VII. EROSION IN MULTIPHASE FLOW AND VALIDATION OF SPPS

Introduction

Erosion is a micro-mechanical process by which material is removed from metal or non-metal surfaces by impact of solid particles entrained in the carrier fluid. The entrained solid particles remove material from the inner wall of pipes, fittings, valves, and other process equipment potentially causing severe damage. Damage to piping and equipment reduces the operational reliability and increases the risk of failure resulting in significant financial loss to the industry and danger to the personnel and environment.

Transportation of fluid is essential in several industries to meet production and operational needs. In the oil and gas industry, crude oil and natural gas are extracted from the reservoirs and transported to processing facilities using piping, fittings and other equipment. The extracted fluid from the reservoir contains sand particles that may cause erosion damage to the inner surfaces of fluid handling equipment. In coal gasification, erosion adds to corrosion problems causing severe damage to valves and fittings. In the mining industry, transportation of slurry such as iron ores, potash and coal causes erosion to the piping and equipment. In the aerospace industry, high velocity intake air with sand particles causes erosion to heat exchangers, engine and rotorcraft blades, and other components. Erosion damage can cause unscheduled repair, removal and replacement of equipment interrupting production and in some cases result in shutdown of the production process. The safety of operating personnel and the environment can also be in jeopardy when harmful chemicals or gases discharge to the surrounding environment. The end result is lost revenue, harm to personnel and increased operational cost that are highly undesirable. To optimize operational efficiencies by minimizing equipment loss and production downtime due to erosion, it is important to reduce damage due to erosion. One of the approaches to minimize or control erosion is to reduce flow velocities during production and transportation that also reduces the production rate. Another approach is to use sand screens; the screen material may erode after a period of time or sand particles may clog the screen. Selecting appropriate erosion resistant materials can also reduce erosion rate.

In the oil and gas industry, elbow, tees, pumps, valves, chokes and other fittings are used in piping systems to transport fluids. Within these geometries, as the flow direction changes, the entrained sand particles in the fluid can cross the streamlines and approach the inner walls. These particles can impact the equipment walls at high velocities that can be detrimental to the metal surface. Repeated impact of a large number of particles at high velocities results in material removal from the equipment wall. Figure VII-1 shows the...
erosion damage in a one-inch elbow due to sand particles entrained in single-phase gas flow. This elbow was used in the single-phase erosion experiments conducted during this study. The eroded elbow shows highest erosion at the outer wall.

![Figure VII-1: Sand Particle Erosion of Elbow in Single-Phase Flow](image)

Erosion in a single-phase flow with entrained sand particles in the carrier fluid is a complex phenomenon. The complexity of erosion increases significantly for a multiphase flow with sand particles in the carrier fluid due to different multiphase flow patterns, distribution of sand particles and their corresponding particle impact velocities that cause erosion. Among various factors that influence erosion, particle impact velocity is known to be the most significant factor. Lack of understanding of particle impact velocities and their effect on the erosion process presents a challenge in analysis of the erosion mechanism. Therefore, a better understanding of the particle impact velocity is essential to understand the multiphase erosion process. Most of the available erosion prediction models are empirical and based on a single-phase gas or liquid carrier fluid. The accuracy of the empirical models is limited to the flow conditions that were used in development of the models. To address the complexities associated with a multiphase erosion problem, a number of assumptions must be made to simplify the problem. The validity of these assumptions must be carefully evaluated to qualify that the assumptions are reasonable.

**Background**

American Petroleum Institute (API) Recommended Practice 14E [1] provides guidelines for maximum allowable threshold velocity to limit erosion. API RP 14E states
that if the production velocities are kept below this limit, severe erosion damage can be avoided. The following equation is used to calculate the threshold velocity [1]:

\[ V_e = \frac{C}{\sqrt{\rho}} \]  

(1)

Where, \( V_e \) is the erosional velocity limit in ft/sec, \( \rho \) is the density of the carrier fluid in lbm/ft\(^3\), and \( C \) is a constant. API RP 14E recommends using \( C = 100 \) for continuous service and \( C = 125 \) for intermittent service. Equation (1) does not consider sand size, sand rate, wall material, flow regimes in multiphase flow, or flow orientation (horizontal or vertical). Equation (1) states that the allowable erosional velocity would be higher for a low density fluid (such as gas) compared to a high density fluid (such as liquid). However, experimental results show higher erosion rates in gas compared to liquid at similar velocities.

It may not be economically feasible to limit the fluid velocity as recommended by Equation (1) because of potential conflict between lower flow rate and production demand. Therefore a different approach to the problem is required to attain a more acceptable solution. The erosive sand particle impact velocity primarily depends upon the geometry and fluid velocity. Elbows and plug tees are the most commonly used geometries for redirecting flows in the piping systems. These geometries are also most susceptible to erosion damage. Analysis by Wang [2] showed long radius elbows (r/D > 1.5, where r is the turning radius of the centerline of the elbow and D is the inside diameter of the elbow) have lower erosion compared to a standard elbow. Field experience also shows long radius elbows having lower erosion than standard elbows. Figure VII-2 shows schematics of an elbow and plug tee.

![Figure VII-2: Sketch of Elbow and Plug Tee Geometries.](image)
In confined piping systems, plug tees are often used instead of long radius elbows due to lack of space. Higher strength alloys such as duplex stainless steel are also used to extend the service life of the equipment from erosion damage. Although these materials increased the service life of the equipment, it may be cost prohibitive to use these expensive materials in large complex piping systems.

Multiphase flow is commonly observed in chemical, oil and gas, nuclear and other fluid handling industries. Unlike single-phase flow, multiphase flow phenomenon is very complicated with lack of clear understanding of all the flow mechanisms. The presence of different phases with different properties and different velocities result in different flow patterns such as annular, slug, churn, and bubble flow. These flow patterns are characterized by the interfacial properties between the phases. Some of the multiphase flow patterns are transient, unstable, and not fully developed. Due to these complex phenomena, the erosion prediction in multiphase flow is far more challenging than single-phase flow.

Simplified erosion prediction models for straight pipe, elbows, and plug tees have been developed at the Erosion/Corrosion Research Center of The University of Tulsa using empirical erosion data and CFD modeling. To account for solid size and liquid-gas mixture, Salama [3] modified Equation (1) to predict erosion. Shirazi et al. [4] developed a semi-empirical erosion prediction model that accounts for pipe size and geometry, sand size, pipe material, fluid velocities and densities. These models are based on empirical erosion data and do not consider the effect of flow regime on erosion in multiphase flow.

