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Erosion of oil&gas industry choke valves using computational fluid dynamics and experiment

Lars Nøkleberg [a,*], Terje Søntvedt [b]

[a] ABB Corporate Research, PO Box 90, N-1361 Billingstad, Norway
[b] Norsk Hydro ASA, PO Box 200, N-1321 Stabekk, Norway

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Abstract

As part of several years research activity with erosion in chokes, Norsk Hydro ASA has developed a model to estimate erosion and lifetime of chokes by incorporating erosion models into particulate flow models. This model has been verified with the results from flow and erosion testing of two different types of chokes, Needle&Seat and External Sleeve. The erosion tests with both the modified Needle&Seat choke and the External Sleeve choke gave peak erosion rates only two or three times larger than calculated. This is assumed to be near the uncertainty of the erosion model alone. This is very satisfactory for such complex flow geometries. The model and the experiments demonstrated that the External Sleeve choke is much more prone to erosion attack, at the given low pressure conditions.

Keywords: Erosion; Choke valves; Computational fluid dynamics; Oil and gas industry

1. Introduction

For production of oil and gas, choke valves on each well are used to balance the pressure of each well into a common manifold. The well stream is normally a mixture of oil, gas and water, which may contain sand particles. For large pressure reductions, up to sonic velocities can be reached within the chokes. Extensive erosion is then often experienced. The expense and lost production associated with choke trim replacements will normally be high, specially for subsea location of the chokes.

As part of several years research activity with erosion in chokes, Norsk Hydro ASA has developed a model to estimate erosion of chokes by incorporating an erosion model into a particulate flow model for:

- choke lifetime predictions for a given design,
- optimising choke geometry to reduce erosion.

This model has been verified with the results from flow and erosion testing of two different types of chokes, the modified Needle&Seat choke and the External Sleeve choke.

Also a liquid droplet erosion model is included into the particulated flow model (Nøkleberg and Søntvedt, 1995). This article, however, will only consider erosion by solids.

2. Numerical model for particulated flow and erosion

2.1. Flow model

The particulated flow version of Fluent (Ref. Fluent user's manual, 1997) has been used to simulate the fluid flow and erosion in the chokes. Fluent is a CFD (Computational Fluid Dynamics) program for modelling fluid flow, heat transfer, chemical reaction and the trajectories of dispersed particles/droplets. It is one of 3 or 4 widely used numerical simulation programs for fluid flow.

For flow in the continuous phase it solves the discretized Reynolds and continuity equations, together with transport equations for the turbulent energy and dissipation rates and the energy equation. Gas flow is treated as a compressible fluid using the ideal gas law. The simulation is based on the finite volume technique. The computational grid is generated as a bodyfitted grid. This permits an accurate representation of the actual geometry in the simulations. The grid representing the choke geometry was based on drawings of the two different chokes.

2.2. Droplet/particle trajectories

Simulation of particle trajectories and erosion requires knowledge of the flow pattern (velocity field) through the chokes.

The trajectory of a dispersed liquid droplet or solid particle is predicted in Fluent by integrating the force balance on the particle. A Lagrangian trajectory calculation with stochastic tracking has been used to account for the effect of local

* Corresponding author. E-mail: lars.noekleberg@nocrc.abb.no

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turbulence quantities predicted in the continuous phase (K–ε model).

The forces on the particles are:
- Drag force,
- Gravity,
- "Virtual mass" force,
- Force due to the pressure gradient of the fluid.

In the simulations several thousand particle (∼10,000) trajectories were calculated in order to obtain a good statistical characterisation of the particulate flow and resulting erosion. Increasing the number of particle trajectories further did not yield a significant change in the erosion distribution. Each "particle" represents a proportion of the total mass flux. The erosion is calculated from the particle impact velocity and angle as it hits the wall, as described in Section 2.3. Effects from several impacts at the same position are summed (Utvik et al., 1994).

2.3. Erosion by solid particles

The most critical wear mechanism in chokes is erosion by solid particles. The following erosion model has been added into the solution software (Hutchings, 1984):

$$E = K_m m_p f(\alpha_p) V_p^n,$$

where E is the erosion rate (kg/s), m_p the particle flux (kg/s), K_m the material constant $(m/s)^{-n}$, α_p the particle impact angle (°), $f(\alpha_p)$ the function of impact angle (–), V_p the particle impact velocity (m/s) and n the velocity exponent, normally between 2.5 and 3.0.

The surfaces in the choke are modelled as steel, as used in the actual test chokes. For steel, a large number of erosion tests at different impact velocities and angles have been performed over many years, leading to well-known erosion behaviour and therefore good test results for verification of the particulated flow model. The material constant giving the best fit (within a factor of about two), together with other parameters pertaining to the erosion model, is specified in Table 1 (Søntvedt, 1989).

