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Particle deposition model for particulate flows at high temperatures in gas turbine components

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ABSTRACT

This study proposes an improved physical model to predict sand deposition at high temperature in gas turbine components. This model differs from its predecessor (Sreedharan and Tafti, 2011) by improving the sticking probability by accounting for the energy losses during particle-wall collision based on our previous work (Singh and Tafti, 2013). This model predicts the probability of sticking based on the critical viscosity approach and collision losses during a particle–wall collision. The current model is novel in the sense that it predicts the sticking probability based on the impact velocity along with the particle temperature. To test the model, deposition from a sand particle laden jet impacting on a flat coupon geometry is computed and the results obtained from the numerical model are compared with experiments (Delimont et al., 2014) conducted at Virginia Tech, on a similar geometry and flow conditions, for jet temperatures of 950 °C, 1000 °C and 1050 °C. Large Eddy Simulations (LES) are used to model the flow field and heat transfer, and sand particles are modeled using a discrete Lagrangian framework. Results quantify the impingement and deposition for 20–40 μm sand particles. The stagnation region of the target coupon is found to experience most of the impingement and deposition. For 950 °C jet temperature, around 5% of the particle impacting the coupon deposit while the deposition for 1000 °C and 1050 °C is 17% and 28%, respectively. In general, the sticking efficiencies calculated from the model show good agreement with the experiments for the temperature range considered.

1. Introduction

Jet engines are increasingly required to operate in hostile environments and thus exposed to fine particulate matter such as sand, ash and dirt. Particle ingestion can cause severe erosion of compressor blades and due to extremely high temperatures can soften and stick to turbine components in the hot gas path. Large amounts of particles can be ingested at takeoff and landing when engines are running at full power and are in ground proximity (Hamed et al., 2006). For an aircraft flying through volcanic dust clouds, particles can also be ingested at cruising altitudes (Kim et al., 1993). Operation in these environments has led to serious aircraft accidents due to jet engine failures (Tabakoff, 1987). The problem of particulate ingestion in the engine has worsened with the use of high bypass ratio turbofan engines (Alge and Moehring, 1994). According to studies by Edwards and Rouse (1994), high sand ingestion can reduce engine stability by eroding blade profiles and lowering the compressor efficiency, as a result of which the line of operation is closer to the surge line. The operating line also rises as a result of decrease in turbine efficiency or a reduction in nozzle throat due to glazing. The gas path immediately downstream of the combustor is a very critical region in this context where the particle deposition can lead to degradation of heat transfer, reduction in engine life and even midair engine failure. The components most likely to experience deposition are first stage nozzle guide vane, the hub, tip regions along with internal cooling circuits of these components where the coolant, the bleed air from the compressor, can carry along with it significant amount of particulate matter. To accurately predict the extent of damage to these turbine components, it is important to identify and understand the underlying physical processes that lead to deposition.

Different aspects of the problem of sand and volcanic ash ingestion have been studied in the past, with the majority of the work focused on erosion and deposition of particles on a wide range of materials and under different operating conditions. It is very likely that a critical threshold temperature exists between erosion dominated and deposition dominated regimes. As the temperature increases the particles soften or become molten leading to increase in agglomeration rates with associated decrease in blade erosion rates and increase in deposition (Wenglarz and Wright, 2002). For aircraft engines this observed critical temperature for deposi-

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Nomenclature

$\vec{a}^i$	contravariant basis vector
C_d	drag coefficient
C_p	specific heat
d_p	particle diameter
D_h	hydraulic diameter
e	coefficient of restitution
g^{ij}	contravariant metric tensor
$\sqrt{g}$	Jacobian of transformation
$\sqrt{g}U^j$	contravariant flux vector
h	heat transfer coefficient
k	thermal conductivity
L_c^*	characteristic length
m	mass of the particle
n	number of particles
Nu	Nusselt number
P	probability of sticking
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Re	Reynolds number
Re_p	particle Reynolds number
St	momentum Stokes number
St_{conv}	convective Stokes number
St_{rad}	radiative Stokes number
t	time
T	temperature
U	velocity
W_A	work of adhesion
ρ	density
μ	dynamic viscosity
ν	kinematic viscosity
$\vec{\xi}$	computational space coordinate
α	angle of impact

Subscripts/superscripts

a	ambient
ep	based on elastic plastic losses
e	based on coefficient of restitution
f	fluid
jet	inlet jet
p	particle
$soft$	softening temperature
t	tangential to the surface
n	normal to the surface
$*$	dimensional quantity

tion is between 980 °C and 1150 °C (Wenglarz and Wright, 2002; Toriz and Thakker, 1988; Smialek, 1992). This temperature threshold for deposition is still well below the turbine inlet temperature (TIT) of gas turbine engines.

