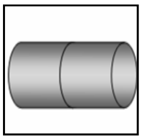
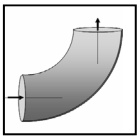
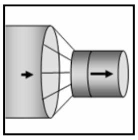
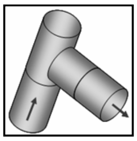
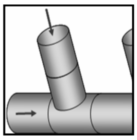
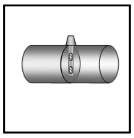
Recommended Practice
RP O501

Erosive Wear in Piping Systems

Revision 4.2 - 2007

This document has been amended since the main revision (2005), most recently in January 2011.
See "Changes" on page 2.

Det Norske Veritas

PREFACE

This document provides guidelines for the assessment of erosive wear in piping systems associated with production and transportation of oil and gas and injection of water and gas into the reservoir.

Guidelines are given both as:

1) Limit states of fluid parameters and material grades which will not result in erosive wear, and

2) a recommended procedure for calculation of erosive wear in fluids containing sand particles.

DNV will be grateful for any comments and suggestions for changes that may be considered for inclusion in future revisions.

Changes

Amendments January 2011

- *In January 2011, the document was updated to include the current versions of DNV's legal clauses on this page. No other changes were made.*

Revision note 4.2-2007 (2007.11.12):

- *Improved calculation of Critical particle diameter for bends at low Re*
- *Some minor editorial changes*

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1 INTRODUCTION

The selection of materials and dimensioning of pipes are performed in order to obtain necessary strength, capacity and service life to cope with the production characteristics for a piping system. Material degradation due to corrosion, erosion and/or erosion-corrosion, may gradually affect the integrity of the piping system. Material degradation will generally depend on the production characteristics for the system; i.e. production rates, pressure and temperature, and the presence of corrosive components and erosive solid particles. The degradation may also be strongly dependant on the pipe material.

Material degradation can, in most cases, not be fully avoided. However, by proper dimensioning, selection of suitable materials, use of inhibitors or other corrosion/erosion reducing measures and/or by application of corrosion/erosion allowance, a system which fulfils the requirements can generally be achieved. Selection of such measures may, however, be associated with high cost. A Life Cycle Cost Analysis should preferably be carried out in order to obtain an optimised solution. No cost evaluations are included in this document.

Sand particles and/or other solids will, in many applications, be present in the liquid, and may result in erosive wear of the pipe components; i.e. in the pipes, in pipe bends, blinded tees, connections etc.

This document provides methods to assess the erosive wear in the pipe components and may thus be applied for dimensioning of pipes, determination of maximum flow rates in existing pipes and defining requirements to sand monitoring units.

The models and recommendations have been worked out based on experimental investigations available in literature, as well as experimental results, experience and models available within Det Norske Veritas. Most experimental data have, however, been obtained at low pressure in small diameter test facilities. The models have been validated with these data. Extrapolation to high pressure conditions and large diameter pipes has been performed based on model simulations and engineering justifications.

A Window-based PC-programme has been developed and is available for purchase.

This document defines an alternative method for dimensioning of pipes exposed to erosive wear to the so-called "erosional velocity" as defined by the widely applied API RP14E relation. The API RP14E relation does not include any physical parameters influencing material degradation; i.e. CO_2, H_2S, O_2 and sand particle content. However, it states that the fluid velocity should be significantly reduced if the fluid contains solids like sand particles.

2 SCOPE / LIMITATIONS

This document provides guidelines for the assessment of erosive wear in piping systems associated with production and transportation of oil and gas and injection of water and gas into the reservoir.

Guidelines are given both as:

1) Limit states of fluid parameters and material grades which will not result in erosive wear

and

2) a recommended procedure for calculation of erosive wear in fluids containing sand particles.

The document provides procedures for calculation of erosion rate for typical components in a pipe and gives advice regarding erosion control and quantitative assessment of erosive wear.

The recommended calculation procedure is not applicable to certain components with highly complicated flow geometry; including manifolds and chokes. I.e. the models do not take into account upstream history effects.

The document does not address corrosion, erosion-corrosion or inhibitor selection and performance. However, for conditions/systems where specific velocity limits are given in the literature, these are referred.

Erosion of organic and ceramic coatings as well as metallic hard-facing coatings or other surface treatment is not covered by this document.

Cavitation is briefly addressed where this is assessed to be a potential problem.

Droplet erosion is briefly addressed where this is assessed to be a potential problem and appropriate velocity limits are given.

Other aspects influencing on pipe dimensioning, flow rate limitations and pipe performance such as pressure drop, vibrations, noise, insulation requirements, hydrate formation, wax deposition, sand accumulation, severe slug flow, terrain slugging, pipe wall thickness estimation, pipe installation limitation/requirements, up-heaval buckling, etc. are not covered by the present document. However, for conditions/materials for which erosive wear will not be limiting with respect to pipe dimensioning or flow rate, other possible limiting parameters will be notified.

3 DEFINITIONS

Definitions of technical terms and symbols used in the present document are given below:

3.1 Technical terms

Piping system:	Includes pipes for transportation of fluids and associated pipe bends, joints, valves and chokes. The general term covers tubing, flow lines for transportation of processed and un-processed hydrocarbons and piping downstream of first stage separator.
Material degradation:	Loss of material or loss of material integrity due to chemical or electro-chemical reaction with surrounding environment and to erosive wear due to particle and droplet impingement.
Corrosion:	Loss of material or loss of material integrity due to chemical or electro-chemical reaction with surrounding environment.
Erosion:	Loss of original material due to solid particle impact on the material surface.
Erosion-corrosion:	Synergetic effect of erosion and corrosion.
Droplet erosion:	Loss of original material due to droplet impact on the material surface.
Stainless steel:	Steels alloyed with more than 12% Cr (weight).
C-steel:	Steels containing less than 1.65% manganese, 0.69% silicon and 0.60% copper.
Low alloyed steel	Steel containing magnesia, silicon and copper in quantities greater than those for C-steel and/or other alloying elements. The total content of alloying elements shall not exceed 5%.
Superficial velocity:	Fluid velocity of one phase in piping as if no other fluid phase were present in the pipe. The mixture velocity is equal to the sum of the superficial velocities for all phases.
Steel carcass:	Inner steel liner used in flexible pipes transporting hydro-carbon fluids.
GRP:	Glass Fibre Reinforced Plastic.
CFD:	Computational Fluid Dynamics.

4 LIST OF SYMBOLS

A	Dimensionless parameter group.	[-]
A_t	Area exposed to erosion.	[m^2]
A_{pipe}	Cross sectional area of pipe.	[m^2]
A_{ratio}	Area ratio between cross sectional area reduction and upstream area of a flow reducer.	[-]
α	Impact angle of particles hitting the wall.	[^{o}]
b	Function of Re.	[-]
$\beta = \rho_p/\rho_m$	Density relation.	[-]
C_1	Model/geometry factor.	[-]
C_2	Particle size correction factor	[-]
C_{unit}	Unit conversion factor (m/s $\rightarrow$ mm/year).	[-]
c	Function of Re.	[-]
D	Inner pipe diameter.	[m]
d_p	Particle diameter.	[m]
$d_{p,c}$	Critical particle diameter for the flow conditions considered.	[m]
$\dot{E}_m$	Erosion rate referred to the mass of eroded material.	[kg/year]
$\dot{E}_L$	Erosion rate referred to depth.	[mm/year]
$\dot{E}_{L,m}$	Erosion rate referred to depth, measured by erosion probe	[mm/year]
$F(\alpha)$	Function characterising ductility of the material.	[-]
G	Correction function for the particle diameter.	[-]
$\gamma = d_p/D$	Diameter relation	[-]
h	Height of weld reinforcement.	[m]
K	Material constant.	[(m/s)$^{-n}$]
$\dot{M}_g$	Mass flow of gas in pipe.	[kg/s]
$\dot{M}_l$	Mass flow of liquid in pipe.	[kg/s]
m_p	Mass of sand particle.	[kg]
$\dot{m}_p$	Mass flow of sand.	[kg/s]

μ_g	Viscosity of gas phase.	[kg/ms]
μ_l	Viscosity of liquid phase.	[kg/ms]
μ_m	Viscosity of fluid mixture.	[kg/ms]
n	Velocity exponent.	[-]
ρ_g	Density of gas phase.	[kg/m^3]
ρ_l	Density of liquid phase.	[kg/m^3]
ρ_m	Density of fluid mixture.	[kg/m^3]
ρ_p	Density of particle.	[kg/m^3]
ρ_t	Density of target material	[kg/m^3]
$R_{curvature}$	Radius of curvature given as Number of Pipe Diameters. Reference of radius of curvature is centreline of pipe.	[-]
Re	Reynolds number	[-]
U_p	Particle impact velocity (equal to the fluid velocity).	[m/s]
U_1, U_2	Fluid velocity in cross section 1 and 2.	[m/s]
V_g^s	Superficial velocity of gas phase in piping.	[m/s]
V_l^s	Superficial velocity of liquid phase in piping.	[m/s]
V_m	Mixture velocity in piping.	[m/s]

Indexes

1,2 - Cross section 1 and 2.
c - Critical
g - Gas
i - Index
L - Length
l - Liquid
M - Mass
m - Mixture
p - Particle
s - Superficial
t - Target material

5 REFERENCES

5.1 Codes and Standards

Some relevant codes and standards applicable for pipe dimensioning and design are given below:

- *DNV Rules for Submarine Pipeline Systems OSF-F101.*
- *DNV Recommended Practice RP B401 on Cathodic Protection Design.*
- *DNV Recommended Practice RP E305 on-bottom Stability of Sub-marine Pipelines.*
- *NACE Standard MR 0175-93: "Sulphide Stress Cracking Resistant Materials for Oil field Equipment".*
- *NORSOK Offshore Standards: "Design Principles Material Selection", 1994.*
- *NORSOK Offshore Standards: "Process Design", P-CR-001*
- *"API Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems", API RP 14E, American Petroleum Institute, Fifth Edition October 1, 1991.*

5.2 Literature

/1/ C. deWaard and D.E. Milliams: “Carbonic Acid Corrosion of Steel” , Corrosion, Vol. 31, No 5, 1975.

