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GAS-PARTICLE FLOWS IN CO_2 PELLET-BLASTING NOZZLES

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Abstract

A numerical study was performed to investigate gas-particle flows in convergent divergent CO_2 pellet-blasting nozzles. The solutions to the compressible Navier-Stokes equations and the equations governing the particles' motion through the gas, in a Lagrangian frame of reference are solved iteratively in order to model the two-way mass momentum and energy exchanges between the two phases. Results are presented for the gas flow field and particle velocities at different particle loadings and inlet velocities. The momentum and energy exchange with the particles reduce the gas velocity in the divergent passage near the center. The presented results demonstrate the effects of particle loading and inlet velocity ratios on pellet and gas velocity and temperature through the nozzle.

1 Introduction

Dry-ice (CO_2) pellet-jet-blast systems have been used for over ten years in surface cleaning and preparation. Unlike grit, plastic, chemical, water or other solid or liquid media that produce significant amounts of contaminated media, the only waste associated with the CO_2 pellet-jet-blasting process is the residue of removed material. Therefore, the production of hazardous waste and disposal cost are greatly reduced. This waste minimizing aspect of CO_2 pellet-jet-blast application occurs because the CO_2 pellets, upon surface impact, simply sublimate immediately to natural inert CO_2 gas. Other advantages of CO_2 pellet-jet-blast cleaning and surface preparation systems include the in place application ability to machinery or production line of manufactured goods. This eliminates the need for disassembly and movement or disruption of the production line processes. Successful supersonic blast nozzle designs can deliver CO_2 pellet with velocities up to 900 ft/sec, using convergent-divergent nozzles. They are often not axi-symmetric and operate over a range of pressure ratios.

Most studies involving multi-phase gas-particle flows in convergent divergent nozzles were conducted for axi-symmetric nozzles of solid rockets, where metallic particles are introduced to stabilize the combustion and increase the specific impulse. In these applications, the axi-symmetric nozzles are operated at sufficiently high-pressure ratios to avoid shock wave formation in the divergent passage and the associated loss in thrust. Due to their higher inertia, the particles deviate from the flow streamlines and their velocities lag behind that of the gas. In these applications rarefaction effects can be significant for the micron size particles involved[1]. Ishi and Kawasaki[2] studied the factors affecting the limiting particle streamline obtained from the solution of the governing equations, assuming very small velocity and temperature difference between the two phases. They treated the flow field as a perturbation from equilibrium, and obtained first order solutions for the particle streamlines using Eulerian formulation for both phases. Later, Ishi et al.[3] obtained second order accurate solution to a suspension flow through an axi-symmetric nozzle using a homogenous flow model. Igra et al.[4] simulated the starting process in a convergent nozzle, and compared the limiting solid particles streamlines to those computed earlier by Ishi et al.[3].

Di Giacinto et al.[5] demonstrated the effects of loading ratio and Stokes number on gas-particle flows through sudden restriction, through numerical simulations assuming a continuum particle phase. Lee and Crow[6] discussed the two-dimensionality of the gas velocity in the throat region of venturi, produced by the low particle density near the wall.

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Hamed and Mesalhy[7] studied gas-particle flows in a 2DCD nozzle at different pressure ratios corresponding to over-expanded conditions. The particles reduced the shock strength, and the extent of flow separation over the flaps. Shock attenuation increased with particle loading and decreased particle size.

In the present investigation numerical simulations are used to study two-phase gas-particle flow in CO_2 pellet-blasting convergent-divergent nozzles. The solution to the Eulerian gas and Lagrangian particle equations is obtained taking into consideration the effects of mass, momentum and energy exchange between the two phases. Results are presented for different particle loadings, and inlet particle velocities.

2. Methodology

The two-phase solutions were obtained for the gas-particle flow governing equations based on Eulerian-Lagrangian methodology. In this approach, the equations of mass momentum and energy conservation for the particles are integrated over discrete time steps. The dispersed particles' effects are introduced through source terms in the viscous compressible flow governing equations, based on an iterative two-way coupling model. Numerical solutions were obtained using FLUENT's[8] implicit solver, for the time dependent Reynolds-averaged Navier-Stokes equations in conservation form for the gas phase. The RNG k-ε turbulence model given by Chaudhury[9] was used since prior assessments by Hamed and Vogiatzis[10] of gas flow in convergent divergent nozzles, indicated that two-equation turbulence models are required to model shock induced flow separation from the divergent flaps, at low nozzle pressure ratios.

