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Simulation of Particle Erosion in a Hydraulic Valve

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Abstract. This paper presents an attempt of simulation particle erosion in a hydraulic flow control valve. A simulation of particle behavior during fluid flow was conducted in the Ansys CFX general purpose CFD code using two phases of flow: hydraulic fluid and solid particles. Simulations were performed for two types of particle material, steel and sand, and Finnie's model of erosion wear was applied. As a result of CFD simulations, particle trajectories were obtained as well as erosion rate on valve components for both particle materials. The obtained results made it possible to compare the influence of particle material on erosion wear in the flow control valve and components of valve which are exposed to particle erosion.

Introduction

Contamination of hydraulic fluid is one of the most common cause of hydraulic system failures. It is estimated that around 70% up to 90 % of total failures of hydraulic systems is caused by contamination of hydraulic fluid. Contaminants might be classified into two groups: particles (solid parts as a result of wear or dirt ingression) and chemical (water, air). Four sources of contamination might be distinguished:

1. Built in contamination: a result of assembly of hydraulic system.
2. Ingressed contamination, which can enter into fluid in a reservoir from air or from a hydraulic cylinder rod (sealing of a hydraulic cylinder cannot protect totally against particles) or during maintenance or repairing when a hydraulic line is disconnected.
3. Contamination of new hydraulic fluid, which might be caused by storage process or take place during manufacturing.
4. Contamination generated directly in a hydraulic system. Such contaminants may appear in the system as a result of abrasive wear, when loose particles are removed from metal and taken by the fluid. Another way in which contaminants can get into fluid is adhesive wear, when parts adhere and surfaces are damaged during relative motion due to the lack of oil film on moving parts. In parts under high structural loads, fatigue cracks may appear, which can be also a source of fluid contamination. Additionally, fluid which includes air and falls below saturation pressure during operation pressure may cause cavitation wear, which is also recognized as a source of internal contamination. Corrosive wear and erosion (particle in fluid erode surfaces of hydraulic components) are also internal contaminants.

Hydraulic fluids cannot be fully prevented against contaminations even by installing sophisticated filtration systems. However, hydraulic fluid may be classified for specific applications by controlling the size and amount of contaminants. Some applications of hydraulic systems do not require high

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cleanliness of working fluid like others. For example, hydraulic drive systems may include more particle contaminants than hydraulic control systems. Currently, the valid ISO 4406:1999 code defines cleanliness of hydraulic fluids as a number and size of particles in 1 [cm^3] of fluid. Figure 1 shows the difference between a selected class of cleanliness of hydraulic oil. The left picture shows fluid which contains 10e3-20e3 particles greater than 4 [μm] and 2.5e3-5e3 particles greater than 6 [μm] and 0.64e3-1.3e3 particles greater than 14 [μm]. The right picture shows hydraulic oil which includes 0.64e3-1.3e3 particles greater than 4 [μm], 80-160 particles greater than 6 [μm] and 10-20 particles greater than 14 [μm].

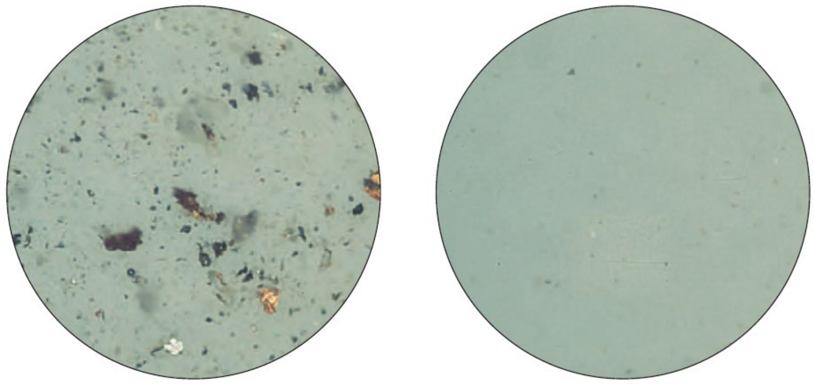

Fig. 1. Cleanliness of hydraulic oil according to the ISO 4406 code [1]
left: ISO 21/19/17, right: ISO16/14/11.

