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Prediction of In-Bed Tube Erosion Rates in Fluidized Beds

**Topical Report
January 1992 - June 1992**

Hisoshi Kono

October 1992

Work Performed Under Contract No.: DE-FC21-87MC24207

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
West Virginia University
Department of Chemical Engineering
Morgantown, West Virginia

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ABSTRACT

The objective of this research is to predict the erosion rates of in-bed tubes of specific materials in fluidized beds by using a novel approach that we have recently developed. This technique assesses the erosion rates of in-bed tubes by considering two key factors: the peaks of the transient forces of solid particles and the characteristic erosion properties of tube materials concerned.

We developed a simple characterization method to assess the erosion rates of in-bed tubes. With this method, an erosion index considering the surface area, weight loss of in-bed tubes, and the operating time, was used.

A systematic study was carried out in a 4" rectangular fluidized bed to study the relationship between erosion rate and maximum transient forces of solid particles in fluidized beds. Three different kinds of metal tubes, with well defined tensile strength (σ_t) and elasticity modulus (E), were used. They are copper, aluminum and stainless steel. By considering the tensile strength and elasticity modulus, together with the peaks of transient forces of solid particles, a characteristic erosion function was introduced. This characteristic function was found to have a good correlation with the erosion rate. Thus, the prediction of in-bed tube erosion rates was achieved, when the peaks of transient forces of solid particles and tube material's characteristic properties are known.

Systematic study were also accomplished to investigate the effect of the fluidization particles on the erosion rates. The fluidized bed configuration effects were further investigated.

A study to assess the peaks of transient force in peripheral direction of the in-bed tube surface, was also accomplished. The probe was mounted on the surface of an in-bed tube, and the transient force of solid particles data were taken and analyzed, using the correlation between the transient forces of solid particles and the gas phase pressure fluctuation. Results show that the peaks of transient particle force (expressed as the average of top five maximum forces) has the maximum value at the location between the side and the bottom of the tube. This observation is in agreement with our earlier observations of erosion rates of ceramic materials.

The erosion rate distribution along the longitudinal direction of in-bed tubes was also measured. The erosion rate reaches the

maximum near the center of the in-bed tube.

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1. EXECUTIVE SUMMARY

The objective of this work is to predict the erosion rates of in-bed tubes of specific materials in fluidized beds by using a novel approach that we have recently developed. As is well accepted, the assessment and reduction of erosion of in-bed tubes is one of the critical engineering problems for the design of fluidized bed combustors. However, there has been no practical answer, nor quick remedy for the above problems. The developed technique assesses the erosion rates of in-bed tubes by considering two key factors: the peaks of transient forces of solid particles and characteristic erosion properties of materials concerned.

A simple characterization method for erosion rate measurement was developed in this study to assess the erosion rates of in-bed tubes. Unlike the conventional erosion measurement method, which considers only the weight loss or diameter change and the operating time, this method defines an erosion index considering the surface area, weight loss of in-bed tubes, and the operating times.

Systematic studies were carried out in a 4" rectangular fluidized bed to study the relationship of erosion rates and peaks of transient forces of solid particles in fluidized beds. Three different kinds of metal tubes, with well defined tensile strength (σ_t) and elasticity modulus (E), were used. They are copper, aluminum (alloy) and stainless steel. By considering the tensile strength and elasticity modulus, together with the peaks of transient forces of solid particles, a characteristic erosion function was introduced. This function was found to have a good correlation with the erosion rate. Thus, the prediction of in-bed tube erosion rates was achieved, when the peaks of transient forces of solid particles and tube material properties are known.

The characterization method of the maximum transient forces of solid particles in fluidized beds was improved for the erosion study. The maximum force (hereafter the peaks of transient forces of solid particles is abbreviated as the "maximum force") concept was refined in order to take the frequency into account. For example, the average of top five maximum forces, which takes both maximum and frequency into account, can be a better index for transient forces of solid for erosion study. From our past experimental data, we know the correlation between the maximum forces and the maximum of the gas phase pressure fluctuation $\Delta P_{\max}$. Using these correlation curves, we can indirectly measure the peaks of the transient force of solid particles at specific location (e.g., at the surface of in-bed tubes), where the erosion of the

material is taking place.

Systematic study were extended to investigate the effect of the fluidization particles to the erosion rates. The fluidized bed configuration effects were also studied.

The maximum forces in peripheral direction around the surface of in-bed tube, were measured and analyzed. The position of the probe on the tube surface in radial direction were changed from 0° , 45° , 90° , 135° to 180° (see Figure 10 on page 27). At each of the five probe locations (0° , 45° , 90° , 135° and 180°) we obtained the peaks of transient maximum forces and their frequency distribution. The maximum forces were measured under various fluidization conditions. Results show that the maximum forces (expressed as the average of top five maximum forces) has the maximum value at the location between the side and the bottom of the tube (see Figure 10 on page 27). This observation is in agreement with our earlier observations of erosion in ceramic materials.

