

COMPONENT LEVEL HOT CORROSION AND DEPOSIT MODELING FOR LARGE GAS TURBINES

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ABSTRACT

Modern gas turbines are operated with fuels that are very clean and within the allowances permitted by fuel specifications. However, the fuels that are being considered contain vanadium, sulfur, sodium and calcium species that could significantly contribute to the degradation of components in hot gas flow path. The main potential risk of material degradation from these fuels is “hot corrosion” due to the contaminants listed above combined with alkali metal salts from ambient air. Depending on the temperature regime hot corrosion can damage both TBC coatings and bond coat/substrate materials. Deposit-induced or hot corrosion has been defined as “accelerated oxidation of materials at elevated temperatures induced by a thin film of fused salt deposit”. For the initiation of hot corrosion, deposition of the corrosive species, e.g. vanadates or sulfates, is necessary. In addition to the thermodynamic stability, the condensation of the corrosive species on the blade/vane material is necessary to first initiate and then propagate hot corrosion. Operating temperatures and pressures both influence the hot corrosion damage. The temperature ranges over which the hot corrosion occurs depend strongly on following three factors: deposit chemistry, gas constituents and metal alloy (or bond coating/thermal barrier coating) composition. This paper reports the activities involved in establishing modeling and simulation followed by testing/characterization methodologies in relevant environments to understand the degradation mechanisms essential to assess the localized risk for fuel flexible operation. An assessment of component operating conditions and gas compositions throughout the hot gas paths of the gas turbines, along with statistical materials performance evaluations of metal losses for particular materials and exposure conditions, are being combined to develop and validate life prediction methods to assess component integrity and deposition/oxidation/corrosion kinetics.

KEYWORDS

Thermal barrier coatings, Hot corrosion, Gas Turbines, Computational fluid dynamics, Deposit modeling

INTRODUCTION

Electrical power generation is becoming increasingly reliant on gas turbines, with research advances focused on increased efficiency/power output, multiple fuel capability and reduced emissions. Gas turbines are utilized in highly efficient, cost

effective, and environmentally acceptable industrial and power generation plants. Most gas turbine plants have been developed to operate with natural gas and oil-derived fuels that contain extremely low levels of ash and impurities. Because of decreasing supplies and increasing costs of these conventional fuels, lower cost alternate fuels that have higher levels of impurities must be considered to maintain the low electricity and energy costs needed to sustain economic progress in the US and other countries. Gas turbines that are run on impure fuel that contain vanadium, sulfur, sodium and calcium species that are significantly contribute to parts corrosion in hot gas flow path. The main potential risk with material degradation is the "hot corrosion" due to above mentioned contaminants. Hot Corrosion depending on the temperature regime could damage both thermal barrier coating (TBC) and bond coat/substrate materials. Deposit-induced or hot corrosion has been defined as "accelerated oxidation of materials at elevated temperatures induced by a thin film of fused salt deposit" [1,2].

Both operating temperatures and pressure affect hot corrosion damage. The temperature range over which the hot corrosion occurs depends strongly on following three factors: deposit chemistry, gas constituents and metal alloy (or bond coating/TBC composition). As shown in Fig. 1 Figure, two types of hot corrosion exist: 1) fluxing processes which occurs above melting point of salt – Type I and 2) salt-component processes which occurs near or below melting point of salt –Type II [3,4].

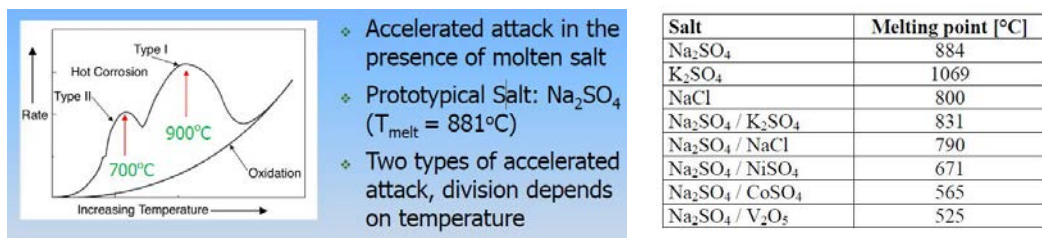


Figure 1: Temperature regions for the two types of hot corrosion.

The typical temperature range for hot corrosion in gas turbines is 600-950°C. Multiple constituents lower the dew points for the corrosion regime. The dew point rises with increasing pressure, which leads to more surface areas with the risk of hot corrosion. The dew point curve depends on the composition of the fuel (C to H ratio), the amount of excess air, injected water and the level of impurities such as S, Na, K, Cl.