/2/ C. deWaard, U. Lotz and D.E. Milliams: “Predictive Model for CO_2 Corrosion Engineering in Wet Natural Pipelines”, Corrosion, Vol 47, no 12, 1991.

/3/ C. deWaard and U. Lotz: “Prediction of CO_2 Corrosion of Carbon Steel”, NACE Corrosion 93, Paper no 69, 1993.

/4/ A. Ikeda, M. Ueda, J. Vera, A. Viloria, J.L. Moralez: “Effects of Flow Velocity of 13Cr, Super 13Cr and - Duplex Stainless Steels”.

/5/ E. Raask: “Tube erosion by ash impaction”, Wear No. 13, 1969

/6/ G.P. Tilly: “Erosion caused by Impact of Solid Particles”, Treatise of Material Science and Technology, Volume 13, 1979.

/7/ I. Finnie: “Erosion of Surfaces by Solid Particles”, Wear 1960.

/8/ K. Haugen, O. Kvernvold, A. Ronold and R. Sandberg: “Sand Erosion of Wear Resistant Materials”, 8th International Conference on Erosion by Liquid and Solid Impact, Cambridge 1994.

/9/ T. Lindheim: “Erosion Performance of Glass Fibre Reinforced Plastics (GRP)”.

/10/ J. S. Hansen: “Relative Erosion Resistance of Several Materials”, ASTM STP 664, 1979.

/11/ O. Kvernvold and R. Sandberg: “Production Rate Limits in Two-phase Flow Systems – Sand Erosion in Piping Systems”, DNV Report No. 93-3252, 1993.

/12/ A. Huser: “Sand erosion in Tee bends. Development of correlation formula” DNV Report No. 96-3226, 1996.

6 IDENTIFICATION OF SERVICE CONDITIONS

Table 6-1 gives a brief characterisation of conditions which may lead to material degradation in various parts of a production system for oil and gas.

Table 6-1: Identification of conditions leading to material degradation

Service	**Water**	**CO_2**	**H_2S**	**O_2**	**Sand**
Upstream 1. stage separator - Well fluid/unprocessed fluid					
Tubing/riser	Likely	Likely	Most likely	Unlikely	Most likely
Pipelines/manifold	Likely	Likely	Most likely	Unlikely	Most likely
Downstream 1. stage separator - top side piping					
Oil	Likely	Likely	Most likely	Unlikely	Most likely
Gas	In parts	Likely	Most likely	Unlikely	Unlikely
Produced water	Likely	Likely	Most likely	Unlikely	Most likely
Processed Hydrocarbons					
Gas/oil export - Gas injection	Seldom	Likely	Most likely	Unlikely	Unlikely
Water systems					
Water injection	Likely	Unlikely	Unlikely	Likely	Seldom
Fire/cooling/utility	Likely	Unlikely	Unlikely	Likely	Unlikely

Denotation:

Likely :	*Likely condition*
Unlikely:	*Unlikely condition*
Most likely:	*Most likely condition/dependant on reservoir characteristics*
In parts:	*In parts of system*
Seldom:	*Seldom (only by incident)*

Erosion may occur in the parts of the system containing sand particles or other solid particles. For systems not containing solid particles, no velocity limitations with respect to erosive wear will apply, and the user may proceed directly to Chapter 10. For gas-condensate systems at high velocities, however, droplet erosion may occur in bends and in obstructions. In the present document it is recommended not to allow for gas velocities above 70-80 m/s under such conditions.

Corrosion degradation may apply in parts of the systems in the presence of liquid water and corrosive constituents like CO_2, H_2S and/or O_2. In such situations, evaluation of the corrosion performance of the pipe material has to be performed; see Ref /1/, /2/, /3/ and /4/ in Chapter 5. See also Appendix A for a summary of relevant material grades applicable for piping systems.

C-steels and low-alloy steels are highly sensitive to flow-induced corrosion ('erosion-corrosion'). At high velocities this may result in accelerated corrosion degradation originating from increased mass transfer, degradation of protective corrosion product layers and reduced corrosion inhibitor efficiency.

For Corrosion Resistant Alloys (CRA), high fluid velocities will in general not induce or accelerate corrosion degradation. However, these materials may be sensitive to other degradation mechanisms not related to fluid flow; e.g. sulphide stress cracking in hydrocarbon systems and pitting/crevice corrosion in water systems.

7 CHARACTERISATION OF EROSIVE WEAR

The terms erosive wear and erosion are, in the present document, defined as material loss resulting from impact of solid/sand particles on the material surface.

Erosive wear can be estimated from the following general relation, provided impact velocities and angles are known for the particles hitting the target surface, Ref. /5/, /6/ and /7/ in Chapter 5; see also Figure 7-1 for definition of parameters:

$$\dot{E} \sim \dot{m}_p \cdot K \cdot U_p^n \cdot F(\alpha) \qquad \textbf{(7.1)}$$

The function *F(α)* characterises the ductility of the target material, see Figure 7-2. Ductile materials attain maximum erosion attacks for impact angles in the range 15 - 30°. Brittle materials attain maximum erosion attacks at normal impact angle. Steel grades are generally regarded as ductile, while cermets like tungsten carbides with a metallic binder phase are defined as brittle. Coatings may be ductile or brittle depending on chemical composition and deposition method, thermal spraying, overlay or galvanic plating methods. Ceramics are generally assessed as being brittle.

The function *F(α)* for steel grades is given by the following relation; Ref. 8:

$$F(\alpha) = \sum \ (-1)^{(i+1)} A_i (\frac{\alpha \cdot \pi}{180})^i \qquad \textbf{(7.2)}$$

or:

$$F(\alpha) = A_1 \cdot (\frac{\alpha \cdot \pi}{180}) - A_2 \cdot (\frac{\alpha \cdot \pi}{180})^2 + A_3 \cdot (\frac{\alpha \cdot \pi}{180})^3 - A_4 \cdot (\frac{\alpha \cdot \pi}{180})^4$$
$$+ A_5 \cdot (\frac{\alpha \cdot \pi}{180})^5 - A_6 \cdot (\frac{\alpha \cdot \pi}{180})^6 + A_7 \cdot (\frac{\alpha \cdot \pi}{180})^7 - A_8 \cdot (\frac{\alpha \cdot \pi}{180})^8 \qquad \textbf{(7.3)}$$

where the A_i's are given in Table 7-1.

Table 7-1: Constants to be used in Equation (7.3)

A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
9.370	42.295	110.864	175.804	170.137	98.398	31.211	4.170

Steel grades typically used in piping systems have largely the same resistance to erosion; see Figure 7-3 - Ref. /8/, showing the Relative Erosion Factor (REF), for some standard steel grades tested at various impact conditions.

REF is defined as:

REF = Volume loss of material / Volume loss of C-steel grade typical for piping systems

If REF < 1; material has better erosion resistance than C-steel

If REF > 1; material has poorer erosion resistance than C-steel

The material 'constants' *K* and *n* have to be determined by experimental investigations; Table 7-2 gives recommended values for various pipe materials; Refs. /8/, /9/ and /10/.

For velocities smaller than 100m/s, the difference in erosion resistance for relevant steel grades is generally within 10-20%. This also applies to Ni-based alloys typically used in piping systems.

Limited data are available in literature with respect to erosion resistance and velocity dependence of Titanium grades and GRP materials.

Table 7-2: Recommended values for material constants to be applied in Equation (7.1) and density of actual pipe materials.

Material	K $(m/s)^{-n}$	n (-)	Density (kg/m^3)
Steel grades	$2.0 \cdot 10^{-9}$	2.6	7800
Titanium grades	$2.0 \cdot 10^{-9}$	2.6	4500
GRP/Epoxy	$0.3 \cdot 10^{-9}$	3.6	1800
GRP/Vinyl Ester	$0.6 \cdot 10^{-9}$	3.6	1800

Figure 7-4 shows an example of resulting weight loss per kg sand impact for steel grades based on Equations (7.1) and (7.2) and the material 'constants' given in Table 7-2.

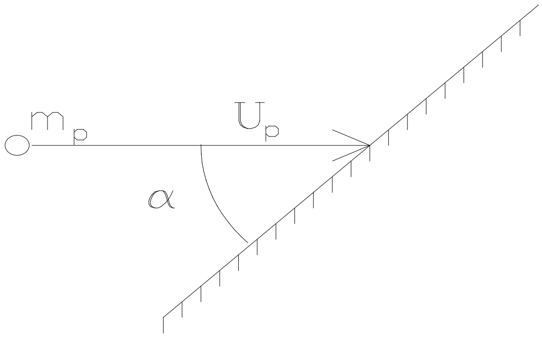


Figure 7-1: **Parameters characterising erosion impact on a surface with reference to Equation (7.1)**

