MODELLING PARTICLE DEPOSITION ON GAS TURBINE BLADE SURFACES

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Abstract Lagrangian particle deposition model is developed in this work. Particle trajectory is solved by integrating the particle equation of motion. The force balance equates the particle inertia with the forces acting on the particle. The applied forces on the particle are the inertia force, turbulent diffusion and Saffman force. User-defined subroutines are used with Fluent to build the deposition model. The model includes particle sticking/rebounding and particle detachment. The results are compared with two sets of experimental data and show very good agreement for both cases.

1. Introduction
Theoretical studies of particle deposition can be developed either by Eulerian approach or by Lagrangian approach. Lagrangian type trajectory models have been used to a much lesser extent than Eulerian models in the prediction of turbulent particle deposition. The reason is primarily due to their computational expense. The previous work showed that the Lagrangian approach provides a more detailed and realistic model of particle deposition because the instantaneous equation of motion is solved for each particle moving through the field of random fluid eddies.

2. Deposition Process
Deposition process consists of the three primary processes:
   a) Particle moving
   b) Particle sticking
   c) Particle detachment

2.1 Particle moving
The particles are moving in the flow field with the following applied forces:
   • Inertia force
   • Turbulent diffusion
   • Brownian diffusion
   • Thermophoresis force
   • Electrophoresis force
   • Saffman lift force
   • Magnus force

   The significance of these forces was studied for the present application. It was found from the previous work that particles with diameters equal to or greater than 0.03 µm are strongly affected by turbulence, even those with a distance one wall unit from the wall and the Brownian force can be neglected. As the particle diameters considered in this work are greater than this diameter, the Brownian force is ignored. On the other hand, the electrophoresis force is
neglected, as the particle concentration is low. Finally, previous work showed that in most regions of the flow field, particles are not rotating and Magnus force is not important and at least an order of magnitude smaller than Saffman lift force. Therefore it is ignored.

2.2 Sticking process

Once particles arrive at the surface, deposit build-up depends on the balance of sticking forces and removal forces acting on the particles at the surface. Under dry conditions, the van der Waals force is the major contribution to the particle sticking force.

Previous experimental results demonstrated that when spherical particles with relatively high initial velocities collide with a surface, the ratio of the final normal velocity to the initial normal velocity called the coefficient of restitution is relatively constant. But, as these velocities decrease, the significance of the adhesion force increases and the rebound velocities drop off considerably. Eventually a point is reached when no rebound occurs and the particle is captured.

The sticking model used in this work calculates the critical velocity for which the rebound velocity is zero and compares this velocity with the particle velocity. If the particle velocity is less than the critical velocity, then the particle sticks otherwise it rebounds.

2.3 Detachment process

If the removal forces from the fluid flow are sufficient to prevent the particles from remaining on the surface, the particles will be detached.

Different mechanisms for particle detachment are:
   a) Rolling
   b) Sliding
   c) Lifting

Previous work proved that in a simple shear flow, spherical particles are released by rolling rather than sliding or lifting.

The detachment model used in this work calculates the minimum shear velocity required for particle detachment. Thus, the particle will be removed from the surface if the turbulent flow has a shear velocity that is greater than the minimum shear velocity required for particle detachment.

3. Deposition model

Figure 1 shows the flow chart for the deposition model as built with Fluent 4.4.7. The flow field is solved in Fluent for the given geometry, inlet boundary conditions and for the fluid properties using one of the available turbulence models. The dispersed phase model that is available in Fluent 4.4.7 is used as the particle moving model. The commercial code is extended with user-defined subroutines to include Saffman force and to model the deposition process that includes particle sticking/rebounding and particle detachment. Table 1 shows a list of user-defined subroutines used in this model and the calculations that are being done in each of them.
Figure: 1 Deposition flow chart

