Influence of the shape of quartz sand particles factor on single particle erosion damage

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Abstract. The paper presents data on the influence of aerodynamic factor of quartz sand particles on a single particle erosion damage as a part of investigation of gas-abrasive wear of field equipment steel elements caused by solid particles impact in conditions of sand production of wells. The studies are mainly focused on calculating geometric characteristics of the crater obtained as a result of a single particle impact, such as maximum penetration depth and equivalent diameter of the crater, affected by the shape of the sand grains. The results have shown the significance of experimental and numerical data, including sphericity, roundness and shape factor of particles determination towards further calculation of particles impact parameters.

1. Introduction

The transportation of oil and gas with large quantities of solid particles can cause repetitive impacts of particles with the inner wall of a range of field equipment elements, for example, high values of erosion rate are often observed for gas-gathering system elements – pipelines, elbows, chokes, blind tees, T-junctions, measuring devices which are locally installed in the pipelines [1].

The erosion of steel elements caused by solid particles is one of several forms of material degradation processes, most commonly classified as wear. The erosion wear of materials is a complex phenomenon including a range of specific processes happening simultaneously. The prediction of maximum erosion rate of steels is quite a complicated task involving a huge quantity of calculation parameters such as chemical, physical, mechanical properties of materials, flow regimes, interaction of a pair of materials specific features and others [2].

In industrial field most of the equipment elements are thin-walled parts, so the calculation of wall thinning rate and residual resource of equipment and single elements is of particular interest.

In oil and gas industry, the particulate erosion is one of the main reasons for premature wear of equipment, which leads to expensive repairs, loss of production time and temporary decrease of efficiency.

Calculating and prognosing erosion rate is an extensive industrial problem of current interest, and at the same time it’s a complicated question that doesn’t fully have the answer nowadays.

There is a huge range of parameters that affect the absolute erosion rate value – particles impact parameters (velocity and angle), properties of the target material, size, shape and properties of the solid particles etc.

The studies are mainly focused on exploring geometrical characteristics of the solid particles as one
of potentially most dangerous factors on the way to predict wall thinning due to erosion wear.

This paper presents the investigation of different shapes of quartz sand particles. The work includes calculation of shape factor of sand grains according to the particles laboratory size and shape analysis, and penetration rate for each particle in order to find out the most dangerous variant.

At the present work the most promising method to calculate the parameters listed above is usage of CAD and CAE technologies as an addition to laboratory analysis.

2. Problem overview
The effect of particles properties, size and shape on the mechanisms of material removal during single impacts under different velocity value has been widely studied as a model of solid particles erosion [2-9]. At low impact velocities sphere shaped particles formed circular depressions at impact angle of 90 degrees [2]. Plastic deformation was indicated by the formation of an slightly raised ridge of material around the crater edge. A detailed study of the craters revealed a limited amount of mass loss from the crater recess by the combination of melting and tearing due to particle surface adhesion [9]. Extensive mass loss was observed at sufficiently high impact velocities which is explained by the fact inertia of the crater edge induced fracture aling the plane of concentrated shear [7].

Brittle sphere shaped erodent particles (glass beads) fractured at the impact angle of 90 degrees at high velocities [10]. As the studies showed, angular brittle particles also fragmented at the same impact angle. Non-brittle particles produces craters at decreased impact velocities, which mirrored impact particles features [11].

All the listed papers are pioneers in the study of particles shape influence on the erosion rate and are supposed to be fundamental towards developing newest models describing different types of solid particles behavior in appropriate conditions.

One of the most burning problems about developing a calculation process including particles shape factor is a range of empirical coefficients that are hard or unable to get from experimental data.

According to the newest studies in single particle erosion effects, geometric properties of the crater are calculated according to the critical impact angle of the particles and the corresponding critical sliding friction force of the particle [12]. There is also a semi-mechanistic model developed for predicting maximum erosion and relating it to measurable mechanical properties such as hardness and fracture toughness [13]. These model showed a good agreement without involving of a huge amount of empirical coefficients.

Most of the newest calculation methods are based on finite element method (FEM) and computational fluid dynamics (CFD) and have a really good agreement with experiments in comparison.

