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SAMPLING SUBMICROMETER PARTICLES SUSPENDED IN NEAR SONIC AND SUPERSONIC FREE JETS

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This investigation was concerned with sampling submicrometer particles in perisonic flows. Aerosol particles having a number mean diameter of 0.8 micrometers and a geometric standard deviation of 1.28 were accelerated to Mach 0.6, 0.8, 1.26, or 1.47 through a flow nozzle. Aerosol mass concentrations were determined using a small bore probe in the jet and by a large bore probe sampling isokinetically upstream of the jet nozzle. The results of both samples were compared to compute the sampling error associated with the

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high speed jet sample. Studies at Mach 0.8 with four sampling probes having inlet wall to bore area ratios ranging from 3.8 to 0.28 (a knife edge) demonstrated that probe wall thickness effects are not significant when the sample is extracted isokinetically. Subisokinetic experiments using the knife edged probe showed relative errors of 124±12 percent when sampling at 20 percent of the isokinetic condition. The subisokinetic results are compared favorably with the extended empirical results of other authors. For the supersonic cases it is shown that the subsonic velocity downstream of the sampling probe bow shock can be used in estimating the sampling error.

PREFACE

This report summarizes work done between 23 July 1975 and 15 December 1976. Joseph A. Martone, Capt, USAF, BSC, was the principal investigator. Project engineering duties were shared by Capt Martone and his supervisor, Peter S. Daley, Maj, USAF, BSC. The work was performed while Capt Martone was a Ph.D. candidate in residence at Oregon State University, Corvallis, Oregon. Richard W. Boubel is Capt Martone's major professor.

The experimental portion of the project was accomplished at the NASA Ames Research Center, Moffett Field, California. The work was supported by the Environics Directorate of the Air Force Civil Engineering Center, the NASA Ames Research Center, and Oregon State University. On 8 April 1977, the Environics Directorate of the Air Force Civil Engineering Center was reorganized into the Environics Directorate, Detachment 1 (CEEDO) HQ ADTC, Tyndall AFB, Florida.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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Introduction

The sampling of particulate emissions from aircraft gas turbine engines is unlike many sampling situations in that submicrometer particles, high speed flows, and elevated temperatures are involved. In addition, the chemical nature, size, and concentration of the particles cannot be pre-supposed with much confidence. Nevertheless, the Air Force must employ proven methods to obtain representative samples to evaluate and characterize particles in aircraft engine exhausts. Although remote monitoring systems may eventually be widely employed, it is very likely that classical extractive particulate sampling methods will continue to be the reference technique for aircraft gas turbines.

The present study was intended to experimentally examine certain parameters which influence the representative sampling of submicrometer particles in high speed flows. Since a particle's size is by far the most important factor in determining its dynamic behavior, this was of major concern. No attempt was made to simulate the chemical composition or temperature of a gas turbine engine exhaust.

Experiments were designed to evaluate three factors likely to cause errors in determining aerosol mass concentrations in high speed flows. First, the effect of varying the ratio of the probe wall to bore area normal to the flow was studied in a Mach 0.8 free jet. Next, the consequence of anisokinetic sampling with a knife edged probe in Mach 0.6 and 0.8 free jets was evaluated. Finally, the influence of shock fronts in the vicinity of the sampling probe inlet was considered at Mach 1.26 and 1.47.

Background

Historically, experimental investigations concerning anisokinetic sampling have dealt with relatively large particles (greater than 4 μm diameter) and low velocities. Some of these studies have resulted in generalized empirical expressions to fit the experimental data. Parker[1] uses the Stokes number (K) as an approximate but convenient guide to indicate when isokinetic sampling is necessary. Based on an examination of theoretical and experimental deposition studies, Parker[1] suggests that isokinetic sampling is required if:

$$0.05 < K = (\rho_p \, d_p^2 \, U_o \, C_s)/(18 \, \mu_g \, D_p) < 50 \qquad (1)$$

where:

C_s = Cunningham slip-flow correction

U_o = ambient flow velocity along the flow line passing through the axis of the probe.

ρ_p = particle density

d_p = particle diameter

μ_g = gas viscosity

D_p = diameter of sampling probe inlet

Voloshchuck and Levin[2] made theoretical calculations and found that the approximate formula for the aspiration coefficient (A) could be written in the form:

$$A = C/C_o = 1 + [(U_o/U) - 1]\ \beta(K) \qquad (2)$$

where:

C = aerosol concentration of sample

C_o = aerosol concentration of free stream

U = mean flow velocity at probe inlet

U_o = ambient flow velocity along the flow line passing through the axis of the probe

$\beta(K)$ = Stokes number function

Other authors have correlated their experimental data using the form of Equation 2 with different expressions for $\beta(K)$. Zenker, as reported by Fuchs[3], sampled vertical air streams containing spherical glass beads or limestone dust with particle diameters from 7 to 73 micrometers. For Stokes numbers between 0.06 and 14 and values of U/U_o between 0.4 and 2.5, $\beta(K)$ was found to be:

$$\beta(K) = 1-N \qquad (3)$$

where:

N = dimensionless coefficient depending only on the Stokes number.

