2013

# Comparison of Impact and Torque Forces on Erosion of Oil Shale Particle Processed in Fluidized Bed Reactor

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# Comparison of impact and torque forces on erosion of oil shale particle processed in fluidized bed reactor

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**Abstract:** Attrition of Tarfaya Oil Shale (Morocco) particle processed in laboratory fluidized bed reactor (5 cm in diameter and 100 cm in height) is measured and compared to erosion due to mechanical impact inside the bed. Fluidized bed velocity used is 1.5 $U_{mf}$ and 2 $U_{mf}$. The weight particle is measured during the fluidization process. Maximum impact effect occurs in a zone under the turbulent bed surface and in the mid height of operating bed. If shale particle rotates in silica bed material, abrasion on surface particle occurs and generates fine particles. Shale particle was submitted to turn in granular medium of silica sand. Angular velocities ω used are: 1.95, 2.25, 4.2, 5.5, 6.75, 9.5 and 22 rpm. Increase in particle rotation increases the number of small size particles detached from the particle surface.
Impact forces related to kinematic energy are in great part more important than the torque (rotation) forces. Rate of erosion due to torque forces and to impact forces contribute to the particle erosion rate of shale particle moving freely in the silica bed.
**Keywords: Impact, erosion, torques forces, fluidized bed, shale, share rate, rotation**

## INTRODUCTION

Oil shale can play an important role to contribute to solve a near future energy demand and they are candidate to be realistic energy substitute for petrol. Many deposits are widely distributed around the globe. Oil shale with organic matter (kerogen) concentration greater than 10% can be burned without processing. Experimental results confirm in great part the theoretical studies A. Martins (1), K.Plamus and S. Soosaar (2). Fluidized bed technology is used to develop combustor to burn oil shale solid particles. Bubbling and circulating fluidized beds are the suitable combustors with good energetic efficiency to burn such fossils fuel. They produce high combustion efficiency and protect environment with low $NO_x$ and $SO_2$ emission J. Loosaar *et al*. (3). Attrition and abrasion of solid particles occurs inside the fluidized bed. They enhance and accelerate combustion and change the distribution of the particle size in the bed. These physical phenomena influence the evolution of organic matter in the reacted shale particle and control the elutriation of small particles out of the reactor. Fine particles are generated by both attrition and fragmentation. Oil shale particle reactivity depends on a number of operating variables: gas composition of the reactants and the products, particle size, organic and mineral of reactive solids, bed temperature and fluidized bed velocity. Oil shale particles once processed in fluidized bed fragment and generate fine particle by attrition A. Bouhafid *et al*. (4) (5). Tarfaya deposit in south of Morocco occupies thousands of square kilometers and contains more than 86 billion ton with 22 liter of oil by ton. Oil extracted from the deposit is estimated to 3.8 billion barrels. In the past decades, considerable work on solid fragmentation and attrition in fluidized bed combustor concerns carbon particle, silica and lime stone F. Scala, P. Salatino (6) and G. Vaux (7). Empirical correlations for attrition rate in bubbling and circulating fluidized bed combustors are proposed by F. Scala, and P. Salatino (8) and Almerinda Di benedetto, P. Salatino (9). Many factors affect the attrition process.

They are related to the bed material properties (size, porosity, shape, hardness..) and to the reactor environment ( reaction time, bed velocity, temperature, turbulence..) . . More detailed works are recently proposed and focus their studies on the behavior of a single particle in particular solid/gas systems J. Werther and E.U Hartge (10) . Theoretical model of particle chipping is proposed by M. Ghadiri and Z. Zhang (11). Studies on hydrodynamic effect on attrition in fluidized bed were proposed by C.L Lin and M.Y Wey (12). A model is proposed by C.Hare *et al.* (13) to predict attrition in agitated particles bed. B. Van Laarhoven *et al.* (14) proposed an experimental device to quantify the particle abrasion by exploring tangential forces acting on solid particle. High fluid mixing of solid generates vortex in the bed and the solid particles rotate with different angular velocities. Particle rotation can also result by repeated impact between the particles with irregular shape and they should have spinning during collision, I.M. Hutchings (15), and M. Pagini and J.K Spelt (16). Appropriate method that uses high-speed digital imaging measurement system confirms the rotation of solid particle in circulating and bubbling fluidized bed system, Xuecheng Wu (17) and Wang Shuai *et al*. (18). In the present paper experiments we present results of (i) erosion due to mechanical impact in laboratory fluidized bed reactor and (ii) erosion due to rotation of shale particle in medium filled by silica solid particle. No fragmentation of the mother particle occurs during all the tests. Rate of erosion by impact and rotation erosion rate are compared to the global erosion rate of shale particle moving in the fluidized bed..

