Final Technical Report

Analysis/Control of In-Bed Tube Erosion
Phenomena in the Fluidized Bed
Combustion (FBC) System

to

U.S. Department of Energy
Pittsburgh Energy Technology Center
P.O. Box 10940, MS 921-118
Pittsburgh, PA 15236-0940

for

Project No: DE-FG22-92MT92021

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November 1996

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1. INTRODUCTION

Since the energy crisis in the early 1970's, the increase in oil prices and the threat of an oil shortage in the near future has prompted interest in coal as a replacement fuel for space heating, water heating, and processed heat. Coal consumption patterns in the United States have shifted dramatically over the past few decades. Electric utilities accounted for only 12% of the coal consumed in the 1940's, but now they account for 86% [1]. However, in the commercial and residential sectors of the economy, coal has supplied only 6-9% of the energy needed since the early 1970's. The energy crisis prompted a reevaluation of our country's fuel supplies, fuel-pricing policies, energy consumption and conservation, and methods of power generation. As a result of this crisis, the United States rediscovered its vast coal reserves and coal became an attractive commodity due to its low price. Since 1973, our annual coal production has increased by 50% (292 million short tons per year) because many big users of natural gas and petroleum fuels (fuel oil, diesel, gasoline, kerosene, and propane) have increased their coal utilization.

Among emerging technologies of coal utilization, such as coal-water slurry, slagging combustors, fluidized-bed combustion (FBC), and coal-derived synthetic fuels, FBC is demonstrably the most promising coal-firing method, offering the capability and flexibility of burning different grades of coal in an economically and environmentally acceptable manner. In bubbling fluidized bed combustion, (BFBC), circulating fluidized bed (CFBC), and vortexing fluidized bed combustion (VFBC) systems, in-bed tube bundles and components are commonly employed for effective absorption and temperature control [2]. Wastage of these surfaces by impingement of bed materials (ash, coal, and sorbents) has gradually been recognized as one of the major areas of difficulty in transferring the FBC technology to actual power and heat generation processes. During the past two decades, problems of erosion and corrosion of in-bed

tube bundles, water tube walls, and downstream heat transfer surfaces, have persistently plagued most atmospheric FBC (AFBC) and pressurized FBC (PFBC) boilers. Unscheduled shutdowns due to serious surface erosion/corrosion by bed material (coal and sorbents) and elutriated particles were experienced in many FBC plants [3,4].

While the wear of a solid surface by particle impingement has been the subject of many studies [5,6], these studies cannot legitimately be expanded to cover the phenomena found in FBC systems. Some surveys have summarized research work [6,7] that concerned the impact on different target materials by particles of various kinds, sizes, and sphericities, at various impinging velocities and angles. These studies were primarily derived from problems of industrial processes, such as erosion of turbine blades, control of sand blasting, damage of helicopter propellers, and wear of pneumatic pipelines. Although the results of these studies have enriched our understanding of surface erosion, their application is limited to low-frequency, and directional impacts of diluted particles (0.1 g/cm^3) at high velocities ($> 25 \text{ m/s}$). None of the results apply to the in-bed tube erosion in FBC systems, an erosion characterized by high-frequency, random (or semi-random) impacts of dense particles ($> 1 \text{ g/cm}^3$) at low velocities ($< 5 \text{ m/s}$).

Very few systematic studies have explored the erosion phenomenon or specifically addressed the in-bed tube erosion problem of FBC systems [8,9]. The general literature about particle impacts upon solid surfaces is extensive, but studies specifically applicable to fluidized bed tube erosion are rare. The fundamental mechanisms of the erosion processes in a fluidized bed are not clearly understood at present. Except for some unsatisfactory palliatives developed by FBC boiler operators [10], there are no effective solutions available; it is not possible to suggest remedies for erosion problems. Innovative research on the analysis and modeling of in-

bed tube erosion and development of anti-erosion techniques for a coal-fired FBC system are clearly needed to achieve PETC's goal of coal utilization, which, if fulfilled, will substantially lessen the nation's dependence on foreign oil while increasing the use of domestic coal.

PROJECT OBJECTIVES

The objectives of this project were twofold. First, our purpose was to determine the characteristics and mechanisms of the erosion phenomena of in-bed tubes of FBC systems. Our second objective was to develop and test such anti-erosion measures as might reasonably be expected to prevent such erosion.

2. EROSION MEASURING EQUIPMENT

(a) BENCH-SCALE COLD MODEL

The bench-scale cold model FBC employed in this project had four major components: a test section (fluidized bed), a plenum chamber with distributor, a freeboard/exhaust system, and air movers. Figure 1 shows the bench-scale cold model.

The rectangular test section, which models the fluidized bed in an actual FBC system, is formed by four (4) Plexiglas walls (chosen for visibility) giving a cross-section of 20 cm x 20 cm. The active bed height for testing ranged from 15-35 cm, depending on the solid loading.

The plenum, or wind chamber provided a damping action to smooth the air flow into the test section. Constructed of 1.27 cm Plexiglas plate with a top bolted flange to the distributor, the plenum chamber is capable of maintaining an air pressure of 140 cm-of-water at a maximum flow rate. Air was delivered to the plenum chamber through a 5.1 cm diameter I.D. PVC pipe. The distributor, shown in Figure 2, controls the quality of bubbling fluidization, the system

Figure 1 Schematic Diagram of the Bench-scale Fluidized Bed System

Figure 2 Schematic Diagram of Gas Distributor (No.2)

pressure drop, and the degree of solid-gas contact. For this study, the distributor was of the perforated plate type. This type of distributor, widely used for industrial and laboratory-scale operations, combines ease of design and construction with good gas distribution. Three perforated plate distributors of varying dimensions were constructed and used in this study. Further data on the plate distributors is shown in Table 1.

Table 1
Design Features of Gas Distributor

Distributor	No. 1	No. 2	No. 3
Material	Plexiglas	Plexiglas	Plexiglas
Dimensions (mm)	200 X 200 X 9.5	200 X 200 X 9.5	200 X 200 X 9.5
Drill Diagram (mm)	1.00 (No. 61)	0.85 (No. 66)	0.78
Actual Hole Size (mm)	1.09	0.94	0.78
Total Number of Holes	2053	2162	1050
Recommended Particle Size Range (mm)	0.6 - 1.9	0.5 - 1.5	0.35 - 0.85

The freeboard, or region above the average surface of the bed, exists to contain particle "splash" that occurs as gas bubbles rise and erupt at the bed surface. The exhaust connects to the freeboard, high enough above the average bed height that entrainment of particles is kept to a minimum. For this study, the freeboard area had the same dimensions as the test section, 20 x 20 x 60 cm, which is a sufficient size to minimize particle entrainment for the particle sizes

and for the fluidizing velocities encountered in this study. In addition, a prototype dust collector was designed and fabricated to collect fine particles through the test section of the fluidized bed. This collector, shown in Figure 3, was installed on the top of the fluidized bed and measured as 21.5 cm x 21.5 cm, with a height of 15.24 cm. The dust collector was constructed to use two dust filters, one located in the base of the exhaust cover and one in the top portion. Both filters were connected to a PVC pipe, 3.8 cm in diameter. The dust collector proved to be effective in collecting fine dust particles during the experimental tests.

The air movers used in this study were two, high-pressure, centrifugal blowers that provided the fluidized bed with fluidizing air having a superficial velocity of up to 110 cm/s. The blowers could be arranged in series, parallel, or a combination in order to meet the needs of desired air flow rate and pressure. A variac transformer was used to control each blower, and to vary input voltage, thus rotating the speed of the driving motors. Blower characteristics, in terms of static pressure head and gas flow rate for the single blower case, were 110 cm-of-water (125 volt power input) and up to 35 m/s air velocity in the 5.1 cm I.D. tube. A summary of single blower characteristics is shown graphically in Figure 4, while the possible combinations of the two blowers and their outputs are graphed in Figure 5. From these, we can see that the parallel arrangement of two blowers increased the gas flow-rate by 55%, while the series arrangement raised the pressure head by 60%. The different combinations of series and parallel connections of blowers allowed the selection of a desired gas flow-rate and static pressure.

Having discussed the physical characteristics of the bench-scale cold model, the operational characteristics of the model need to be examined. The minimum fluidization velocity, u_{mf} , the most fundamental data for in-bed tube testing, is responsible for the onset of fluidization. This occurs when the drag force exerted by upward moving gas equals the weight

Figure 3 Schematic Diagram of Prototype Dust Collector for the Bench-scale FBC System (All dimensions in cm)

Figure 4 Characteristics Curve of Blower for Fluidized Bed System (Single Blower Arrangement)

Figure 5 Characteristic Curve of Blower for the Fluidized Bed System

of the bed particles. At this point, the bed voidage, e_{mf} , can be assumed to be slightly larger than that in a packed bed, in this case, 0.41. The superficial velocity at minimum fluidizing conditions, u_{mf} , can then be estimated from a correlation equation [11]

$$u_{mf} = \{[1,136 + 0.048 d^3 p_g (p_p - p_g)g/u^2]^{1/2} - 33.7\} u/(dp_g)(2-1)$$

where the air material density, $p_g = 0.001205 \text{ g/cm}^3$ and the dynamic viscosity of air, $\mu = 0.000181 \text{ g/cm}^2\text{s}$. The minimum fluidization velocity was also obtained from the measurement of bed pressure drops. For small gas flow rates, particles remained stationary and the pressure drop through the packed bed was approximately proportional to gas velocity. When the gas velocity exceeded the minimum fluidization velocity, the packed bed abruptly unlocked and particles started moving, thus expanding the bed materials and allowing the rise of gas bubbles of various sizes. The pressure drop through the fluidized bed remained practically unchanged when the fluidizing velocity increased further, as is shown in Figure 6. The constant pressure required to sustain fluidization was roughly equal to the weight of the bed particles per unit bed area. The intersection of the inclined line and the horizontal line designated the onset of fluidization. The superficial gas velocity at the intersection was called the minimum fluidization velocity, and was determined to be 19 cm/s, again referring to Figure 6. The value for u_{mf} , found through the correlation equation, confirmed this empirically determined value within ten percent.

The minimum fluidization velocity formed the lower limit for testing, while the upper limit was constrained by entrainment of particles in the upward moving gas. This upper limit was the terminal velocity of the smallest in-bed particle under the gravitational field. Using the multi-phase theory, the particle terminal (or free-fall) velocity, u_t , can be determined as follows:

Particle: Micro Glass Beads
Density: 2.48 g/cm³, Dia: .55 mm

Figure 6 Static Pressure Drop versus Gas Velocity

$$u_t = [4 g d (p_p - p_g) / 3 p_g C_d]^{1/2}$$

where $C_d = 10 \text{ Re}_p^{-0.5}$ for 0.5 mm glass spheres and particle Reynolds number, $\text{Re}_p = d u_o p_g / \mu$.

