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INVESTIGATION OF THE GAS FLOW DISTRIBUTION AND PRESSURE DROP IN XINJIANG OIL SHALE RETORT

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Abstract. *Xinjiang oil shale retort is a new type of retorting device developed for exploiting Xinjiang oil shale according to the rock characteristics. Knowledge of the gas flow distribution in the retorting zone and the pressure drops across the retort is important to increase production rate and achieve the stable operation of the retort. In this paper, the structure and working principle of Xinjiang oil shale retort are introduced. The gas flow distribution in the retorting zone and the pressure drops across the retort system were investigated through a three-dimensional cold model of the retort. It was found that the distribution of vertical velocities of gas flow became more uniform with the increase of gas flow rate and bed depth. The optimal cold recycled gas amount is about 10% of the amount of hot recycled gas. In general, the results show that the gas flow distribution in the retorting zone is maldistribution, and the gas inlet structure should be modified. The empirical constants of the Ergun equation for the retort were determined, and the pressure drops across the retort were predicted and verified.*

Keywords: *oil shale, retort, Xinjiang, gas flow distribution, pressure drop.*

1. Introduction

Oil shale, which is a sedimentary rock containing kerogen and certain minerals, has the second largest abundant reserves among all fossil fuels in

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the world if converted into heat [1–5]. With the shortage of conventional energy resources and the high energy prices, developing an effective and economic retorting process to obtain oil and gases from oil shale as an alternative energy source has been the focus of many countries rich in oil shale, including China [6, 7]. In the Jimsar oil shale mineralized belt, Xinjiang Province, northwestern China, the oil shale resource has been estimated at over 11.4 billion tons, which can be converted into 0.57 billion tons of shale oil [8]. The Xinjiang oil shale retort was developed in 2011 for exploiting Jimsar oil shale of Xinjiang, considering the rock characteristics.

The Xinjiang oil shale retort is a vertical cylindrical vessel, as shown in Figure 1a. The retorting zone is divided into three parts – A, B and C, by three support structures (Fig. 1b). The gas inlet structure consists of two gas

