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Original Research Paper

# Experimental investigation of the sphericity of irregularly shaped oil shale particle groups

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ABSTRACT

In this work, the modified Ergun equation was proposed to determine the sphericity of irregularly shaped oil shale particle groups. The experimental packed beds were constructed by using twelve different oil shale particle groups, one sinter particle group and one pellet particle group to validate the applicability of this method. The effect of bed length, particle size and superficial velocity on pressure drops was studied. The equivalent volume diameters of the particle groups were determined and compared in different ways, and the relation between sphericity and equivalent volume diameter of Jimsar oil shale particle groups was obtained. The current experimental investigation shows that the modified Ergun equation is reliable to be used to determine the sphericity of irregularly shaped oil shale particle groups, and the geometric average works well to represent the equivalent volume diameter of sieved oil shale particle group.



## 1. Introduction

In the oil shale retorting industry, the pressure drop through the packed bed determines the flow rate of gas heat carrier, and thus the heat transfer rate inside the bed. Therefore, the pressure drop greatly influences the quality of derived oil and gas, and as well as the measurements of industrial production process and equipment capacity. For the conversion process to be undertaken under optimal process conditions, the modified Ergun Equation is extensively used to predict the pressure drops through packed beds [1–4]:

$$\frac{\Delta P_{\mathrm{Bed}}}{L} = k_1 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{\Phi^2 d_V^2} + k_2 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho U^2}{\Phi d_V} \tag{1}$$

where $\Delta P_{\mathrm{Bed}}/L$ is the pressure drop per length unit of the bed, $\Phi$ and $d_V$ are the sphericity and equivalent volume diameter of the particles, $\varepsilon$ is bed porosity, $\mu$, $\rho$ and $U$ are the dynamic viscosity, density and superficial mean fluid velocity of the fluid, $k_1$ and $k_2$ are the empirical constants of Ergun equation.

However, in the prediction of the bed pressure drops, the determination of the sphericity of irregularly shaped oil shale particle groups is always a tough task.

Sphericity describes how closely the particle resembles a sphere [3–7], which is defined as:

$$\Phi = S_V/S = d_{\mathrm{SV}}/d_V \tag{2}$$

where $S_V$ is the surface area of the equivalent-volume sphere, $S$ is the external surface area of the particle, $d_V = 6V/S_V$ and $d_{\mathrm{SV}} = 6V/S$ are the equivalent volume diameter and the equivalent surface diameter of the particles. It is always difficult to measure $S$ and $d_{\mathrm{SV}}$ of irregularly shaped particles which are rough, uneven and porous [8–14]. With the development of three-dimensional digital imaging techniques, e.g., laser scanner technology, X-ray computed tomography [11,15–17], $d_{\mathrm{SV}}$ ($S$) of single particles could be characterized accurately. But in industrial systems, the particle groups have a wide size distribution and billions of irregular particles, and the particle groups in different size ranges are often mixed for production requirements, so that the $d_{\mathrm{SV}}$ and $d_V$, i.e., $\Phi$ of the whole particle group are difficult to be measured depending on the aforementioned approaches which are only appropriate for measuring single particles. Although a number of empirical equations [18–24] are proposed and used in the industry, they are only able to make a broad estimate of sphericity values.

In this paper, the modified Ergun equation was proposed to determine the sphericity of irregularly shaped oil shale particle groups. The sphericity of oil shale particle groups in different size ranges, as used in the oil shale retorting industry, were

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**Nomenclature**

| | |
|---|---|
| $d_A$ | the sieve size (m) |
| $d_{SV}$ | the equivalent surface diameter of the particles (m) |
| $d_V$ | the equivalent volume diameter of the particles (m) |
| $D$ | inner diameter of the packed bed (m) |
| $D_{max}$ | the maximum size of particles (m) |
| $f_P$ | the particle friction factor |
| $k_1$, $k_2$ | empirical constants of Ergun equation |
| $L$ | bed length or height (m) |
| $M_s$ | the total mass of the oil shale particles (kg) |
| $n$ | the number of size interval |
| $P$ | pressure (Pa) |
| $R$ | correlation coefficient |
| $Re_P$ | the particle Reynolds number |
| $S$ | the external surface area of the particle ($m^2$) |
| $S_V$ | the surface area of the equivalent-volume sphere ($m^2$) |
| $U$ | superficial mean fluid velocity (m/s) |
| $V$ | the volume of the particle ($m^3$) |
| $V_{tot}$ | the total volume ($m^3$) |
| *Greek* | |
| $\delta$ | relative error |
| $\varepsilon$ | bed porosity |
| $\mu$ | fluid dynamic viscosity (kg/ms) |
| $\rho$ | fluid density ($kg/m^3$) |
| $\rho_s$ | the real density of oil shale ($kg/m^3$) |
| $\Phi$ | sphericity |

experimentally investigated through the investigation of the pressure drops across the packed beds. The macroscopic bed parameters (particle size, bed length, superficial mean fluid velocity) were varied to study their effect on pressure drops to make sure of the consistency of this approach. The equivalent volume diameters were determined and compared in different methods, and the relation between sphericity and the equivalent volume diameter of oil shale particle groups was discussed. The applicability and reliability of this approach was verified through verification experiments.