Substituting the above quantities into the equation gives

$$u_t = 430 \text{ cm/s.}$$

Thus, the flexibility of possible operating velocities was determined by u_{mf} (19 cm/s) and u_t (430 cm/s). The ratio of u_t/u_{mf} for 0.5 mm glass spheres tested was 23:1. Although, according to these figures, the maximum allowable fluidization velocity was 430 cm/s, the maximum achievable velocity using the two centrifugal blowers was limited to 120 cm/s when using a No. 2 gas distributor.

Reynolds number, Re , can be calculated by the following formula for the total flow approaching the distributor.

$$\text{Re} = D u / \nu$$

For typical operating conditions, $u = 67 \text{ cm/s}$, $D = 20.5 \text{ cm}$, fluidizing air is at ambient temperatures, thus $\text{Re} = 9517$, as shown in Figure 7. For most operating conditions, the Reynolds Number is greater than 3,000, so the orifice coefficient takes a constant value of 0.59.

The quality of particle fluidization was determined by the direct visual observation of bed motion through the transparent Plexiglas walls. Also, a static pressure distribution in the fluidized bed also indicated the general quality of fluidization. Figure 8 presents a typical result of the static pressure contour in a horizontal plane, right above the distributor for a fluidized bed, loaded with glass beads to a static bed height of 8 cm. The pressure contour was measured by traversing the pressure probe in the horizontal plane. It was found that the static pressure varies only in a small range (80-89 mm of water). This result indicates that the quality of fluidization is reasonable and sufficient for the purposes of this study.

Figure 7 Orifice Coefficient for Perforated Plate in the Fluidized Bed

Figure 8 Pressure Contour in a Horizontal Plane above the the Distributor in the Bench-scale Fluidized Bed

(b) ELEVATED TEMPERATURE EROSION TESTER

The material wastage tests were carried out in an elevated temperature blast nozzle type of tester to simulate material wastage of in-bed tubes in the bubbling fluidized bed combustor (BFBC). The detailed instrumentation of this equipment is discussed in section.

(c) FLOW MEASURING INSTRUMENTS

(i) Pitot Probe for Measurement of Gas Velocity

To measure gas velocity, a Pitot probe was mounted along the center of the inlet PVC pipe and connected to an inclined oil manometer. From this instrumentation, the superficial velocity of the fluidizing gas (u_m) was determined by substituting the manometer reading (h), of the pressure differential into the following equations:

$$\begin{aligned}u_m [\text{cm/s}] &= (14/15) \times 2045 \times (h)^{1/2} \\&= 1909 \times [h(\text{inch-of-water})]^{1/2} \\V [\text{liters/s}] &= u_m \times \text{Pipe Area} \\&= 1909 \times (h)^{1/2} \times 3.1416 \times 2.54^2/1000 \\&= 38.7 \times [h(\text{inch-of-water})]^{1/2} \\u [\text{cm/s}] &= u_m \times \text{Pipe Area/Distributor Area} \\&= 1909 \times (h)^{1/2} \times 3.1416 \times (2.54/20.0)^2 \\&= 96.7 \times [h(\text{inch-of-water})]^{1/2}\end{aligned}$$

(ii) Pressure Taps for Static Gas Pressure Measurements

The static pressure in the system was monitored by means of four pressure taps located on the side wall of the fluidized bed and one pressure tap located on the wall of the wind box.

These taps were connected to five separate water column manometers which were dyed red to facilitate observation. Static pressure was visually read from the manometers.

3. EROSION MEASURING INSTRUMENTS

(a) Electrostatic Impact Probes

An electrostatic impact probe was employed in this study to explore the solid flow pattern and to measure the particle-tube collision frequency in the fluidized bed. The impact probe generates signals from collisions using a working principle derived from charge transfer due to the triboelectric effect. In short, solid surfaces of different materials normally have Fermi energies and distinct work functions [12]. The work function is the potential barrier that an electron must overcome to leave the solid material. The energy level diagram and the resultant contact potential of two bodies before and after contact are schematically shown in Figure 9. If the Fermi energies of the materials are denoted as E_{f1} and E_{f2} , and the work functions as ϕ_1 and ϕ_2 , then bringing the two uncharged bodies (a particle and a probe sensor tip) into contact for a period of time establishes the equilibrium condition by making the contact potential difference $V_1 - V_2$ compensate for $E_{f1} - E_{f2}$. Figure 9 shows this compensation. This compensation is the charge transfer mentioned above. These charge transfers, converted to voltage pulses by means of a charge-to-voltage converter, are then amplified by a variable-gain amplifier circuit composed of an operational amplifier (TL084 CN), two resistors, and a feedback capacitor (100 pf). The analog voltage signals are finally transformed into digital signals using adjustable Schmitt trigger circuits. They are then recorded, and displayed by a multi-function frequency counter. Figure 10 shows the converting/amplifying circuit in detail.

This system of measuring collision frequency was verified using a point probe and a tube

(a) After Contact

(b) Before Contact

Figure 9 Schematic Diagram of Energy Levels and Contact Potentials for Two Bodies in Contact

Figure 10 Schematic Diagram of the Associated Signal/Circuit Processing Unit

probe. The diameters of the inner copper sensors, of the impact probes, were selected to be in the range of 0.7 mm to 10 mm for testing collisions with glass beads of 0.5 mm diameter. A copper wire with a 0.7 mm diameter, in a shielded coaxial, was used for the sensor. Under this condition, the probability of having two or more particles striking the sensor at the same time was minimized, thus reducing the likelihood of false counting and electronic noise during testing. An aluminum tube with a 19 mm OD was used as a shielding and supporting tube and was constructed with the same dimensions as the target tubes used in the erosion tests.

The tube probe was designed to simulate the embedded tube for the erosion tests in the bench-scale FBC system, as shown in Figure 11. Two sensor tips were made in opposite directions on the tube surface at the middle point. This design was chosen to provide simultaneous measurement of particle collisions at opposite points of the target tube under the same test conditions.

Verification of the working principle of the electrostatic impact probe was established through testing. First, a compressed air jet was directed at the probe to determine whether or not simple pressure could cause a false collision reading. No reading resulted, thus removing the possibility that vibration of the probe tip by air or particles impacting on anything other than directly on the probe tip, could cause false readings. Additionally, as fluidizing air increased, the readings of the impact probe increased as the air velocity increased. This was expected, since increasing the air velocity increases particle movement and collision frequency. Finally, results of collision frequency using this probe for measurement were consistent and reproducible.

The electrostatic impact probe was designed in two ways: an I-shape probe and a Dummy Tube probe. In the I-shape probe, the probe instrumentation was inserted vertically downward into the exploratory fluidizing bed. The Dummy Tube probe, designed to simulate the

Figure 11 Schematic Diagram of the Electrostatic Impact Probes/Associated Signal Processing Unit

embedded test tubes for the FBC model, was located horizontally in the bed, as the test tubes were, and provided data on collision frequency for the tested tubes. Figure 11 depicts the uses and designs of the electrostatic impact probes.

(b) Balance for Weight Loss Measurement

A precision electric balance was used to measure the weight loss occurring in test specimens during the test intervals. This information was needed as an indicator of the material loss occurring due to erosion. The balance, a Model XE-100A from Fisher Scientific, was connected to a personal computer/printer for efficient data analysis.

(c) Microscope for Surface Evaluation

A mono-specular microscope (Model EH, Fisher Scientific) was used to examine the surfaces of the eroded test tubes. The information gained from this analysis concerned the mechanisms of erosion, the presence of embedded particles, and the shape of the test particles. The microscope had an adjustable magnification from 40X to 1000X, sufficient for the task at hand.

(d.1) EROSION MECHANISMS: THEORY AND OBSERVATIONS

Mathematical modeling of gas-particle flow in the fluidized bed with an in-bed tube can be pursued to explore the particle motion and its effect on tube erosion. An erosion model is expected to describe and to analyze the experimental results of in-bed tube erosion in the FBC model. The comparison of different erosion models might be useful to understand the phenomena of in-bed erosion. Currently, two types of modeling exist that might be helpful in

understanding the nature of in-bed tube erosion. The first of these, the single particle model, counters the interaction of a single particle with a tube wall. Depending on the specific model, the wall material is assumed to be removed in either a purely ductile mode, a purely brittle mode, or a combination of ductile and brittle modes. This group of models may be appropriate for understanding erosion phenomena in diluted solid suspensions, such as those found in pneumatic conveying pipelines and elbows or turbine blade cascades [13,14]. The second type of modeling is the fluid mechanic model, which attempts to add fluid mechanics to the single particle model. While useful, this model still incorporates particle velocities and impact angles into the models, rather than incorporating the local properties which cause those velocities and angles. In addition, these models (as do the first type) fail to account directly for particle fragmentation and particle concentration in the fluid stream. Current models can be extended and modified by the addition of portions of other models; such as using the particle impact velocity to estimate the portion of kinetic energy transferred to the tube surface, and in turn estimating the material removal. However, a purely empirical erosion correlation is not sufficient to explain the phenomenon. It is hoped that, with sufficient modification, an erosion model can be developed that will explain the erosion phenomenon and the methodology of computing erosion patterns in the fluidized bed, using hydrodynamic models of fluidization.

Since no complete model of the erosion phenomenon currently exists, empirical observation is required to determine the relative importance of different factors in the erosion problem. In general, the extent of surface wastage, or erosion, caused by the impingement of abrasive particles in FBCs depends on the nature of target tube materials. Specifically, material properties, tube orientation and curvature, and surface condition depend on the properties of impacting particles, particularly particle type and grade, mechanical properties, size, and

sphericity. They also rely on system operation condition, notably, particle impinging velocity, collision frequency, impact angle, and operation temperature and pressure. Each of these topics was researched in the development of the FBC model and will be discussed in detail in this section to provide a coherent picture of the erosion mechanism including target tube materials, material properties, tube orientation and curvature, the surface condition, and different particle velocities. Hard bed particles such as silica sand are more erosive than softer solids such as dolomite or limestone. Also, the presence of a deposit layer of coal char or bed materials on in-bed tubes can prevent tube wastage even when scouring action from bed particles is present.