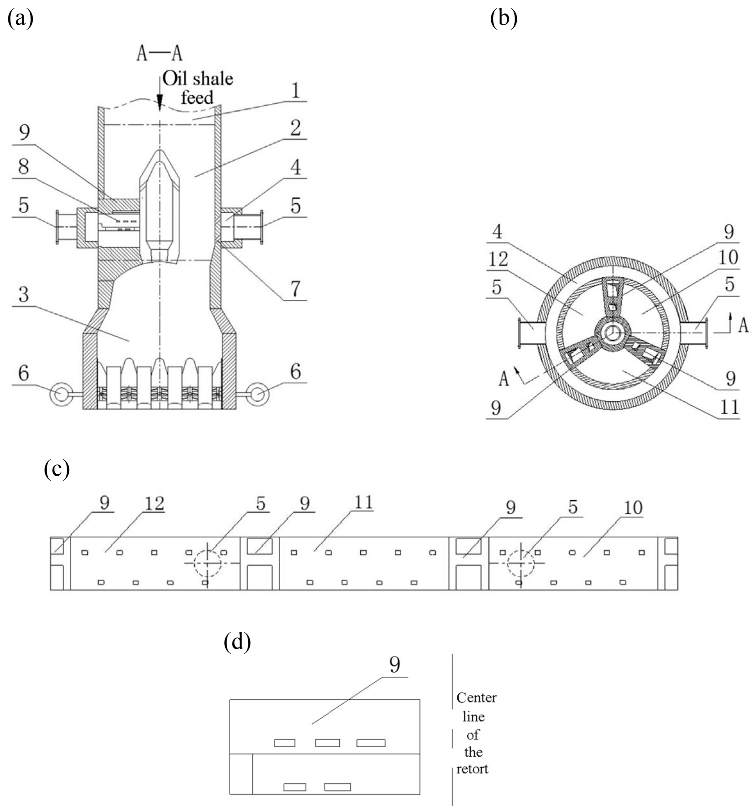

Fig. 1. The structure of Xinjiang oil shale retort: (a) main view (A-A sectional drawing; the A-A section line is shown in (b)); (b) cross-sectional view of the retort; (c) distribution of orifices in the wall of the retorting zone (inner side of the retorting zone); (d) distribution of orifices in the support structures (inner side of the retorting zone). 1 – preheat zone; 2 – retorting zone; 3 – cooling zone; 4 – annular gas channel; 5 – reheated recycled gas intake pipe; 6 – cold recycled gas intake pipe; 7 – orifices in the wall of the retorting zone; 8 – orifices in the support structures; 9 – support structure; 10 – Part A; 11 – Part B; 12 – Part C.

intake pipes and an annular gas channel which is connected with the retorting zone through the orifices. The reheated recycled gas flows first from the gas intake pipes into the annular channel and then via the orifices in the wall of the retorting zone and support structures into the retort. The distribution of orifices is shown in Figures 1c and 1d. Oil shale is poured and packed into the retort through the top and is heated at the retorting zone with reheated recycled gas. The cold recycled gas is blown into the retort from the bottom to make full use of the heat of spent shale. Spent shale is discharged from the bottom after being cooled. Oil vapors and gases are discharged through the top. Part of the gas is burned to heat the other part which is returned to the retort through the inlet structure to heat oil shale.

The distribution of the heating gas in the retorting zone and the pressure drop across the retort are responsible for heat exchange efficiency, products yield, oil quality, and the benefits of the oil shale retorting process. Therefore, knowledge of the gas flow distribution in the retorting zone and the pressure drop across the retort is important to increase production rate and achieve the stable operation of the retort. Xinjiang oil shale retort is a new type of retorting device, its gas flow distribution and pressure drop characteristics have not been figured out yet. Even though various mathematical models (CFD, OpenFOAM, etc.) have been developed to simulate gas flow in packed beds, the theoretical prediction of flow distribution and pressure drop is not yet possible due to the very complex flow of gas in irregularly shaped vessels of oil shale particles [9].

The main aim of this paper is to describe the gas flow distribution (gas velocity patterns) in the retorting zone and investigate the pressure drops across the Xinjiang oil shale retort through cold model experiments. Thus, the gas flow distribution in the retorting zone was measured using a customized control device system, the uniformity of gas flow in each part was calculated and the results were compared, and the sizes of "dead zone" were estimated. The pressure drops across the retort system were investigated to determine the empirical constants of the Ergun equation for the retort, and the pressure drops across the real retort were predicted and verified.

2. Experimental

The experiments were performed in the cold model of the Xinjiang oil shale retort made of transparent Perspex. The height of the model was 2.0 m (scale 1:5).

2.1. Gas flow distribution measurements

In order to simulate the complex vessels and voids of oil shale particles in the retort, soybean and corn mixture particles were fed to the retort through a disperser via a vibrating system. The packed height of the mixture particles was 1.95 m, and their bed porosity was 0.45 which is similar to that of oil shale particles.

A thermal anemometer equipped with a customized control device system was adopted for the measurement of gas flow velocities in the retorting zone. Using the control device system, the thermal anemometer can reach specific positions in the retort. Hence, it is possible to measure the gas flow velocities at various levels and radial positions in the three parts of the retorting zone. The gas flow velocities at six levels were measured, the distribution of the levels is shown in Figure 2a (the height of the level h = 1.03, 1.15, 1.27, 1.39, 1.51, 1.63 m). The radial distribution of measuring points (nine different mathematical degrees) at each level of the parts is shown in Figure 2b. Experiments were conducted with different gas flow rates for the purpose of comparison.

The uniformity of gas flow in each part of the retorting zone reflects the flow distribution from the viewpoint of statistics. In this work, the flow uniformity in the retorting zone is calculated by the following equation [10]:

$$Opt = \frac{W_{\text{mean}} - \frac{1}{n}\sum_{i=1}^{n}\left|W_i - W_{\text{mean}}\right|}{W_{\text{mean}}} \times 100\% , \quad (1)$$

where Opt is the uniformity of gas flow in each part of the retorting zone, %; W_i is the gas flow velocity at position i, m/s; W_{mean} is the average flow velocity, m/s; n is the number of measuring points.