## 2. Experimental

### 2.1. Oil shale particle groups and packed bed

The experiments were performed in a test set-up consisting of horizontal rigid pipes and a vertical cold model of oil shale packed bed made of steel. The inner diameter ($D$) of the bed is 0.60 m. The experimental set-up is shown in Fig. 1, where air with ambient temperature is used as the working fluid.

Eight oil shale particle groups were packed into the bed respectively. Four different packed bed lengths ($L_i$ = 0.30, 0.50, 0.70, 0.90 m) were systematically experimented for each of the packing particle group. To obtain the experimental particle groups, raw Jimsar oil shale particles produced by BaoMing Mines Ltd. (Xinjiang, China) were sieved into different size groups at first, and then the sieved groups were mixed at a certain ratio according to the industrial production. To avoid the wall effect, the diameters of the particles were limited at the range of $D/D_{max} > 10$ ($D_{max}$ is the maximum size of particles) [25].

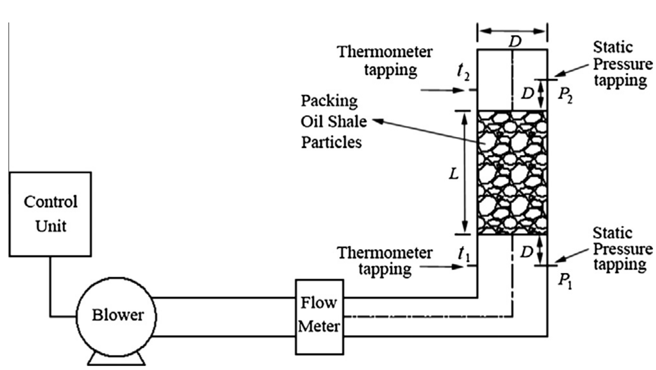


**Fig. 1.** Sketch of the experimental test set-up.

The two main dimensions (the volume $V_i$ and the surface area of the equivalent-volume sphere $S_{V,i}$) of a sample consisting of 200–300 particles for each particle group were calculated. Using the $V_i$ and $S_{V,i}$ of each particle, the equivalent diameter $d_{V,i}$ was defined according to Eq. (3) [26].

$$d_{V,i} = 6V_i/S_{V,i} \tag{3}$$

At the same time, the geometric average was proposed to determine the $d_V$ of oil shale particle group:

(1) The particle group which was obtained by sieving through two adjacent sieves:

$$d_V = \sqrt{d_{A,1} \cdot d_{A,2}} \tag{4}$$

(2) The particle group which was obtained by mixing sieved particle groups at a certain ratio:

$$d_V = d_{V,1} \cdot V_1\% + d_{V,2} \cdot V_2\% + \ldots + d_{V,n} \cdot V_n\% \tag{5}$$

where $d_{A,2}$ and $d_{A,1}$ are the aperture sizes of the stacking sieves in ascending order; $V_n$ is the volume fraction of particle group in the size interval $n$.

The porosity of the experimented packed bed was determined by measuring the total mass of the oil shale particles $M_s$, the real density of oil shale $\rho_s$ and the total volume of the bed $V_{tot}$ [27,28]:

$$\varepsilon = \frac{V_{Void}}{V_{tot}} = \frac{V_{tot} - V_S}{V_{tot}} = \frac{V_{tot} - M_S/\rho_S}{V_{tot}} \tag{6}$$

The average density of the crushed oil shale particles was measured using a volume displacement technique with water. The amount of water absorbed by the oil shale is determined by weighing the particles before and after the soaking. Surface water is removed in advance by drying the particles carefully using paper towels.

### 2.2. Measurements of sphericity

The pressure drops per length ($\Delta P_{Bed}/L_i$) through the packed beds were measured for superficial velocities ($U_i$) ranged from 0 to 1.0 m/s. To present the pressure drop measurements in dimensionless form, the particle friction factor, $f_P = (\Delta P/L)\cdot(d_V/\rho U^2)$, and the particle Reynolds number, $Re_P = \rho U d_V/\mu(1-\varepsilon)$, are introduced. According to literature [29], the constants $k_1 = 160$ and $k_2 = 1.61$ are chosen, then the modified Ergun equation is expressed as: