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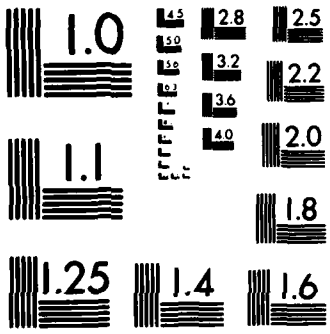

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This report outlines studies conducted to characterize the flow of a gas-particle mixture in an axisymmetric jet including the characterization of particle interactions with shock waves formed in the jet in compressible flow. The measurements made include profiles of axial and radial velocity components of the particles and turbulence characteristics of the flow. Flow visualization was used to measure particle concentration and the structure of the shock waves. Samples extracted from the flow provide the particle size distribution in the jet. These studies are needed because of the lack of a sufficiently detailed understanding of these flows, particularly particle-shock interactions, to verify existing computational techniques.

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I. Research Objectives

There are many practical examples of engineering systems in which small, solid particles are mixed with a gas and the mixture flows through the system. The visible trailing plume from a rocket engine is formed in part by burning of small particles flowing from the rocket engine when they mix with the air in the atmosphere. These particles can also collect on the outer surfaces of spacecraft windows and reduce transmission and reception of light used for navigation and scientific data collection. When finely crushed powders of coal (pulverized coal) are burned in a power plant the coal powder must be sprayed with a nozzle into the boiler and mixed with air before it can burn. One method for producing a synthetic natural gas (entrained gasification) is to spray powdered coal into a heated gas mixture containing steam and hydrogen under carefully controlled conditions. Mixtures of small particles and gases also occur in aircraft engines, diesel engines, and woodburning fireplaces and stoves.

Understanding of these flows with gases and particles is necessary to design the systems and predict their performance. For example, how fast the particle burns depends on how far into the surrounding air it moves and how much air it is exposed to. Unfortunately, these flow systems are very complex and poorly characterized even though they occur so frequently. The particles usually move in a different direction than the gas, with a different speed and a different temperature. All of these quantities should be known to design the practical system and they are influenced by the spray nozzle shape and gas flow. Because the particles are so small (about one millionth of a meter), measurements on the system are difficult. In addition, particles of different size and shape move to different locations in the gas flow. Careful measurements under well-characterized conditions are needed to understand the flow and to develop an ability to design the flow.

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Previous studies of two phase round jet flow have been reviewed in considerable detail in recent reports describing our experimental results (Hayashi[1], Hayashi and Branch[2,3]). In dilute two phase jets with few solid particles, Hetsroni and Sokolov[4], and Popper, et al[5] showed that the solid particle velocity is higher than the gas velocity in many regions of the jet. Other authors have investigated the characteristics of turbulence in a suspension of solid particles. Goldschmidt, et al[6] and Hedman and Smoot[7] showed that turbulent transport is dependent on particle size distribution. Other studies have reported that the turbulent energy level decreases with the suspension of particles into a jet[4,8]. Carrier[9] showed theoretically that behind a shock wave the velocity of the gas is smaller than the velocity of the suspended particles and that the particles are then decelerated. Korkan et al[10] observed no change in the particle direction through an oblique shock wave, even though the gas does change direction.

The studies considered above are for systems with few particles in the flow. There is a significant lack of detailed experimental characterization of gas particle jets in flow with high particle concentration where particles can interact or collide. Among the uncertainties are axial and radial particle drag coefficients. These data are necessary both to develop phenomenological models of two phase jet flow and to provide comparison data for evaluation of theoretical models. A second area of almost no current understanding and experimental characterization is particle interactions with shock waves in these flows. This is particularly true of oblique shock waves. The details of flow of particles and gas in passing through a shock wave are needed to evaluate the important processes describing the interaction in order to model these effects.

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II. Status of Research

Previous studies supported by this grant have concentrated on the experimental characterization of gas-solid two phase jet and nozzle flow. These studies have included the development of a flexible two phase flow facility, development and utilization of a new optical technique for measurement of particle concentration and the use of other diagnostic methods for measurement of gas velocity and temperature, particle velocity and particle size distribution. The most recent measurements which have been made examined the effect of jet Mach number, particle size, particle loading and nozzle configuration on the detailed structure of the two phase free jet.