## EXPERIMENTAL

### Apparatus

- A circular Pyrex glass atmospheric bubbling fluidized bed column with 4.8 cm in diameter and 100 cm in height was used for all the experiments as depicted in Fig. 1. A perforated steel plate with 118 perforations disposed in triangular pitch was used as distributor. Air was used as gas of fluidization. It was dried in a glass tube filled with zeolith to avoid humidity adsorption by bed material. The air flow rate was measured by volumetric flow meter. Bed material consists of 200 g of granular silica particle with 0.5 – 0.63 mm in diameter. Density of sand material is 2.3g/cm$^3$.

Solid shale particle (diameter 2.5-3 mm) was attached in the extremity of rigid stainless thin rod and positioned at different positions inside the fluidized bed. Microbalance Radwag (AS 310, C/2) with precision $10^{-4}$g was used for all the mass measurement.

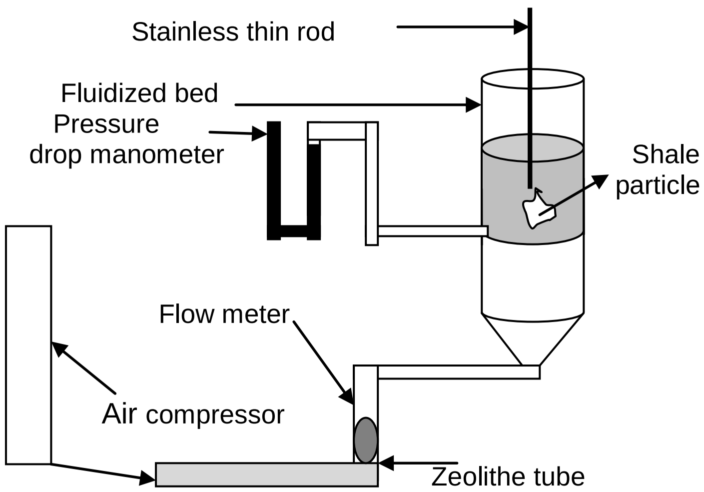



Fig.1. Schematic diagram of impact test system

Minumum fluidized bed velocity $U_{mf}$ was measured by the pressure drop method: $U_{mf}$ = 27.6 cm/s. Fluidized bed velocity varies from 1.5 $U_{mf}$ to 2.5 $U_{mf}$

- To study the erosion of shale particle during its rotation in granular medium the experimental device illustrated in Fig. 2 was used. It consists of a cylindrical recipient with diameter D (45mm) filled with silica sand with 0.5-0.63 mm in diameter. Shale particle is attached in the extremity or stainless rod and immerged slowly in the recipient to a depth h. Sand silica is then poured gently in the recipient to a height H. Electric motor with controlled speed rotation was used to rotate the stainless rod in the granular medium. Angular velocities ω used were 1.95, 2.25, 4.2, 5.5, 6.75, 9.5 and 22 rpm.