The erosion rate distribution along the longitudinal direction of the in-bed tube was also measured.

The maximum forces calibrated from the pressure fluctuation obtained from the tube surface were also compared with those measured away from the tube. Results shows that the maximum force (expressed as the average of top five maximum forces) is generally lower at the top of the tube surface.

These conclusions indicate that the local erosion rate can be predicted by measuring the local maximum forces under the specific geometric configuration using the same material of construction.

2. TECHNICAL BACKGROUND

Fluidized beds commonly contain heat transfer in-bed tubes and others (diplegs, probes, etc.), all of which are immersed. These immersed objects are exposed to transient forces of solid particles caused by the bubble and particle motion in the bed. These transient forces commonly lead to the erosion of in-bed tubes. According to experimental results, it seems that the peaks and frequencies of transient forces of solid particles were to be responsible for the erosion of in-bed tubes. It is therefore important to be able to predict the maximum forces for the design of the in-bed tubes and their supports.

Fundamentally speaking, the erosion of in-bed tubes is a fracture process of solid materials occurring on the surface of tube materials caused by the collision of solid particles with transient motion in fluidized beds. Therefore, it is logical to say that the erosion rates of in-bed tube should be strongly affected by the peaks and frequency of transient forces of solid particles and the mechanical properties (mechanical strength, elasticity modulus or Young's modulus, rigidity etc.) of related solid materials (solid particles, in-bed tubes etc.).

Conventionally the erosion rate of in-bed tubes has been measured by exposing the in-bed tubes in fluidized beds under a certain fluidization condition in a defined fluidized bed with specific scale and configuration. Accordingly, the application of the results obtained was rather limited due to the very restricted experimental condition.

A novel approach we developed is different from the conventional approach in the following aspects. First we measure the transient forces of solid particles in fluidized beds. Then we characterize the data and obtain the peaks and frequencies of these transient forces. Further, when the properties (mechanical strength, elasticity modulus or Young's modulus, rigidity etc.) of related material (in-bed tubes, solid particles etc) are known, we will be able to predict the erosion rate. This is really a very logical approach.

Forces on objects immersed in fluidized beds were studied by several investigators. Bordet and coworkers (1968) measured the kinetic energy of particles and the collision frequency against a wall by a small piezo-electric crystal microphone immersed in the liquid fluidized bed. Their experimental results were used to explain some wall mass transfer properties in fluidized beds.

However, this method was reported to have some technical difficulties as applied in gas-solid fluidized beds.

Nguyen and Grace (1978) reported that the net buoyancy force imposed on an immersed object in the fluidized bed can be estimated by taking the particulate phase density as equal to the bed density at minimum fluidization. By synchronizing the photographic films and pressure fluctuations on the surface of submerged tubes, they also concluded the bubbles passing immersed objects cause transient forces leading to tube vibrations.

Kennedy, Donovan, and Trigas (1981) used strain-gauge local cell to measure the external forces imparted by the bed material on tubes in a fluidized bed pertinent to the structural design of heat-exchanger tube systems. They reported that the load cell data support the view that the force pulses on the tubes are produced by the passage of bubbles. They also suggested that the forces on the tubes are the result of an impulse caused by the transfer of the momentum of a body of solids in the wake of the bubble striking the tube.

Grace and Hosny (1985) measured vertical and horizontal forces using externally-mounted strain-gauge force transducers for three bare tubes and one finned tube in fluidized beds. They concluded that static forces dominated at low gas flow rates, while bubble-induced pulses become dominant at high flow rates. Vertical forces tend to be much larger than horizontal forces. They also proposed a simple mechanistic model for the prediction of the root-mean-square forces and of the variation of these forces with superficial gas velocity, tube size, and particle properties.

Meijer and coworkers (1986) used a scaled-up liquid fluidized bed to study particle impact against bed column. They reported that the Maxwell-Boltzmann velocity distribution appeared not to be valid when the values of comparatively low velocity impacts were included. They also reported that the mean perpendicular velocity at impact was about a factor 10 lower than the superficial fluid velocity at a porosity of 0.8.

Some other experimental techniques (Hirato, 1982; Raso, 1983; Lanauze, 1975; Shaozong, 1982) were presented for investigating the particle dynamics in fluidized beds. However, due to the difficulties involved in analyzing the data, none of these techniques have been successfully applied for systematic measurements of transient forces.