3. Erosion tests – experimental conditions

The tests were performed by DNV (Det Norske Veritas) in a test facility specially built for these tests, see Fig. 1. The chokes were tested with sonic flow conditions of air and sand. A compressor supplied the air. Transmitters for pressure, temperature and gas flow rate were used to control the flow conditions in the chokes.

The test conditions for the chokes were:
- Gas – Air,
- Inlet pressure 6 bar,
- Outlet pressure 2 bar,
- Inlet temperature 60–70°C,
- Inlet pipe diameter 88.7 mm,
- Solid particles 0.28 mm particle size, fresh silica sand, maximum mass fraction 0.04,
- Choke internal materials of Stainless Steel (tests were also performed with Tungsten Carbide and PolyCrystalline Diamond (Needle&Seat choke)).

Recordings of the material loss in the choke internals were performed with weight loss and, profile measurements before and after the erosion testing. The accuracy of the profile measurements was approximately ±10 μm.

Table 1
Input to model – erosion data for steel

Material constant, K_m	1.8×10^{-9}
Velocity exponent, n	2.62
Function of impact angle, $f(\alpha_p)$	Linear from 0–1 (for impact angles 0–20°) Linear from 1–0.3 (for impact angles 20–90°)

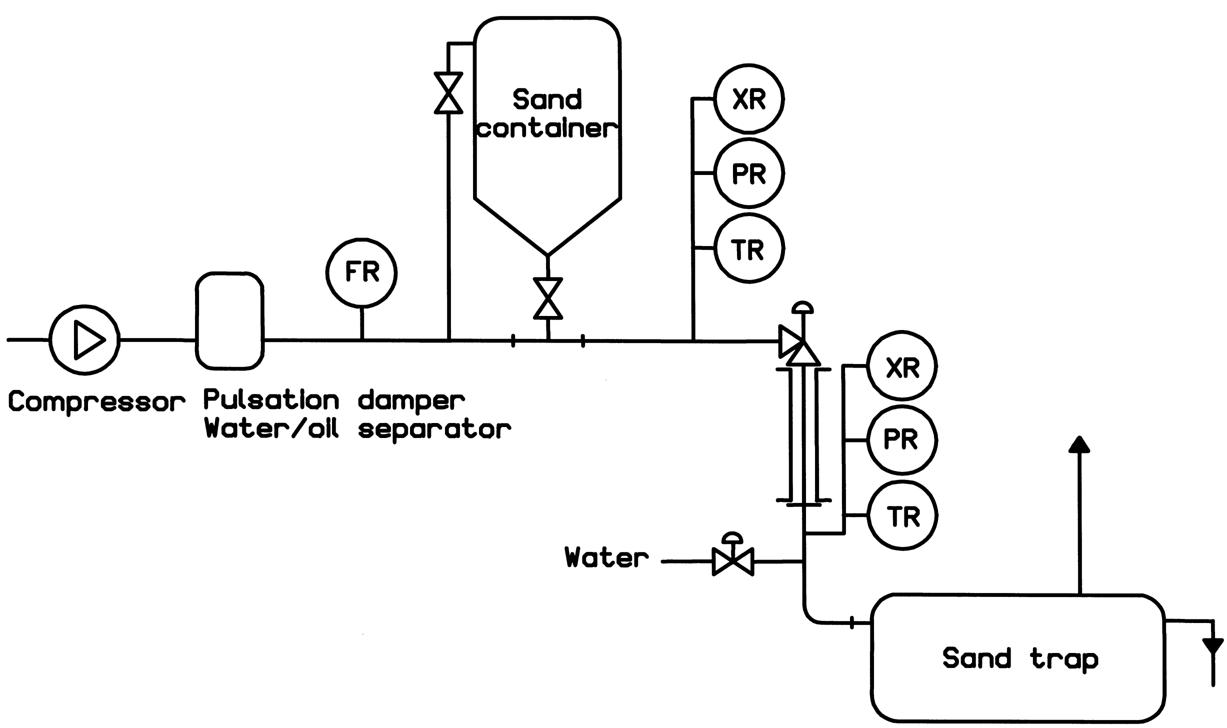

Fig. 1. Test loop for low pressure tests.

4. Results from the simulations – needle&seat choke

This choke design had been optimised with respect to internal erosion as part of a Joint Industry Project which was initiated in 1993, using this numerical flow model. A prototype was designed and fabricated using the results from previous testing by DNV (Haugen et al., 1995) and detailed flow and erosion simulations (Nøkleberg and Søntvedt, 1995), see Fig. 2.

The 3-dimensional grid representing the modified needle and seat choke comprised 99,750 control volumes. Symmetry made it sufficient to model a 180° slice of the choke geometry. One grid was generated, with a relative open flow area of 25%, see Fig. 3.

