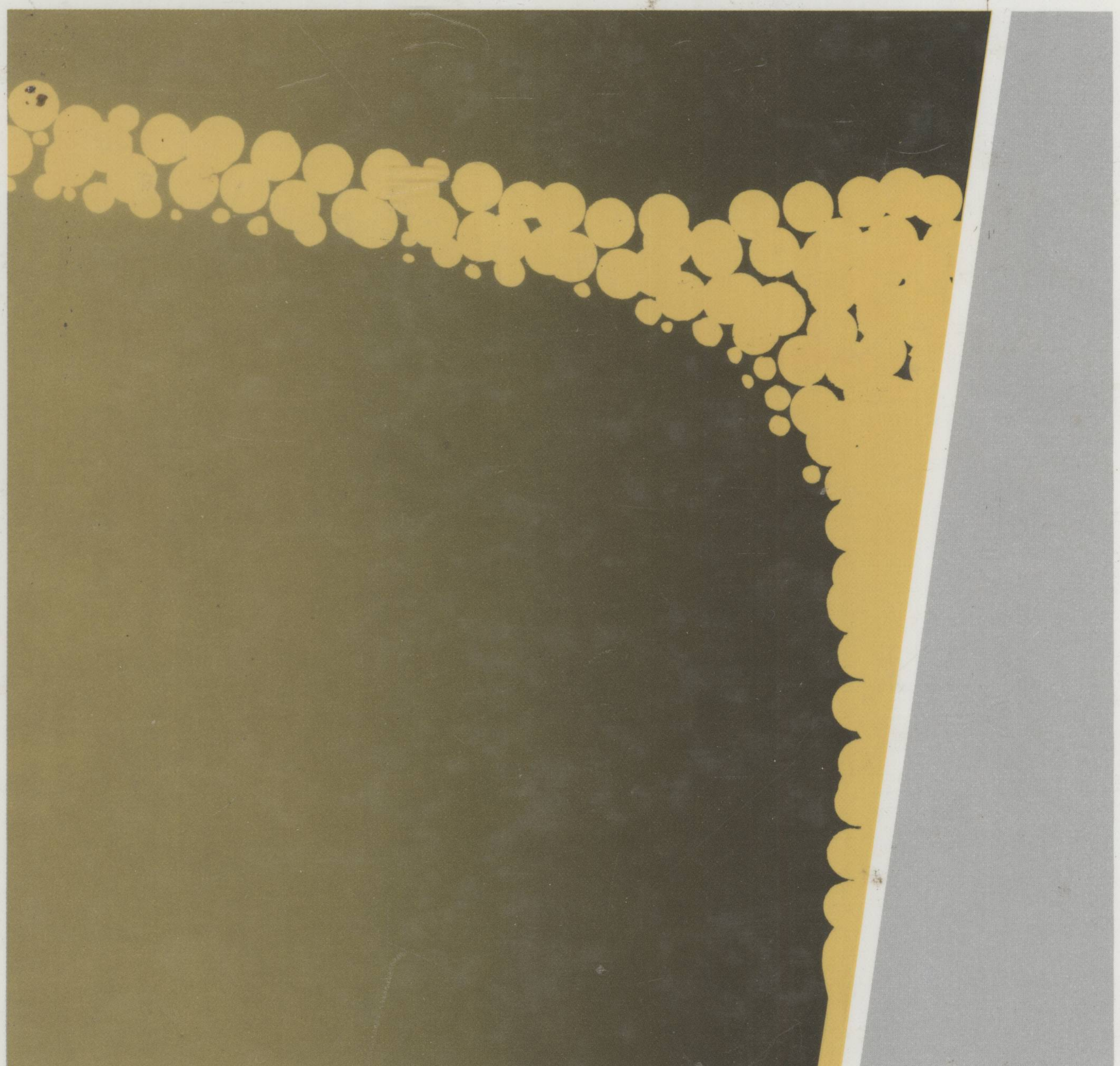
ASM INTERNATIONAL®
The Materials Information Society

Thermal Spray Research and Applications

edited by Thomas F. Bernecki
Conference Proceedings



THERMAL SPRAY RESEARCH AND APPLICATIONS

Proceedings of the
3rd National Thermal Spray Conference
Long Beach, California
20–25 May 1990

Edited by
Thomas F. Bernecki

Sponsored by
Thermal Spray Division of
ASM International®
Co-sponsored by the
High Temperature Society of Japan