3. Calculation details
As it was mentioned above, CFD-method is considered to be one of the most full techniques to obtain the operating parameters of particles dynamic movement in gas or liquid field. The attractiveness of CFD-methods is connected not only with simplicity of usage, but also with the level of accuracy of the evaluated results and an opportunity to combine fluid dynamics and structural analysis methods. In this paper a single sand grain motion model is obtained with the help of coupling two major methods: modelling dynamics of the particles in the gas flow field and modelling impact dynamics of the particles at the moment of particles’s impingement into the flat steel target sample.

It is possible to predict a trajectory of the discrete phase particle by integrating the force balance of the particle, which is written in Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for the x direction in Cartesian coordinates) as:

\[
\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x, \tag{1}
\]

where \(F_D(u - u_p)\) is the drag force per unit particle mass and
Here, $u$ is the fluid phase velocity, $u_p$ is the particle velocity, $\mu$ is the molecular viscosity of the fluid, $\rho$ is the fluid density, $\rho_p$ is the density of the particle and $d_p$ is the particle diameter. $Re$ is the relative Reynold number which is defined as

$$Re \equiv \frac{\rho d_p|u_p - u|}{\mu}$$

The drag coefficient $C_D$ can be taken from

$$C_D = \frac{24}{Re} \left(1 + b_1 Re^{b_2}\right) + \frac{b_3 Re}{b_4 + Re}$$

where

$$b_1 = \exp(2,3288 - 6,4581\varphi + 2,4486\varphi^2)$$
$$b_2 = 0,0964 + 0,5565\varphi$$
$$b_3 = \exp(4,90 - 13,8944\varphi + 18,4222\varphi^2 - 10,2599\varphi^3)$$
$$b_4 = \exp(1,4681 + 12,2584\varphi - 20,7322\varphi^2 + 15,8855\varphi^3)$$

which is taken from Haider and Levenspiel [14]. The shape factor $\varphi$ is defined as

$$\varphi = \frac{s}{S}$$

where $s$ is the surface area of a sphere having the same volume as the particle, and $S$ is the actual surface area of the particle.

4. Experimental data

According to the analysis of mechanical impurities samples selected from a range of sand productive wells (Fig.1, a) the quantity of quartz sand is supposed to be prevalent. Since quartz sand appears to be the most aggressive abrasive agent according to the particles hardness analysis (Fig.1, b), quartz sand particles are chosen as discrete phase for modelling.

**Figure 1.** Solid particles component analysis result obtained from sand productive wells: a – Components composition, %; b – particles Mohs hardness value

According to the laboratory analysis of quartz sand grains fractions size, the smallest grain is supposed to be about 45 μm in its equivalent diameter, the biggest one – about 500 μm (Fig.2).
For further modelling mean diameter of the quartz sand particles equals 150 µm as the most common size for solid particle met in the examined wells.

For the samples obtained from a range of sand productive wells particles geometric characteristics were evaluated. Particle shape was determined visually from microscopic images by comparison with samples from the Crumbien-Schloss diagram [15]. According to the diagram there are two common parameters by which particles geometry is determined – roundness and sphericity coefficients. There are mean values of roundness and sphericity of the examined quartz sand particles in table 1 for each of the well.

### Table 1. Roundness and sphericity coefficients for quartz sand particles

| Well no. | Mean roundness coefficient | Mean sphericity coefficient |
|----------|---------------------------|----------------------------|
| 1        | 0.4                       | 0.3                        |
| 2        | 0.3                       | 0.5                        |
| 3        | 0.6                       | 0.4                        |
| 4        | 0.4                       | 0.7                        |
| 5        | 0.5                       | 0.5                        |
| 6        | 0.3                       | 0.4                        |
| 7        | 0.6                       | 0.8                        |
| 8        | 0.7                       | 0.4                        |

Sand grains parameters like roundness and sphericity are necessary in order to determine the mean geometry of the sand grains for further impact parameters calculation. Despite the fact these characteristics are common in industrial field to understand the particles geometry, the data is not enough to determine the sand grains shape in visual representaion for further penetration depth calculation, thus according to the information from table 1 3d-models of particles have been created automaticly (Fig. 3).

