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Reactor Experimental Engineering Division

EROSION DUE TO PARTICLE IMPINGEMENT UPON BENDS IN CIRCULAR CONDUITS

R. V. Bailey

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SUMMARY

A qualitative analysis, based on a number of assumptions, has been made of the erosion caused by small solid particles impinging upon a bend in a circular conduit. The resulting equation is

$$E = C_6 \frac{U_{av}^{3.8}\, r\, (\rho_s - \rho_e)}{\mu R\, \rho_s^{.6}} \left[1 + \frac{U_{av}^{2}\, (\rho_s - \rho_e)^{2.8}\, r^{5.6}}{68 \mu^{2.8} R^{2.8}} \right]$$

The analysis has been simplified by a number of assumptions which are not strictly valid. However, it is considered that a more rigorous analysis is not justified without more complete experimental data on which the analysis can be made.

INTRODUCTION

Erosion can occur when a small solid particle impinges upon a solid surface. Under some conditions the erosion would perhaps depend primarily upon the hardness of the eroded metal. However, the importance of other factors, such as elasticity and fatigue resistance, is indicated by the erosion resistance of materials such as rubber.

Quantitative, basic information concerning erosion by particle impingement upon a solid surface is practically nonexistent. Therefore, any analysis of the problem must take the form of a guess until more is known concerning the physical phenomena taking place during the disintegration of the material at the point of erosion.

Stoker (4) obtained quantitative data of rather limited scope on erosion due to dust particles in a gas stream. The experimental method consisted of sand-blasting targets at different jet velocities and angles of impingement with different entrained dusts. The erosion, expressed in terms of weight loss of the target per unit weight of sand, was proportional to $U_{av}^{14/5}$ for jet velocities from 60 to 660′ per second.

U_{av} = velocity of air stream issuing from the jet.

The effect of the angle of impingement could be expressed approximately by the following equations:

From 0 to 20°

$$\frac{E}{E_{90}} = 0.11\ \theta$$

From 20° to 90°

$$\frac{E}{E_{90}} = 0.0171\ \theta + 2.54$$

Where θ = angle of impingement, degrees

E, E_{90} = Wt. loss of target per unit weight of dust at an angle of impingement of θ° and 90° respectively.

Fisher and Davis (1) studied the erosive action of fly-ash on vitallium using an air jet impinging on a target at a 90° angle. The range of air velocities was 750 to 1050 feet per second. For a given distance from the nozzle to the target the erosion per unit weight of fly-ash varied approximately as $U_{av}^{14/5}$. As the distance from the nozzle to the target was increased from 1/8 in. to 1 in. the erosion increased sharply. This was attributed to a greater time elapse for acceleration of the particles.

Rosenburg (3) studied the resistance of steels to abrasion by sand. Various steel targets were blasted with sand from an air nozzle. For a nozzle pressure of 30 psi the erosion resistance of a variety of steels was essentially the same. However, at a nozzle pressure of 60 psi the difference in erosion resistance became more apparent. The erosion per unit weight of sand at a nozzle pressure of 60 psi was approximately four times that for a nozzle pressure of 30 psi. It is of interest to note that small sharp sand was about four times as erosive as larger, more rounded sand. This could be due to the following:

1. The surface condition of the sand.
2. The greater surface area of the target scoured by the smaller sand per unit weight of sand impinging on the target.
3. The greater acceleration of the smaller particles.

ANALYSIS

The erosion of solid surfaces by impinging particles appears to be a process whereby a portion of the kinetic energy of the particles is utilized to provide the necessary energy required to displace and detach loosely bound particles from the solid surface. If this is true, then it would seem likely that the erosion, expressed in terms of weight loss of the solid surface, would be directly proportional to the kinetic energy of the impinging particle, $\frac{m V^2}{2g}$.

where m = mass of the particle.

V = velocity of the particle.

g = acceleration of gravity.