The work presented here is an improvement of the previous model developed at E/CRC [4] and development of a mechanistic erosion prediction model for multiphase flow. This new mechanistic model accounts for multiphase flow behavior and flow regimes in predicting erosion. The effect of particle velocities and their distribution in liquid and gas phases were considered in the model. As this model accounts for the important variables that cause erosion, this model is more general and can predict erosion over a wide range of flow velocities. To simplify the complexities of multiphase flow, a number of assumptions were necessary during the model development process. These assumptions were based on careful evaluation of erosion mechanism, two-phase flow theory and past experience with erosion characteristics. This chapter describes the current status of the 1-D version of SPPS including recent improvements. The 2-D version of SPPS is described in Chapter ???.

**Research Goal**

The primary objective of this research is to investigate erosion behavior in multiphase flow and to develop a mechanistic model to predict erosion in elbows for a wide
range of single and multiphase flow conditions. This mechanistic model should be able to predict erosion considering the significant parameters that affect erosion. The model should compute the solid particle velocity and their concentration in both gas and liquid phases of multiphase flow. The model should rely on principles of fluid mechanics, two-phase flow theories, and physical mechanisms that cause erosion. Results of the mechanistic model can be used to predict erosion and study the effects of different parameters that influence erosion.

**Approach**

The mechanistic model development process involves the following steps. The semi-empirical erosion prediction procedure previously developed at the Erosion/Corrosion Research Center of The University of Tulsa was evaluated by using available experimental erosion data reported in the literature. The semi-empirical model uses superficial liquid and gas velocities to calculate the initial particle velocity, $V_0$ that is used to calculate particle impact velocity at the wall. The model does not account for the effect of different flow regimes in multiphase flow. The mechanistic model developed in this research first calculates the flow regimes. The corresponding liquid and gas velocities were then calculated using two-phase flow equations. For example, in annular flow, the sand entrainments in the liquid and gas phases were estimated using experimental data and correlations. Using the sand particle velocities and entrainments in different phases, the corresponding erosion rates were calculated separately for gas and liquid phases using erosion equations. Finally, the erosion rates for gas and liquid phases are added together to compute the total erosion rate for the flow condition.

The erosion rate or penetration rate is defined as the rate of wall thickness loss due to sand particle impact on the wall. A dimensionless parameter used to define erosion is the erosion ratio. Erosion ratio is calculated by dividing the mass loss from the pipe wall by the mass of sand particles that cause erosion.

**Literature Review**

This research mainly focused on understanding the physical phenomenon of solid particle erosion on metal surfaces by evaluating the factors that affect erosion and development of a generalized mechanistic model to predict erosion in single and multiphase flows. Most of the currently available erosion prediction models are based on empirical data and assumptions that are unable to accurately predict erosion in flow conditions beyond the
experimental conditions. While some of these models are only valid for predicting the erosion in single-phase flow. This creates a need for a generalized multiphase erosion prediction model.

To develop a mechanistic model for multiphase flow, experimental, theoretical, analytical and mechanistic approaches can be used. Each of these approaches has their unique advantages and disadvantages. The experimental approach requires using a geometry of interest (such as pipe, elbow, and tee) and/or a representative test specimen to conduct the erosion tests under specific flow conditions. The erosion ratio (mass loss of the geometry/mass of the sand that causes erosion) and/or penetration rates (thickness loss per unit sand throughput, mils/lb) are then calculated from the mass loss or thickness loss data, geometry, flow and test conditions. This experimental erosion data can be used to validate erosion models.

One of the main disadvantages of the experimental approach is the cost and time required to conduct erosion tests at different flow conditions and using different geometries. Construction of a multiphase erosion test loop may be a very expensive and time-consuming project. Gathering reliable and useful erosion data often requires experiments to be run for long periods of time and then repeating the tests. The above constraints can make the experimental approach cost-prohibitive and time-consuming. The theoretical or analytical approach requires a clear understanding of the different variables and their interactions that cause erosion in multiphase flow. The understanding of these variables and their effect on erosion is still being developed and evaluated. A lack of clear understanding of these variables prevents the development of an accurate theoretical or analytical erosion prediction model.

Considering the above factors, the development of a mechanistic model using multiphase flow theory, erosion equations and then validating the model with experimental erosion data appears to be a more feasible and practical approach in addressing the erosion problem. The work presented here discusses the efforts in the development of a mechanistic model.

In order to understand the erosion phenomenon in multiphase flow, it is essential to have knowledge and understanding of several concepts. First, a good understanding of the solid particle erosion process in single-phase and multiphase flow is important. The major factors that affect solid particle erosion are impact velocity, impingement angle, wall material, particle shape, size, density, carrier fluid properties (density, viscosity), and carrier fluid velocity. Among these factors, particle impact velocity has the greatest influence on erosion, as erosion rate is a function of the exponent of the impact velocity. Second, knowledge of multiphase flow and how the erodent solid particles are distributed in different
phases is essential. In a two-phase gas-liquid flow, the gas and liquid have different spatial distributions with their corresponding velocities that influence the solid particle velocity. Particle impact velocities can be calculated from the corresponding gas and liquid phase velocities. The third important factor is the fraction of solid particles entrained in the gas and liquid phases. In multiphase flow, gas bubbles can be entrained in the liquid phase and liquid droplets can be entrained in the gas phase. The particles entrained in the liquid and gas phases will have velocities similar to the corresponding phase velocities.

Finally, to calculate the erosion caused by solid particles, one must understand how the particles impact the wall of the geometry causing removal of the wall material. The remainder of this chapter discusses the above factors and how they contribute to erosion.

**Erosion Phenomenon and Erosion Models**

Erosion is a process by which material is removed from the inner surface of a fluid-handling device as a result of repeated impact of small solid particles. In ductile materials erosion is caused by localized plastic strain and fatigue resulting in material removal from the surface. In brittle material, impacting particles cause surface cracks and chipping of micro-size metal pieces.

Erosion behavior in a single-phase gas was investigated by Brinell [5] as early as 1921. One of the first erosion models developed by Finnie [6] in 1958 was based on the assumption that erosion is a result of the micro-cutting mechanism. Later, other investigators demonstrated that micro-cutting is not the primary erosion mechanism for ductile material. In 1982, Levy [7] proposed the platelet mechanism of erosion in ductile material. To determine the effects of specific steel microstructures on erosion, Levy analyzed the eroded surfaces by using a Scanning Electron Microscope (SEM). From the micrographs, Levy observed that the platelets from the metal surfaces are initially extruded due to impact of smaller solid particles; the platelets are then forged into distressed conditions and are eventually removed from the surfaces by further subsequent impacts. A work hardening zone developed underneath the platelet zone during the erosion process. After the removal of metals from the platelet zone, the steady-state erosion process begins.