The simulations of the modified needle and seat choke were carried out for the same conditions as in the erosion test rig.

The simulations displayed the following general features:

- Sonic gas flow in the throat section.
- Supersonic gas flow downstream the throat section (max. velocity = 600 m/s).
- Small solid particle impact angles (0–10°).
- Solid particle erosion in both the seat area and on the needle was low (max 4 μm/kg sand).
- The predicted asymmetry of erosion was small.

4.1. Comparison with experiments.

The calculated and measured flow rate are shown in Table 2. The results from the simulations of erosion are shown in Figs. 4–6, as maximum solid particle erosion loss along the length. As seen the calculated erosion fits well with the test result for the seat area, outlet pipe and needle. The best fit with the erosion tests was achieved when adjusting the velocity restitution factor after wall impacts (normal velocity ratio) to 90–95%. A similar result was found by Utvik et al. (1994), when simulating flow and solid particle erosion in a pipe bend

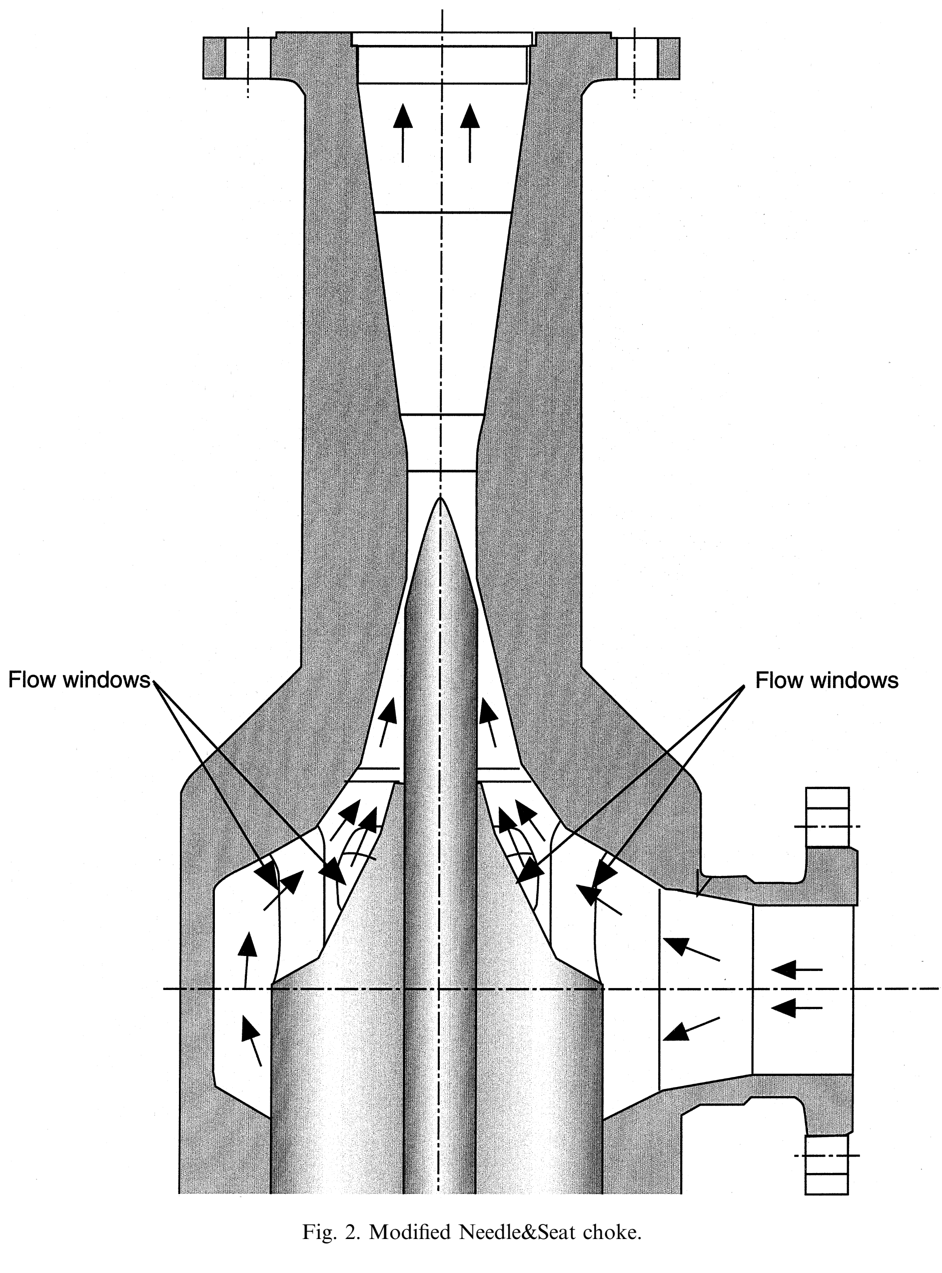

Fig. 2. Modified Needle&Seat choke.