Davies, as reported by Belyaev and Levin[4], suggests the following formula:

$$\beta(K) = 1 - [1/(1+4K)] \qquad (4)$$

Belyaev and Levin[4] used the same form as Equation 4 to correlate their data. They employed flash illumination to study the aspiration process for willow pollen (aerodynamic diameter 24 μm) and Lycopodium spores (aerodynamic diameter 17 μm) near a sampling probe inlet. The sampling errors were determined from the limiting trajectories of particles entering the sampling nozzle. For probes with very thin (0.1 millimeter) walls their results were accurately approximated by:

$$\beta(K) = 1 - [1/(1 + BK)] \qquad (5)$$

where:

$$B = 2 + 0.62\ (U/U_o) \qquad (6)$$

Equations (5) and (6) are applicable for U/U_o between 0.18 and 6.0 and a Stokes number between 0.18 and 2.03.

The results of these relatively recent authors suggest that anisokinetic sampling errors might be significant even for submicrometer particles if sampled in high speed air flows with small bore probes. The errors predicted by these expressions are greater than would be predicted by the empirical relationships presented in the often cited but considerably older work of Badzioch[5] and Watson[6].

Experimental Methods

The experimental approach to this study was simple in concept; submicrometer particles (d_p = 0.8 μm, σ_g = 1.28) were injected into an air stream and accelerated to the desired velocity (Mach 0.6, 0.8, 1.26 or 1.47) through a sonic or supersonic nozzle. Experimental probes were used to sample aerosol particles at the free jet exit while a conventional isokinetic sampling probe upstream of the nozzle was used to withdraw a sample assumed to accurately represent the true aerosol concentration. Differences between the two observations reflected errors due to conditions at the free jet sampling probe inlet. Figure 1 illustrates the experimental equipment.

Free Jet Air Flow System

Clean, dry, oil-free air at a nominal pressure of 10.5 atm was delivered to the experimental system. Constant air flow was maintained by manually controlling the static pressure in the settling chamber. Downstream of the aerosol generator inlet line the diluted aerosol was passed through a wide angle diffuser and three 40 mesh screens to spread the flow and reduce turbulence. The aerosol then traveled approximately 0.76 m before being sampled by the settling chamber sampler and accelerated through the appropriate 5.08 cm exit diameter flow nozzle. The aerosol was exhausted as a free jet into still room air. The experimental sampling probe inlets were placed 1.3 cm from the nozzle exit, well within the "potential core" where the jet velocity is equal to nozzle exit velocity.

One subsonic and two supersonic axisymmetric flow nozzles were designed and fabricated for this study. The subsonic nozzle design was a standard ASME long-radius, low-ratio type[7] while the supersonic nozzle contours were generated by the computerized version of a design method due to Sims[8]. The subsonic nozzle was used to achieve exit Mach numbers of 0.6 and 0.8 while the properly expanded supersonic nozzles proved to produce exit Mach numbers of 1.26 and 1.47.

Aerosol Generation

The aerosol generator was a high volume (30-45 liters per minute) condensation unit similar to that described by Katz et al[9]. Stearic acid was chosen as the aerosol material because it results in nearly spherical solid particles. One tenth weight percent anthracene was added to provide a stable source of condensation nuclei. This practice has been suggested by Tomaides et al[10].

An aerosol charge neutralizer containing a 10 mCi ^{106}Ru - ^{106}Rh beta radiation source was used to bring the aerosol to an equilibrium Boltzman charge distribution. The charge neutralizer was considered necessary since Tomaides et al[10] reported that aerosols produced by condensation generators could be electrically charged. The neutralizer design was based on guidelines presented by Cooper and Reist[11].

Particles were collected on 142 mm diameter, 0.4 μm pore size, polycarbonate membrane filters manufactured by the Nuclepore Corporation, Pleasanton, CA. A small piece of the filter membrane was mounted on a cylindrical brass stud which could be staged directly into a JSM-U3 scanning electron microscope (SEM). The size of the particles was determined by direct counting of the particle images on the micrographs. A minimum of 100 particles were counted for each sample sizing.

The average of 22 particle size samples taken in the free jet and the settling chamber gave a number mean particle diameter of 0.78 μm (std. dev. 0.06) and a geometric standard deviation, σ_g, of 1.28 (std. dev. 0.04). The output of the condensation aerosol generator was on the order of 10^6 particles/cc.

