energies

Article

Experimental Investigation on Pressure Drops of Purge Gas Helium in Packed Pebble Beds for Nuclear Fusion Blanket

Hao Cheng [1,*], Baoping Gong [1,*], Bing Zhou [1], Juemin Yan [1], Long Wang [1], Long Zhang [1], Yongjin Feng [2] and Xiaoyu Wang [1]

[1] Southwestern Institute of Physics, Chengdu 610041, China
[2] Nuclear Power Institute of China, Chengdu 610041, China
* Correspondence: chengh@swip.ac.cn (H.C.); gongbp@swip.ac.cn (B.G.); Tel.: +86-18810907263 (H.C.); +86-18382001656 (B.G.)

Abstract: The flow characteristics of purge gas helium in the pebble bed of the tritium breeding blanket are important in analyzing the tritium purging process and optimizing the design of the solid breeder blanket. Therefore, the flow characteristics of helium gas in randomly packed pebble beds are investigated experimentally with a focus on the analysis of the pressure loss distribution. The results show that gas velocity, bed dimension, and pebble diameters have an obvious influence on the helium flow characteristics in pebble beds. With the increase in the inlet helium gas velocity, the pressure drop gradient of helium in the pebble bed gradually increased. With increases in the pebble bed dimension, the pressure drop gradient of helium in the pebble bed gradually increased. With the increase in the pebble diameter, the pressure drop gradient gradually decreased. In addition, the effect of temperature on the pressure drop of helium in the pebble bed was also preliminarily investigated. The pressure drop gradient of the helium through the pebble bed obviously increased with the increase in the helium and the bed temperature. The experimentally obtained pressure loss characteristics can be used for the validation of the simulation of a blanket pebble bed and as input parameters in the thermo-hydraulic analysis of solid-tritium breeder blankets.

Keywords: pressure drops; flow resistance; helium; pebble bed; packing factor

check for updates

Citation: Cheng, H.; Gong, B.; Zhou, B.; Yan, J.; Wang, L.; Zhang, L.; Feng, Y.; Wang, X. Experimental Investigation on Pressure Drops of Purge Gas Helium in Packed Pebble Beds for Nuclear Fusion Blanket. *Energies* **2024**, *17*, 1309. https://doi.org/10.3390/en17061309

Academic Editor: Sung Joong Kim

Received: 2 January 2024
Revised: 29 February 2024
Accepted: 6 March 2024
Published: 8 March 2024

1. Introduction

Solid-tritium breeding blankets are the critical core components of fusion reactors, mainly performing the functions of tritium breeding and energy extraction [1]. In solid-tritium breeding blankets of fusion reactors, tritium production is achieved mainly through the reaction of Li(n, α) T, where T is also called tritium, represented by the symbols T or ^{3}H; it is a rare and radioactive isotope of hydrogen, from between the neutrons and lithium atoms in ceramic breeder materials, such as Li_4SiO_4, Li_2TiO_3, and Li_2O, etc. [2]. To increase the tritium production rate, neutron multiplication is usually achieved by adding neutron multiplier materials, such as beryllium or beryllide, into the blanket [3,4]. To mitigate the swelling effect of neutron irradiation and facilitate tritium extraction, tritium breeders and neutron multipliers are usually in the form of spherical or pebble-like particles, which are packed in the different cavities of the solid blanket [5–7]. For instance, the Li_4SiO_4 pebbles and beryllium (Be) pebbles with diameters of ~1 mm are selected as tritium breeders and neutron multipliers, respectively, in helium-cooled ceramic breeder test blanket modules (HCCB TBMs) [8,9] and Chinese Fusion Engineering Test Reactor (CFETR) HCCBs [10].

The tritium produced in the tritium breeder is gradually released from the grains to the grain boundaries and then to the pores of the breeder and pebble bed through mechanisms such as diffusion and migration. Finally, the helium purge gas carries tritium out and transfers it to the tritium extraction system (TES) and tritium factory for further processing [11,12]. The release of tritium from the tritium breeder is primarily governed by the material's properties and the tritium transport mechanism [13]. However, after tritium is released into the pores of the pebble bed, the tritium transport process is mainly determined by the flow behaviors of the purge gas. Therefore, the pressure drop and flow resistance characteristics of the helium inside the pebble bed are critical to the design of the tritium extraction system and solid blanket.