Cold recycled gas is sometimes blown into the retort from the bottom to make full use of the heat of semi-coke according to the requirements of production, which will affect the flow distribution in the retorting zone. Hence, different amounts of cold recycled gas were used to study its effect on the flow distribution in the retorting zone.

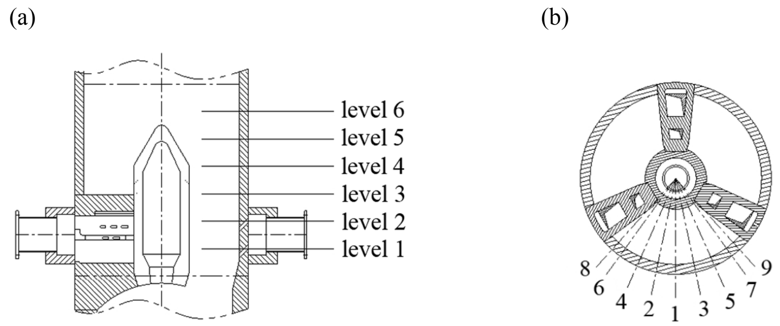

Fig. 2. The distribution of measuring points in the retorting zone: (a) level distribution, (b) radial distribution.

2.2. Pressure drop measurements

Three different oil shale particle groups, as used in the real retort, were packed into the model and experimented respectively. Four different packed bed lengths (L_i = 1.1, 1.3, 1.5, 1.7 m) were systematically tested for each packing particle group. The pressure drops per length ($\Delta P / L_i$) through the packed beds were measured for superficial velocities (U_i) ranging from 0 to 1.0 m/s.

The air flow was generated by means of two blowers combined with two alternating-current motor speed control units (Siemens MicroMaster 420). The flow rate was determined by an LUGB-2120D turbine flowmeter (Tianjin, China). The pressure drop (ΔP) was measured using a ZCYB-1000 digital micro-manometer (Yiou, China). In each experiment, repacking was performed four times to check the reproducibility of measurements.

The modified Ergun equation is extensively used to predict the pressure drops through packed beds:

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

where $\Delta P_{\mathrm{Bed}} / L$ is the pressure drop per length unit of the bed; Φ and d_{V} are the sphericity and equivalent volume diameter of particles, respectively; ε is bed porosity; μ, ρ and U are the dynamic viscosity, density and superficial mean fluid velocity of the fluid, respectively; k_1 and k_2 are the empirical constants of the Ergun equation.

The particle parameters (Φ, ε, d_{V}, etc.) of the above oil shale particle groups were determined according to Pan et al. [11], Geldart [12] and Mayerhofer et al. [13]. Through a linear regression analysis of experimental data, the empirical constants for the retort were determined. Then the pressure drops of the real retort were predicted by the Ergun equation. To verify the reliability of empirical constants and predicted data, the pressure drops across the real retort were measured by the manometric apparatus set up on the retort.

3. Results and discussion

3.1. Gas flow distribution in the retorting zone

Figures 3 and 4 illustrate the radial distribution of vertical velocities of gas flow measured at levels 1 and 6 in the retorting zone at a constant air flow rate, Q = 285 m^3/h. The lines in the figures are calculated by fitting the experimental data with a mathematical model [9, 14]. The model was derived using the streamline method by superposing potential sources at the radial direction of the retort onto a viscous flow stream.

The results indicate that in parts A and C of Xinjiang oil shale retort, the vertical velocity of gas flow is considerably higher in the regions around the

