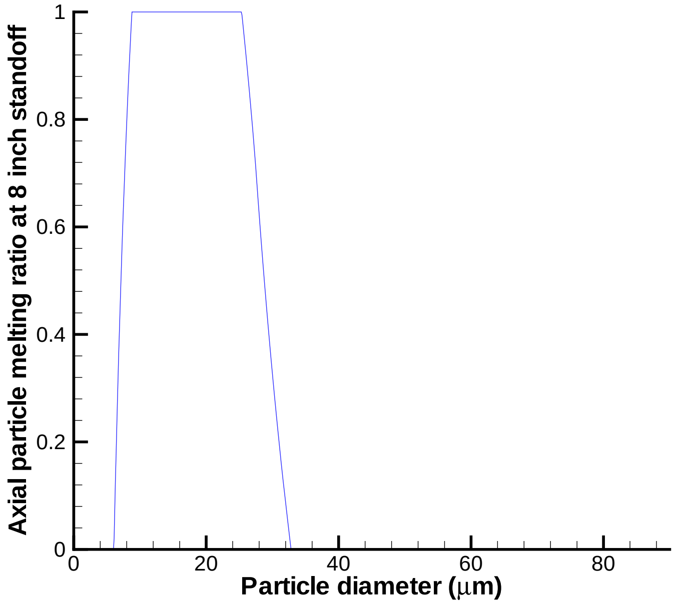


- Gas velocity & temperature decay in the free jet due to entrainment of air.
- Particles are accelerated and heated first, and then decelerated and cooled because of the velocity and temperature decay of the supersonic free jet.
- Small particles change velocity and temperature easier than bigger ones because of their smaller momentum and thermal inertias.

PARTICLE VELOCITY AND TEMPERATURE AT IMPACT







- ◇ Particle velocity, temperature and degree of melting are strong functions of particle size.
- ◇ Particles of moderate sizes have the larger velocity and temperature than other ones.
- ◇ Particles of different sizes may have different molten states.

MODELING OF POWDER SIZE DISTRIBUTION
(Li and Christofides, CES, 2003; JTST, 2003)

- Lognormal size distribution.

$$\boxed{f(d_p) = \frac{1}{\sqrt{2\pi}\sigma d_p} \exp\left[-\frac{(\ln d_p - \mu)^2}{2\sigma^2}\right]}$$

- Cumulative weight function.

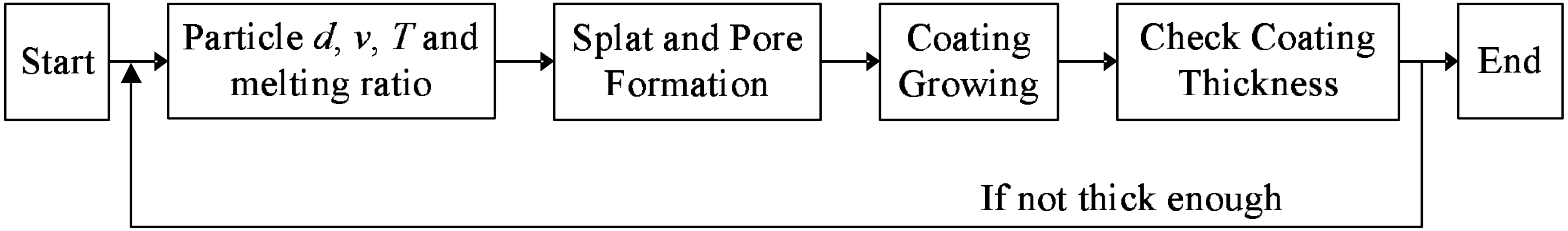
$$\boxed{F = \frac{\int_0^{d_p} \frac{1}{6}\pi\rho x^3 f(x)dx}{\int_0^{\infty} \frac{1}{6}\pi\rho x^3 f(x)dx} = \int_{-\infty}^{\frac{\ln d_p - (\mu+3\sigma^2)}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx}$$

- Volume-based average of particle properties (PP).

