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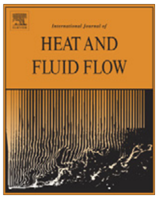

Composition dependent model for the prediction of syngas ash deposition in turbine gas hotpath

Sai Shrinivas Sreedharan, Danesh K. Tafti *

High Performance Computational Fluid-Thermal Sciences and Engineering Lab, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, United States

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ABSTRACT

An improved physical model to predict flyash deposition is developed and discussed in this paper. This model differs from its predecessor (Rozati et al., in press; Sreedharan and Tafti, 2009) by accounting for deposition of syngas ash particles below the ash softening temperature. The modified deposition model is based on the critical viscosity approach. To test this model, deposition of ash particles impacted on a flat, 45° wedge shape geometry is computed and the results obtained from the numerical model are compared to Crosby et al. (2007). Large Eddy Simulation (LES) is used to model the flow field and flyash particles are modeled using a discrete Lagrangian framework. Results quantify deposition for 4 μm particles of various ash composition samples. Most of the deposition occurs at the stagnation region of the target plate. At 1456 K, out of all the ash samples considered in this study, WY and ND ash sample show the highest capture efficiency (15%) and KL1 ash sample exhibits the lowest capture efficiency (0.02%). In general, capture efficiencies for all ash samples followed an exponential trend with temperature. Additionally, this model is also compared to results obtained from the flat plate deposition experiments conducted here at Virginia Tech using PVC particles (Wood et al., 2010). In the case of PVC particles, the sticking probability in the deposition model assumed an exponential increase in deposition rate with temperature and was calibrated with one experimental data point. The results obtained from this model for PVC particles showed excellent agreement with the experimental measurements over a range of temperatures.

1. Introduction

The vision of DOE's fossil energy turbine program is to provide power generation technology essential to the success of advanced fossil energy power systems based on Integrated Gasification Combine Cycle (IGCC) before 2015 time frame (Dennis, 2003). One of the key capabilities needed to achieve this goal is the use of Syngas from coal gasification. One of the issues in achieving this goal relates to the durability of turbine components subjected to a harsh high temperature, high pressure, and high velocity environment in the gas path immediately downstream of the combustor. Despite advances in gas cleanup procedures, Syngas produced from coal gasification contains traces of flyash particles whose diameters range from 1 μm to 10 μm (Wenglarz, 1985; Tabakoff, 1991; Bons et al., 2005). The components most likely to experience deposition and erosion and corrosion (DEC) are the first stage nozzle guide vane, the hub and tip regions. One of the region's most susceptible to DEC is the leading edge region of the vane. Deposition and erosion increases the surface roughness of the vane, causing the heat transfer coefficient to increase (Bons, 2002). In extreme cases, deposition can also lead to blockage of the coolant flow. Kawagishi et al. (1992) reported a decrease in stage efficiency by 20% due to deposition. To accurately predict the extent of damage to the turbine vane, it is important to identify and understand the underlying physical processes that lead to deposition.

Experiments have shown that ash deposition is sensitive to turbine inlet gas temperatures (Wenglarz and Fox, 1990a; Hamed et al., 2006; Bons et al., 2005) which can be in the range of 1600–1900 K. The softening temperature (ST) for most of the coal flyash composition is found to be in a range of 1450K–1500 K (Crosby, 2007; Wenglarz and Fox, 1990a). This implies that the flyash particles exiting the combustor are molten and sticky. These hot molten particles are transported to the vane surface and interact with the cooling jets. The particle's residence time together with its thermal inertia decides the physical state of the particle when it comes into contact with the vane surface. Our previous studies (Rozati et al., in press; Sreedharan and Tafti, 2009) modeled the physical state of the particle by defining a particle softening temperature, which acts as an on–off switch for particle deposition. If the particle temperature is above the softening temperature, it is assumed to stick to the surface or otherwise rebound

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* Corresponding author.
E-mail addresses: shrini@vt.edu (S.S. Sreedharan), dtafti@vt.edu (D.K. Tafti).

