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Erosion analysis of coal mine pipeline valves at different opening conditions

Solid particulates carried with the flow in pipeline can be potentially erosive to many engineering materials used for coal mine pipeline components. Sometimes slow removal of acidic mine water may cause deposition of the yellow body material in coal mine pipeline components followed by corrosion. Various models have been developed to predict erosion rates in various complex geometries of valve. In this study computational fluid dynamics (CFD) based erosion prediction model in the ANSYS-FLUENT is used to find out the erosion behaviour of the butterfly and ball valves in different opening (i.e. operating) conditions. The erosion rates are obtained for valve angles 40°-90° for butterfly valve and 10°-60° for ball valve.

Keywords: *Erosion; butterfly valve; ball valve; CFD; FLUENT; valve angle.*

Introduction

Slurries, coarse or fine coal particles are abrasive in nature. The action of the slurry on pipeline is sand blast or sand paper type. Often the slurry acts as a grinding mixture. Usually, following phenomenon is observed in pipeline. In a welded pipe joint there is strong erosion at the downstream side of the weld. In straight lengths, sand paper action is mostly in the lower region of the pipe resulting in a crescent shape of the pipe instead of circular section. In elbow, thinning of the material takes place on the larger radius wall from the inside. It is more pronounced in short bends. Internal wall protection against corrosion is scrapped out by the slurry easily. Most of the cutting action depends upon the content of the slurry example sand, iron, copper, coal concentration etc. Nearly every fluid transport system contains components that are susceptible to erosion by solid particles. This phenomenon can be extremely costly, requiring frequent replacement of components as well as system down time. Certain geometries like valves in the pipeline are more susceptible to erosion damage than others [1].

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Especially mining piping system suffers by following types of erosion and corrosion problem. When acidic water i.e. acid water interacted with metals or minerals of pipeline or piping components sulphates are formed. This scale sticks to the inner side of the pipes and reduces the flow area. Sometimes the evolution of free CO_2 and O_2 in water i.e. aerated water has direct effect on the valves. At higher velocity, the mud particles i.e. muddy water strikes against the metal surface and erode it. The acidic water further aggravates the action of the erosion [2].

Generally, in coal mines foot valves, main/sluice valve, retaining valve, by pass valve, waste seal regulating valve, ball valve, butterfly valves etc. are used. Out of these, in this paper, an aim is set to evaluate the performance of ball valve and butterfly valve geometries in erosive service especially in mines in different opening condition. An attempt is made to predict the area in valves that are most susceptible to erosion i.e. to detect location in the geometry where sever erosion is likely to occur. Gaining knowledge of such area where high erosion takes place in valves before the actual wear can be very helpful in combating erosion by taking necessary precautions. Moreover, authors tried to predict the intensity with which erosion wear takes place i.e. to know how much surface gets eroded by impact of sand particles so that one can be able to estimate the service life of valves.

Generally, following methods are applied to determine the erosion rate for a given set of operating conditions to prevent any failures from occurring. Finnie (1958) revealed that when solid particles strike the inner wall of a pipe, cutting mechanism starts, causing wear due to kinetic enginery [3]. Bitter (1963) put forward different views to describe the mechanism of the cutting process [4]. Accordingly due to impact of the particles, surface materials are removed by scratching and making a small impact angle. Due to deformation in the process micro crack occurs, ultimately fragments are formed [5, 6]. At a later stage Bitter modified the Finnie model. The earlier model was based on exchange of kinetic energy, and was described for small impact but it was unable to predict for high impact angle. Bitter formulated cutting mechanism and deformation are both responsible for erosion [6, 7]. In the opinion of Neilsen and Gilchrist total erosion is equal to the summation of erosion due to deformation and cutting mechanism [7]. Neilsen and Gilchrist model was further developed by Wallace et al. taking different impact angles which is greater and smaller than 450 [8]. The shape of the particles were considered by Hashish in 1987. Here the velocity exponent of the system was modified [9]. Multiple particle erosion was considered by Hutching et al. in 1976. Accordingly a series of experiments were done using steel spheres impacting mild steels having 900 impingement angle [10].