**Table 1: List of user-defined subroutines**

<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>USERC2.F</td>
<td>This subroutine allows the user to perform tasks whenever the command is given to initialise the calculation of the dispersed second phase. It is used in the present work to calculate the values of $Y^+$ and the velocity gradient and to save them in common blocks when the calculation is performed for the second phase.</td>
</tr>
<tr>
<td>USRFOR.F</td>
<td>This subroutine allows the user to add additional components of forces acting on the particles. It is used to calculate the value of Saffman force when the particle is moving in the boundary layer.</td>
</tr>
<tr>
<td>USREFL.F</td>
<td>This subroutine allows the user to modify the particle boundary interaction. It is used to model the sticking and detachment mechanisms, accumulates the mass of deposited particles, and saves it in common blocks.</td>
</tr>
<tr>
<td>USSET2.F</td>
<td>This subroutine allows the user to create new menu and to supply input. It is used to supply inputs for particle and surface properties required for the sticking and detachment models.</td>
</tr>
<tr>
<td>USRFN.F</td>
<td>This subroutine is responsible for the postprocessing of deposition results.</td>
</tr>
</tbody>
</table>
4. Internal deposition in a vertical pipe

Liu and Agarwal (1974) measured the deposition rate of olive droplets from turbulent air flow inside a smooth glass tube for nominal Reynolds numbers of 10000 and 50000 and for particle diameters of 1.4 to 21µm.

4.1 Experimental system

Liu and Agarwal (1974) generated particles by using a vibrating orifice aerosol generator at its rated output as $1.5 \times 10^{-3}$ m³/s of air. The particles were uniform and spherical droplets of olive oil containing 10% by weight uranine. They were considered to stick once they hit the surface. The deposition pipe was 1.02 m long and 12.7 mm id. The deposition pipe was divided into three sections. The central section was used in the deposition measurement. Deposition measurement in the first section near the entrance was not considered because a finite length is needed for the flow to become fully turbulent. The deposition in the third section near the exit was not considered either due to the expansion of the flow.

4.2 Computational procedure

The flow field was solved as incompressible isothermal flow using two turbulence models: the standard k-ε model and the RNG k-ε model. The near wall region was solved using two methods: the standard wall function and the two-layer zonal model.

Two structured two-dimensional grids had been generated. A grid with 1920 cells was used to study particle deposition using turbulence models with the standard wall function. A dense grid with 6400 cells was used to solve the flow field using turbulence models with the two-layer zonal model all the way to the viscous sublayer and to study the deposition using this near wall treatment.

Samples of 50 particles of a particular diameter were injected with velocities equal to the fluid velocity. Each particle trajectory was calculated 200 times to account for the effect of turbulence. The particles were assumed to stick once they hit the surface. The numbers of deposited particles in each section were counted for each of the turbulence models. The deposition velocity was then calculated for the middle section using the equation given by Liu and Agarwal (1974).

\[
V = \frac{Q}{\pi DL} \ln \left( \frac{L}{P} \right) \quad (1)
\]

\[
V_v = \frac{V}{v_v} \quad (2)
\]

\[
\tau = \frac{\rho_p d_p^2}{18 \mu} \quad (3)
\]

\[
\tau_v = \frac{\tau v_v^2}{v} \quad (4)
\]

where

- $Q$ - volumetric flow rate
- $D$ - id of the deposition pipe
- $L$ - length of the deposition pipe
- $P$ - fraction penetration
- $v_v$ - friction velocity of turbulent flow
- $\rho_p$ - density of the particles
4.3 Results and discussion

Deposition velocity computations with different turbulence models are compared with the measurements of Liu and Agarwal (1974) in Fig. 2 as a function of particle relaxation time. The RNG k-ε model with the two-layer zonal near wall model gives good agreement with the experimental data over a wide range of particle relaxation time. The standard k-ε model with standard wall function overpredicts the deposition velocity for particles with relaxation times less than 10. The agreement for particle relaxation times greater than 10 is moderate. The agreement among all turbulence models for large particle relaxation times is due to particle inertia for large particles, which makes the details of the boundary layer not important for particle trajectories. When the particles reach the boundary layer they continue to move toward the surface by their inertia. Smaller particles are highly affected by the turbulence in the boundary layer and the details of the boundary layer play an important role in their movement.