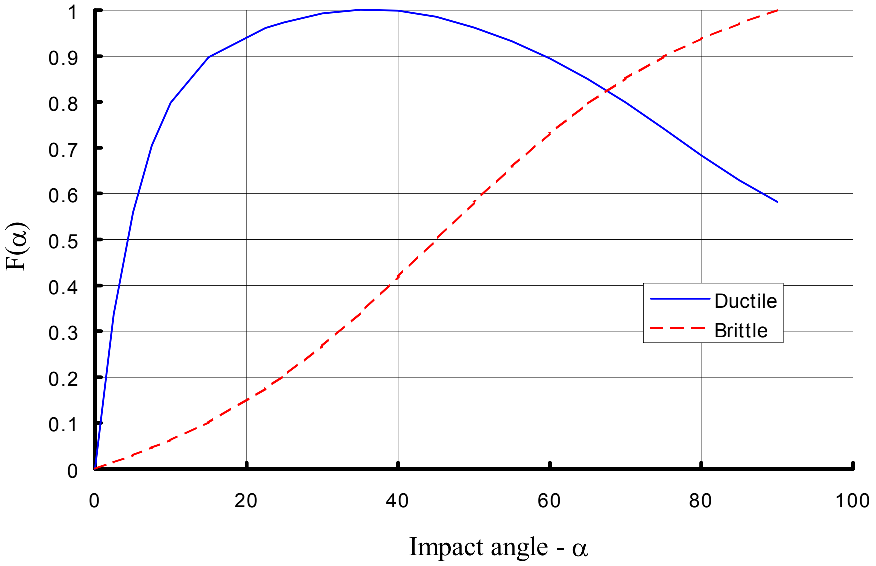


Figure 7-2: **Function F (α) for typical 'ductile' and 'brittle' materials**

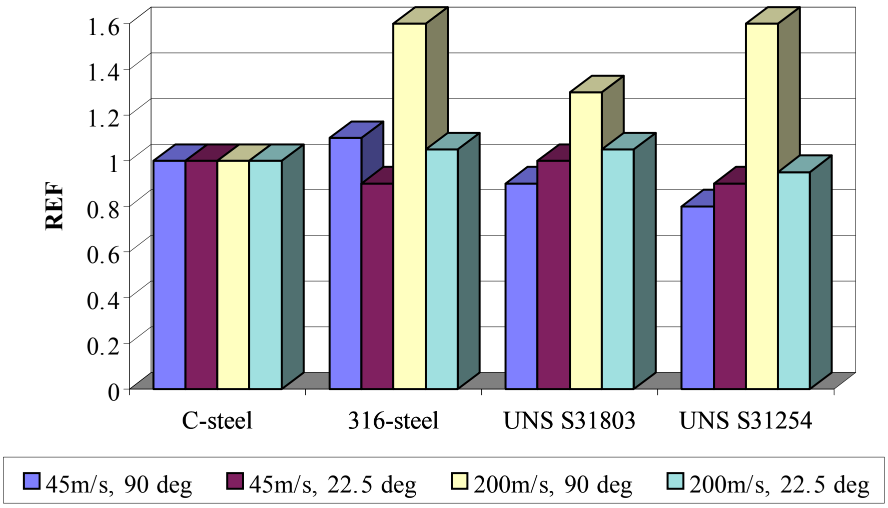


Figure 7-3: **Relative erosion resistance for some steel grades. C-steel is used as a reference material**

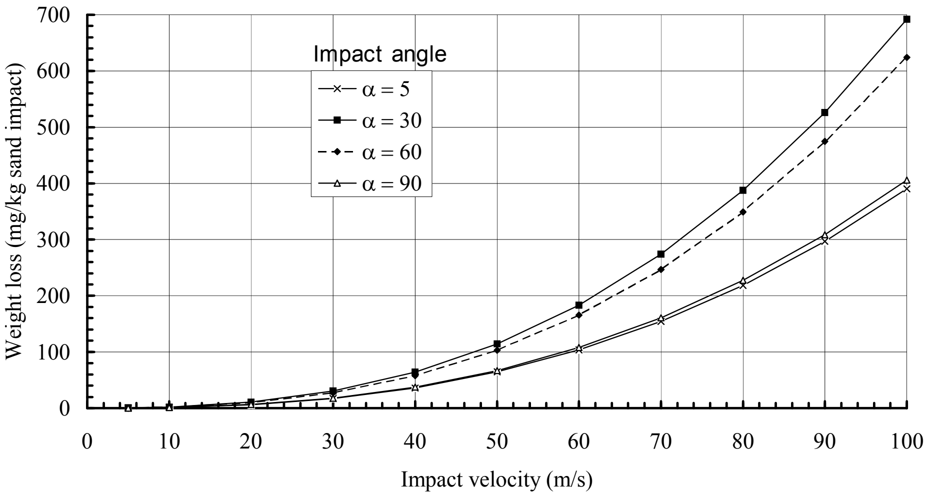


Figure 7-4: **Weight loss (mg/kg sand impact) for steel grades based on Equation (7.1) as function of impact angle and impact velocity**

8 PREDICTIONS/ASSESSMENT OF EROSIVE WEAR

The following chapters present a procedure for quantitative assessment of erosion in various parts of a piping system. The procedure is developed based on numerical simulations, model equations and experimental investigations. The procedure is intended to give conservative estimates for the erosion attacks in order to avoid excessive erosion in the system during operation.

8.1 General

Equation (7.1) is used as a basis for an estimation of erosion rates. The equation requires input of particle impact velocity, particle impact angle and mass of sand impacting on the target area. If these parameters are known, the resulting erosion rates can be calculated from the following relation:

$$\dot{E}_L = \frac{\dot{m}_p \cdot K \cdot U_p^n \cdot F(\alpha)}{\rho_t \cdot A_t} \cdot C_{unit} = \frac{\dot{E}_m}{\rho_t \cdot A_t} \cdot 10^3 \quad \text{[mm/yr]}, \; C_{unit}=3.15E10 \tag{8.1}$$

Impact angles, impact velocities and the amount of sand hitting a surface are dependent on the multi-phase flow characteristics, the grain size distribution and component geometry. In the calculation procedure, these effects are accounted for by model/geometry factors applied to Equation (8.1). The model/geometry factors account for multiple impact of the sand particles, concentration of sand particles due to component geometry and model uncertainty.

In the procedure, impact velocity is, if not otherwise defined, determined by the relation:

$$U_p = V_l^s + V_g^s = V_p \tag{8.2}$$

$$V_g^s = \frac{4 \cdot \dot{M}_g}{\rho_g \cdot \pi \cdot D^2} \tag{8.3}$$

$$V_l^s = \frac{4 \cdot \dot{M}_l}{\rho_l \cdot \pi \cdot D^2} \tag{8.4}$$

Physical properties of the fluids are described as mixture properties and are determined by the following relations.

$$\rho_m = \frac{\rho_l \cdot V_l^s + \rho_g \cdot V_g^s}{V_l^s + V_g^s} \qquad \textbf{(8.5)}$$

$$\mu_m = \frac{\mu_l \cdot V_l^s + \mu_g \cdot V_g^s}{V_l^s + V_g^s} \qquad \textbf{(8.6)}$$

If the sand content is given as 'part per million values' (ppm), the resulting sand flow rate can be calculated according to the following relations:

For ppm given on mass basis (ppmW):

$$\dot{m}_p = \dot{M}_m \cdot ppmW \cdot 10^{-6} \qquad \textbf{(8.7)}$$

For ppm given on volume basis (ppmV):

$$\dot{m}_p = \rho_p \cdot \frac{\dot{M}_m}{\rho_m} \cdot ppmV \cdot 10^{-6} \qquad \textbf{(8.8)}$$

Note that ppmV will change with pressure and temperature. Care must therefore be taken to relate the ppmV to the specific conditions.

Generally, sand content in the range 1 - 50 ppmW is experienced in well streams upstream of the first stage separators. Typical sand particle sizes are experienced to be in the range 250 - 500 µm if no gravel or other sand exclusion techniques are applied. If gravel is used, sand particles less than 100 µm are to be expected.

8.2 Smooth and Straight pipes

Erosion in smooth pipes is generally small and negligible and is therefore, in most cases, not limiting with respect to pipe sizing.

The erosion rate (mm/year) for smooth straight steel pipes can be found by using the empirical correlation given in Equation (8.9), Ref. /11/. (All input values to be given in SI-units, see Chapter 4):

Vertical pipes

The erosion rate for steel:

$$\dot{E}_L = 2.5 \cdot 10^{-5} \cdot U^{2.6} \cdot \dot{m}_p \cdot D^{-2} \qquad \text{(mm/year)} \qquad \textbf{(8.9)}$$

8.3 Welded Joints

The erosion rate calculation procedure for welded joints with internal reinforcement is based on the initial weld geometry. The geometrical change of the weld reinforcement, when eroded, is not taken into account.

A schematic drawing of the weld, showing parameters needed, is presented in Figure 8-1.

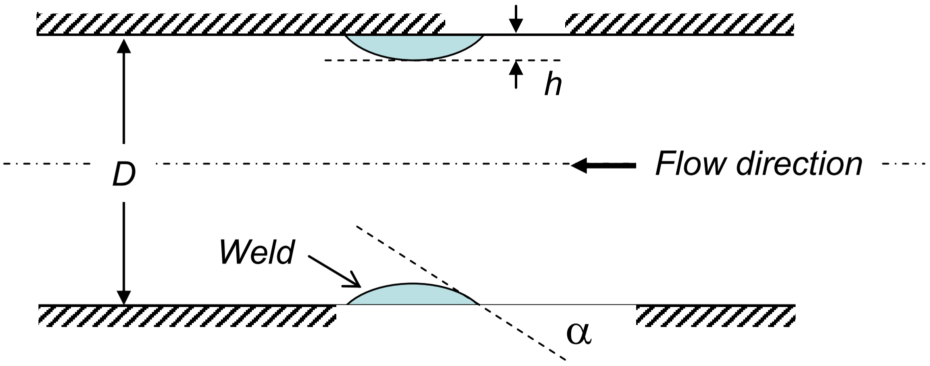


Figure 8-1: Schematic drawing of a welded joint

8.3.1 Erosion of flow facing part of weld reinforcement

The erosion rate of the flow facing part of welded joints is found by the following 5 step calculation procedure:

1) Estimate the particle impact angle, α, between the weld and the flow direction (see Figure 8-1). If the angle is unknown, the conservative value $\alpha = 60^{\circ}$ should be used giving $F(\alpha)\cdot\sin(\alpha) = 0.78$.

2) Find the value of the function $F(\alpha)$ by using the impact angle, α, found in step 1. $F(\alpha)$ can be found graphically from Figure 7-2 or from Equation (7.2). The values for $F(\alpha)$ is in the range <0, 1>.