Particle impact velocity has been recognized as the most significant contributing factor for erosion and erosion-corrosion by several investigators. Experimental results show the erosion rate to be proportional to the particle impact velocity or flow velocity raised to an exponent. The value of this velocity exponent has been reported to be between 0.8 and 8.0 by different investigators depending upon the flow conditions, material properties, corrosion, and other parameters that contribute to mass loss [8]. Stoker [9] proposed the erosion rate to be proportional to the cube of the air velocity in single-phase gas flow.

\[
ER = \begin{cases} 
    c \rho_w \left( V \left( \cos \theta - \frac{3}{2} \sin \theta \right) \sin \theta \right) & \text{for } \theta \leq 18.5^\circ \\
    \left( \frac{c \rho_w (V \sin \theta)^2}{12 \sigma_o} \cos^2 \theta \right) & \text{for } \theta > 18.5^\circ
\end{cases}
\]

Where, \( ER \) is the erosion ratio, \( c \) is an empirical constant (nominal value for \( c \) is 0.50), \( V \) is the particle impact velocity, \( \theta \) is the particle impact angle, \( \rho_w \) is the density of the wall material, \( \sigma_o \) is the yield strength of the target wall material. Tilly [13] presented the following erosion model where he expressed erosion in terms of particle impact angle with different coefficients for ductile and brittle materials.

\[
ER = J \cos^2 \theta + K \sin^2 \theta
\]

Where, \( ER \) = Erosion in cc/kg, \( \theta \) is the particle impact angle, \( J \) and \( K \) are the coefficients based on material properties. Tilly proposed \( J=0 \) for pure brittle material and \( K=0 \) for pure ductile material. Many materials exhibit a combination of brittle and ductile erosion so that the ductile term dominates at small angles and the brittle term dominates at large angles.

Ahlert [14] conducted an experimental investigation of erosion on dry and wetted surfaces at different impingement angles. His experimental results showed that erosion on dry surfaces depends upon the impingement angle with higher erosion rates at a 15-30 degree impingement angle. Erosion behavior on wet surfaces was similar at all impingement angles between 15-60 degrees. Contrary to the lower expected erosion for a wetted specimen than a dry specimen, the wetted specimen showed 2-3 times more mass loss than the dry specimen. Further investigation of the eroded surfaces was conducted using a Scanned Electron Microscope (SEM). The SEM micrographs revealed larger and deeper craters in the wetted specimen surface that extruded more metal. The displaced material from the craters is pushed upwards, piling up at the edge of the crater and eventually breaking apart from the surface. For dry specimens, the craters were comparatively smaller and removed less material from the surface.

Erosion as a result of particles entrained in flow systems adds another dimension to the complexity of erosion prediction. Erosion due to particle impact can be caused by two mechanisms: 1) direct impingement, and 2) random impingement. In geometries like
elbows and plug tees that are used to redirect the flow, the entrained particles can cross the flow streamlines. At high velocity, these particles approach the wall with a high momentum causing direct impingement to the wall. In geometries like straight pipe, where the mean flow directions do not change, particles approach the wall due to turbulent fluctuations causing random impingement to the wall. Figure VII-3 shows direct impingement in an elbow and random impingement in a straight pipe.

**Figure VII-3: Direct and Random Impingement in Elbow and Pipe**

Generalized models such as the computational fluid dynamics (CFD) based erosion models [15] which take into account details of flow effects and pipe geometry require a significant computational effort to simulate the particles’ trajectories, impingement angles and speeds. Blatt [16] studied the particle velocity close to the target wall of a pipe with sudden expansion in a two-phase liquid-particle flow and proposed that the flow velocity in the form of the power law influence the erosion rate with exponents of 2.0. Salama [3] proposed an erosion prediction model using mixture density and mixture velocities to account for multiphase flow. The model considers particle diameter, sand production rate, a geometry constant and calculates erosion rate using an exponent of 2.0 of mixture velocity. McLaury and Shirazi [17] developed a mechanistic model for predicting the maximum penetration rate in geometries, such as elbows and tees, that was based on a CFD-based erosion model. The mechanistic model for multiphase flow was based on extensive empirical information gathered at The University of Tulsa, Louisiana State University, Harwell and Det Norske Veritas (DNV) for erosion in multiphase flow. The model uses a characteristic impact velocity of the particles while taking into account factors such as pipe geometry and size, sand size and density, flow velocity, and fluid properties. The model also can be used to determine the threshold velocity for a corresponding maximum allowable penetration rate.

Shadley [4] proposed a simplified stagnation length model for predicting erosion in simple geometries. According to the model, the maximum penetration rate for simple geometries such as elbows and tees the following equation can be used.
\[ h = F_M F_S F_P \frac{W V_L^{1.73}}{(D/D_0)^2} \]  \hspace{1cm} (4)

where:

- \( h \) = penetration rate in mm/year
- \( F_M, F_S \) = empirical factors for material and sand sharpness
- \( F_P \) = penetration factor for steel based in 1” pipe diameter, (mm/kg)
- \( F_{r/D} \) = penetration factor for long radius elbows
- \( W \) = sand production rate, (kg/s)
- \( V_L \) = characteristic particle impact velocity, (m/s)
- \( D \) = pipe diameter, (mm)
- \( D_0 = 25.4 \text{ mm} \)

For carbon steel material, Shadley proposed \( F_M = 1.95 \times 10^{-5} / B^{-0.59} \) (for \( V_L \) in m/sec) where \( B \) is the Brinell hardness factor. Table VII-1 shows \( F_M \) for 1018 Steel and 316 Stainless Steels.

**Table VII-1. Empirical Material Factor (FM) for Different Materials [4]**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Yield Strength (Ksi)</th>
<th>Tensile Strength (Ksi)</th>
<th>Brinell Hardness (B)</th>
<th>Material Factor for ( V_L ) in m/sec ((F_M \times 10^6))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1018</td>
<td>90.0</td>
<td>99.5</td>
<td>210</td>
<td>0.833</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>35</td>
<td>85</td>
<td>183</td>
<td>0.918</td>
</tr>
</tbody>
</table>

For known pipe diameter, \( D \), and sand production rate, \( W \), the values of \( F_S \) and \( F_P \) are provided in Table VII-2 and Table VII-3.
### Table VII-2. Sand Sharpness Factors (F_S) for Different Types of Sand [4]

<table>
<thead>
<tr>
<th>Description of Sharpness</th>
<th>Sand Sharpness Factor, F_S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp (angular corners)</td>
<td>1.0</td>
</tr>
<tr>
<td>Semi-Rounded (rounded corners)</td>
<td>0.53</td>
</tr>
<tr>
<td>Rounded (spherical glass beads)</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Table VII-3. Penetration Factors (F_P) for Elbow and Tee Geometries [4]

<table>
<thead>
<tr>
<th>Reference Stagnation Length for 1” Pipe, L_o</th>
<th>F_P (for steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>mm</td>
</tr>
<tr>
<td>90° Elbow</td>
<td>30</td>
</tr>
<tr>
<td>Tee</td>
<td>27</td>
</tr>
</tbody>
</table>

The penetration factor $F_{v/D}$ is obtained by Wang [2] using the following equation

$$F_{v/D} = \exp \left\{ - \left( 0.1 \frac{\rho_f 0.4 \mu_f 0.65}{d_p 0.3} + 0.015 \rho_f 0.25 + 0.12 \right) \left( \frac{r}{D} - C_{std} \right) \right\}$$

(5)

where, $\rho_f$ is the fluid density in kg/m$^3$, $\mu_f$ is the fluid viscosity in Pa-s, $d_p$ is the particle diameter in m, $F_{v/D}$ is the elbow radius factor for long radius elbow, $C_{std}$ is the $r/D$ ratio for a standard elbow ($C_{std}=1.5$).