Particle Momentum Exchange:

Particle trajectories are determined from the step-wise integration of their equations of motion in a lagrangian reference frame under the influence of drag, neglecting inter-particle collisions, and particle rotation.

$$\frac{d\,\bar{u}_p}{dt} = F_D\,(\bar{u} - \bar{u}_p)$$

Where, $F_D = \frac{18\mu}{\rho_p D_p^2}\frac{C_D\,Re}{24}$

In the above equations, $\bar{u}$ represents the fluid velocity, $\bar{u}_p$ the particle velocity, μ the gas molecular viscosity, ρ_p the particle material density, and D_p the particle diameter. The Reynolds number, Re, is based on the slip velocity and particle diameter. The compressibility effect on the drag coefficient, C_D, are taken into consideration through the multiplication of the incompressible drag coefficient, C_{DI}, by a function of the slip Mach number, M_s[12]:

$C_D = C_{DI}\,\{0.66 + 0.26\tanh(2\ln M_s) + \exp[-2.5(\ln M_s/1.4)^2]\}$

Correlations of the standard drag curve[11] were used for C_{DI} over the range of Reynolds numbers.

Particles Heat and Mass Exchange:

Energy is exchanged between the particles and gas though convection and mass transfer.

$$m_p C_p \frac{dT_p}{dt} = hA_p(T_\infty - T_p) + \frac{dm_p}{dt}h_{fg}$$

Where, C_p is the particle specific heat, A_p is the particle surface area, h_{fh} is the latent heat of sublimation. The film coefficient h is evaluated using Ranz and Marchall's[12,13] correlation of for spherical particles:

$$h = \frac{k}{D_p}(2.0 + 0.6\,Re^{1/2}\,Pr^{1/3})$$

Where k is thermal conductivity of the gas, and Pr is the Prandtl number.

The energy exchange due to sublimation was neglected in the current investigation.

Boundary Conditions:

The boundary conditions for the gas consists of the stagnation pressure and temperature at the nozzle inlet, the static pressure at the nozzle exit, and adiabatic no slip conditions at the wall. The particles were introduced after the flow solution was converged, based on four orders of magnitude reduction in the residuals. Particle trajectories were terminated upon surface impacts, based on experimental observations of sublimation to CO_2 gas.

3. Results and Discussion

Results are presented for the 2DCD nozzle shown schematically in Figure 1. It has 1.564" inlet, 0.4" throat, and diverges to a 1.14" exit, 22" downstream of the throat. A 5" long straight segment was included in the solution domain upstream of the convergent nozzle section, and the numerical simulations were performed in one half because of symmetry, using a 51x436 grid, which was clustered near the walls. The grid selection was guided by prior experience with grid refinement studies by Hamed and Vogiatzis[14].

Gas-particle flow computations were performed for air with dispersed solid particles of 1.53 specific density and 1000μ diameter, to simulate CO_2 pellets. Solutions were first obtained for the airflow in the nozzle without particles, then the particles were introduced uniformly at the nozzle inlet, with the specified inlet velocity and temperature. Two-phase flow solutions were obtained for a gas inlet stagnation temperature of 419.5 ^{0}R, and particle inlet temperature of 346.5 ^{0}R. Results are presented for a nozzle pressure ratio of 10.5, over a range of particle loading, and particle to gas inlet velocity ratios. The two-phase flow simulations were based on 100 particle injections. Since the particle flow rate is dependant on the loading ratio α, each trajectory simulated a number of particles that is proportional to the loading ratio, and the time step.

The effect of loading ratio on the particle and gas velocities is presented in Figures 2 and 3, and the effect of inlet particle to gas velocity ratio is presented in Figures 4 and 5. In these figures, the computed velocities are normalized by the speed of sound, based on the air inlet stagnation temperature, and the axial distance by the length of the nozzle divergent section. Figures 2 and 3 show that particle loading has a pronounced effect on both gas and particle velocities. Lower loading ratios are required for higher pellet velocities. The inlet particle velocity ratio affects the centerline gas velocity variation as shown in Figure 5. Heat transfer from the particles to the gas causes a local dip in gas velocity at the low inlet particle velocity ratios.

The effect of particle concentration on the gas and particle temperature at the centerline is presented in Figures 6 and 7, and the effect of particle inlet velocity ratio is presented in Figures 8 and 9. Comparing the two sets of Figures, one can see that the particles are initially heated then later cooled by the gas as it expands in the divergent section. The heat exchange rate of is influenced by the particle inlet velocity ratio, and is higher for the slower particles causing a local rise in gas velocity combined with a local drop in gas temperature. This effect is delayed and weakened with increased inlet particle velocity ratio, and is absent in the case of zero inlet particle slip velocity.

The exit gas velocity and temperature profiles are presented for different loading ratios in Figures 10 and 11. As can be seen, the momentum and energy exchange with the particles reduce the gas velocity and increase the gas temperature in the central region and produce the opposite effects near the flaps, causing inverted velocity and temperature profiles.

Conclusions

The results show the effects of loading and inlet particle velocity ratios on the CO_2 pellet and gas velocities in 2DCD nozzles. High exit particle velocities are achieved at lower loadings and higher inlet particle velocities. The expanding gas cools the pellets except for a short initial distance at the nozzle inlet where the cooler particles are heated. The gas velocity at the centerline can drop locally due to heat absorbed from the low velocity particles. The momentum and energy exchange with the pellets produce inverted gas velocity and temperature profiles at the nozzle exit.

Acknowledgements

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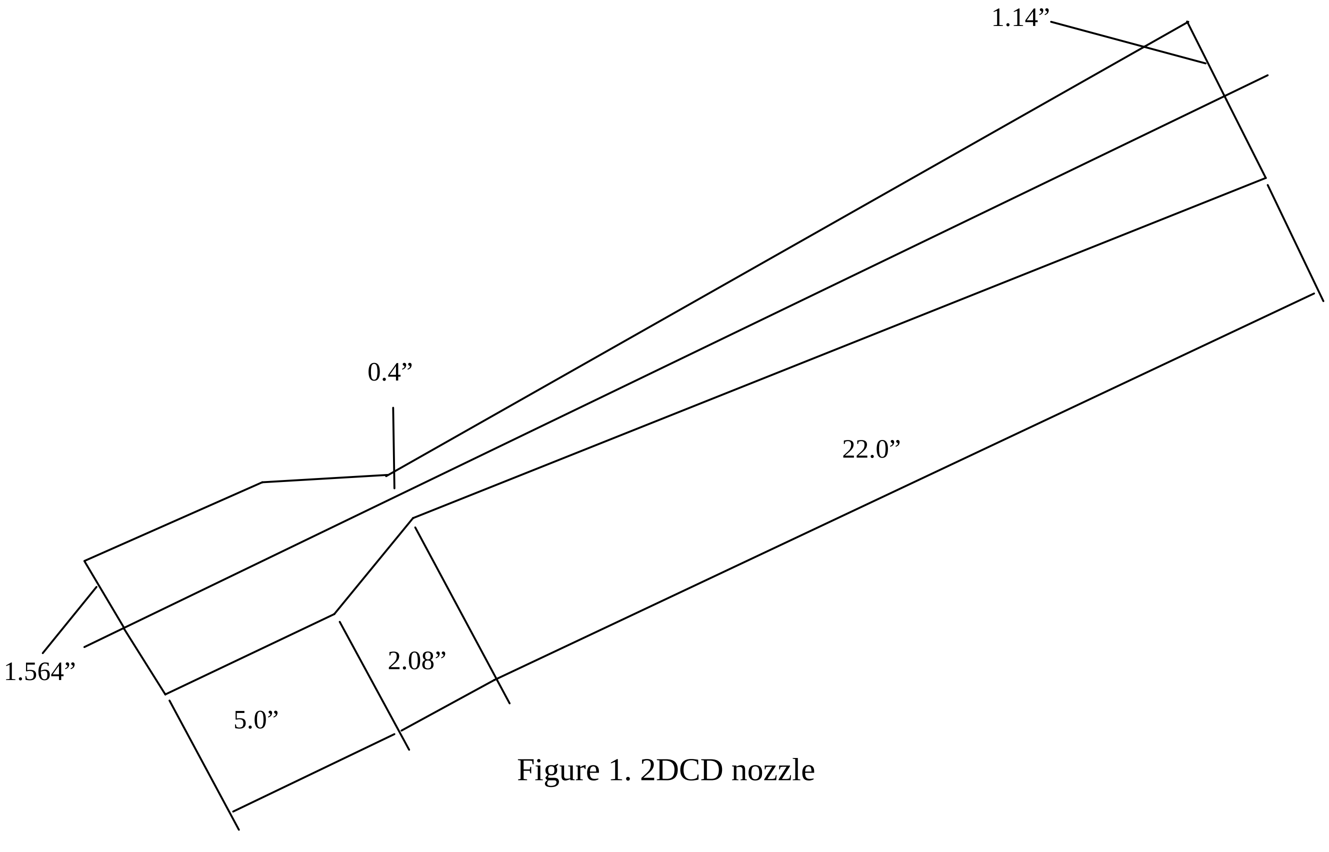

