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PRELIMINARY STUDY OF PARTICULATE FOULING IN A HIGH TEMPERATURE CONTROLLED EXPERIMENTAL FACILITY

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ABSTRACT

Fouling is a highly complex process and numerical modeling of fouling has been an evasive task. One of the reasons for this is attributed to the lack of detailed experimental data. In-situ experiments performed at the power plants give a global picture of the overall deposition process in a qualitative manner. However, detailed understanding of the underlying mechanisms becomes difficult. This is due to the fact that too many parameters like varying particle composition and size, gas phase dynamics, chemical reactions etc. are lumped together in such experiments. On the other hand, controlled lab-scale experiments that have been reported are meager and those that have been published are performed either at low temperatures or at very high temperatures (>1000 ^{o}C). In order to understand the underlying mechanisms of particulate fouling and to provide experimental data for validation, a high temperature controlled fouling experimental facility has been built.

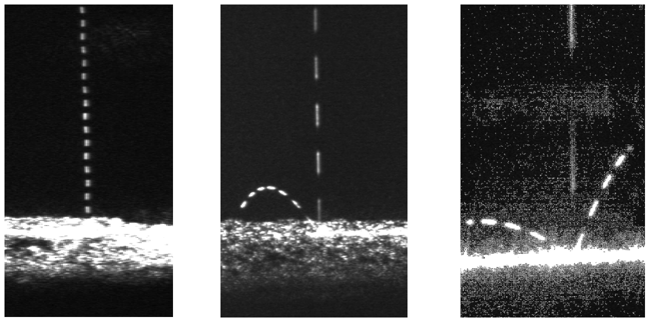
The facility is a vertically oriented closed loop wind tunnel with which parameters like gas phase temperature, velocity and particle concentration can be controlled.

The setup was tested for proper operation and preliminary experiments were performed on particulate fouling over a circular cylinder as function of gas phase velocity and temperature. It was found that the gas phase velocity and temperature has a major influence on particulate fouling. This is a preliminary study and will be extended in future.

INTRODUCTION

Of the many forms of fouling, particulate fouling is of particular interest as it is one of the major forms of fouling. One of the main requirements of the day is the development of validated numerical models that are able to describe the fouling process. However, owing to the complex nature of fouling, progress in this direction has been very limited. It is noted by several authors [Baxter (1993) and van Beek et al. (2001)] that the growth of fouling layers displays an asymptotic behavior which is not well understood.

After the initiation and growth period, the asymptotic behavior indicates that the rate of deposition and removal are balanced. In order to model particulate fouling, the deposition and removal mechanisms have to be well understood or in other terms, the "sticking" criteria and "removal" criteria have to be well established. Figure (1) shows the process of deposition, rebound and removal of an impacting particle over a bed of particles at different impaction velocities.



a) b) c)

Fig. 1 Impaction of a particle with a bed of particles
a) Deposition, b) Rebound and c) Removal (Abd-Elhady, 2005)

Sticking Models

To evaluate the sticking criteria, many authors have resorted to different approaches. The sticking criterion mainly depends on the specific application area and basically there are three different approaches to evaluate this parameter. Srinivasachar et al. (1990) had proposed the use of particle viscosity as a determining factor for particle deposition. Walsh et al. (1990), Baxter and DeSollar (1993) and Huang et al. (1996) have used the critical viscosity criterion in their work related to ash deposition on superheater tubes from pulverized coal combustion. This approach is suited for modeling the particle deposition in coal fired boilers especially in the high temperature regions i.e. to model slagging behavior.

For high alkali containing processes like grass/straw based biomass units, the amount of melt fraction has been used as a criterion for sticking. The presence of condensables in vapor form enhances the deposition pattern over cooler surfaces of heat exchangers. Tran et al. (2002), Mueller et al. (2005) and Strandström et al. (2007) have studied the deposition behavior of alkali rich particles. In order to account for the condensables, a sticking criterion based on the melt fraction is used. This approach, as the name suggests, is mainly applicable to model alkali rich processes.