Recent studies (2,11,12,13,14) have focused on prediction of the characteristics of nozzles and exhaust plumes of rocket engines in order to evaluate nozzle flow and plume visibility, radiation signatures, and impingement effects. Oblique shock waves occur in these flows and accompany detonation and blast waves in heterogeneous media. The nature of oblique shock waves in two phase flow has not been extensively characterized experimentally or theoretically.

In our studies, oblique shock waves in two phase flow were studied, and the relation between gas-particle flow properties ahead of an oblique shock wave and gas particle flow properties behind the shock wave were derived by a solution of the steady-state conservation equations of mass, momentum, and energy for the mixture phase. Some of the important assumption made are that the particles are uniform in size, uniformly distributed, and in thermal equilibrium with the gas ahead of the oblique shock wave. Large particles (>10 μm) do not change direction immediately after passing through the shock wave. Particle drag coefficients in two phase flow were reviewed, and the data used in this study were obtained from aeroballistic range measurements. Results of the oblique shock wave calculations are presented as the relation between the incident angle β of the two phase flow and the deflection angle θ. The

solution considered the effects of the shock wave Mach number, particle velocity lag, particle feeding rate, and particle size. A comparison of the calculations to experimental data was used as a guide to selection of the drag coefficient and gave good agreement between theory and experiment for the available data. It was found that the shock wave structure was influenced by shock wave Mach number, particle feeding rate, and particle velocity lag.

The deflection angles of gas in two phase flow are smaller than those in single phase flow and become smaller when the particle feeding rate increases. The suspension of particles affects weak shock waves more than strong shock waves. The deflection angle of the gas becomes smaller when the particle velocity lag increases. Particle size and particle type have little effect on the oblique shock wave relations in two-phase flow.

The drag coefficient of large particles is smaller than that of small particles and does not change significantly over a large range of incident angels. The pressure ratio between that ahead of the shock wave and that behind the shock wave in two phase flow is smaller than the ratio in single phase flow and decreases at any incident angle as the particle feeding rate increases. An increase in the suspension of particles strengthens the oblique shock wave, but the large particle velocity lag weakens the oblique shock wave in two phase flow.

This study provides some fundamental characteristic features of the oblique shock wave in two phase flow and suggests an appopriate choice of drag coefficient for the problem. The equations developed in this study may be used further for the problems of triple shock waves, detonation, and blast waves in multiphase media.

Solid particle-gas mixture flows have been examined in a wide variety of systems of engineering interest. Some of these are, for example, the pulverized coal combustion system in a power plant and small particles entrained

in rocket exhaust plumes. There are, however, few measurements of heat and mass transfer effects on heavily particle-laden two phase jets because of difficulties in the measurement.

Abramovich, et al.[15] investigated turbulent jets of different gases and measured the Prandtl and Schmidt numbers for those gases. They showed that both dimensionless number depend on the local density ratio between the two different gases. Rychkov[16] and Blagosklonov and Strasenk[17] showed that the gas temperature at the jet axis was increased and the particle temperature was decreased due to heat transfer between the two phases. The gas and particle temperatures equilibrated further downstream.

The Schmidt number is a measure of the diffusion of an additional phase through the gaseous phase. The effect of turbulence can be determined by comparing a turbulent Schmidt number with a laminar Schmidt number. Goldschmidt, et al[18] defined and interpreted the Schmidt number as a function of the velocity, concentration and particle size. Their Schmidt numbers in two phase flow experiments were larger than unity and became larger with an increase in particle size. Abramovich and Girshovich[19] defined the Schmidt number as a ratio of the gaseous diffusion scale to the particle dispersion scale. Their Schmidt number was unity in the laminar air jet case, but it was less than unity in the turbulent air jet case. Hedman and Smoot[20] as well as Abramovich and Girshovich observed an interesting phenomenon that the heavier particle in the two phase system dispersed faster than the lighter particle.