Figure 1. 2DCD nozzle

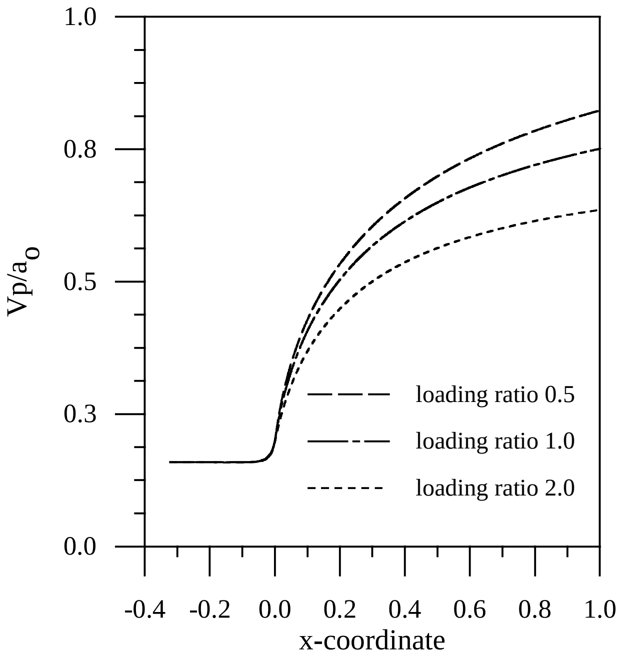

Figure 2. Effect of loading ratio on particle velocity

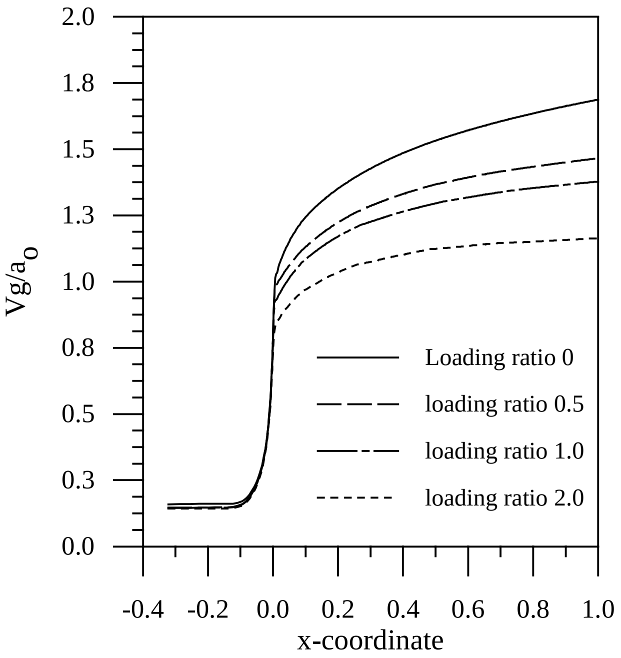

Figure 3. Effect of loading ratio on gas velocity

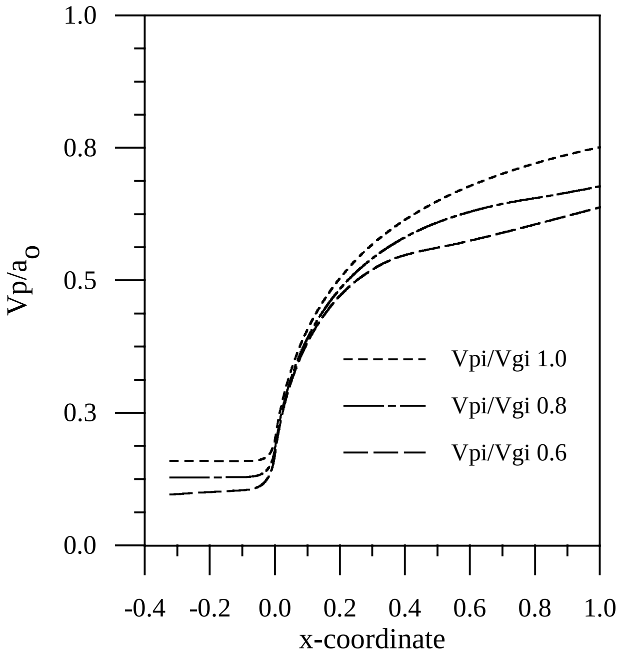

Figure 4. Effect of Vpi/Vgi on particle velocity

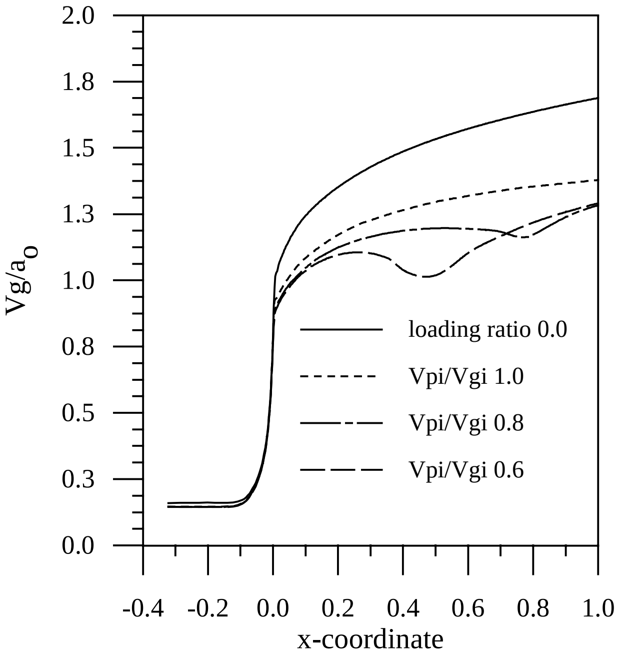

Figure 5. Effect of Vpi/Vgi on gas velocity

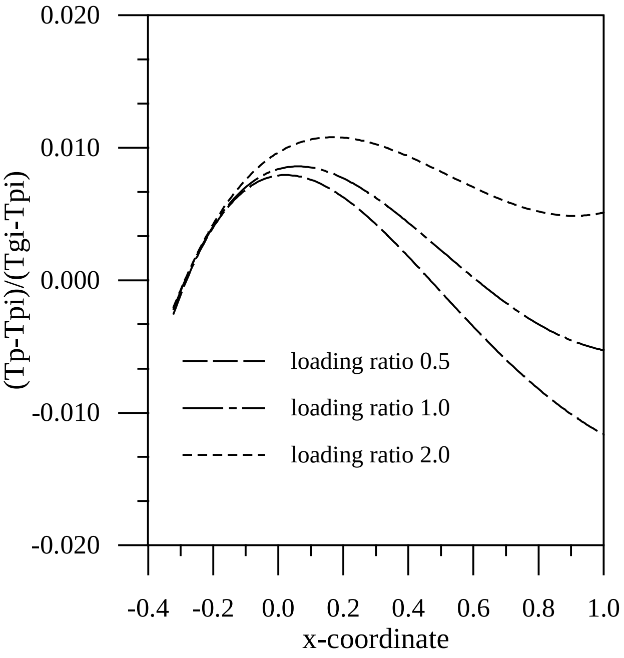

Figure 6. Effect of loading ratio on particle temperature

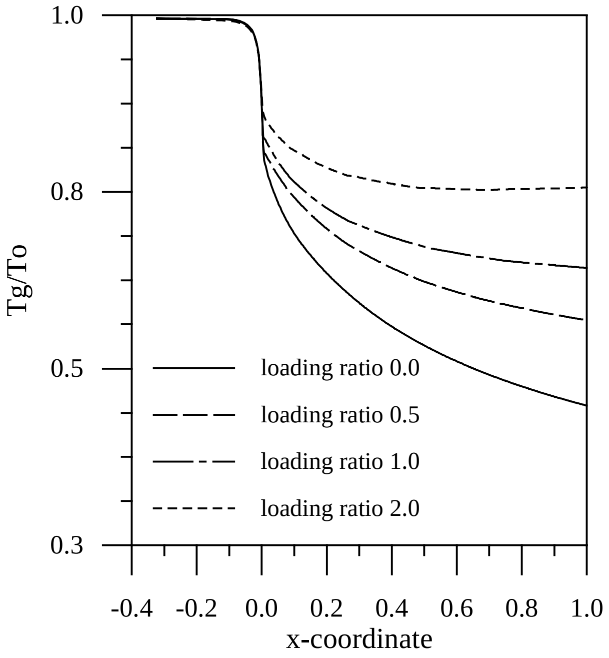

Figure 7. Effect of loading ratio on static gas tempertaure

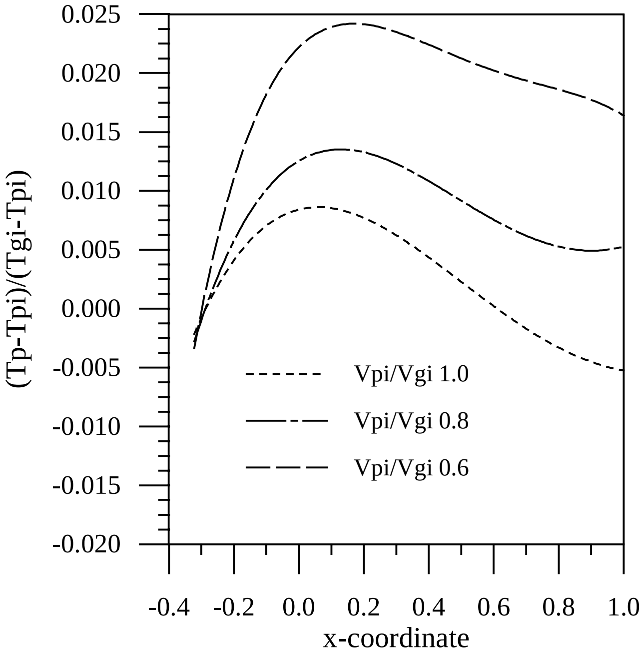

Figure8. Effect of Vpi/Vgi on particle temperature

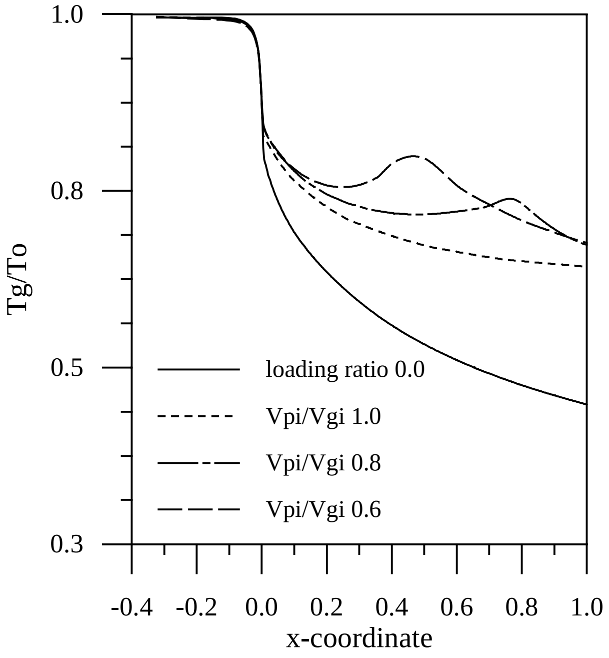

Figure 9. Effect of Vpi/Vgi on static gas temperature