As it is seen from Figure 3, most of the particles represent angular geometry for the sand grains. Taking into account previous research [16] angular particles are much more aggressive to the target material than rounded particles comparing total mass loss for both of the cases.

Since a 3d-model is a full geometry representation for each of the sand grains, calculation of surface area for each of the particle is automatic. Data on the surface area for the particles and for the equivalent volume spheres are shown in table 2.

According to (9) shape factor is calculated due to the known surface area values.
With the use of CFD-method a single particle motion in gas flow field has been simulated for different shaped grains.

Taking into account so called near wall effects, the area around the whole particle is supposed to be the boundary layer, so the size of the mesh elements around the particles are generated by adding the inflation method with elements growth rate coefficient 1.4 (Fig. 4).

Particles are tracked in a gas flow field which has properties of a real gas. Absolute impact velocity of the grains is 10 m/s. In addition to the basic boundary conditions, gravity force is also taken into account. As a result of the calculation there are streamline contours for each of the particle in the gas flow field (Fig. 5).

| Particle no. | Particle surface area, mm² | Body volume, mm³ | Equivalent volume sphere surface area, mm² | Shape Factor, φ | Shape Factor Mean Value |
|--------------|-----------------------------|------------------|---------------------------------------------|-----------------|------------------------|
| 1            | 0.0508047                   | 0.0009043        | 0.0452162                                   | 0.89            |                        |
| 2            | 0.1106665                   | 0.0002571        | 0.0907465                                   | 0.82            |                        |
| 3            | 0.1139832                   | 0.0023509        | 0.0854874                                   | 0.75            |                        |
| 4            | 0.0736023                   | 0.0017663        | 0.0706582                                   | 0.96            |                        |
| 5            | 0.0918318                   | 0.0018379        | 0.0725471                                   | 0.79            |                        |
| 6            | 0.0873741                   | 0.0021436        | 0.0803841                                   | 0.92            |                        |
| 7            | 0.1105326                   | 0.0028048        | 0.0961634                                   | 0.87            |                        |
| 8            | 0.1240693                   | 0.0030521        | 0.1017368                                   | 0.82            | 0.85                   |

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Figure 4. Boundary layer mesh for the particles
Figure 5. Influence of shape factor of the particles on the streamline contours

The process of indentation of the particles into the target material (steel density is $7850 \text{ kg/m}^3$) was calculated at the impact angle of 90 degrees. As far as sliding angles (0-30 degrees) represent a much more complicated mechanism including frictional force components, this aspect will be fully described in the next research devoted to complex single particle erosion impact.

Typical single particle indentation depth values for each of the particles are shown in table 3. Maximum penetration depth was analysed for different shapes of the grains.

Table 3. Geometric characteristics of the crater for the different shaped grains after the impact

| Particle no. | Maximum Penetration Depth, µm | Approximate particle crater diameter after the impact, µm |
|-------------|-------------------------------|----------------------------------------------------------|
| 1           | 24                            | 20,5                                                     |
| 2           | 22                            | 15                                                       |
| 3           | 56                            | 12,5                                                     |
| 4           | 12                            | 24                                                       |
| 5           | 10                            | 24,5                                                     |
| 6           | 28                            | 13,5                                                     |
| 7           | 48                            | 14                                                       |
| 8           | 76                            | 12                                                       |

As it is seen from Table 3 maximum penetration rate is observed for the most angular particle of all. It is also necessary to take into account the orientation of the particle in space and additional forces, including particle rotational law, since the geometry of the crater after the particle impact directly depends by which side the particle hits the wall during the indentation process.

5. Conclusion

The main purpose of this paper was to study the dependence of geometric features of the quartz sand particles on the penetration characteristics caused by a single particle impact.

After conducted studies of sand grains shape factor on the penetration depth analysis, it is possible to conclude that the material removal mechanism appears to be the function of the particles’ shape. Quartz sand grains having lower shape factor (or higher angularity) produces deep craters and most possibly generates higher mass loss as compared to particles having higher shape factor.

To sum up, penetration depth obtained by a single angular solid particle impact, is significantly high. Numerical modelling shows the importance of a single particle impact simulation, in contrast to calculating total erosion rate, to determine the mechanism of abrasive wear for different shapes of particles.
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