$$\boxed{\overline{PP} = \frac{\int_0^{\infty} \frac{1}{6}\pi d_p^3 PP(d_p) f(d_p) d(d_p)}{\int_0^{\infty} \frac{1}{6}\pi d_p^3 f(d_p) d(d_p)} = \frac{\int_0^{\infty} d_p^3 PP(d_p) f(d_p) d(d_p)}{\exp(3\mu + \frac{9}{2}\sigma^2)}}$$

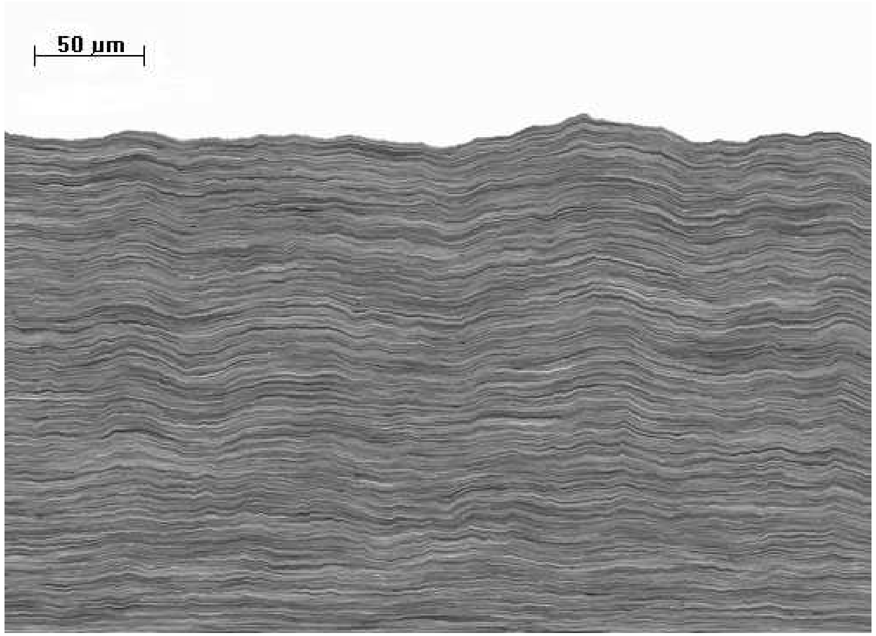
STOCHASTIC MODELING OF COATING MICROSTRUCTURE
(Shi, Li and Christofides, IECR, 2003)

- Modeling procedure.