The third approach to evaluate sticking is the critical velocity approach based on the Rogers and Reed (1984) model wherein the collision behavior of an incoming particle and the previously deposited particles over a heat exchanger determines whether the particle becomes a part of the deposit or not.

Based on the critical velocity approach, van Beek (2001) used particle impaction experiments to evaluate the sticking criteria and developed a 2-body collision model to describe particle deposition. This model describes the interaction between an incident particle and a bed of particles as collision between two particles. Though this is a simple way to define deposition and rebound of particles, the model is not suitable to account for the removal of particles.

It is a well established fact that depending on the inertia of an incoming particle, an impaction can result in three possibilities: the particle may deposit, it can rebound or if it possesses enough inertia, it can remove other particles out of the deposit. Figure (1) shows the above mentioned probabilities for a particle impacting a bed of particles.

In order to define a model for particle removal by inertial impaction, Abd-Elhady et al. (2006) conducted several impaction experiments and used a Discrete Element Modeling (DEM) technique for numerical simulations. The particles are treated as discrete entities that interact with each other when they are in contact. Using the principles of contact mechanics, this method evaluates the coefficient of restitution as a solution rather than assuming it as a constant value. Another interesting feature of this approach is the modeling capability of removal of particles by impaction.

Removal models

The removal models that have been successfully used to model fouling are very limited. Removal of particles is basically due to fluid shear stress and impaction mechanisms. Strandström et al. (2007) account for the removal of deposit by sand particles. The impact energy of a sand particle hitting a deposited ash particle is the basis of the model. If the impact energy overcomes the work of adhesion, particles will be removed, else, the sand particle is considered to stick to the previous deposit. The (DEM) model which is primarily based on the concepts of contact mechanics provides a detailed understanding of the removal of particles from a bed of particles when a particle impacts the bed with sufficient inertia. The model is based on the work of Rogers and Reed (1984) and can accurately predict the outcome of an impact. However, the computational costs involved are prohibitive to implement this in a full fledge deposition simulation.

The shear force of the gas phase acting on the particles also removes the particles from a surface. For a particle resting on a surface Zhang et al. (2000) define the ratio of rolling friction moment and the adhesion resting moment as a removal criterion. If the ratio is greater than 1, the rolling friction moment is greater and the particle is considered as eroded from the surface which depends on the flow velocity acting at the centre of the particle on the surface.

Aim of the present study

The main focus of this study is to understand fouling from a phenomenological point of view and to provide experimental data for numerical validation. Kaiser et al. (2002) have earlier reported similar controlled experiments with a dryer exhaust gas simulator in the presence of condensables and report a strong relation between vapor condensation and particle deposition. Abd-Elhady et al. (2009) have reported the influence of gas phase velocity and flow direction on particle deposition. As indicated earlier, the published experimental articles relate to the experiments performed at comparatively very high temperatures (> 1000^0 C) or low temperatures (25-200^0C). Also, the controlled parameters and experimental data sets are limited to few.

Thus, experiments with controlled parameters like temperature, particle size, particle type, gas phase velocity, heat exchanger tube material, condensable species etc are thus necessary to avoid the complexities. The focus is to perform experiments by varying each parameter in a systematic way using factorial experimental approach. This will provide valuable insight into the fouling process with isolated parameters and also provides data to develop and validate numerical models.

The following sections will cover the experimental facility and preliminary experimental results. Though the experimental facility can be operated for gas phase temperatures up to 500^0C, this preliminary study reports experiments performed at comparatively low temperatures.