Sampling Systems

Both the free jet and settling chamber samplers employed front facing aspirating probes, polycarbonate membrane filters, oiless rotary vane vacuum pumps, and calibrated orifice meters. The membrane filters were held in specially constructed, double o-ring sealed, stainless steel filter holders. Orifice meter calibration over a range from 0.014 to 0.85 standard m^3/min was accomplished by a method[12] involving the use of a saran bag with a known volume.

The probe used to sample isokinetically in the settling chamber had a large bore (19.1 mm) and a low cone angle (4°) to insure representative sampling. The required isokinetic sampling rates were determined from velocity data obtained during pitot tube traverses of the settling chamber. The average velocity in the settling chamber ranged from 5.3 m/sec at Mach 1.47 to 6.1 m/sec at Mach 0.8.

Four sampling probes each with a different inlet wall to bore area ratio (Table I) were used in the free jet sampling system. All the probes were used to evaluate probe wall thickness effects when sampling isokinetically in a Mach 0.8 free jet; however, only the knife edged probe (number 4) was used in the anisokinetic studies at all Mach numbers.

Probe number 4 was designed by Aerotherm Acurex Corp, Mtn. View, CA as a divergent supersonic inlet. For low supersonic Mach numbers, the divergent inlet portion, with sufficiently low back pressure, accelerates the flow to the vicinity of Mach 2. The flow is decelerated in a shock pattern within a constant area cross section immediately downstream of the divergent inlet. The constant area cross section is also intended to enhance the pressure recovery characteristics of the probe. The supersonic inlet portion of the sampling nozzle has an intentional surface roughness to reduce the tendency of the shock to move once it is swallowed by the probe. Figure 2 is a set of shadowgraphs showing probe number 4 submerged in a Mach 1.47 free jet with no probe flow, at $U/U_o = 0.5$, and at $U/U_o = 1.0$ (shock swallowed).

Determination of Stearic Acid Mass

In the free jet and settling chamber sampling systems, stearic acid particles were collected on polycarbonate membrane filters. The mass of stearic acid collected on a particular filter was determined by gravimetric and gas chromatographic techniques. The gravimetric determinations were used to make rapid, approximate computations and therefore no extraordinary precautions were used to insure their accuracy. It was found that sample handling and weight reproducibility were greatly enhanced by exposing the filter to a small alpha radiation source to eliminate static charges on the filter just before a weighing. The range of sample weight gains, excluding blanks, was from 1.0 to 15.0 mg.

The gas chromatographic method involved washing the filters with diethylether and converting the dissolved stearic acid to its methylester before separation in a gas chromatograph equipped with a flame ionization detector. Sampling probe deposits were determined similarly after washing the probes with pesticide grade acetone and careful evaporation of the acetone. In both filter and probe wash analyses an amount of a non-interfering organic acid (heptadecanoic acid) was added as an internal standard.

All chromatographic analyses were performed by Stoner Laboratories, Inc., Santa Clara, California. A method verification study[13] showed that, within the experimental range, essentially 100 percent stearic acid recovery from the Nuclepore filters could be expected even after a storage time as long as a week.

A paired t statistical comparison of 240 gas chromatographic and corresponding gravimetric results indicated that they had equivalent distributions, although the variance of the gravimetric results was greater than that for the chromatographic results. Therefore, only the chromatographic results were used in the final computations.

Procedure

System Operation. Obtaining experimental data involved phased operation of the aerosol generator, the free jet system, and both particle sampling systems. First, the aerosol generator was permitted to thermally equilibrate using dry, filtered purge air. Then, with clean wind tunnel air in the free jet system, the flow control valves in both particle samplers were adjusted to achieve the proper sampling rate; the vacuum pumps were used only if required. Following a momentary shut down, aerosol was permitted to enter the settling chamber and the chamber was brought to proper stagnation pressure. After operating for about one minute, the particle samplers with pre-set sampling rates were activated for a five minute sampling period. When a sample was taken for particle size analysis the sampling time was ten to fifteen seconds; however, the sampling was performed at the mid-point of a usual five minute run.

After collection, the samples to be used for particle sizing were prepared for SEM examination while the pre-weighed filters to be used for particle mass concentration calculations were placed in glass petri dishes until they could be reweighed and subjected to the gas chromatographic analysis. Probe washings awaiting gas chromatographic examination were stored in glass sample bottles fitted with Teflon® lined screw caps.

