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Experimental study on heat storage and transfer characteristics of supercritical air in a rock bed

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ABSTRACT

Experiments were carried out to investigate the heat storage and heat transfer behavior of supercritical air flowing through a rock bed with the working temperature and pressure ranging up to 120 °C and 6.55 MPa, respectively. The particle-to-fluid heat transfer coefficients were determined at low Reynolds numbers of 55–125, and the effects of the air pressure, mass flow rate and the entrance distances on the heat transfer coefficient were studied. The results indicate that the radial temperature profile and the entrance effect would be decreased at high pressure, and the experimental heat transfer coefficients at both pressures fit well with Chandra's correlation and Yang's equation of non-uniform spherical particles.

1. Introduction

Recent years, with the development of concentrated solar power (CSP), the advanced adiabatic compressed air energy storage (AACAES) and the waste heat recovery et al. much interest has been paid in the sensible thermal energy storage (TES) with the material of rock beds [1,2]. Such rock beds thermal storage have the advantage as: (1) economical storage material; (2) large heat transfer area (3) a thermal efficiency higher than 95% can be obtained; (4) suitable for wide temperature range and (5) good mechanical and chemical stability. For the AACAES system, the use of TES to recover heat during compression and to heat compressed air during expansion is the prominent advantages compared with the traditional CAES system which need fossil energy [3,4]. Due to the advantages in cost, efficiency and reliability, rock bed is almost the optimal TES for the AACAES system and the heat is charge/discharge by the heat transfer between the compressed air at supercritical pressure with the particles of rock beds directly.

Since the early equation for modeling flow in porous media was proposed by Darcy in 1958, considerable investigations were carried out on the packing structure, flow, heat transfer and mass transfer behaviors of packed beds [1,2,5–17]. Although there are many practical applications of high pressure packed beds, such as trickle bed reactors, supercritical fluid extraction, adiabatic compressed air energy storage, etc., few attempts have been made to study the pressurized packed beds and very little fundamental knowledge is currently available [10–19]. Al-Dahhan presented a review of high pressure trickle bed reactors, it was pointed out that, in general, atmospheric models and correlations cannot be extrapolated to high pressure operations, particularly when the gas flow rate is higher than 2 cm/s [10]. Wammes et al. conducted experiments to determine the influence of trickle bed reactor pressure with gas pressure up to 7.5 MPa and found that high gas density is the main influence on the hydrodynamic behavior [11–13]. Tan and Funazukuri respectively studied the axial dispersion coefficients employing supercritical CO_2 in packed beds by experiments, the influence of the factors such as velocity, operating pressure and temperature, etc. on the coefficients were analyzed and the correlation was obtained [14,15]. Jiang et al. experimentally and numerically studied the convection heat transfer between supercritical CO_2 and wall when fluid flowing through porous tubes, and the influence of the inlet temperature, pressure, mass flow rate, particle diameter and heat flux on the convection heat transfer at supercritical pressures were analyzed [16].

The particle-to-fluid heat transfer coefficient in packed beds is of prime importance when analyzing the heat transfer characteristics

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Nomenclature

a	particle surface area per unit volume of bed, /mm
c	specific heat, kJ/(kg K)
D	diameter of packed bed, mm
d	average diameter of particles, mm
h	heat transfer coefficient, W/(m^2 °C)
k	thermal conductivity, W/(m K)
T	temperature, K
t	time, s
U	superficial velocity, m/s
V	volume flow rate, L/h
x	distance, m

Greek letters

ρ	density, kg/m^3
ε	average bed void fraction
λ	thermal conductivity, W/(m K)
δ	average radius of particles, mm