Although the above achievements have been accomplished by various

investigators, no useful results on the prediction of erosion rates of in-bed tubes have been reported in open literature, which can predict the erosion rate from the data of maximum forces in fluidized beds. It was also not recognized that the peak and frequency of the transient forces of solid particles will substantially determine the erosion rates of the in-bed tubes in fluidized beds.

Recently Kono et al developed experimental techniques to measure the peaks and distribution of transient forces of solid particles (1988,1989,1990) by using sensor particle method and piezoelectric sensor method. These measuring techniques have made the novel approach possible.

To apply this technique to the erosion rate study, the maximum force concept was defined by taking the frequency into account. We assumed that there exists a threshold of transient forces that determines the fracture process. Forces exceeding this threshold should have significant impact to erosion process. This threshold should also be determined by the specific properties of in-bed tubes.

Figure 1 (a) and (b) are illustrated to show the uniqueness of the new approach we used in this project (Figure 1(b)), against the conventional approach (Figure 1(a)).

Figure 1 (a). Conventional Approach to Access Erosion Rates of In-Bed Components in Fluidized Beds

Figure 1(b). Uniqueness of the New Approach to Access Erosion rates of In-Bed Components in Fluidized Beds

3. EXPERIMENTAL METHODOLOGY

The following approaches were developed and used:

(1). Recognition of transient forces of solid particles.

Although the measurement methods of transient forces of solid particles have already been developed, these methods were directed to measure the peaks of the forces. Now a recognition of the maximum transient forces of solid particles was developed to characterize the erosion rates of in-bed tubes. The characteristics of transient forces of solid particles was expressed by peaks, frequencies, intensity distributions, etc.. It is important to measure not only the maximum forces in fluidized bed, but also the frequencies of the maximum forces. The average top five maximum forces was found to be appropriate as an index of the force, which substantially determines the erosion rates.

(2). Index of erosion rates of in-bed tubes.

Most of conventional approaches published in the past literature used the weight loss (or diameter change of the in-bed tube) per hour (or per 1000 hours) as an index. However, it is not convenient to evaluate the erosion rate with different sizes of in-bed tubes. We used the weight loss per unit surface area of the gas-solid contact per unit time as an index to assess the erosion rates. The testing in-bed tubes (1/2") were copper, aluminum (alloy) and stainless steel. The selection of these materials of construction was made to evaluate experimentally the effect of tensile strength and Young's modulus on the erosion rate. Fluidization particles were silica sand(0.8-2.0mm) and glass beads (1mm). Results show that this index can well quantify the erosion rate regardless the tube size. Therefore, this index was used in the entire range of this research.

(3). Simultaneous measurements of erosion rates of in-bed tubes and transient forces of solid particles in fluidized beds.

The erosion rates of in-bed tubes of specific metals (stainless steel, copper and aluminum alloy), and the peak and frequency of transient forces of solid particles acting on the tubes were simultaneously measured in a fluidized bed (4" I.D.). The measurement point was located near the testing tube.

The erosion rate is not only determined by the transient forces of solid particles but also by the mechanical properties of the in-bed tubes and fluidized particles. Since the erosion phenomena is a fracturing process of solid materials, the mechanical strength (e.g. tensile strength) and elasticity modulus will be important. Therefore the use of steel, copper and aluminum should be a useful combination of mechanical strength and elasticity of in-bed tubes to represent the property of material concerned. To simulate the coal ash, the silica and glass beads were used.

(4). Introduction of the tensile strength and elasticity modulus into the erosion assessment model.

Our erosion assessment model in this research is improved against conventional approaches to evaluate quantitatively the effect of the mechanical properties of the in-bed tube material on erosion rates. This model can predict erosion rates for virtually the in-bed tubes made of any materials with known mechanical properties, if the maximum force in the bed is provided.

The tensile strength and elasticity modulus were introduced. The effect of elasticity modulus (Young's modulus, E) and tensile strength (σ_t) of in-bed tubes on the erosion rates were investigated. We found that good correlation exists between the erosion rate index and the erosion characteristic function including the maximum force and properties of in-bed tubes and fluidized particles.

(5). Measurement of transient forces of solid particles in peripheral direction of in-bed tube surface

It is our intention to investigate where the critical erosion takes place on the in-bed tube surface. To achieve this, the measurements of transient particle force distribution in peripheral direction of the tube surface are necessary.

We achieved to measure the maximum force distribution on the peripheral surface of in-bed tube. The probe was mounted on the surface from inside of in-bed tube (see Figure 10 on page 27), and the maximum force data were taken and analyzed. By rotating the in-bed tube 45° at each experiment run, we obtained the maximum force distribution in peripheral direction of the in-bed tube surface, which can be characterized indirectly by measuring $\Delta P_{\max}$. Experiments were accomplished with various fluidization conditions.