Aerosol Concentration Profiles. Table II summarizes the concentration profile results at Mach 0.6, 0.8, and 1.26 for both the free jet and settling chamber. The mean and standard deviation of results taken at any single location were comparable with the mean and standard deviation of the results obtained during a traverse. For this reason it was assumed that average concentration in either the settling chamber or free jet could be adequately determined by samples taken on the center line. Table II also shows that the mean deviation between the settling chamber and free jet concentrations was 11 percent. This good agreement allowed settling chamber samples to be used as the reference aerosol concentration (C_o) during the probe wall effects and anisokinetic sampling studies.

Blanks. During the course of the experiments many blank filter samples were submitted for analysis. Ten Nuclepore filters carried through sample handling procedures, but not used in either sampling system, gave an average result of +0.07 milligram This amount was considered negligible since in 95 percent of the samples the correction would be less than 2.0 percent of the filter weight gain; in the worst case, the possible error was less than 9 percent. Twenty-two filter samples were obtained in the settling chamber and in the free jet without the aerosol generator operating. These indicated whether particle re-entrainment from the settling chamber wall, screens, or wide angle diffuser was significant. The analysis showed that particle re-entrainment would account for at most a 0.5 percent error in the computed reference aerosol concentration, C_o.

Probe Washes. Although the free jet and settling chamber sampling probes were washed with acetone between sampling periods, not every probe wash was retained for analysis. Average probe wash values were used with the filter weight gain to compute the total sample weight gain. Twenty-six settling chamber probe washes indicated that the average probe deposit was 2 percent of the amount deposited on the filter (std. dev. 1%); 46 free jet sampling probe washes gave an average probe deposit that was 12 percent of the filter weight gain (std. dev. 5%).

Results

Probe Wall Effects

Four sampling probes with wall to bore area ratios ranging from 0.28 to 3.8 were used to isokinetically sample stearic acid aerosol on the center line of a Mach 0.8 free jet. The intention was to demonstrate sampling errors due to the probe inlet wall thickness. Replicate samples were taken with each probe; the results are presented in Table I. Using the fifteen data points, no linear correlation (coefficient of determination, $r^2 = 0.1$) could be obtained between the sampling probe wall to bore area ration, A_w/A_b, and the relative percent error $((C - C_o)/C_o) \times 100$.

Anisokinetic Studies

Sampling probe number 4 was used to sample at less than isokinetic conditions (U/U_o <1.0) on the center line of free jets having Mach numbers of 0.6, 0.8, 1.26 and 1.47. The average result of isokinetic samples taken simultaneously in the settling chamber was used as the reference concentration, C_o. Figure 3

shows the experimentally determined relative percent sampling errors, $((C-C_o) / C_o) \times 100$ as a function of the percent of the isokinetic sampling velocity $((U/U_o) \times 100)$ for each Mach number. A non-linear regression analysis of the data gave:

$$C/C_o = 0.69 + 0.31\ (U_o/U) \pm 12\% \qquad (7)$$

Equation 7, shown graphically in Figure 3, predicts relative sampling errors greater than 124% for $U/U_o < 0.2$.

For the supersonic cases the percent of isokinetic sampling and the Stokes number were initially computed using the supersonic free jet velocity, U_o. However, in cases when a bow shock exists, the stream velocity is subsonic between the shock front and the sampling probe inlet. If the bow shock is considered to be a normal shock, the subsonic velocity may be predicted from normal shock relationships. For example, compressible flow tables[14] show that for a Mach number of 1.26 (M_1) the mach number ratio across a normal shock (M_1/M_2) will be 1.56, or $M_2 = 0.81$. Thus, the actual Mach number immediately upstream of the sampling probe inlet is Mach 0.81.

Using the post shock subsonic velocity as U_o, the percent of isokinetic sampling was recomputed for the Mach 1.26 and 1.47 free jets. These derived data points are included in Figure 3. The good agreement between the derived data and the data actually obtained at subsonic free jet velocities suggests that within the experimental limits supersonic anisokinetic sampling errors can be estimated using the subsonic velocity which exists downstream of a sampling probe bow shock to compute the sampling velocity ratio, U/U_o.

Figure 4 compares the anisokinetic errors predicted by Equation 7 with the results of other authors for a Stokes number of 0.12. Even though previous investigators used relatively large bore probes and low speed flows, they studied a Stokes number range that approached or included the Stokes numbers encountered in the present study (i.e. $0.1 < K < 0.14$). The good agreement between the results of the present study and the relatively recent work of Zenker[3], Belyaev and Levin[4], and Davies[4] demonstrates the usefulness of these correlations for predicting sonic range, subisokinetic sampling errors when the Stokes number of the particle-nozzle system is near 0.1.

Conclusions

In this study aerosols containing solid, spherical stearic acid particles with a number mean diameter of 0.8 μm and a geometric standard deviation of 1.28 were sampled with small bore front facing aspirating probes in near sonic and supersonic unheated free jets. The conclusions are:

1. The sampling probe wall to bore area ratio, A_w/A_b, in the range from 0.28 to 3.77 does not affect the sampled aerosol concentration, C, when sampling isokinetically in Mach 0.8 free jets.