(d.2) OPERATING CONDITIONS

Erosion of in-bed tubes may result from a variety of impacting conditions, including high velocity single particle impact, multiple particle impact, or an abrasive action of bed particles that are being pressed against the tube surface under the influence of bed forces. In-bed tubes may also be eroded by low-velocity (stress) particles in the emulsion phase by particles passing onto the surface by a block or other particles, by relatively fast-moving particles in the wakes of bubbles, by particles thrown to the tube surface because of bubble collapse, by local air jets associated with particle injection and recirculation ports, and by long-term, slow-moving particles. To simplify the causes of in-bed tube erosion, Figure 12 shows the types of interaction between solid particles and target tube surfaces, classified into three basic categories: impaction, interception, and diffusion. These classifications are based upon the relative velocity between the surface of the particle and upon the mass of the solid particle [15]. Impaction, the first type of interaction, occurs when a solid particle moves at a high velocity toward a tube surface; erosion is the result of the particle impinging upon the tube surface. The second type

Figure 12 The Schematic Diagram of Particle Paths near the In-Bed Tube in the Anti-Erosion Provisions

of interaction, interception, occurs when traveling particles are unable to follow the streamlines through the tube, as occurs when the tube flow changes direction. The type of interaction, diffusion, occurs as coal is fed into the FBC. During this operation, the mixing of particles is intensive. Tube orientation and locations also affect the erosion rate, as shown in Figure 13, which is discussed in Chapter 6-b. The presence of tubes within the bed decreases the rate of solid particle mixing, primarily because the particles impact upon the tubes. Erosion due to the diffusion mechanism is proportional to the fluidization velocity and bubble size [16]. In addition to the mechanisms listed above, erosion also occurs when significant particle movement is caused by the gas bubbles.

(d.3) DESIGN AND FABRICATION OF THE PROTOTYPE DUST COLLECTOR

Because gas bubbles rise and erupt at the bed surface, they splash solid particles into the freeboard of the cold flow model. If the exhaust system is installed immediately above the bed surface, considerable amounts of solids would be entrained by the gas. The prototype dust collector was designed and fabricated to collect fine particles through the test section of the fluidized bed, which was installed on the top of the fluidized bed, as shown in Figure 3. As shown in Figure 3, this exhaust measures 21.5 cm x 21.5 cm, with a height of 15.24 cm, which may give us the option of utilizing one or two filters. One filter at the base of the exhaust cover and one filter at the top portion were connected to a PVC pipe of 3.8 cm diameter. The bottom filter should have covered the entire base of the exhaust section to capture some large particles that are blown through the exhaust section. The sponge or perforated wire mesh are suitable for use as this filter. This exhaust system was very effective for collecting fine particles during the experimental testing.

Figure 13 Effect of Tube Orientation and Location on In-Bed Tube Erosion Tube Size $1.7\phi \times 18 \text{ cm}$, T-to-D Clearance Measured based on the Bottom of Tube Center)

4. DESIGN AND CONFIGURATION OF THE ELECTROSTATIC IMPACT PROBE

Electrostatic impact probes, for measuring the particle-surface collision frequency, were designed to verify some of the measurement points and to identify the primary erosion points. The working principle of an electrostatic impact probe, for measuring particle-tube collision frequency, is based on the charge transfer due to the triboelectric effect [17].

As shown in Figure 10, two versions of the electrostatic impact probe, namely the point probe, are being designed and fabricated to explore the solid flow pattern and to measure the particle-tube collision frequency in the fluidized bed. The impact probe generates charge signals from the successive particle-probe collisions. A sequence of converting, amplifying, monitoring, and recording component are employed to measure the total number of collisions per unit in time.

The impact charge signals can be converted into voltage pulses by means of a charge-to-voltage converter. A variable-gain amplifier circuit is used to stretch the signal pulses to match the pulses sampler downstream. In order to count the total number of signal pulses, analog voltage signals are further transformed into digital signals by a set of adjustable Schmitt trigger circuits. The digital signals can then be recorded and displayed by a multi-function frequency counter.

The instrument tube probe was designed to simulate the embedded tube for the erosion tests in the FBC model, as shown in Figure 10. The aluminum tube, used as the shielding and supporting stem, is made in the same dimensions as one of the test tubes (wax cylinder). Two 0.7 mm copper sensor tips are glued into the opposite holes on the tube surfaces. This design provides simultaneous measurements of particle collisions at the opposite points of the target tube under the same testing conditions.

(a) Working Principle of the Electrostatic Impact Probe

Design and fabrication of the electrostatic impact probe were continued for measuring particle-tube collision frequency in the fluidized bed under the various experimental conditions.

The working principle of the electrostatic impact probe, for measuring tube-particle collision frequency in a fluidized bed, is based on the charge transfer due to the triboelectric effect, as outlined below.

Solid surfaces of different materials normally have Fermi energies and distinct work functions [12]. The work function is the potential barrier that an electron must overcome to leave the solid material. The energy-level diagram and the resultant contact potential of two bodies before and after contact are schematically shown in Figure 9.

The Fermi energies of the materials are denoted as E_{F1} and E_{F2} . When two uncharged bodies (for instance, particle and probe sensor tips) with different work functions ϕ_1 and ϕ_2 are brought into contact for a period of time, an equilibrium condition is established. Therefore, the contact potential difference $V_1 - V_2$ is arranged to compensate $E_{F1} - E_{F2}$, as shown in Figure 9. The charge transfer phenomena, between two bodies, follows the triboelectric process [12]. When glass beads in the fluidized bed strike the impact copper-probe sensor, the probe may carry the negative charge and the glass beads will be positively charged.

(b) The Characteristics of the Electrostatic Impact Probe

The electrostatic probe was designed to serve as an impact transducer to generate impact charge signals. The series of converting/amplifying network circuit was built to count the number of charge signals, as shown in Figure 9. The power supply was also built in the laboratory to supply appropriate voltages to IC components/signal processing unit. A center tap

transformer was used to step down 120 volts to 36 volts, and was installed at ground potential along with a connection of ground circuit. The positive and negative unregulated voltages across the capacitor are applied to the input of the positive and negative IC regulator, respectively [18].

The charge signals are first converted into voltage signals by means of a charge-to-voltage (Q-to-V) converter, which is combined with an operational amplifier (TL084 CN), two resistors, and a feedback capacitor (100 pf), as shown in Figure 10. A simple amplifier circuit was used to apply the converted signals and forward them to the pulse sampler at the downstream. The analog voltage signals are transformed into digital signals by the pulse sampler, which corresponds to the particle-sensor collision. The digital signals are then recorded and displayed by a digital frequency counter.

The point probe and the tube probe were designed to verify the working principle. The diameters of the inner copper sensors of the impact probes were selected to be in the range of 0.7 mm to 10 mm for testing glass beads of a 0.5 mm diameter. A copper wire of 0.7 mm diameter, in a shielded coaxial, was used for the sensor. Under this condition, the probability of having two or more particles striking on the sensor at the same time is very unlikely. Problems of false counting and electronic noises can be minimized during the tests. An aluminum tube with a 19 mm OD is used as shielding and a supporting tube is made with the same dimensions of the target tubes in the erosion tests.

The tube probe was designed to simulate the embedded tube for the erosion tests in the bench-scale FBC system, as shown in Figure 11. Two sensor tips were faced in the opposite direction on the tube surface at the middle point. This design provides simultaneous measurements of the particle collisions at two opposite points of the target tube under the same testing condition. When the particles touch the probe sensor, an impact charge signal will be generated

and stored by the associated electronic circuits.

To verify the working principle of the electrostatic impact probe and establish the reliability of probe readings, several tests were performed. When the compressed air jet was suddenly directed to the probe sensor tip, no electric charge signals were generated or detected by the impulse force. This indicated that the vibration of the probe tip, caused by the impact of the moving particles, would not affect the probe readings. When the fluidizing air increased, the readings of the impact probes increased with the air velocity. The impact signals could not be generated without the particle-surface contact. The number of impact particles could be conveniently read from the frequency counter by the impact probe. Test results of collision frequency, when using this probe, were reproducible and consistent in the bench-scale fluidized bed system.

(c) Instrumentation for the particle-tube collision frequency measurement

To measure the particle-tube collision frequency, a bench-scale cold fluidized bed system was used. The instrumented tube probe was designed to simulate the embedded tube for measuring the maximum wastage loss, as discussed previously. The aluminum tube was glued onto the tube surface. This design is used to provide measurement of particle-tube collision frequency at the peripheral location of the tube. The working principle of the impact probe was tested and the measurement error was assessed. No signals were generated when there were not direct contacts between the probe and the particles. Even when the pressurized air jet from the compressor was suddenly directed to the probe sensor tip, no electrical signals were generated by this impulse force. This demonstrates that the vibration of the probe tip, caused by the particle's impact, will not result in signals. Three different types of impact probes were also

used to measure the collision frequencies along the major flow directions at the various locations in the fluidized bed.

(d) Instrumentation for metal wastage measurement

In order to simulate material wastage of in-bed tubes in the BFBC [19], the tests were carried out in an elevated temperature blast nozzle type of tester, as shown in Figure 14. Air was utilized as the carrier gas for the particles, thereby creating a generally oxidizing atmosphere at elevated temperatures. Erosive particles flowed down a vibrating tube into a chamber where they were mixed with incoming heated air. The velocity of the heated air propelled the particles down a nozzle where they impacted the specimen. Temperatures from 20°C to 850°C were achievable with a temperature variation not exceeding 10°C over the test range. Particle velocity was established by setting a pressure drop across the nozzle using a meeting system that was connected to an air compressor. The air pressures were determined by using a calculation program of two-phase particle flow [20].

The target material for the test was AISI 1018 plain carbon steel, which is commonly used in in-bed tubes of BFBC. Quartz silica (SiO_2) particles with an average size of 741 μm was used for the erosive material, which is a primary constituent of bed materials. Although the particle primarily consisted of Si (as SiO_2), they also contained a minor amount of Al (as Al_2O_3). Figure 15 shows an appearance of SiO_2 quartz particles and particles size distribution. The mean particle density was 2556 kg/m^3 .

All tests were carried out at a test temperature of 300°C, and at impact angles of 30°, 45°, and 90°. Additional test conditions included a test time of 96 hours, using a particle loading of 9000 g and a particle velocity of 2.5 m/s. The material wastage of the specimen was predicted by weight measurements, which was weighed after the test period on a balance with a resolution

Fig. 14 Schematic diagram of elevated temperature material wastage tester.

Fig. 2a Particles appearance of SiO_2 quartz.

Fig. 15 Particle size distribution of quartz .

of 0.1 mg. The metal wastage of the specimen was also determined by microscopic dimensional measurements of cross-sections through the area of greatest metal loss to determine the thickness of the remaining sound metal. This experiment was conducted by collaborative efforts of the private sector; the Metallurgical Laboratory of Metal Spray, Inc. in Richmond, Virginia.