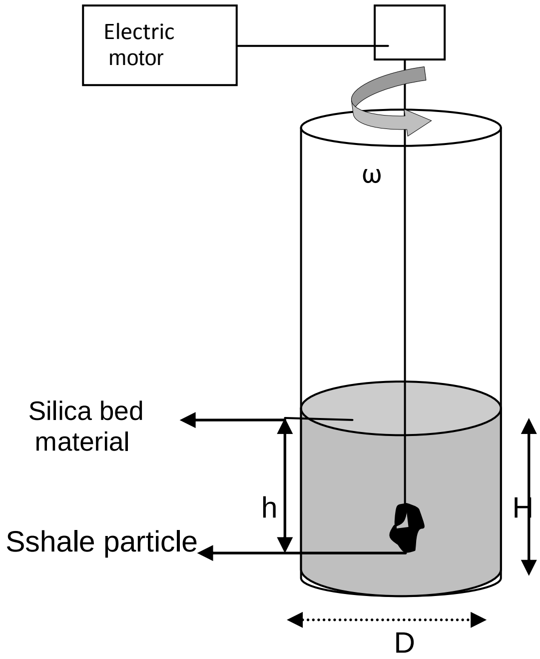


Fig.2: Experimental facility for rotation-erosion test

For each angular velocity weight loss of shale particle ($m_0$ - m) was measured during the time and the number of detached particles was counted. $m_0$ *is the* initial particle mass and m is the particle mass at time t.

**Material**

The R2B2 oil shale seams was ground and sieved to prepare the initial size fractions. The ultimate analyses (wt.) give carbon 15.5, hydrogen 1.17, nitrogen 0.28, oxygen 23.65, and sulphur 1.6. The heat of combustion value is 3386 kcal/kg, and the shale density 2.1 g/cm3. Mineral matter and organic matter represent 15% and 85% of weigh respectively. Total CO2 evolved at 900°C is approximately 22% of total solid particle weigh. Oil shale and ash analysis of Tarfaya oil shale R2B2 deposit is presented in table 1. Calcite, silicates and dolomite are the main minerals constituents of oil shale.

| Composition analysis | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | $P_2O_5$ | $TiO_2$ | Others |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Shale chemical analysis** | **6.25** | **0.83** | **0.54** | **40.42** | **0.41** | **3.43** | **0.05** | **0.10** | **0.08** | **0.05** | **1.67** |
| **Ash chemical analysis** | **11.61** | **1.55** | **1** | **75.08** | **0.76** | **6.38** | **0.09** | **0.19** | **0.15** | **0.09** | **3.10** |

Table 1: Oil shale and ash analysis, (wt.%) Tarfaya R2B2 deposit

## RESULTS

### Impact fluidization tests

The following figures report relative solid shale particle weight loss (wt.% $= (m_0 - m)/m_0$ ) as function of processing time for each experiment. Results concerning the impact effect on particle are presented in Fig.4 for bed velocity of 1.5 $U_{mf}$ .The total height of the bed is 13.5 cm. The total power of the fluidized bed is E = M.g.(U-$U_{mf}$)

where M is the silica bed mass and g is the gravity, E = 0.27 J/s. Solid shale particle is placed at different position along the central axis of the bed: 1cm, 3cm, 5 cm, 9 cm, 11 cm and 13cm. The % shale particle weight loss approaches an asymptote after 100 min of fluidization. Maximum impact takes place at a distance of 9 cm above the bed basis. The corresponding rate of mass loss is $R_\infty = 5\ 10^{-4}$ g/min. The minimum impact effect occurs at 3 cm above the distributor, $R_\infty = 0.22\ 10^{-4}$ g/min. The order of maximum impact effect along the bed axis ( r = 0 cm) is as follow: 9cm, 11 cm, 7cm, 5cm, 1cm and 13cm.