Apart from fuel bound impurities, operational conditions such as surrounding environments (sand), filter clogging or just operation at hotter temperatures also cause deposition on the surface of the TBCs. Typically, TBCs have been critical to the operation of such gas turbines in aircraft and land-based applications as they provide thermal, oxidation and hot corrosion protection of high temperature components [5,6]. However, reliability concerns over thermomechanical integrity of these coatings arise due to fine particle ingestion, when operated in a variety of environments ranging from volcanic zones, to desert conditions, resulting multiple failure mechanisms shown in Fig. 2 below. This leads to spallation of the TBCs and hence detrimental to the structural integrity of the first stage stationary and rotating component resulting in loss in power or catastrophic failures [7,8]. Thus, there is a growing need to address the particulate behavior and its interaction with TBCs for increased sustainment and performance of engines under sand-ingestion conditions and operational constraints.

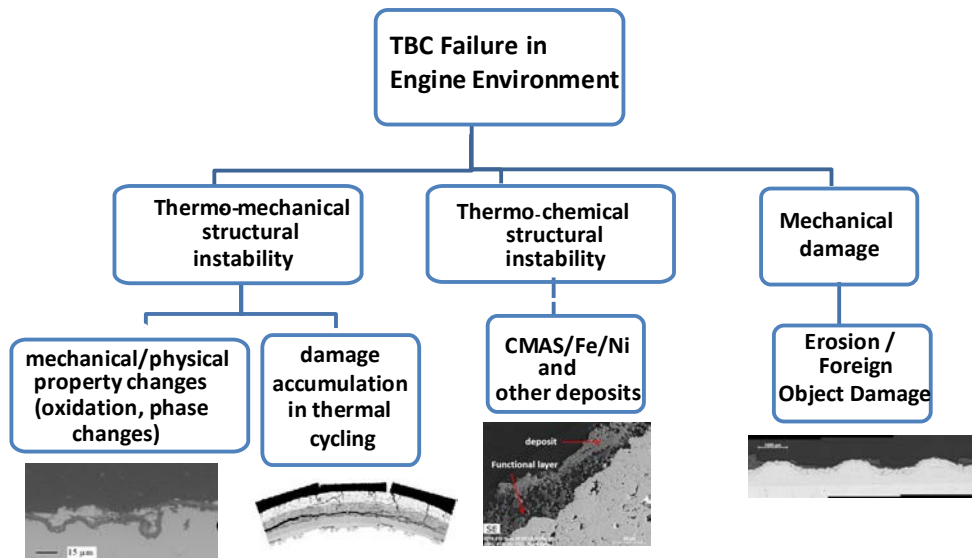


Figure 2: Observed TBC failure mechanisms in gas turbines.

MODEL INFRASTRUCTURE

Our advanced strategy to tackle a multidisciplinary problem involves a robust deposition model, shown in Fig. 3, being developed that incorporates the particulate characteristics and component design conditions to identify high risk areas for deposit buildup. The deposit modeling will involve a sticking model and detachment model of particles using deposit material properties, surface properties and local gas conditions for the part to map all surface locations to generate a deposition map.

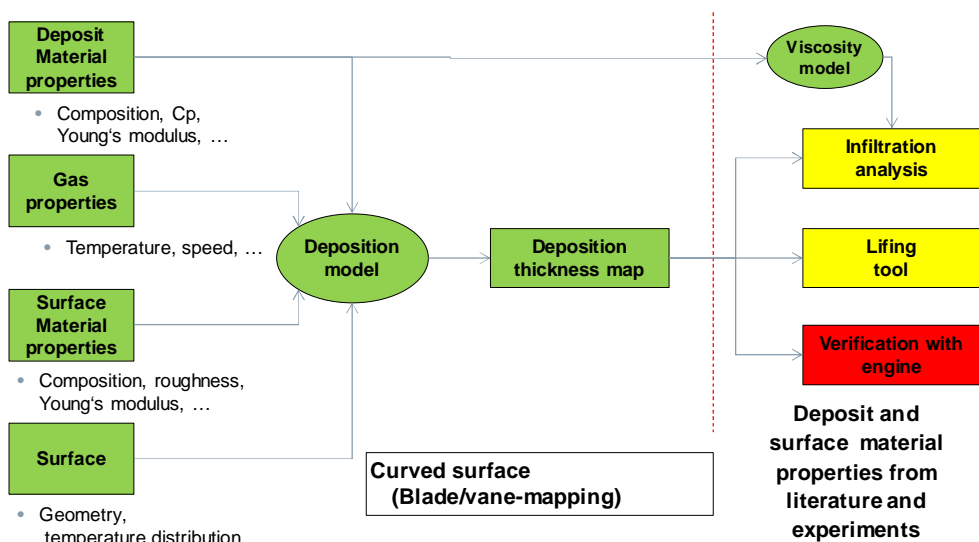


Figure 3: Deposition model tool development.

