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EXPERIMENTAL VERIFICATION OF VAPOR DEPOSITION MODEL IN MACH 0.3 BURNER RIGS*

Süleyman A. Gökoğlu
Analex Corporation

Gas turbine failures associated with accelerated "hot" corrosion motivated this research intended to obtain a better understanding of the deposition phenomenon of corrosive species on turbine blades. A comprehensive yet tractable theoretical framework of deposition from combustion gases has been developed covering the spectrum of various mass delivery mechanisms including vapor (refs. 1 and 2), thermophoretically enhanced small particle (ref. 3), and inertially impacting large particle (ref. 4) deposition. Rational yet simple correlations have been provided to facilitate engineering surface arrival rate predictions (refs. 5 to 7). The objective of the program at the NASA Lewis Research Center has been the experimental verification of the deposition theory using burner rigs. Toward this end, a Mach 0.3 burner rig apparatus has been designed to measure deposition rates from salt-seeded combustion gases on an internally cooled cylindrical collector (ref. 8).

The results of the previous experiments have been reported in detail in reference 8. Different sodium salt solutions (e.g., NaCl, sea salt, $NaNO_3$, and Na_2SO_4) were sprayed into the combustor; however, in all cases the expected deposit was Na_2SO_4. Indeed, the X-ray analysis of the deposit verified this prediction. There were two regions of disagreement between the deposition rate prediction of the chemically frozen boundary layer (CFBL) vapor deposition theory and the experimentally observed deposition rates of Na_2SO_4, depending on whether the collector temperature was above or below the melting point of Na_2SO_4. The discrepancy for collector temperatures above the melting point of the deposit is attributed to the shear-driven molten deposit layer run off from the smooth collector surface (ref. 9). However, for collector temperatures below the melting point of the deposit the results were puzzling. Although both the theory and the experiments showed plateau deposition rate behavior, the disagreement level depended on the sodium salt sprayed, ranging from good agreement for NaCl seeded experiments to almost three times the predicted deposition rate for Na_2SO_4 seeded experiments.

As a first attempt to analyze the experimental system more carefully and systematically, droplet sizes were determined from the salt solution probe using a Malvern particle/droplet size analyzer as a function of atomizing air pressure and solution composition for different probes. Based on the droplet sizes obtained, vaporization time calculations of the droplets during their residence times inside the combustor showed that droplets survived and were, in fact, large enough to impact inertially on the collector. Deposition rate predictions for Na_2SO_4 seeded experiments based on the particle inertial impaction theory agreed well with the experimental observations. A particle capture test was designed to verify experimentally the theoretical prediction of the presence of particles in the previous experiments. Indeed, SEM

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photographs of the deposits collected on targets in a few seconds at the original collector location show the particles very clearly even for NaCl seeded flames (ref. 10). Therefore, the agreement between the CFBL vapor deposition theory and the previous NaCl seeded experiments was coincidental, the arrival rate by particle inertial impaction mechanism giving the same rate as one would expect from vapor convective-diffusion mechanism. Moreover, the chemical analysis of the deposit collected in about 5 sec in particle capture tests for a NaCl seeded flame showed about 80 percent NaCl and 20 percent Na_2SO_4 by weight. This indicates that NaCl particles of 1 to 5 μm size range are able to react chemically and convert to Na_2SO_4 on the collector in such short durations. The fact that only Na_2SO_4 was observed in X-ray analysis of the deposits for all sodium salts seeded is explained by the fast reaction times of small (1 to 5 μm) sodium salt particles to convert to Na_2SO_4 as compared with the deposition run times of 30 min. Only those particles that deposited during the last few seconds of the experiment had no time to react and, therefore, were able to preserve their identity. However, their concentration was too low to be detected by X-ray analysis.

When predicting vapor deposition rates the CFBL theory makes use of the "cylinder-in-crossflow" assumption in estimating the average mass transfer coefficient (Nusselt number). This assumption needed to be checked, because our cylindrical collector diameter (3/4 in) is not small compared with the jet stream diameter from the burner rig nozzle exit (1 in). Indeed, under typical experimental conditions there is about 250° to 300° C difference in temperature between the forward and the backward stagnation point of the stationary collector (ref. 10), which invalidates the "cylinder-in-crossflow" assumption. In order to regain a correct predictive capability of vapor deposition rates, even if there were no particles present, an experimentally determined mass transfer Nusselt number has to be supplied to the theory.

