

DOE/PC/90756--T7

QTR 3

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**Research on Thermophoretic and Inertial Aspects of Ash Particle  
Deposition on Heat Exchanger Surfaces in Coal-Fired Equipment**

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## 1. Introduction

DOE-PETC has initiated at the Yale HTRC Laboratory a systematic three-year experimental and theoretical research program directed toward providing engineers with the data, methods, and rational correlations needed to dramatically improve the generality and accuracy of predictions of inorganic particle deposition rates under typical coal combustion conditions (i.e., those leading to the importance of thermophoretically-enhanced diffusion (submicron mode) and the inertially-enhanced "impaction" (supermicron mode). After a brief statement of objectives (Section 2) we outline our experimental and theoretical progress during this quarterly reporting period (Section 3), with our results summarized in Section 4 and in the references documented in Section 6. Section 5 gives relevant administrative information (personnel, research plans).

## 2. Background Statement: Objectives

The goal of our research in the area of ash transport is to develop the capability of making reliable engineering predictions of the dynamics of net deposit growth for surfaces exposed to the products of coal combustion. To accomplish this for a wide variety of combustor types, coal types, and operating conditions, this capability must be based on a quantitative understanding of each of the important mechanisms of mineral matter transport, as well as the nature of the interactions between these substances and the prevailing "fireside" surface of the deposit. This level of understanding and predictive capability could be translated into very significant cost reductions for coal-fired equipment design, development and operation.

Our emphasis in the present program: "Research on Thermophoretic and Inertial Aspects of Ash Particle Deposition on Heat Exchanger Surfaces in Coal-Fired Equipment" is on experimentally validating\* and developing rational, theoretical methods for predicting the role of inertia and ash particle thermophoresis in determining net deposition rates. We also wish to quantify how simultaneous vapor deposition (eg., alkali sulfate) can influence the sticking and erosion associated with impacting particles. Specifically, as a result of this DOE-PETC

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\* Our previous DOE-PETC supported experiments have been confined to vapor and submicron particle systems in the absence of inertial phenomena. For an overview of convective mass transfer, see the PI's recent textbook (Rosner, 1986), especially Chapters 6, 8.

supported program, we believe that it will be possible for us to develop:

- a. An understanding of the factors governing impacting particle capture and deposit erosion probabilities, leading to rational correlations.
- b. Clever applications of recent mass transfer theories and available heat and momentum transfer data to develop predictions methods for important practical situations - eg. deep tube bundles ('banks').
- c. Necessary extensions of available particle deposition rate theory: eg. 'eddy impaction' for general nonisothermal turbulent gaseous boundary layers on curved surfaces.

To be able to develop tractable but realistic/rational 'subroutines' to predict the evolution of wall deposits\*, it will be necessary to intensify our communication with more empirically oriented engineers/chemists who have the necessary boiler fouling/slagging experience. If we are successful, we will ultimately be able to recommend economical 'subroutines' (compatible with practical requirements of global computer codes, recent deposition research results and cumulative empirical observations) to predict the evolution of wall deposits for, say, design studies of coal-fired furnaces and boilers.

### 3. Experimental/Theoretical Research Progress

#### 3.1. Inertial Impaction Experiments Using Optical Techniques and the Free Jet Produced by a Seeded, Pressurized, Microcombustor

As outlined in QTR#1, to study the behavior of impacting particles over a three-decade particle diameter range (say  $10^{-1}$ - $10^2$   $\mu\text{m}$ ) at gas velocities up to ca.  $10^4$  cm/s<sup>†</sup>, we have designed

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\* While beyond the scope of the present program, we believe it will also be timely and necessary to determine the relation between deposit micro-structure (and ancillary thermophysical properties) and deposition conditions (eg., arrival rate mechanisms).

† Gas velocities in our seeded premixed flat-flame burners used in our laboratory for studying alkali sulfate vapor and submicron particle deposition (Rosner and Atkins, 1983; Rosner and Kim, 1984; Rosner and Liang, 1986; Liang and Rosner, 1987) are of the order of only 10cm/s. Under these conditions, inertial effects, of primary interest in the present program, are negligible.

and constructed a micro-combustor based facility (QTR 1) which provides a well-defined 5 x 5 mm jet of ca. 1500 K particle-laden gas suitable for both particle sticking and deposit erosion studies. This micro-combustor (QTR 2, Fig. 3.1) can be supplied via (Fig.3.1 below) a monodispersed spray of aqueous droplets (which will simultaneously produce particles and alkali vapors), or the output of the powder feeder for the introduction of larger solid particles (say,  $d_p > 20 \mu\text{m}$  diam.). Real-time reflectivity changes and post-mortem microscopy are being used to characterize deposition and erosion rates on initially reflective targets. These experiments have been initiated, with our initial attention focused on the ability of impacting supermicron MgO particles to remove predeposited submicron MgO particles.