Solid particles in hydraulic oil during fluid flow gather momentum from fluid and may erode critical component surfaces which may lead to component failure or significant reduction of its lifetime. Therefore, prediction of wear caused by solid particles during flow is a more and more important feature. Erosion phenomenon is a complex task and has been investigated for decades, mostly by means of experimental tests [1], [2]. With the expansion of simulation tools and methods, including computational fluid dynamics (CFD), simulation of flow of fluid which includes solid contaminations (particles) is more and more often used. In case of hydraulic components, such attempts are also conducted. Y. Yaobaoa, Y. Jiayanga, G. Shengrongb [4] combined a CFD tool and MATLAB to resolve particle trajectory to predict erosion and worn profile of a hydraulic spool control valve.

This paper presents an attempt to predict erosion wear on a flow control valve using the Ansys CFX general purpose CFD code and an implemented erosion model.

Erosion model

The wear caused by the impact of solid particles on walls for almost all metals is a function of impact angle and particle velocity [5]:

$$E = kV_p^n f(\gamma) \tag{1}$$

where:

E - dimensionless mass (mass of eroded wall material divided by the mass of particle), V_p – particle velocity, n –exponent value which for metals is between 2.3 and 2.5, $f(\gamma)$ - function of impact angle.

The Finnie model is one of the models that describe the rate of wear [6]:

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$$\mathrm{E} = \mathrm{k}\mathrm{V}_\mathrm{p}^2\mathrm{f}(\gamma) \tag{2}$$

where:

$$f(\gamma) = \frac{1}{3}cos^2(\gamma)\ if\ tan(\gamma) > \frac{1}{3} \tag{3}$$
$$f(\gamma) = sin(2\gamma) - 3sin^2(\gamma)\ if\ tan(\gamma) > \frac{1}{3} \tag{4}$$

Tabakoff and Grant is another model which describes the erosion rate [7]:

$$E = k_1 f(\gamma) V_p^2 cos^2(\gamma)\,[1 - R_T^2] + f(V_{PN}) \tag{5}$$

where:

$$f(\gamma) = \left[1 + k_2 k_{12} \sin\left(\gamma \frac{\frac{\pi}{2}}{\gamma_0}\right)\ \right]^2 \tag{6}$$

$$R_T = 1 - k_4 V_p \sin(\gamma) \tag{7}$$

$$f(V_{PN}) = k_3\left(V_p \sin(\gamma)\right)^4 \tag{8}$$

$$k_2 = \begin{cases} 1.0\ if\ \gamma \le 2\gamma_0 \\ 0\ if\ \gamma > 2\gamma_0 \end{cases} \tag{9}$$

k_1, k_{12}-constants

Simulation of particles in continuous fluid in the CFD is treated as two phases flow: discreet one (particles) and continuous one (fluid). Discreet particles are tracked into a fluid domain during fluid flow. The equation of a motion for a single particle according to Basset, Boussinesq and Oseen may be presented in the following way:

$$m_p \frac{dU_p}{dt} = F_D + F_B + F_R + F_{VM} + F_P + F_{BA} \tag{10}$$

where: $\mathrm{F_D}$ – drag force, $\mathrm{F_B}$ – buoyancy force, $\mathrm{F_R}$ – Coriolis force, $\mathrm{F_{VM}}$- is inertia force of fluid occupied by particle (Virtual Mass), $\mathrm{F_P}$ – pressure force, $\mathrm{F_{BA}}$ – Basset force

The inertia force of fluid occupied by particle (Virtual Mass) is expressed by the following equation:

$$F_{VM} = \frac{C_{VM}}{2} m_F \left(\frac{dU_F}{dt} - \frac{dU_P}{dt}\right) \tag{10}$$

Transforming Eq. 10 we obtain:

$$\frac{dU_p}{dt} = \left(\frac{1}{m_p + \frac{C_{VM}}{2} m_F}\right)(F_D + F_B + F_R + F'_{VM} + F_P + F_{BA}) \tag{11}$$

where

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$$F'_{VM} = \frac{C_{VM}}{2} m_F (U_F \nabla U_F) \tag{12}$$