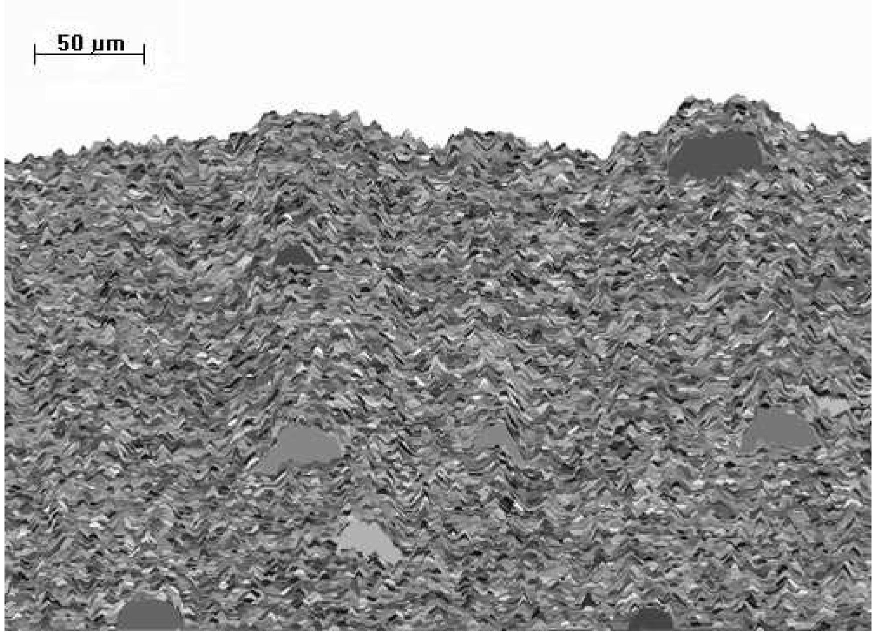


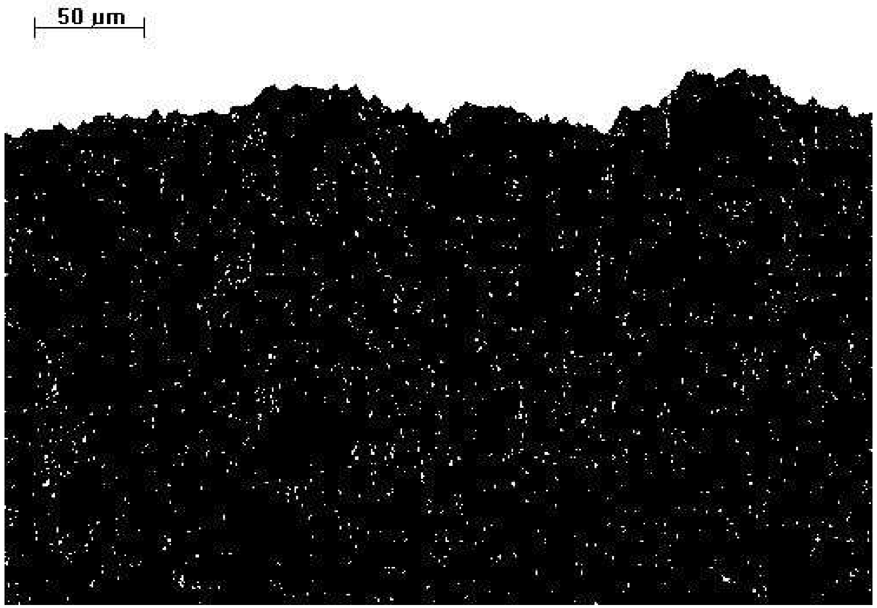
- Particle size and hitting point are determined by random numbers following lognormal distribution and uniform distribution, respectively.
- Particle velocity, temperature and melting ratio at impact are solved by the previously described thermal spray process model.
- Coating growth is described by several rules.
  - ◇ Particle deformation obeys Madejski model (1991).
  - ◇ Melted part of a particle fits the coating surface as much as possible.
  - ◇ Unmelted part of a particle bounces off the coating surface if it hits a solid surface and attaches to it otherwise.