2. Relative concentration errors of approximately 125% are encountered when sampling in Mach 0.6, 0.8, 1.26 and 1.47 free jets if the sampling velocity is 20 percent of the free stream velocity.

3. With low supersonic free stream Mach numbers the subsonic velocity downstream of the sampling probe bow shock can be used with subsonic anisokinetic data to estimate sampling errors. Therefore, representative samples can be obtained by matching the sampling velocity with the post shock subsonic velocity rather than the free stream supersonic velocity.

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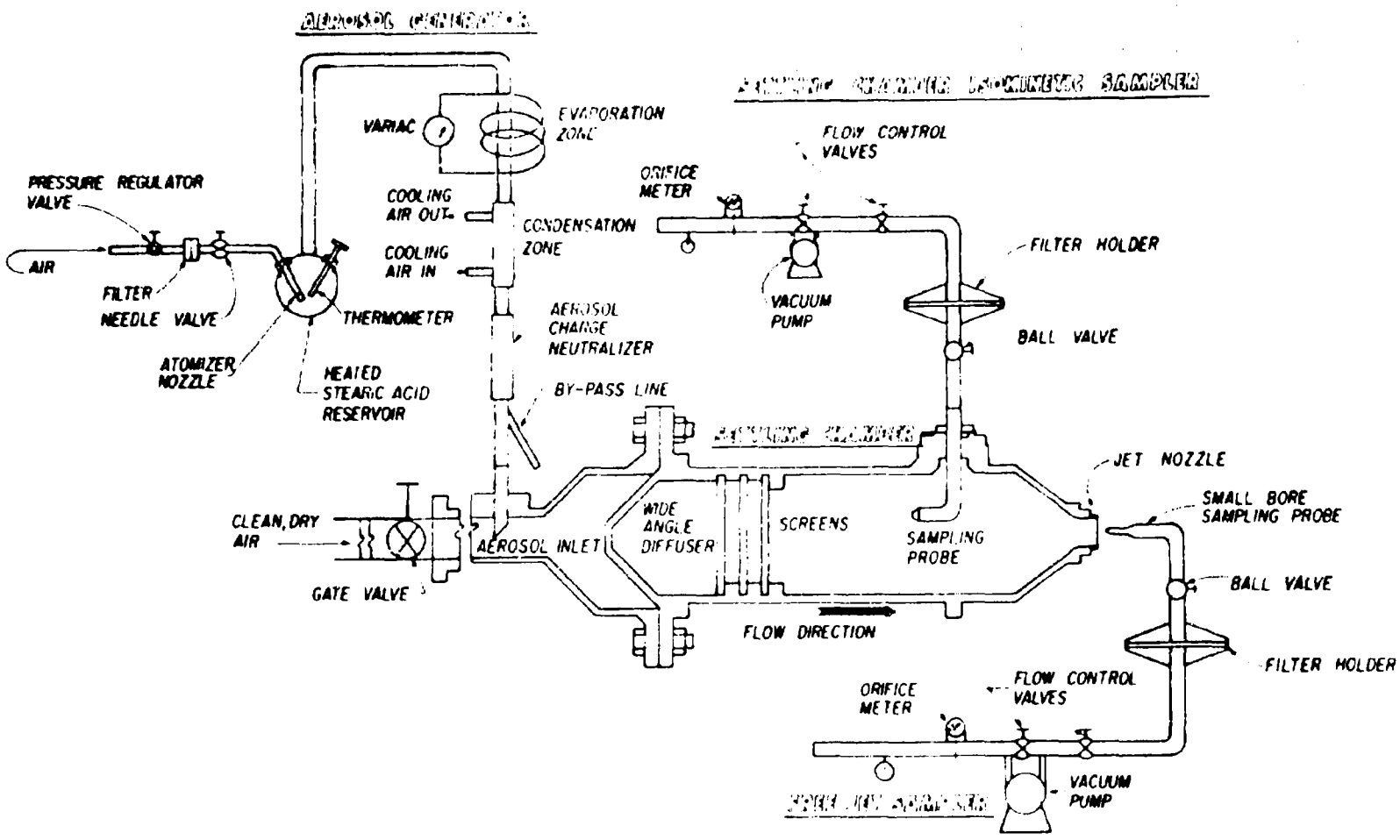
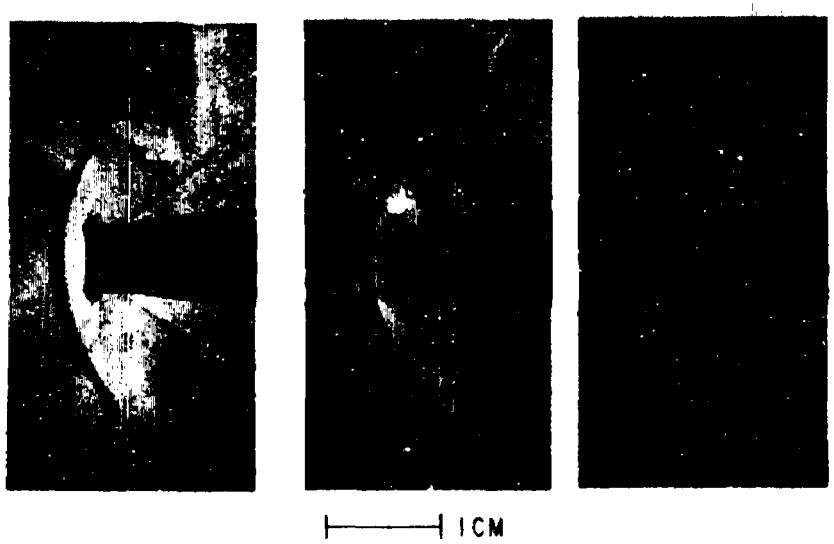


Figure 1. Experimental Equipment



$U/U_0 = 0$ $U/U_0 = 0.5$ $U/U_0 = 1.0$

Figure 2. Shadowgraphs of Probe Number 4 in a Mach 1.47 Free Jet

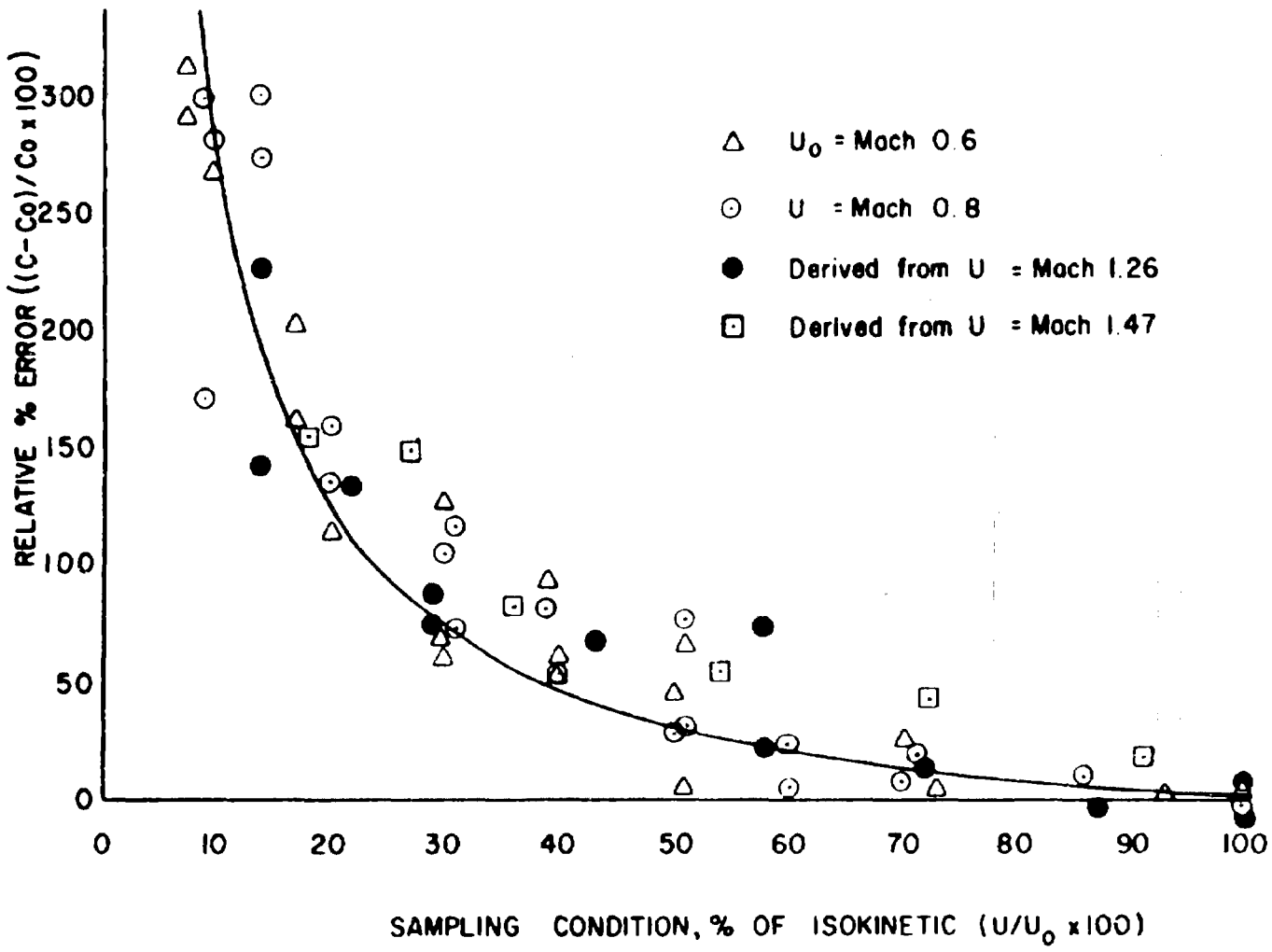


Figure 3. Relative Aerosol Concentration Errors for Subisokinetic Velocity Ratios

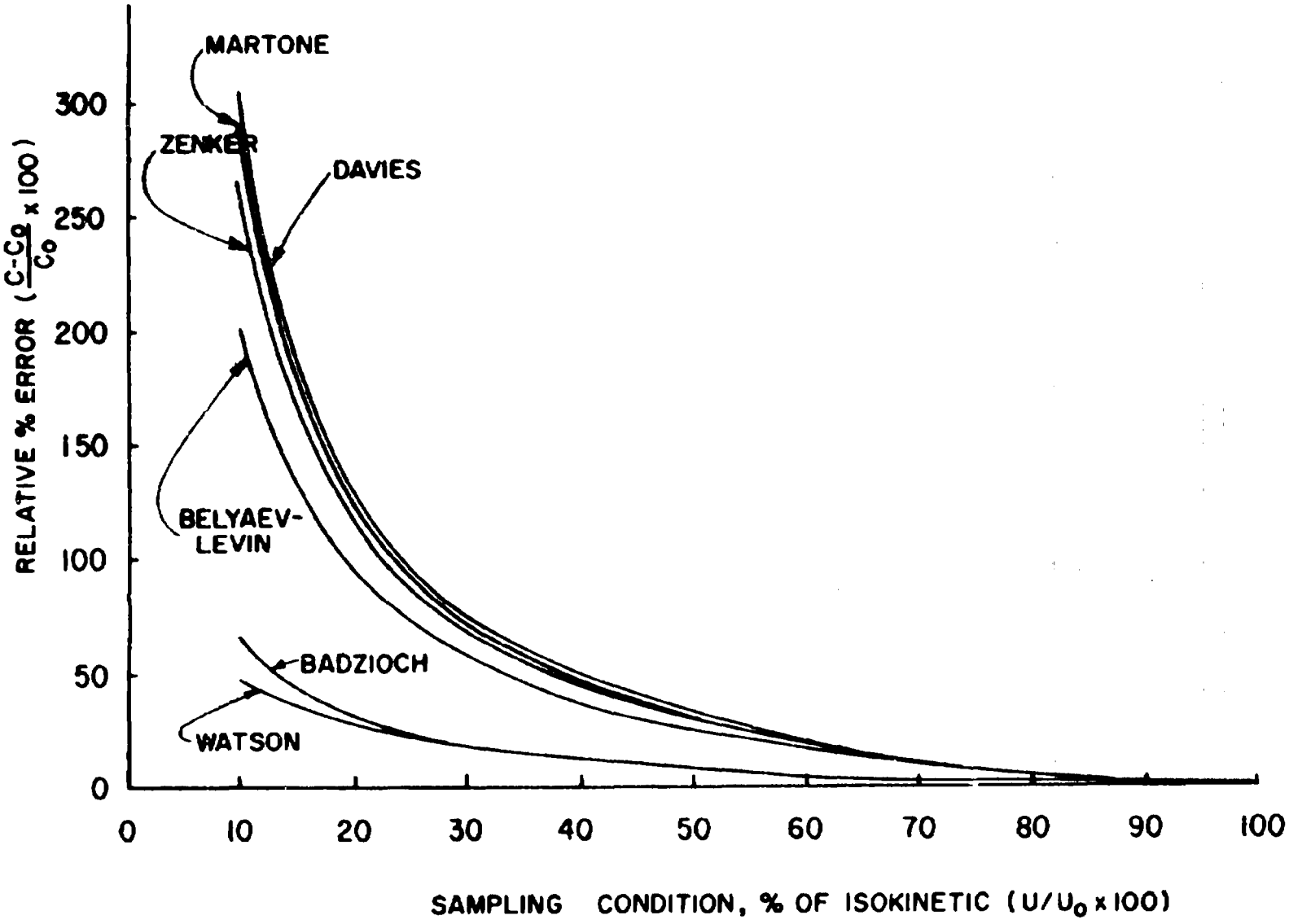


Figure 4. Comparison with the Results of Other Authors for a Stokes Number of 0.12