Particle mass $\mathrm{m_P} = \frac{\pi}{6}\mathrm{d_P^3 \rho_P}$
Fluid mass $\mathrm{m_F} = \frac{\pi}{6}\mathrm{d_P^3 \rho_F}$
$\mathrm{d_p}$ is the particle diameter, ρ_P, ρ_F is density of particle and fluid respectively
Assuming that:

$$R_{VM} = \frac{m_P}{m_P + \frac{C_{VM}}{2} m_F} = \frac{\rho_P}{\rho_P + \frac{C_{VM}}{2}\rho_F} \tag{13}$$

Finally Eq. 10 has the following form:

$$\frac{dU_p}{dt} = \left(\frac{R_{VM}}{m_p}\right)(F_D + F_B + F_R + F'_{VM} + F_P + F_{BA}) \tag{14}$$

Object of study

The object of study is a flow control valve whose main function is to maintain constant flow rate independently on pressure on inlet and outlet port. The valve presented in Fig. 2 is manufactured by PONAR Wadowice as a proportional, solenoid control valve.

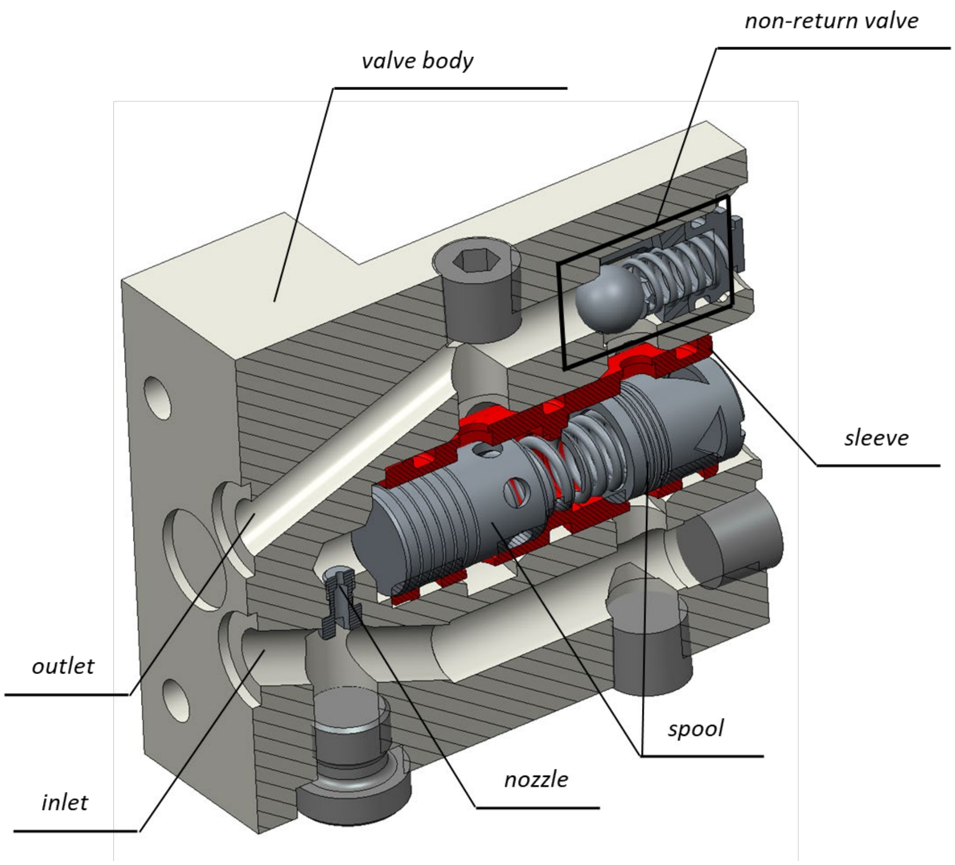

Fig. 2. Cross section of valve

Hydraulic oil flows at the inlet port to the valve, then through the holes in the sleeve inside and flows out to the outlet port by the holes at the spool. The position of the spool is determined by forces

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generated on it during flow and pressure drop at the nozzle. For simplification, fixed positions of spool were assumed without taking into consideration dynamic behavior of the valve components.