EXPERIMENTAL FACILITY

SETUP

The controlled fouling experimental facility is shown in figure (2). The experimental setup is vertically oriented and consists of different parts interconnected by stainless steel ducting. The experimental facility mainly consists of: blower, electric heater, flow conditioner, particle feeder, test section, stainless steel ducting and cyclone particle separator. A specially designed blower that can operate at high temperature serves the purpose of delivering required flow rate of air. A 50kW electric heater is mounted above the blower. The electric heater has a completely controllable feedback loop system to maintain the temperature of air at the outlet of the heater within ± 1 ^oC of the set point temperature. The flow conditioning unit has a turbulence grid to condition the flow. A screw feeder is used for seeding the flow with required quantity of particles which can be controlled by regulating the speed of the motor. Downstream of the flow straightener, the test section is positioned. The test section basically comprises a stainless steel tube of 28 mm outer diameter and 24 mm inner diameter, whose ends are connected to cooling water inlet and outlet piping. The test section is optically accessible through a set of glass windows to observe fouling. A cyclone separator is used to remove the particles from the flow. The facility is designed to be controlled through a central computer with programmable logic controls.

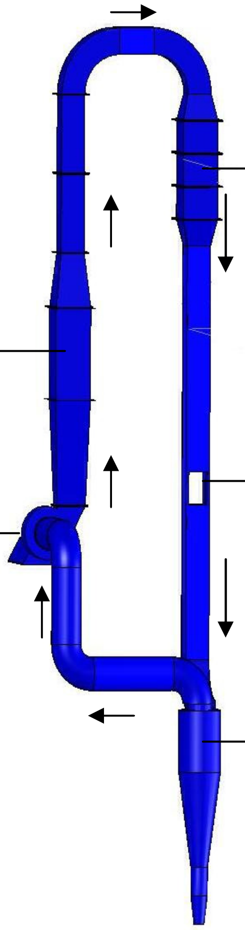


Fig. 2 Schematic of the controlled fouling experimental setup.

Operating principle

The blower maintains the required flow rate ranging from 0.08 - 0.2 m^3/s. The air then passes through a diverging duct to enter the electric heater. In the heater, the air is heated to the required temperature by several heating elements. The hot air emanating from the heater passes through the ducting which consists of a straight section and two 90^o bends by which the motion of air is changed from upward to downward direction. A combination of grids, diverging and converging zones are used to condition the flow soon after the second bend. A particle feeder positioned on the top of the setup discharges the required amount of particles into the flow in a tube. The amount of particles inserted into the flow can be controlled by regulating the speed of the particle feeder motor. The outlet of the particle seeding tube is positioned just at the turbulence grid in order to obtain a homogeneous particle distribution. Several CFD calculations were done to choose the position of the particle inlet into the gas phase to get equal particle distribution in the flow. The test section is positioned 2m below the grid and particle inlet. This is to allow sufficient distance for the flow to develop and to provide sufficient residence time for the particles in the hot air so that the particles can attain a quasi thermal equilibrium state with the gas phase. The deposition of the particles and their growth over a cylinder is observed in the test section. After the test section, the hot air and the seeded particles move straight in the duct for 1.5 m downstream and then enter the cyclone separator through a 90^0 bend. The bend is positioned 1.5 m away from the test section to avoid upstream disturbances due to the presence of bend. The outlet of the cyclone separator and the inlet of the blower are connected by circular tubing. Except for the transition zones, a square ducting of 200 x 200 mm cross section is used. A picture of the test section is shown in figure (3).

Fig. 3. Test section of the experimental setup

Instrumentation and Measurement techniques

Thermocouples installed at the entrance and exit of the cooling water to the probe provides the temperature measurements of the cooling water and a flow meter measures the mass flow rate of the cooling water. All temperatures are measured using K type thermocouples with an accuracy of ± 0.4 ^oC. A hot film anemometer and pitot tube in conjunction with a sensitive pressure transmitter are used to measure the gas phase velocity. A digital video camera with a resolution of 600x480 pixels is used to measure the growth of fouling layer thickness over the cylindrical tube. Images of the tube are taken before, during and after the experiments. The clean tube is taken as a reference and the fouling layer thickness can be measured using pixel count. Glass particles with a size range of 5 to 56 micrometer are used. An image of the particles taken from a scanning electron microscope is shown in figure 4 (a).