COMPUTER SIMULATION OF COATING MICROSTRUCTURE

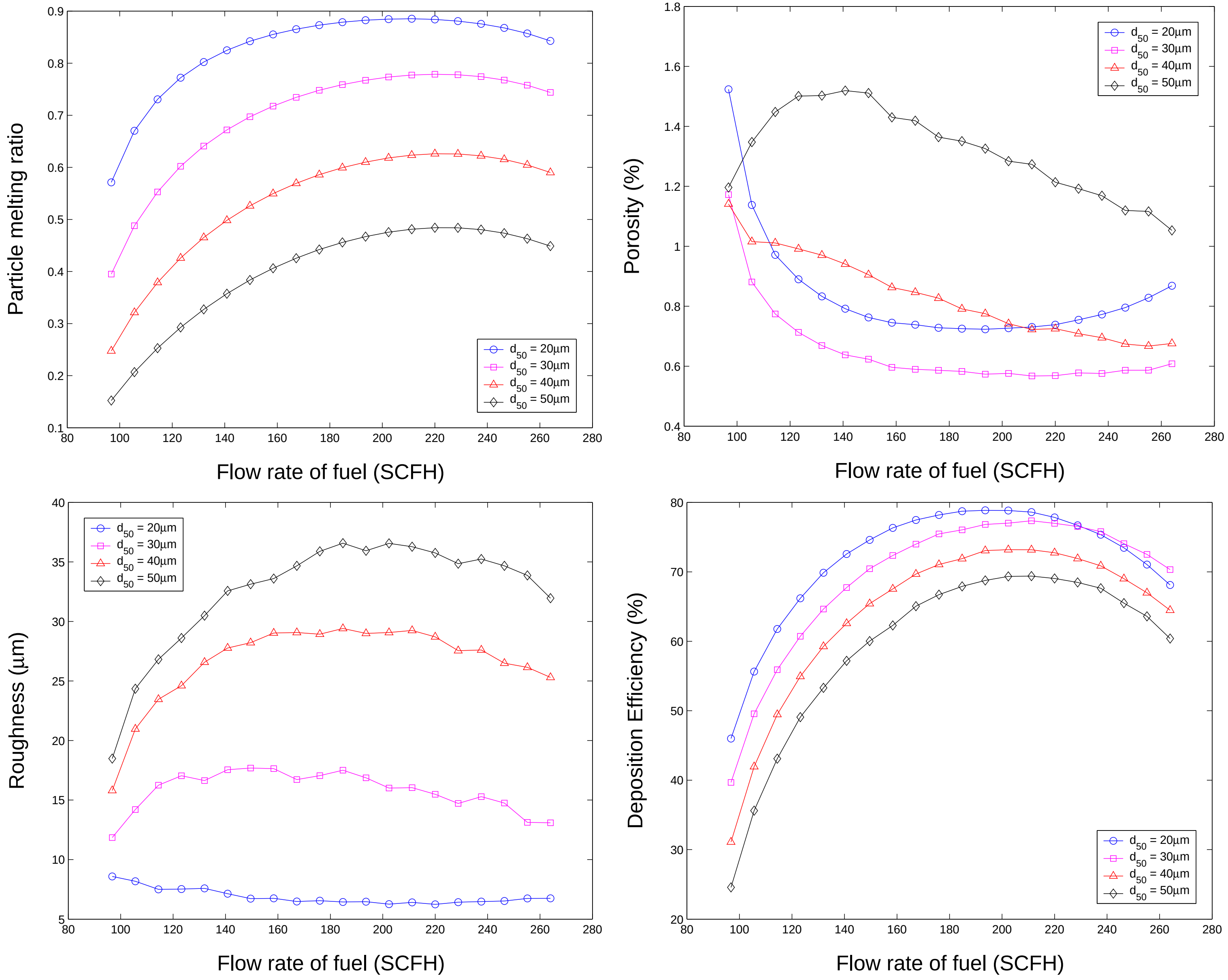


- ◇ Ideal lamellar microstructure of a coating formed by fully melted particles (top).
- ◇ Microstructure of a coating formed by particles of nonuniform molten states (bottom left).
- ◇ Pores distribution in a coating formed by particles of nonuniform molten states (right bottom).