CFD simulations

Flow simulation was conducted in the commercial Ansys CFX general purpose CFD code, which uses the Finite Volume Method (FVM) for solving flow governing equations. For the numerical simulation, half of a valve model was used. Boundary conditions and a grid is presented in Fig. 3.

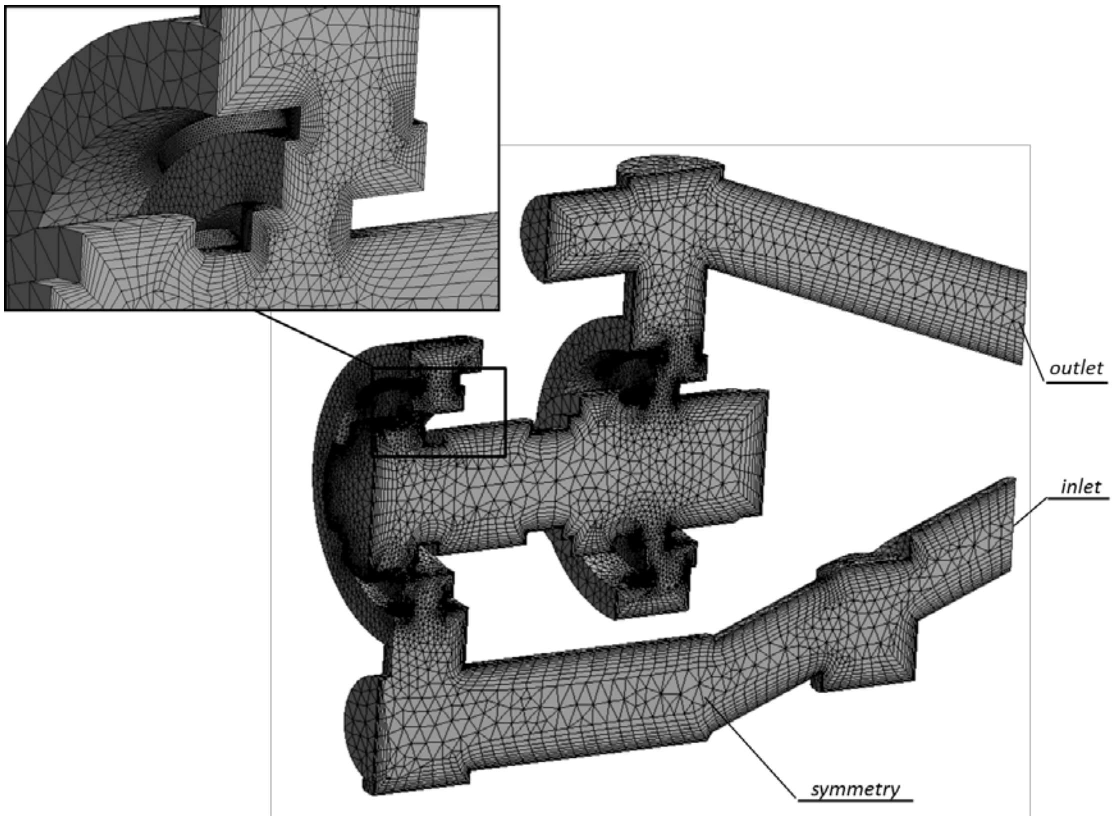

Fig. 3. CFD model: grid and boundary conditions

The CFD simulation was performed for a fixed component position for steady state conditions and for the following assumptions:

- Fluid (hydraulic oil) has the following constant properties: density 880 [kg/m^3], viscosity υ=40 [mm^2/s]
- Flow is turbulent: k-ϖ turbulence model was used,
- Model is in thermodynamic equilibrium, heat transfer is not included.
- Particles parameters have a uniform shape (spheres with a diameter of 20 [μm]) and constant properties, 20 particles in 1 [cm^3]
- Erosion model: Finnie.
- Interaction of particles and fluid is fully coupled.
- Simulations were performed for two particle materials: metal (steel) and sand.
- Particles are uniformly injected at the inlet to the valve.
- Half of a geometrical model was used in simulations.

