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Slurry erosion of steel – Review of tests, mechanisms and materials

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ABSTRACT

Slurry erosion is a severe problem and a major concern for slurry handling equipment, as it leads to considerable expense caused by failures, downtime and material replacement costs. Slurry erosion is dependent on several parameters such as slurry properties, service conditions, and material properties. Hence, much high-quality research has been aimed at obtaining a fundamental understanding of this complex failure mode and developing new test methodologies and erosion resistant materials to minimize erosion rates. This is a review of the literature covering research into the effects of the main parameters influencing the slurry erosion of different types of steels, focusing on those which have been developed for pipeline applications. The types of bench-scale erosion test rigs, the mechanisms involved, and the behavior of different microstructures under slurry erosion conditions are discussed.

1. Introduction

Recently, slurry erosion caused by solid particles has received considerable attention amongst researchers, owing to the intensity of the problems it causes to equipment in service, especially for short- and long-distance pipeline systems used for the transportation of slurries containing ores or tailings in mining operations, or oil and gas transportation in the power generation industry.

Erosion-related problems cause serious financial losses in these industries. Any failure of a pipeline component results in expensive repairs, loss of production time, or possibly harmful environmental effects. Since failure is usually not predictable due to variable operating conditions, methods for reducing the erosion and increasing the lifetime of the pipe including the development of new steels for pipeline systems are of interest to these industries. The erosion rate of a slurry pipeline depends on various factors such as slurry and solid particle properties, flow rate, and pipeline material. The most popular way to study the effect of the influencing variables and to understand the erosion mechanisms is to conduct investigations using laboratory equipment, i.e. bench-scale test rigs.

Erosion, abrasion, and corrosion are the main types of damage mechanisms taking place in slurry equipment and hydraulic components, the main one being erosion [1–4]. Slurry erosion is a complex phenomenon which was systematically investigated for the first time by Finnie [5] and Bitter [6] in the 1960s. Since then much research has been conducted on the assessment of erosion using various evaluation techniques and test methods.

In order to develop solutions to minimize the effects of erosion, it is essential to have a fundamental and comprehensive understanding of the erosion and tribological mechanisms involved. Hence, the purpose of this work is to provide a comprehensive review of the literature concerning the slurry erosion of steels, especially those that have been developed for pipeline applications. The types of erosion bench-scale test rigs, the mechanisms involved, proposed models and the parameters affecting the erosion rate in different steel microstructures are discussed. It must be emphasized that, despite the possible synergetic effects of erosion and corrosion [7,8], this review has been limited to erosion only; other wear mechanisms such as abrasion, corrosion or cavitation erosion are not covered.

2. Theoretical background

2.1. Types of slurry

A slurry is generally defined as a heterogeneous mixture of a fluid, i.e. a gas or a liquid, here mostly liquid, and one or more kinds of solid particles varying in size from a few microns to a few millimeters [9]. Owing to the high particle concentration, a slurry can sometimes be classified as a highly viscous fluid. The most important characteristics of slurries are defined by their rheology. The rheology is a dynamic property of the microstructure of the slurry, which is affected by various factors such as the shape, size, density and mass fraction of the suspended solid particles and the viscosity and density of the carrier fluid [10]. Slurries could be categorized into two general types: settling