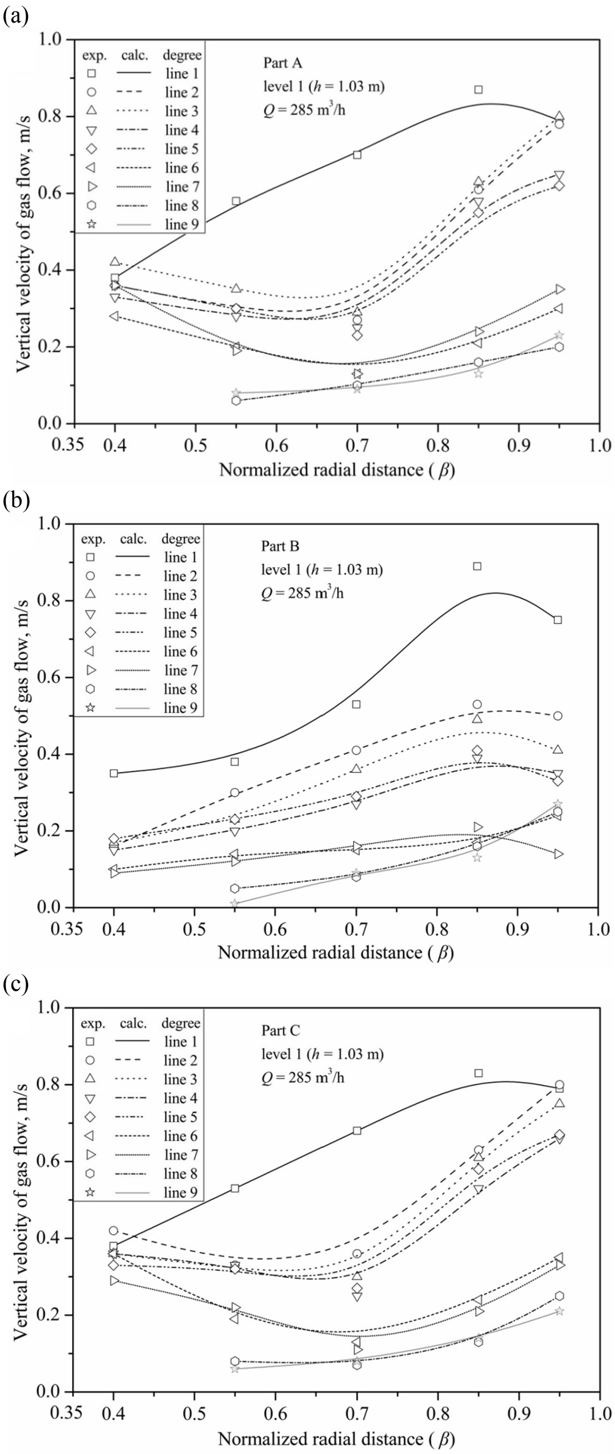

Fig. 3. Radial distribution of vertical gas flow velocities in: (a) Part A, (b) Part B, (c) Part C at level 1 at a constant air flow rate, Q = 285 m^3/h.