3) Calculate the cross sectional area of the pipe:

$$A_t = \frac{\pi \cdot D^2}{4\cdot\sin(\alpha)} = \frac{A_{pipe}}{\sin(\alpha)} \qquad \textbf{(8.10)}$$

4) The following unit conversion factor must be used (m/s → mm/year):

$$C_{unit} = 1000\cdot 3600\cdot 24\cdot 365 = 3.15\cdot 10^{10} \qquad \textbf{(8.11)}$$

5) Calculate the particle size and fluid density correction factor C_2:

$$\left(\frac{10^6\cdot d_p}{30\cdot(\rho_m)^{1/2}}\right) < 1,\ C_2 = \left(\frac{10^6\cdot d_p}{30\cdot(\rho_m)^{1/2}}\right) \qquad \textbf{(8.12)}$$

$$\left(\frac{10^6\cdot d_p}{30\cdot(\rho_m)^{1/2}}\right) \geq 1,\ C_2 = 1$$

6) The erosion rate is then found by applying all the calculated parameters in the basic erosion rate equation, Equation (8.1). The maximum erosion rate (mm/year) of the weld is then found from the following formula (all input values are given as SI-units):

$$\dot{E}_L = \dot{m}_p\cdot K\cdot F(\alpha)\cdot U_p^n\cdot\frac{\sin(\alpha)}{\rho_t\cdot A_{pipe}}\cdot C_2\cdot C_{unit} \qquad \textbf{(8.13)}$$

It should be noted that erosion on the flow facing part of the weld will result in rounding and smoothing of the weld, generally not affecting the integrity of the pipe. Erosion of the weld will therefore not be a limiting factor with respect to dimensioning of the pipe.

8.3.2 Downstream weld

The maximum erosion rate downstream a weld is found to be larger than for the smooth part of the pipe. The erosion rate (mm/year) can be estimated by using the following formula, Ref. 11 (all input values to be given in SI-units):

For steel :

$$\dot{E}_L = 3.3\cdot10^{-2}\cdot(7.5\cdot10^{-4}+h)\cdot U_p^{2.6}\cdot D^{-2}\cdot\dot{m}_p \qquad \textbf{(8.14)}$$

Where h is the weld height (m)

8.4 Pipe bends

Pipe bends are usually one of the most erosion prone parts in a pipe system, and will, for conditions where erosion is the most critical degradation mechanism, be limiting both with respect to dimensioning of the piping system and the production rate.

When the flow direction is changed in the bend, the particles do not follow the fluid but hit the bend wall as shown in Figure 8-2. The current bend model assumes a straight pipe section upstream the bend. Experience has shown that in case of complex isometric, both the location and maximum erosion rate may vary. This should be taken into account when imposing safety factors on the calculations.

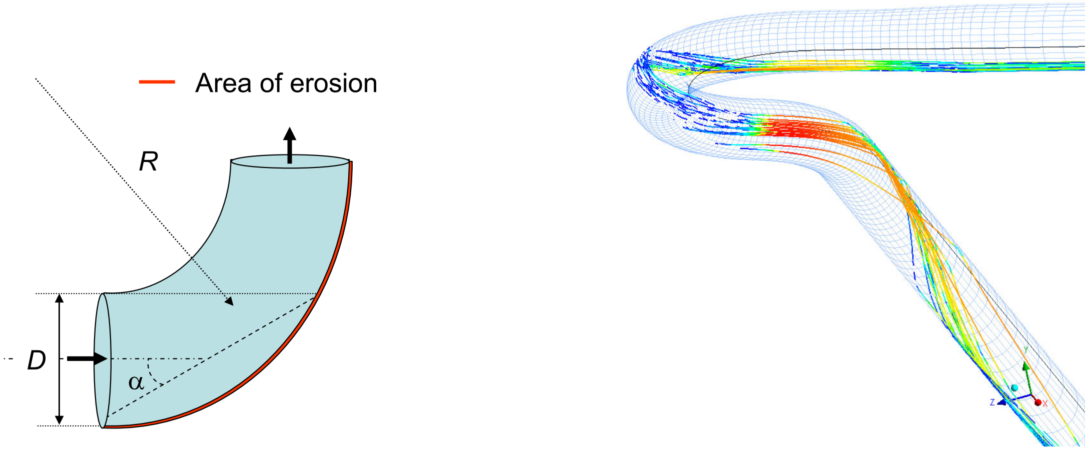


Figure 8-2: **Impact angle, α, in bend. R is radius of curvature, $R_{curvature}$=R/D (left). Particle trajectories in complex isometrics from detailed CFD simulations (right)**

The erosion rate for pipe bends is calculated in the following calculation procedure:

1) Calculate the characteristic impact angle, α, for the pipe bend geometry as shown in Figure 8-2, Note: Radius of curvature is given as the Number of Pipe Diameters:

$$\alpha = \arctan\left(\frac{1}{\sqrt{2 \cdot R_{curvature}}}\right) \qquad \textbf{(8.15)}$$

2) Calculate the dimensionless parameter group, A:

$$A = \frac{\rho_m^2 \cdot \tan(\alpha) \cdot U_p \cdot D}{\rho_p \cdot \mu_m} = \frac{\mathrm{Re}_D \cdot \tan\alpha}{\beta} \qquad \textbf{(8.16)}$$

3) Use the dimensionless group, A, from step 2 in the following equation in order to obtain the critical particle diameter, $d_{p,c}$:

$$\frac{d_{p,c}}{D} = \gamma_c = \begin{cases} \dfrac{\rho_m}{\rho_p \cdot [1.88 \cdot \ln(A) - 6.04]} = \dfrac{1}{\beta \cdot [1.88 \cdot \ln(A) - 6.04]} \ , & \gamma_c < 0.1 \\ 0.1 \ , & \gamma_c > 0.1 \wedge \gamma_c \leq 0 \end{cases} \qquad \textbf{(8.17)}$$

4) Calculate the particle size correction function *G* by using the critical particle diameter found in step 3:

$$G = \begin{cases} \dfrac{\gamma}{\gamma_c} & \gamma < \gamma_c \\ 1 & \gamma \geq \gamma_c \end{cases} \qquad \textbf{(8.18)}$$

5) Calculate the characteristic pipe bend area exposed to erosion:

$$A_t = \frac{\pi \cdot D^2}{4 \cdot \sin(\alpha)} = \frac{A_{pipe}}{\sin(\alpha)} \qquad \textbf{(8.19)}$$

6) Determine the value of the function *F(α)* by using the angle, *α*, found in step 1. *F(α)* can be found graphically from Figure 8-2 or from Equation (7.2). The values for *F(α)* is in the range <0, 1>.

7) The model/geometry factor, C_1, is set equal to (*reduced from C_1=5 in Rev.4.1*):

$C_1 = 2.5$

The model/geometry factor accounts for multiple impact of the sand particles, concentration of particles at the outer part of the bend and model uncertainty.

8) The following unit conversion factor must be used (m/s → mm/year):

$$C_{unit} = 1000 \cdot 3600 \cdot 24 \cdot 365 = 3.15 \cdot 10^{10} \tag{8.20}$$

9) The erosion rate is then found by applying all the calculated parameters into the basic erosion rate equation (Equation (8.1) in Chapter 8.1). The maximum erosion rate (mm/year) in the pipe bend is found by the following formula (all input values are given as SI-units):

$$\dot{E}_L = \frac{\dot{m}_p \cdot K \cdot F(\alpha) \cdot \sin(\alpha) \cdot U_p^n}{\rho_t \cdot A_{pipe}} \cdot G \cdot C_1 \cdot C_{unit} \tag{8.21}$$

8.5 Blinded Tee

A Blinded Tee is generally expected to be less exposed to erosion than ordinary pipe-bends, since the impact velocity of the particles will be reduced as the particles moves into the low velocity blinded Tee. Such effects will be particularly pronounced for conditions with a low fluid density or large particles. For conditions with a high fluid density or small particles, the sand particles will be deflected by the flow and will impact in the blinded Tee/outlet pipe intersection region, resulting in erosion attacks smaller than or comparable to erosion in ordinary bends. Effects of complex isometrics should be considered with respect to amplitude and location of maximum erosion.

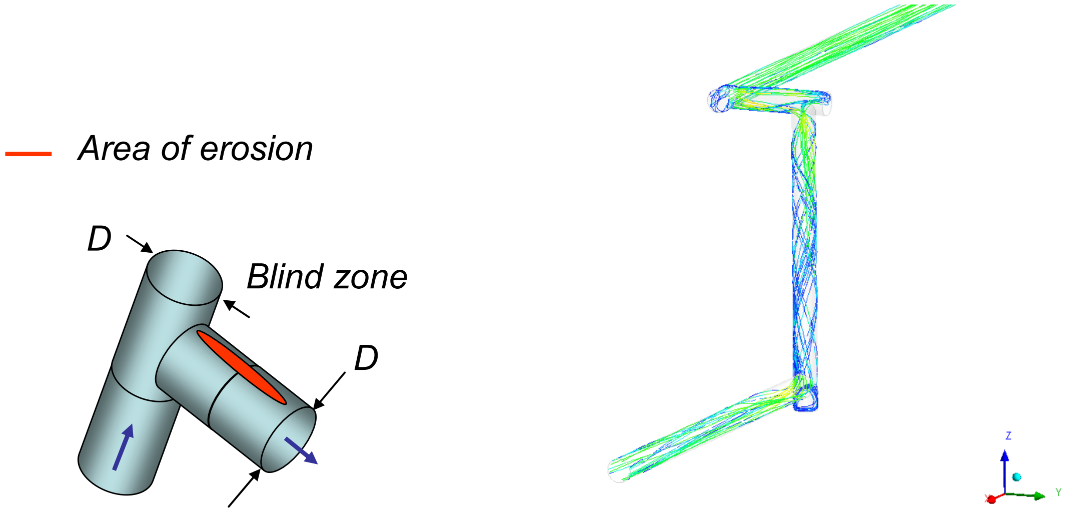


Figure 8-3: **Schematic, Blinded Tee – area of erosion calculated by the model (left). Effects of complex isometric on particle trajectories from detailed CFD simulations (right)**