The results of the CFD simulations are presented in the pictures below which show fluid velocity at a symmetry plane, trajectories of solid particles and erosion rate. Two types of solid particles were

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used in the CFD simulations to investigate erosion rate on the valve components for the same flow conditions. The results of steel particles are presented on the left side, sand particles on the right.

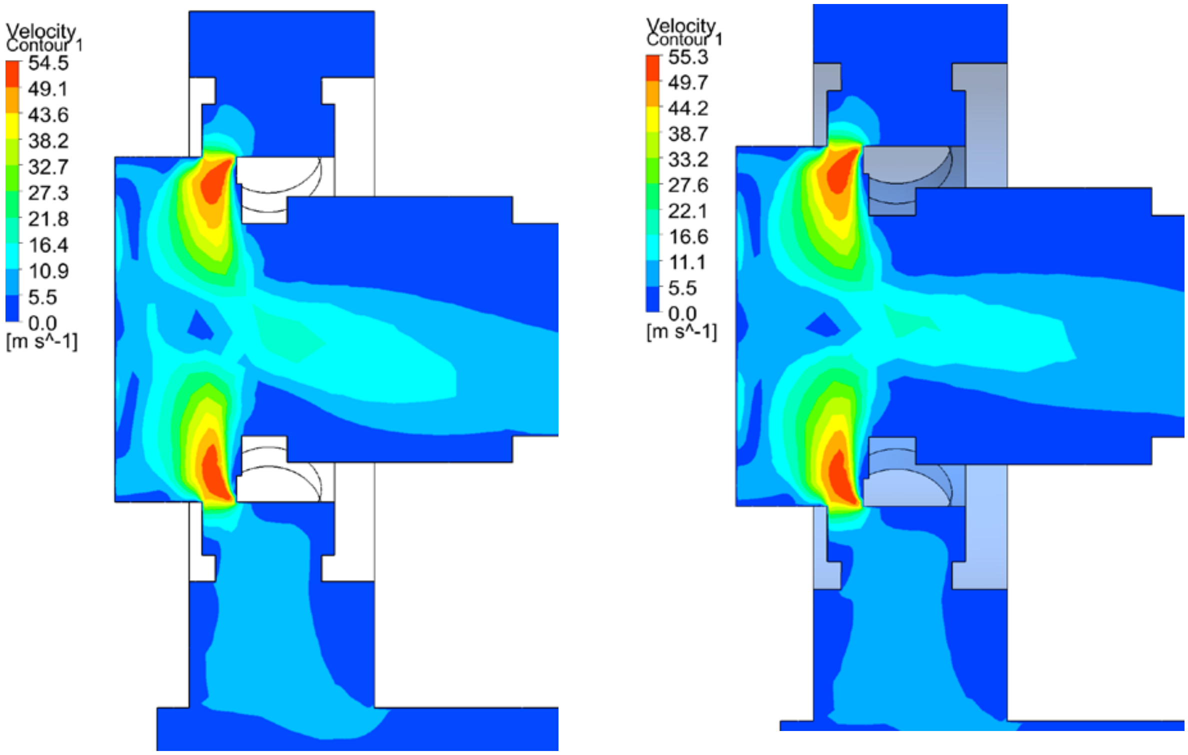

Fig. 4. Fluid velocity on a symmetry plane, right: steel particles, left: sand particles