The first insight needed is the chemistry/melting characteristics of the deposits which are closely related to observed mechanisms as shown in Fig. 4. Contrary to model

Calcium Magnesium Alumino Silicate (CMAS) composition observed in literature, land-based TBC systems see more iron/nickel (up to 50%) in the deposits. The heating curve shows the melting point, which determines the particle interaction in hot gas path and the cooling curve shows the solidification characteristics on the surface. If the surface temperature is hotter than the solidification point, ash infiltration is observed in the TBC. If it is cooler than the solidification point, ash deposition is observed. Hence the component vane/blade surface conditions (temperature, flow velocity, density and surface finish) and melting characteristics of particles are the prime drivers on which to focus for improved deposit resistance.

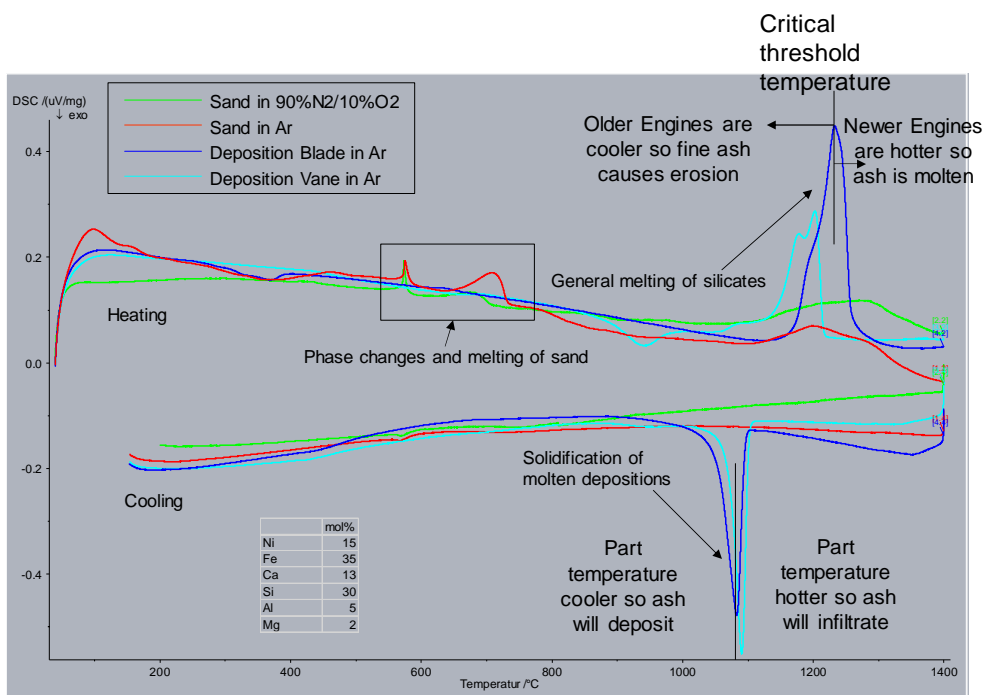


Figure 4: Correlation of deposit melting characteristics to TBC interactions.

While 3D-Computational Fluid Dynamics (CFD) analysis for sand particulate ingestion and its size distribution of fine particles on deposition zones and rates has been investigated, as a function of thermal and velocity fields of the gas phase [7], such studies only modelled Silica Dioxide (SiO₂) particles and only evaluate adherence of particle on impact. The planned efforts not only account for particle size/chemistry observed in the field, it also evaluates the interaction of these particles on component surface at all surface locations to generate a deposit thickness map, taking the component design conditions into consideration.

The modeling activities will involve two aspects, first the interaction of the particles in the hot gas path and second the interaction of the particle with the TBC surface. The first interaction needs the summary of the thermophysical and mechanical characteristics of CMAS(Fe/Ni) compositions observed in service, including particle size, melting range, viscosity and surface tension as well as chemical reactivity, will need to be compiled to establish the boundary conditions (low/high) for this modeling effort. The interaction of the particles with local gas conditions to capture particle interaction for the sticking model and detachment model is critical to establish the particle behavior on the surface of the component, shown in Fig. 5, that involves:

- 1) Calculation of particle speed and temperature based on known particle size distribution. These calculations will be based on the influences known from gas turbines.
- 2) Calculation of Young's modulus of particle, dependent upon temperature and chemical composition influencing the thermochemical and mechanical behavior.
- 3) Determine if particle sticks, dependent upon the calculated Young's modulus of the particle.
- 4) Determine if particle is removed, which is triggered by component surface, shear velocities and local temperatures.