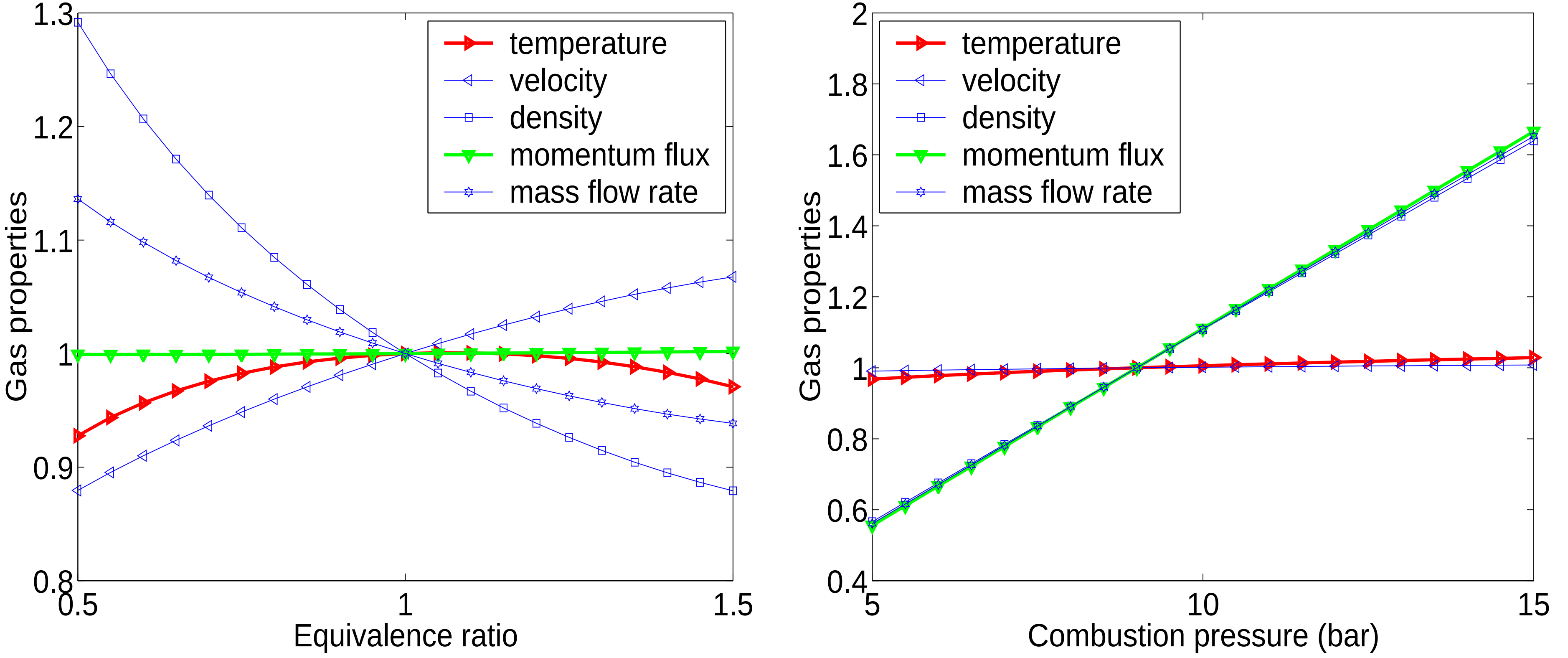


INFLUENCE OF OPERATING CONDITIONS ON COATING MICROSTRUCTURE - FUEL FLOW RATE



PARAMETRIC ANALYSIS OF GAS DYNAMICS

- Gas properties at gun exit for different pressures and equivalence ratios*.



*Equivalence ratio (φ) is the fuel/oxygen ratio divided by its stoichiometric value.

- T_g is a function of φ but changes little with P.
  ρv_g^2 is a linear function of P but does not change with φ.

CONTROL PROBLEM FORMULATION

(Li, Shi and Christofides, IECR, 2003)

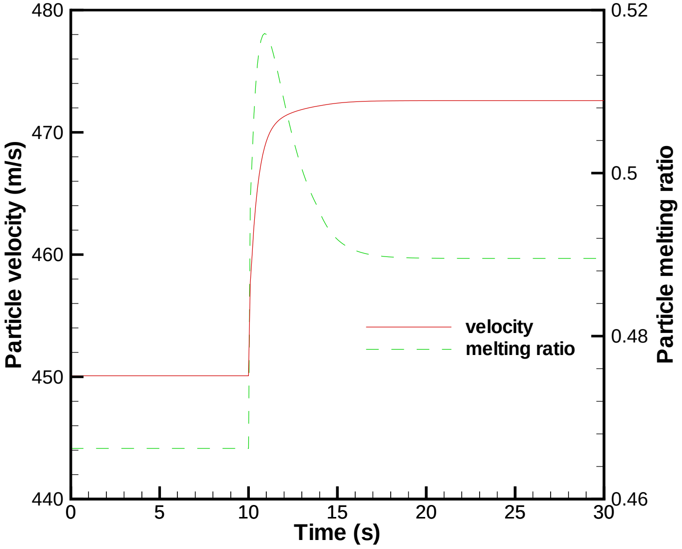
- Differential equation for particle flow and thermal field.