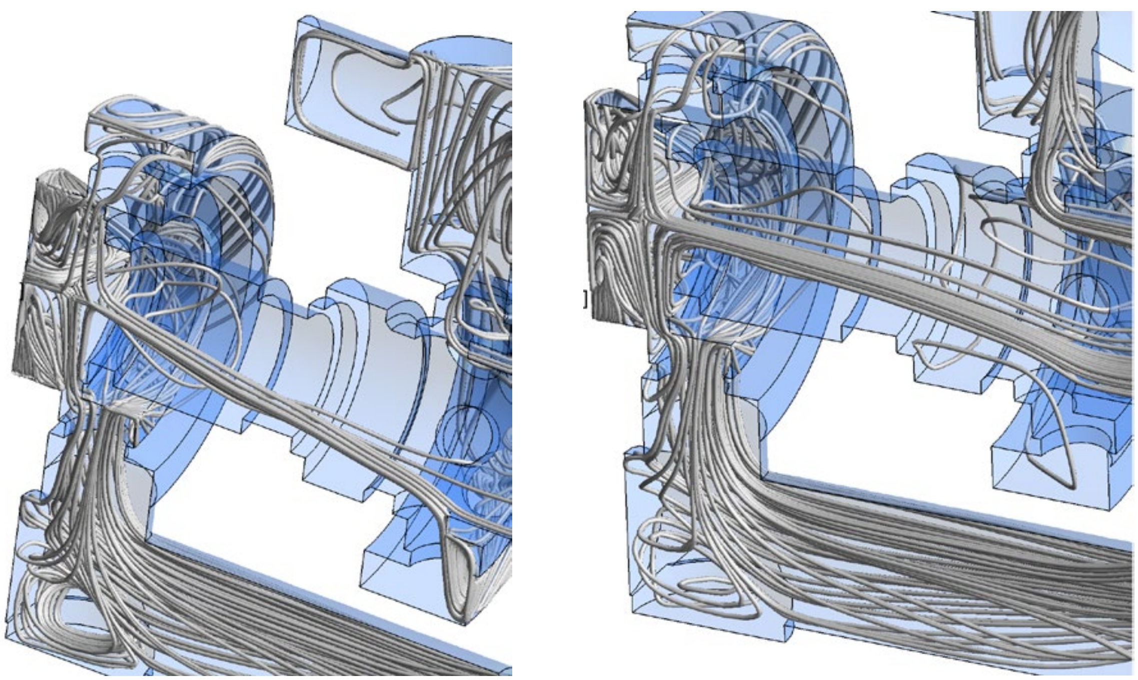

Fig. 5. Particle trajectory, right: steel particles, left: sand particles

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The results of simulations show that, for given particle size and number, the flow of fluid is almost not disturbed. Fluid velocity distribution in both cases looks almost the same for both materials of particles (Fig. 4.). However, there is a difference with captured trajectories of particles between steel and sand (Fig. 5.). It was also found that surfaces which are exposed to erosion wear do not differ much in both cases, which is shown in Fig.6.