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Nomenclature

η	adiabatic effectiveness
C_s	Smagorinsky constant
C_d	drag coefficient
d_p	particle diameter
D	coupon diameter
L_c	characteristic length
m	mass of the particle
n	normal distance from vane surface
Nu	Nusselt number
Pr	Prandtl number
Re_L	Reynolds number, $Re_L = \frac{(U_{jet})L}{\nu}$
Re_p	particle Reynolds number, $Re_p = \frac{(U_{jet}-U_p)L}{\nu}$
s	streamwise direction along the vane surface
S	strain rate tensor
St_p	momentum Stokes number
St_{conv}	convective Stokes number
St_{rad}	radiative Stokes number
t	time
y^+	non-dimensional wall distance
θ	non-dimensional temperature $(T - T_a)/(T_{jet} - T_a)$
U	velocity
V_{normal}	particle velocity normal component
x^p	particle location
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ζ	normally distributed random number

Subscripts/superscripts

a	ambient air
f	fluid
jet	inlet jet temperature
$melt$	PVC melting temperature
p	particle
s	softening temperature
t	turbulent
$*$	dimensional quantity
$'$	fluctuating quantity

Abbreviations

DE	deposition and erosion
DEC	deposition, erosion and corrosion
DPM	Discrete Phase Model
DRW	Discrete Random Walk
GT	gas turbine
IGCC	Integrated Gasification Combined Cycle
LES	Large Eddy Simulations
NBO/T	non-bridging oxygens to tetrahedral oxygens
PVC	Polyvinyl Chloride
RANS	Reynolds averaged Navier–Stokes
rms	Root Mean Square
ST	softening temperature
TBC	thermal barrier coating
TKE	turbulent kinetic energy

back into the flow. However in reality, the ash particle deposition is not a discontinuous function of a single softening temperature. At ST, ash is making a transition from an initial deformation temperature to fluidity. At this temperature the ash particles are said to be in plastic state and show a tendency to stick to the vane surface. To predict the amount of deposition better, this paper discusses an improved model to its predecessor by accounting for ash composition and estimating deposition at temperatures below the ash softening temperature.

Bons and co-workers have conducted considerable amount of research to identify factors influencing flyash particle deposition in gas turbine (GT) applications. Jensen et al. (2005) describe the Turbine Acceleration Deposition Facility (TADF) used to study the deposition of ash particles on the first stage turbine blades in land based turbines. Following the validation of TADF, Bons et al. (2005) presented a comparative analysis of various alternative fuels like straw ash, sawdust ash, coal and petcoke at actual engine conditions. The particles injected had a mass mean diameter of 10 μm. They observed penetration of particles into the cracks of the thermal barrier coating (TBC), consequently hampering the performance of the blade material system. Wammack et al. (2006) investigated the physical characteristics of the evolution of surface deposition on a turbine blade. 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 et al. (2007) then characterized the effect of particle size, gas temperature and cooling of the blade sample from the backside on deposition from coal derived fuels. All the effects were studied independently. The conclusions from their study are as follows. First, deposition increased by a factor of 2 as the mass mean diameter of the particle was increased from 3 μm to 16 μm. Second, particle deposition decreased with decreasing gas temperature. The threshold gas temperature at which ash particle deposition initiates was found to be 960 °C. Furthermore, they concluded that the TBC damage was reduced as the cooling levels were increased.

Among all the studies carried out on ash DE, it was found that ash particle size distribution and their physical properties were among the factors that influenced DE (Wenglarz, 1985). The level of molten species contained in flyash particles is a function of its chemical composition. Wenglarz (1985) observed the sticking fraction of ash particles to be primarily dependent on the surface temperatures. They define the sticking fraction as the mass fraction of particles deposited to the mass of particles injected. In order to reduce molten deposits, he recommends high rates of wall surface cooling. Ahluwalia et al. (1989) investigated flyash particle (15 μm and 40 μm) deposition on a wedge shaped (10°, 30° and 45°) target model, representative of a real gas turbine engine condition. They found the sticking coefficient to be 0.04–0.11 at gas temperatures of 1325 K. Deposition rates were found to increase in a non-linear manner with an increase in wall surface temperature. They also reported that the deposition of the flyash particles was significantly more sensitive to the surface temperature than to other factors such as the impact angle. Another study by Wenglarz and Fox (1990a,b) also confirmed the above observation. The above studies show that the physical state of ash particles is a decisive factor in the accurate prediction of deposition.

Walsh et al. (1990) used particle viscosity as a means to measure the physical state of the particle to account for observed influences of various ash composition and temperature on deposition. They assumed that the sticking probability is inversely proportional to the viscosity of ash. Along similar lines, Huang et al. (1996) also used the viscosity approach to predict the deposition of flyash particles. The model calculates the particle viscosity based