In this paper, following methodology is adopted to solve the above said objectives.

Methodology

The current research project focuses on the application of an erosion prediction procedure that makes use of a commercially available computational fluid dynamics (CFD) code. This work is performed using ANSYS FLUENT software [11]. Model of a ball and a butterfly valve are used in this analysis, which are placed in between two 40 mm diameter pipe. The length of the pipe assumed at the inlet and outlet of the both the valves is 160 mm long (4 times pipe diameter) each. The length of the ball valve is 120 mm while the length of butterfly valve is 80 mm. Water flows in the pipe with entrained solid particles at 5m/s normal velocity and the outlet is assumed to be an outflow boundary. Turbulent, isothermal, and steady state conditions will be considered to solve the flow field. Solid particles with 1500 kg/m^3 density (i.e. sand) are released from the inlet of the pipe with an initial velocity of 5 m/s assuming no slip between the particle and fluid. 50 micron particle diameter is used in this analysis with mass flow rate of 1 kg/s. Erosion rates are predicted for different valve angles, taken at the interval of 10°. Initial geometry of ball and butterfly valves made on CATIA V5 software and it is imported into FLUENT (Figs.1 and 2). A pre-processor is available in FLUENT were computational grid is made. An Eulerian-Lagrangian model of the flow is used in combination with erosion wear equations for the mass removal, to examine erosion in valve components for aqueous slurry flows. The liquid and dispersed phase (solid particles) are modelled using the Eulerian and Lagrangian approaches respectively. The fluid phase modelling used the Reynolds Averaged Navier-Stokes equations and the realizable k-ε model for turbulence closure. Lagrangian force balance for particle drag, virtual mass force, and pressure gradient force treats the particle dynamics. Fluent predicts the dispersal of liquid droplet or solid particle by integrating the force balance. The effect of the fluid turbulence on the particle motion is accounted for by using a discrete random walk model. To obtain a good statistical characterization of the particulate flow and resulting erosion is simulation several thousand particle (~10,000) trajectories are calculated. For particle rebound effects with the wall Forder et al developed restitution coefficients. The normal and tangential reflection coefficient for the wall boundary is a polynomial function of the particle impact angle. The diameter and velocity exponent functions are defined at values of 1.8e-9 and 2.6 respectively. The erosion rates in valve geometries are estimated by a material removal model in fluent. The material wear model consists of a set of equations that has been developed to relate erosion rates to particle impact angle and velocity for a range of materials used in valve components. Initially, to determine flow, field one-way coupling was used since particle concentration is small and its effect on the continuous flow field is neglected. It takes less time with one-way coupling for the solution to converge than two-way coupling. However, after the flow field is calculated, to compute the erosion rates for two valves at different valve angles we had to switch to two-way coupling in fluent by enabling interaction with continuous field.

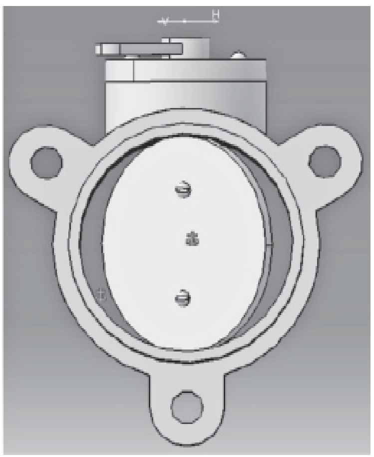

Fig.1 Butterfly valve (40° open)

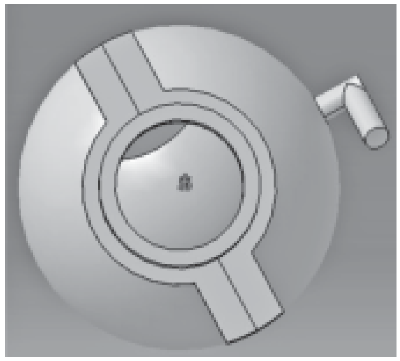

Fig.2 Ball Valve (10° open)