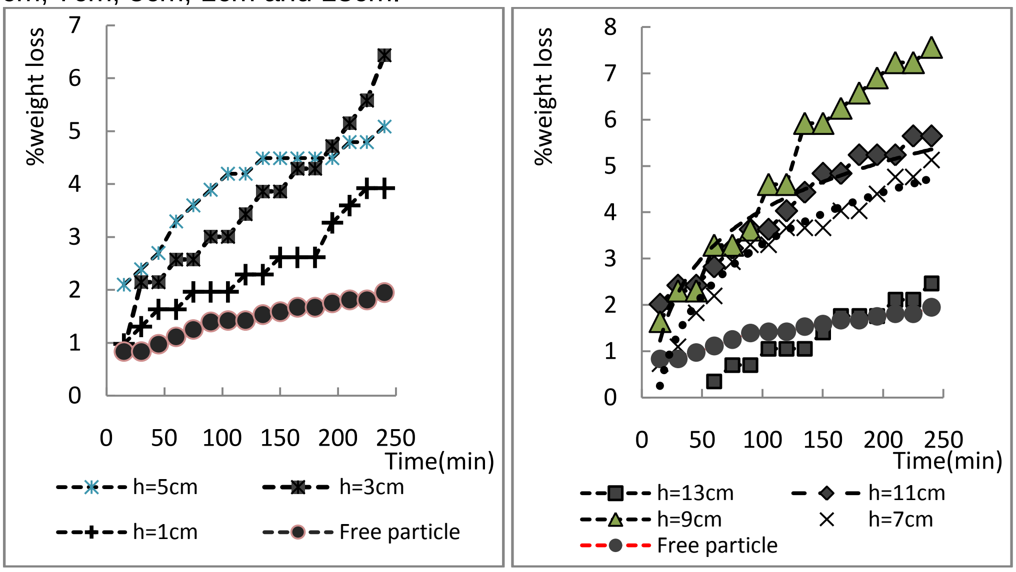



Figure 4: Shale particle weight loss along the bed axis at different heights On the distributor, r = 0cm, (U= 1.5 $U_{mf}$)

As it can be seen there are two mains zones along the bed axis where the impact forces are important: at a distance between 2.5 and 4.5 cm and between 8 and 10 cm above the distributor. The solid-solid interaction is more intense in these impacting zones and the amount of detached small particles is three times higher than others zones along the axis. The impact effect along axis at a distance r= 2.1 cm from the bed axis is shown in Fig.6. The situation slowly changes. The same trend observed in the central axis is to be noted here. Whoever two regions are present where there is minimum forces impact: at 5cm and 11 cm above the distributor. The maximum impact occurs near the top of the fluidized bed in a region between 7cm and 11 cm above the distributor. The global impact effect is less intensive near the bed wall (r ≈ 2.5 cm) and the weight loss does not exceed 4.5%.Figs. 6-7 show the impact weight loss of the solid shale particle if the fluidized bed velocity is 2 $U_{mf}$. The increase of total power of fluidized bed E'= M.g. (U-$U_{mf}$) = 0.54 J/s increases the height of the bed to 21.5 cm. The impact submitted by the shale particle is intense along the bed axis (r = 0) at distances of 5.5 cm and 15.5 cm over the distributor.

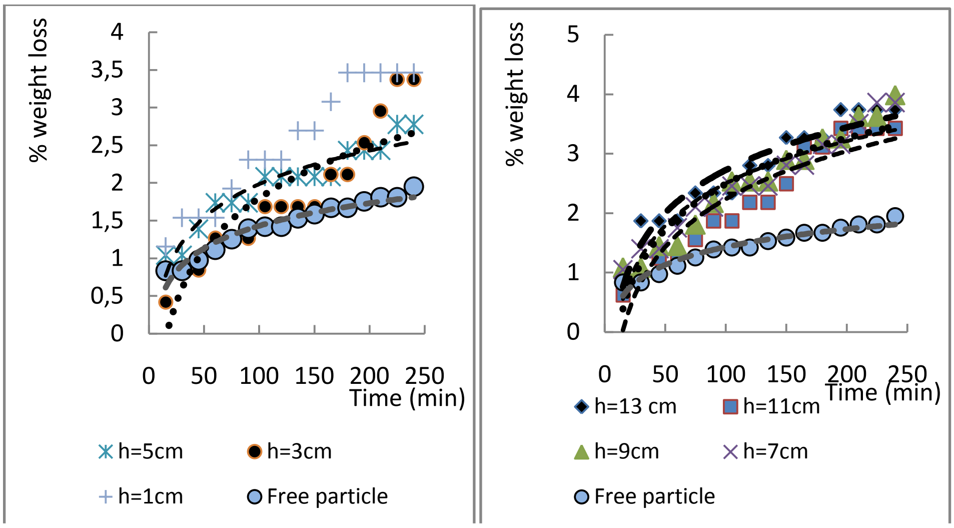



Fig. 5: Shale particle weight loss along the axis at different heights on the distributor, r=2.1 cm and U= 1.5 $U_{mf}$