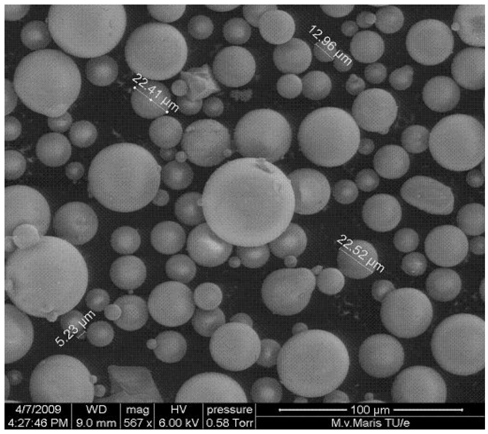


Fig. 4 (a) SEM picture of the glass particles used.

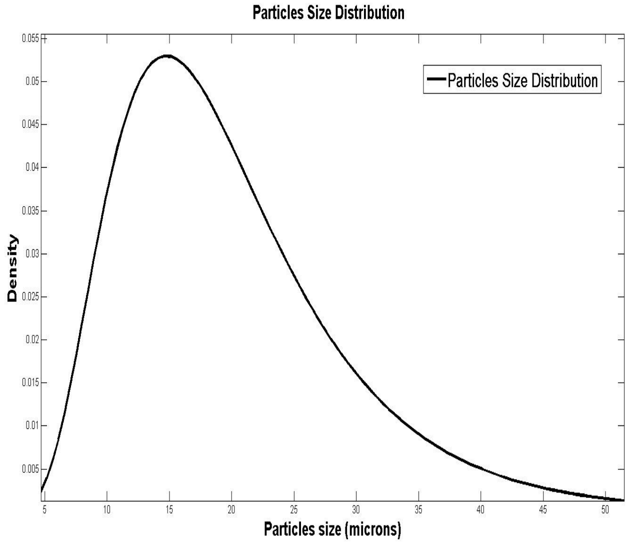


Fig. 4 (b) Particle Size Distribution of the glass particles

The particles have a mean diameter of 20 micrometer and a standard deviation of 8 micrometer. The PSD for the bulk glass powder is shown in figure 4 (b).

PRELIMINARY EXPERIMENTAL RESULTS AND DISCUSSION

The experiments were carried out for the cases shown in table (1).

Table 1 Variation of different parameters for experimentation.

No.	T_g (^{0}C)	V_g (m/s)	C_p (g/m^3)	H (mm)	W (mm)
1	24	2	2	2.5	5.5
2	24	2	8	2.5	5.5
3	100	2	8	4	8
4	100	1.5	8	7	15

The variables Tg, Vg and Cp correspond to gas phase temperature, gas phase velocity and concentration of particles in the flow respectively. H and W represents the thickness and width of the fouling layer formed as shown in figure 5.

The first experiment was performed to establish a base case for comparison with other cases. Particles were seeded into the flow at the rate of 2 g/m^3 in a flow of 2 m/s of air at nominal conditions. It was observed that the deposition initiates as small clusters along the stagnation line of the cylinder. After 10 minutes, a continuous line of deposit layer was formed. After 60 minutes, the growth of the layer was very limited and after 180 minutes, the deposit layer did not show any considerable changes. After 240 minutes, the final deposit thickness was found to be 2.5 mm and the width was found to be 5.5 mm.

In the second experiment, the rate of particle seeding was increased to 8 g/m^3. The initiation was observed to be similar to the first case forming clusters of deposits along the stagnation line of the cylinder. However, due to the increased mass loading, the formation of a continuous layer was faster as compared to the first case. At the end of 4 hrs of operation, the formation of deposit layer was exactly same as in the first case indicating that the mass loading does not have much effect on the overall growth pattern except for formation of the layer at a much faster rate. The particle deposition pattern over the cylinder surface is shown in figure (5).