Published by
ASM International®
Materials Park, Ohio 44073

ASM INTERNATIONAL®
The Materials Information Society

Library of Congress Catalog Card Number: 91-070802
ISBN: 0-87170-392-0
SAN: 204-7586

ASM International®
Materials Park, Ohio 44073

Printed in the United States of America

ORGANIZING COMMITTEE

Merle L. Thorpe
TAFA Incorporated
Concord, NH
Organizing Committee Chairman

Herbert Herman
State University of New York
Stony Brook, NY
Program Chairman

Jack R. Kittle
Cincinnati Thermal Spray, Inc.
Cincinnati, OH
Conference Chairman
Vice Chairman of the ASM International® Thermal Spray Division

Mark F. Smith
Sandia National Laboratories
Albuquerque, NM
Second Vice Chairman of the ASM International® Thermal Spray Division

Conference Organizing Committee

Frank J. Hermanek
Sulzer Plasma Technik
Troy, MI

Jack Ritchie
Bender Machine Inc.
Vernon, CA

David Houck
GTE Products
Towanda, PA

Ronald Smith
Drexel University
Philadelphia, PA

Saed Safai
Pratt & Whitney
East Hartford, CT

Committee Chairmen

Proceedings
Thomas F. Bernecki
Basic Industry Research Lab.
Evanston, IL

Ad-Hoc Emissions
Tony Rotolico
Metco
Westbury, NY

Equipment
Robert Miller
Sulzer Plasma Technik
Troy, MI

Materials Science
Paul Stanek
Los Alamos National Labs
Los Alamos, NM

Testing & Characterization
Larry Moskowitz
Amoco Research Center
Naperville, IL

Vendor Session
Robert Unger
TAFA Inc.
Concord, NH

Membership
Gary Ritchie
Bender Machine
Vernon, CA

Government Advisory
Jeff Waldman
Naval Air Development
Warminster, PA

Applied Process Technology
Val Zanchuk
TAFA Inc.
Concord, NH

FOREWORD

More than 1600 people from 25 countries attended the technical sessions, tutorials, and exposition at the third annual National Thermal Spray Conference in Long Beach, California on May 20-25, 1990. This conference was held in conjunction with AeroMat'90 which allowed participants of NTSC'90 to interface with the individuals and organizations at the cutting edge of aerospace technology. Thermal spray is a rapidly growing worldwide technology base that holds many of the answers to the demanding requirements of coatings performance. One of the highlights of the conference was increased participation as a result of Glasnost.

Included in these proceedings are most of the papers presented at the conference. I would like to thank the authors and those who volunteered their time for peer review. The reviewers were the following: A. Adamski, T. Bernecki, D. Crawmer, M. Dorfman, H. Herman, F. Hermanek, D. Houck, J. Jonkouski, R. Kaufold, F. Longo, R. Miller (SPT), R. Miller (NASA) L. Moskowitz, J. Nerz, E. Novinski, S. Rangaswamy, J. Reardon, W. Riggs II, S. Safai, G. Schubinsky, M. Smith, R. Smith, P. Stanek, D. Varacalle.

The next National Thermal Spray Conference will be held May 4–10, 1991 in Pittsburgh, Pennsylvania.

Thomas F. Bernecki

TABLE OF CONTENTS

PROCESSING SCIENCE

VENDOR'S SESSION

ABRADABLES

WEAR/EROSION

CORROSION

SURFACE TREATMENT
POST-SPRAY

PRE-SPRAY

COATING CHARACTERIZATION AND EVALUATION

SPRAY FORMING AND COMPOSITES

BIOMEDICAL APPLICATIONS

EQUIPMENT AND PROCESSES

CERAMICS

THERMAL BARRIER COATINGS

HVOF

HIGH TEMPERATURE CERAMIC SUPERCONDUCTORS

AUTOMATION

STATISTICAL METHODS IN THERMAL SPRAY

FEEDSTOCK MATERIALS

Thermal Spray Research and Applications, Proceedings of the Third National Thermal Spray Conference, Long Beach, CA, USA/20–25 May 1990