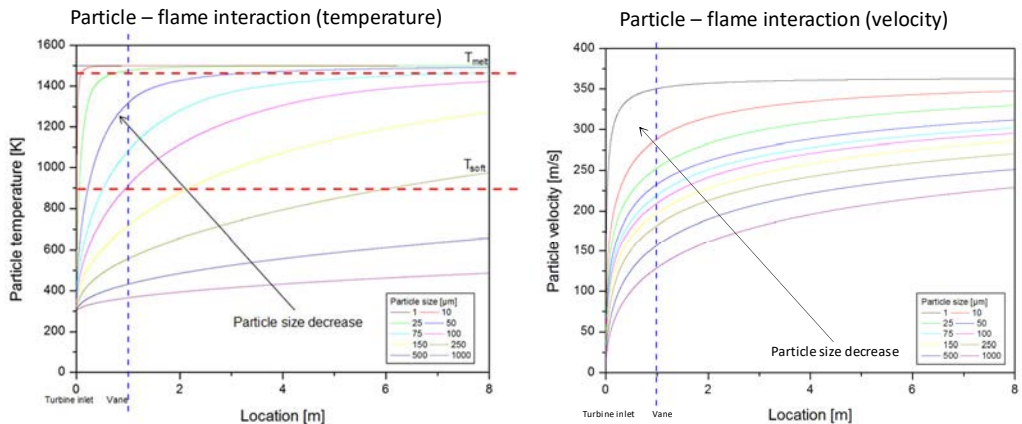


Figure 5: Particulate interactions with the hot gas path to determine surface interactions.

The results show the melting characteristics of particles in the hot gas path for different particle size before they reach the vane surface. It is seen that only particles with diameter smaller than $100\ \mu\text{m}$ will be heated high enough to (partly) melt during flight. Particles smaller than $25\ \mu\text{m}$ will be in fully molten state before they reach vane 1. Also shown is the particle velocity dependence on the particle size. The particle velocity is compared with the velocity of capture at the surface to determine if the particle will stick or rebound off the surface. Fig. 6 shows this surface interaction where the capture velocity is correlated to particle Young's modulus. The graph shows the behavior of the particles for 2 different particle sizes ($1\ \mu\text{m}$ and $10\ \mu\text{m}$) and also for two different surface elastic modulus ($14\ \text{GPa}$ for new TBC coating and $70\ \text{GPa}$ for aged TBC surface) of the surface. The rule of thumb for deposits says if the velocity of impact is less than velocity of capture then the particle sticks, otherwise it will rebound off the surface. Higher capture velocity implies more deposition. When the CMAS(Ni/Fe)-particle is molten (or its surface only), the capture velocity increases strongly as the Young's modulus decreases. Also, only a small difference is observed in capture velocity for different particle size for new TBC ($14\ \text{GPa}$) and aged TBC ($70\ \text{GPa}$), which does not lead to a significant decrease in deposition rate over time. It is seen that the melting/softening temperature of the particle influences the deposition rate more than the aging of the surface.

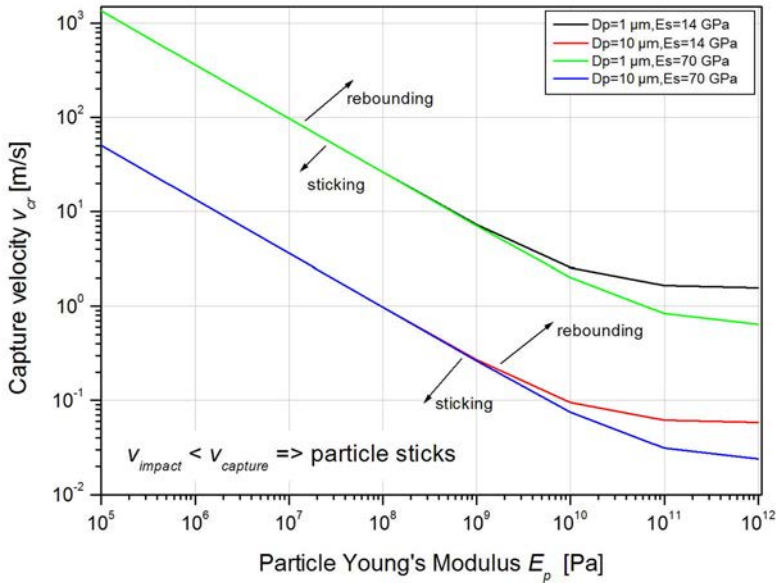


Figure 6: Particle modulus correlation to capture velocity for surface interaction.

MODEL SIMULATIONS

Following the particle interactions with the hot gas path, there is a need to evaluate its interaction with the component surface, taking the design conditions (surface temperature, wall shear velocity, etc.) into effect as shown in Fig. 7. This involves subjecting the particle characteristics to component conditions (temperature/flow characteristics) in CFD and tracking them in the flow field, followed by first interaction/deposit on the surface of the component. Subsequent loading of the particulates on the component will generate the deposition profile and this resultant deposit thickness map will be an input to define mitigation options in high-risk areas.