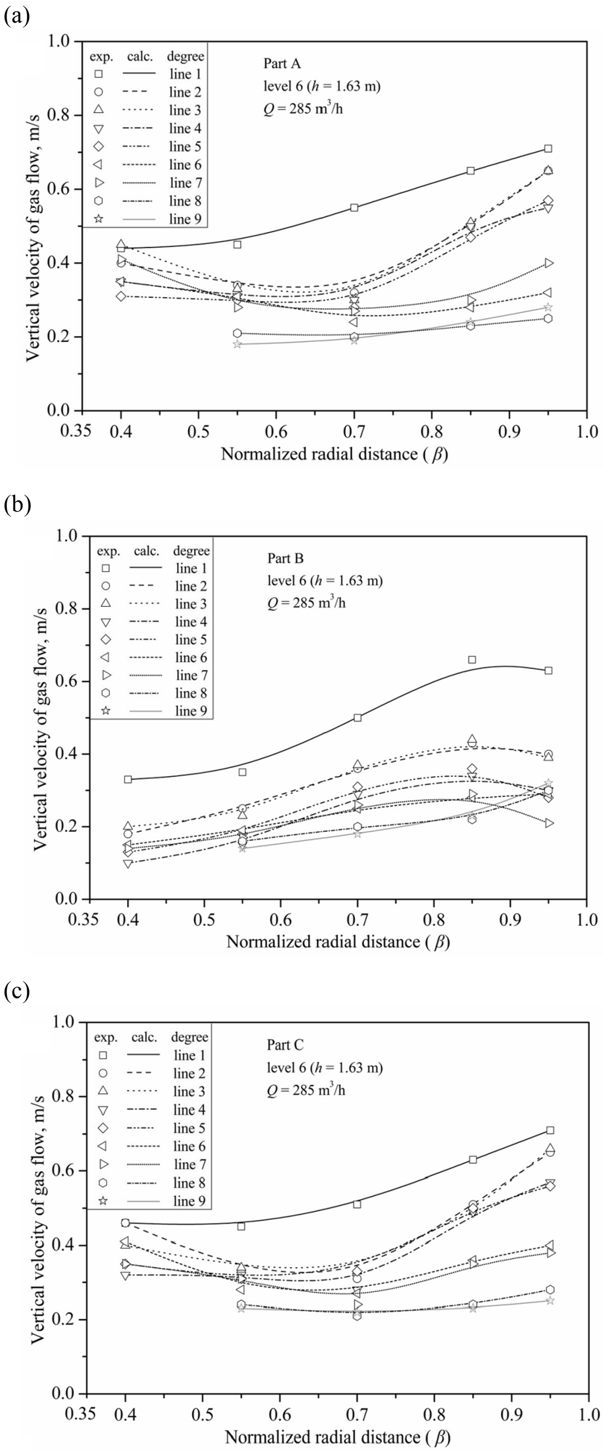

Fig. 4. Radial distribution of vertical gas flow velocities in: (a) Part A, (b) Part B, (c) Part C at level 6 at a constant air flow rate, Q = 285 m^3/h.

walls than that in the core regions; for Part B, the case is vice versa. For all three parts, the maximum velocities are around the center line (line 1), the velocities are regularly reduced in a parabolic curve along the circle direction. The velocities of the gas flow around the support structures (around lines 8 and 9) are close to zero.

The gas flow maldistribution may be reasoned by the structure of the retort. The Xinjiang retort is a packed bed connected with an annular gas intake channel, whereas such structure is widely used in industrial production. In many studies, flow maldistribution due to such structure has been figured out [15–18]. For example, Heggs et al. [16] developed a simplified model for predicting the radial gas flow distribution in the packed bed configured into an annular structure, and showed that this arrangement caused additional flow distribution problems. Wu [18] investigated the operation of Fushun oil shale retort of a similar structure and found the retort to have difficulties in managing its gas flow maldistribution.

Another reason for gas flow maldistribution is the existence of support structures. The flow of gas to the corners of each part of the retorting zone is hampered by the support structures, which in turn results in the low velocity of gas flow around lines 8 and 9.

The design location and sizes of orifices also have some effect on gas flow distribution. A series of gas flow distribution tests have been carried out to project the optimal location and sizes of orifices on the basis of their initial design location. However, the results show that the modified sizes and location of orifices have a limited effect only. The optimal location of orifices is shown in Figures 1c and 1d.

Table 1 compares the uniformities of gas flow (*Opts*) in the three parts of the retorting zone measured at different levels at different gas flow rates. The *Opt* increases linearly with the increase of bed depth (from bottom to top) and gas flow rate, which means that the distribution of vertical velocities becomes more uniform with increasing gas flow rate and bed depth.

As parts A and C are similar in structure, the gas flow distribution in them is also similar. At the same time, the flow distribution in Part B is more uniform than that in parts A and C, as can easily be seen from Figures 3 and 4, too.

An area where the vertical velocity of gas flow is less than 0.2 m/s is called "dead zone" because the flow intensity is so weak that oil shale in such a region cannot be completely pyrolyzed. The sizes of "dead zone" at different levels for various gas flow rates are shown in Figure 5. "Dead zone" size decreases with increasing bed depth and gas flow rate. For example, the area of "dead zone" at level 1 diminished from 27.13 to 23.07% while the gas flow rate increased from 285 to 360 m^3/h.