A NEW LOOK AT THE THERMAL AND GAS DYNAMIC CHARACTERISTICS OF A PLASMA JET

E. Pfender, W.L.T. Chen
University of Minnesota
Dept. of Mechanical Engineering
Minneapolis, Minnesota, USA

R. Spores
Dept. of the Air Force
Air Force Astronautical Laboratory
Edwards Air Force Base, California, USA

Abstract

There is increasing evidence that reproducibility of the plasma spray process depends to a large degree on the reproducibility of the plasma jet which is utilized for spraying. Recent research using a broad range of diagnostic techniques, including LDA, electric and acoustic probing, spectroscopy, and enthalpy probes, has greatly enhanced our present understanding of the thermal and fluid dynamic characteristics of plasma jets. Experimental results strongly imply that the entrainment mechanism in turbulent plasma jets is more of an engulfment type process as opposed to simple diffusion. Turbulence measurements indicate that the velocity fluctuations are non-isotropic, contrary to what has been assumed in most numerical work. Measurements of electric, acoustic, and light fluctuations demonstrate that there are correlations between some of these fluctuations and that turbulence in the plasma jet may be strongly affected by fluctuations in the torch nozzle. Temperature measurements using spectrometric and enthalpy probes indicate strong discrepancies, particularly in the jet fringes.

THE INABILITY TO REPRODUCE PLASMA JETS, due to lack of understanding of the physics [1], is a major source of inefficiency in the plasma spray industry today. For example, rejected plasma sprayed turbine blades, due to inadequate parameter control, result in high economic losses. For this reason, a better understanding of the fundamental characteristics of the plasma spray process such as: substrate material properties, particle-plasma interaction, plasma torch operation, etc. are essential. This paper concentrates on recent research pertaining to plume properties of plasma torches.

Significant gains into the understanding of the flow structure and thermal properties of plasma torches has been made over the last several years by research performed in the High Temperature Laboratory of the University of Minnesota. In this paper, recent results obtained by a wide range of diagnostic techniques (Laser Doppler Anemometry, Emission Spectroscopy, Enthalpy Probes, Spectral Analysis and Numerical Modeling) will be discussed. When the information obtained by these individual techniques is combined, it significantly adds to our understanding of plasma plumes and their interaction with the external air environment.

Recently spectral analysis has been introduced for analyzing the dominant frequencies of the internal voltage fluctuations in a plasma torch and for determining both temperature and pressure fluctuation frequencies in the plasma jet. Autocorrelation can be used to calculate the periodicity in time of an individual parameter while cross-correlation between signals can determine their inter-dependence or common relationship. This paper is thought to represent the first use of a spectral analyzer as a diagnostic tool for D.C. plasma torches.

I. FLUID DYNAMICS OF PLASMA JETS

VELOCITY MEASUREMENTS - Mean velocity and turbulence intensity measurements were

---

* now with the Dept. of the Air Force, Air Force Astronautical Laboratory, Edwards Air Force Base, CA 93523-5000

made using a single velocity component argon ion Laser Doppler Anemometry system operating in the forward scattering mode [2, 3]. Unless otherwise noted, the operating conditions for all runs discussed in this paper were as follows: total gas flow rate (Argon) = 23.6 liters/min (50 SCFH), torch current and voltage, I = 450 A and V = 24V, respectively.

The development of the mean plasma velocities are shown in Fig. 1 which reveals that a plasma jet is qualitatively similar to isothermal jets [4]. Note the steep mean velocity gradients measured at the edge of the nozzle exit. This is where turbulence energy is generated and thus the whole entrainment process initiates. The velocity profiles further downstream show the obvious spreading of the jet and leveling off of the velocity.