Euler-Lagrangial approach

Here, the fluid phase deals with as a continuous phase by solving the Time-Averaged Navier-Stokes equations, while the dispersed phase is solved by tracing large number of particles, droplets, or bubbles trajectories through the domain of the calculated flow. The dispersed phase has an effect on continuous phase which is represented by the force applied at the dispersed phase. Mass, momentum, and energy can be exchanged in the dispersed phase with continuous phase. The particle trajectories are dealt with individually in the flow domain and the second dispersed phase occupies a low volume fraction despite of the difference in the mass loading in case of the mass of particle is greater than the mass of fluid. I advantages are modelling the particle flow interaction, collision, and wall interaction.

Reynolds averaged Navier-Stoke (RANS)

Reynolds-Averaged Navier-Stoke (RANS) equations are time averaged equations for the fluid motion used as a basis of modelling many Two-equation models including K-Epsilon and K-Omega model. Reynolds decomposition is the idea behind RANS equations, where time averaged part can be separated from fluctuating parts of quantities.

$$\begin{cases}\widetilde{P} = \overline{P} + P' \\ \widetilde{v} = \overline{v} + v'\end{cases}$$

where and $\overline{P}$ are time averaged velocity and pressure respectively, while P' and v' are velocity and pressure fluctuating component.

These transforms can be expressed as Reynolds Stresses or Reynolds stress tensor. This is a function of the velocity fluctuations required for turbulence modelling such as a k-ε or K-ω.

$$-\alpha\nabla p + \nabla.\left[\alpha\left(\tau + \tau'\right)\right] + \nabla.\left(-\rho v' v'\right) + \rho g + M$$

In equation 4.6, τ can be written as:

$$\tau = -\rho\left(\overline{v' v'}\right) = \mu\left(\nabla V + \nabla V^{\tau}\right) - \frac{2}{3}\left(\mu_t \nabla.V + \rho k\right)I$$

Equation 4.7 can be further modified to equation 4.8:

$$\tau = -\rho\overline{v' v'} = \mu_t\left[\nabla V + \nabla V' - \frac{2}{3}(\nabla.V)I\right] - \frac{2}{3}\rho k I$$

where ($\overline{v' v'}$) is the Reynolds stress, μ_t is the turbulent viscosity and k is the turbulent kinetic energy, ∇V is the velocity divergence, and I is the unit tensor.

K-epsilon (k-ε) turbulence

The K-epsilon (k-ε) turbulence model is one of the Two-equation models for predicting the behaviour of the turbulent flow. Where k is the kinetic energy, ε is the dissipation rate of the turbulent energy, and the model transport equations are solved for those two quantities. In this model, conservation equations for both turbulence kinetic energy and dissipation rate are solved besides Navier-Stokes equation of the flow.

There are three types of k-ε model: standard, re-normalized group (RNG) and realizable group.

Coupling

Coupling is done between continuous and dispersed phase. Four kinds of coupling are as follows. (i) One-way coupling – When the concentration of the dispersed phase is very small compared to continuous phase, and then the effect of dispersed phase can be ignored. (ii) Two-way coupling – If there is an interaction between the continuous and dispersed phase and the dispersed flow can effect on the continuous flow. (iii) Three-way coupling – An additional interaction when the particle disturbance of the fluid in the dispersed phase affects the motion of the particles. (iv) Four-way coupling – which has an additional interaction when the collision between particles in dispersed phase affects motion of individual particles.

Results and discussions

In the current study, sand particle injections, representing actual field conditions, were released from the pipeline inlet at a uniform velocity equal to that of the water and steadily tracked. The geometries of the ball valve and butterfly valve were modeled. Maximum erosion rates of these valves at various valve angles were analyzed by running the CFD simulations. Maximum erosion rates occur at the valve surface but not at the pipes connecting the valve as seen in the contour plot of erosion rate for both ball valve and butterfly valve (Figs.3 and 4).