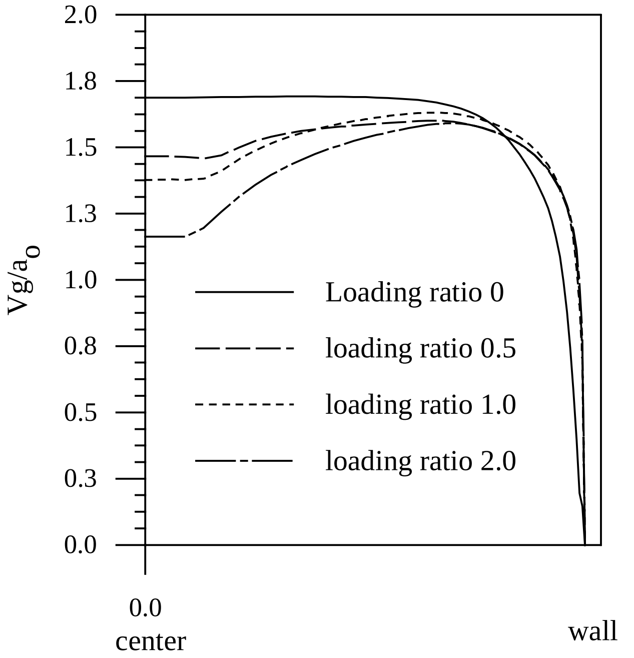

Figure 10. Effect of loading ratio on exit velocity profile

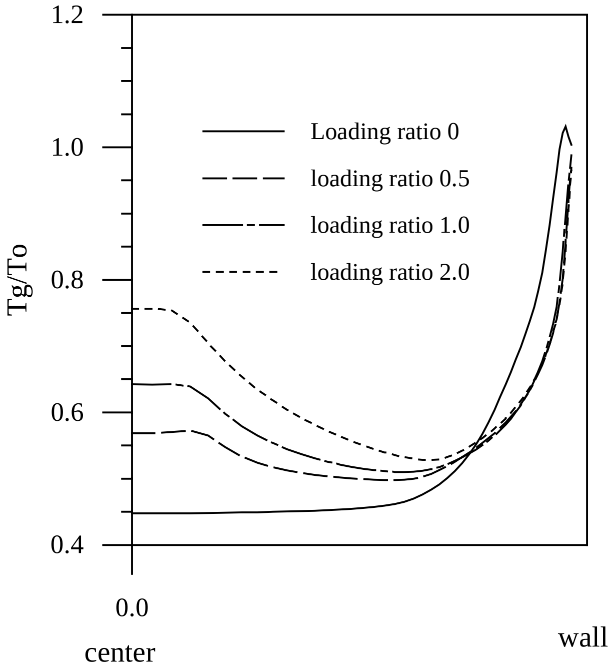

Figure 11. Effect of loading ratio on exit static temperature profile

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ABSTRACT

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EXTENDED ABSTRACT

A numerical study was performed to investigate gas-particle flows in convergent divergent CO_2 pellet-blasting nozzles. The solutions to the compressible Navier-Stokes equations and the equations governing the particles' motion through the gas, in a Lagrangian frame of reference are solved iteratively in order to model the two-way mass momentum and energy exchanges between the two phases. Results are presented for the gas flow field and particle velocities at different particle loadings and inlet velocities. The momentum and energy exchange with the particles reduce the gas velocity in the divergent passage near the center. The presented results demonstrate the effects of particle loading and inlet velocity ratios on pellet and gas velocity and temperature through the nozzle.

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Biographical Sketch

Dr. Awatef A. Hamed is Professor and Department Head of Aerospace Engineering and Engineering Mechanics at the University of Cincinnati. She has many publications in the areas of high-speed propulsion system integration and turbomachinery performance deterioration. She gave professional courses at VKI, the Cranfield Institute of Technology, several international ASME gas turbine conferences, and seminars at many universities in the United States, Europe Japan and China. She has advised many Ph D and master degree graduate students, and several senior engine design teams that won awards in national competitions.

Prof. Hamed had continuous research support from DOD, DOE, NASA, NSF and industry for over twenty years. Her services include NASA Aeronautics Research & Technology Advisory Committee, ASME Fluids Engineering Division Advisory Board, NSF review committees, and several AIAA, ASME, and SAE technical committees. She received best paper awards from ASME, and AIAA, and NASA award for technical innovation, is editor of the International Journal of Computational Fluid Dynamics, and is a Fellow of AIAA and ASME.