The erosion rate for a Tee-bend is calculated in a 7 step calculation procedure:

1) Calculate the normalised critical particle diameter (**$\gamma_c = d_{p,c}/D$**), the particle size correction function **(G)**, and the model geometry factor **(C_1)**:

$\gamma = \frac{d_p}{D}$	
$\beta = \rho_p/\rho_m$	
for $\beta < 40$	**for $\beta \geq 40$**
$\gamma_c = \frac{d_{p,c}}{D} = \frac{0.14}{\beta}$ **(8.22)**	$\gamma_c = 0.0035\left(\frac{\beta}{40}\right)^b$, **(8.23)** where $b = \left[\ln\left(\frac{\mathrm{Re}}{10000}+1\right)+1\right]^{-0.6} - 1.2$
$c = \begin{cases} \frac{19}{\ln(\mathrm{Re})}, & \gamma < \gamma_c \\ 0, & \gamma \geq \gamma_c \end{cases}$	$c = \begin{cases} \frac{19}{\ln(\mathrm{Re})}, & \gamma < \gamma_c \\ -0.3 \cdot (1 - 1.01^{-(\beta-40)}), & \gamma \geq \gamma_c \end{cases}$ **(8.24)**
$G = \left(\frac{\gamma}{\gamma_c}\right)^c$ **(8.25)**	
$C_1 = \frac{3}{\beta^{0.3}}$	$C_1 = 1.0$ **(8.26)**

2) Calculate the characteristic pipe area exposed to erosion:

$$A_t = \frac{\pi \cdot D^2}{4} \tag{8.27}$$

3) The following unit conversion factor must be used (m/s → mm/year):

$$C_{unit} = 1000 \cdot 3600 \cdot 24 \cdot 365 = 3.15 \cdot 10^{10} \tag{8.28}$$

4) The erosion rate is then found by applying all the calculated parameters in the basic erosion rate equation (Equation (8.1) in Chapter 8.1). The maximum erosion rate (mm/year) in the pipe bend is found by the following formula (all input values are given as SI-units):

$$\dot{E}_L = \frac{\dot{m}_p \cdot K \cdot U_p^n}{\rho_t \cdot A_t} \cdot G \cdot C_1 \cdot C_{unit} \tag{8.29}$$

8.6 Reducers

The erosion rate in a flow reducer (contraction) is based on the basic erosion rate equation (Equation (8.1) in Chapter 8.1) applied on the principle geometry changes of a flow reducer. A schematic drawing of a flow reducer is presented in Figure 8-4.

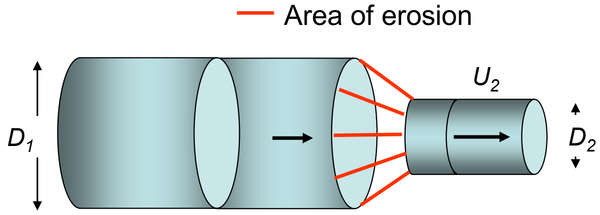


Figure 8-4: Schematic, flow reducer

The erosion rate for a flow contraction is calculated in the following 7 step calculation procedure

(All input values are given as SI-units):

1) Assess/set the particle impact angle, α, between the contraction and the flow direction shown in Figure 7-3. If the angle is unknown, the conservative value $\alpha = 60^o$ should be used giving $F(\alpha) \cdot \sin(\alpha) = 0.78$.

2) Calculate the area exposed to particle impact (directly hit by the particles):

$$A_{target} = \frac{\pi}{4 \cdot \sin \alpha} \cdot (D_1^2 - D_2^2) \tag{8.30}$$

3) Calculate the ratio between area exposed to particle impact and the area before the contraction:

$$A_{ratio} = 1 - \frac{D_2^2}{D_1^2} \tag{8.31}$$

4) The particle impact velocity is set equal to the fluid velocity after the contraction:

$$U_p = U_2 = U_1 \cdot \left(\frac{D_1}{D_2}\right)^2 \tag{8.32}$$

5) Find the value of the function *F(α)* by using the impact angle, α, found in step 1. *F(α)* can be found graphically from Figure 7-2 or from Equation (7.2). The values for *F(α)* is in the range <0, 1>.

6) Calculate the particle size and fluid density correction factor C_2:

$$\left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) < 1,\ C_2 = \left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) \tag{8.33}$$

$$\left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) \geq 1,\ C_2 = 1$$

7) The following unit conversion factor must be used (m/s → mm/year):

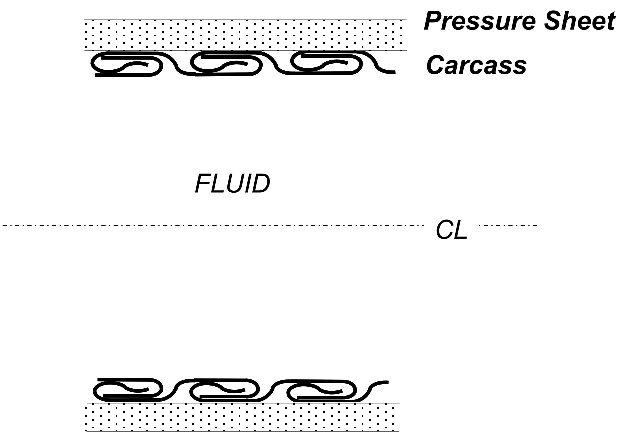
$$C_{unit} = 1000 \cdot 3600 \cdot 24 \cdot 365 = 3.15 \cdot 10^{10} \tag{8.34}$$

8) The erosion rate is then found by applying all the above calculated parameters into the basic erosion rate equation (Equation (8.1) in Chapter 8.1). The maximum erosion rate (mm/year) in the contraction is then found by the following formula:

$$\dot{E}_L = \frac{\dot{m}_p \cdot K \cdot F(\alpha) \cdot U_p^n}{\rho_t \cdot A_t} \cdot A_{ratio} \cdot C_2 \cdot C_{unit} \tag{8.35}$$

8.7 Flexible pipes

Flexible pipes (risers/jumpers) consist of a multilayer composite structure, i.e. with several external protection and armour layers and an internal pressure barrier. Normally flexible pipes are configured with an internal carcass. The main function of the internal carcass is to prevent collapse due to external pressure, but also to protect the pressure sheet from mechanical or abrasive damage.



To retain the flexibility of the pipe, the internal carcass is normally made from interlocked steel strips. I.e. in radial direction the carcass consists of multiple thin layers of steel. With respect to erosion, a flexible pipe will experience similar erosion in curved sections as for ordinary bends. However, the radius of curvature is normally significantly larger than for adjacent hard piping. The effects of the rougher surface structure of the carcass compared to hard piping is experienced to have moderate effects on the erosion rate.

For flexible pipes applied in service with sand particles in the fluid, dimensioning can be performed in accordance with the procedure described in Chapter 8.4. The internal diameter of the inner liner (carcass) should be used in combination with the smallest radius of curvature for the flexible pipe to calculate the erosion rate.

8.8 Intrusive erosion probes

Intrusive erosion probes are extensively applied both subsea and topside to continuously monitor and control erosion rates due to solids production. The output from the erosion probes are normally the erosion rate, e.g. in terms of *nm/d*, in combination with the accumulated erosion on the probe elements.

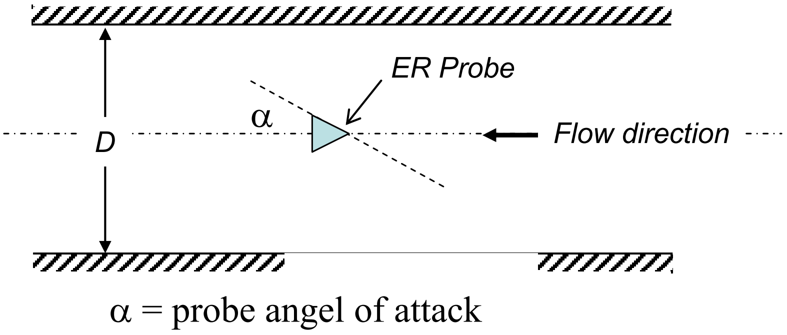


Figure 8-5: ER probe

The relation between the erosion rate measured on a probe element for a given element configuration can be deduced from the basic equation 7.1 and the particle size correction factor.

$$E_L = K_1 \cdot \underbrace{\left(\frac{K \cdot U_p^n \cdot F(\alpha)}{A_t \cdot \rho_t}\right)}_{m/kg} \cdot \underbrace{C_2}_{d_p-correction} \quad \text{, (mm/ton),(}10^3\text{ nm/kg)} \qquad \textbf{(8.36)}$$

, where the density correction factor C_2 reads:

$$\text{For } \left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) < 1,\ C_2 = \left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) \qquad \textbf{(8.37)}$$

$$\text{For } \left(\frac{10^6 \cdot d_p}{30 \cdot (\rho_m)^{1/2}}\right) \geq 1,\ C_2 = 1$$

, and the impact area corresponds to the pipe cross section area:

$$A_t = \frac{\pi}{4} D^2 \qquad \textbf{(8.38)}$$

K and *n* are the probe element material erosion properties, ref. Table 7-2. Normally these can be set according to the properties of steel grades, i.e. *K=2.0E-9* and *n=2.6*. For a probe element orientation of 30-45° to the flow direction, $F(\alpha)=1$ for ductile materials. Otherwise the $F(\alpha)$ for the specific materials may be applied.

The probe geometry facto K_1 is a geometrical correction factor, compensating for the orientation of the probe elements. If the probe element is oriented $\alpha=45°$ to the flow direction, K_1=Sin (α)=Sin(45)=0.71. Calibration in situ to increase precision may be required.

The model assumes that the sand is homogenously distributed over the cross section of the pipe at the location of the probe. Normally erosion probes consist of several erosion elements, such that the output from the probe represents an average erosion rate.