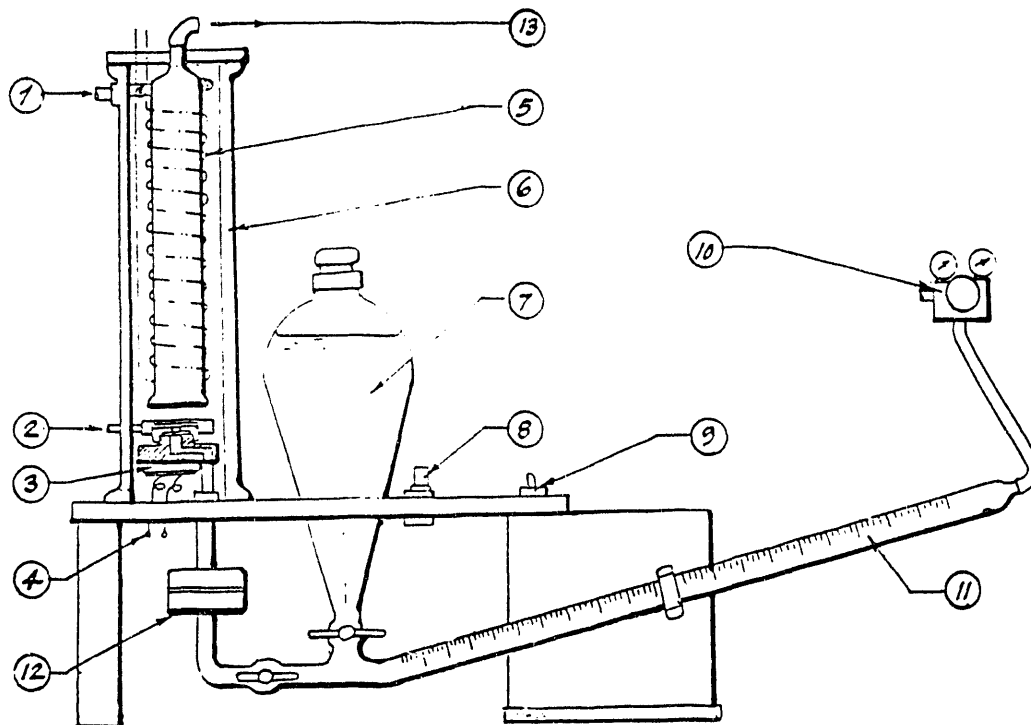


Fig. 3.1. Vibrating orifice system for the production of controlled-size, monodispersed aerosol particles supplied to the microcombustor; code: 1. dilution  $\text{N}_2$ ; 2. dispersion  $\text{N}_2$ ; 3. piezoelectric ceramic vibrator; 4. from signal generator; 5. electrical heater; 6. main body; 7. liquid solution storage; 8. dispersion flow regulator. 9. signal amplifier switch; 10. pressure regulator; 11. volumetric flow-meter; 12. filter ( $0.5 \mu\text{m}$ ); 13. aerosol to pressurized combustor.

The abovementioned 'monodispersed' particle generator (Fig.3.1) exploits the vibrating orifice principle (Berglund and Liu, 1973). The generator produces aerosol droplets of a known, single size, which can be changed from approximately 0.5 to 50  $\mu\text{m}$  diam with an average geometrical standard deviation of only 1.03. For exploratory experiments we have used a 35  $\mu\text{m}$  diam orifice and a 52 kHz electrical signal to produce  $\text{MgSO}_4 + \text{Na}_2\text{SO}_4$  particles of ca. 16  $\mu\text{m}$  diameter at the rate of about 52,000 particles per second. Our entire generator system consists of a calibrated liquid storage vessel, a volumetric flow-meter (provided with controllable gas pressure drive), a 0.5 micron pore size filter, a replaceable orifice head and either a desiccant bed drier or electrically heated drier section. A signal generator (Hewlett-Packard, Model 606) and a power amplifier (EIN, Model 240 RF) are used to drive the orifice head causing controlled liquid jet breakup.