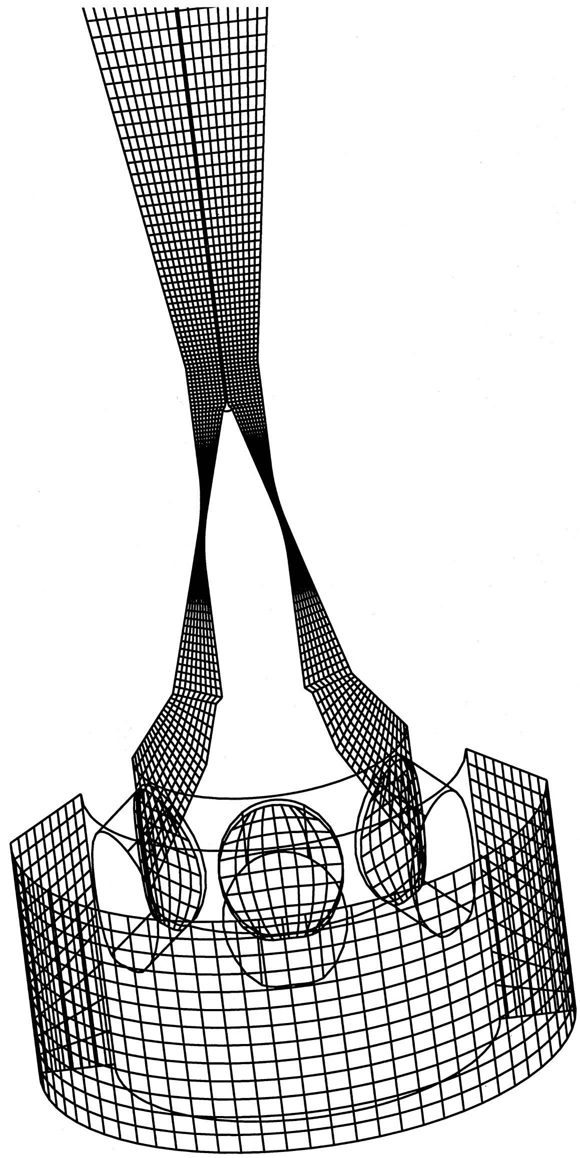

Fig. 3. Grid – modified Needle&Seat choke.

with the same basic software, and comparing with erosion tests.

4.2. Results from the simulations – external sleeve choke

The External Sleeve choke, which has been widely used for several years, has been designed such that several high velocity fluid jets impinge on each other. One important objective of this design is to reduce erosion by reducing the particle impact velocities on the choke internal surfaces, see Fig. 7.

The 3-dimensional grid representing the External Sleeve choke comprised 103,360 grid cells. Four grids were generated, with relative open flow areas of 10%, 12.5% (half of the '25% open' holes blocked), 25% and 50%, see Fig. 8. The flow simulations of the external sleeve choke were carried out for the same conditions as in the erosion test rig. Three different choke openings were simulated with flow, particle tracking and erosion: 10%, 12.5% and 25% open. In addition the flow field was simulated for 50% choke opening. A velocity restitution factor after wall impact (normal velocity ratio) of 90% was used.

Table 2
Measured and calculated mass flow rates for the Needle&Seat Choke

Nominal % open	25%
Measured mass flowrate (kg/s)	0.26–0.27
Computed mass flowrate (kg/s)	0.31

4.3. Comparison with tests

The calculated and measured flow rates are shown in Table 3. In Table 4 the measured and calculated maximum erosion inside the cage are shown.

Visual observations showed the formation of sand beds in the inlet pipe and choke gallery during the test. To avoid circulation of particles and formation of beds in the choke gallery in the simulations, the particles were injected with a similar concentration some distance outside the holes in the cage, where the fluid velocities were low compared to the velocities through the holes. For field conditions the higher fluid density will reduce or eliminate this problem.

The results from the simulations are shown in Figs. 9–11, as maximum solid particle erosion loss inside the steel cages along the length. Erosion losses in the outlet pipe are shown in Fig. 12, where the difference between calculation 1 and 2 is related to the stochastic particle tracking which account for the effect of local turbulence.

5. Discussion

In simple flow geometries such as bends, the impact velocities and impact angles of solid particles can relatively easily be determined with a reasonable accuracy. Then predictions of erosion are quite simple, using the method described in section 'Erosion By Solid Particles' directly. The design of chokes, however, has been optimised over a period of many years to reduce erosion as much as possible. For example the External Sleeve choke which had been expected to be very erosion resistant, has been designed such that several high velocity fluid jets impinge on each other.