In many cases it is of interest to use the “real-time” measured erosion rate to assess the “real-time” amount of solids produced.

I.e. the real time sand production can be determined from the measured erosion rate $E_{L,m}$ (mm/yr) and the equation above:

$$\dot{m}_p = \frac{E_{L,m}}{E_L \cdot C_{unit}} \quad (kg/s),\ C_{unit}=3.154 \cdot 10^4\ (ton/yr \rightarrow kg/s) \qquad \textbf{(8.39)}$$

8.9 Headers

Erosion in collection headers are normally less critical than in other parts of the production system, however depending on the diameter ratio of the header (D_2) relative to the diameter of the inlet flow lines (D_1) and the momentum of the flow in the inlet relative to the momentum of the flow in the header, illustrated in Figure 8-6.

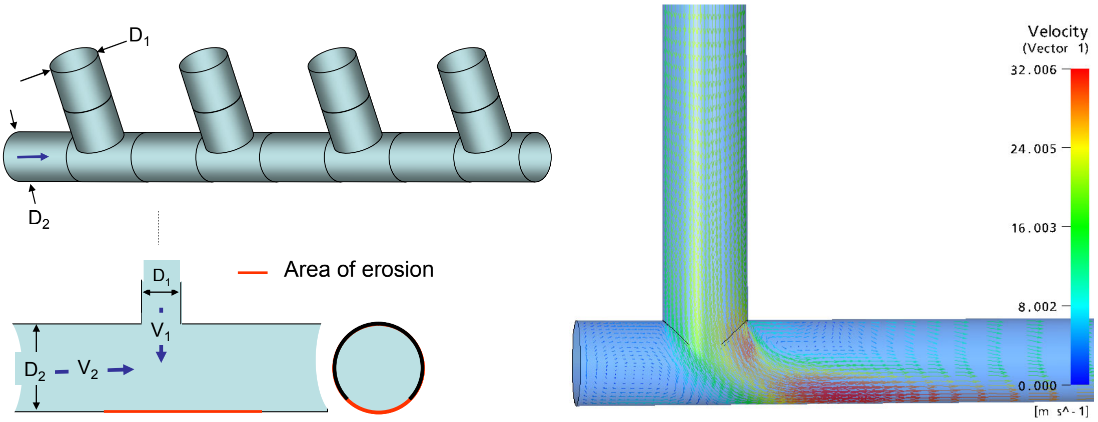


Figure 8-6: Schematic, header (left), CFD simulation (right)

For calculation of the erosion rate in headers it is recommended to apply detailed CFD simulations.

9 SOFTWARE APPLICATION

In order to simplify the use of the above procedures, a Microsoft Windows-based software application has been developed as a part of the RP. A description of the programme is given in Appendix B. We recommend this programme to be used when applying the present procedure.

9.1 Alternative models

If high precision erosion rates are required or "non-standard" flow geometries are used, more sophisticated methods must be used in order to obtain a more detailed and less conservative result.

9.1.1 ERBEND

ERBEND is a Microsoft Windows computer programme which can be used to estimate erosion rates in ordinary pipe bends. Particle trajectories are calculated by solving the equation of motion for each particle, and the position of particle impact on the pipe wall is determined. The corresponding impact velocities and impact angles are used to determine the resulting erosion attacks. The model calculates the effect of:

- Particle size/particle concentration
- Fluid characteristics
- Flow rate
- Geometry of pipe bend

The models for the erosion calculations are based on extensive experimental investigations. ERBEND simulations are showing good agreement with pipe-bend tests.

ERBEND is a commercially available computer programme, supported by DNV.

9.1.2 General particle tracking models (CFD)

For complex non standard geometries detailed computer simulations have to be performed. The flow field in an arbitrary geometry can be found with a CFD-code (Computational Fluid Dynamics), for instance FLUENT, PHOENICS or CFX. The flow field is used when calculating the particle trajectories. The impact velocities and impact angles are then used to determine the resulting erosion attacks. The model reflects effects of:

- Particle size/particle concentration
- Fluid characteristics
- Flow rate
- Geometry of component

The erosion rate is calculated by means of Equation (7.1) for individual particles and added to give an estimate of the overall erosion profile in the geometry.

10 DIMENSIONING / HC SYSTEMS

10.1 General

In addition to material degradation mechanisms also limitations related to pressure drop, vibrations and noise have to be evaluated related to dimensioning of a piping system.

In general, the compatibility of the material type with the CO_2-content, H_2S-content, pH, chloride content, temperature and chemicals has to be evaluated.

For flow lines transporting unprocessed HC, also minimum production rate limitations have to be evaluated due to the potential for sand accumulation in the flow lines at low production rates.

Furthermore the potential for formation of extreme slugging at low production rates has to be evaluated.

10.2 Non corrosive - no particles

For non-corrosive systems with no sand particles there is no limiting velocity with respect to material degradation.

A system is non-corrosive if no free water is present and/or if no corrosive agents, i.e. CO_2, H_2S or O_2, are present.

For gas-condensate systems, velocities should in all cases be kept below 70 - 80 m/s to avoid droplet erosion.

10.3 High alloyed steel - no particles

For high alloyed steel applied in services with no sand particles in the well-stream there is generally no limiting velocity with respect to material degradation provided that the material is selected to meet the corrosive atmosphere.

For gas-condensate systems, velocities should in all cases be kept below 70 - 80 m/s to avoid droplet erosion.

10.4 High alloyed steel - sand particles

For high alloyed steel applied in services with sand particles in the well stream, the dimensioning can be performed according to the procedure described in Chapter 8.

Pipe bends, blinded tees and restrictions like reducers, control chokes and valves will generally be the most critical components with respect to erosive wear.

10.5 C-steel

For C-steel applied in services with sand particles in the well-stream, the erosion effect can be determined according to the procedure described in Chapter 8.

For C-steel additional evaluation of corrosivity and inhibitor performance has to be performed. Special attention should be given to possible application limits for corrosion inhibitors. Such application limits will be specific for the different inhibitors and process parameters.

11 DIMENSIONING - WATER SYSTEMS

11.1 General

In addition to material degradation mechanisms also limitations related to pressure drop, vibrations, noise and cavitation have to be evaluated related dimensioning of a piping system. Cavitation will generally not be a problem in the piping for water injection systems due to the high pressures involved. However, cavitation has been experienced in chokes when operating at high pressure reduction/partly closed conditions.

In general, the compatibility of the material type with the O_2-content, pH, chloride content, temperature and chemicals has to be evaluated.

Intermittent service; i.e. fire water systems, justifies higher velocities than recommended below.

11.2 Steel grades - No sand

For steel grades applied in water systems with no sand particles, there is no limiting velocity with respect to erosive material degradation. However, corrosion degradation may be a limiting factor. The corrosion rate can increase due to increased mass transfer in the corrosion process and the increased risk for corrosion product break down at higher velocities.

11.3 Steel grades - Sand particles/soft particles

For steel grades applied in systems with sand particles or other soft particles such as organic particles in the water, dimensioning can be performed in accordance with the procedure described in Chapter 8. This approach will give conservative estimates since soft particles will result in less erosion attacks than a similar amount of sand particles.

11.4 Cu-base alloys

Maximum recommended velocities for Cu-base alloys are given by the following limits - applicable to undisturbed pipe flow:

Copper-nickel:	3 m/s
Aluminium brass:	2.6 m/s

Data related to erosion resistance of these materials are not available. However, erosion by sand particles will generally not be limiting at these low velocities under normal sand contents for offshore conditions. At high sand contents; i.e. slurries or injection of drill mud, Cu-base alloys should not be applied.

11.5 Ti-base alloys

For Ti-base materials applied in systems with sand particles or other soft particles in the water, dimensioning can be performed in accordance with the procedure described in Chapter 8. Material constants to be used in the models are given in Table 6-2.

11.6 Flexible pipes, polymer liner and GRP pipes

Only limited information is available on the erosion resistance of GRP materials. Based on recent experimental investigations performed by Sintef, it is recommended to apply material constants as given in Table 7-2.

The recommended values are based on tests performed at a maximum of 10 m/s. Due to lack of experimental data it is therefore not recommended to apply velocities larger than 10 m/s even if no sand is present in the water.

12 MITIGATION AND CONTROL OF EROSIVE WEAR

Some measures which can be applied to reduce and control erosive wear are given below.

12.1 Geometry

Increased wall thickness can be applied in local parts of the system being most exposed to erosion, i.e. pipe bends.

Large radius of curvature pipes should be applied.

12.2 Materials

Erosion resistant materials, such as cermets (tungsten carbides with metallic binder) or ceramics can be applied as coatings or inserts in local parts of the system being most exposed to erosion. Pipe bends are the components being most relevant for such measures. Careful examination of erosion resistance as well as corrosion performance and compatibility with the pipe material have to be performed for the coating/insert material.

12.3 Sand exclusion

The use of a sand screen, gravel pack or chemical consolidation of the reservoir will reduce the sand production and can thereby increase service life or reduce pipe diameter. The use of sand screens will, however, generally be associated with reduced production capacity.

12.4 Monitoring/inspection

Careful monitoring of the sand production should be performed to ensure that excessive sand production does not occur.

Inspection of most exposed components should be performed on a regular basis to control the material degradation.

12.5 Flow control

A reduced flow rate may be a measure to reduce both sand production and erosion attacks in the pipe system, however often with significant impact on the well productivity.

APPENDIX A - CANDIDATE MATERIALS

A1 Candidate materials

Table A1 gives an overview of possible candidate material applicable for the services and environments identified in Table 6-1.