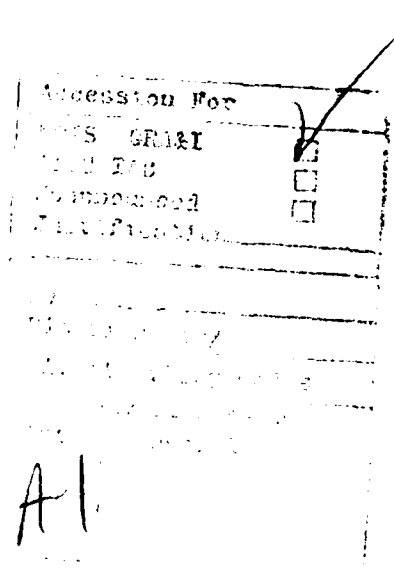
In previous studies[1,2] we have developed an optical method to measure particle concentration, gas velocity and gas temperature to evaluate the turbulent particle Schmidt number and turbulent gas Prandtl number in two-phas jet flows. From measurements of average turbulent gas velocity, average turbulent gas temperature and average particle concentration in gas-solid two-phase jet flows, the turbulent gas Prandtl number and the turbulent particle Schmidt number have been investigated.

It was found that the turbulent particle Schmidt number is large at the nozzle exit and decreases slightly downstream. The turbulent gas Prandtl number is lower when particles are suspended in the flow than without particles. However, the thermal diffusion rate in air is similar to the viscous diffusion rate of air.

The effect of jet velocity on the turbulent gas Prandtl number is significant, but not that of gas Reynolds number of the Prandtl number. The Prandtl number in the jet flow with the faster velocity is smaller than that with the slower velocity. The effect of particle size on the turbulent particle Schmidt number was found to be significant also. The turbulent particle Schmidt number in the heavier particle-gas two phase flow was smaller than that in the lighter particle gas flow. The gas Reynolds number had a linear relation with the turbulent particle Schmidt number in this measurement range. These results indicate that a large lag in two phase flows affects the thermal and momentum transports significantly. Another important result is the finding that heavier particles disperse faster than lighter particles in the two phase jet flows. A simplified treatment of the interaction between solid particles and turbulent eddies gave results which supported the conclusions of the experimental study.

A dual beam, self-aligning LDV system was developed to measure the particle vleocities. The system which is used in our experiments has a commerically available TSI counter-type signal processor. This signal processor serves as a high frequency filter which identifies and validates individual particle doppler bursts and calculates the frequency and hence corresponding particle velocity of the bursts. The data rate from the signal processor is very rapid and these data must be averaged externally to the signal processor.

The principal challenges presented by these investigations are the very high (~300 MHz) doppler signals characteristic of the optical arrangement used and the tradeoff between doppler frequency and spatial resolution. Heavily particle laden jets have additional problems of overlapping doppler bursts which must be separted from single particle bursts for accurate data interpretation. It is also clear from our investigations that the particle velocities and trajectories are significantly different than the gas velocity for large (greater than 10 μm) particles (Figs. 1 and 2).