(6). Measurement of transient maximum forces of solid particles in longitudinal direction of in-bed tube surface

It is also our intention to investigate the erosion rate distribution in longitudinal direction of the in-bed tube. To achieve this, tube erosion rates were measured in different locations longitudinally (see Figure 14 on page 32). Five short tubes were installed longitudinally, and erosion rate data were taken simultaneously.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1. Gas Pressure Fluctuation (ΔP) in the 4" Rectangular Fluidized Bed

The maximum forces of solid particles acting on the surface of in-bed tubes were indirectly obtained by measuring the maximum of the gas phase pressure fluctuation ($\Delta P_{\max}$) simultaneously while erosion test was operating. By using our previous basic research on the erosion mechanism as shown in Figure 2, knowing the $\Delta P_{\max}$, the maximum force can be obtained by using the correlation between these two parameters. The measurement points were located at the same level of the tube center and 1" away from it. The schematic diagram of experiment setting is shown in Figure 3. The bed is 4" rectangular, tubes are (1/2)" in diameter, and fluidization particle is silica sand. Figure 4 shows the data under the following fluidization condition: superficial gas velocity $U_o/U_{mf}=1.5, 2.0, 2.5$ and 3.0 ; bed aspect ratio $H/D_i=2$; particle size $d_p=0.8-2.0\text{mm}$, $\bar{d}_p=1.1\text{mm}$.

4.2. Erosion Rates of Specific Metals

The erosion rates of in-bed tubes of specific metals (stainless steel, copper and aluminum alloy) were measured in a rectangular fluidized bed (4"x4"). The experiments were conducted in a systematic manner. The fluidization conditions were: superficial gas velocity $U_o/U_{mf} = 1.5, 2.0, 2.5$ and 3.0 , bed height $H=8"$, Bed aspect ratio $H/D_i = 2$, Fluidization particle was silica sand ($0.8-2.0\text{ mm}$, $\bar{d}_p=1.1\text{mm}$). The size of in-bed tube was (1/2)". The erosion indices were calculated according to the following definition:

$$I = \frac{\Delta W}{A(\Delta t)} \dots\dots\dots (1)$$

where I is the erosion index, A is the surface area, and Δt is the operating time, ΔW is the weight loss during the time interval of Δt .

Table 1, 2 and 3 give the erosion index data for aluminum alloy, copper and stainless steel. Data are available in U_o/U_{mf} range of $1.5, 2.0, 2.5$ and 3.0 .

Figure 2. Correlation between Transient Forces and Maximum Pressure Fluctuation

Figure 3. Schematic Diagram of Experiment Setting

Figure 4. Pressure Fluctuation versus Superficial Gas Velocity

Table 1. Erosion Index Data (Aluminum alloy)

Al	D=15.80mm	L=48.30mm	$A_p=23.97\text{cm}^2=2.397\times 10^{-3}\text{m}^2$			
U_o/U_{mf}	I_1	I_2	I_3	I_4	I_5	I_{total}
3	9.850E-5 $\Delta W=.017\text{g}$ hr=72	7.648E-5 $\Delta W=.0044\text{g}$ hr=24	9.387E-5 $\Delta W=.0054\text{g}$ hr=24	8.344E-5 $\Delta W=.0048\text{g}$ hr=24	8.344E-5 $\Delta W=.0048\text{g}$ hr=24	9.039E-5 $\Delta W=.0364\text{g}$ hr=168
2.5	3.477E-5 $\Delta W=.006\text{g}$ hr=72	5.389E-5 $\Delta W=.0031\text{g}$ hr=24	6.605E-5 $\Delta W=.0038\text{g}$ hr=24	6.605E-5 $\Delta W=.0038\text{g}$ hr=24	5.447E-5 $\Delta W=.0094\text{g}$ hr=72	5.041E-5 $\Delta W=.0261\text{g}$ hr=216
2	3.592E-5 $\Delta W=.0062\text{g}$ hr=72	2.781E-5 $\Delta W=.0016\text{g}$ hr=24	3.687E-5 $\Delta W=.0019\text{g}$ hr=21.5	4.581E-5 $\Delta W=.0028\text{g}$ hr=25.5	2.177E-5 $\Delta W=.0012\text{g}$ hr=23	3.443E-5 $\Delta W=.0137\text{g}$ hr=166
1.5	1.564E-5 $\Delta W=.0027\text{g}$ hr=72	0.869E-5 $\Delta W=.0005\text{g}$ hr=24	0.869E-5 $\Delta W=.0005\text{g}$ hr=24	1.391E-5 $\Delta W=.0008\text{g}$ hr=24	6.953E-6 $\Delta W=.0012\text{g}$ hr=72	1.101E-5 $\Delta W=.0057\text{g}$ hr=216

