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[Extended Abstract]

Experimental deposition of NaCl particles from turbulent flows at gas turbine temperatures

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Introduction

The deposition of micron-sized particulates from turbulent gas flow has been a subject of investigation for over 60 years. Interest from within the gas turbine community has become very significant over the last 15-20 years due to numerous threats to engine life. Ingested sand, dust, volcanic ash, salt, and ice crystals can drive various damage mechanisms which can substantially reduce component life [1]. Studies of deposition within secondary air systems studies have shown that significant blockage of film cooling hole can occur for high pressure turbine (HPT) blade conditions [2].

Computational studies of such geometries have tended to apply standard and widely-available numerical models for the interaction of particles with gas turbulence, including the discrete random walk. These have been shown to be inappropriate for such modelling; to address this the continuous random walk model has been applied to gas turbine flows [3]. This model requires validation at engine-representative temperatures.

This paper presents experimental data for assessment of the validity of the continuous random walk model at temperatures and Reynolds numbers representative of conditions in gas turbine secondary air systems. Horizontal pipe flow experiments are reported, using a sodium chloride (NaCl) aerosol. Tests are undertaken with both isothermal and wall-gas temperature gradient conditions in order to assess thermophoretic effects. Thermophoresis is a particle force due to temperature gradients within the gas phase, proportional to the (negative direction of) temperature gradient. When $T_{gas} > T_{metal}$ increasing deposition is seen ('positive' thermophoresis), for $T_{gas} < T_{metal}$ the reverse is observed ('negative' thermophoresis). To the authors' knowledge very few studies have addressed negative thermophoresis experimentally.

1. Methods

An experimental rig was built in a horizontal pipe flow configuration. Heating of the gas was achieved using inline pipe heaters and a section wrapped in heater tape. Heating of the test piece body was undertaken using an oven. Gas was compressed air, pre-dried and supplied by the laboratory 7barg line. Flow regulation and measurement was done using a pair of mass flow controllers and an orifice plate. Gas velocities ranging 22-33m/s and Reynolds numbers 6500-10000 were achieved, corresponding to friction velocities 1.5-2.1m/s. Temperatures representative of secondary air systems were used for both gas (390°C and 480°C) and metal (390-730°C). The test piece was machined from grade 304 stainless steel.

NaCl particles were produced from solution using a vibrating orifice aerosol generator (VOAG) at

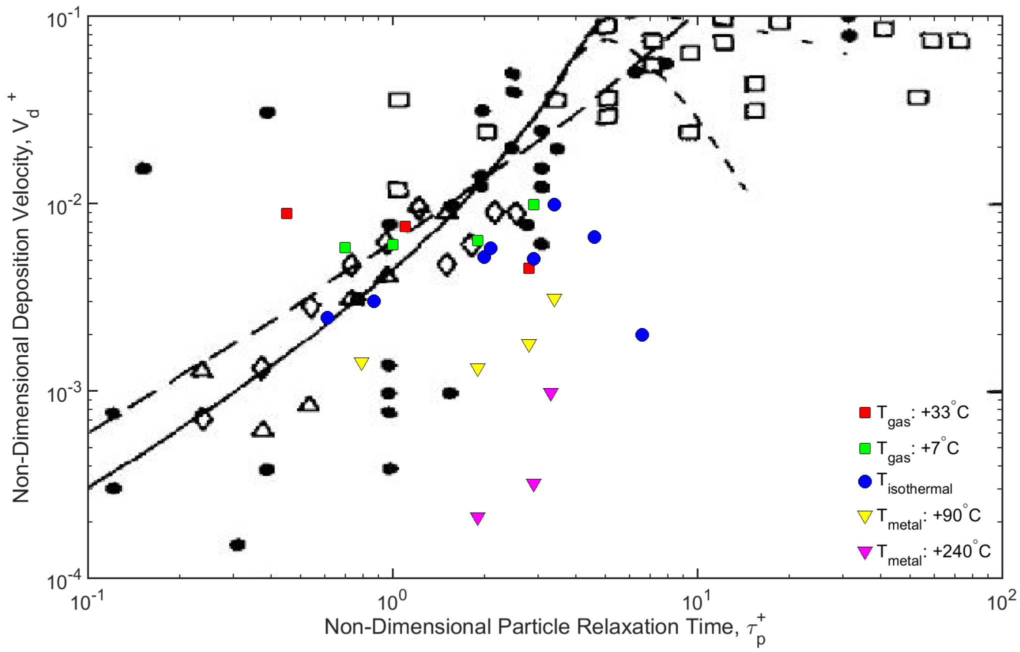

Figure 1. Experimental data for deposition of NaCl particles at engine-representative temperatures. $T_{gas} = 390°$. Black shapes indicate experimental data of Kvasnak et al. [4].

ambient temperature and mixed with the heated flow. Particle diameters 2-6.5μm were generated, giving non-dimensional particle relaxation times τ_p^+ of 0.6-7. NaCl was chosen do to its close relation to sea salt, with the advantage that its single compound nature allows simpler measurement of the deposited mass. Its high melting temperature, 801°C, made it appropriate for use in engine-like conditions.

2. Results

Deposition is presented here in terms of non-dimensional deposition velocity V_d^+, Eq. 1 and non-dimensional particle relaxation time τ_p^+, Eq. 2.

$$V_d^+ = \frac{J}{C_0 u^*} \tag{1}$$

$$\tau_p^+ = \frac{C_c \rho_p \rho_f d_p^2 u^{*2}}{18\mu^2} \tag{2}$$

The experimental data, Fig. 1 is plotted against that of Kvasnak et al. [4], who carried out deposition experiments in a horizontal configuration at ambient conditions with a 'sticky' measurement surface to reduce particle bounce. Considering the isothermal case, it can be seen that for $\tau_p^+ < 4$, V_d^+ behaves as would be expected in comparison to the ambient measurements. For $\tau_p^+ > 4$ a reduction in V_d^+ is seen. This is thought to be related to some NaCl particles rebounding upon impact, and is noted for higher Reynolds number cases.

Both thermophoretic directions (increasing and decreasing deposition) are observed; for $T_{gas} < T_{metal}$ very substantial reductions are seen in deposition velocity. Positive thermophoresis is shown to give large increases in deposition velocity for small temperature differences. For $\tau_p^+ = 0.75$ particles ($d_p = 2.5\mu$m) T_{gas} : +7°C increases deposition by 2.1x; for T_{gas} : +33°C the increase is 3.1x.

Further thermophoretic comparisons are made. Assessment is also made of surface roughness effects at two engine-representative surface finishes ($R_a = 0.4, 1.8\mu$m), of gravitational effects, of Reynolds number effects, and with experiments carried out using the same rig at ambient conditions. Experimental uncertainty is addressed. These provide a large data set for assessment of models for particle - turbulence interaction in numerical simulations.

References

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