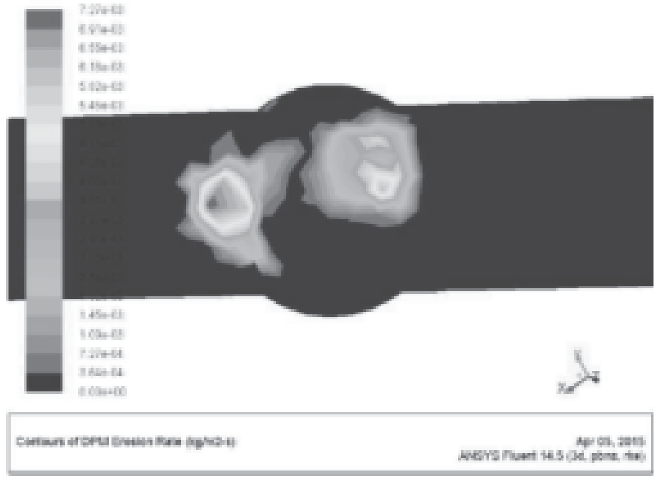

Fig.3 Contour of erosion rate on the 40° open butterfly valve surface

$$\frac{\partial}{\partial t}\left(\rho V\right) + \nabla\left(\rho V V\right) =$$

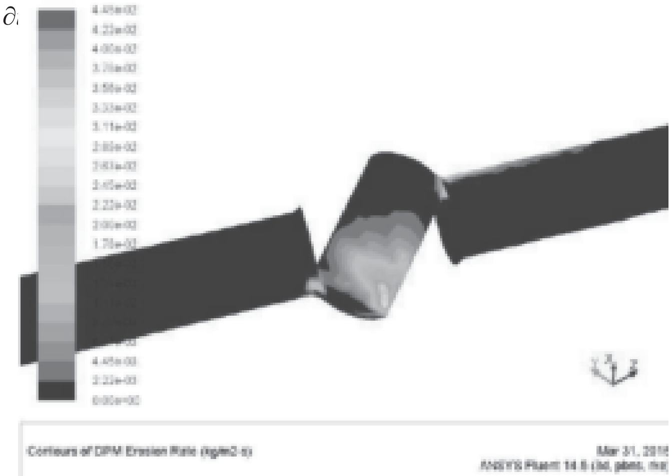

Fig.4 Contour of erosion rate on the 10° open ball valve surface

For large valve angles (70°-90° for butterfly valve and 40°-60° for ball valve) change in direction of flow is small due to which flow can be considered laminar. Also with it particles follow smooth path and erode less material from wall surface as can be seen from erosion plots of two valves. But for small valve angles (40°-60° for butterfly valve and 10°-30° for ball valve), flow is extremely turbulent and eddy currents are formed at the other side of the plate in the butterfly valve. Large erosion rates can be seen from the erosion contour for