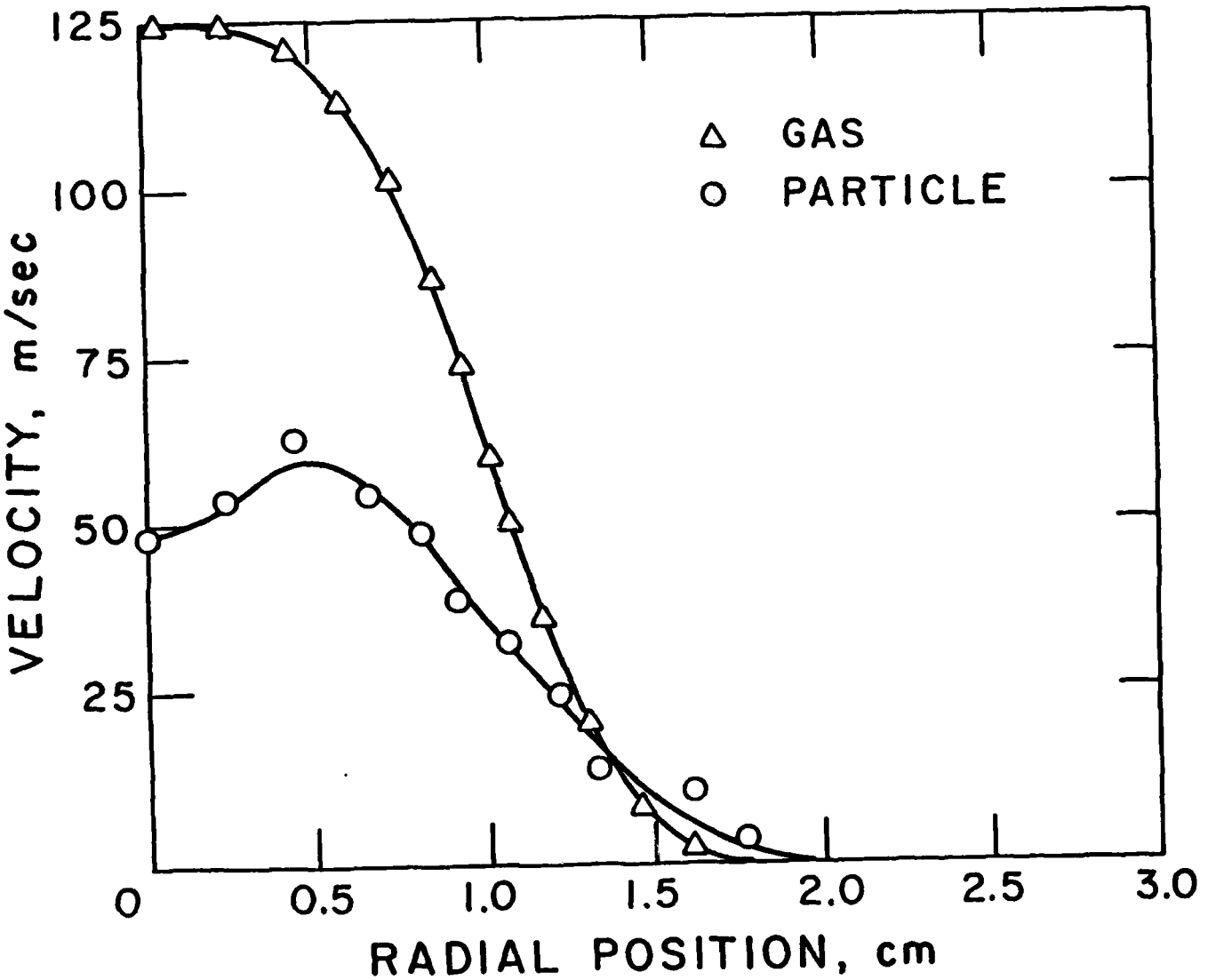


Figure 2. Mean velocity profiles of particles and gas in an axisymmetric jet of air measured 5 nozzle diameters from the nozzle exit plane.