In our own experiments, all the tests were carried out at a test temperature of 300°, and at impact angles of 30°, 45°, and 90°. Our testing conditions also included a test time of four hours, using a particle loading of 375 g and a particle velocity of 2.5 m/s. The erosive wear of the test specimens was determined by weight measurements and by measuring the thickness change of the specimens through the area of greatest material loss, the remaining oxide scale and erosive deposition on the surface. The material wastage loss of the specimens, which was weighed after the test period using an electronic balance with a resolution of 0.1 mg, was predicted by weight measurements. The morphologies of the specimens were examined and analyzed by implementing scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS).

5. Collision Frequency Measurements

(a) Particle-probe Collision Frequency by Point Probe

Measurements of the particle-probe collision frequency in the fluidized bed were conducted to understand major parameter characteristics of tube erosion. Two series of tests were conducted by a point probe. In one test, the probe traversed vertically along the bed axis; while in the other, the probe traversed from the center position to the quarter point of the bed diagonal and the wall section.

The particle-probe collision frequency of the lateral moving particles at the center

(position 1) were much lower than those near the wall (position 12). When the probe was close to the distributor, the collision frequency was increased, as shown in Figure 16. The particle-probe collision frequency of outward flowing particles is shown in Figure 17. The collision frequency near the wall showed a similar trend of declining particle-probe collision frequencies.

Since the collision frequency indicates the total number of particle impacts per unit time through the probe tip area (also called the particle number flux), it is directly related to the product of the local particle velocity and the particle phase density (concentration). In the dense fluidized bed, the average particle phase density remained constant [21]. The measured collision frequency indicated that the particle velocity varied according to bed height, bubble velocity and bubble distribution.

The measured collision frequency generally represented the particle phase density, and decreased rapidly when the height was increased. The average particle flow pattern and distribution in the fluidized bed could be explored by measuring collision frequencies along the different flow directions of the bed. In general, the mean particle flow pattern, revealed by the present measurements, is in agreement with the results of the radioactive particle tracking techniques [22].

(b) Particle-tube collision frequency

Measurements of particle-tube collision frequencies were conducted in the fluidized bed with a static bed height of 11 cm, an active bed height of 18.5 cm, and a superficial fluidizing velocity of 64 cm/s. The experiment with the probe traversing vertically along the bed axis was conducted. Figure 18 shows the axial distribution of the particle-probe collision frequencies of the ascending particles, descending particles, and laterally moving particles at the center of the

Figure 16 Particle-Probe Collision Frequency by an Impact Point Probe at Different Heights/Positions

Figure 17 Particle-Probe Collision Frequency by an Impact Point Probe for Wall Region in the Bench-Scale Fluidized Bed System

fluidized bed.

As seen in Figure 18, the ascending particles exhibited a minimum collision at 3.5 cm and 11.5 cm above the distributor. The descending particles exhibited two peaks (minimum collisions) and one valley. It is evident that the ascending-particles curve and the descending-particles curve exhibit almost opposite behavior. The particle's interest lies in finding that almost all the peaks and the valleys appeared in a consistent way near location Nos. 1, 2, and 3. At location No.1 of Figure 18, the highest measured count of particle collision frequency, was in the ascending particles. Therefore, the mean local particle velocity at location No.1 should be upward. Similarly, the mean local particle velocity at location No.2 should move sideways, and at location No.3, the mean local particle velocity should point downward. In the dense fluidized bed, the averaged particle phase density remained roughly constant. The measured collision frequency thus indicated the particle velocity which varies with the location of the bed, bubble velocity, and bubble distribution.

In order to identify the effects of particle impact on the material wastage of in-bed tubes, a series of measurements were conducted to determine the peripheral distribution of the collision frequencies. Measurements of the collision frequencies at different circumferential locations were made by rotating the tube. This data was the averaged values taken over 50 seconds of measurements with 0.55 mm glass beads at 64 cm/s fluidizing velocity.

It can be seen in Figure 19 that more particles collided on the lower half of the tube than did on the upper half of the tube. In the diluted freeboard, the measured collision frequency generally represented the particle phase density, which decreased rapidly when the height was increased. The highest particle impact was found at about 45°, 315° and apart from the bottom center of the target tube, 0°, as shown in Figure 19.

Fig. 18 Results of particle-probe collision frequency measured by I-, J-, and L-shape impact probe at different heights along the bed axis.

Fig. 19 Particle collision frequency of a horizontal tube immersed at superficial velocity of 64 cm/s.

6. EROSION MEASUREMENTS AT AN AMBIENT TEMPERATURE CONDITION

(a) Effect of Superficial Fluidizing Velocity

The erosion measurement was conducted under different superficial fluidizing velocity. The superficial fluidizing velocity is defined as the mean air velocity in the fluidized bed in the absence of particles. The air flow rate could be varied by controlling the two blowers' speeds. Twenty five data points, each requiring five hours of testing were obtained for the in-bed tubes at 3 cm and 5 cm clearances. Results of specific weight loss were plotted versus the excess air velocity (air velocity above the minimum fluidization velocity, $u - u_{mf}$) in Figure 20.

The minimum fluidized velocity is defined at the onset of fluidization, which occurs when the drag force exerted by upward moving gas equals the weight of the bed particles. It is of great interest to note that the erosion occurred at a velocity (26 cm/s) above the minimum fluidizing velocity (19 cm/s), for 0.55 mm glass beds, and increased with increasing superficial velocity. This threshold velocity, caused by an abrupt change, is believed to be related to the bubbling velocity of bed particles [23,24].

It was found that the bed particles may vigorously interact with each other and with the target tube specimen below the threshold velocity, but no apparent weight loss can be detected. Above the threshold velocity, the tube erosion was found to increase almost linearly with increasing fluidized velocity. A modified power law representation suggests that:

$$\Delta M/A \text{ (mg/cm}^2\text{)} = (\Delta A/A)_o + C (u - u_{mf}(\text{cm}))^m$$

where subscript o denotes the threshold condition. The least squares method [25] was employed to determine the power law constant C and exponent m in the above equation. In general, the exponent m ranges from 1.0 to 1.3, depending primarily upon the location of the target cylinder in the fluidized bed system.

Figure 20 Effect of Superficial Fluidizing Velocity on In-Bed Tube Erosion

(b) Effect of Tube Orientation and Location

In order to study the effects of tube orientations on in-bed tube erosion, the experiments were conducted with wax cylinders mounted at the bed center. The test tube was arranged at four different inclined angles (0° , 30° , 60° , and 90°). For successive test runs, the sample tubes were also placed horizontally and vertically (at the center and vertically near the wall) to quantify the effects of the tube location.

Figure 13 shows the averaged specific erosion rate for the embedded tube in a bed with 0.55 mm glass beads at superficial fluidizing velocity of 67 cm/s. The sample tubes were tested at the above bed conditions for three hours for different tube locations and orientations. The averaged specific erosion rates for 0° , 30° , 60° , and 90° , were found to be 0.58, 0.49, 0.34 and $0.27/\text{cm}^2 \text{ hr}$, respectively. Horizontal tubes were found to experience a weight loss of about 215% of that which vertical tubes lost under the same conditions. The specific erosion rate of the vertical tube near the wall was found to be only $0.15 \text{ mg}/\text{cm}^2\text{hr}$, being 55% of that of the tube in the core region. These results agree with other observations which show that the erosion rate of the horizontal tubes is more serious than in the inclined and vertical tubes [26].

Results of the single tube erosion test also plotted against the angular orientation, as shown in Figure 13. The specific weight loss of a horizontal tube is $1.74 \text{ mg}/\text{cm}^2$, which is about two times that of a vertical tube near the wall. The influence of the tube orientation and location was much more pronounced for the horizontal tube than for the inclined tube.

(c) Effect of Tube-to-Distributor Clearance

The target tube was horizontally placed in the fluidized bed filled with 0.5 mm diameter glass beads. The distance between the top surface of the distributor plate and the bottom line of

the test tube and the tube-to-distributor (T-to-D) clearance was carefully adjusted to be 3 cm, 5 cm, and 7 cm, respectively. The superficial fluidizing velocity was kept fixed during each experimental run. The mass of the test tube was precisely measured by a digital balance at one hour intervals up to a total of four hours testing time for different tube materials (wax, PVC, and aluminum). The single tube erosion tests were repeated for low (26 cm/s), medium (67 cm/s), and high (85 cm/s) superficial fluidizing velocities. Since tube erosion processes are surface-related phenomena, the measured total weight loss was divided by the exposure area to obtain the specific weight loss in order to provide a fair comparison among data from experimental runs of different tube sizes. Properties and dimensions of test tubes are summarized in Table 2.

Table 2
Properties and Dimensions of Test Tubes

Target Material	Whitewax	PVC	Aluminum
Compressive Strength (psi)	230	10,150	31,200
Surface Hardness (Mohs)	0.2	3	-
Material Density	0.91	1.38	2.71
Single Tested Tube:			
	Dimension (cm)	1.7 X 18	
	Surface Area (cm ²)	96.1	

Figure 21 shows the effect of T-to-D clearance on the tube's specific weight loss for low, medium, and high superficial velocities. For the wax cylinder, the tube's specific weight loss at 3 cm clearance was 0.98 mg/cm^2 , which was two times that of the 5 cm clearance tube (0.45 mg/cm^2) and four times that of the 7 cm clearance tube (0.25 mg/cm^2), at medium fluidizing velocity (67 cm/s). For the PVC tube, the specific weight loss at 3 cm was 0.42 mg/cm^2 , which was two times that of the 7 cm clearance tube. For the aluminum tube, the specific weight loss at 3 cm clearance was 0.27 mg/cm^2 , being three times that of the aluminum tube at 3 cm clearance.

It can be calculated from Figure 21 that the average specific erosions were 0.4., 0.2, and $0.1 \text{ mg/cm}^2/\text{hr}$ for four hour tests at 3, 5, and 7 cm clearances. The results for wax cylinders were about two orders of magnitude higher than the steel tubes in the practical PFBC boiler system [27]. This permits us to explore the current approach of using erosion-prone material with the qualitative behavior of in-bed tube erosion in a reasonably short time.

The tube specific weight loss decreased with increasing tube-to-distributor clearance. This was because high velocity jets from the orifices near the distributor carried more bed particles to strike on the lower half of the tubes causing serious erosion. The influence of local air jets diminished as they penetrated through the bed. This could be seen by examining the bottom surface condition of the eroded tubes. The present observation of the local jetting effect may explain the existing problem of severe erosion of in-bed tubes that werewlose to solids reinjection ports, pneumatic feeding points, and broken-off air nozzles in a circulating FBC boiler [28]. The effect of fluidizing velocity is also indicated in Figure 21. The tube erosion was increased with increasing velocities.