### 3.2. Theoretical Studies

In support of the abovementioned objectives, we are also carrying out theoretical studies in the following three interrelated areas:

- a. Interaction of inertial- and thermophoretic effects in well-defined laminar 'dusty-gas' flows (Park and Rosner, 1987).
- b. Self-regulated sticking and deposit erosion in the simultaneous presence of vapor or submicron 'glue' (Rosner and Nagarajan, 1986, a, b; 1987).
- c. Use of packed bed and tube-bank heat transfer and friction correlations to provide the basis for future tube-bank fouling predictions.

These initial studies will be broadened considerably, and the results brought to bear the objectives outlined in Section 2, later in the present program.

## 4. Results\*

During this third quarter of Grant DE-FG22-86 PC 90756, we have obtained preliminary experimental results on the deposition behaviour of submicron and supermicron solid particles ( $\text{MgO}$ ,  $\text{Al}_2\text{O}_3$ ) on a two-dimensional surface exposed to a high

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\* See, also, the archive publications cited in Section 3, and spelled out in Section 6.

temperature/velocity particle 'laden' atmospheric pressure jet. The uniform velocity ('plug flow') jet, with temperatures up to about 1520 K, derives from a pressurized gaseous fuel micro-combustion chamber (110 cc) equipped with a platinum guiding (exit) channel. Particles were generated by several methods (Berglund-Liu type aerosol generator [Fig.3.1], ultrasonic nebulizer [Rosner and Kim, 1984], or syringe feeder with aerodynamic particle off-take) and were introduced into the combustion chamber with a carrier stream of nitrogen or air. Laser light scattering and reflectivity techniques were used for the study of particle deposition (see, eg., Rosner and Kim, 1984), supplemented by post-mortem microscopy on the exposed surface. We observed a linear deposition rate of submicron particles due to the thermophoretic mechanism (until the first layer was developed), under both high and low velocity conditions. On the contrary, supermicron particle deposits reach a steady-state, evidently due to a dynamic equilibrium between particle deposition and dislodging caused by the impacting particles. At several temperatures particle-free subsonic gas jets (up to 120 m/sec) were unable to remove the submicron particle layer. However, supermicron particles carried by a jet were able to remove the layer and even erode the initially polished collecting platinum surface. The presence of a condensable alkali salt ( $\text{Na}_2\text{SO}_4$ ) in the jet has been shown to strongly influence the adhesive characteristics of the impacting supermicron particles when the surface temperature was below the vapor dew point. Additional experiments of this type are in progress and our preliminary results will be presented at the 18th Annual Meeting of the Fine Particle Society - Symposium on Multiphase Flow, August 3-7, 1987, in Boston, MA (Konstandopoulos, Goldman and Rosner, 1987).

In parallel with these impaction experiments, we are continuing our theoretical studies of the interaction of inertial and thermophoretic effects (Park and Rosner, 1987), the role of simultaneous vapor arrival in determining particle sticking and erosion probabilities (Rosner and Nagarajan, 1987), and mass transport phenomena in deep tube banks (Section 3.2.).

## 5. Administrative Information

During this 3 month period, the following personnel have contributed to the present program:

Name	Position	Role
D.E. Rosner	Professor ChE, P.I.	Overall program direction
Y. Goldman	Visiting Research Engineer <sup>§</sup>	Microburner facility design and aerosol generator development (Fig. 3.1)
A. Konstandopoulos	GRA <sup>*</sup>	Microburner facility calibration and preliminary experiments
H.M. Park	PDRA <sup>+</sup>	Theory of combined inertial and thermophoretic effects

<sup>§</sup> On leave from Technion-Israel Institute of Technology, Dept. of Aeronautical Engineering.

<sup>\*</sup> Graduate Research Assistant.

<sup>+</sup> Completed postdoctoral extension at Yale on 5/29/87.

We have prepared and submitted an abstract for an experimentally oriented paper to be presented at the 18th Annual Meeting (August 3-7, 1987, Boston) of the Fine Particle Society - Symposium on Multiphase Flow (Konstandopoulos, Goldman and Rosner, 1987). The self-regulation concept which will guide and focus our experimental effort is now concisely described in a paper we have prepared for the AIChE Symposium Series Volume: High Temperature Heat Transfer (1987) (Rosner and Nagarajan, 1987).

We are eagerly awaiting the outcome of our December 1986 DOE University research equipment grant proposal since the requested equipment would not only greatly facilitate and enhance the abovementioned experiments, but would also open the possibility of more ambitious experiments on high velocity particle impaction.

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