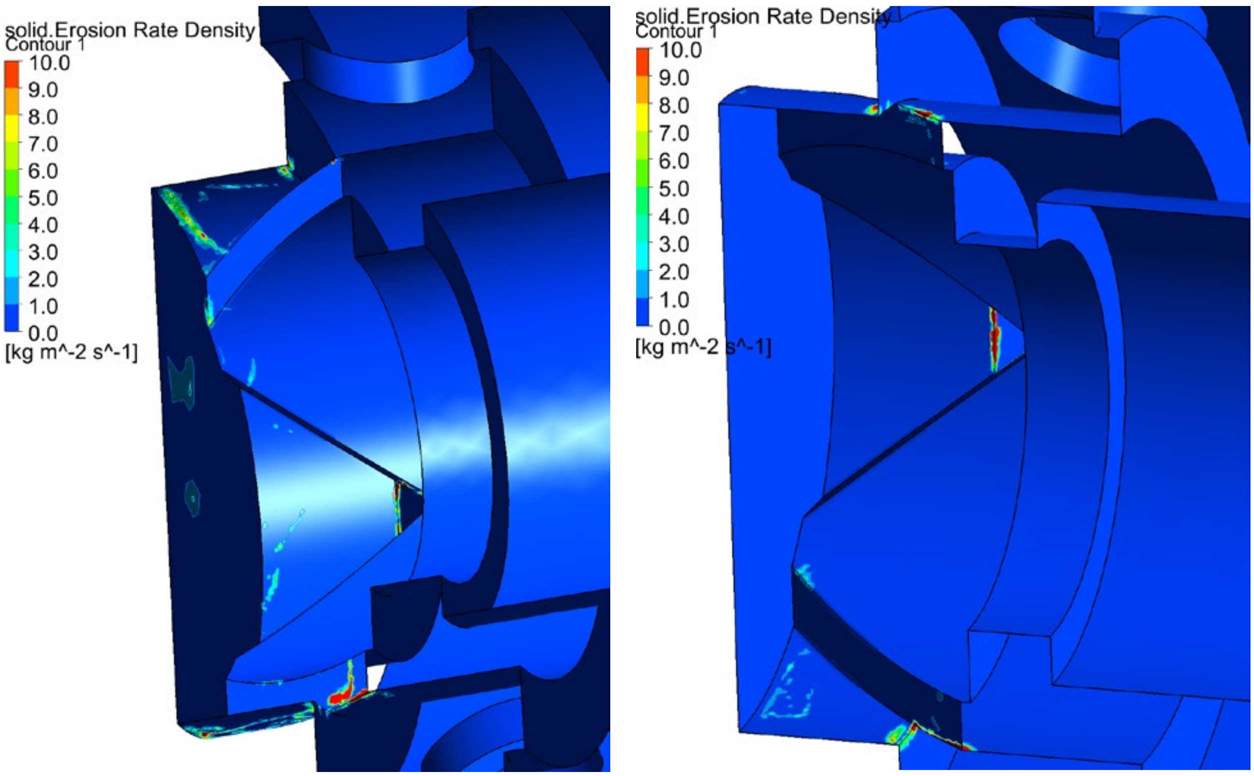

Fig. 6. Erosion rate, right: steel particles, left: sand particles

Summary

This paper is an attempt to predict particle erosion in a hydraulic flow control valve. A simulation of particle erosion is a complex task, however, simulation methods which have lately expanded their possibilities offer such capabilities. Among such methods, CFD tools seem to be very effective in a simulation of erosion wear. This work presents a simulation of flow of fluid containing solid particles in a flow control valve. Two materials of solid particles were investigated: metal (steel) and sand. The CFD simulations made it possible to obtain a trajectory of solid particles as well as erosion rate using Finnie's model. Simulations conducted for two materials of particles showed that, depending on particle material, various surfaces of valve components are exposed to erosion wear.

References

[1] Handbook of Hydraulic Filtration, Brochure Ref: FDHB289UK, Parker Hannifin Corporation 2006.

[2] A.T.Fry, P.Lovelock, N.Smith, M.Gee, A.J.Gant, An innovative high temperature solid particulate erosion testing system, Wear, Volumes 376–377, Part A, 15 April 2017, 458-467

[3] V.B.Nguyen C.Y.HLim Q.T.Trinh S.Sankaranarayanan Y.W.Zhang M.Gupta, Effect of impact angle and testing time on erosion of stainless steel at higher velocities, Wear Volume 321, 30 December 2014, 87-93

[4] Y. Yaobaoa, Y. Jiayanga, G. Shengrongb, Numerical study of solid particle erosion in hydraulic spool valves, Wear 392-393 (2017) 147-189. https://doi.org/10.1016/j.wear.2017.09.021

[5] Hutchings, I.M.,“Mechanical and metallurgical aspects of the erosion of metals”,Proc. Conf. on Corrosion-Erosion of Coal Conversion System Materials, NACE (1979) 393.

[6] Dosanjh, S., and Humphrey, J.A.C., “The influence of turbulence on erosion by a particle laden fluid jet, Wear”,V102, 1985, pp. 309-330. https://doi.org/10.1016/0043-1648(85)90175-9

[7] Dosa Tabakoff W., Grant G., Ball R., An experimental investigation of certain aerodynamics effect on erosion, AIAA Paper No. 74-639, 1974.

[8] J. Fabis-Domagala, Analysis of dfefects and failures of hydraulic gear pumps with the use of selected qualitative methods, Tribologia 2/2017, 33-38, ISSN 0208-7774

[9] H. Momeni, M. Domagala, CFD simulation of transport solid particles by jet pumps, Technical Transactions, ISSN 1897-6328, 2015, 185-191

[10] E. Lisowski, G. Filo, CFD analysis of proportional flow control valve with an innovative opening shape, Energy Conversion and Management 123, 2016, 15-28. https://doi.org/10.1016/j.enconman.2016.06.025

[11] E. Lisowski, G. Filo, J. Rajda, Analysis of Flow forces in the initial phase of throttle gap opening in a proportional control valve, Flow Measurement and Instrumentation, Volume 59, March 2018, 157-167. https://doi.org/10.1016/j.flowmeasinst.2017.12.011