However the rate of weight loss decrease significantly if the particle is placed near the radial position r = 2.1 cm in the vicinity of the bed wall. Bed collisions with silica particles occurs at frequencies which are about one order less than the collisions in the central region of the bed.

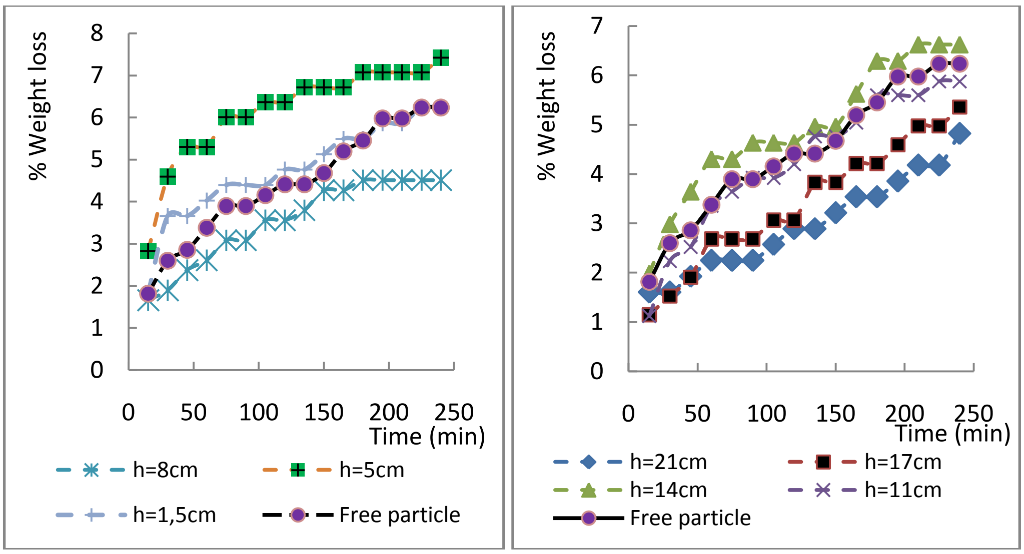



Figure 6: Shale particle weight loss along the bed axis at different heights on the distributor, r = 0 cm and U= 2 $U_{mf}$