Experiments have shown that ash deposition is sensitive to turbine inlet gas temperatures (Hamed et al., 2006; Wenglarz and Fox, 1990a,b; Bons et al., 2005) which can be in the range of 1600–1900 K. Bons and co-workers have conducted an extensive amount of research to investigate factors influencing flyash particle deposition in gas turbine components. Jensen et al. (2005) described the Turbine Accelerated Deposition Facility (TADF) used to study the deposition of ash particles on the first stage turbine blades in land based turbines. The surface topography of the accelerated deposits closely resembled that of actual turbine blades under up to 25,000 h of service. For test conditions, the observed temperature threshold for accelerated deposition was between 900 °C and 1100 °C. Bons et al. (2005) presented a comparative analysis of various alternative fuels like sawdust ash, coal, straw ash and petcoke at actual engine conditions. The particles injected had a mass mean diameter of 10–20 μm. For the same particle loading, coal and petcoke showed orders of magnitude higher deposition compared to biomass fuels. They observed penetration of particles into the cracks of the thermal barrier coating (TBC), consequently hampering the performance of the blade material. Wammack et al. (2006) investigated the physical characteristics of the evolution of surface deposition on a turbine blade at a gas temperature and velocity representative of first stage high pressure turbine. Their experiments concluded the following: first, the deposit roughness height and shape experience a temporary lull in growth during the deposit evolution. Second, the initial surface roughness has a significant effect on deposit growth. Third, thermal cycling combined with particle deposition caused extensive TBC spallation while thermal cycling alone caused none. Hence the deposit penetration into the TBC was a significant contributor to spallation. Crosby, 2007studied the effect of particle size, gas temperature and metal temperature on the deposition from coal derived fuels. The main conclusions from their study are as follows. First, deposition rates were more than doubled as the mass mean diameter of the particle was increased from 3 μm to 16 μm. Second, particle deposition decreased with decreasing gas temperature and increased coolant flow. The threshold gas temperature at which ash particle deposition initiates was found to be approximately 960 °C. Furthermore, they showed decrease in TBC damage as the cooling levels were increased.

Anderson et al. (1984) studied adhesion characteristics of flyash on a heated target with normal impingement. They observed sticking coefficients between 0.04 and 0.10 for bituminous coal ash. Ahluwalia et al. (1989) investigated the adherence of flyash particles (15 and 40 μm) on a wedge shaped target (10°, 30° and 45°). The inferred sticking coefficients ranged from 0.04 to 0.11 at 1325 K gas temperature and from 0.0003 to 0.01 at 1256 K gas temperature. The sticking coefficient also increases with surface temperature but was found insensitive to the impact angle. These observations were further confirmed by studies from Wenglarz and Fox (1990a,b). Kim et al. (1993) conducted experiments investigating the effects of volcanic ash on turbine components and found that film cooling holes are susceptible to deposition and clogging. Dunn et al. (1996) also reported that particulate deposition can clog film cooling holes and hence deposition is a major issue for modern aircraft engines. Walsh and Thole (2006) studied the effect of sand ingestion on film cooling hole blockage, using a leading edge coupon over a range of sand particle size, particle loading and metal temperatures. Metal temperatures were shown to be the most important parameter for particle deposition. At temperatures above 1000 °C, sand particles started melting and promoted blocking of cooling holes. Land et al. (2010) investigated a double walled cooling design to reduce sand blockage. It was found that impingement air-flow holes and staggered arrangement of cooling holes could aid in breaking up of larger particles to pass through cooling holes. All these studies imply that the physical state of particles plays a decisive role in the particle deposition.

To account for observed influences of various ash composition and temperature on deposition, Walsh et al. (1990) used particle viscosity as a means to measure the physical state of the particle. They assumed that the sticking probability of the particle is inversely proportional to the viscosity of the particle and below a threshold viscosity the particle will stick with certainty. Huang et al. (1996) also used a similar viscosity approach to predict the