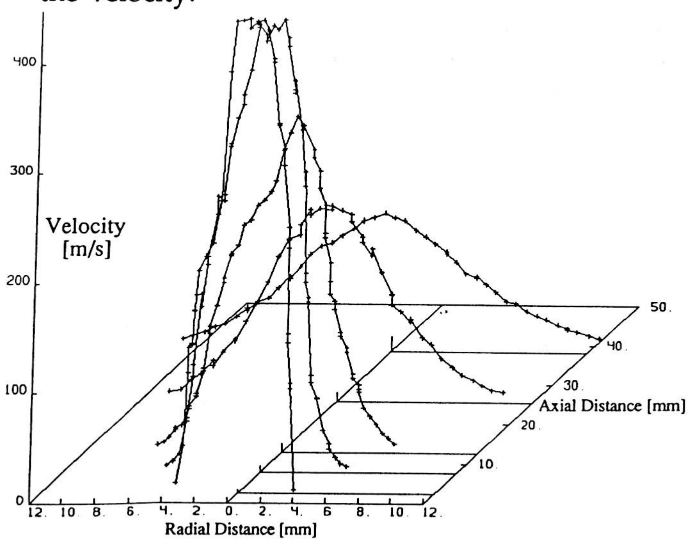


Figure 1 Mean Axial Velocity of a Plasma Jet

TURBULENCE MEASUREMENTS -The amount of turbulence not only dictates the quantity of air entrained into the jet and thus the volume of useful plasma, but it also affects heat transfer rates to particles traveling through the jet. Turbulence in this case is defined as the ratio of the standard deviation of the individual velocity measurements for a given data point (also known as fluctuating velocity) divided by the maximum centerline mean velocity for a given axial distance downstream.

The development of turbulence in a plasma jet is shown in Fig. 2 which reveals a rapid increase in axial velocity fluctuations at the edge of the jet due to the mixing and entrainment of external air. The initial rise of turbulence at the edge of the jet and the progression of the maximum turbulence towards the centerline are likewise characteristic of both combustion and isothermal jets [4,5].

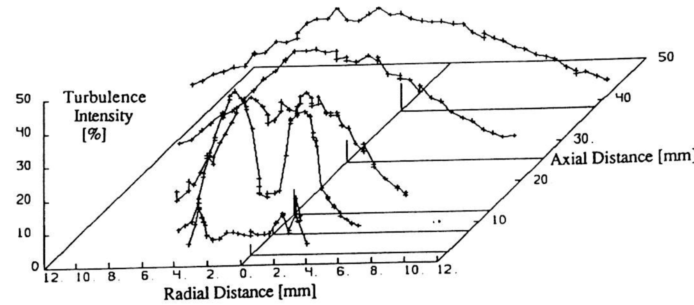


Figure 2 Turbulence Intensity of a Plasma Jet

Experimental and numerical centerline mean velocity and experimental turbulence intensity have been plotted together in Fig. 3. Note the sharp increase in turbulence and dramatic drop in axial velocity starting at z=8 mm. This corresponds to the point where eddies of entrained air from the surrounding fluid have finally reached the centerline of the jet. The stretching of the plasma gas eddies as they flow over the slower cold eddies, is thought to be the main reason for the large increase in axial velocity fluctuations in the transition region of the jet. The low turbulence level in the exiting plasma jet exists because the central portion is still in the potential core region of the jet and the increased viscosity, due to the high temperature, relaminarizes the flow.

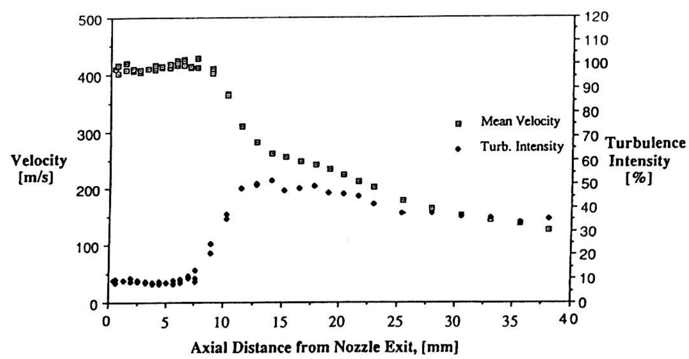


Figure 3 Centerline Mean Velocity and Turbulence Intensity

A finite-difference parabolic numerical code using a K-ε turbulence model was developed for comparisons with the experimental results [6]. Fig. 4, illustrates the centerline numerical and experimental mean velocities revealing dissimilarities in the initial nozzle exit region of the plasma jet. This discrepancy is most likely due to the measured particles still weakly accelerated in this region. The particles have not yet attained the true gas velocity which is probably more closely represented by the numerically calculated values.