The uniformity of gas flow distribution in the retorting zone is improved while cold recycled gas is blown into the retort from the bottom. In this work, the influence of different amounts of cold recycled gas on the flow distribution in the retorting zone was investigated. Considering synthetically

Table 1. *Opts* of the parts of the retorting zone at different levels at different gas flow rates, %

Gas flow rate, m^3/h	Level	Part A	Part B	Part C
Q = 285	1	51.12	53.31	51.46
	2	53.70	56.71	53.79
	3	57.10	60.12	87.11
	4	61.23	64.03	61.39
	5	65.37	67.42	65.25
	6	69.21	71.23	69.15
Q = 320	1	53.26	55.42	53.34
	2	55.93	58.57	56.10
	3	60.03	62.33	59.32
	4	62.89	66.51	63.46
	5	66.84	68.89	66.89
	6	70.52	72.11	70.78
Q = 360	1	54.79	57.10	54.73
	2	57.86	60.23	57.51
	3	61.93	64.11	60.82
	4	64.10	67.79	64.53
	5	68.41	70.03	68.11
	6	71.63	73.23	71.77

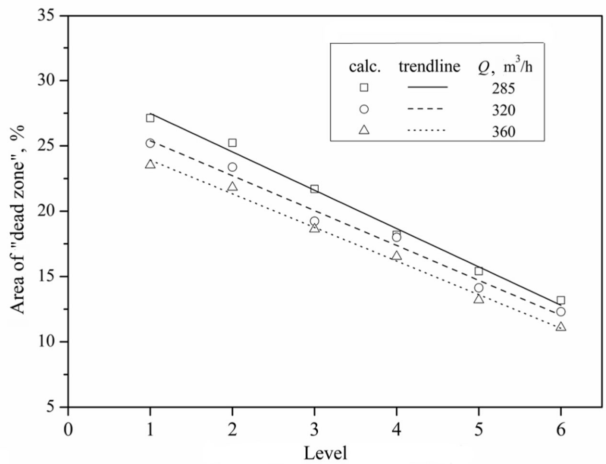

Fig. 5. “Dead zone” sizes at different levels for various air flow rates.

the influence of heat exchange rate, cost, equipment capacity, etc., the flow distribution was optimal while the amount of cold recycled gas accounted for about 10% of that of hot (reheated) recycled gas. Figure 6 shows the radial distribution of vertical gas velocities at level 1 while cold recycled gas is blown into the retort from the bottom. The *Opts* of the parts of the retorting zone at different levels are given in Table 2.

