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Experimental study on helium pressure drop across randomly packed bed for fusion blanket

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ABSTRACT

Pebble beds are used in many tritium breeder designs of fusion blanket, which is purged by a flow of low velocity helium. In this paper, experimental study of the pressure drop of helium through packed sphere beds was carried out. The pebbled beds were sealed in a rectangular container. The spheres of five different diameters varied from 0.5 mm to 2.0 mm. The Darcy regime and Forchheimer regime were identified within the range $2.47 < Re < 27.59$. The transition region was identified and discussed in detail. The pressure drop was characterized by Kozeny-Carman constants or Ergun's constants for the experimental range. Some commonly used correlations were evaluated by the experimental data.

1. Introduction

Lithium orthosilicate Li_4SiO_4 pebble beds have been selected as tritium breeder in many TBM(Test Blanket Module) designs for fusion research [1]. The tritium generated in the pebble beds is purged by a flow of low velocity helium gas. Thus, the pressure drop of the helium across the randomly packed pebble beds is a key parameter to design helium supply system. Pebble beds are also widely used in other industrial fields like chemical catalysis reactors and pebble-bed nuclear reactors. The spheres of pebble beds used in tritium breeder are quite small (about 0.5 mm in diameter). The flow velocity of purge helium is quite low (about 0.1–0.5 m/s). Although the studies of flow through packed beds of spheres were extensive, there was no reliable universal correlations for the TBM designs.

Abou-Sena et al. [2,3] performed an experimental measurements of the helium pressure drop across pebble beds. In their research, glass pebbles in diameter from 0.25 to 1.20 mm were used. It should be noted that the packed spheres in each case have different diameters. The weighted average diameter (WAD) of pebbles was calculated as the effective diameter. Fand et al. [4] analyzed the flow resistance through randomly packed spheres in different regimes. They concluded that there exists six regimes in porous media: (1) The pre-Darcy flow which is attributed to non-Newtonian behavior. (2) The Darcy regime where viscous forces is dominated. (3) The transition zone from Darcy to Forchheimer flow. (4) The Forchheimer flow where inertial flow is pronounced. (5) The transition from Forchheimer flow to turbulent flow. (6) The turbulent flow which is highly unsteady and chaotic. The Reynolds number of each regime boundary was discussed. The Kozeny-Carman constant for Darcy flow and Ergun's equation for Feichheimer flow was suggested.

Ergun's equation has been widely adopted to estimate the pressure drop through packed beds for Darcy and Feichheimer flow. The application of Ergun's equation depends on two constants, which have been discussed and improved by many researchers [5–8]. Although some universal values of the two constants were recommended by some researchers, these values have not reached an agreement [9].

The present study experimentally measured the helium pressure drop across randomly packed spheres. To cover a parameter range relevant to blanket design, five different diameters range within 0.5–2.0 mm were chosen. The helium velocity ranged from 0.1 to 2.0 m/s. The experimental results, compared with theoretical predications, are analyzed based on different flow regimes.

2. Experimental setup and procedures

The helium flow diagram of the facility is shown in Fig. 1. The experimental setup consisted of the test section and the helium supply system. The helium was supplied by four 40 L helium bottles. The pressure of helium was reduced to the desired value by a regulator (V1). Then the helium flowed into the test section. Finally, the helium flow was discharged to air. The helium flow rate was measured by a thermal gas mass flowmeter before the test section. The helium temperature was measured by the K-type thermalcouples before and after the test section (T1,T2). The absolute pressure was measured by pressure transmitters. Two pressure probes (P1,P2) were located before and after the test section. The differential pressure was measured by three pressure

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Nomenclature

Re_p	particle Renolds Number, $Ud/(1-\epsilon)\nu$
Re_{DH}	The lower bound of Darcy regime
Re_{FL}	The upper bound of Darcy regime
Re	Renolds number, Ud/ν
d	pebble diameter, mm
P'	pressure gradient, Pa/m
μ	dynamic viscosity, kg/ms
U	mean flow velocity, m/s
ν	kinematic viscosity, m^2/s
ϕ	sphericity
ϵ	porosity
f	friction factor, $P'd/\rho U^2$

transmitters (dP1–dP3) at different range, see Fig. 2. All five differential pressures were measured with the same single transducer. Therefore, the differential pressure can be measured accurately in wide range. All sensors were connected to a Data Acquisition System.

The pebble beds were formed by packing the stainless steel pebbles in a 20 × 20 rectangular channel, which was cut from a cylindrical container, see Fig. 3. The pebbles were made of 310ss stainless steel with surface mirror polishing. The ball diameter variation is not over 2.5 µm. The roundness is not over 2.5 µm. The roughness is not over 0.2 µm. Wire mesh filters were used to seal the pebble beds in the inlet, outlet and pressure probes, see Fig. 4. The aperture of the filters is 0.27 mm. To determine the pressure drop across the pebble bed, five pressure probes were located at intervals of 100 mm along the pebble beds.