The equivalent stagnation length for an elbow and tee geometries were obtained by flow modeling, erosion testing and particle tracking of sand in gas and liquid phases. The equivalent stagnation length ($L$) is a function of pipe diameter and can be calculated

Elbow:  

$$L = L_o \left\{ 1 - 1.27 \tan^{-1}(1.01 D^{-1.89}) + D^{0.129} \right\}$$

(6)
The simplified particle tracking model used in this erosion model assumes a one-dimensional flow field in the stagnation zone that has a linear velocity profile in the direction of particle motion. For single-phase flow, the initial particle velocity, $V_o$, can be assumed to be the same as the flowstream velocity which may not be accurate for two-phase flow. Assuming the “equivalent characteristic flowstream velocity” before the particles reach the stagnation zone is known, the characteristic particle impact velocity was calculated using a simplified particle tracking model developed at the Erosion/Corrosion Research Center [4]. The characteristic particle impact velocity depends upon a number of parameters such as particle Reynolds number, density and viscosity of fluids, particle size and density. The particle Reynolds number, $Re_o$, is calculated as

$$Re_o = \frac{\rho_m V_o d_p}{\mu_m}$$

where:

- $V_o$ = equivalent flowstream velocity, m/sec
- $\rho_m$ = mixture density of fluid in the stagnation zone, kg/m$^3$
- $\mu_m$ = mixture viscosity of fluid in the stagnation zone, pa-s or N-s/m$^2$
- $d_p$ = diameter of particles, m.

A dimensionless parameter, $\phi$, is used that is proportional to the ratio of mass of fluid displaced to the mass of the impinging particles

$$\phi = \frac{L \rho_m}{d_p \rho_p}$$

where:

- $L$ = equivalent stagnation length, m
- $\rho_p$ = density of particles, kg/m$^3$.

Using the dimensionless parameter $\phi$, particle Reynolds number $Re_o$, and $V_o$, the particle impact velocity $V_L$ can be determined from Figure VII-4.
Figure VII-4. Effect of Different Factors on Particle Impact Velocity [4]

The equivalent flowstream velocity, \( V_o \), must be specified to calculate the particle Reynolds number, \( R_{eo} \). For single-phase flow, it is assumed to be the average flow velocity. For two-phase flow, the following ad hoc equations are used to calculate the equivalent flowstream velocity.

\[
V_o = \lambda^n V_{SL} + (1 - \lambda)^n V_{SG}
\]  

(10)

where,

\[
\lambda = \left( \frac{V_{SL}}{V_{SL} + V_{SG}} \right)^{0.11}
\]  

(11)

\[
n = \left[ 1 - \exp \left( -0.25 \frac{V_{SG}}{V_{SL}} \right) \right]
\]  

(12)

The exponent n is used so that when \( (V_{SG}/V_{SL}) < 1 \), \( V_o = V_m = V_{SL} + V_{SG} \).

For a given geometry, material, sand sharpness and sand rate, all the terms in Equation (4) become constant except the characteristic impact velocity, \( V_L \) and can be written as

\[
h = KV_L^{1.73}
\]  

(13)
The term $V_L$ in the equation represents the characteristic particle impact velocity of particles, which must be deduced by solving a simplified particle tracking equation. The investigators [17] developed a method for calculating $V_L$, which is obtained through creating a simple model of the stagnation layer representing the pipe geometry. The stagnation zone is a region that the particles must travel through to penetrate and strike the pipe wall for erosion to occur. This approach is graphically displayed in Figure VII-5. The severity of erosion in this zone depends on a series of factors such as fitting geometry, fluid properties and sand properties. It was demonstrated that for elbows with different diameters the stagnation length varies. A simplified particle-tracking model is used to compute the characteristic impact velocity of the particles; the model assumes movement in one direction with linear fluid velocity profile. Initial particle velocity is assumed to be the same as the flowstream velocity, $V_o$. Validity of this assumption is limited to single-phase flow when there is no-slip between the particles and fluid.

![Figure VII-5. Schematic Description of Stagnation Length Model [17]](image)

The next variation developed by Mazumder [18] at E/CRC used initial particle velocities that were a function of the flow regime. For example, the initial particle velocity used in the particle tracking for annular flow was a mass-weighted average of the gas core velocity and liquid film velocity. Mazumder took the model one step further for annular flow by calculating the erosion from particles in the gas core and in the liquid film separately then adding together [19]. The gas and liquid properties along with the gas core and liquid film velocities, respectively, were used in the particle tracking to determine the
representative impact velocities. The fraction of particles present in the gas core was assumed to be equal to the entrainment fraction of the liquid in the gas core.

Jordan [20] also extended the McLaury and Shirazi semi-empirical model to multiphase flow. He also analyzed the gas and liquid phases separately. Salama also developed an empirical model for use with a multiphase carrier fluid [3]. This model uses mixture properties and mixture velocity to determine erosion. This model still calculates the erosion as a function of the fluid (mixture) velocity, effectively assuming that the particle impact velocity is similar to the fluid velocity. This model also relies on a geometry dependent constant that must be determined experimentally. DNV has also developed a recommended practice based on experimental data and computational fluid dynamic results [21]. Details of the practice are not published in open literature.

Several researchers have used a computational fluid dynamics (CFD) approach to calculate erosion [22, 23, 24]. This approach generally consists of three steps: calculating the flow field for a given geometry, calculating thousands of representative particle trajectories, and using the impingement information in erosion equations to determine a penetration rate. The CFD approach is the most general approach and is the best way to capture the effects of geometry. This approach also accounts for a variety of parameters that influence the severity of erosion. However, this approach is essentially limited to a single-phase carrier fluid or multiphase flow with a homogenous flow structure such as bubbly flow. This limitation results from difficulties in obtaining solutions for multiphase flow regimes such as annular flow due to lack of appropriate models. CFD for multiphase (gas-liquid) flow is still in its beginnings, but work is progressing in this area. Chen [25] performed some preliminary erosion simulations in multiphase flow that used a combination of CFD and mechanistic models. For example, he would use CFD to simulate an annular flow using the gas core properties and velocities. However when the particles hit the wall, an additional routine would be used to simulate the particle crossing the liquid film to impact the wall. Information on the film thickness and velocities were generated using mechanistic models. All of the CFD approaches are computationally intensive and require the CFD software and expertise of its use.