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Nomenclature

a, b, c, e	equation constant
A_i	equation constant
A_P	projected particle impact area
A_{Pipe}	pipe cross-sectional area
B	material dependent exponent
C	equation coefficient
C_0	volume of delivered slurry
$C_{avg.}$	mean slurry concentration
C_K	cutting characteristic velocity
C_W	slurry concentration
$C_{w,k}$	slurry concentration of the specific particle class size of K
d′	particle diameter experimental constant
d_i	the average particle diameter of two consecutive sieve sizes
d_P	particle size (diameter)
$d_{P,W}$	mass-weighted mean particle size
$\frac{dr}{dt}$	velocity of surrounding slurry
$\frac{drp}{dt}$	radial particle velocity
$\frac{d_y}{dt}$	normal particle velocity
D	equation coefficient
D_K	deformation characteristic velocity
D_P	pipe diameter
e_T	elongation of target material
E_{90}	erosion damage at normal impact
E_α	angular dependence of erosion damage
E_C	cutting component of the erosion damage
E_D	deformation component of the erosion damage
E_P	elastic modulus of target material
E_S	specific energy
$E_{S,k}$	specific energy of particulate species k
E_t	elastic modulus of target material
E_T	total erosion rate
E_T^{max}	maximum erosion rate
f(α)	erosion impact angle dependence function
$f(\alpha_k, d_{P,k})$	specific energy coefficient
f	fraction of volume loss caused by the median spalling
f_i	the fraction of each specific particle size in a multi-size particle slurry
f_l	volume fraction of liquid flow
$F_{cent.}$	centrifugal force
$F_{d,V}$	degree of particle fragmentation
F_{dr}	drag force
F_e	specific erosion factor
h	erosion depth
H_{ch}	height of channel
H_P	particle hardness
H_T	target material hardness
i	material dependent exponent
k_1	hardness exponent in the erosion equations
K	empirical constant
K_i (i = 1–4)	equation constant
K_T	target material toughness
l_p	particle displacement
L_P	particle length
m	particle velocity exponent in the erosion equations
M_P	mass of the impacting particle
MS_F	modified particle shape factor
n	particle size exponent in the erosion equations
n_i (i = 1–4)	equation constants
N_P	number of particles throughput
p	slurry concentration exponent in the erosion equations
P_n	function of material work hardening properties
P_l	function of material plastic flow stress
P	projected particle impact perimeter
P_F	friction power per unit area
P_{TR}	particle tangential restitution ratio
q_p	flow rate of solid particles
Q	volumetric flow rate
r	instantaneous location of liquid unit
r_p	instantaneous location of particle
r_P	particle radius
R_{Ch}	mean Coriolis channel radius
Re_H	reynold number (for average inlet velocities) for the channel height of H_{ch}
R_f	particle roundness factor
S_F	particle shape factor
$(S_F)_{Avg}$	mean particle shape factor
$(S_F)_{Max}$	maximum particle shape factor
$(S_F)_{Min}$	minimum particle shape factor
S_T	stiffness of target material
t	erosion time
u_P	tangential velocity of the solid particles
$u_{P,k}$	tangential velocity of particulate species k
v'	standard impact velocity experimental component
v_*	friction velocity
v_f^z	velocity of fluid in the axial direction
V_m	mean velocity
v_p^r	velocity of particle in the radial direction
v_p^z	velocity of particle in the axial direction
v_{pt}^r	impact velocity in the radial direction
V	volume of removed material
V_N	particle normal velocity
V_P	particle velocity
$V_{P,k}$	velocity of the specific particle class size of K
V_{Ref}	reference particle velocity
V_{SL}	superficial liquid velocity
V_T	particle tangential velocity
W^{-1}	erosive-abrasive wear resistance
W_0	proportion of the particle (by weight) within the specified particle size range before test
W_1	proportion of the particle (by weight) within the specified particle size range after test
W	passage width
W_I	impact erosive wear
W_P	particle width
W_s	sliding erosive wear
Y_s	yield stress

Greek letters

α_1	angle at which erosion experimentaly starts
α	particle impact angle
α_m	angle of maximum erosion
δ	boundary layer thickness
$\hat{\varepsilon}_1$	maximum erosion for the reference velocity of primary erosion
$\hat{\varepsilon}_2$	maximum erosion for the reference velocity of secondary erosion
ε	empirical constant
ε_{Cr}	critical strain
η	erosion efficiency
η_δ	attenuation coefficient
ν_P	Poisson's ratio of particle
ν_T	Poisson's ratio of target material
ξ	erosion mechanism identifier
ρ_L	density of carrier liquid
ρ_P	particle density
$\rho_{P,k}$	density of the specific particle class size of K