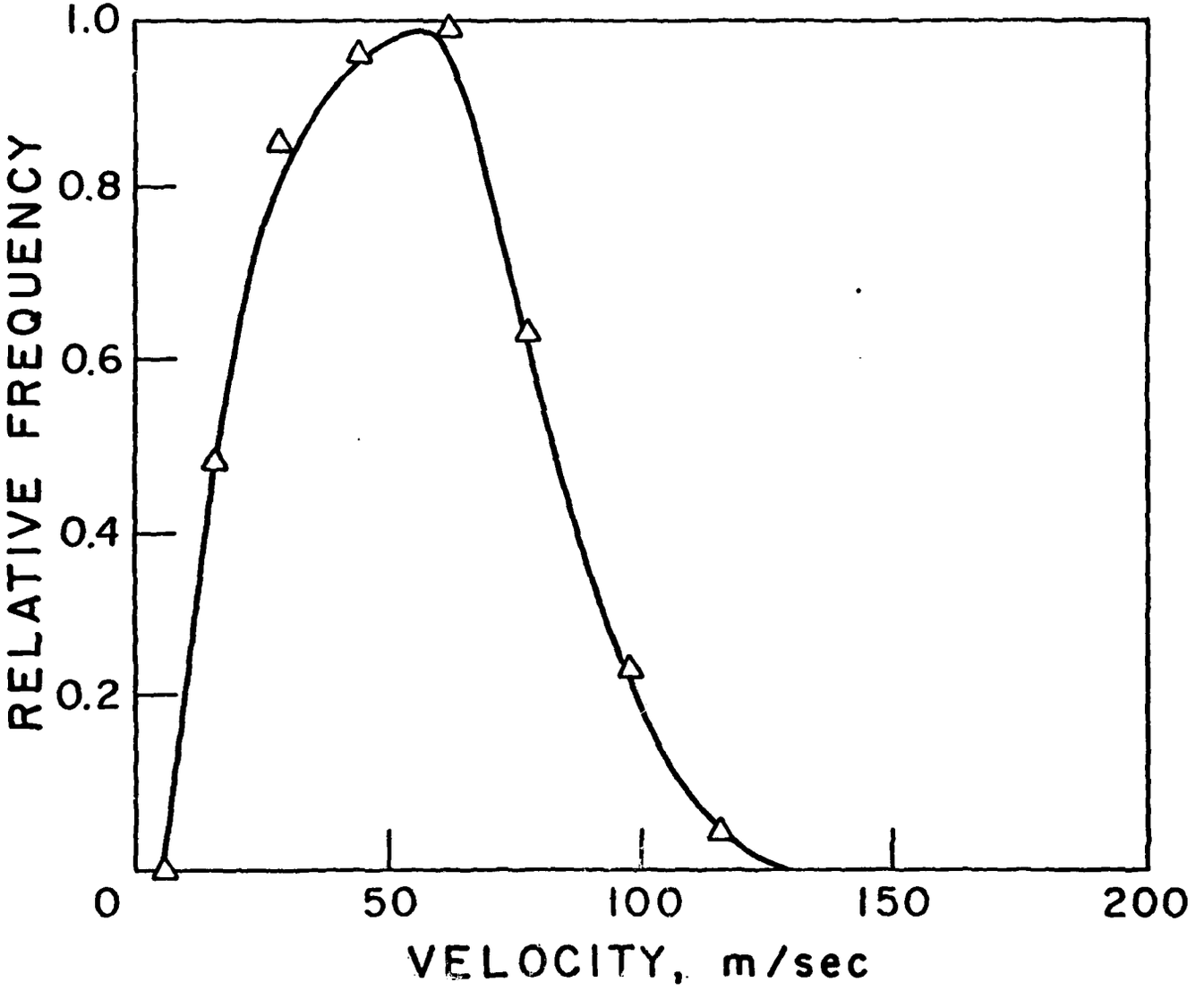


Figure 1. Particle velocity distribution function for 27 μm (mean) diameter particles in an axisymmetric jet of air. The velocity profile is given in Figure 2.

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IV. Recent Publications from this AFOSR Support

1. K. Hayashi and M.C. Branch, "Concentration, Velocity and Particle Size Measurements in Gas-Solid Two-Phase Jets," J. of Energy, 4, 193-198, 1980.

2. K. Hayashi and M.C. Branch, "Particle Transport Effects in Gas-Solid Two-Phase Nozzle and Jet Flow," Paper No. 81-2100, AIAA 14th Fluid and Plasma Dynamics Conference, Palo Alto, CA, June 23-25, 1981.

3. K. Hayashi and M.C. Branch, "Oblique Shock Waves in Two Phase Flow," Progress in Astronautics and Aeronautics, 87, pp. 22-40, 1983.

4. K. Hayashi and M.C. Branch, "Some Aspects of Heat and Mass Transfer in Gas Solid Two Phase Flow," Proceedings of the ASME/JSME Thermal Engineering Conference, ASME, pp. 441-449, 1983.

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6. K. Hayashi and M.C. Branch, "Particle Transport Effects in Gas-Solid Two Phase Nozzle and Jet Flow," submitted to Israel Journal of Technology.

V. Personnel

1. Melvyn C. Branch, Associate Professor of Mechanical Engineering, Project Director and Principal Investigator.

2. Gary Shamshoian, Research Assistant. Awarded M.S. in Mechanical Engineering, May 1983. Thesis Title: "Design Study of a Laser Velocimeter for Heavily Particle Laden Two Phase Jets".

3. Ke Nguyen, Research Assistant, PhD Candidate.

VI. Interactions

Formal presentations of results obtained in this study have included a paper presented at the ASME/JSME Thermal Engineering Conference in May 1983 entitled "Some Aspects of Heat and Mass Transfer in Gas-Solid Two-Phase Jets". An oral progress report and abstract entitled "Flow of Gas Particle Mixtures" was presented at the AFOSR/AFRPL Rocket Propulsion Research Meeting, March 1983 in Lancaster, California. Publications from this AFOSR support are summarized in Section III.

Interaction with Edwards Air Force Base, California and Aeronautical Research Associates of Princeton has been maintained to determine the availability of numerical prediction codes for two phase nozzle and plume flow. Data obtained in the present study will be compared to predictions using these codes when they become available.

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