**Multiphase Flow and Flow Patterns**

A physical understanding of the flow characteristics with more than one phase is much more complex than single-phase as the phases are distributed in different configurations. The reason is that the phases do not uniformly mix and that small-scale interactions between the phases can have a profound effect on the macroscopic properties of the flow [26]. The interface between the phases can be highly unstable, irregular and
transient. The interfacial forces between the phases develop different flow configurations or flow patterns in multiphase flow. The flow pattern changes with the change of phase velocities and properties. Another factor that influences the flow pattern is the flow orientation and inclination angle of the pipe. For example, different flow patterns may exist at similar liquid and gas phase velocities for horizontal, vertical or inclined pipes. Flow configurations have different spatial distributions of the gas-liquid interface, resulting in unique flow characteristics such as entrainment, and different velocity profiles of the phases [27]. Different flow patterns are also observed in horizontal and vertical flows. The major flow patterns observed in horizontal multiphase flow are stratified, slug, annular and dispersed bubble flow as shown in Figure VII-6. In vertical flow, the major flow patterns observed are annular, churn, slug and bubble flows as shown in Figure VII-7.
Due to the large number of variables and complex nature, a rigorous solution of multiphase flow systems is not possible. Generalized models have been developed to solve multiphase flow problems. The homogeneous model assumes the mixture of the phases as a pseudo single-phase fluid with an average velocity and properties. In the homogeneous model, conservation of mass and momentum equations are solved for the total mass flow rate, and average mixture density and velocity. The limitation of this model is that this model assumes no slippage between the phases and that is true only for dispersed bubble flow. Another approach is the separated flow model where gas and liquid phases are assumed to flow separately. In this model each phase is analyzed using a single-phase flow method based on the hydraulic diameter concepts for each of the phases. The separated flow model is limited to horizontal stratified flow as the phases are usually mixed in two-phase flow. The drift flux model assumes phases to be mixed homogeneously, but allows relative slip between the phases. The two-fluid model is a multiphase model in which both the mass and momentum equations are solved for each phase by considering several physical effects [28].

Flow velocities of the gas and liquid phases greatly influence the particle impact velocity. In two-phase flow, superficial gas and liquid velocities are used in the calculation of particle velocity. The superficial velocity of a phase is the velocity that would occur if only that phase was flowing in the pipe. Therefore, the superficial velocities are the volumetric flow rates per unit area of the pipe as shown in Equation (14) and Equation (15):
\[ V_{SL} = \frac{Q_L}{A_p} \]  
\[ V_{SG} = \frac{Q_G}{A_p} \]

where:

- \( V_{SL} \) = Superficial Liquid Velocity, ft/sec
- \( V_{SG} \) = Superficial Gas Velocity, ft/sec
- \( Q_L \) = Volumetric Liquid Flow Rate (ft\(^3\)/Sec)
- \( Q_G \) = Volumetric Flow Rate (ft\(^3\)/Sec)
- \( A_p \) = Cross-Sectional Area of the Pipe (ft\(^2\))

Due to differences in flow behaviors in multiphase flow, the particle impact velocities may be different for different flow regimes. For example, the particle impact velocity in annular flow may depend upon the annular liquid film velocity and gas core velocity. In slug flow, particle impact velocity may depend upon the liquid slug velocity and fraction of total liquid in the liquid slug. In churn and bubble flows, it may depend upon the superficial liquid and gas velocities. Due to different flow characteristics in different flow regimes, the attempt to develop a single model for all flow regimes may not be practically possible. Therefore, different erosion prediction models will be required for different flow regimes.

**Sand Distribution in Multiphase Flow**

The presence of sand in multiphase flow adds to the complexity of the erosion problem. Therefore, the sand entrainment and distribution patterns need to be considered in the mechanistic model. Santos [29] measured sand distribution in multiphase flow using an intrusive probe of 4.7 mm (0.185 inch) diameter inside a one-inch pipe with air and water annular flow. Sand and water samples were collected from five different uniformly spaced locations across the pipe at superficial gas velocities of 25, 50, 75 and 100 ft/sec and superficial liquid velocity of 1.0 ft/sec in both horizontal and vertical pipes. The probe was placed at 900 mm upstream of the erosion test cell to minimize flow disturbances to the erosion specimen. The sand concentration in the collected sample was measured by weighing the wet sample and then after drying the sample. The percentage of sand was calculated by dividing the amount of sand collected by the total sand throughput during the experiment. The percentage of liquid was calculated by dividing the amount of liquid
collected by the total liquid throughput during the experiment. The percentage of sand in water was nearly the same in both the gas core and liquid film region in vertical pipe. In the horizontal pipe, a higher amount of sand in water was measured at the bottom section of the pipe where a thicker liquid film is present.

Selmer-Olsen [30] conducted similar sand distribution experiments in a 26.6 mm pipe and collected sand and water samples using an intrusive probe. Experiments were conducted at superficial gas velocity of 31.0 m/sec and superficial liquid velocity of 0.9 m/sec using gaseous nitrogen and water with 200 μm sand. Their experimental results showed similar sand and liquid concentrations in the gas core and annular liquid film region for vertical annular flow.

**DEVELOPMENT OF MECHANISTIC MODELS**

A mechanistic model is developed to predict erosion in multiphase flow using the characteristic initial particle velocity of sand particles. The characteristic initial particle velocity of sand particles plays an important role in the erosion process due to strong influence of particle velocity on the erosion rate. Thus, the ability to accurately predict the characteristic initial particle velocity in two-phase flow is very important. The early predictive means for characteristic impact velocity was based on a semi-empirical model [4] for $V_o$ as described earlier. The semi-empirical model did not consider the complex flow behaviors that exist in multiphase flow. The mechanistic model presented in this work calculates an initial sand particle velocity, $V_o$, based on the physics of two-phase flow and is expected to be more reliable and general because it incorporates the important parameters of multiphase flow that are critical to erosion.

**Model for Annular Flow**

Annular flow exists at high gas velocity and low liquid velocity. Due to high gas velocity, erosion is usually higher in annular flow than other flow regimes. In gas production wells, the flow is usually annular, gas-liquid, two-phase flow. The gas flows in the core region at high velocity, the liquid flows as a thin film inside the pipe wall at a slower velocity. A schematic of annular flow is shown in Figure VII-8.
A fraction of the liquid is entrained in the gas core region as droplets and travels at a velocity similar to the local gas velocity. The gas core to liquid film interface is unstable and wavy with high interfacial shear stress.