To restrict the total number of grid cells, only four grid cells were used in the cross-section of each hole in the cage (External Sleeve Choke). This is not enough to get a good representation of the flow pattern through these holes. Faster computers are required however, if more detailed grids are to be simulated with acceptable computing times. It is therefore very difficult to calculate the erosion rate in such complex flow geometries as chokes. As CFD moves towards a more widespread use of unstructured grids, a better representation of the flow in chokes can be obtained.

Nevertheless, the erosion tests in both the modified Needle&Seat choke and the External Sleeve choke gave peak erosion rates only 2–3 times larger than calculated. This is near the uncertainty of the erosion model alone. Other uncertainties are particle sharpness and reflection velocities after several impacts in the chokes. The predicted behaviour is thus very satisfactory for such complex flow geometries, especially since there was such a large difference in the maximum erosion rate for the two types of chokes for the same test condition. The main reason for this difference is that the smooth geometry of the modified Needle&Seat choke gives very low particle impact angles, compared with the External Sleeve choke.

Also the fact that a standard commercial CFD code succeeded in calculating the flowrate through the choke quite well, improves confidence in the erosion calculations.

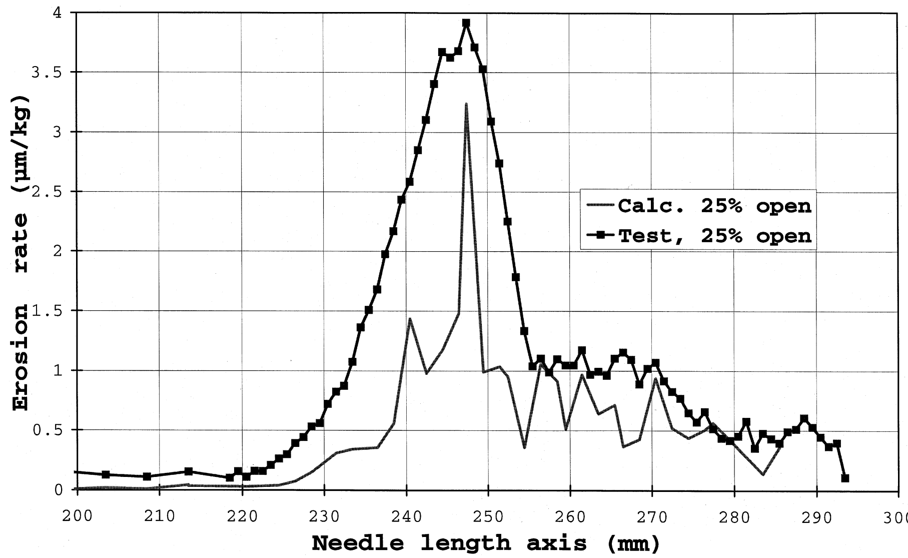

Fig. 4. Max. erosion on steel needle along length axis, modified Needle&Seat Choke (25% open).

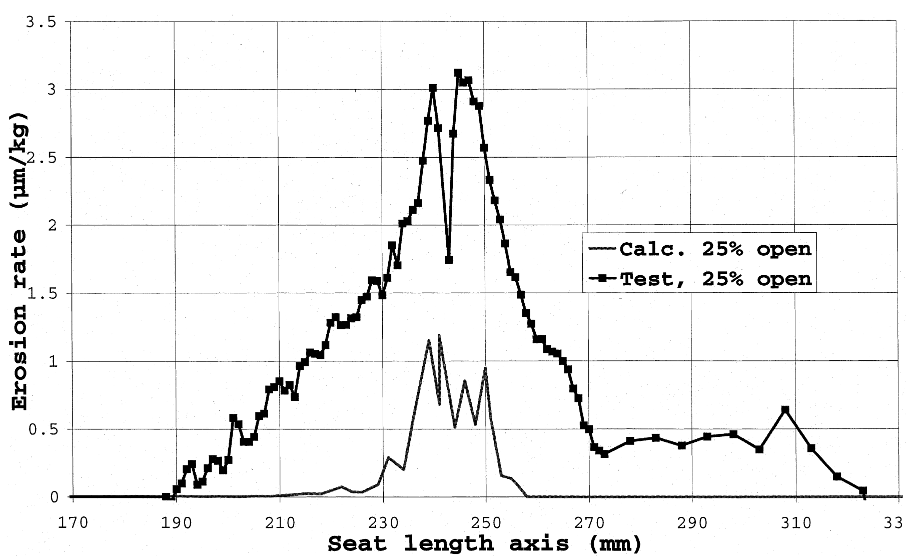

Fig. 5. Max. erosion inside steel seat along length axis, modified Needle&Seat Choke (25% open).