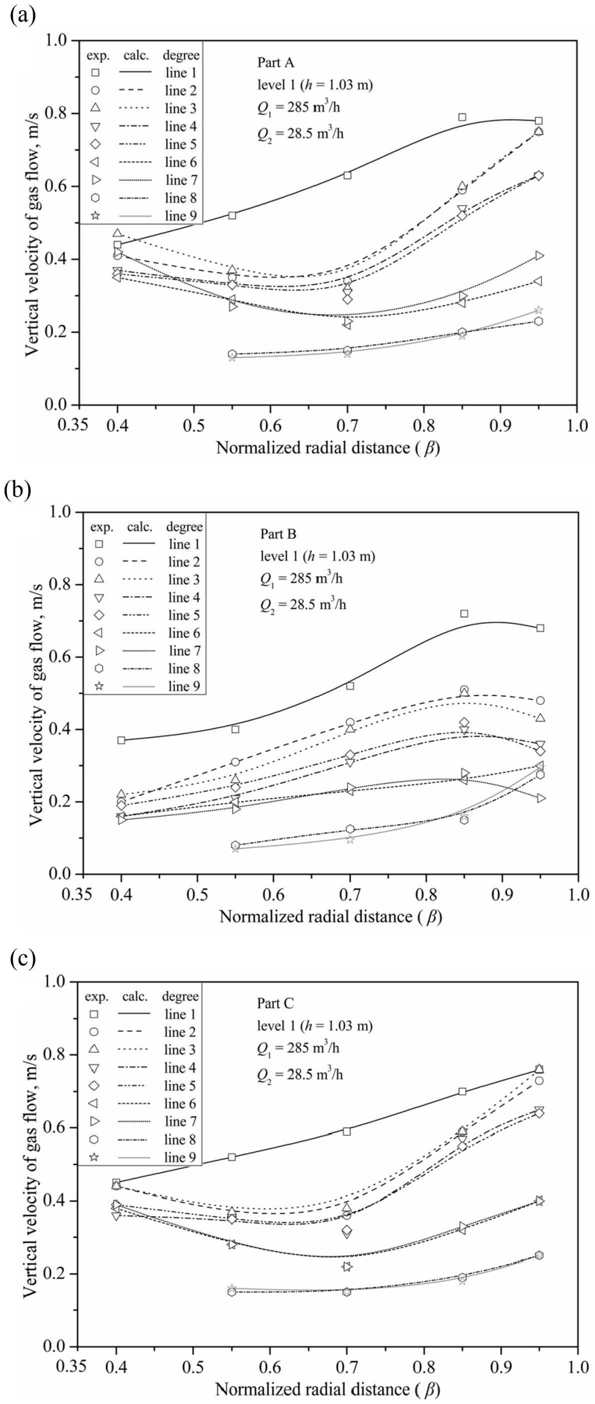

Fig. 6. Radial distribution of vertical gas flow velocities in: (a) Part A, (b) Part B, (c) Part C at level 1 while cold recycled gas is blown into the retort from the bottom (the flow rate of hot recycled gas Q_1 = 285 m^3/h; the flow rate of cold recycled gas Q_2 = 28.5 m^3/h).

Table 2. *Opts* of the parts of the retorting zone while cold recycled gas is blown into the retort from the bottom

Flow rate of hot recycled gas, m^3/h	Flow rate of cold recycled gas, m^3/h	Level	Part A	Part B	Part C
285	28.5	1	57.32	59.45	57.19
		2	59.29	62.37	59.47
		3	62.17	65.17	62.13
		4	65.37	68.31	65.68
		5	68.77	69.83	69.75
		6	72.34	73.42	73.44

The oil shale particles will collide heavily and move randomly during the packing and retorting process. Consequently, the operating conditions in the real retort are so complex that the gas flow distribution could not be measured directly. However, analysis of the amount of shale spent shows that about 20–30% of the shale remains unpyrolyzed, which corresponds to the volume of "dead zone" in the retorting zone calculated in this work. The main purpose of cold model experiments is to simulate and describe the flow distribution in the Xinjiang oil shale retort to find a way to enhance its heat exchange efficiency. The results show that the gas flow in the corners of the retorting zone is too weak to pyrolyze oil shale, and a feasible and effective way for improving the gas flow distribution in the retort is to modify the gas inlet structure.

3.2. Pressure drops across the retort

The variations of the experimental pressure drop ($\Delta P / L_i$) against superficial velocity (U_i) for the oil shale retort model packed with oil shale particles are depicted in Figure 7. The particle sphericity and bed porosity values and equivalent volume diameters of three oil shale particle groups are given in Table 3. For the retort, the pressure drop increases with increasing superficial velocity (U_i) and decreasing equivalent volume diameter (d_V). The measured pressure drops in Figure 7 (solid lines) represent the function of the Ergun equation. Through linear regression analysis, the empirical constants of the Ergun equation for the retort were derived:

$$k_1 = 192, \quad k_2 = 1.69$$

The above values fit all the experimental data with correlation coefficient values larger than 0.96.

With the determined particle parameters, empirical constants and known properties (μ, ρ) of recycled gas, the pressure drops across the real retort were predicted through the Ergun equation, as shown in Figure 8. To verify the reliability of the predicted data, the pressure drops across the real retort were measured. As the normal operation of the retort cannot be affected, this paper measured the pressure drops under some representative operating conditions (the superficial velocity of recycled gas U_i = 0.5, 0.6, 0.7, 0.8 m/s), as shown in Figure 8. It can easily be seen from the figure that the predicted pressure drops fit the operational data well (with correlation coefficient values larger than 0.99).