The particle temperature is increased during flight through the combustor. The amount of deposit increases with duration time in hot gas environment as a larger fraction of the particles is heated above the melting temperature. If the gas temperature is below the melting point, no deposition is observed. For particle interaction on the vane surface, the local wall shear velocity and local surface temperature of all positions on the vane must be known.

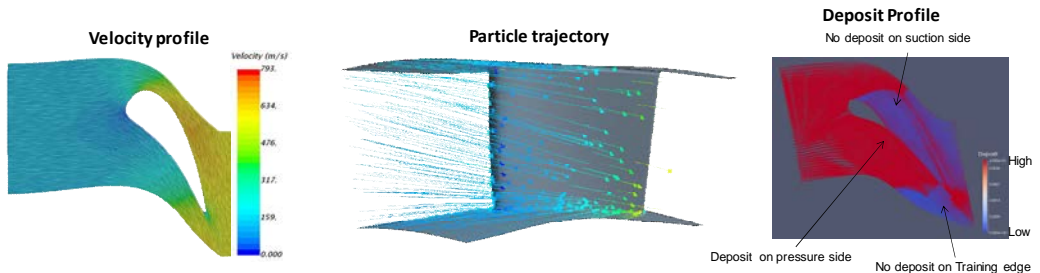


Figure 7: Deposit thickness map utilizing CMAS characteristics and components conditions.

A more detailed correlation of the wall shear velocity of the row 1 vane and the particle trajectory resulting in the deposit of the particles is shown in Fig. 8. In the current simulation, a uniform deposition on the pressure side is observed when the particle temperature exceeds its melting temperature and the local wall shear velocity is not exceeded. Hence, no deposits are observed on the suction side and the trailing edge of the vane since the local wall shear velocity is exceeded.

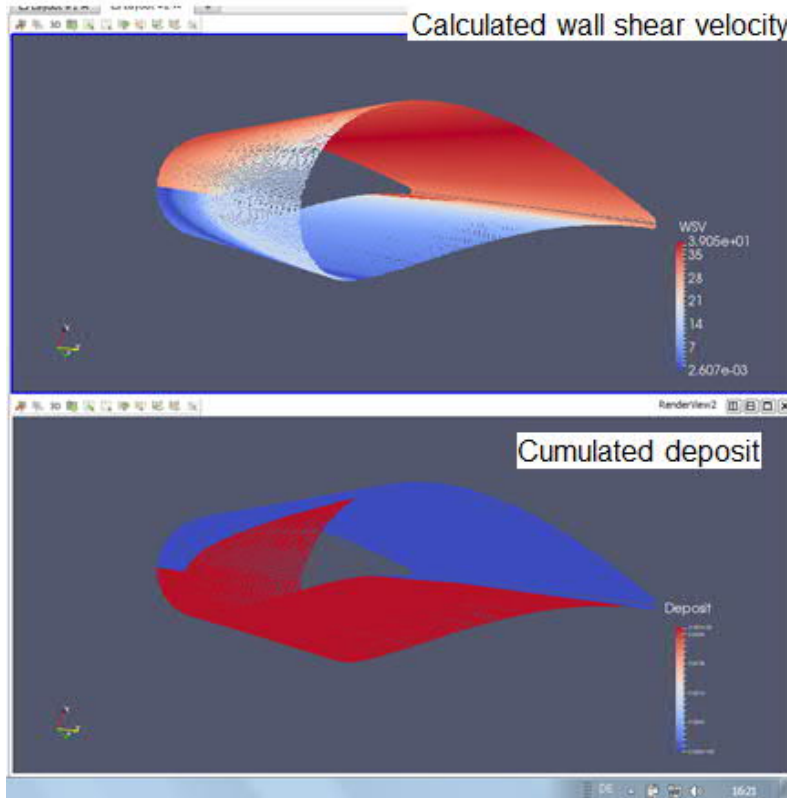


Figure 8: Direct correlation of velocity with deposition map on the component.

As hottest components in first and (depending on turbine) second row behind combustion chamber require active film cooling, it is of interest to assess and to evaluate in detail the influence of cooling holes and to evaluate the deposition mechanism and the resulting thin film cooling into account. Locally differing gas velocities due to film cooling will result in slightly changing deposition conditions and identify the risk of clogging of these holes. This will be also be evaluated as part of this ongoing effort.