It is assumed that sand is uniformly distributed in the liquid phase and travels at the same velocities of the phase they are present. Another assumption is that there is no slip between the liquid and gas phases in the gas core. The velocities of the liquid film and liquid droplets entrained in the gas core are considered in calculating the initial particle velocities. Additionally, the mass fractions of sand in the film and in the gas core are assumed to be equal to the mass fraction of liquid in the film and gas core region. This means that the mass fraction of sand in the annular film and gas core is assumed to be the same as the mass fraction of liquid in these regions. The model for annular flow is divided into two parts to account for particles in the gas core and the liquid film. The erosion resulting from the particles in the gas core and liquid are then summed to provide the total erosion.

Figure VII-8. Schematic Description of Annular Flow
Impact Velocity for Particles in Gas Core

A two-step approach is used to determine the representative impact velocity of particles present in the gas core. The motion of a representative particle through the gas core is simplified to a one-dimensional path. A simplified Lagrangian particle tracking routine developed at E/CRC described previously is applied across the gas core. This first step is to determine the representative velocity of a particle leaving the core region and entering the liquid film. The particle motion through the gas core is represented by the particle passing through a one-dimensional flow field that has an initial velocity equivalent to the gas core velocity. The fluid properties, density and viscosity, in this region are assumed to be that of the gas. The representative length used for the particle tracking calculation is based on the diameter of the pipe. The initial particle velocity is assumed to be the liquid droplet velocity in the gas core. The particle velocity at the end of the stagnation length is assumed to represent the particle velocity at the interface of the gas core and liquid film. For many cases, the particle velocity at the interface is similar to the gas core velocity due to the differences in density between the particle and gas. However, the exchange of momentum between the gas and the particle is greater for a more dense gas causing the deceleration of the gas to slow the particles more effectively. The next step is to represent the motion of the particle through the liquid film. A two-dimensional particle tracking is applied across the liquid film. A linear fluid velocity profile is assumed, ranging from twice the average film velocity at the interface between the film and the gas core and a value of zero at the wall. The direction of the velocity is parallel to the wall, tangential velocity. The normal fluid velocity is assumed to be zero. The film thickness is determined by a method proposed by Paz [31]. The particle enters the liquid film in the direction normal to the wall with a velocity calculated with the previous particle tracking procedure. As the particle moves through the liquid film, it develops a tangential velocity component. Upon impact, both the normal and tangential velocity components are used to determine the impact speed. This procedure provides a representative impact velocity for particles initially in the gas core.

Impact Velocity for Particles in Liquid Film

Several approaches have been implemented to determine the representative particle impact velocity for particles in the liquid film. The results have shown that the predicted erosion in annular flow varied little for the various approaches applied. Therefore, the representative particle impact is assumed to equal the average liquid film velocity.
Calculating Erosion Rate in Annular Flow

The entrainment rate, $E$, is the fraction of liquid entrained in the gas core and is defined as

$$E = \frac{\text{Mass of liquid in the gas core}}{\text{Total mass of liquid}}$$

Assuming the mass fraction of liquid is equal to the mass fraction of sand, then $E$ is the fraction of sand entrained in the gas core,

$$E = \frac{\text{Mass of sand in the gas core}}{\text{Total mass of sand}}$$

The fraction of sand entrained in the liquid film,

$$1 - E = \frac{\text{Mass of sand in the liquid film}}{\text{Total mass of sand}}$$

The erosion rate due to sand particles in the liquid phase is calculated by using representative impact velocity of particles in the liquid film in Equation (4) and then multiplying by the fraction of sand entrained in the liquid film, $(1 - E)$. The erosion rate due to sand particles in the gas phase is calculated by using the representative impact velocity for particles in the gas core in Equation (4) and multiplying by the fraction of sand entrained in the gas core, $E$. The total erosion rate is calculated by adding the erosion rates due to sand particles in the liquid and gas phases.

The entrainment rate, $E$, is calculated using an expression developed by Zhang et al. [32] as shown in Equation (16). Zhang rearranged an expression developed by Olieman [33] in terms of dimensionless parameters. The Olieman correlation used seven different input parameters and their corresponding exponents using Harwell well data reported by Whalley [34].

$$\frac{E}{1 - E} = 0.003 \text{We}_{SG}^{1.8} \text{Fr}_{SG}^{-0.92} \text{Re}_{SG}^{-1.24} \text{Re}_{SL}^{0.7} \left( \frac{\rho_L}{\rho_G} \right)^{0.38} \left( \frac{\mu_L}{\mu_G} \right)^{0.97}$$

(16)

$E$ is the entrainment fraction; $\rho_L$ and $\rho_G$ are the densities of the liquid and gas; $\mu_L$ and $\mu_G$ are the viscosities of the liquid and gas; and $\text{We}_{SG}$, $\text{Fr}_{SG}$, $\text{Re}_{SG}$ and $\text{Re}_{SL}$ are given by

$$\text{We}_{SG} = \frac{\rho_G V_{SG}^2 D}{\sigma} \quad \text{Fr}_{SG} = \frac{V_{SG}}{\sqrt{gD}}$$

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\[ \text{Re}_{SG} = \frac{\rho G V_{SG} D}{\mu_G} \quad \text{Re}_{SL} = \frac{\rho L V_{SL} D}{\mu_L} \]

D is the diameter of the pipe, \(\sigma\) is the surface tension, and g is gravitational acceleration.

The liquid film thickness, \(\delta\), is assumed to be uniform or the cylindrical gas core to be of uniform diameter, \(D_C\). The film thickness is determined based on approach proposed by Paz [31]. Also, the gas core is considered to be composed of homogeneous gas and tiny liquid droplets with no relative slip between the gas and the entrained liquid droplets. Thus, various geometric parameters can be easily expressed.

The cross-sectional area of the gas-core:

\[ A_C = (1 - 2 \delta)^2 A_p \quad (17) \]

The cross-sectional area of the film:

\[ A_F = 4\delta (1 - \delta) A_p \quad (18) \]

Where \(A_p\) is the cross-sectional area of the pipe and \(\delta\) is the ratio of the film thickness to the pipe diameter, D.

The velocity of the film can be determined from simple mass balance calculations yielding,

\[ V_{Film} = V_{SL} \frac{(1 - E)D^2}{4\delta(D - \delta)} \quad (19) \]

Where \(V_{SL}\) is the superficial liquid velocity, D is the pipe diameter, and E is the fraction of the total liquid entrained in the gas core.

In this investigation, a method for calculating the droplet velocity is proposed by assuming no relative slip between the gas and liquid film. The diameter of the gas core is calculated as:

\[ D_c = D - 2\delta \]

The average gas core velocity,
In annular flow, droplets generate from the disturbances in the wavy liquid film surfaces near the wall, accelerate in the gas core and deposit back on to the film. The droplet acceleration in the gas core contributes to erosion due to high impact velocity of sand particles entrained in the gas core and the droplets. The droplet velocities in the gas core are less than the gas velocity, \( V_G \), due to interphase slip between the gas and droplets.