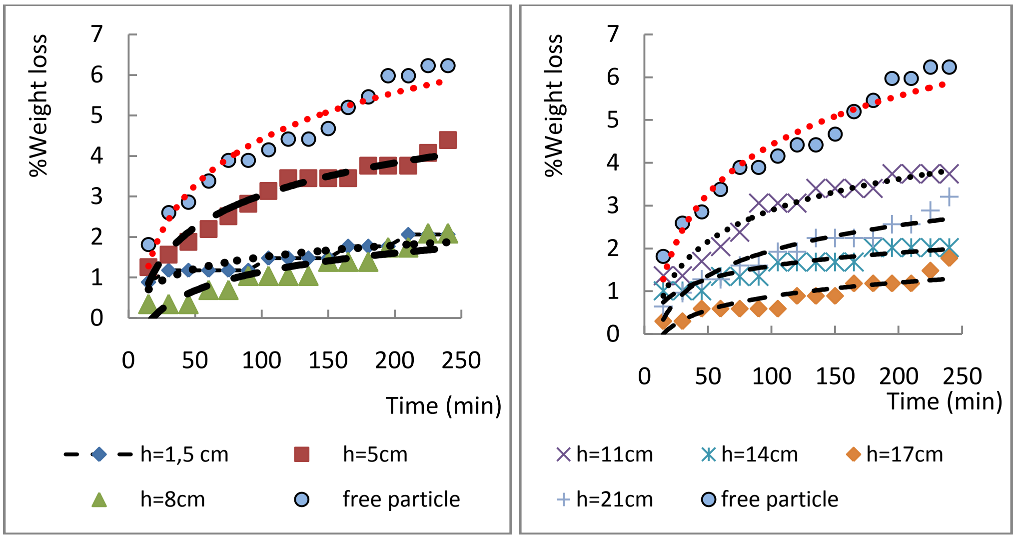



Fig. 7: Shale particle weight loss along the axis at different heights
on the distributor, r = 2.1 cm and U= 2 $U_{mf}$

Based on the results shown in Figs.4-7, the flow patterns and solids-solids contacting modes change with the variation of the superficial gas velocity. Compared to the weight loss of shale particle moving freely in the fluidized silica bed, we see that impact affects particle in the two cases of experimented bed velocity. The contribution by impact to the global attrition process depend on others mechanisms and in particular it local residence time in each region in the bed.

**Particle rotation tests**

In the operating conditions the rheological parameters that describes the tangential forces exerted on the shale particle are: Share rate γ ($s^{-1}$), particle frequency ω (rpm), ρ sand density ($kg.m^{-3}$), η bed sand viscosity, share stress $\tau$ (Pa), solid particle diameter d, k ratio between particle diameter and cylindrical recipient k=d/D, and particle Reynolds number *Re.* Bed viscosity was measured at 0.8 $U_{mf}$ fluidized bed velocity. The relations between these parameters were established by B. Bobić et *al.*(19).

$$\tau = \eta * \frac{4*\pi*\omega}{(1-k^2)} \qquad \gamma = \frac{4*\pi*\omega}{(1-k^2)} \qquad Re = \frac{\omega*\rho*d^2}{\eta}$$

| **ω (rpm)** | **22** | **9.5** | **6.75** | **5.5** | **4.2** | **2.25** | **1.95** |
|---|---|---|---|---|---|---|---|
| $R_e$ | **1.49 $10^{-3}$** | **6.45 $10^{-4}$** | **4.58 $10^{-4}$** | **3.73 $10^{-4}$** | **2.85 $10^{-4}$** | **1.52 $10^{-4}$** | **1.32 $10^{-4}$** |
| **$\gamma$ ($s^{-1}$)** | **4.62** | **1.99** | **1.42** | **1.15** | **0.88** | **0.47** | **0.41** |
| **$\tau$ (Pa)** | **20.79** | **8.98** | **6.40** | **5.21** | **3.98** | **2.13** | **1.84** |

Table 2: Operating parameters for shale erosion due to rotation

Experimental parameters concerning the tests are regrouped in table 2. Fig. 8 shows the weight loss of shale particle during rotation in solid silica medium at different angular velocities. Particle is exposed to large tangential forces and therefore surface particle is abraded and some material is chipped off. The rotating particle does not fragment for all the performed experiments.

A large rate of mass loss occurs during all the stage of particle rotation and probably the surface irregularities with sharp edges contribute initially to release macro and micro solid particles. The number of micro particles released was counted during process and a typical profile is shown in Fig.9.