1 - Well fluid/unprocessed oil and gas
2 - Processed oil or gas (export)
3 - Produced water (injection)
4 - Treated sea water (injection-generally < 20 ppb O_2)
5 - Untreated sea water (fire/cooling, process, injection)

Table A1: Overview of materials and services

Type of material	Tubing	Pipelines & flow lines	Piping (Welded)
Carbon steel		1,2	1,2,3,4
Low-alloy steel	1,3,4		
13Cr stainless steel	1,3,4		
316 stainless steel		1(**)	1,3,4
Duplex stainless steel (SAF2205)	1,3,4(*)	1	1,3,4
Duplex stainless steel (SAF2507)	1,3,4(*)	1	1,3,4,5
High-alloyed austenitic (6Mo, Alloy 625)	1(*)	1(**)	1,5
Ti-base alloys			5
Cu-base alloys			3,5
GRP			5

(*) - Cold worked
(**) - Cladding

A2 Material characteristics

Table A2 gives the characteristics of weld ability and corrosion resistance for the various candidate pipe materials.

Table A2: Material characteristics; weld ability and corrosion resistance

Type of material	Weldability	Corrosion resistance		
		CO_2 corrosion	Untreated Sea water	Produced water/ Treated sea water*
Carbon steel	++	÷	÷	o
Low-alloy steel	÷	÷	÷	o
13Cr stainless steel	÷	+	÷	÷**
316 stainless steel	+	++	o	+
Duplex stainless steel (2205)	+	++	o	+
Duplex stainless steel (2507)	o	++	+	++
High-alloyed austenitics (6Mo, Alloy 625)	o	++	+	++
Ti-base alloys	o	++	++	++
Cu-base alloys	+	+	+	++
GRP	n.a	++	++	++

Denotation:

++; Excellent

+; Good

o; Fair

÷; Poor

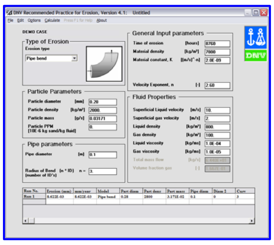
* < 20 ppb O_2 content (average value). Will also be sensitive to water chemistry and temperature

** Localised attacks may be critical

Note: Additional limitations with respect to pH, temperature, chloride content, CO_2, H_2S, and O_2 contents may apply for the various material types listed in Table A2.

APPENDIX B - DESCRIPTION OF SOFTWARE APPLICATION

B.1 Short description



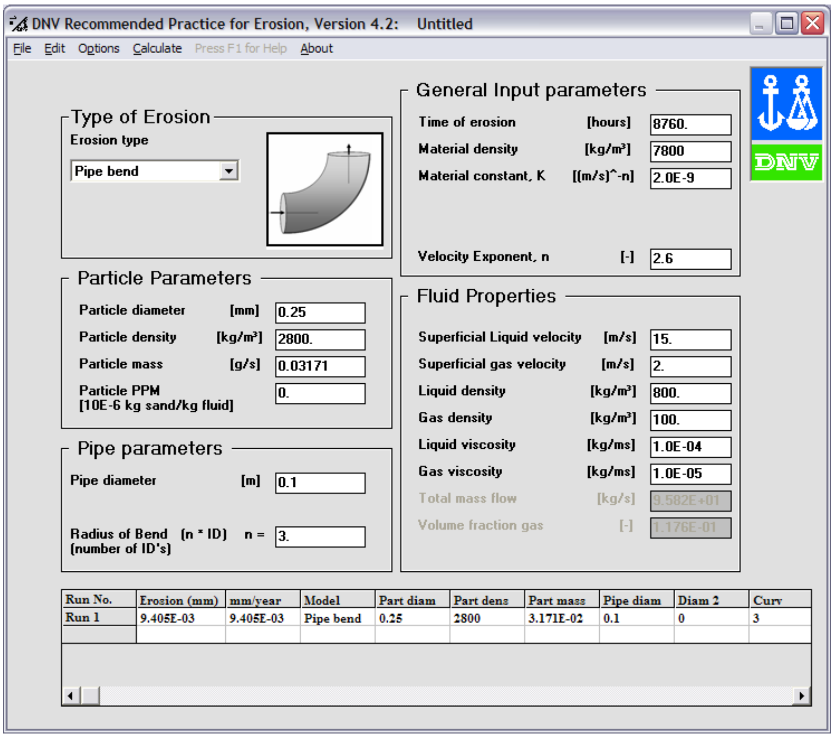
The models described in the DNV RPO501 are implemented in a Microsoft Window based software application. The application is offered in addition to this RPO501-document in order to simplify the use of the correlations and reduce the probability of making errors in the erosion calculations.

<u>The following options are included in the application version 4.2:</u>

1) Estimation of erosion rate for a given set of input values; Figure B2 shows the main window. In the main window, the user may carry out single calculations and obtain a calculation-log.
2) Allows for "Goal Seek" of <u>one</u> parameter to get a predetermined erosion attack; Figure B-3 shows the input window.
3) Perform a parameter study for one or two parameters. The results are presented in a table and a graph.

The programme offers possibilities to paste the results into other applications.

B.3 Main window



Type of Erosion
Erosion type: Pipe bend

General Input parameters
Time of erosion [hours] 8760.
Material density [kg/m³] 7800
Material constant, K [(m/s)^-n] 2.0E-9
Velocity Exponent, n [-] 2.6

Particle Parameters
Particle diameter [mm] 0.25
Particle density [kg/m³] 2800.
Particle mass [g/s] 0.03171
Particle PPM [10E-6 kg sand/kg fluid] 0.

Fluid Properties
Superficial Liquid velocity [m/s] 15.
Superficial gas velocity [m/s] 2.
Liquid density [kg/m³] 800.
Gas density [kg/m³] 100.
Liquid viscosity [kg/ms] 1.0E-04
Gas viscosity [kg/ms] 1.0E-05
Total mass flow [kg/s] 9.582E+01
Volume fraction gas [-] 1.176E-01

Pipe parameters
Pipe diameter [m] 0.1
Radius of Bend (n * ID) (number of ID's) n = 3.

Run No.	Erosion (mm)	mm/year	Model	Part diam	Part dens	Part mass	Pipe diam	Diam 2	Curv
Run 1	9.405E-03	9.405E-03	Pipe bend	0.25	2800	3.171E-02	0.1	0	3

Figure B2 The DNV-RPO501 input window

The main input window, shown in Figure B2, has the following menu options:

Option	Description
New:	Reset all input parameters as well as the input file name. All input data will be lost unless previously saved.
Open:	Open input files. The current file should be saved prior to opening a new file. Input files will have the default extension: "*.RPI"
Save:	Save the input file with the current file name. If the file has no name, the user will be prompted for a new file name.
Save As:	Save the input file with a new file name.
Exit:	Terminate the programme.
	The user will be asked to save the input file before exiting !
Edit / Copy table Ctrl+C	Copy the selected results in the table to the clipboard (ref. Table in Figure B2). The results can then be pasted to a spreadsheet.
	If the upper left corner cell of the table is selected, the entire table will be copied to the clipboard. A selection of the table may also be copied. The table contains all input parameters used in the calculation.
Edit massflow / Edit velocities	A toggle option. If "Edit mass flow" is an option in the menu, then the "Edit velocities" option is active and vice versa. The "Edit mass flow/Edit velocities" option rules the following relation:
	Edit mass flow: The liquid and gas velocities will be changed corresponding to the mass flow, void fraction, pipe diameter and liquid and vapour density.
	Edit velocities: The mass flow and void fraction will be changed corresponding to the superficial velocities, pipe diameter and liquid and vapour density.
Parameter study	Loads the parameter study window. The parameter study is based on the input data in the main input window. However, the input data in the main window are overruled by any parameter set in the parameter study window. The parameter study is described separately
Goal Seek	The "Goal seek" option is described separately. (B.3.4)
Calculate:	If the Calculate button is pressed, a calculation for the current input data is performed. The results will immediately be displayed in the table in the lower part of the screen. The table displays the results as well as all input data used. The table can easily be copied to spreadsheets for documentation.
	Note: Saving studies can only be performed by using the "Copy Table" command and then paste the results to other applications!

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B.3.1 Editing the input

The input data are entered into input boxes in the main window. To move between the boxes, the **Tab-key** or the **Mouse** must be used.

If input data are "out of range" the error is detected when the user moves the cursor away from the input-box. The input box will then be painted red and a flashing text will display: "The last input is out of bounds". If the user wishes, calculations with "data out of range" can still be performed.

B.3.2 Presentation of results

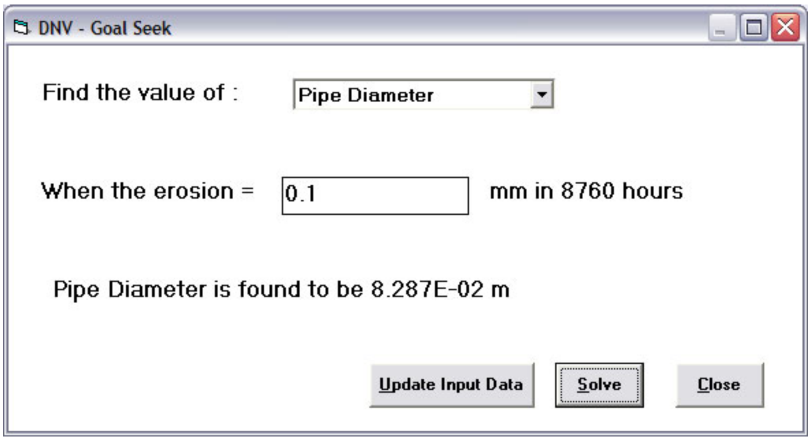
The results are presented in the result table in the lower part of the main input window. The most recent result is shown on the bottom of the list. The results are presented as erosion for the "Time" specified and as erosion rate in mm per year. The result table also shows all input variables used for the calculation as a quality assurance and/or a log.

B.3.3 Help

The PC-programme offers on-line help. The help file can be called any time during programme execution by pressing the F1-key or the Help-icon in the Program Manager. The help file have a simple explanation of parameters and the menu options.

