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Original Research Paper

Effect of a draft tube on oil shale particle drying process of a spouted bed: CPFD simulation studies

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A B S T R A C T

Material drying pretreatment plays an important role in the oil shale retorting process. In this study, the drying process of particulate oil shale in a spouted bed was simulated using computational particle fluid dynamics numerical schemes. This study analyzes the effect of the draft tube and inlet air temperature on the drying rate and drying uniformity, and establishes a new insight into the drying process and multi-phase flow characteristics inside the spouted bed. The results indicate that using an ordinary cylindrical spouted bed results in a poor drying uniformity, which causing by a large number of the annulus-region particles fall into the spout region from the height of approximately 150 mm and resulting in a stirless area usually observed at the height of 50–150 mm near the wall. Inserting the draft tube and reducing the drying temperature can improve the uniformity of the drying process, and the former is more efficient than the latter.

1. Introduction

Oil shale is a type of sedimentary rock rich in kerogen, and is also a type of sapropelic coal. Retorted shale oil is a substitute for petroleum [1]. Exploration data demonstrate that the global oil shale reserves can be converted into about 400 billion tons of shale oil. Therefore, the research into comprehensive oil shale utilization technology has great significance for alleviating the current global energy crisis [2,3]. Majority of oil shale contains a high level of moisture, and moisture significantly decreases the quality of the obtained shale oil, as well as the energy consumption during the retorting process. Therefore, drying pretreatment plays an important role in the oil shale retorting process.

The retorting of particulate oil shale requires the moisture content of the raw material to be below 5%, and the oil shale material is usually dried to a moisture content of about 2% after the drying pretreatment [4]. Since Gishler and Mathur [5,6] invented the spouted bed, spouted bed technology has widely been used in drying, gasification, combustion, flue gas desulphurization, particle crushing, and certain other fields [7–10]. Owing to its rapid particle circulation and efficient heat and mass transfer [11], spouted bed could be applied for high-efficiency and high-quality drying of particulate materials. Bai et al. [12] conducted the experiments of oil shale drying using the spouted bed. The results indicate that the particle size is the primarily important effect factor of the drying efficiency, and that the spouted bed has significant advantages for the drying of 1–3 mm particulate oil shale.

The improved structures of the spouted bed are used to meet various application requirements. The draft tube can block the mass exchange between the annulus region and spouted region and reduce particle mixing and circulation. Inserting a draft tube increases the regularity and stability of the particle circulation. Meanwhile, the minimum spouted pressure drop reduces, and the maximum bed height limit of spouted-bed operation is relaxed. The basic form of the draft tube is a nonporous draft tube [13,14]. In addition, there are a variety of draft tube improvement forms to adapt to different requirements, such as a porous draft tube [15], open-sided draft tube [16], conical-cylindrical draft tube [17], and rotating draft tube [18,19]. The porous draft tube and open-sided draft tube are used to improve the gas-solid exchange efficiency between the spouted region and annul region, which makes possible the gas percolation or solid cross-flow from the annulus into the spout region. The conical-cylindrical draft tube increases the diameter of the lower end, thus enhancing the solids circulation rate. A rotating draft tube is used to prevent particles from falling back into the draft tube, and a rotating draft tube is more suitable for large-diameter spouted beds. Mahmoodi et al. [20] simulated a conical spouted bed with open-sided draft tube through CFD-DEM (computational fluid dynamics-discrete element) model. They investigated the different between open-sided draft tube protruding above the bed surface and open-sided draft tube flushed with the bed surface. Altzibar et al. [21] studied a conical spouted bed for drying fine particles with three types of draft

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Nomenclature

T	temperature	r_p	particle radius
θ_f	fluid volume fraction	θ_{cp}	volume fraction at close packing limit
υ_f	fluid velocity	P_s	positive constant
ρ_f	fluid density	h_1	dilute phase heat transfer coefficient
S_f	fluid source term	h_d	particle heat transfer coefficient
P	fluid stress tensor	k_f	mass transfer coefficient
g	gravitational acceleration	Nu_p	Nusselt number of particles
F	momentum exchange rate per volume between the fluid and particle phase	Re	Reynolds number
		d	average proportion of the wall covered by particle phase
q	energy transfer due to conduction	$C_{H_2O,liq}$	the concentration of water vapor at the particle surface
$\dot{Q}$	energy source term	$C_{H_2O,bulk}$	the concentration of water in the surrounding gas
E	energy	M_w	molecular weight of water
H	enthalpy for ideal gases	W	mass of water in a particle
θ_p	particle volume fraction	T_p	particle temperature
ρ_p	particle density	c_p	heat capacity
υ_p	particle velocity	m_p	mass of the particle
τ_p	particle normal	X	ratio of evaporated water to original moisture
D_p	interphase drag coefficient	τ_{sim}	simulation characteristic time
V_p	particle volume	M_R	relative moisture content
C_d	drag coefficients	U_{ms}	minimum spouting velocity
C_{dw}	drag coefficients calculated by WenYu model	ϵ	void fraction of the dried particle shell
C_{de}	drag coefficients calculated Ergun A model	Sh	Sherwood number
μ_f	gas viscosity		