Figure 21 Effect of Tube-to-Distributor Clearance on In-Bed Tube Erosion at Different Fluidization Velocities

7. Metal Wastage Tests at an Elevated Temperature Condition

(a) Test Results/Discussion at Low Particle Velocity

A series of the metal wastage test was carried out on AISI 1018 low carbon steel at an elevated temperature condition (300°C) with different particle impact velocities. At both low velocity (2.5 m/s) and high velocity (30 m/s), the metal wastage rate of AISI steel specimens demonstrated higher wastage at shallow angles rather than at steep angles, with a maximum erosion rate occurring at a 45° impinging angle, as shown in Figure 22. For low velocity, the thickness loss was increased from 8 μm to 14 μm at a 90° impinging angle as compared with that at 45°. For high velocity, it was increased from 49 μm to 86 μm , respectively. It can be seen that the erosion wastage rates at a low particle velocity were two to three orders of magnitude lower than those at a high particle velocity.

These results are correlated with the material wastage observations of in-bed steel tubes in FBCs [29]. In the operating of actual AFBC boilers, the maximum wastage occurred at approximately 30° to 45° to either side of the center line [22], in other words, at the bottom 135° and 225° [30]. Typically, ductile materials exhibit maximum wastage at shallow impact angles, whereas the brittle materials exhibit maximum erosion at steep impact angles. In these tests, the higher angle of maximum erosion for the 1018 steel (a ductile material) was attributed to the formation of a thin oxide scale on the surface of the 1018 steel, which would influence the erosion mechanisms.

It is known that the mass removal process of the in-bed tube of the FBC is effected by the particle impact velocity. The test results indicated that the bottom surface had a higher wastage rate due to the frequent particle impacts, while the top tube surface had a lower wastage rate due to less particle collisions.

V =2.5 m/s, t = 96 hrs. loading 9000 g

V=30 m/s, t=4 hrs. loading 375 g

Figure 22 Erosion Wastage for 1018 Low Carbon Steel Specimen Eroded at Different Test Conditions.

For the low particle velocity (2.5 m/s), the oxidation of the surrounding surfaces after 96 hours test period was combined with very low erosion wastage rates which accounted for the weight gain of specimens tested at particle impact angles of 30° and 90°. At the low particle velocity, the oxide scale-particle deposition layer developed at an elevated temperature condition (300°C), which caused less wastage loss, as shown in Figure 23.

Figure 23 shows the surfaces and cross sections of the specimens at three different particle impact angles for the low particle velocity (2.5 m/s). It can be seen that a thin, continuous scale layer formed on the surface of the AISI 1018 steel specimens at the 30° and 45° angles, while a discontinuous scale layer formed on the surface at 90°, as shown in Figure 23. A great amount of erosive particles was also embedded in the worn surface as proven by the energy-dispersive spectroscopy (EDS) analysis. Figure 23 shows the different morphologies of surfaces at the three different impact angles. The maximum material wastage occurred at an impact angle of 45°. When the thickness loss at 90° was compared with that at the 30° angle, thickness loss was increased from 8 μm to 14 μm .

(b) Test Results/Discussion at High Particle Velocity

The metal wastage test was also conducted to observe the erosion phenomena at a relatively high velocity (30 m/s) during the test period of four hours. The shortest exposure time could minimize the oxide scale formation and potential weight gain at an elevated temperature condition (300°C). The maximum material wastage occurred at an impact angle of 45°, as shown in Figure 24. The relatively low erosion wastage rates were counted at particle impact angles of 30°, and 90°. A possible reason for this is considered to be the influence of the particle velocity on the metal wastage.

(A) Eroded surface.

tested at $V=2.5$ m/s and $\alpha=30^\circ$.

(B) Cross-section.

(A) Eroded surface.

tested at $V=2.5$ m/s and $\alpha=45^\circ$.

(B) Cross-section.

(A) Eroded surface.

tested at $V=2.5$ m/s and $\alpha=90^\circ$.

(B) Cross-section.

Fig. 23 Surface, cross-section and EDS peak analyses of 1018 steel material wastage at low particle velocity, 2.5m/s.

Figures 24-A to 24-C show the surface and cross sections of the specimens tested at three different angles. No oxidation layer could be seen on the worn surface. Figure 24-B shows the eroded surface of the specimen at an impact angle of 45°. The eroded surface of the specimen exhibited the typical ductile erosion behavior as indicated by craters, striations, platelet formation and plastic flow [21]. Some broken pieces of erosive particles (SiO_2) embedded in the surface and pushed down into the soft metal. This might result in a severely convoluted surface interface, which was analyzed by energy dispersive spectroscopy (EDS). Results are shown in Figure 24-D.

The metal wastage rate of AISI 1018 carbon steel demonstrated higher wastage at a shallow angle rather than at a steep angle, with a maximum erosion rate occurring at an impact angle of 45°. These results also correlate to erosion test results reported [29]. In operating AFBC boilers, the maximum wastage of in-bed carbon steel tubes occurred at an angle of 30° to 45° on either side of the center tube [22], or bottom portion of 135° and 225° [30]. Typically, ductile materials exhibit maximum wastage at shallow impact angles, whereas brittle materials exhibit maximum wastage at steep impact angles, whereas brittle materials exhibit maximum wastage at steep impact angles.

Anti-Erosion Devices: Principle and Design

(a) Characteristics of Anti-Erosion Design Considerations

The material wastage of in-bed tube surfaces is a problem which has become increasingly important to the designer of bubbling fluidized bed combustors. As the operational experience has increased, the problem of material wastage has become more widely reported. In-bed tube erosion is a problem of the fluidized bed combustion systems for which no simple remedy is

(1) Eroded surface

(2) Cross section

Fig. 24-A 1018 specimen tested at $V = 30$ m/s and $\alpha = 30^\circ$

(1) Eroded surface

(2) Cross section

Fig. 24-B 1018 specimen tested at $V=30$ m/s and $\alpha=45^\circ$

(1) Eroded surface

(2) Cross section.

Fig. 24-C 1018 specimen tested at $V = 30 \text{ m/s}$ and $\alpha = 90^\circ$

Fig. 24-D EDS spectra collected from eroded surface of 1018 specimen tested at high particle velocity

available. Some basic design guidelines are being identified, but the prediction of the life expectancy of in-bed tubes remains an art which currently relies more upon experience than theories [32].

The remedies for in-bed tube erosion can include the following:

- o fitting protective systems
- o changing system variables
- o consideration of alternative materials for tubing
- o surface treatments and coating for the tubing

Several factors influence the erosion of the in-bed tube of the cold model: tube position within the bed, the distance of the tube from the distributor, bed materials and particle size, location along the tube circumference, and the use of the flow disruptive devices.

(i) Design and Approach

It is suggested that if a successful plant is to be designed with a minimum risk of tube wastage problems, a number of points should be addressed before a detailed design is commenced.

Main considerations for the designer are:

- o to acknowledge that the tube material wastage exists
- o to consider a cost effective solution addressing both capital and maintenance costs
- o to design for ease of access and maintenance
- o to consider previous experience and learn from catastrophic failures
- o to consider plant operating load pattern
- o to review the possible effects of system variables

(ii) Provide a Cost Effective Design

An FBC system could be designed based on low fluidizing velocities and the best available materials. As an example, the Foster Wheeler power products recently investigated the capital and maintenance cost implications of a variety of alternative solutions to the erosion problem [33]. The cost variations were considered with several options as follows:

- o plain tube
- o finned tube
- o finned and pinned tubes
- o ball-studded tube

(iii) Consider the Effect of System Variables

The factors considered to influence the rate of in-bed tube erosion are as follows:

- o fluidizing velocity
- o bed material
- o bed particle size
- o bundle geometry
- o tube-to-distributor clearance
- o tube material and coating of tube surface
- o tube protection system

(b) The Working Principle and Mechanism of Anti-Erosion Devices

The material wastage of the in-bed tube is mainly caused by erosion. Erosion occurs whenever there is an interaction between erosive solids and in-bed surfaces. As shown in Figure

12, the types of interactions between the solid particles and the target tube surfaces can be classified into three basic categories: impaction, interception, and diffusion. These classifications are based upon the relative velocities between the tube surface; erosion is the result of the particle impinging upon the tube surface. The second type of interaction, interception, occurs when the tube flow changes directions, thus the particles impact upon the tube surface. Feeding coal into the FBC creates gradient fuel concentration. Mixing of solid particles within the bed decreases the rate of solid particle mixing. The measured value of the diffusion coefficient has shown that it was proportional to the fluidization velocity and bubble size [34]. In addition, erosion occurred whenever there was significant solid movement by the gas bubbles [16].

The control of tube erosion can occur either before or after the design of the FBC facility. Clearly, designing for erosion prevention is preferable when it can be protected. The optimal designing for the elimination of erosion would avoid creating those which are vigorous in movement. Since, from observation, the most volatile region in a bed is the center, where most of the bubbles coalesce in an accelerated upward movement, a design for low erosion would avoid this region [16]. However, designing for prevention may not always be practical, as is the case for large utility boilers which use large bed areas for shallow bed operation. In these cases, the remedies currently operate under the basic principle of creating a protective stagnant layer of solids to ward against incoming, high velocity, solid particles. This principle is embodied in the action of anti-erosion studs (or pins), fins, and baffles.

(c) Design and Discussions of Anti-Erosion Devices

As shown in Figure 25, three different types of anti-erosion devices were designed with the goal of breaking up the local flow patterns at the eroding tube surface. These devices will

(a) Ball-Studded (in-line) Tube

(b) Ball-Studded (staggered) Tube

(c) Finned and Ball-Studded Tube

Figure 25 Design Configuration of Anti-Erosion Devices

be used for experiment in the laboratory-scale FBC. The first type of device, the ball studded tube, has two configurations: in-line studding pattern and staggered studding pattern. The pins in both patterns were installed on the tube surface where erosion is observed. By attaching a number of studs using a sufficient stud-to-stud distance to avoid the bridging of solid particles, the tube wastage can be retarded to prolong the boiler tube life.

The recommended stud-stud clearance is to be 3 to 8 times the diameter of the largest bed material in the actual in-bed tube of the FBC. The average bed particle size in a conventional bubbling FBC is about one millimeter in diameter. Additionally, anti-erosion studs leak out the gas from the incoming bubble and reduces its momentum, yielding weaker impacts. The second type of device, the anti-erosion fins can, for an actual FBC, be welded to the wind side or underside of horizontal in-bed tubes in at least three radial locations. Three anti-erosion fins can be attached to the underside of the in-bed tube in the 4, 6, and 8 o'clock positions.