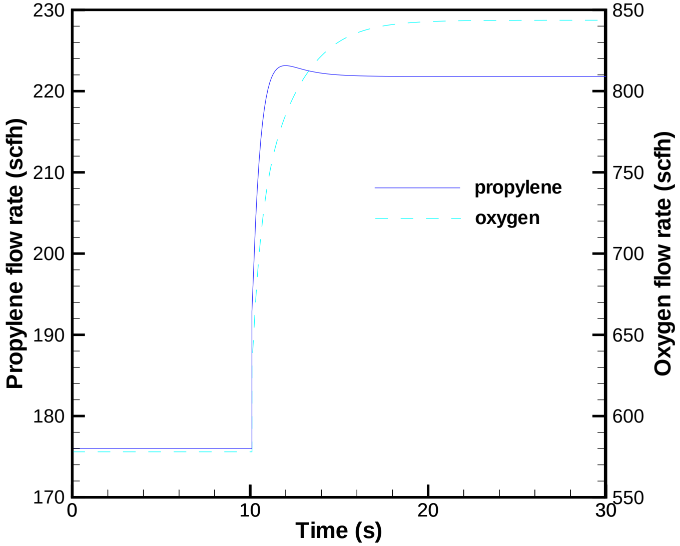
$$
\boxed{
\begin{aligned}
m_{p_i}\frac{dv_{p_i}}{dt} &= \frac{1}{2}A_{p_i}C_{D_i}\rho_g(v_g - v_{p_i})|v_g - v_{p_i}|,\ v_{p_i}(0) = v_{p_{i_0}},\ i = 1, ..., N \\
\frac{dx_{p_i}}{dt} &= v_{p_i},\ x_{p_i}(0) = 0,\ i = 1, ..., N \\
hA'_p(T_g - T_{p_i}) &= \left\{ \begin{array}{ll} m_{p_i}c_{p_p}\dfrac{dT_{p_i}}{dt}, \quad (T_{p_i} \neq T_m), \quad T_{p_i}(0) = T_{p_{i_0}} \\ \Delta H_m m_{p_i}\dfrac{df_{p_i}}{dt}, \quad (T_{p_i} = T_m), \quad f_{p_i}(0) = 0 \end{array} \right. ,\ i = 1, ..., N \\
t &= t_f, \bar{v}_p = v_{p_{sp}}, \quad \bar{f}_p = f_{p_{sp}}
\end{aligned}
}
$$

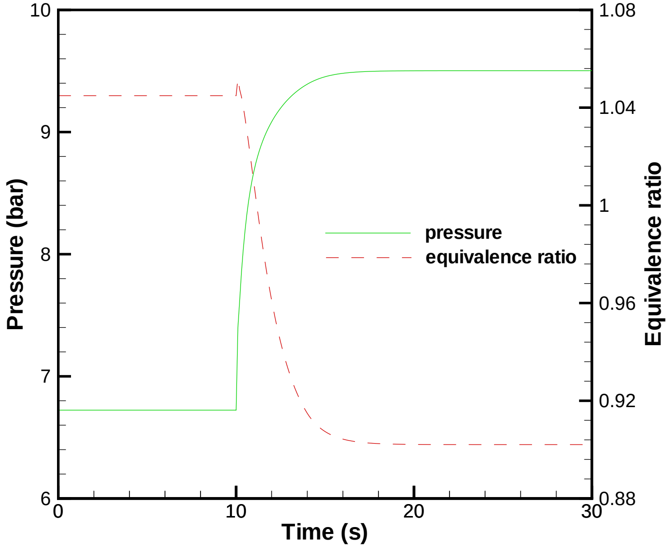
- 100 particles of different sizes are traced to calculate volume-based average of velocity, temperature and melting ratio.
- Two PI controllers are used.

CLOSED-LOOP SIMULATION RESULTS

- Step response in the presence of change in set-points (5% increase in particle velocity and 5% increase in particle melting ratio).