Table 2. Erosion Index Data (Copper)

Cu	D=15.85mm	L=101.30mm	As=50.442cm =5.044x10 ⁻³ m ²			
U _o /U _{mf}	I ₁	I ₂	I ₃	I ₄	I ₅	I _{total}
3	22.06E-5 ΔW=.079g hr=71	20.98E-5 ΔW=.0254g hr=24	21.85E-5 ΔW=.027g hr=24.5	17.55E-5 ΔW=.0208g hr=23.5	19.49E-5 ΔW=.0236g hr=24	18.055E-5 ΔW=.153g hr=168
2.5	N/A	11.68E-5 ΔW=.0277g hr=47	9.75E-5 ΔW=.0118g hr=24	8.76E-5 ΔW=.0106g hr=24	8.95E-5 ΔW=.0325g hr=72	9.806E-5 ΔW=.0826g hr=167
2	4.048E-5 ΔW=.0049g hr=24	4.520E-5 ΔW=.0057g hr=25	5.430E-5 ΔW=.0063g hr=23	5.121E-5 ΔW=.0062g hr=24	3.910E-5 ΔW=.0138g hr=70	4.410E-5 ΔW=.0369g hr=166
1.5	2.46E-5 ΔW=.0032g hr=24	1.98E-5 ΔW=.0022g hr=22	2.31E-5 ΔW=.0028g hr=24	1.817E-5 ΔW=.0022g hr=24	1.625E-5 ΔW=.0059g hr=72	1.947E-5 ΔW=.0163g hr=166

Table 3. Erosion Index Data (Stainless Steel)

Fe	D=15.80mm	L=50.90mm	As=25.26cm ² =2.526x10 ⁻³ m ²			
U _o /U _{mf}	I ₁	I ₂	I ₃	I ₄	I ₅	I _{total}
3	3.299E-5 ΔW=.0060g hr=72	3.464E-5 ΔW=.0021g hr=24	3.629E-5 ΔW=.0022g hr=24	3.629E-5 ΔW=.0022g hr=24	2.639E-5 ΔW=.0016g hr=24	3.323E-5 ΔW=.0141g hr=168
2.5	2.584E-5 ΔW=.0047 hr=72	3.629E-5 ΔW=.0022g hr=24	2.969E-5 ΔW=.0018g hr=24	1.979E-5 ΔW=.0012g hr=24	2.584E-5 ΔW=.0047g hr=72	2.676E-5 ΔW=.0146g hr=216
2	1.375E-5 ΔW=.0025g hr=72	0.825E-5 ΔW=.0005g hr=24	2.025E-5 ΔW=.0011g hr=21.5	2.018E-5 ΔW=.0013g hr=25.5	1.549E-5 ΔW=.0009g hr=23	1.502E-5 ΔW=.0063g hr=166
1.5	8.248E-6 ΔW=.0015g hr=72	4.949E-6 ΔW=.0003g hr=24	1.650E-6 ΔW=.0001g hr=24	6.598E-6 ΔW=.0004g hr=24	E-6 ΔW=.0005g hr=72	1.502E-6 ΔW=.0028g hr=216

4.3. Erosion Rates Expressed as Function of Maximum Force

For the experiments described in section 4.2, the erosion index versus the maximum force is shown in Figure 5. These characterization curves indicate that the correlation between erosion index and maximum force exists. These characterization curves also indicate that the mechanical properties of testing metals also can determine the erosion index.

4.4. Erosion Rates Expressed as Function of Maximum Force, Tensile Strength and Elasticity Modulus

The erosion assessment model in this research is better than conventional approaches, because this model can provide the quantitative prediction on erosion rates for different types of fluidized beds under various operating conditions.

The tensile strength and elasticity modulus (Young's modulus) were introduced. we found that a good correlation exists between the erosion rate index and a function of maximum force, tensile strength and elasticity modulus.

The standard tube materials were stainless steel, copper, and aluminum alloy with 1/2 " ID. The material properties of these tubes are given in Table 4. Table shows that the use of steel, copper and aluminum is an effective combination of mechanical properties to evaluate the effect of the material property on the erosion rates of the in-bed tube.