When a particle strikes a solid surface, a portion of the kinetic energy of the particle may be utilized for the following:

1. Shearing particles from the solid surface.
2. Shearing portions off the impinging particle.
3. Compressing and heating the solid surface.
4. Compressing and heating the impinging particle.

If one mass unit of particles is selected as the basis for the analysis, then

$$E = f \left(\frac{V^2}{2g}\right) \tag{1}$$

where E = erosion, wt. loss of solid surface per pound of impinging particles.

f = fraction of the kinetic energy of the impinging particles which is utilized for shearing particles from the solid wall.

Now, if it can be concluded that, above a given energy level of the particle, the fraction of the kinetic energy of the impinging particle which is used for erosion is directly proportional to the area of contact between the particle and the solid wall, then

$$E = f' A\left(\frac{V^2}{2g}\right) \tag{2}$$

where A = area of contact between one pound of particles and the solid wall.

f' = constant for a given particle, solid wall, and angle of impingement.

Timoshenko (5) has shown that for an elastic collision of a spherical particle with a plane surface at an angle of 90° to the plane of the surface

$$a = C\,(Pr)^{1/3} \tag{3}$$

$$P_1 = n\left(\frac{5}{4}\,\frac{V^2}{nn_1}\right)^{3/5} = C_2 r^2 \rho_s^{3/5}\, V^{6/5} \tag{4}$$

where a = radius of surface of contact

C, C_1, C_2 = constant dependent upon the elastic properties of the particle and the surface.

r = radius of the spherical particle

P = compressive force exerted by the particle at any time of contact

P_1 = maximum compressive force exerted by the impinging particle.

$n = C_1\,(r)^{1/2}$

$n_1 = \frac{1}{m} = \frac{3}{4\,\pi\,r^3\,\rho_s}$

m = mass of the particle

ρ_s = density of the solid

V = velocity of the particle at the start of the compression

Substituting equation (4) into equation (3) to obtain the radius of the surface of contact at the instant of maximum compression

$$a_1 = C_3\, r\, \rho_s^{1/5}\, V^{2/5} \tag{5}$$

where a_1 = radius of the surface of contact at the instant of maximum compression

C_3 = constant dependent upon the elastic properties of the particle and the plane surface.

The area of the plane surface, A_s, contacted by the perpendicular impingement of the sphere is given by

$$A_s = \pi\, a_1^2 = \pi\, C_3^2\, r^2 \rho_s^{2/5}\, V^{4/5} \tag{6}$$

For one pound of particles the number of particles, N, is given by

$$N = \frac{3}{4\,\pi\,r^3\,\rho_s} \tag{7}$$

Then the total area of contact per pound of particles elastically impinging perpendicularly upon a plane surface becomes

$$A = \frac{3\, C_3^{\,2}\, V^{4/5}}{4\, r\, \rho_s^{\,3/5}} \tag{8}$$

Substituting equation (8) into equation (2) yields

$$E_{90} = C_4 \left(\frac{1}{r\, \rho_s^{\,3/5}} \right) V^{14/5} \tag{9}$$

where E_{90} = erosion for 90° impact

C_4 = constant for a given particle and solid wall.

An attempt to analyze the effect of angle of impingement met with failure. However, at least as an approximation, the effect of angle of impingement as obtained experimentally by Stoker (4) may be incorporated in equation (9) to yield

$$E = C_4\, \psi(\theta) \left(\frac{1}{r\, \rho_s^{\,3/5}} \right) V^{14/5} \tag{10}$$

where $\psi(\theta) = 0.11\, \theta$ for θ from 0 to 20°

$\psi(\theta) = -\, 0.0171\, \theta + 2.54$ for θ from 20° to 90°

(θ) = angle between the path of the impinging particle and the surface of the solid.

On the basis of equation (10) an analysis can now be made of the erosion in a bend of a circular conduit.