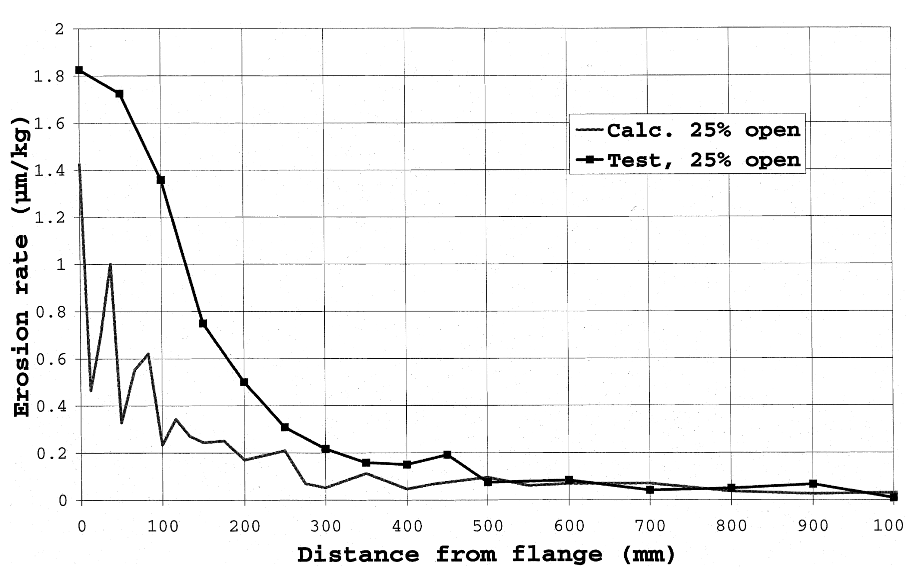

Fig. 6. Max. erosion in outlet steel pipe along length axis, modified Needle&Seat Choke (25% open).

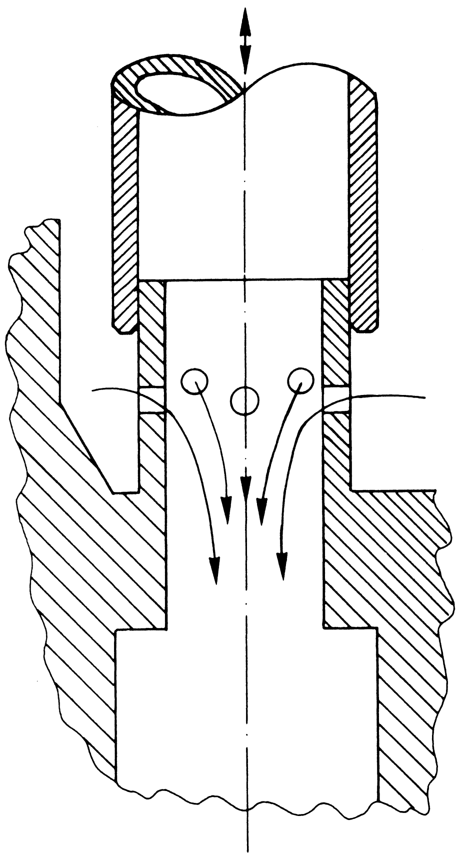

Fig. 7. External sleeve choke.

Table 3
Measured and calculated mass flow rates for the External Sleeve Choke

Nominal % open	10%	25%	50%
Measured mass flowrate (kg/s)	Not measured	0.088	0.24
Computed mass flowrate (kg/s)	0.047	0.14	0.28

Table 4
Measured and calculated maximum erosion inside the steel cage – External Sleeve Choke

Choke opening	Measured max. erosion (μm/kg)	Calculated max. erosion (μm/kg)
10%	226	143
12.5%-blocked	650	517
25%	161	79.2

6. Conclusions

Extensive erosion in chokes can lead to very short lifetimes. The model developed for erosion in chokes has successfully been verified with experiments.The erosion tests with both the modified Needle&Seat choke and the External Sleeve choke gave peak erosion rates only 2–3 times larger than calculated. This model has been used in Norsk Hydro ASA to:

- optimise the design of a Needle&Seat choke, giving 50–100 times reduction in erosion,
- estimate expected choke lifetime for new installations and determine safe operation criteria.