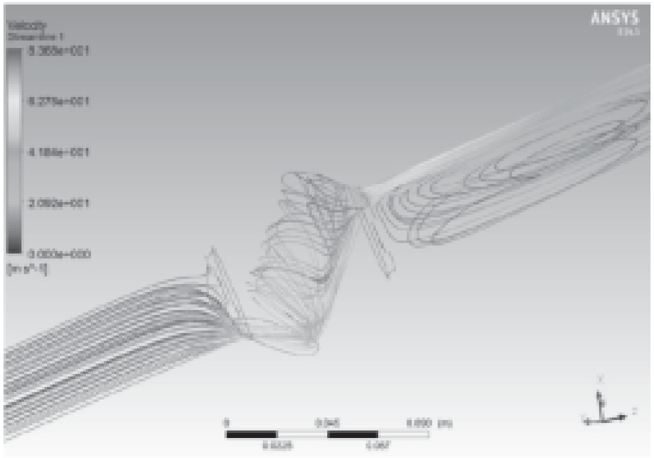

Fig.5 Streamlines of flowing water in the 40° open butterfly valve surface

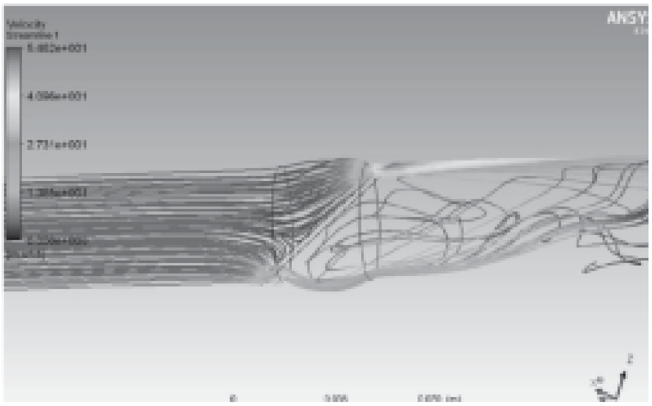

Fig.6 Streamlines of flowing water in the 10° open ball valve surface

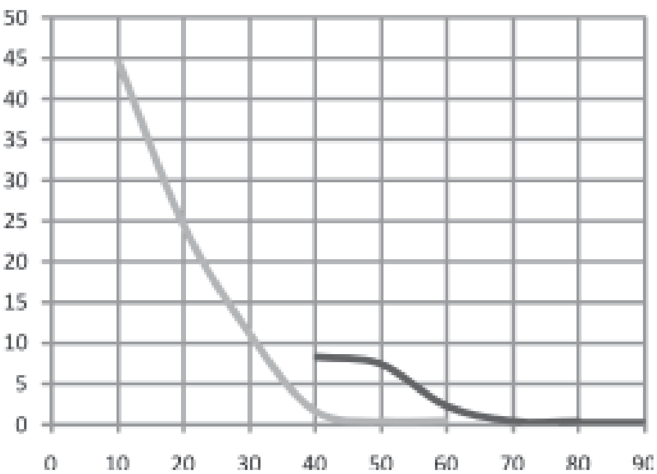

Fig.7 Variation of erosion rate at different valve opening condition for butterfly and ball valve

small valve angles due to rapid change in flow direction. Also maximum velocities can be found in the valves than in the pipes. In Fig 7, it is observed that erosion rate E decreases as valve angle θ increases for both butterfly and ball valve. E is a function of 2nd order polynomial of θ.

Conclusions

Mines water gets dirty because it mixes with the dirt and dust of the mine. The dirt and dust is held in suspension by the water. In case pyrite nodule or sulphide minerals are present in the mine, the water flows over them and form sulphuric acid. This acid mixes up with the water and makes it acidic. Acidic water corrodes metallic parts unless the acidic is neutralized, the acidic water produce serious effects on the life of the pump parts, piping network including valves due to corrosion. Moreover, suspended particle like sand erode the inner part of the pipe fittings valves etc. In this paper an attempt is made to analyze erosion behavior of butter and ball valve at different operating condition, i.e. at different exposure of valve angle. It is found that erosion rates increases considerably if the passageway has more curves (i.e. flow become turbulent) in its path than the straight line (i.e. laminar). Maximum erosion rates occur at the valve surface but not at the pipes connecting the valve as seen in the contour plot of erosion rate for both ball valve and butterfly valve. This happens because of the sand particles that are travelling with the water, and are not able to change their direction easily due to their inertia and momentum. Due to this phenomenon the sand particles strike the wall and erode the inner surface. It is also observed that for large exposure of valve angles, change in direction of flow is small, hence flow can be considered laminar and less erosion rate is observed compared to less exposure of valve angles cases, where flow is more turbulent. This phenomenon also observed in the ANSYS FLUENT software model through the erosion contours. It is found that maximum erosion takes place in that region where there is rapid change in the direction of sand particles. Therefore, from this study an idea is obtained regarding using different material lining for erosion prone zones of the valves. In this study, variations of erosion rate corresponding to different opening valve angles are observed. Similar study can be performed in future for varying fluid flow rate with different types of suspended particle having different inner material lining.

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