Table 4. Material Properties of Test Tubes

Material	Young's Modulus E (kPa)	Tensile Strength σ_t (kPa)
Copper	1.17×10^8	2.76×10^5
Stainless Steel	2.09×10^8	5.76×10^5
Aluminum (alloy)	7.05×10^7	2.90×10^5

EROSION INDEX VERSUS MAXIMUM FORCE

Figure 5. Erosion Index versus Maximum Force

The fluidization conditions were: Bed size $D_i = 4''$ square, superficial gas velocity $U_o/U_{mf} = 1.5, 2.0, 2.5$ and 3.0 , bed aspect ratio, i.e. H/D_i , was taken as 2 in all experiments. The fluidization particle was silica sand ($0.8-2.0$ mm, $\bar{d}_p=1.1$ mm)

An erosion rate characteristic function $f(ER)$ can be expressed as:

$$f(ER) = C(F_{\max})^{2.18} * \left(\frac{E^{1.08}}{\sigma_t^{3.26}} \right) \dots \dots \dots (2)$$

where $F_{\max}$ is the maximum force (N/m^2) acting on the surface of in-bed tubes, and C is a constant. When $F_{\max}$ is replaced by $\Delta\Delta P_{\max}$, using the correlation between $\Delta\Delta P_{\max}$ and $F_{\max}$, $f(ER)$ can be expressed as follows:

$$f(ER) = (\Delta\Delta P_{\max})^{2.18} * \left(\frac{E^{1.08}}{\sigma_t^{3.26}} \right) \dots \dots \dots (3)$$

which is a function of maximum force, tensile strength and elasticity modulus, was found to have a good correlation with erosion index, I . Therefore, prediction of erosion rate of in-bed components can be achieved when $\Delta\Delta P$, σ_t and E of the component material are known.

Figure 6 shows the correlation curve.

The prediction equation takes the form of

$$I = 2.45 * 10^4 (\Delta\Delta P_{\max})^{2.18} * \left(\frac{E^{1.08}}{\sigma_t^{3.26}} \right) \dots \dots \dots (4)$$

Where I has the unit of $kg/m^2/hr$, E , σ_t and $\Delta\Delta P$ have the unit of kPa .

The correlation coefficient is 0.997 .

We are trying to understand the physical meaning of this experimentally obtained equation in terms of the solid fracture theory.

EROSION VERSUS ΔP AND MATERIAL PROPERTY

Figure 6. Erosion versus ΔP_{max} and Material Property

4.5. Fluidization Particle Effect on Erosion Rates

To investigate the effect of the properties of fluidization particle on the erosion rates, systematic experiments were carried out, using glass beads. The elasticity modula of silica sand and glass bed are listed in Table 5.

Table 5. Elasticity Modulus of Fluidization Particle

Material	Elasticity Modulus E_p (kPa)
Silica Sand	1.05×10^8
Glass Bead	6.90×10^7

The 4" x 4" square fluidized bed was again used, and the copper tube was used for these experiments. The fluidization conditions were: Superficial gas velocity $U_o/U_{mf} = 1.50, 2.00, 2.21, 2.94, 3.68$ and 4.42 , Bed aspect ratio $H/D_t = 2$. The fluidization particles, glass bead and silica sand, have the diameter of $d_p = 1.00$ mm and $d_p = 1.1$ mm, respectively. The results are shown on Table 6 and Figure 7. Figure 8 gives the comparison for the results in silica sand and glass beds cases. It can clearly be seen that particle with higher elastic modulus (silica sand) resulted a higher erosion rates.

The shape of the particles can also effect the erosion rates. Irregularly shaped particles cause higher erosion rates. In our case, the silica sand is irregularly shaped, and the glass bead is sphere shaped. The combined effects caused significant higher erosion rates in the silica sand case.

4.6. Fluidized Bed Configuration Effect on Erosion Rates

Other experiments were accomplished to investigate the fluidized bed configuration effect on the erosion rate. A cylindrical

Table 6. Erosion Index Data (Copper) with Glass Beads

Cu	D=15.85mm	L=101.30mm	As=50.442cm =5.044x10 ⁻³ m ²			
U _o /U _{mf}	I ₁	I ₂	I ₃	I ₄	I ₅	I _{total}
4.42	9.913E-5 ΔW=.0120 hr=24	1.050E-4 ΔW=.0127 hr=24	9.252E-5 ΔW=.0112 hr=24	8.591E-5 ΔW=.0195 hr=45	8.447E-5 ΔW=.0409 hr=96	8.963E-5 ΔW=.0963 hr=213
3.68	4.956E-5 ΔW=.0060 hr=24	5.617E-5 ΔW=.0068 hr=24	6.856E-5 ΔW=.0083 hr=24	7.600E-5 ΔW=.0092 hr=24	6.749E-5 ΔW=.016 hr=47	6.419E-5 ΔW=.0463 hr=143
2.94	2.643E-5 ΔW=.0032 hr=24	3.056E-5 ΔW=.0037 hr=24	3.800E-5 ΔW=.0046 hr=24	2.310E-5 ΔW=.0028 hr=24	2.913E-5 ΔW=.0169 hr=115	2.932E-5 ΔW=.0312 hr=211
2.21	2.230E-5 ΔW=.0027 hr=24	3.220E-5 ΔW=.0039 hr=24	2.230E-5 ΔW=.0027 hr=24	1.652E-5 ΔW=.0020 hr=24	2.279E-5 ΔW=.0050 hr=43.5	2.316E-5 ΔW=.0163 hr=139.5
2.00	9.087E-6 ΔW=.0011 hr=24	1.189E-5 ΔW=.0015 hr=25	1.074E-5 ΔW=.0013 hr=24	9.494E-6 ΔW=.0034 hr=71	9.637E-6 ΔW=.0035 hr=72	9.913E-6 ΔW=.0108 hr=216
1.50	4.130E-6 ΔW=.0005 hr=24	7.209E-6 ΔW=.0008 hr=22	4.506E-6 ΔW=.0005 hr=22	1.950E-6 ΔW=.0007 hr=71	1.652E-6 ΔW=.0002 hr=24	3.284E-6 ΔW=.0027 hr=163