The general equation for motion of a particle in a fluid stream undergoing simple rotational motion is (2)

$$\frac{d\, V_r}{dt} = \frac{V_t^{\,2}}{R} \left[1 - \frac{\rho_e\, U_t^{\,2}}{\rho_s V_t^{\,2}} \right] - \left(\frac{\rho_e\, f_D\, A_p\, V'\, V_r}{2\, m} \right) \tag{11}$$

where V_r = radial velocity of the particle

V_t = tangential velocity of the particle

t = time

R = radius of curvature for rotational motion of the fluid

ρ_e = density of the fluid

ρ_s = density of the particle

U_t = tangential velocity of the fluid

$V' = \sqrt{V_r^2 + (U_t - V_t)^2}$ = velocity of the particle relative to the fluid

f_D = friction factor

A_p = projected area of the particle

m = mass of the particle

The following simplifying assumptions are made:

1. The tangential velocity of the particle is about equal to the tangential velocity of the fluid.

2. The radial velocity of the particle is relatively small.

3. The particle is spherical

For a spherical particle in laminar flow relative to the fluid

$$\frac{m}{A_p} = \frac{4 \rho_s D_p}{6} \tag{12}$$

$$f_D = \frac{24 \mu}{D_p V_r \rho_e} \tag{13}$$

where μ = viscosity of the fluid

D_p = diameter of the particle

From the above simplifying assumptions and equations (12) and (13), equation (11) may be reduced to

$$V_r = \frac{U_t^2 (\rho_s - \rho_e) D_p^2}{18 \mu R} \tag{14}$$

If the problem is further simplified by assuming that the diameter of the pipe is small compared to the radius of curvature of the bend and that the velocity at any point in the bend is equal to the bulk mean velocity, U_{av}, then equation (14) may be written

$$V_r = \frac{U_{av}^2 (\rho_s - \rho_e) D_p^2}{18 \mu R} \tag{15}$$

where U_{av} = bulk mean velocity

If it is now assumed that the angle of impact which controls the erosion process is the angle between the path of the particle and a plane perpendicular to the radius of curvature, then

$$\frac{V_r}{U_{av}} = \tan \theta = \frac{U_{av} (\rho_s - \rho_e) D_p^2}{18 \mu R} \tag{16}$$

Under the conditions of the simplifying assumption that the radial velocity of the particle is relatively small compared to the tangential velocity, θ will be less than 20°.

For values of θ less than 20°

$$\theta \cong \frac{\tan \theta}{.0176} \tag{17}$$

then $\psi(\theta)$ in equation (10) becomes

$$\psi(\theta) = \frac{.11}{.0176} \tan \theta = \frac{.11}{.0176} \frac{U_{av}(\rho_s - \rho_e) D_p^2}{18 \mu R} \tag{18}$$

Therefore, the erosion of a bend in a circular conduit is

$$E = C_5 \frac{U_{av} (\rho_s - \rho_e) D_p^2}{\mu R} \left(\frac{1}{r \rho_s^{3/5}} \right) V^{14/5} \qquad (19)$$

where C_5 = constant for a given particle and solid surface

However,

$$V = \sqrt{V_r^2 + U_{av}^2} \qquad (20)$$

Substituting equations (20) and (15) into equation (19), the final equation for the erosion in a bend of a circular conduit becomes

$$E = C_6 \frac{U_{av}^{3.8} r(\rho_s - \rho_e)}{\mu R \rho_s^{.6}} \left[1 + \frac{U_{av}^2 (\rho_s - \rho_e)^{2.8} r^{5.6}}{68 \mu^{2.8} R^{2.8}} \right] \qquad (21)$$

where C_6 = constant for a given particle and solid surface.

For small particles in a viscous medium the term within the brackets of equation (21) approaches unity.

For concentrated suspensions of solids in a fluid, the problem is analogous to the problem of hindered settling and the physical properties in equation (21) should be evaluated for the suspension rather than for the carrier fluid. However, even with this modification of equation (21), the predicted erosion would be higher than the erosion actually encountered since equation (21) is derived on the basis of the contact of each particle with the wall of the tube. Due to particle interference this individual contact of each particle with the tube wall is not realized for concentrated suspensions.

DISCUSSION

The validity of equation (21) depends to a great extent on the validity of equation (10). Stoker (4) has shown experimentally that the erosion of a solid surface by impinging particles carried in an air stream issuing from a nozzle is directly proportional to $U_{av}^{14/5}$.

U_{av} = bulk velocity of the air stream issuing from the nozzle.

If it may be assumed that, for a given target distance and a given particle, the velocity of a particle striking the target is directly proportional to the velocity of the air stream issuing from the jet, then the velocity portion of equation (10) may be said to have been experimentally confirmed. A simplified calculation of the acceleration of the particle indicates that the above assumption is at least approximately true under the conditions of the experiments by Stoker.

The effect of the angle of impingement in equation (10) is based on experimental data (4) of rather limited scope and may not be valid under all conditions.

From the available experimental data on erosion (1,3,4) it was impossible to arrive at any specific conclusions with respect to the effect on erosion of particle size and density. Rosenburg (3) obtained data which indicated an erosion effect that varied inversely as the radius of the particle. This would be predicted from equation (10). However, this effect may have been due to the nature of the surface of the smaller particles or the greater acceleration of the smaller particles issuing from the jet.

In addition, the analysis of the erosion of bends in circular conduits has been appreciably simplified by a number of assumptions which are not strictly valid.

However, it is considered that a more rigorous analysis is not justified without more complete experimental data on which the analysis can be based.

CONCLUSIONS

Equation (21) should, at least qualitatively, indicate the relative effect of a number of variables on the erosion of bends in circular conduits by particle impingement. However, any analysis of the problem must take the form of a guess until more is known concerning the physical phenomena taking place during the disintegration of a solid surface at the point of erosion. More quantitative, basic information is needed.

/gd

NOMENCLATURE

a	=	radius of area of contact at any time for a spherical particle impinging elastically and perpendicularly on a plane surface, ft.
a_1	=	maximum radius of area of contact for a spherical particle impinging elastically and perpendicularly on a plane surface, ft.
A_s	=	maximum area of contact for a spherical particle impinging elastically and perpendicularly on a plane surface, sq. ft.
A	=	maximum area of contact for one pound of spherical particles impinging elastically and perpendicularly on a plane surface, sq. ft.
A_p	=	projected area of a particle, sq. ft.
$C, C_1, C_2, C_3, C_4, C_5, C_6$	=	constants dependent upon the materials of construction for the particles and the plane surface.
D_p	=	diameter of a particle, ft.
E, E_{90}	=	erosion wt. loss of plane surface per unit weight of particles impinging on the plane surface at θ^o and 90° respectively, lb/lb.
f'	=	constant
f	=	fraction of the kinetic energy of the impinging particles which is utilized for shearing particles from the solid wall.
f_D	=	friction factor
g	=	gravitational constant, ft/sec^2.
m	=	mass of the particle, lb.
n	=	$C_1(r)^{1/2}$
n_1	=	reciprocal of the mass of the particle
N	=	number of particles per lb., 1/lb.
P	=	compressive force of particle on plane surface, lb.

P_1	=	maximum compressive force exerted by a particle impinging on a plane surface, lb.
r	=	radius of particle, ft.
R	=	radius of curvature of a bend in a circular conduit, ft.
U_{av}	=	bulk mean velocity of the fluid, ft/sec.
U_t	=	tangential velocity of the fluid, ft/sec.
V	=	velocity of the particle, ft/sec.
V_r	=	radial velocity of the particle, ft/sec.
V_t	=	tangential velocity of the particle, ft/sec.
V''	=	$\sqrt{V_r^2 + (U_t - V_t)^2}$ = velocity of the particle relative to the fluid, ft/sec.
ρ_e	=	density of the liquid, lb/ft^3
ρ_s	=	density of the solid, lb/ft^3
μ	=	viscosity of the liquid, lb/ft-sec.
ψ	=	function
θ	=	angle between the path of the particle and the plane surface, deg.

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