Anti-erosion baffles also can be used to discourage the scouring action of solids carried by the gas bubbles along the vertical positions of the in-bed tubes. The baffles usually take the form of a half-moon shaped disk. The gas bubbles tend to slide along the vertical surface. As long as the vertical movement of solids meets no sharp turns in the tube, the solid is unlikely to impinge on or intercept the tube surface. Subsequently, no significant tube wastage will take place due to the baffles. The tube bundle is extended into the boiler; there are bound to be portions of tube that will be exposed inside the bed in the vertical orientation. Additionally, for deep-bed bubbling FBC, such as pressurized FBC, some in-bed tube bundles were also vertical in configuration.

In the early design of the PFBC pilot plant, erosion was noted on the turns of the horizontal in-bed tube bundles [35]. A number of baffles were welded inside of vertical tubes to build up

a number of solid pockets underneath the inside tube bends. The erosion was stopped instantaneously. Baffles should be used to deter erosions in the vertical wall as well. For small FBC boilers, the in-bed tube designs can be altered to reduce the tube erosion resulting from a vertical design. Instead of conducting the heat extraction at upward movement of the "gulf" action in the central region of the bed, the heat extraction is implemented at the downward movement of the gulf. This is especially feasible for small FBC boilers with an enlarged fluidized bed. Two rows of vertical tubes protrude from the wall right above the expanded bed section and extend all the way up the full length of the vertical expanded walls. As the fuel is introduced to the center of the fluidized bed, vigorous gulf action will take the fuel up to the top and then take it down alongside the enlarged walls. The vertical tube arrangement requires compartmentalized walls to support the vertical in-bed tube bundle. For large utility bubbling FBC boilers, such a design may not be feasible.

(d) Experimental Results and Discussion of Anti-Erosion Devices on Tube Erosion.

The four different types of anti-erosion tubes are: the pinned tube, the ball-studded tube, the finned tube, and the fin/ball studded tube. These were designed and tested to aid in the understanding of the flow disruptive methods of preventing in-bed tube erosion. The ball studded tube had two configurations: an in-line studding pattern and a staggered studding pattern.

Based upon the working principle and mechanisms of anti-erosion devices, these devices were applied to break up the local flow patterns at the surfaces of eroding tubes. The pins were installed on half of the tubes, as shown in Figure 26. For the bare tube, after a four hour testing time, the specific weight loss at 3 cm was 1.42 mg/cm^2 , and the specific weight loss of the pinned tube was 0.87 mg/cm^2 . This indicates that the weight loss of the pinned-tube was 40%

Figure 26 Effect of Anti-Erosion Device on In-Bed Tube Erosion at Different Fluidization Velocities

of that of the bare tube. The specific weight loss versus the excess air velocity in the diagram exhibits a characteristic jump at a threshold velocity of 26 cm/s, this is slightly above the minimum fluidization velocity.

The ball-studded tube with the in-line pattern was less effective in reducing weight loss in the ball-studded tube with the staggered pattern. Figure 27 shows the measured results of the specific weight loss for the different types of anti-erosion tubes. The staggered studding tube had an erosion rate that was three times lower than that of a regular tube. It is believed that the flow drag of the in-line pattern was less than that of the staggered pattern, which permitted a higher particle velocity and, therefore, a higher erosion. By using the finned and the ball-studded tube, in-bed erosion could be reduced more than threefold. According to these results, the finned/ball-studded tube is considered to be the most effective device in terms of tube erosion in FBCs.

A higher weight loss rate was observed on the bottoms of the tubes in the regions of upward moving bubbles relative to the tube surface. The enhanced erosion in the splash zone was considered to be the result of bed material being projected upward by erupting bubbles and striking the bottoms of the tubes [36]. Velocity and frequency of the rising bubbles change with many parameters (eg. particle size, bed height, fluidizing velocity, etc.).

Bubbles interacted with submerged tubes in many ways, depending upon such parameters as bubble size, velocity, tube size, and bed material [16]. Bubbles erupt from the free surface of the fluidized bed in different ways, and each type of eruption process leads to different rates and velocities of particle projection into the freeboard region [37,38].

The main function of protective devices (pins, fins, and balls) is to decrease the bubble momentum and form a stagnant layer of bed material on the tube surface by changing the local flow pattern. Impaction is thus minimized because the protective devices impede the motion of

Figure 27 Effect of Anti-Erosion Device Configuration on In-Bed Tube Erosion

the particles near the surface of the tube. Thereby, the protective stagnant layer of solid particles is able to withstand the incoming high velocity solid particles and prevent them from striking the actual tube surface.

9. Effect of Erosion Resistant Coatings of In-Bed Tube Materials

In order to understand the characteristics of erosion resistant coatings of the in-bed tubes in FBC, different thermal-sprayed coatings were tested under different test conditions. Reducing the material wastage by erosion of in-bed tubes in FBCs is one of the most vital steps in theory development and maintenance for large-scale commercial use. In this study, different resistant coatings are applied to protect the surface of in-bed tube materials as erosion remedies.

Test Conditions

(a) Test Specimens and Materials

AISI 1018 low carbon steel and two thermal-sprayed coatings were used as target materials. High velocity Oxygen (HVOF) thermal spraying (DS-200) was employed as the coating process for one specimen. For the other specimen, wire arc spraying (Armacor M) was employed. The characteristic of the test specimens are listed in Table 3. The test surfaces of the target materials were polished using a succession of SiC paper down to 600 grit prior to testing. Figure 28 shows cross sections of the target coating specimens.

a) HVOF Cr₃C₂-NiCr coating

b) Arc-sprayed FeCrSiB coating

Figure 28 Cross Sections of Target Coating Specimens

Table 3**Characteristics of the Test Specimens**

Target Material	Application Process	Normal Composition	Thickness (um)	Porosity (%)
1018 Steel	---	Fe 0.2C	---	0
DS-200	HVOF	75Cr3C2-25NiCr	566	< 2
Armacor M	Wire ARC Spray	Fe25Cr3B2Si	302	2 - 4

(b) Test Procedures

The tests were carried out in the elevated temperature blast nozzle-type tester to simulate material wastage of in-bed tubes in the FBC. Quartz silica particles having a mean size of 742 μm , and a mean particle density of 2556 kg/m^3 , were used as the erosive particles. The tests were carried out at a temperature of 300°C and impact angles of 30°, 45°, and 90°. With a test time of 96 hours, a low particle impact velocity (2.5 m/s) was applied to simulate the erosion condition [22]. Another test, with a four hour test time and using the same test procedures, was used at a particle loading of 375g. The higher particle impact velocity (30 m/s) was employed to provide comparison with the test results of low particle impact velocity.

The material wastage of the specimen was determined by weight measurements, which were weighed after the test period on the balance with a resolution of 0.1mg. The metal wastage of the specimen was also determined by microscopic dimensional measurements of cross-sections through the area of greatest metal loss to determine the thickness of the remaining sound metal. The morphologies of the specimens were examined and analyzed using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS).

10. Effects of Cooled Thermal-Sprayed Coatings on In-Bed Tube Erosion in Fluidized Bed Combustors

The need to reduce the material wastage which occurs in in-bed tubes in fluidized bed combustors (FBCs) is an important aspect of the development of fossil fuel power generation equipment. Protective surface treatments and coatings have proven to be effective in combating material wastage of in-bed tubes in FBCs [22]. In our previous work, the erosion behavior of AISI 1018 steel and several thermal-sprayed coatings were studied. In other investigations, the isothermal specimens were used. However, in service heat exchanger tubes are usually cooled by water or steam being heated. The tubing is subjected not only to gas-particle mixture, but it also has both a temperature gradient across the thickness of the tube wall, and a positive heat flux during operation. Therefore, the material wastage and mechanism in actual in-bed tubing could be quite different from those determined from isothermal specimens. In this experiment, tests were carried out using cooled specimens, which could be used to investigate the effects of the temperature difference between the gas-particle mixture, and the surface of specimens on material wastage rate, and mechanisms of thermal-sprayed coatings at low velocity erosion conditions.

Experimental Test Conditions

(a) Test Specimens and Materials

Target material for the test were three thermal-sprayed coatings and AISI 1018 steel, which are commonly used in in-bed tubes of FBCs. The characteristics of each target material are listed in Table 4. The microstructures of the three coatings are shown in Figure 29. Angular silica quartz particles were used for erosive material. Their mean particle size was approximately

Material designation	Coating process	Nominal composition	Thickness (μm)	Hardness HVN ₃₀₀	Porosity %
DS-200	HVOF	75Cr ₃ C ₂ -25NiCr	589	614-810	<2
DS-105	HVOF	Cr ₃ C ₂	495	804-990	<2
Rokide C	Flame spray	90Cr ₂ O ₃ -6SiO ₂ -4Al ₂ O ₃	548	1900	4

Table 4 Characteristics of Target Materials

Figure 29 The microstructures of coating specimens: a) HVOF Cr₃C₂-25NiCr coating; b) HVOF Cr₃C₂ coating; c) Flame-sprayed 90Cr₂O₃-6SiO₂-4Al₂O₃ coating.

742 μm with a mean particle density of 2556 kg/m^3 . These particles mainly consisted of silica with a small amount of aluminum.

(b) Test Conditions

Laboratory tests on material wastage were carried out in the elevated temperature blast nozzle type tester. The surface of the specimen was exposed directly to the environmental temperature while the backside of the specimen was water-cooled. The environmental temperature is defined as the temperature of the gas-particle mixture, which affected the surface of cooled specimen. The low particle velocity (2.5 m/s) and low elevated temperature (300°C) simulated the material wastage conditions at the in-bed tube of the FBC. In our previous work, it was found that all the tested coatings exhibited "ductile behavior" as demonstrated by their having higher wastage rates at shallow impact angles rather than at steep impact angles. Thus, this work focused on material wastage at a shallow impact angle (30°). Material wastage rates were determined from the thickness loss measurements of the specimens.

11. Results and Discussions for the Erosion Resistant Coatings

(a) Effect of Erosion Resistant Coatings at a Low Impact Velocity

At low impact velocity, 2.5 m/s , the metal wastage rate of AISI 1018 steel specimens showed higher wastage at a shallow angle of impingement than at a steep angle, with a maximum erosion rate occurring at 45° impingement angle. These results correlate to erosion test results reported and to wastage observations of in-bed steel tubes in the FBC [29,30]. In this test, the higher angle of maximum wastage for 1018 steel (ductile material) was attributed to the formation of a thin oxide scale on the surface of the steel, which influenced the erosion

mechanism.