The mean slip ratio, \( S_R \), is defined with the droplet velocity, \( V_d \), as

\[
S_R = \frac{V_d}{V_G}
\]  

(21)

The droplet velocity is calculated by multiplying the gas core velocity by the above slip ratio. For annular flow at superficial liquid Reynolds number \( (Re_L) \) between 750 and 3000, experimental results of Fore and Dukler [35] measured the average slip ratio between the droplet and gas core velocities to be approximately 0.80. The droplet velocity is calculated by multiplying the average gas velocity by the slip ratio between droplet and gas velocities.

\[
\text{Droplet velocity, } V_d = V_G S_R
\]  

(22)

**Model for Very Low Liquid-High Gas Flow**

In this work, very low liquid-high gas flow refers to gas dominant flows where there is insufficient liquid to form a continuous liquid film around the pipe creating annular flow. Higher erosion rates are observed in gas dominant wells that can damage production equipment, piping and fittings. The erosion in very low liquid-high gas flows ranges from the erosion in gas only flows to erosion in annular flow depending on the liquid rate.

To develop the erosion model for very low liquid-high gas flow, the boundaries of very low liquid-high gas must be determined. A fit was developed for very low liquid-high gas flow where the superficial liquid velocity ranges from 0.001 ft/s to the local minimum erosion near the annular flow transition. The erosion in the very low liquid-high gas flow region is given by Equation (23).
EROSION IN MULTIPHASE FLOW AND VALIDATION OF SPPS

\[ ER = (ER_2 - ER_1) \frac{\ln \left( \frac{V_{sl}}{V_{sl1}} \right)}{\ln \left( \frac{V_{sl2}}{V_{sl1}} \right)} + ER_1 \]  

(23)

Where

\( V_{sl} \) = Superficial liquid velocity of interest
\( V_{sl1} \) = Superficial liquid velocity of 0.001 ft/s
\( V_{sl2} \) = Superficial liquid velocity at local minimum in erosion near the transition to annular flow
\( ER_1 \) = Erosion prediction for \( V_{sl1} \) (assuming gas only)
\( ER_2 \) = Erosion observed for \( V_{sl2} \) (using annular flow model)

In order to apply Equation (23), the value for \( V_{sl2} \) must be determined. Dosila [36] compared this local minimum to a ratio of particle diameter to film thickness, where the film thickness values for different flow conditions were calculated using the SPPS program. Figure VII-9 gives the value of ratio of film thickness to particle diameter for experimental data at \( V_{sg}=95 \) ft/s and sand size- 150 µm on 2-inch loop for probe at 45° of elbow. This figure shows that the local minimum in erosion occurs at a film thickness to particle diameter of approximately 2. Figure VII-10 is a similar graph and is for the same conditions as Figure VII-9 except that the particle diameter is 300 µm. In this case, the local minimum in erosion occurs at a film thickness to particle diameter ratio of 0.8. Additional comparisons were made for other very low liquid-high gas conditions in the 2 and 3-inch loops. These results demonstrated the local minimum in erosion occurred at film thickness to particle diameter ratios between 0.8 and 2.0. Based on an analysis of these cases, it was decided to set the critical film thickness to particle diameter ratio at a value of 1.0.
Figure VII-9. Comparison of ER Probe Erosion with Ratio of Film Thickness to Particle Diameter for Sand Size of 150 µm, Vsg-95 ft/s on 2-Inch Boom Loop.

Figure VII-10. Comparison of ER Probe Erosion with Ratio of Film Thickness to Particle Diameter for Sand Size of 300 µm, Vsg-95 ft/s on 2-Inch Boom Loop.
Model for Slug Flow

Slug flow occurs over a wide range of gas and liquid flow rates. It is the dominant flow pattern in upward inclined flow. Slug flow hydrodynamics is very complex with unique and unsteady flow behaviors. It is characterized by an alternate flow of a gas pocket, named Taylor bubble, and liquid slugs that contain numerous small gas bubbles. A thin liquid film flows downward between the Taylor bubble and the pipe wall in vertical slug flow. The Taylor bubble is assumed to be symmetric around the pipe axis for fully developed vertical slug flow. Figure VII-11 shows a schematic description of slug flow in vertical pipe. For fully developed slug flow, the length of the Taylor bubble is approximately in the order of 100 times the diameter of the pipe.

The slug body of unit length $L_U$ is divided into two parts: the Taylor bubble of length $L_F$, and the liquid slug of length $L_S$. The Taylor bubble occupies nearly the entire pipe cross-section and propagates downstream around the wall. The average liquid velocity in the liquid slug is $V_S$ and the liquid holdup of the liquid slug is denoted by $H_{LS}$.

Due to unsteady hydrodynamic characteristics of slug flow, it has a unique velocity, holdup and pressure distribution. Therefore, the prediction of the liquid holdup, pressure drop, heat and mass transfer are difficult and challenging. Several mechanistic models have been proposed that enable reasonable prediction of the liquid holdup in the slug, slug length, slug frequency and velocities of Taylor bubble and liquid slug.

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Figure VII-11. Schematic Description of Slug Flow in Vertical Pipe.
For calculation of erosion in slug flow, it is assumed that sand is uniformly distributed in the liquid phase and the mass fraction of sand in the liquid slug is equal to the mass fraction of liquid in the liquid slug, which is given by Equation (24).

\[
m = \frac{L_{LS} H_{LLS} V_S}{L_{LS} H_{LLS} V_S + L_{TB} H_{LF} V_F}
\]

where \( m \) is the liquid mass ratio in the liquid slug (slug body), \( L_{LS} \) is the length of the liquid slug, \( H_{LLS} \) is the holdup in the liquid slug, \( V_S \) is the velocity of the liquid slug, \( L_{TB} \) is the length of the Taylor bubble (film zone), \( H_{LF} \) is the holdup in the film zone, and \( V_F \) is the velocity of the film. A model developed by Zhang et al. [32] is applied to determine the parameters needed for Equation (24). This model also sets the velocity of the liquid slug equal to the mixture velocity.