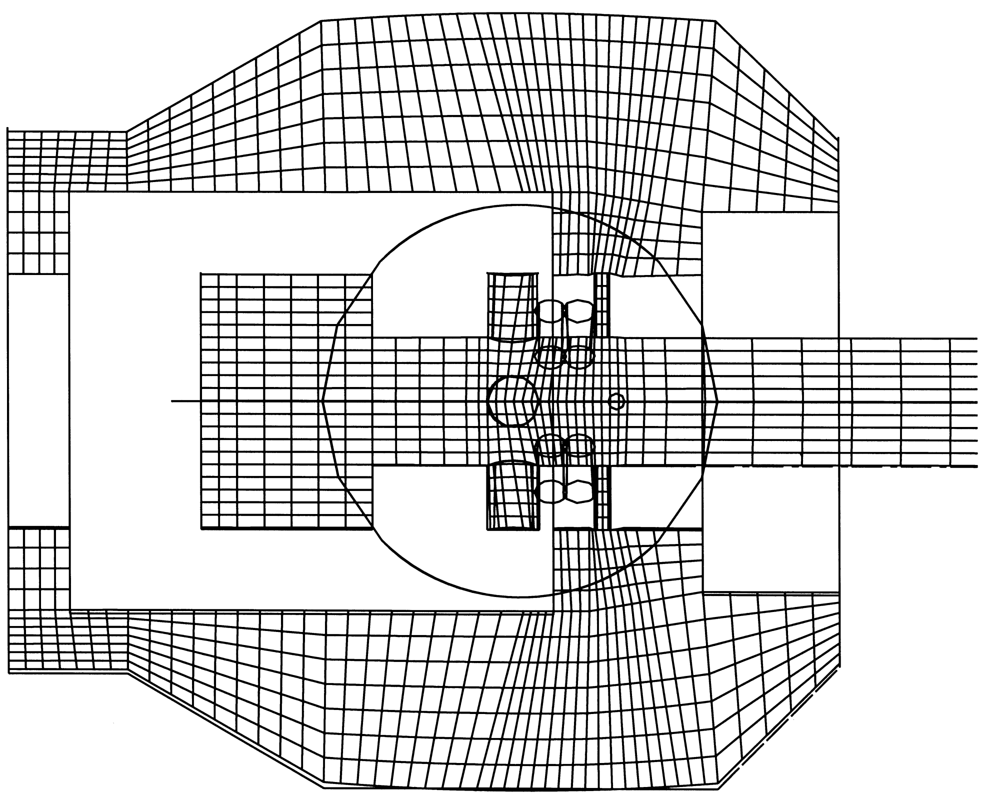

Fig. 8. Grid – external sleeve choke.

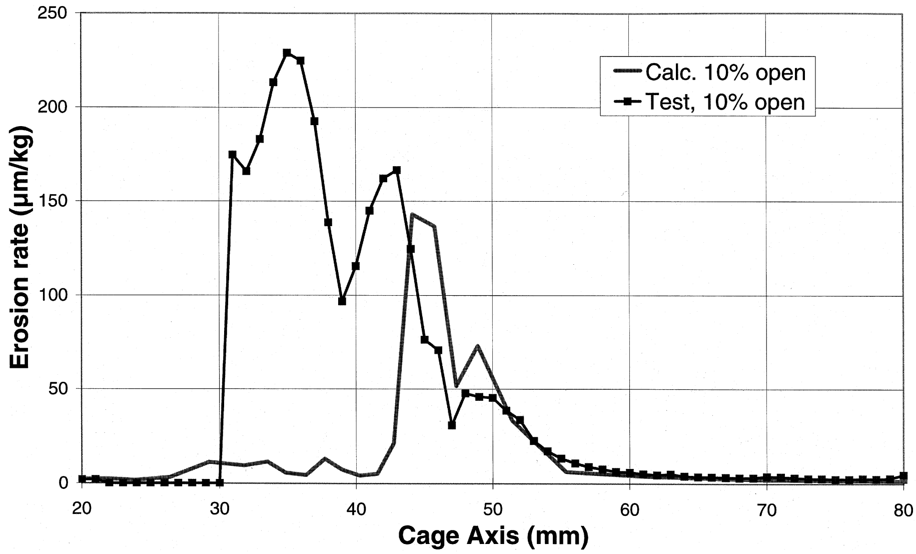

Fig. 9. Max. erosion inside steel cage along length axis, external sleeve choke (10% open).