Figure 7. Erosion Index versus Maximum Force with Copper Tube and Glass Beads

EROSION INDEX VERSUS MAXIMUM FORCE

Figure 8. Fluidization Particle Effects (Copper Tube)

fluidized bed (4.25" I.D.) was used, and copper tube was tested to obtain the erosion data.

The fluidization conditions were: superficial gas velocity $U_o/U_{mf} = 1.5, 2.0, 2.5$ and 3.0 , $H/D_i = 2$, bed diameter $D_i = 4.25"$ cylindrical. Fluidization particle was silica sand ($0.8-2.0$ mm, $\bar{d}_p=1.1$ mm). The results, together with the data in square bed case, are shown in Figure 9. Figure 9 shows that there is no much significant effect on erosion rates, when the fluidized bed configuration is changed.

4.7. Maximum Forces of Solid Particles in Peripheral Direction of the In-Bed Tube Surface

Systematic studies were carried out to investigate the transient force distribution in peripheral direction of the in-bed tube surface. Figure 10 shows the layout of measurement points. The probe was mounted on the surface from inside of in-bed tube, and the maximum force data were taken and analyzed. At the beginning the measurement point was located at the top center of the tube (0° or 12 o'clock). Then the tube was rotated 45° (clockwise) at a time (see Figure 10), and the maximum force data (indirectly expressed by $\Delta\Delta P_{max}$) were also taken and compared. At different location peripherally around the tube surface (top or 0° ; center of the curve between top and side, or 45° ; side or 90° ; center of the curve between side and bottom, or 135° ; and bottom or 180° ; of in-bed tubes).

Through the systematic studies we obtained the peaks of transient force of solid particles (indirectly expressed by gas phase $\Delta\Delta P_{max}$) and their frequency distribution. The experiment was carried out under the following fluidization conditions: Particle size $d_p=0.8-1.1$ mm, $\bar{d}_p=1.1$ mm, Bed diameter $D_i=4"$ square, Bed aspect ratio $H/D_i=2.14$, Superficial gas velocity $U_o/U_{mf}=1.5, 2.0, 2.5$ and 3.0 . Results show that the maximum force (expressed as the average of top five maximum forces) has the maximum value at the center of the curve between side and bottom, or 135° from the top, of the tube. This is in agreement with our earlier observations of erosion in ceramic materials.

Figure 11 shows the maximum force (expressed as the average of top 5 maximum force) distribution in peripheral direction around the in-bed tube surface. Four curves are in the figure, representing superficial gas velocity (U_o/U_{mf}) of $1.5, 2.0, 2.5$ and 3.0 . The distribution curves are flat when superficial gas velocity is low. As the superficial gas velocity increases, a peak forms (see Figure

Figure 9. Fluidized Bed Configuration Effects (Copper Tube with Silica Sand)

Figure 10. Layout of Measurement Points in Peripheral Direction

$\Delta\Delta P_{\max}$ DISTRIBUTION AROUND TUBE SURFACE

Figure 11. The Distribution of Pressure Fluctuation
In Peripheral Direction of In-Bed Tube Surface

11).

4.8. Maximum forces of solid particles on and away from the In-Bed Tube

Experiments were also accomplished systematically to assess the maximum transient forces of solid particles on and away from the in-bed tube.

To measure the peaks of gas pressure fluctuation, which can be correlated with the maximum forces at the location away from the in-bed tube, three measurement points were selected. They are located 16mm from the wall, Figure 12 shows the locations of measurement points.