The density and viscosity used in the particle tracking routine are mixture properties based on the amount of liquid and gas in the liquid slug body and not the entire slug unit. The manner in which the particle impact velocity is calculated is different than for other flow regimes. In the other models, one representative particle impact velocity is calculated with the exception of the annular model which calculates two. However, the current slug model calculates many. The current model assumes that the particles at the leading edge of the liquid slug will impact at higher velocities than particles further back in the liquid slug, thus resulting in less erosion. This assumption is made since the gas pocket is in front of the liquid slug, so when the front of the liquid slug meets an obstruction like a probe or wall of a bend, there is only a relatively small amount of liquid in front of it to slow the particle impacts as shown in Figure VII-12. To determine the representative particle impacts, the liquid slug is divided into two zones: front of the liquid slug and the remainder of the liquid slug. The length of the front of the slug is currently set to one pipe diameter. This zone is divided into 500 lengths, and a particle impact velocity is determined for each length. For example, the representative impact velocity of a particle at the front of the liquid slug is determined using a length equivalent to 1/500\(^{th}\) of the pipe diameter, and the next representative particle impact velocity is determined using a length of 2/500\(^{th}\) of the pipe diameter. In this manner, a total of 500 different particle impact velocities are calculated for the front of the liquid slug. For the remainder of the liquid slug, one representative particle impact velocity is used and is determined using a length equivalent to a pipe diameter. This essentially defines the latest slug flow model for the bend with one exception. The latest model also assumes that the erosion is spread over the entire inner surface of the bend.
instead of a projected area that was previously used. The decision to spread the erosion over
the entire inner surface of the bend was made based on comparisons with experimental data.

![Figure VII-12. Schematic of Assumed Slug Flow Profile near a Bend.]

**Model for Churn Flow**

Churn flow is somewhat similar to slug flow except churn flow is more chaotic. The
liquid and gas phases have oscillatory motion and without stable and clear boundaries
between the phases. As the gas velocity in slug flow increases, the liquid slug becomes
shorter, breaks and mixes with the following slug. Due to this mixing phenomenon, the
shape of the Taylor bubble gets distorted resulting in churn flow. Kaya [38] defined the
churn flow pattern as consisting of highly aerated slugs with repeated destruction of liquid
continuity in the slug during an oscillatory motion of the slug. Churn flow is normally
observed between the slug and annular flow pattern in vertical or nearly vertical upward
flow. As the pipe inclination angle changes from vertical to horizontal, churn flow changes
to slug flow. Churn flow does not exist in horizontal flow. A schematic of the churn flow
is shown in Figure VII-13.

There is no available mechanistic model in the literature to predict hydrodynamic
behavior of churn flow due to its highly disordered and chaotic nature. Churn flow exhibits
intermittent behavior, similar to slug flow. Hasan [39] attempted to develop a separate
model for churn flow by redefining the transitional velocity coefficient as 1.15. Tengesdal
[40] adapted the slug flow model to churn flow with a different closure relationship for the
transitional velocity of the Taylor Bubble and void fraction in the liquid-phase based on experimental churn flow data of Schmidt [41] and Majeed [42]. According to Tengesdal, under turbulent flow conditions, the maximum centerline velocity of flow can be approximated as the average mixture velocity.

In churn flow, it is assumed that the sand is uniformly distributed in the liquid phase. The velocities of the liquid and sand are assumed to be the same as the mixture velocity. Therefore, the characteristic initial sand particle velocity for churn flow is assumed to be the mixture velocity and is calculated as

\[ V_o = V_m = V_{SL} + V_{SG} \]  

\( (25) \)

![Figure VII-13. Schematic Description of Churn Flow.](image)

**Model for Bubbly and Dispersed Bubble Flows**

Bubble flow is characterized as small gas bubbles that are distributed in the continuous liquid phase. Bubble flow can be classified as bubbly and dispersed bubble flows based on the relative slip between the bubbles and the surrounding liquid phases. Bubbly flow exists in relatively large pipe diameters with upward vertical or inclined pipes. Due to slippage and buoyancy effects, in bubbly flow, gas bubbles tend to flow near the
upper part of inclined pipes. In bubbly flow, slippage between the bubble and liquid phase is present and the bubbles are not distributed homogenously. In dispersed bubble flow, gas bubbles are uniformly distributed in the liquid phase and can be treated as homogeneous flow. Due to homogeneous distribution of gas bubbles, the mixture properties can be used in expressing dispersed bubble flow. In this section, the mechanistic model is developed for dispersed bubble flow.

At lower gas flow rates, smaller and fewer bubbles exist. As the gas flow rate increases, the number of bubbles also increases and the shape of the bubbles changes from smaller round bubbles to larger, irregularly shaped bubbles due to coalescence and collision of bubbles. In bubble flow, it is assumed that the gas phase is approximately uniformly distributed in the form of discrete bubbles that move at different velocities in a continuous liquid phase. Bubble flow occurs at low gas rates. Figure VII-14 schematically describes bubbly flow in a vertical pipe.

In bubble flow, it is also assumed that the sand is uniformly distributed in the liquid phase. The velocities of the liquid and sand in the bubble flow region is assumed to be the same as the mixture velocity. Therefore, the characteristic initial sand particle velocity for bubble flow is assumed to be the mixture velocity and can be calculated using Equation (25).

![Figure VII-14. Schematic Description of Bubble Flow.](image)
Validation of the Mechanistic Models

The mechanistic model predicted erosion rates were compared with available single-phase and multiphase erosion data reported in the literature and obtained at E/CRC. The data is for a broad range of conditions. The gas velocities achieved values over 200 m/s, and the liquid velocities nearly achieved 15 m/s. The geometries were primarily elbows (standard and long radius) with diameters of 1, 2, and 3-inches. The data was also obtained for the vertical and horizontal orientations, but the model is intended for use in the vertical orientation. Previous studies at E/CRC have shown that erosion in the vertical orientation is often substantially higher in the vertical orientation especially in annular flow. It should also be noted that the data was obtained through a variety of techniques, and it is not certain that the reported erosion is the maximum erosion. The flow patterns for the test conditions were not reported by the investigators. Therefore, the flow regimes were calculated using the mechanistic model. The calculated flow regimes included gas only, very low liquid-high gas, annular, slug, dispersed bubble, and liquid only. A comparison of the experimental data and results obtained from the mechanistic model are shown in Figure VII-15.

![Figure VII-15. Comparison of Mechanistic Model Predictions with Experimental Data.](image-url)
Comparison between the mechanistic model predicted erosion rates and data shows that the model often predicts higher erosion than indicated by the experimental data.

**Summary**

The main goal of this research is to develop a mechanistic model that is capable of predicting erosion in both single and multiphase flows. The model should be general and applicable to a wide range of flow conditions in different flow regimes.

A mechanistic model was developed considering the effects of liquid and gas velocities, sand distribution, entrainment and particle impact velocities. The mechanistic model is flow regime dependent, so a flow regime prediction procedure is incorporated into SPPS. Based on the flow regime predicted, different procedures are used to predict erosion. The mechanistic model predicted penetration rates were compared to erosion measurements reported in the literature for annular, slug, churn, and bubble flow regimes. The model predictions showed reasonably good agreement with the measured erosion rates. When compared with the experimental erosion data, the model slightly overpredicted erosion in most cases.

**Bibliography**