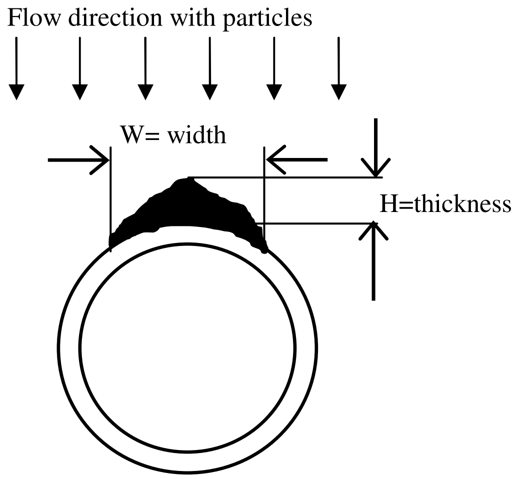


Fig. 5 Particle deposition pattern over the cylinder surface

In the third experiment, the gas phase temperature was increased to 100 ^{0}C and the velocity was maintained at 2 m/s with a particle seeding rate of 8 g/m^3. The initiation process was much similar to the earlier cases. The deposit thickness and the width were found to be 4 mm and 8 mm respectively as shown in table (1). The increase in the layer thickness and width is a direct result of change in the temperature. The physical properties like Young's modulus and surface energy are invariably altered by temperature changes which reflect in a different deposition behavior. The Rogers and Reed (1984) model suggests that particle properties are important parameters.

The gas phase velocity was reduced to 1.5 m/s in the fourth case and the deposition observed was different from other cases. Though the initiation was similar to other cases, the final thickness and the width of the fouled layer were found to be 8 mm and 15 mm respectively. Along with changes caused in the physical properties of the particles due to higher temperature, the gas phase velocity also plays a vital role in the deposition process. The deposition and removal are not only function of particle impactions but the shear and lift forces acting on the particles by the flow field also play a vital role.

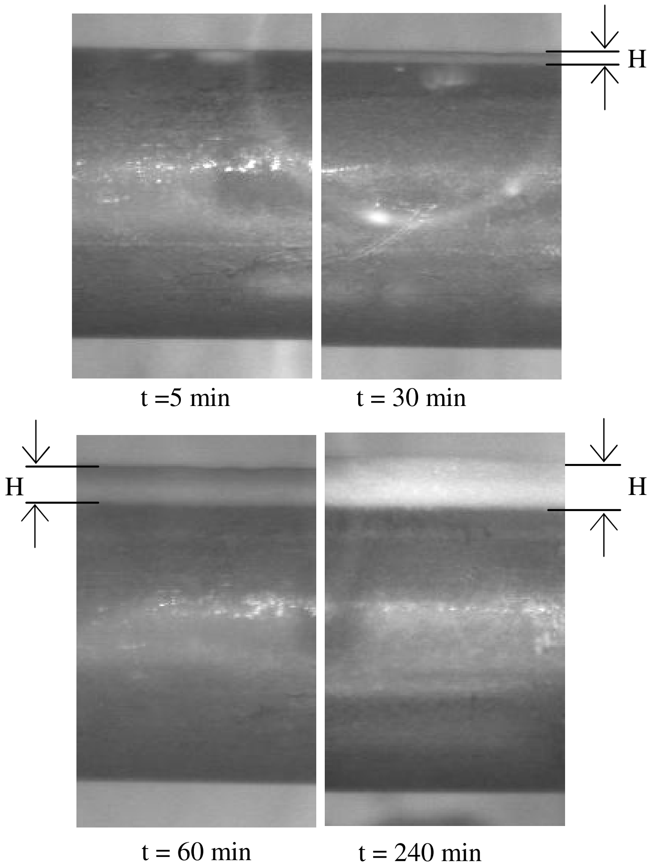


Fig. 6 Deposition of glass particles on stainless steel tube and the evolution of a fouling layer. [Ref. case 3, Table (1)].