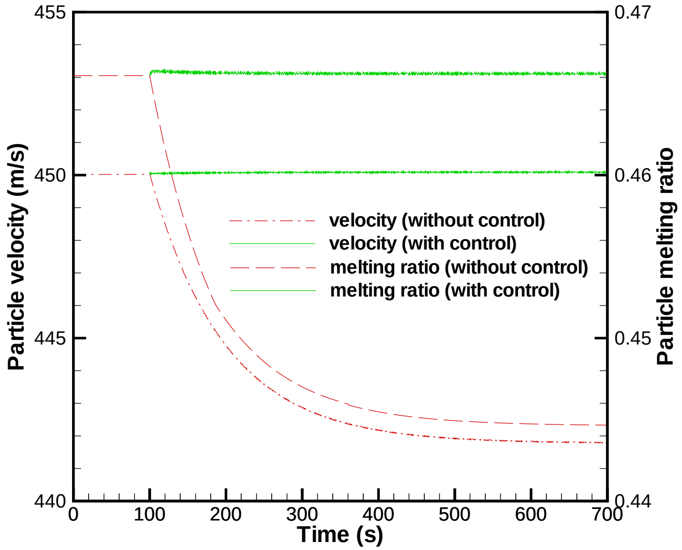


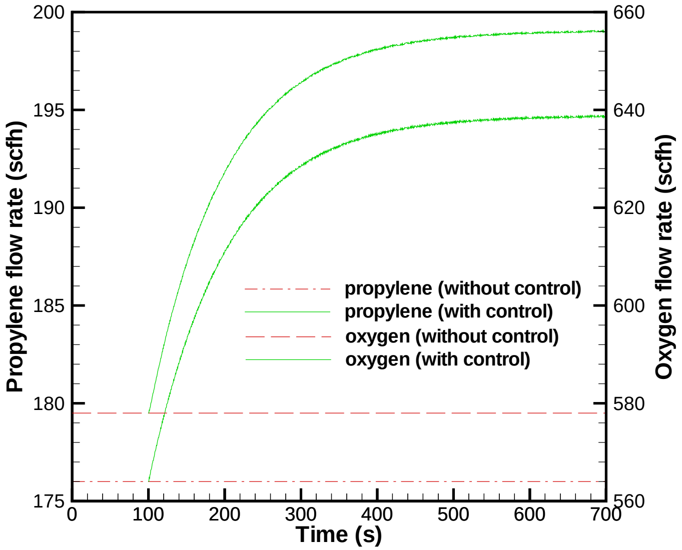


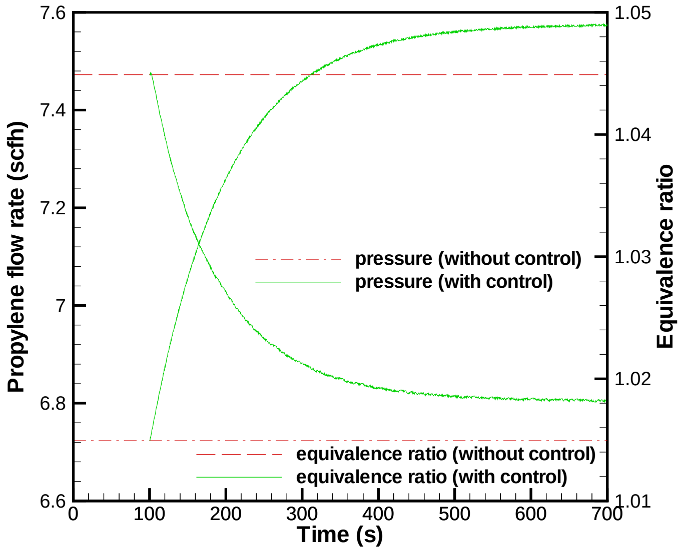
- ◇ The feedback controller drives the controlled outputs into the new set-point values in a short time.
- ◇ The system switches from a fuel-rich condition to a fuel-lean condition.

CLOSED-LOOP SIMULATION RESULTS

- Controlled output and manipulated input profiles in the presence of variation in powder size distribution.







- ◇ Particle velocity and melting ratio drop as the powder size increases.
- ◇ The controller compensates for the variation in powder size distribution and maintains velocity & melting ratio of particles at impact.

SUMMARY

- Modeling and analysis of gas dynamics and particle inflight behavior in the Diamond Jet Hybrid HVOF thermal spray process.
    - ◇ Particle velocity is a strong function of combustion pressure.
    - ◇ Particle temperature is highly dependent on equivalence ratio.
    - ◇ Particle velocity and temperature are highly dependent on particle size.
- Modeling of coating microstructure using stochastic simulation.
    - ◇ Ideal lamellar coating microstructure may be disturbed due to nonuniform melting behavior of particles.
    - ◇ A good melting condition helps to decrease coating porosity and to improve deposition efficiency.
- Formulation and solution of control problem for the Diamond Jet Hybrid HVOF thermal spray process.
    - ◇ Control of particle velocity and melting ratio at impact.
    - ◇ Robustness test of the proposed controller in the presence of external disturbances.

ACKNOWLEDGEMENT

- Financial support from a 2001 ONR Young Investigator Award, is gratefully acknowledged.