Also, since the deposit interacts with the TBC leading to destabilization or spallation, there is a need to evaluate the impact on TBC properties to evaluate the strain energy. Hence, effect of deposit infiltration on coating properties such as porosity and thermal conductivity are being evaluated. Two deposit ash compositions with vastly different viscosities were selected for evaluating the impact on thermal/mechanical properties of the TBC coatings. The difference in the viscosity is mainly due to presence of silica. The first CMAF (Calcium Magnesium Aluminum Iron) ash had a very low viscosity due to the absence of silica compared to the CMAFS ash. The viscosity influences the infiltration of the ash into the TBC and impacts the TBC porosity, its thermal and mechanical properties. The infiltration was predicted to result in an increase in both

thermal conductivity and elastic modulus. As seen in Fig. 9, repeated measurements performed show a small decrease in porosity of YSZ and Low-K TBC resulted in only the top layer of the coatings being infiltrated by CMAFS. For the CMAF ash, the infiltration in Low K TBC is much lower than in standard 8YSZ. The large decrease in porosity (74%) in 8YSZ indicates a much deeper infiltration by CMAF. The higher infiltration is attributed to the lower viscosity.

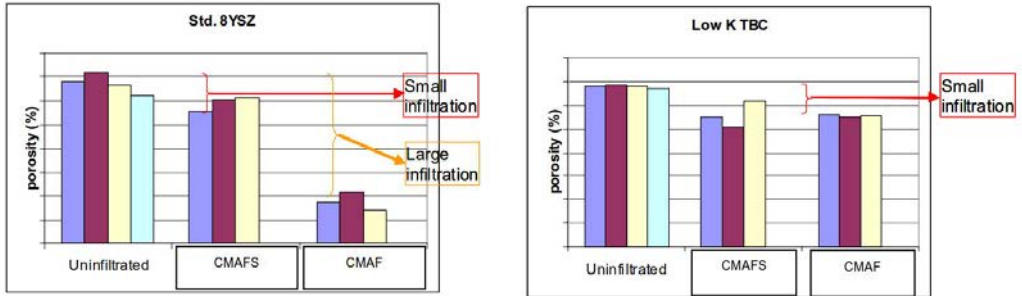


Figure 9: Density change with ash infiltration in 8YSZ and Low K TBCs.

The change in porosity also translated into a change in thermal conductivity. Fig. 10 shows that the TBC coatings with the deepest level of infiltration and greatest reduction in porosity also had the highest increase in thermal conductivity. There was 10-15% increase in conductivity with the CMAFS deposit compared to 25-40% increase in conductivity with CMAF.

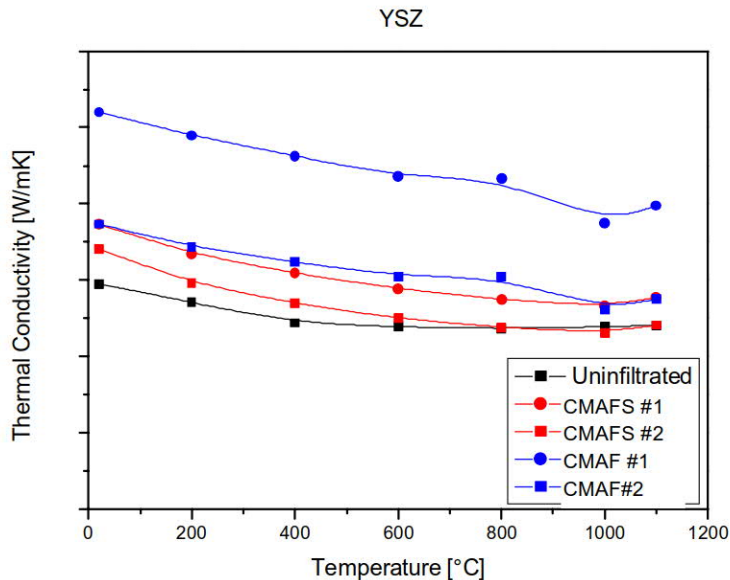


Figure 10: Impact of infiltration on thermal conductivity.

MODEL TRANSITION TO CORROSION

Advanced modeling has been demonstrated with Siemens STAR-CCM+ CFD package, wherein a case study for biomass fired incinerator power plants was used to demonstrate the effect of high levels of corrosives species such as alkali salts in the hot gas path and also the huge build ups of ash deposits (fouling) in the boilers on the super heaters as shown in Fig. 11[9]. The trajectory of the corrosion species (KCl in this case) is shown based on design/operating conditions. The fireside corrosion risk regime along

with location of deposit buildup was successfully predicted and validated with plant data. Predicting and proactively minimizing the boiler corrosion and/or fouling problems could therefore save the power plants large sums of money in expensive components (e.g. new super heaters) as well as maintenance costs. Furthermore, it could yield higher boiler efficiency and fewer unintended shut downs.