For the material wastage of the coating specimens, HVOF $\text{Cr}_3\text{C}_2\text{-NiCr}$ cermet coatings (DS-200) and the arc-sprayed FeCrSiB coating (Amarcor M) at elevated temperature condition exhibited 2 to 3 times lower erosion wastage than that of AISI 1018 steel, as shown in Table 5. For the angular dependence of erosion rate, two coatings exhibited the ductile behavior as demonstrated by higher wastage rates at shallow impact angles rather than at steep impact angles. Most metals including mild steel eroded by hard angular particles exhibit ductile erosion behavior in angular dependence of the erosion rate, and material removed from the surface by ductile cutting and deformation cutting.

Table 5
The Material Weight Loss at Test Conditions

Target Materials	Weight Loss (mg)			Thickness Loss (μm)		
	Impact Angles:			Impact Angles:		
	30	45	90	30	45	90
1018 Steel	(2.0)	1.6	(2.2)	12	14	8
DS-200	(0.7)	(1.1)	(2.2)	6	4	0
Amarcor M	0.9	0.8	(1.0)	10	5	3
() denotes weight gain						

As shown in Figures 30, 31, and 32, there were some evidences of deformation indicated by narrow gouges, striations, small craters and indentations on the eroded surfaces of the coated specimens. Some erosive particles were also embedded in the surface of the specimen eroded at 90° of impact angle as proven by Energy Dispersion Spectroscopy (EDS) analysis. As shown in Figure 28, the low erosion resistance of Amarcor M coating was attributed to larger "splat"

a) Surface ($\alpha=90^\circ$, $V=2.5$ m/s),

b) Surface ($\alpha=30^\circ$, $V=2.5$ m/s)

Fig. 30 . The surface of HVOF Cr₃C₂ coating eroded at $V=2.5$ m/s.

a) Surface ($\alpha=30^\circ$, $V=2.5$ m/s),

b) Surface ($\alpha=90^\circ$, $V=2.5$ m/s)

Fig. 31. The surface of arc-sprayed FeCrSiB coating eroded at $V=2.5$ m/s.

Fig. 32 The cross section of arc-sprayed FeCrSiB coating eroded at $V=2.5$ m/s, $\alpha=90^\circ$.

size, higher porosity and presence of radial and tangential microracks of inclusions within the coating. When these weak boundaries were impacted by hard angular particles at a normal angle, this kind of coating cracked readily along the weak boundaries and impact damage was dominated by a brittle fracture mechanism, even though they were impacted at a very low velocity.

(b) Effect of Erosion Resistant Coatings at a High Impact Velocity

At high impact velocity, 30 m/s, the short exposure time of four hours minimized oxidation of surrounding surfaces of specimens, thus minimizing the potential weight gain. No oxidation layer formed on the worn surface of the specimen of AISI 1018. Specimens tested under high velocity exhibited typical ductile erosion behavior as indicated by craters, striations, platelet formation, and plastic flow [39].

For the material wastage of the coating specimens, the data clearly shows that in the high velocity impact tests, erosion rates were higher and erosion behavior was markedly different from that seen in the low velocity testing. At steep impact angles, all of the coatings demonstrated lower resistance than that of the AISI 1018 steel. These results are shown in Table 3. Compared to testing at low velocity, there was an opposite angular dependence of erosion rate for coatings tested at high velocity. For high velocity testing, all of the coatings exhibited "brittle behavior", i.e. the erosion rate at shallow angles was higher than at steep angles and the maximum erosion rate occurred at an impact angle of 90°.

It is worth noting that when eroded at high velocity and shallow impact angles, the hardness of the coatings had an inverse relationship to the erosion rate. In this case, references [40,41] confirm that based on the indentation fracture mechanics of the target materials, the

erosion rate should be inversely proportional to the hardness of the surface of the target materials.

The materials conventionally thought of as brittle, such as ceramic and cermet coatings, are usually eroded by the brittle cracking mechanism and suffer maximum erosion rate at normal impingement. However, the angular dependence of erosion rate is not characteristic of material alone, but depends also on the conditions of erosion. Nominally brittle materials are eroded by very small particles, or are eroded at low impact velocity. The brittle materials do show ductile behavior under these conditions.

Figures 33, 34, and 35 show the morphologies of the coating specimens, which were examined using scanning electron microscopy (SEM). As shown in Figures 33, 35, and 36, the microscopic examination of specimens showed signs of ductile deformation as indicated by small craters, striations, gouges, and indentations in their surfaces, especially when eroding at shallow angles.

Figure 35 shows more brittle than ductile mode of deformations in the surface of the coating specimen. In this study, however, the erosion rate also correlated with the ductility and fracture toughness of target materials. These mechanical properties of materials are strongly dependent on the composition and microstructure of materials.

(c) Effect of Cooled Thermal-Sprayed Coatings at a Low Impact Velocity

Test results compared with the data of isothermal specimens (uncooled specimens), as shown in Figure 36. It is found that the cooled specimens had greater material wastage than that of the uncooled specimens. Test results indicated that the cooled 1018 steel specimen lost two times as large a thickness as that of the uncooled specimen. The thickness loss of the cooled

a) HVOF Cr₃C₂-NiCr coating (V=30 m/s, $\alpha=30^\circ$).

b) HVOF Cr₃C₂-NiCr coating (V=30 m/s, $\alpha=90^\circ$).

Figure 33 The surface of HVOF thermal spray coating (DS-200) eroded at high velocity, 30 m/s.

c) HVOF Cr₃C₂ coating (V=30 m/s, $\alpha=30^\circ$).

d) HVOF Cr₃C₂ coating (V=30 m/s, $\alpha=90^\circ$).

Figure 34 The surface of HVOF Cr₃C₂ coating eroded at high velocity, 30 m/s.

e) Arc-sprayed FeCrSiB coating (V=30 m/s, $\alpha=30^\circ$).

Figure 35 The surface of wire arc spray coating (Armacor M) eroded at high velocity, 30 m/s.

Table 6. Summary of the Erosion Wastage Tests

Target material	Material Wastage (thickness loss)			
	Cooled specimens		Isothermal specimens	
	μm	Rate($\mu\text{m/g}$)	μm	Rate($\mu\text{m/g}$)
1018	23	0.00256	12	0.00133
DS-200	8	0.00089	6	0.00067
DS-105	2	0.00022	1	0.00011
Rokide C	6	0.00067	4	0.00044

Cooled specimen: $V = 2.5 \text{ m/s}$, $T_1/T_2 = 750\text{deg.C}/300\text{deg.C}$, 9000g quartz, 96 hrs.

Isothermal specimen: $V = 2.5 \text{ m/s}$, $T_1/T_2 = 300\text{deg.C}/300\text{deg.C}$, 9000g quartz, 96 hrs.

Fig. 36 Erosion wastage for four target materials eroded at different test conditions.

coating specimens had less increase compared with the results of the uncooled coating specimens.

Figures 39 to 40 show the eroded surfaces with EDS analyses and cross sections of the cooled specimens. Some counterparts of the uncooled specimens are shown in Figures 41 to 43. It is found that a thin, continuous scale layer formed on the surface of the uncooled 1018 specimen while no scale formed on the surface of the cooled 1018 specimen, as shown in Figures 41-c and 37-c. A great amount of erosive particles deposited on the eroded surfaces of the uncooled specimen as proven by EDS analysis, as shown in Figure 41-b.

By contrast, a lesser amount of erosive particles are deposited on the eroded surface of the cooled 1018 specimen, as shown in Figure 37-b. The continuous scale and the depositions of erosive particles contributed to the reduction of material wastage by protecting the surface [42]. From EDS analysis of the eroded surfaces of the thermal-sprayed coatings, it was also found that the amounts of deposited erosive particles on the surfaces of cooled thermal-sprayed coating specimens were less than those on the surfaces of the uncooled specimens.

The surfaces of the uncooled specimens were more receptive to retaining erosive particles. Since a combination of increased oxide formation trapped the depositions of the fine particles and a general softening of the material surface, the surface temperature's increase of the uncooled specimens immediately occurred as the result of the localized plastic deformation by impact particles. The continuous observation showed less increase of temperature in the cooled specimens than that of the uncooled or isothermal ones. In addition, part of the heat was drawn away cooling the water through conduction. Thus, the lower surface temperature resulted in less ductility of the surface and a higher erosion wastage rate.

It was found that both surface morphology of cooled specimens and that of uncooled

Figure 37 Cooled DS-200 coating specimen, (A) Eroded surface; (B) EDS from surface; (C) Cross-section.

Fig. 38 Cooled 1018 specimen, (A) Eroded surface; (B) ESD from surface; (C) Cross-section.

Fig. 39 Cooled DS-105 coating specimen, (A) Eroded surface; (B) EDS from surface; (C) Cross-section.

B

Figure 40 Cooled Rokide C coating, (A) Eroded surface; (B) EDS from surface.

Figure 41 Uncooled 1018 specimen (A) Eroded surface;(B) EDS from surface;
(C) Cross-section.

Figure 42 Uncooled DS-200 specimen. (A) Eroded surface.
(B) EDS from surface

Figure 43 Uncooled DS-105 specimen, (A) Eroded surface.
 (B) EDS from surface.

specimens were similar. At relatively low impact velocity, the load carried by each particle was below the threshold, which is needed to cause cracking for "brittle materials" [43]. So, the brittle fracture could be suppressed and the material wastage is believed to occur through the plastic processes. As shown in Figures 38 to 40, the eroded surface of the thermal-sprayed coatings displayed the evidence of deformation, such as narrow gouges, striations, and small craters.

Compared with the cross section of the DS-200 coating specimen and that of the DS-105, the DS-105 coating specimen had a fine structure and a smaller splat size than that of the DS-200 coating specimen. Thus, the DS-105 coating specimen exhibited the lowest erosion wastage due to its favorable composition and morphology.

(d) Effect of Cooled Thermal-Sprayed Coatings at a High Particle Velocity

Material wastage of in-bed tubes in atmospheric fluidized-bed combustors (AFBC) continues to be an important issue. In our previous work, the erosion phenomena of AISI 1018 steel and several thermal-sprayed coatings under simulated in-bed tube erosion conditions of FBCs were studied. The actual service heat exchanger tubes were usually cooled by water or steam being heated [22]. So, the cooled specimens were tested to observe the material wastage and its mechanism under different test conditions.

In this work, tests continued to analyze the erosion phenomena of the cooled specimen at a high particle velocity (60 m/s), which was compared with the results of the isothermal specimens.