Having determined the problematic features of the previous experiments and having been able to interpret the previous results to our sufficient satisfaction, new experiments and procedures have been designed as remedies. In order to eliminate the presence of particles two possible routes are being taken: (1) Na dispersions in light oil or mineral spirits which are both soluble in Jet A-1 fuel will be used, or (2) alcohol will be used as fuel, and Na acetate (Na source) and thiourea (S source) will be dissolved in it to desired concentrations. The predictions based on (1) the experimentally determined droplet size distributions of the fuel nozzles used in our experiments, (2) Na particle size in the dispersions, and (3) the longer residence times of the droplets in the combustor show that both methods are feasible and complete vaporization (burning) should be attained.

The naphthalene sublimation technique (ref. 11) will be used at room temperature for the cylindrical collectors to determine the average mass transfer coefficient as a function of the Reynolds number in our experimental configuration. This technique is superior to the previously tried calorimetry technique in eliminating the temperature gradients that inevitably exist in our experiments. Another approach that will provide a predictive capability is to use a simpler collector geometry. For that purpose only a segment which is 20° on both sides of the forward stagnation point of our previous cylindrical targets will be used as the collection (deposition) surface. In this way, the stagnation region mass transfer will be studied simulating the nose region of blades.

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BURNER RIG

COLLECTOR ASSEMBLY

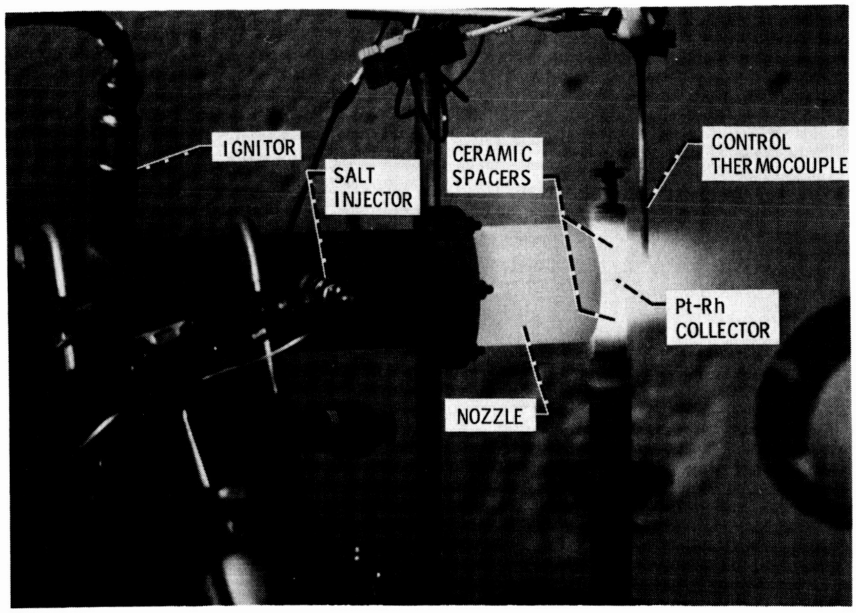

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Figure 1

BURNER RIG

SHORT EXIT NOZZLE

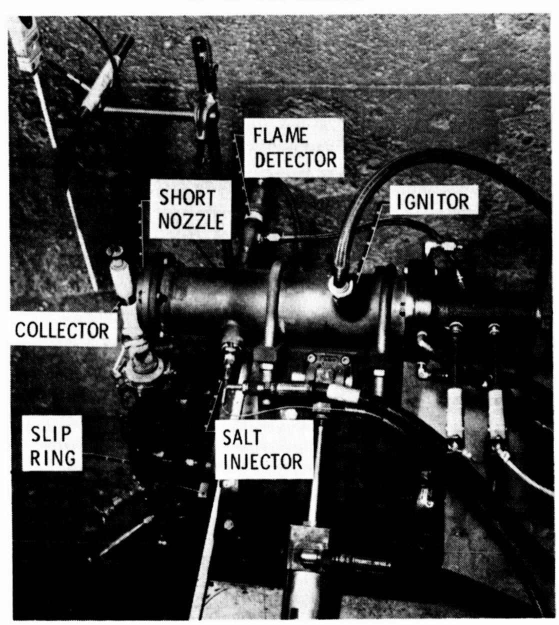

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Figure 2

BURNER RIG AND COLLECTOR CONFIGURATION

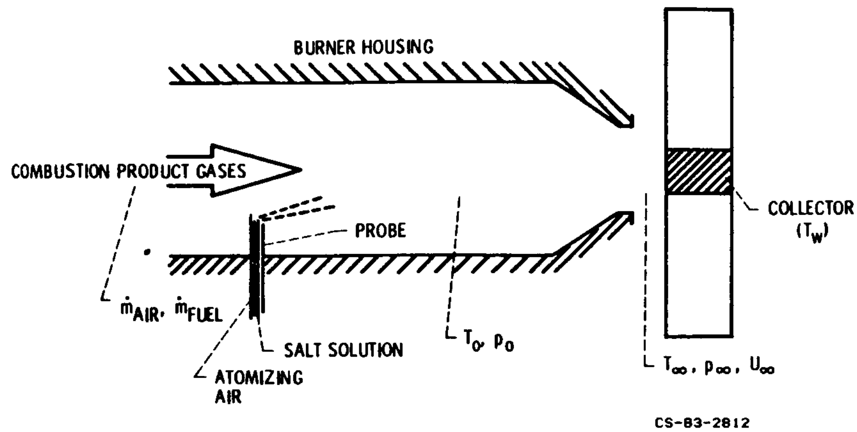

Figure 3

NaCl SEEDED

T_{mp}: MELTING POINT OF Na_2SO_4 (884 °C)