The maximum force was measured under the following fluidization conditions: Particle size $d_p=0.8-1.1\text{mm}$, $\bar{d}_p=1.1\text{mm}$, Bed diameter $D_t=4"$ square, Bed aspect ratio $H/D_t=2.14$, Superficial gas velocity $U_o/U_{mf}=1.5, 2.0, 2.5$ and 3. Results are shown in Figure 13. The general tendency is that the maximum force away from the tube is higher than that on the tube top, and the maximum force values are higher at lower measurement points.

These results indicate a very interesting conclusion that the distribution of the local maximum of transient forces does exist and that it can provide useful information on the design of the configuration of in-bed tubes.

4.9. Erosion Rate Distribution in the Longitudinal Direction of the In-Bed Tube

Erosion rate distribution in the longitudinal direction of in-bed tubes was tested. Five aluminum tube rings were installed as shown in Figure 14, to take the erosion rate at each local points in the axial direction of in-bed tubes. Under these experimental set-ups, the local erosion index was measured.

The experiments were carried out under the following fluidization conditions: Particle size $d_p=0.8-1.1\text{mm}$, $\bar{d}_p=1.1\text{mm}$, silica sand; Bed diameter $D_t=4"$ square; Bed aspect ratio $H/D_t=2$, Superficial gas velocity $U_o/U_{mf}=3$. Results are shown in Figure 15. The general tendency is that the erosion rate index is the highest near the tube center. It decreases and becomes lowest at the wall.

Figure 12. Layout of Measurement Points

$\Delta\Delta P_{\max}$ AT DIFFERENT MEASUREMENT POINTS

Figure 13. Maximum Pressure Fluctuation At and Away from The Tube

Figure 14. Layout of the Tube Rings

EROSION INDEX IN LONGITUDINAL DIRECTION (ALUMINUM ALLOY WITH SILICA SAND)

Figure 15. Erosion Index in Longitudinal Direction
(Aluminum Alloy Tube with Silica Sand)

5. CONCLUSIONS

1). To predict the erosion rates of in-bed tubes in fluidized beds, the transient forces of solid particles were measured, and data were processed by PC. The maximum transient force of solid particles in fluidized bed was defined and obtained. The frequency of the peak of transient forces was also characterized. Thus, the maximum of transient forces of solid particles were correlated with erosion index measurements.

2). As a tool of measuring the transient forces of solid particles, the gas phase pressure fluctuation method was used. Because there is a good correlation, the maximum forces of solid particles can be correlated to $\Delta\Delta P_{\max}$ according to our past experiments (Kono et al., 1987, 1988, 1989, 1990).

3). The characterization method for the transient forces of solid particles was improved to take the frequency into account, and a simple erosion index was also defined to quantify the erosion rates better.

4). Experimental results indicate that there is a good correlation between the erosion index and the characterized maximum force.

5). A prediction model was developed to assess the erosion rates. This model includes two important parameters. They are characteristic mechanical properties of the tube material, and the maximum transient forces of solid particles in fluidized beds.

6). As the third parameter, properties of fluidization particles (e.g., particle size and mechanical properties) affect significantly erosion rates of in-bed components. In general, the particle with a higher elastic modulus causes a higher erosion rates. The shape of the particles can also effect the erosion rates.

7). There is no significant effect of fluidized bed configuration on erosion rate.

8). The higher erosion rate were observed for the in-bed tube near the tube center than those near the wall.

9). The transient force distribution in the peripheral direction around the in-bed tube surface was obtained. The transient maximum force has the maximum value at the center of the curve between side and bottom of the in-bed tube.

10). The transient maximum force away from the tube is higher than that on the top of the in-bed tube.

11). The locally prevailing transient forces of solid particles can be predicted by measuring the local maximum force of solid particles. The results indicate that, there exists a distribution of local maximum forces of solid particles which can provide useful information for the design of the fluidized beds.

12). Based upon the comparison between the experimental erosion data and the prediction model, we found a pretty satisfactory accuracy of our prediction model.

6. NOMENCLATURE

A	Surface area of in-bed tube
C	Constant in Equation (2)
d_p	Diameter of fluidized particle
$\bar{d}_p$	Average diameter of fluidized particle
D_t	Diameter of fluidized beds
E	Elasticity modulus of in-bed component material
E_p	Elasticity modulus of fluidization particle
$F_{\max}$	Maximum transient forces of solid particles in fluidized bed at the specific measurement point
$f(ER)$	Erosion rate characteristic function of Equation (2)
g	Gravitational constant
H	Loosely packed bed height
I	Erosion index of in-bed tube
M	Mass of the total fluidized particles in the bed
U_{mf}	Minimum fluidization velocity
U_o	Superficial gas velocity
Δt	Time period during which ΔW is observed
W	Weight of in-bed tube
ΔW	Weight loss of in-bed tube
$\Delta\Delta P_{\max}$	Maximum gas phase pressure fluctuation

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