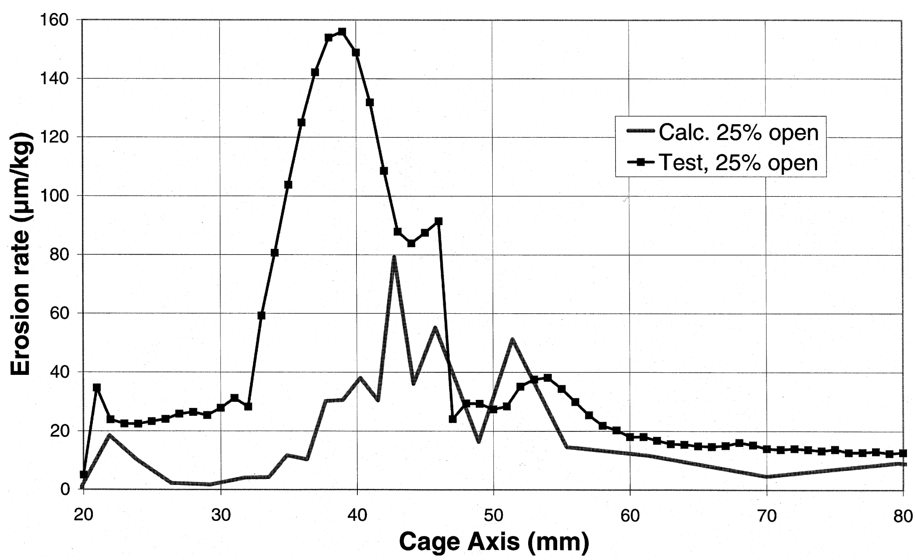

Fig. 10. Max. erosion inside steel cage along length axis, external sleeve choke (25% open).

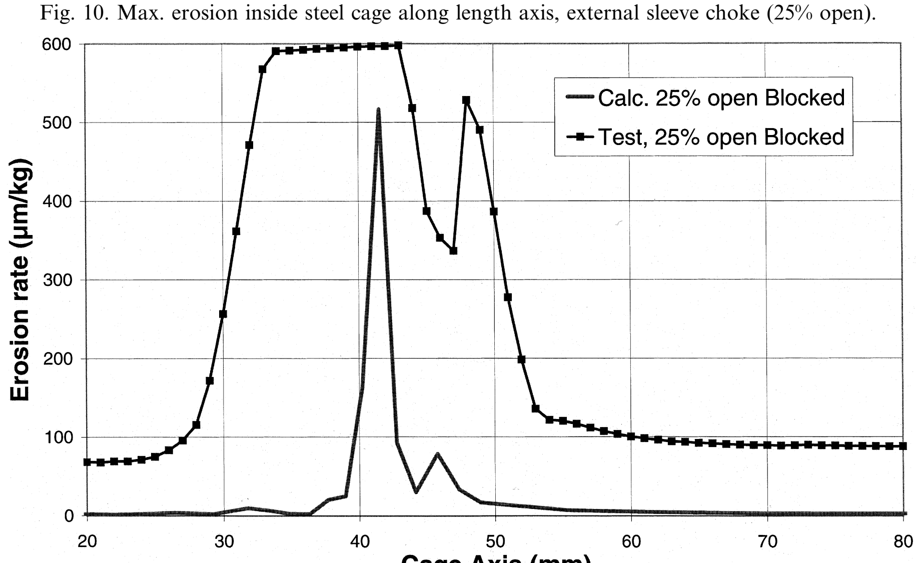

Fig. 11. Max. erosion inside steel cage along length axis, external sleeve choke (25% open Blocked).

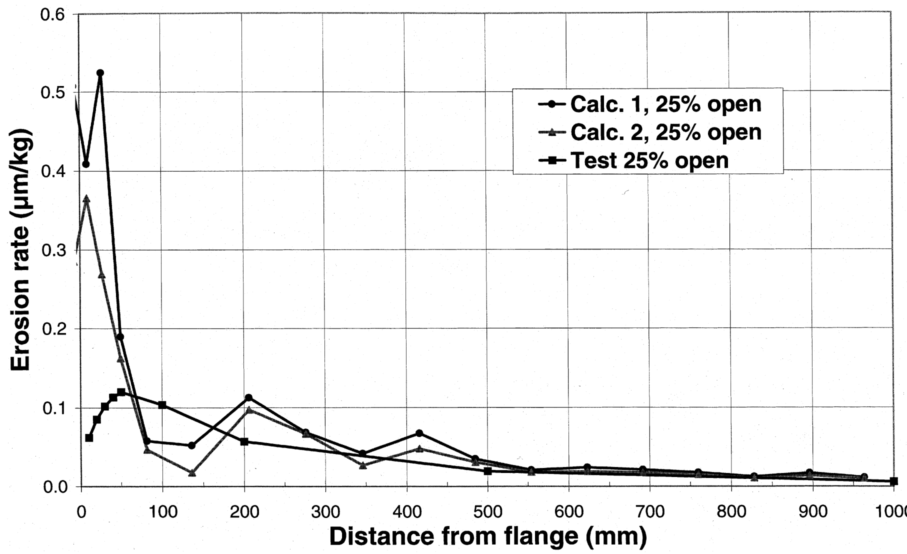

Fig. 12. Max. erosion in outlet steel pipe along length axis, external sleeve choke (25% open).

The model can also be valuable in optimising the design of External Sleeve chokes (and other choke types), due to a better understanding of the internal flow pattern and particle motion.

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