Before the experiments, the test facility was evacuated by the vacuum pump and filled with helium for three times. The gas flow rate and inlet pressure were controlled by the regulator (V1,V2) and the outlet valve (V3). After the flow was stable, the pressure switch values (VP1–VP5) were opened respectively to measured the pressure drop of every point.

Table 1 shows the test matrix in the present study. The porosity was kept 0.38 in each case. Based on the volume flow rate measured in the experiments, the superficial velocity of the pebble bed channel is calculated. The max superficial velocity was limited by the measure range of the flow meter (0–3 NCMH). In the experiments, helium superficial flow velocity was increased from 0.1 m/s to the max velocity by 0.1 m/s step. The outlet valve (V3) was full open in the experiments, therefore the outlet pressure measured by P2 is atmospheric pressure. The inlet pressure measured by P1 is listed in Table 1.

3. Results and discussion

3.1. Regimes of flow

Due to the different dominant forces in Darcy flow and Forchheimer flow, we can distinguish these regimes by some treatment of experimental data. For Darcy flow, the flow velocity is proportional to the negative of pressure gradient. The relationship is called Darcy's law as follows:

$$P' = \frac{\mu}{K}U, \tag{1}$$

where K is the permeability. The equation was divided by μUd^{-1} as follows,

$$\frac{P'd}{\mu U} = \text{Cd} \tag{2}$$

where $C = K^{-1}$. The permeability K for uniform spheres beds was suggested in [4] as,

$$K = \frac{d^2}{36\kappa\alpha} \tag{3}$$

In Forchheimer flow, in addition to the Darcy flow, inertial effects become more important. Ergun's equation for sphere pebble beds ($\Phi = 1$) was adopted as follows,

$$P' = A\frac{(1-\epsilon)^2}{\epsilon^3}\frac{\mu U}{d^2} + B\frac{1-\epsilon}{\epsilon^3}\frac{\rho U^2}{d}, \tag{4}$$

where A, B are Ergun constants. For convenience, the equation was divided by μUd^{-1} with the following expression,

$$\frac{P'd}{\mu U} = \frac{A\alpha}{d} + \frac{B\beta\rho U}{\mu} \tag{5}$$

The above equation is derived to be a more convenient form by defining two new constants,

$$\frac{P'd}{\mu U} = C_1 d + C_2\,\text{Re}, \tag{6}$$

where

$$C_1 d = \frac{A\alpha}{d},\ C_2 = \frac{B\beta}{d} \tag{7}$$

A graph of $P'd/\mu U$ with Re was plotted in Fig. 5. The Darcy flow and Forchheimer Flow were clearly shown in this figure. Zone 'a' represents Darcy flow regime, where Cd remains constant. Zone 'b' represents transition regime between Darcy flow and Forchheimer Flow. The Cd values changed irregularly when transition occurred. Zone 'c' represents Forchheimer Flow, where Cd increased with the Re. Two dashed line represents Re_{DH} and Re_{FL} for each case respectively. The two transition points were characterized when the pressure drop change abruptly. It appears that Re_{DH} and Re_{FL} increases with pebble diameter, which is listed in Table 2. The transition zone 'b' is too irregularly to

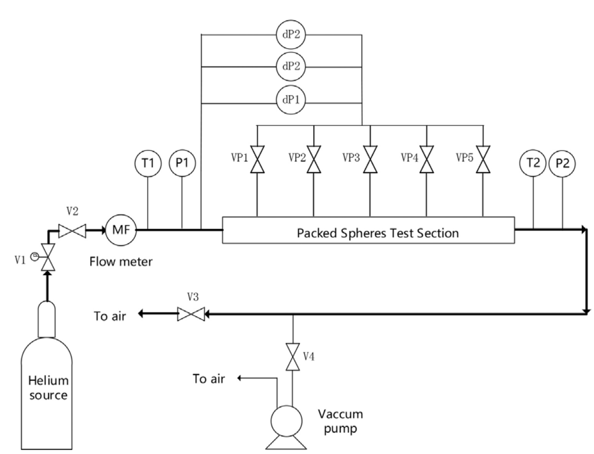

Fig. 1. Test facility diagram.

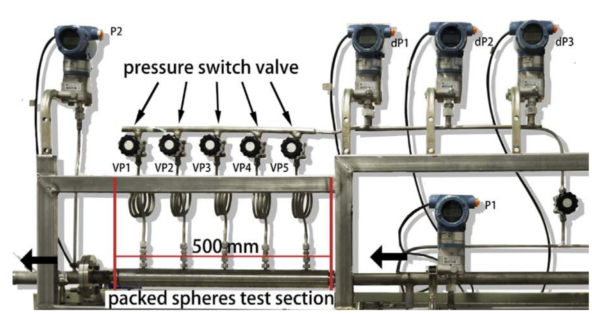

Fig. 2. photo of test section and pressure drop measurement.