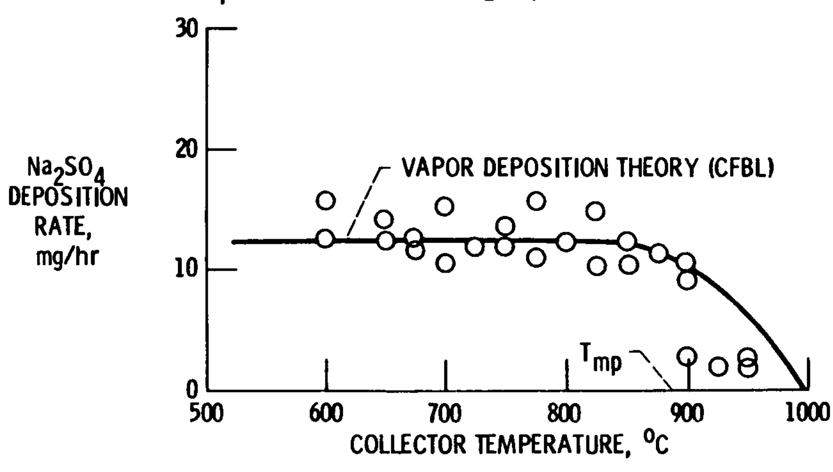

Figure 4

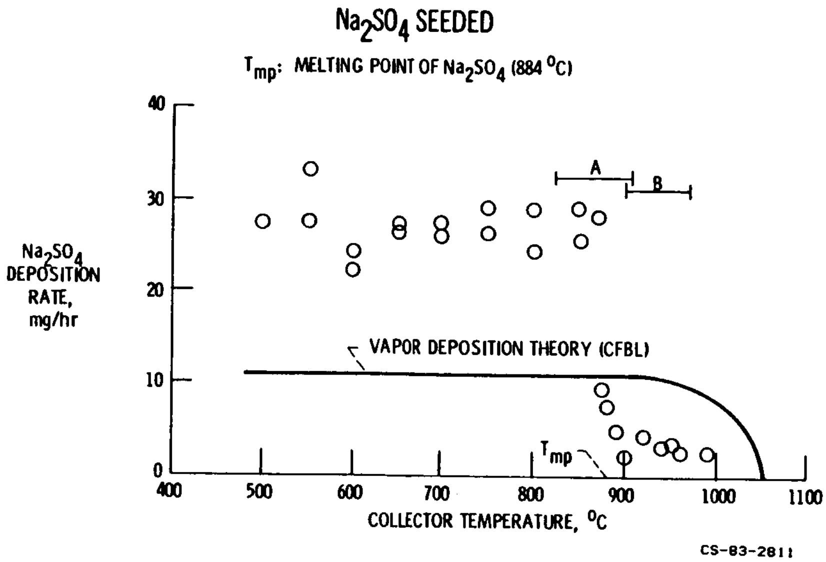

Figure 5

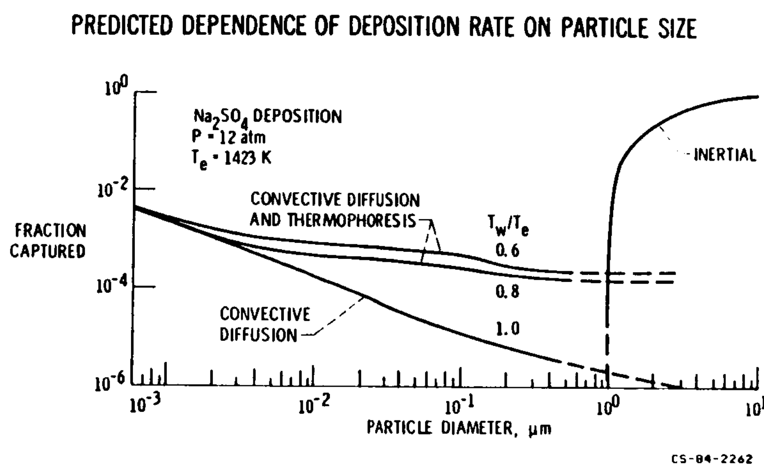

Figure 6

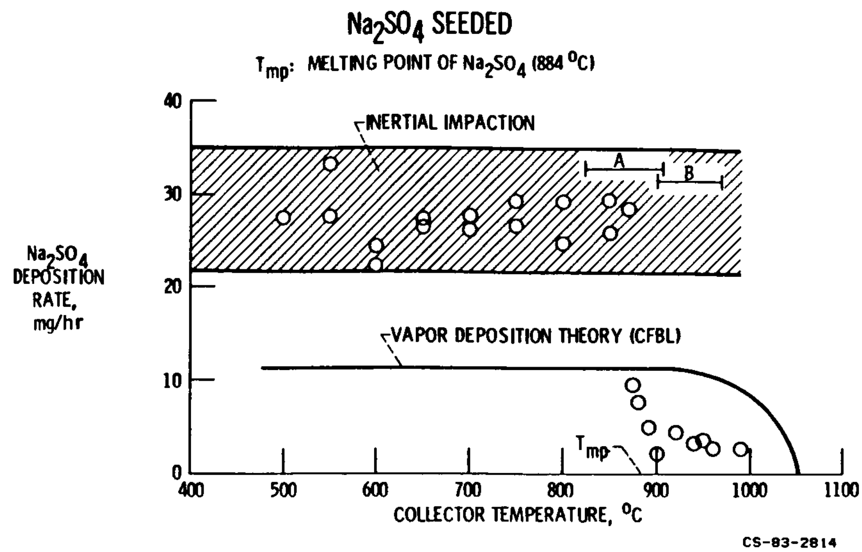

Figure 7

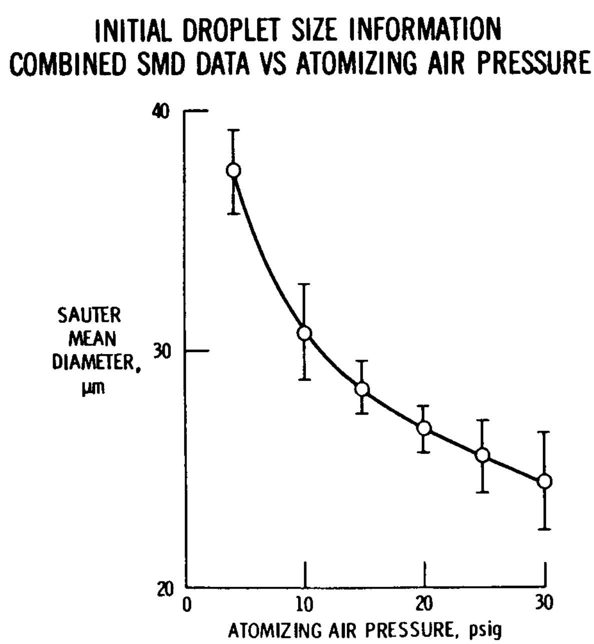