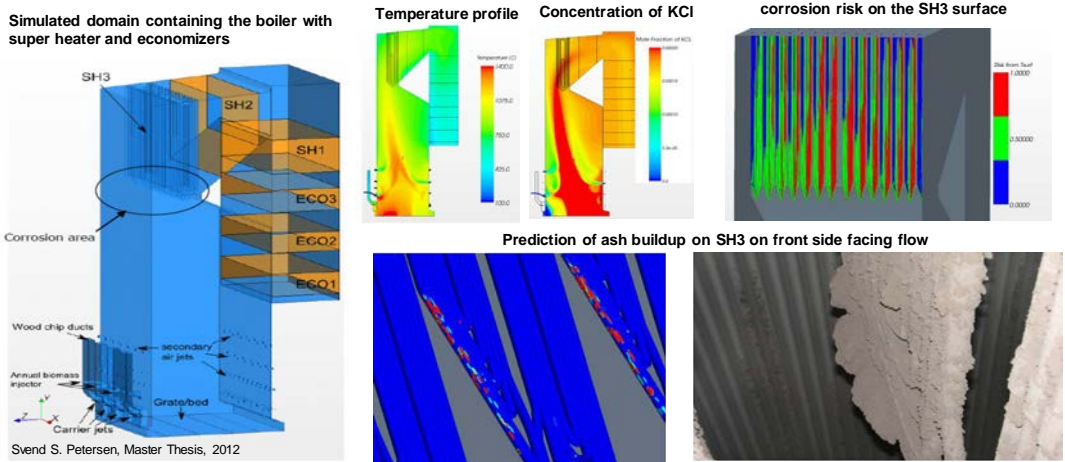


Figure 11: Initial attempt on CFD component level modeling in STAR-CCM+.

Similar to the biomass fired incinerator case, efforts have been carried out to map the flow path of the turbine. The intent is to define the conditions of components (temperatures/pressures/air and fuel flow rates) and operating conditions (duty cycles of interest, fuel/air contaminants) for CFD analysis. Experimental activities are being carried out in parallel to establish the algorithms for the metal wall loss for each turbine stage (alloys/coatings) for input into the model. A cross section of the turbine flow path is shown in Fig. 12.

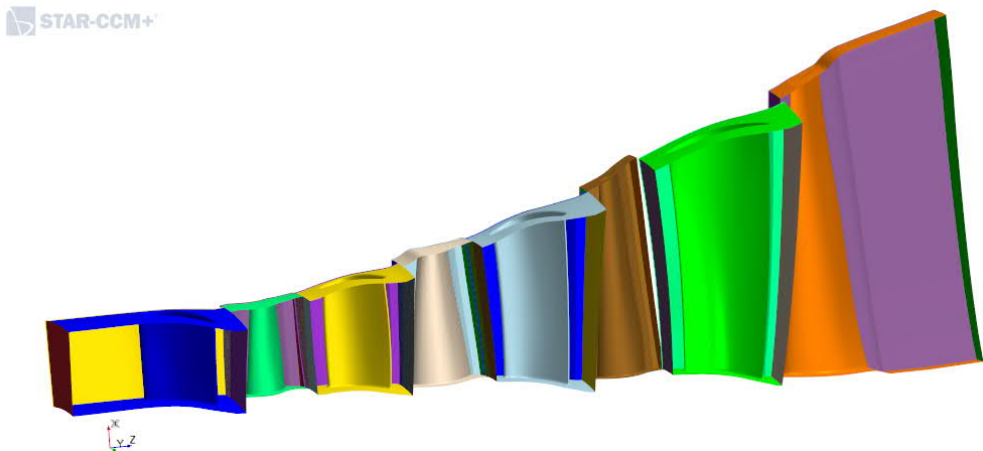


Figure 12: Turbine flow path for corrosion modeling.

Unlike deposit modeling where single chemistry of ash with solid/liquid transition is traveling through the turbine flow path, corrosion modeling is more complex with multi-species having different melting/dew points traveling through the hot gas path. Also, the chemistry of the species for the corrosive environment for each stage is decided based

on the thermodynamic stability and dew points of each corrosion compound for the concentration of the individual corrosion species, as shown in Fig. 13. Hence, the distribution of materials which cause high temperature corrosion in hot gas path needs to be calculated using dispersed multiphase flow approach.