tubes, namely, nonporous, porous and open-sided draft tubes. They investigated the effects of different types of draft tubes on the drying characteristics. Results show that nonporous draft tubes are also very stable but perform poorly, while porous draft tube and open-sided draft tube perform better but requiring higher air flow rate, approximately double that of nonporous.

Owing to the extremely complex characteristics of multiphase flow, there are no efficient experimental methods that can reveal the online features of the drying process inside three-dimensional spouted beds, such as the air flow dynamics and the drying profile [22]. The recent development of numerical simulation technology provides another option to study the characteristics of the multiphase flow. The dynamics of multiphase flow and the chemical reactions in a complex system can be obtained rapidly and cost-effectively by numerical simulation. Hosseini et al. [23–25] carried out a series of numerical simulation studies on various spouted beds using a Eulerian-Eulerian two-fluid model, in which they investigated the effect of various types of essential modeling parameters on spouted-bed simulation, such as the particle-wall restitution coefficient, specularity coefficient, and frictional stress models. Yang et al. [26] simulated a cylindrical spouted bed with a nonporous draft tube using computational fluid dynamics discrete-element method CFD-DEM model. They performed a comprehensive analysis of the effect of the inserting draft tube on the particle flow characteristics in the spouted bed. Setarehshenas et al. [27] studied the spouted behavior of c heavy particles in various spouted beds and analyzed the differences of flow characteristics when using light particles. The predicted drying results showed good agreement with the experimental data [28–30] in the numerical simulation of the fluidized drying process.

The CPFD (computational particle fluid dynamics) method is considered to be a powerful tool for the large complex multiphase flow system simulation. This method has widely been applied to study various multiphase flow systems. Bigda [31] simulated the hydrodynamics of the gas-solid flow and the drying process of Polish coal with three construction variants. Wang [32,33] simulated the gas-solid flow in a circulating fluidized bed with a loop seal. They investigated the effect of the operating parameters, such as loop seal aeration rate, fluidized air velocity in the riser, and the total bed inventory, on the solid circulation characteristics. Abbasi [34] simulated the feeding section of a fast-fluidized bed for coal gasification. Fotovat and Liang [35,36] simulated a bubbling fluidized bed for mixing biomass and sand. From these results, the effectiveness of the CPFD method for the modeling of gas-solid flows in complex systems has been demonstrated extensively. It could simulate the gas-solid two-phase system efficiently and accurately.

In this study, the drying process of particulate oil shale in the spouted bed was simulated using the CPFD method. The effect of the inlet air temperature and draft tube on the drying rate and drying uniformity was analyzed from particle motion characteristics and moisture content distribution. Results show that the drying process has poor drying uniformity. The cause of this phenomenon was studied based on the particle trajectories and moisture distribution, and an attempt was made to improve the drying uniformity of the bed by inserting a draft tube. Meanwhile, the effect of inserting a draft tube on the drying rate and drying uniformity was analyzed from the stirless area distribution and particle velocity distribution. Additional insight into the drying dynamics and the multiphase flow characteristics of the spouted-bed drying process was gained. Numerical simulation of the spouted-bed drying process is an extension of the experimental research. It provides an important reference and guidance for the research and design of the oil shale drying device.

The paper is further organized as follows: Section 2 briefly introduces the CPFD method and its mathematical model. Section 3 describes the simulation configurations. In Section 4, the prediction results are discussed and compared to investigate the drying characteristics in the spouted bed. Finally, the conclusions are summarized in Section 5.

2. CPFD mathematical model

Based on the MP-PIC (multiphase particle-in-cell) method, the CPFD numerical schemes are developed to solve the simulation of large complex multiphase flow system [37]. CPFD numerical schemes deal with the coupled calculation of multiphase flow