Figure 8

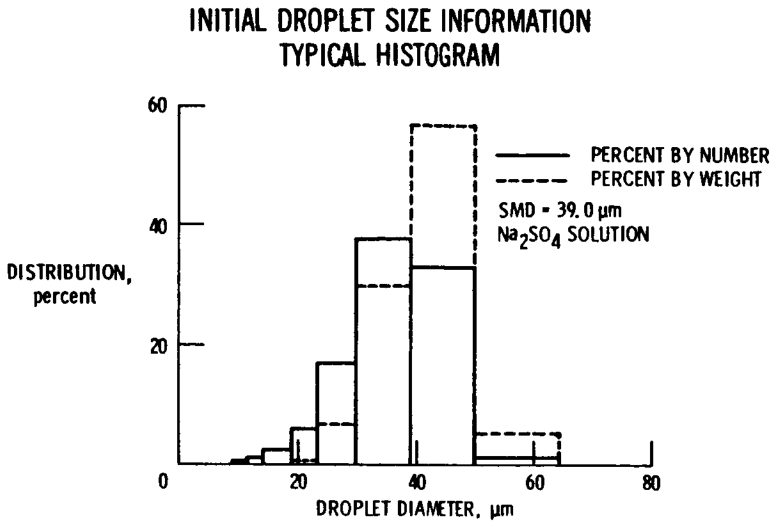

Figure 9

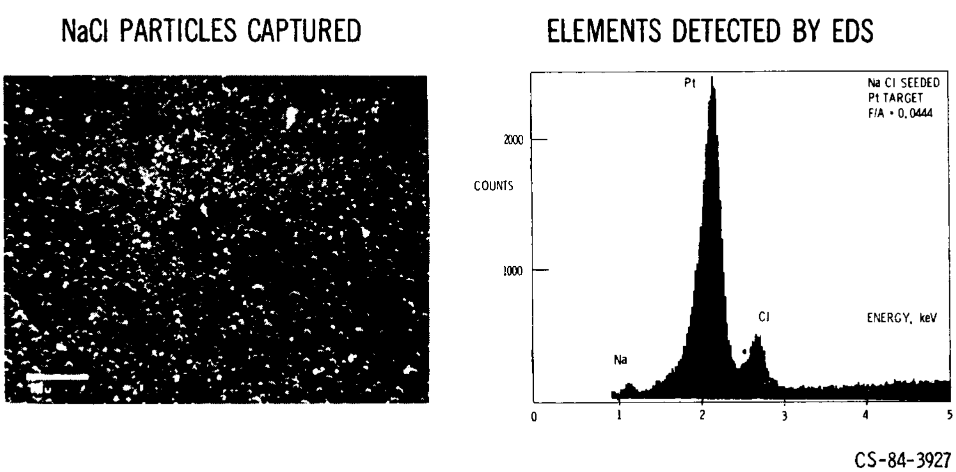

Figure 10

Na_2SO_4 PARTICLES CAPTURED

ELEMENTS DETECTED BY EDS

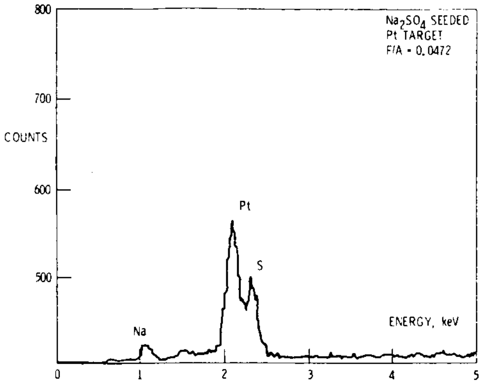

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Figure 11

PARTICLE CAPTURE EXPERIMENTS
CHEMICAL ANALYSIS OF DEPOSIT

FLAME SEEDED WITH NaCl SOLUTION
PARTICLE CAPTURE DURATION, ~5 sec

83% NaCl 17% Na_2SO_4	(BY WEIGHT)
OR	
93% NaCl 7% Na_2SO_4	(BY MOLE)