B.3.4 Goal Seek

Goal Seek is an option in the main input window. The Goal Seek option is designed for calculation of one selected input parameter by setting the allowed erosion rate. The goal seek calculation is based on the input data specified in the main window. The Goal Seek window is shown in Figure B3



DNV - Goal Seek

Find the value of : Pipe Diameter

When the erosion = 0.1 mm in 8760 hours

Pipe Diameter is found to be 8.287E-02 m

Figure B3 The Goal seek window

Example:

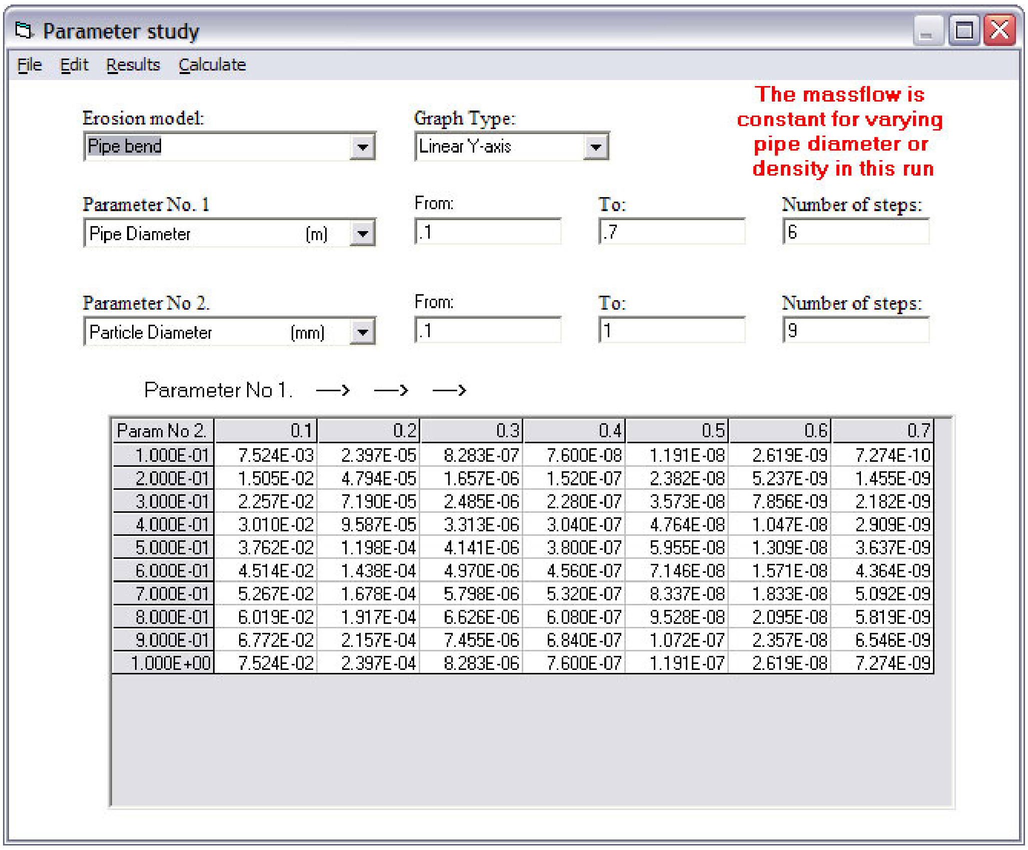
In Figure B3 the “Pipe Diameter” is selected as the parameter to optimise. The allowed erosion is 0.1 mm in 1 year (8760 hours). After having pressed the Solve button, the pipe diameter is found for the input data specified in the main window.

Update Input Data:

Copy the goal seek result to the main window. The result of the goal seek is not saved, so the user should either note the result or use the **“Update Input Data“**.

B.4 Parameter Study

In **Parameter Study** the effect of variation of one or two parameters can be examined. The results are presented in a table and a graph.



Erosion model: Pipe bend

Graph Type: Linear Y-axis

The massflow is constant for varying pipe diameter or density in this run

Parameter No. 1: Pipe Diameter (m) From: .1 To: .7 Number of steps: 6

Parameter No 2.: Particle Diameter (mm) From: .1 To: 1 Number of steps: 9

Parameter No 1. —> —> —>

Param No 2.	0.1	0.2	0.3	0.4	0.5	0.6	0.7
1.000E-01	7.524E-03	2.397E-05	8.283E-07	7.600E-08	1.191E-08	2.619E-09	7.274E-10
2.000E-01	1.505E-02	4.794E-05	1.657E-06	1.520E-07	2.382E-08	5.237E-09	1.455E-09
3.000E-01	2.257E-02	7.190E-05	2.485E-06	2.280E-07	3.573E-08	7.856E-09	2.182E-09
4.000E-01	3.010E-02	9.587E-05	3.313E-06	3.040E-07	4.764E-08	1.047E-08	2.909E-09
5.000E-01	3.762E-02	1.198E-04	4.141E-06	3.800E-07	5.955E-08	1.309E-08	3.637E-09
6.000E-01	4.514E-02	1.438E-04	4.970E-06	4.560E-07	7.146E-08	1.571E-08	4.364E-09
7.000E-01	5.267E-02	1.678E-04	5.798E-06	5.320E-07	8.337E-08	1.833E-08	5.092E-09
8.000E-01	6.019E-02	1.917E-04	6.626E-06	6.080E-07	9.528E-08	2.095E-08	5.819E-09
9.000E-01	6.772E-02	2.157E-04	7.455E-06	6.840E-07	1.072E-07	2.357E-08	6.546E-09
1.000E+00	7.524E-02	2.397E-04	8.283E-06	7.600E-07	1.191E-07	2.619E-08	7.274E-09

Figure B4 The parameter study window

The menu options in the parameter study are:

File / Close	Close the parameter study. The results from the parameter variation will be lost unless the graph or resulting table is copied into the clipboard or other applications.
Edit / Copy table	Copy the table to the clipboard.
Results / Graph	Calculate and present the results in a graph. The y-axis may either be displayed linearly or logarithmic (default). The results are also presented in the result table.
Calculate	Calculate and present the results in the result table.

B.5 The Parameter Study graph

The Parameter Study results can be presented in a graph with a linear or logarithmic y-axis.

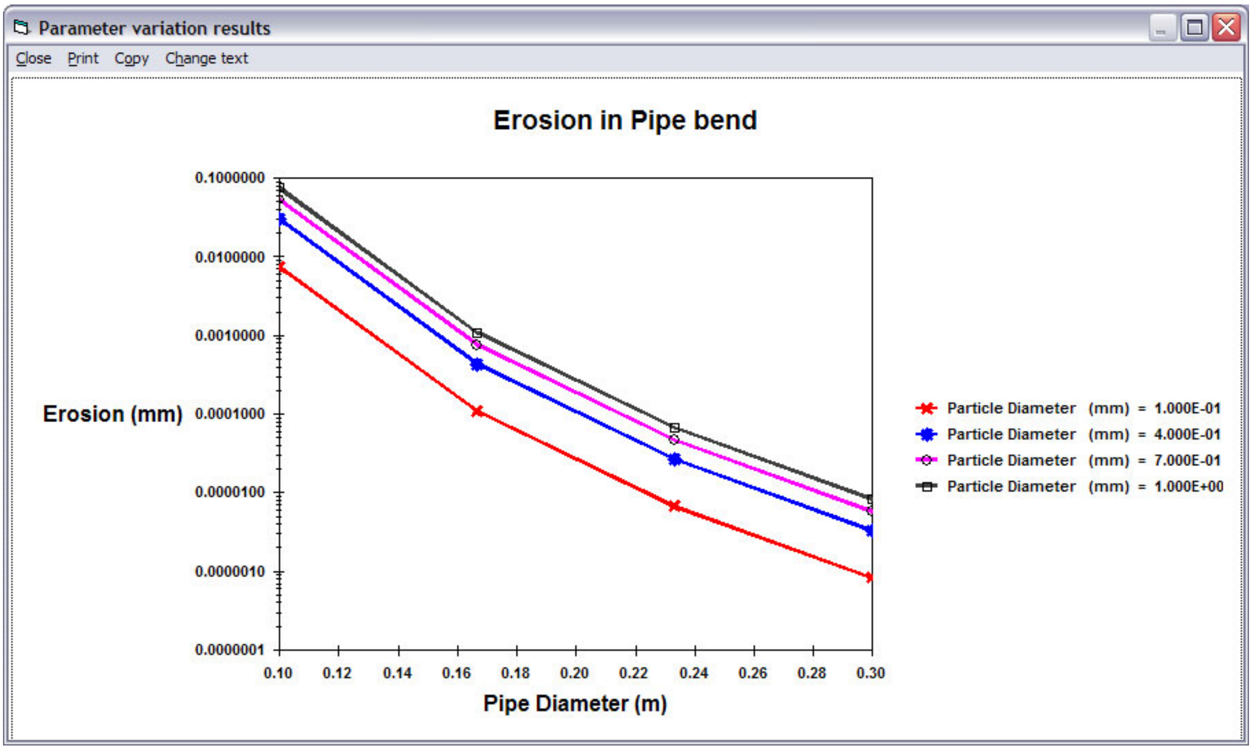


Figure B5: Graphical result from parameter study (logarithmic)

The menu options in the parameter graph are:

Close	Close the parameter graph. The graph can not be saved, but it can be copied to the clipboard or printed directly before closing it.
Print	Print the graph on the default printer.
Copy	Copy the graph to the clipboard. It can then be pasted into other applications.
Change text	Change the text and size of text in the graph.

B.6 Input value dependencies

Some of the input data depend on other input values. The user can set the dependency between some input data by use of the options "Edit velocities" or "Edit massflow".

The dependencies between variables are presented in the following table:

Option selected**	When these input data are changed	These will be updated*
Edit velocity	Superficial liquid velocity Superficial gas velocity Pipe diameter Liquid density Gas density	Total mass flow Volume fraction gas
Edit mass flow	Total mass flow Volume fraction gas Pipe diameter Liquid density Gas density	Superficial liquid velocity Superficial gas velocity

* The input boxes for the updated parameters will be grey.

** With one input option active, the opposite option is available in the menu.

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