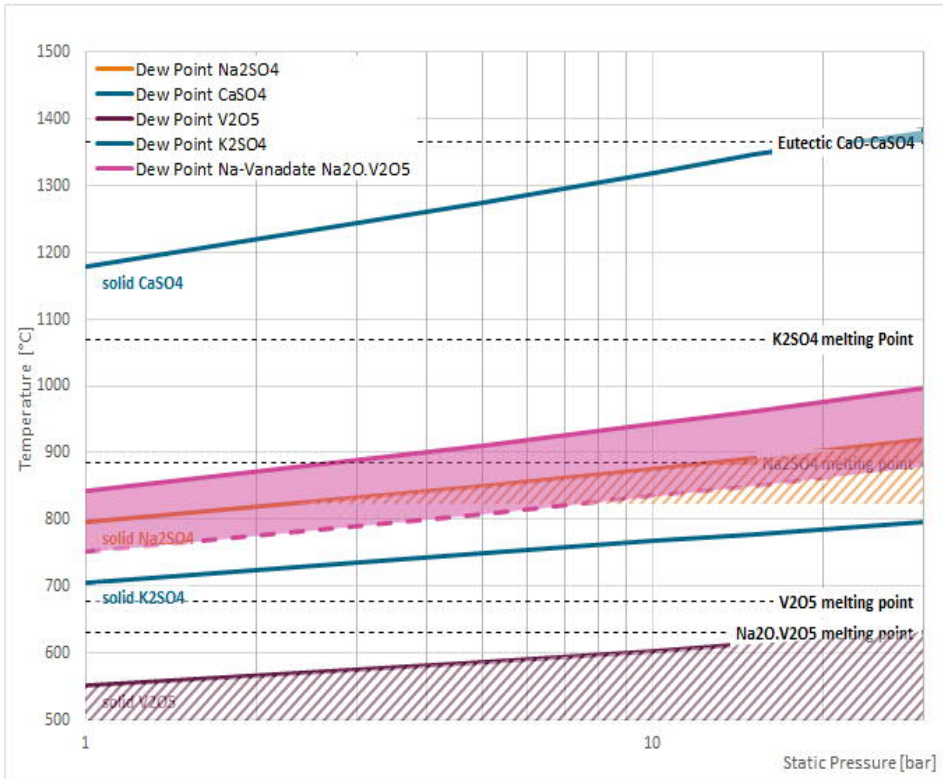


Figure 13: Thermodynamic stability of the corrosion species for hot corrosion model.

The dispersed multiphase (DMP) flow approach predicts the distribution of particle in Eulerian manner. This approach is less computationally expensive for large distribution of particles than Lagrangian approach which tracks the path of each particle. In dispersed multiphase flow approach, droplet density, particle diameter and specific heat are specified as phase properties. Volume fraction and temperature of droplet are specified as boundary condition at inlet as shown in Fig. 14. Volume fraction and temperature of dispersed multiphase on the surface of component is obtained from the calculation along with flow field. Corrosion risk occurs at high volume fraction of dispersed multiphase and the high temperature which is above melting temperature of particles at same location.

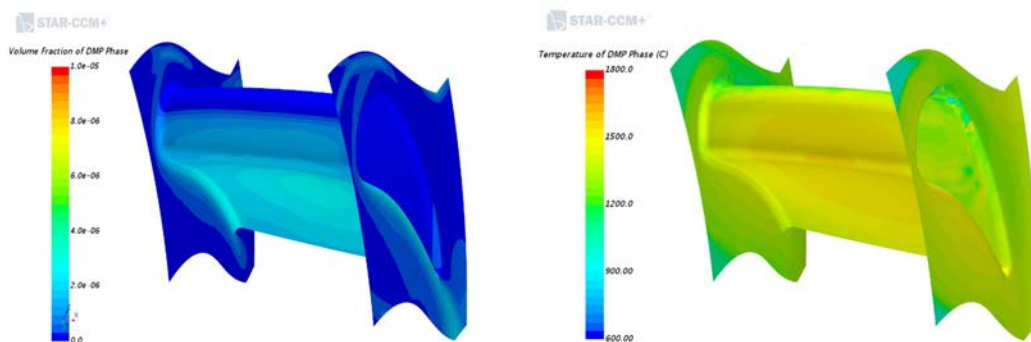


Figure 14: Volume fraction and temperature of DMP flow.

The next steps would be to integrate the component materials information and the algorithms for corrosion wall loss calculations to predict the corrosion rate for different contaminant levels/flows in engines for multiple duty cycles/fuels.

CONCLUSIONS

- The work tackles a multidisciplinary problem that involves a systematic approach utilizing deposit characteristics and flow modeling for identification of high-risk areas.
- This is accomplished via a sticking model and detachment model of particles fed with ash material properties, surface properties and local gas conditions on the surface of the component to generate a deposition map for all surfaces.
- The local wall shear velocity and local surface temperature of all positions on the vane must be known to calculate the deposition map. Also, the particle softening temperature and the wall shear velocity of the CMAS particle influences the deposition rate more than the TBC properties.
- Efforts are initiated to build the corrosion model infrastructure to calculate the corrosion rate for different duty cycles/fuels for component risk analysis.
- Dispersed multiphase flow approach is being utilized for the distribution of materials which cause high temperature corrosion in hot gas path.
- Predicted corrosion rates utilizing the levels of contaminant flux will eventually allow extrapolation to high temperature/high pressure conditions to develop corrosion maps appropriate to a range of fuels.

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