Figure (6) shows the typical deposition of glass particles over a cylinder. In all the cases, the deposition starts on the stagnation line of the cylinder and grows outwards circumferentially. The general trend is that the particles form small clusters and then form a continuous layer. A very thin layer of small particles were found on the circumference next to the thick layer and it can be inferred that fouling initiates with the deposition of small particles which was also observed by Abd-Elhady (2005).

After each fouling experiment, the seeding of the particles into the flow was stopped and the effect of removal of particles by flow alone was observed. The cylinder was oriented at different angles to study the erosion characteristics of the flow as shown in figure (7). The gas phase velocity was changed to 2, 3, 4 and 5 m/s.

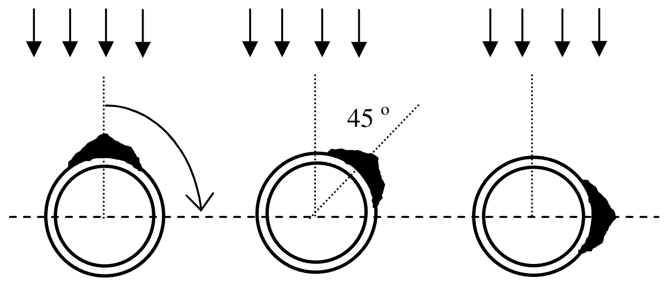


Fig. 7 Orientation of deposit to the flow without particles

It was observed that the particle erosion by the flow was a very slow process and no significant change in layer thickness was observed for the duration of 30 minutes for each orientation and velocity. However, at the end of the experiment the probe was taken out of the test section and it was found that the particle deposits can be easily removed by mechanical means like a brush. Due to the complex mechanism of particle impaction and interactions, the particles undergo plastic-elastic deformations and develop strong bonds. The shear force due to the flow of gas phase over the particles is overcome by the adhesion force of the particles in contact with each other and hence the erosion was observed to be negligible.

CONCLUSIONS

A controlled fouling experimental setup has been built and tested successfully to study the mechanism of fouling from a fundamental view point. The preliminary experiments provided some insight into the particle deposition process. Some conclusions that can be derived from the observation of experimental results are:

1. Deposition invariably initiates at the stagnation region on the tube and slowly grows circumferentially. The fouling layer formation is observed to be strongly dependent on the gas phase temperature and gas phase velocity.
2. For the same gas phase temperature and gas phase velocity, higher mass loading only results in a faster deposit formation but does not result in a larger deposit build up.
3. The smaller particles tend to deposit first and then provide a base for the deposition of larger particles.
4. Once the deposit has formed, it was observed that the gas phase velocity (of max 5 m/s) did not have any effect on removal of particles from the layer even when the tube was oriented at different angles to the flow.

Particle deposition is dependent on several factors and the study of deposition process under controlled conditions will provide more information on the fouling process. Starting with particles of known physical and chemical properties, the deposition process can be understood and based on this; a simple deposition model can be developed. Later, the model can be extended for real-time industrial fouling processes and in this regard, the controlled fouling experiment is an important aspect in understanding and modeling particle deposition.

Future work

1. Experiments with variable gas phase temperatures (up to 500^{0}C) and gas phase velocities will be carried out.
2. Experiments with different particles have been planned and the experimental setup will be further developed to include the effects of condensable species in the gas phase and also with real ash particles.
3. A method of measuring fouling layer evolution as a function of circumferential and axial growth is being developed for inline measurements of fouling layer.
4. It has been reported that fouling can be reduced with frequent seeding of sand particles in the flow. The effect

of adding sand and other particles in the flow, the effect of particle size distribution and the limiting particle size for deposition will be studied in detail.

5. A simplified model will be developed and validated against experimental observations.

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