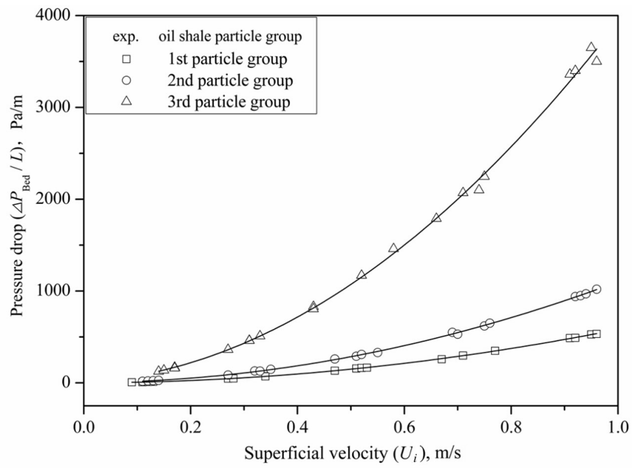

Fig. 7. The variations of experimental pressure drop ($\Delta P / L_i$) against superficial velocity (U_i).

Table 3. The particle parameters of Jimsar oil shale of Xinjiang

Oil shale particle group	Size range, mm	d_V/mm	ε	Φ
1st	35–60	43.9	0.471	0.768
2nd	26–50	31.4	0.463	0.676
3rd	10–26	17.6	0.439	0.509

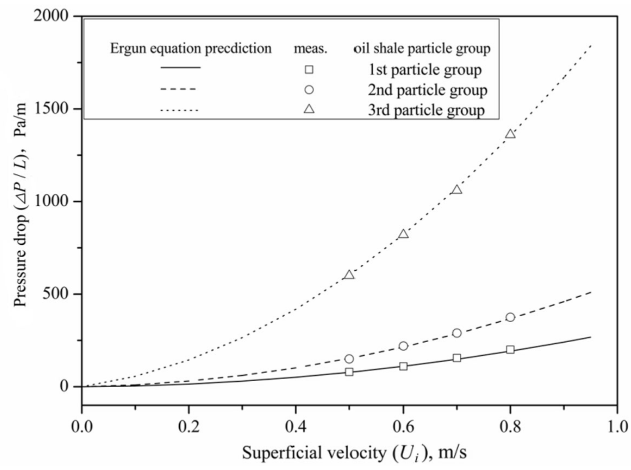

Fig. 8. Comparison of the predicted pressure drops and measured pressure drops of the real retort.

4. Conclusions

In this study, the gas flow distribution and pressure drops in Xinjiang oil shale retort were investigated through cold model experiments. Based on the results obtained as well as analysis of data, the following may be concluded:

(1) The distribution of vertical gas flow velocities becomes more uniform with increasing flow rate and bed depth. The size of "dead zone" decreases with the increase of flow rate and bed depth.

(2) The uniformity of gas flow distribution in the retorting zone is improved while cold recycled gas is blown into the retort from the bottom. The optimal amount of cold recycled gas is about 10% of the amount of reheated recycled gas.

(3) In general, the gas flow distribution in the retorting zone is maldistribution. The gas flow in the corners of the retorting zone is too weak to pyrolyze oil shale. The flow distribution can be improved through modifying the gas inlet structure to enhance the heat exchange efficiency of Xinjiang oil shale retort.

(4) The empirical constants of the Ergun equation for the retort were determined. The pressure drops across the retort were accurately predicted through the Ergun equation.

Nomenclature

d_V	–	equivalent volume diameter of oil shale particles, m;
h	–	height of the level from bottom to top, m;
k_1, k_2	–	empirical constants of the Ergun equation;
L	–	bed depth from the retort bottom to top, m;
n	–	number of measuring points;
Opt	–	uniformity of gas flow in each part of the retorting zone;
ΔP	–	pressure drop, Pa;
Q	–	gas flow rate, m^3/h;
r	–	radial distance, m;
R	–	bosh radius of the retorting zone, m;
U_i	–	superficial velocity of gas flow in the retort, m/s;
W_i	–	vertical velocity of gas flow at position i, m/s;
W_{mean}	–	average flow velocity, m/s;
Greek	–	
β	–	normalized radial distance, r/R;
ε	–	bed porosity;
μ	–	fluid dynamic viscosity, kg/ms;
ρ	–	fluid density, kg/m^3;
Φ	–	sphericity.

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