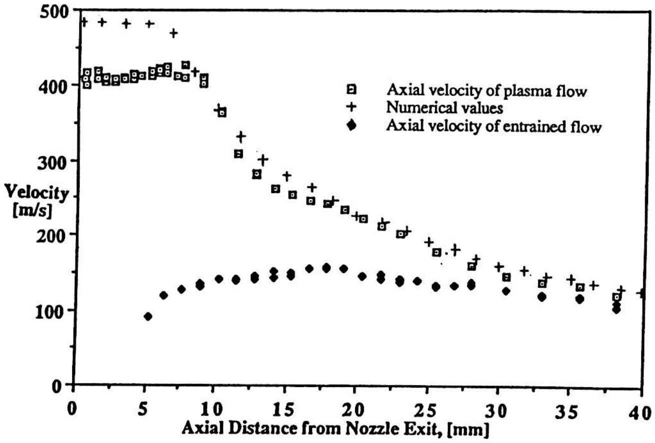


Figure 4 Comparison of Plasma Jet and Entrained Fluid Velocity on Centerline

CONCENTRATION MEASUREMENTS - Experimentally determined argon concentrations shown in Fig. 5 were derived from samples taken with an enthalpy probe [7]. The experimental results, which are only available from z=20mm and farther downstream, show a large drop in centerline concentration between the 25mm to 35mm profiles indicating the end of the potential core. By 30 mm downstream the jet consists of only 50% argon on the centerline and overall the jet is probably less than one-third argon. Increasing the mass flow from 23.6 to 35.4 1/min, argon concentrations were significantly reduced for the same locations while a further jump in mass flow did not generate nearly as large an effect. This seems to indicate a transition in flow from laminar at 23.6 1/min to turbulent at 35.4 1/min.

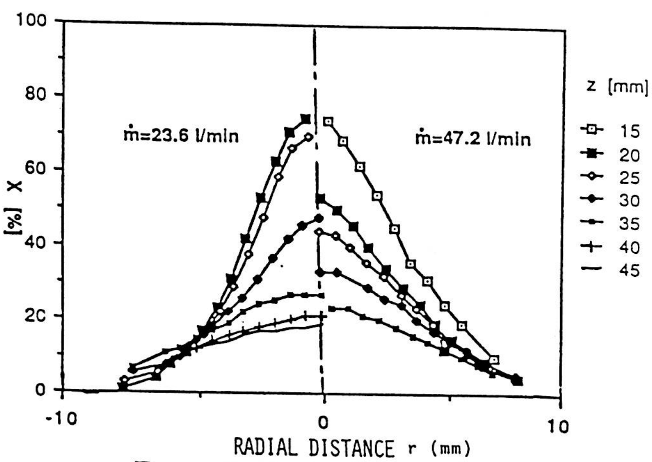


Figure 5 Argon Concentration Profiles: I=450 A

As shown in Ref. [7] air entrainment is reduced for higher arc currents. As more power is dissipated inside the torch, the temperature of the jet increases and likewise the molecular viscosity increases. The flow thus remains laminar longer causing both mixing and turbulence levels to decrease. Since the higher arc currents increase the power and temperature of the jet, the density decreases and mixing is reduced. If the mass flow rate of the main gas is increased, it increases the swirl of the torch and reduces the plasma temperature leading to a greater effect on entrainment than current variation. The air which is entrained has a higher specific heat than argon resulting in lower temperature for the same energy content.

CONDITIONAL SAMPLING - In this case, velocity measurements are taken conditionally on the origin of the fluid. These conditional velocity measurements (obtained by alternately seeding only the plasma jet or the entrained air) provide a gauge of the "degree of mixing" in the plasma jet along with giving insight into the intermittency and entrainment processes of the jet. This seeding technique enables one to conveniently mark the fluid originating from the plasma jet and from the surrounding environment while the resulting conditional velocity statistics reveals considerable information about the details of the interaction between the two flows at the small-scale level [4, 5]. Differences in the conditional quantities are attributable to the presence of larger-scale eddies in the flow field.

The axial plot, Fig. 4, shows that for $z \leq 30$ mm fluid from the plasma jet has a much higher mean velocity than the entrained air which has reached the centerline. At z=5 mm, the first centerline location at which both conditional measurements could be taken, the velocity difference between eddies of the two flows is a remarkable 300 m/sec. Entrained air does not mix well with the plasma gas initially but instead travels with a much slower mean velocity than the plasma, thus forcing plasma gas to flow around it. Radial plots indicate that velocity discrepancies between the two flows prevail outward almost to the edge of the jet. By z=30 mm, the mean velocities of both flows have come together indicating an equilibrium in the momentum of the two flows but not necessarily a homogeneous (well mixed) fluid. All of this evidence seems to indicate that the more classical belief of entrainment and mixing by stochastic small-scale eddies is not a realistic picture of the transport mechanisms in a turbulent plasma jet. These findings have been recently confirmed by CARS measurements at INEL [8].

By plotting the plasma gas and entrained air axial velocity fluctuations in Fig. 6, it is