Figure 2: Comparison between theoretical results and the data of Liu and Agarwal (1974)

5. Deposition in a turbine cascade

Detailed experimental data of particle deposition on compressor and turbine blade surfaces are almost non-existent with the exception of the data of Parker and Lee (1972). They studied experimentally the deposition of uranine particles on turbine blades in an open circuit low speed wind tunnel. The wind tunnel was constructed to provide an air velocity of about 70
m/s at the exit from a cascade of six blades. The blade inlet velocity magnitude was 11 m/s. The profile geometry used in this experiment is shown in Fig. 3. Particle deposition on the blade was measured by placing an adhesive tape on the centre zone of the blade surface.

5.1 Computational procedure

A Structured, body-fitted, and 2-dimensional grid was generated. The grid has a total number of cells of about 65000. The isothermal, incompressible flow field was solved in Fluent with the Parker and Lyley (1970) air inlet flow conditions as:

- Air inlet velocity = 11 m/s
- Air inlet pressure = 1,013×10^5 Pa
- Air inlet flow angle = γ = 60°
- Air inlet turbulent intensity = 2%.

5.2 Results and discussion

5.2.1 Flow field

The flow field was solved by the RNG k-ε model. The near wall region was solved by the two-layer zonal near wall model.

<table>
<thead>
<tr>
<th>Dimensions in mm</th>
<th>C</th>
<th>247 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade span</td>
<td>H</td>
<td>167 mm</td>
</tr>
<tr>
<td>Blade spacing</td>
<td>S</td>
<td>127 mm</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>H/c</td>
<td>0.676</td>
</tr>
</tbody>
</table>

Figure 3: Geometry of turbine cascade

5.2.2 Deposition calculations

Using statistical software, samples of 33000 particles were generated with particle mean diameters and standard deviations. These statistical parameters were obtained from the data of Parker and Lee (1972). The particles were distributed over the blade spacing and injected with a velocity equal to the fluid velocity. Each particle trajectory was calculated 25 times to account for the effect of turbulence.

Figure 4 shows comparison between theoretical results using RNG k-ε model with the two-layer zonal model and experimental data. Two particle mean diameters were used to test the deposition model and to investigate the effect of this turbulence model. The agreement for both mean diameters is very good.
The small discrepancies between the theoretical results and the experimental data on the blade pressure surface for the sample with the particle mean diameter of 0.098 µm can be explained by the effect of the secondary flow that is not present in the two-dimensional calculations. As the blade aspect ratio of this geometry is relatively small (0.676), the passage vortex may affect the particle movement at mid-span near the blade trailing edge. The direction of the passage vortex as shown in Fig. 5 is from the pressure side to the suction side near the end wall and from the suction side to the pressure side near mid-span. If the passage vortex exists near mid-span, it will carry the small particles to the blade pressure surface and result in an increase of the deposition rate in this region. The passage vortex is unable to carry relatively large particles with mean diameter of 0.13 µm and the theoretical result shows very good agreement with the experimental data. Further work is still required to study the effect of secondary flow on particle deposition.

Figure 4: Comparison between theoretical results using RNG k-ε model with the two-layer zonal model and experimental data
6. Conclusions and remarks

Lagrangian particle deposition model was developed. The model includes the three main deposition processes: particle moving, sticking and detachment. Different turbulence models were tested. The RNG k-ε model with near wall modelling leads to more accurate simulation for particle deposition. The particle moving model was tested with two sets of experimental data. The agreement is very good for both cases. The non-isothermal flow will be studied which affects deposition process by the thermophoresis force and the particle sticking force. Experimental data is still required to test the sticking and the detachment models.

References