Experimental Test Conditions

(i) Test Specimens and Materials

The target materials for the tests were three thermal-sprayed coatings, DS-200, DS-105, Rokide C, and AISI 1018 steel. The characteristics of each target coating materials were introduced in the previous report. Bed ashes retrieved from the operating biomass-fired boiler were used for erodent particles. Table 6 shows the different compositions and phases of the bed ash particles. The shape of the bed ash particles is shown in Figure 44. The mean particle size was 421 μm with a mean particle density of 2439 kg/m^3 . The particle size distribution is shown in Figure 45. These particles mainly consisted of silica with a small amount of other elements, which is shown in the results of the energy dispersive spectrometry (EDS) in Figure 46.

(ii) Conditions and Material Wastage Measurements

The tests of material wastage were carried out in the elevated temperature blast nozzle type of tester. In the test facility, erodent particles flowed down a vibration tube into a chamber where they impacted the test specimens. The temperature ranges in the tester extended from 20 (degrees) C to 850 (degrees) C. Two different conditions for the specimens were implemented by cooled specimens and isothermal specimens. The surface of the specimens were exposed directly to the environmental temperature (750 degrees C), while the backsides of the specimens were water cooled.

The high particle velocity (60 m/s) was applied to compare with the results of low particle velocity conditions. Tests were carried out at a specimen surface temperature of 300 (degrees) C, using an impact angle of 30 (degrees) and 90 (degrees). In our previous work, it was found that all tested coatings exhibited "ductile behavior" such as that of a steep impact

Table 7 Composition of the Bed Ash Particles

Element	O	Si	Al	Mg	S	K	Ca	Ti	Fe	Na	P	Cl
Chem.	45.28	33.69	5.74	1.008	0.029	5.602	4.981	0.215	1.39	1.706	0.358	-
EDS	47.6	31.68	6.45	1.01	0.04	5.14	4.59	0.4	1.13	1.02	0.95	0.59
Phase	SiO ₂ (Quartz), (Na,K)AlSi ₃ O ₈ (Anorthoclase), NaAlSi ₃ O ₈ (Albite)

Figure 44 Particle Appearance of Bed Ash

Ave. 421 microns, Density 2439 kg/m3

Figure 45 Particle size distribution for bed ash A3.

Figure 46 EDS spectra collected from the bed ash.

angle. Thus, this work focused on material wastage at shallow impact angles of 30 degrees and 90 degrees. A test time of 4 hours was used at a particle loading of 375 g.

The material wastage of the specimens was determined by thickness measurements. The microscopic dimensional measurements of cross-sections of the area of greatest material loss were applied to determine the thickness of the remaining sound metal.

The measurement of the thickness change was considered to be a more valid measurement of the material wastage and included material erosion wastage, the remaining oxide scale, and ash deposition. The material wastage conditions are summarized in Table 8.

Table 8

Material Watsage Test Conditions

Particle Velocity	60 m/s
Particle Impact Angle	30 degrees
Bed Particle Loading	375 g
Erodent Particles	Bed Ash A3
Environmental Temperature	750 degress C
Specimen Surface Temperature	300 degrees C
Testing Time	4 hours

(iii) Erosivity of Erodent Particles

Bed ashes retrieved from the operating biomass-fired boiler demonstrated high erosivity, which was characterized by low ash and low sulphur contents. Thus, the erosion potential of

the fuel was relatively low. However, other media were added into the combustor in order to provide a sufficient amount of circulating material. Typically, sand (silica quartz) was used, which has been shown to increase the erosion wastage [44]. Chemical analysis and EDS spectra results confirmed the high concentration of silica quartz in bed ash particles, as shown in Figure 46.

The high erosivity of these ash particles can also be related to their larger mean particle size and to the presence of "chemically active" compounds in the ash particles. Such compounds contain potassium (K), sodium (Na), phosphorus (P), and chlorine (Cl), which increased the material wastage [45].

(iv) Thickness Loss of Material Wastage and Ranking

Erosion test results are shown in Table 8, and also attached is the compared data of isothermal (uncooled) specimens. From this Table, it can be seen that the cooled specimens had higher thickness losses than the uncooled specimens at both shallow and steep impact angles. The data shows that at a shallow impact angle, the cooled AISI 1018 steel specimens lost a thickness of 60% greater than that of the uncooled specimens; while, cooling the coated specimens resulted in only a 30% increase in thickness loss. It seems as if, at a shallow impact angle, the effect of cooling the specimens on the erosion wastage for 1018 steel is greater than that for thermal-sprayed coatings. However, at a steep impact angle, the cooled AISI 1018 steel specimens, lost a thickness of only 20% higher than those of the uncooled specimens. In reverse, the cooled coating specimens had a thickness loss over 50% higher than those of uncooled specimens. This implied that at a steep impact angle the effect of cooling the specimens on the erosion wastage for thermal-sprayed coatings was greater than that for AISI

1018 steel.

In comparison to the testing for uncooled specimens, the testing for cooled specimens showed the same erosion resistance ranking for target materials at both 30 (degree) and 90 (degree) impact angles. At both impact angles, the DS-200 specimen showed the highest erosion resistance. Thickness loss results from Table 8 at a 30 (degree) impact angle demonstrates that for both cooled and uncooled specimens all of the coatings reduced erosion wastage compared with AISI 1018 steel.

Thickness loss results at a 90 (degree) impact angle demonstrated that the two HVOF coatings (DS-200 and DS-105) reduced erosion wastage as compared with AISI 1018 steel, as shown in Figure 47.

(v) Effects of Impact Angle on Erosion Wastage

The thickness loss of AISI steel tested at a shallow impact angle of 30 (degrees) was higher than that tested at a steep impact angle of 90 (degrees) for the cooled specimen. Such erosion behavior is typical of ductile materials [46]. For AISI 1018 steel, only a thin oxide scale developed at this low surface temperature (300 C), thus allowing the impacting bed ash particles to penetrate the thin oxide scale and plastically to deform the ductile base metal beneath it [42]. The three coatings tested exhibited greater thickness loss at a steep impact angle of 90 (degrees) than at a shallow impact angle of 30 (degrees).

Materials conventionally thought of as brittle, such as ceramic coatings, usually eroded by a little cracking mechanism and suffered maximum erosion wastage at steep impingement. Such was the case for HVOF Cr₃C₂ and flame-sprayed Cr₂O₃ coatings, as tested in this work. For cermets containing less than 80 vol. % carbide, erosion is controlled by the metallic binder

Table 9 Summary of the Material Wastage Test Conditions

Target Material	Material wastage(thickness loss)			
	Cooled specimens		Isothermal specimens	
	μm	Rate($\mu\text{m/g}$)	μm	Rate($\mu\text{m/g}$)
1018	494	1.317	306	0.816
DS-200	48	0.128	38	0.101
DS-105	28	0.0747	18	0.048
Rokide C	32	0.0853	23	0.0613

Figure 47 Comparison of erosion wastage data.

[47]. However, the cermet material still behaves in a brittle manner as long as the binder is severely constrained by the carbides. Thus, maximum erosion rates occurred at a 90 (degree) impact angle. Such was the case with the DS-200 target material, as tested in this work. It is worth noting that the material wastage of two HVOF coatings (DS-200 and DS-105) was still much lower than that of AISI 1018 steel at a 90 (degree) impact angle, in spite of the brittleness of the coatings. The good performance of two HVOF coatings at both shallow and steep impact angles was closely related to their chemistry and microstructure.

12. CONCLUSIONS

This research program for the analysis and control on in-bed tube erosion phenomena in the fluidized bed combustion system has been successfully completed. The major accomplishments in this project for the cold flow FBC model are summarized below:

- o The systematic test was conducted to measure the erosion of the in-bed tube of the FBC under various test conditions
- o The specific weight loss was strongly affected by the gas flow rate; it increased with increasing superficial fluidizing velocity.
- o The electrostatic impact probes were employed to measure the particle-tube collision frequency in the cold model of the fluidized bed. These probes were convenient and reliable for exploring the solid flow pattern in the fluidized bed.
- o The characteristics of in-bed tube erosion and particle-tube collisions in bench-scale cold fluidized beds have provided some qualitative and quantitative descriptions of the erosion processes.

In order to simulate erosion wastage of in-bed tubes in the BFBC, the tests were carried out in the elevated temperature blast nozzle type of tester. The target material for the test was AISI plain carbon steel, which is commonly used in in-bed tubes of BFBC. In addition, different resistant coating materials were applied to protect the surface of in-bed tube materials as erosion remedies. The major results are summarized below.

- o The erosion tests under low impact velocity using a nozzle-type erosion tester can simulate the erosion conditions of in-bed tubes in BFBCs.

- o There are some differences on erosion mechanism and behavior of steel coatings under low impact velocity of 2.5 m/s from those under high velocity of 30 m/s. A significant change in the ranking of erosion resistance occurred when steel and coatings were tested under different impact velocities.
- o At low impact velocity, all coatings tested exhibited lower erosion wastage rates than AISI 1018 steel with the HVOF Cr₃C₂ coating exhibiting the highest erosion resistance.
- o At high impact velocity, several coatings exhibited higher erosion wastage than AISI 1018 steel with the flame sprayed 90Cr₂O₃-6SiO₂-4Al₂O₃ coating exhibiting the highest erosion resistance.
- o The erosion resistance of coating is related to their composition and microstructure rather than their hardness.

The tube surface temperatures are quite different from the environmental temperature. Therefore, the material wastage and mechanisms in the actual heat exchanger tubing could be quite different from those determined for isothermal specimens.

Tests were also conducted on cooled specimens, in order to investigate the effects of the temperature difference between the gas-particle mixture and the surface of specimens on material wastage and mechanism of thermal sprayed coatings at waterwall tube erosion conditions of FBCs.

- o The cooled specimens had greater material wastage than the isothermal (uncooled) specimens.

- o At a shallow impact angle, the effect of the cooling specimen on the erosion wastage for thermal sprayed coatings was less than that for 1018 steel, while at a steep impact angle this effect for the thermal-sprayed coating is greater than that for 1018 steel.
- o The HVOF Cr₃C₂ ceramic coating exhibited the highest erosion resistance due to its favorable composition and fine structure.
- o The poor erosion resistance of arc-sprayed FeCrSiB coating was attributed to a larger splat size, higher porosity and the presence of radial and tangential microtracks within the coating.
- o The erosion mechanism of the cooled specimens was similar to that of the isothermal specimens despite the material wastage.
- o All coatings tested exhibited characteristics of brittle material erosion behavior, i.e. greater material wastage at 90 degrees than at 30 degrees.

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