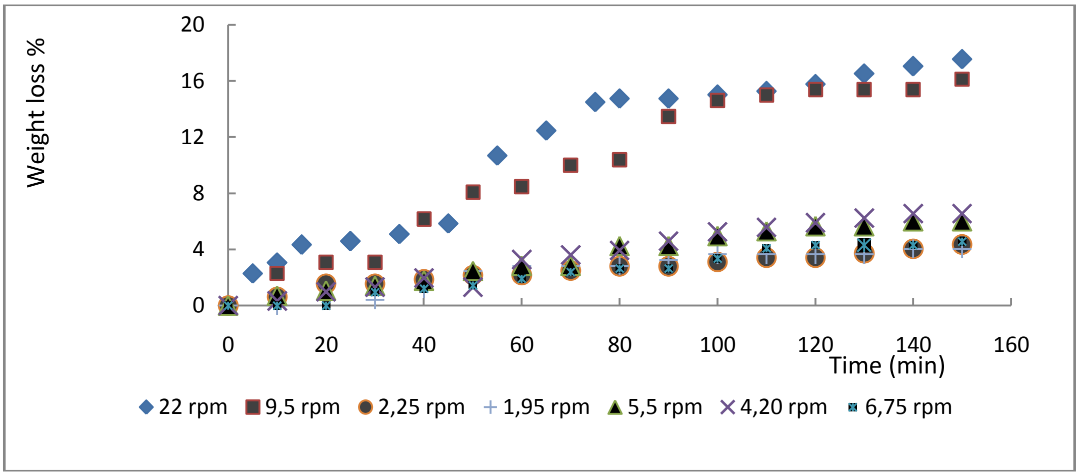
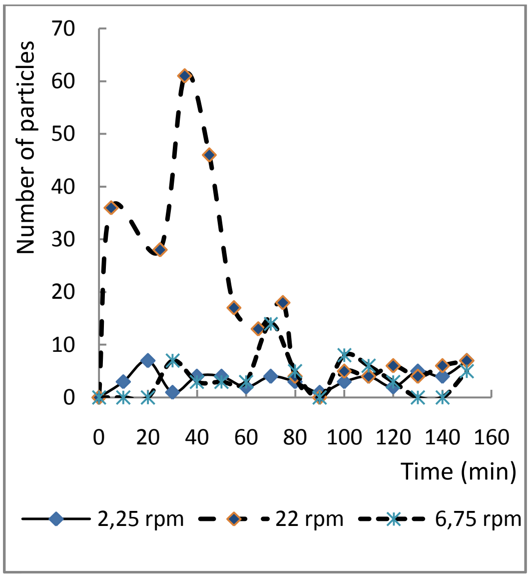



Fig. 8 Oil shale particle erosion during rotation
in silica bed material

The particles number generated by interaction with bed medium takes place during all the period of rotation. This process unfolds in disorderly and fluctuating manner and it reflects the heterogeneity of dispersed matter in the solid particle.



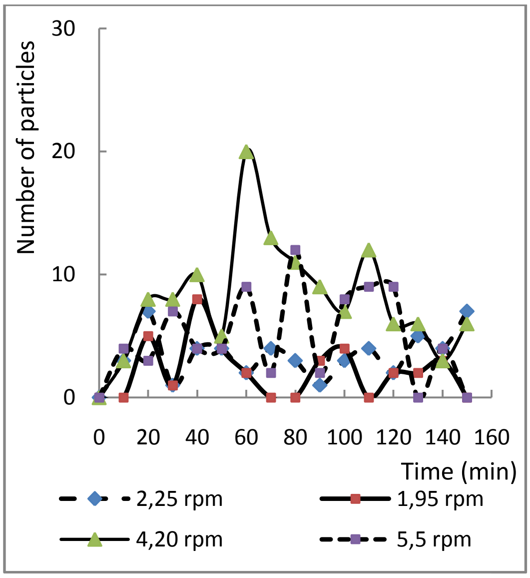




Fig.9. Number of particles released during time for different solid particle angular rotation

## Conclusion

Experimental procedures have been developed to study the attrition by impact and erosion due to the rotation of solid particle in silica bed material. It was found that mechanical impact forces are more important near the central region of the reactor. Maximum impact effect occurs in a zone under the turbulent bed surface and in the mid height of operating bed. Minimum impact effect occurs near reactor wall. Detached particles from rotating particle follow a pseudo periodic process and mainly related to the particle morphology. Frequency of this process depends on angular particle rotation. The contribution of both mechanisms to the global particle abrasion will be clarified in subsequent work.

*This work was funded by the Hassan II Academy of Sciences and Technology under the project "Moroccan oil Shale combustion in fluidized bed reactor" 2010-1014.*

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