TABLE 1. AEROSOL CONCENTRATION IN A MACH 0.9 FREE JET DETERMINED BY DIFFERENT SAMPLING PROBES

Probe Number	Outside Diameter Of Probe Inlet, D_1 (mm)	Inside Diameter Of Probe Inlet, D_2 (mm)	Wall to Bore Area Ratio A_w/A_b	Aerosol Concentration, C (mg/m^3)	
				Mean	Std. dev.
1	6.05	2.77	3.77	9.3 (3)[a]	1.23
2	6.12	3.96	1.39	8.4 (4)	0.67
3	6.17	5.16	0.436	9.3 (4)	0.63
4	5.08	4.50	0.277	8.0 (4)	0.44

Footnote a ( ) number of observations

TABLE 2. SUMMARY OF AEROSOL CONCENTRATION PROFILES

	SETTLING CHAMBER CONCENTRATION (mg/m³)				FREE JET CONCENTRATION (mg/m³)			
	All traverse points		Centerline samples		All traverse points		Centerline samples	
Mach no.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
0.6	8.2 (13)[a]	1.00	7.9 (5)	0.54	8.4 (13)	0.70	8.7 (5)	0.88
0.8	6.7 (19)	0.82	6.8 (9)	0.62	7.6 (19)	1.11	7.6 (9)	1.02
1.26	2.9 (11)	0.34	2.6 (3)	0.28	3.2 (11)	0.20	3.1 (3)	0.07
1.47	–	–	2.0 (3)	0.51	–	–	2.0 (3)	0.09

Footnote a) Number of samples used to determine mean value

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AFSC/SGB	1	NASA AMES RES CTR/MS 213-4	1
AFSC/DLCAM	2	NASA AMES RES CTR/MS 239-1	1
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USAFA/DFSLB	1	NASA AMES RES CTR/MS 227-5	1
AFIT/DEM	1	NASA AMES RES CTR/MS 206-3	1
AUL	1	NASA AMES RES CTR/MS 227-8	1
AFOSR/NA	1	NASA AMES RES CTR/MS 227-9	1
AFAPL/TBC	1	NASA AMES RES CTR/MS 245-5	1
AMPL/DAL	1	ORE ST UNIV/MECH ENGR	4
AFML/DO	1	ORE ST UNIV/LIB	1
OEHL/CC	3	ORE ST UNIV/CHEM ENGR	1
OEHL/OL-AV	1	ORE ST UNIV/CIV ENGR	3
OEHL/OL-AB	1	ORE ST UNIV/MATH DEPT	1
AFWL/SUL	1	STONER LABS INC	1
USAFSAM/EDE	2	ACUREX CORP	1
AFRPL/Lib	1	AFAPL/SFF	1
FTD/LGM	1	NAPF/CODE 64270	1
SAMSO/SG	1	NAV AIR PROP TEST CTR/PE-71	1
AMD/RDU	1	NAV FAC ENGRG CMD	1
DDC/TCA	12	PRATT&WHITNEY ACFT	1
Def Res & Eng (AD E&LS)	1	USAF HOSP/SGPE/Edwards	1
OASD/(I&L)ES	1	FINE PARTICLES RESEARCH IITRI	1
USA ENVIR HYGN AGEN	1	ARO, INC [AEDC (AFSC)]	1
CH OF ENGRG/ENGMC-RD	1	ENV PROTEC AGN/MD 46	1
CHF OF NAV OP (OP-45)	1	EXXON RES AND ENGRG CO	1
NCEL, CODE 25111	1	BOEING COM AIRPLANE CO	1
NAV AIR DEV CTR/MAE	1	FAA-ARD 550	1
NAV SHIP R&D CTR/Code 2031	1	USAAMRDL/SAVDL-EU-TAP	1
U of New Mexico/Tech Ap	1	NASA LEWIS RES CTR/MS 60-4	1
TECH TRANS STAFF (EPA)	1	AEDC/DYR	1
OF OF R&D (EPA)	1	FAA-AEQ-10	1
NATL SCI FND	1	EPA/ACFT PROJ MGR	1
USA MED BIOENGRG R&D LAB	1	AFRPL/DYCA	1
USA CERL	1	AFRPL/DOF	1
DIR USA ENG R&D LAB/MERDC	1	GE CO/ADV COMB & EMIS CTRL	1
CH OF R&D/DARD-ARE-E	1	GM CORP	1
USAFSAM/VNL	1	AIRESEARCH MFG CO OF ARIZ INC	1
AFIT/CIMK	1	NATL ENV RES CTR	1
Det 1 HQ ADTC/ECA	7	AFATL/DLODL	1
Det 1 HQ ADTC/CC	1	AFATL/DLODR	1

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