Subscripts

F	air
p	particle or particle to air
r	particle surface
S	particle
V	volume

of rock bed heat storage. Lof and Hawley experimentally investigated the unsteady-state air-granitic gravel heat transfer coefficients with the size of 0.19-inch to 1.5-inch in diameter and obtained a relation between the coefficients, air flow rate, and rock size [17]. Closely, Coutier and Farber, Chandra and Willits also conducted experiments to determine the volumetric convective heat transfer coefficient of rock particle-to-air at different conditions and proposed such equations [18–20]. Wakao and Kaguei derived an empirical formula based on the published particle-to-fluid heat transfer coefficient data using various experimental techniques [21]. The effects of packing form and particle shape on the forced convective heat transfer between packed bed and air were experimental investigated by Yang et al. and the heat transfer constants of different packings were obtained based on the experimental points [22]. Augier et al. carried out CFD simulations of particles scale to investigate the transport and transfer properties inside packed beds of spherical particles at low to moderate Reynolds numbers [23]. As to the high pressure condition, Guardo et al. analyzed the mixed (free and forced) convection at high pressure in a fixed bed and predicted the particle-to fluid heat transfer coefficient by numerical simulation but no experimental data is available for the high pressure or supercritical situation [24,25].

In this paper, the experimental study on the thermal storage and unsteady-heat transfer behavior of supercritical air flowing through the rock bed was carried out at *Re* number of 55–125 under the pressure condition of 0.22 MPa and 6.55 MPa. The particle-to-air heat transfer coefficients were found out and the effects of air pressure, flow rate and entrance distance were also studied. Due to the low pressure drop under conditions in this work, the pressure drop behavior will not be studied in details.

2. Rock bed properties

The rock bed is made from the crushed granite and screened to the size of 7–11 mm. The void fraction ε is determined by the traditional water saturation method [26], and the mass increase due to the addition of water was measured: the quotient between the volume of water introduced and the total volume of the container gives the average porosity of the packed bed. The measurements were repeated four times and the results were listed in Table 1, the average void fraction was found to be 0.40.

Dozens of rock particles were selected at random and their densities were tested via Mettler Toledo XS205DU analytical balance and the accessories for density measurement, the average rock density was found to be 2688 kg/m^3. The heat capacity of the rock was measured via TA DSC Q2000 with the "modulate DSC" function such that the specific heat capacity could be analyzed directly. The dependence of rock specific heat capacity on temperature in the range of 20–170 °C was plotted in Fig. 1 and it was found that heat capacity of the rock increased almost linearly with the increasing of temperature from 0.825 J/(g °C) at 40 °C to 1.08 J/(g °C) at 160 °C. Due to the irregular shape of the granite rock, the average equivalent diameter and the specific surface area were analyzed by Retsch Camsizer as shown in Fig. 2(a) and (b). By averaging the results of 3 groups of granite rocks, the average equivalent diameter was found to be 9.0 mm. The bed to particle diameter ratio (D/d_p) in the packed bed is as high as 38 where the wall effects can be neglected for heat transfer [27–29].

Table 1
Void fraction measurement results of the rock bed.

Exp. Sequence	Mass of rock beds (kg)		Volume of water (L)	Void fraction	Average void fraction
	Before addition of water	After addition of water			
1	30.90	38.28	7.38	0.399	0.40
2	30.74	38.13	7.39	0.400	
3	30.92	38.28	7.36	0.398	
4	30.93	38.37	7.44	0.400	

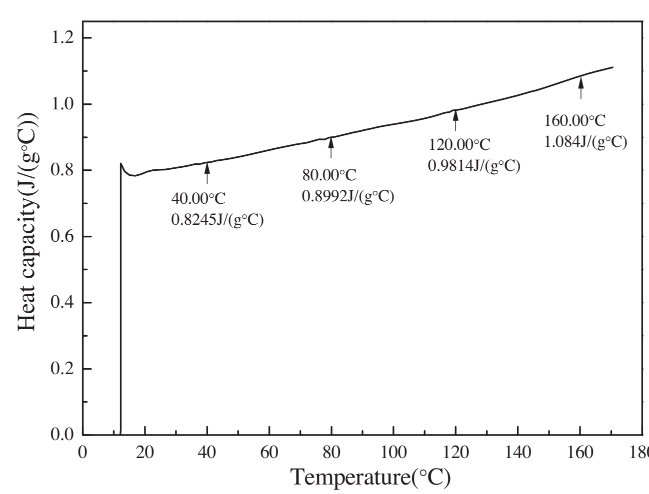

Fig. 1. Specific heat capacity of rock vs. temperature by DSC.