Figure 12

APPROACHES TO ELIMINATE PARTICLES

(A) USE Na DISPERSIONS IN LIGHT OIL (OR MINERAL SPIRIT) WHICH IS SOLUBLE IN JET A-1 FUEL. Na PARTICLES ARE IN 1 TO 10 μm SIZE RANGE

(B) USE ALCOHOL AS FUEL. DISSOLVE Na-ACETATE (Na-SOURCE) AND THIOUREA (S-SOURCE) IN ALCOHOL

(C) FUEL NOZZLE DROPLET SIZE MEASUREMENT RESULTS ENCOURAGING

Figure 13

DETERMINATION OF AVERAGE MASS TRANSFER COEFFICIENT (⟶ Nu_m)

"CYLINDER IN CROSSFLOW" ?

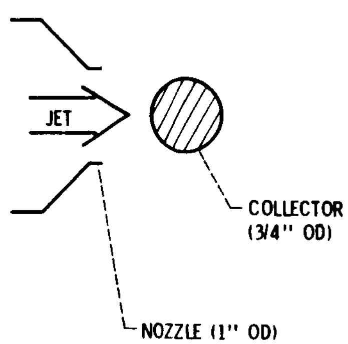

Figure 14

TEMPERATURE DISTRIBUTION ON STATIONARY Pt-Rh COLLECTOR

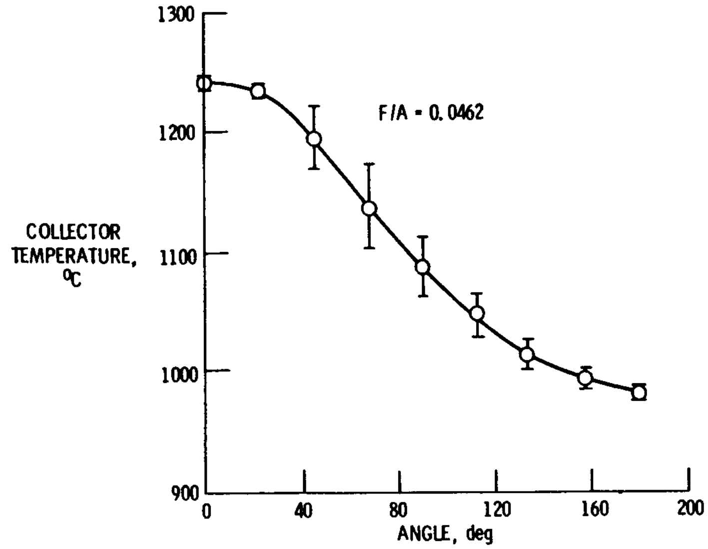

Figure 15

DETERMINATION OF AVERAGE MASS TRANSFER COEFFICIENT

($\longrightarrow Nu_m$)

(A) NAPHTHALENE SUBLIMATION EXPERIMENTS FOR PRESENT CYLINDRICAL COLLECTORS

(B) DESIGN SEGMENTED COLLECTORS TO STUDY STAGNATION POINT MASS TRANSFER, SIMULATING NOSE REGION OF BLADES

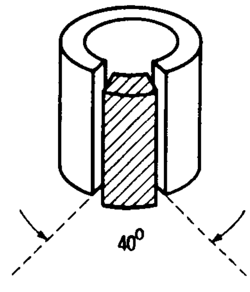

Figure 16

SUMMARY

- CAREFUL ANALYSIS AND INTERPRETATION OF PREVIOUS EXPERIMENTAL RESULTS
- DETERMINATION OF PROBLEMS
  - (A) PRESENCE OF PARTICLES
  - (B) "CYLINDER IN CROSSFLOW" ASSUMPTION NOT TRUE
- REMEDIES
  - (A) CONTAMINATE FUEL
  - (B) NAPHTHALENE SUBLIMATION EXPERIMENTS
  - (C) SEGMENTED COLLECTORS

Figure 17