The pressure drops and flow behaviors of the tritium purge gas through the pebble beds, obtained from experimental measurements, can provide important experimental data to support the design of a solid-tritium breeding blanket. Seki et al. [14] experimentally investigated the pressure drops of the tritium purge gas through the tritium breeder Li_2TiO_3 pebble bed, with a focus on the semi-cylindrical array structure walls and flat-plate walls. The results show that, due to the higher packing factor, the increasing trend of the pressure drop is slightly higher for the rectangular bed with the flat-plate walls than for the rectangular bed with semi-cylindrical array structure walls. Abou-Sena et al. [15,16] explored the helium gas flow characteristics in cylindrical and rectangular pebble beds by experiments measuring the pressure drop. The results showed that, for the case of the helium moving through the pebble bed with constant inlet velocity, the pressure drops increase with the increase in bed length and inlet pressure, which agreed well with the Ergun model with a modified constant. Panchal et al. [17] experimentally measured the pressure drop of nitrogen gas in beds with different pebble sizes and gas flow rates. The results showed that the pressure drop in a pebble bed increases with the decreasing pebble diameter. The effect of the different pebble materials on the pressure drop is small and negligible. Mandal et al. [18] established an experimental setup for the helium purge and thermophysical property measurements of pebble beds. Wang et al. [19] and Liu et al. [20] developed an open-ended helium flow characteristic measurement device. The pressure loss characteristics in square pebble beds packed with steel pebbles were investigated experimentally. The effects of the bed porosity, pebble size, and gas flow on the pressure drop were analyzed in detail. In addition, the detailed helium flow characteristics in localized pebble bed models were investigated numerically [21–29]. Lei et al. [25] numerically investigated the helium flow characteristics in the pebble bed and verified the dependency of flow behaviors on the packing structures of pebble beds by DEM and CFD simulation. Cheng et al. [22] explored the relation of the flow characteristics of helium gas in pebble beds with different local structures, such as simple cubes (SC), face-centered cubes (FCC), body-centered cubes (BCC), and randomized packing (RP). The results show that the macro pressure drop and the mesoscopic flow characteristics are strongly correlated with the packing structures of the pebble beds.

A macroscopic pressure drop of helium through the pebble bed can be obtained from experimental measurements, and numerical simulations can determine the localized helium flow characteristics of the pebble bed. The above results can provide support for the thermo-hydraulic analysis of the pebble bed in fusion blankets. However, for the service conditions of the tritium breeding blanket, the pressure drop of purge gas helium inside the pebble bed of fusion blanket is influenced by many factors, such as bed dimension, pebble size, temperature, superficial velocity, etc. However, the existing experimental data about the helium gas through the fine-pebble-packed (~1 mm) bed are still insufficient. Therefore, we developed a measurement facility for measuring the pebble bed high-temperature gas pressure drop and flow characteristics at the Southwestern Institute of Physics (SWIP).

The present study experimentally investigated the flow behaviors of purge gas helium inside the pebble bed with a focus on the effects of different helium flow superficial velocities, pebble sizes, bed dimensions, temperature, etc., on the helium-flow-resistance characteristics in the pebble bed, which can provide experimental data as input parameters for the thermo-hydraulic analysis of solid-ceramic-tritium breeder pebble beds.

2. Experimental Methodology

2.1. Experimental Setup

To experimentally investigate the flow resistance characteristics of tritium purging gas in a solid-tritium breeding blanket, a measurement facility was developed for measuring the high-temperature helium gas flow resistance in pebble beds for a fusion blanket. A schematic diagram of the experiment facility is shown in Figure 1. The facility mainly consists of pebble-bed-testing sections, measurement units, and gas flow pipes.

The inlet end of the pebble-bed-testing section is connected to the helium source system by a connecting tube. A series of temperature and differential pressure measurement points are installed along the helium gas flow direction in the pebble-bed-testing section. A measuring unit comprises a pressure pipe, a tee connector, a thermocouple, and a differential pressure sensor. The tee connector is connected to the pressure pipe, the thermocouple, and the low-pressure side of the differential pressure sensor, respectively. The other end of the pressure pipe extends into the pebble bed, and the thermocouple also extends into the pebble bed through the tee connector and the pressure pipe. The high-pressure side of the differential pressure sensor is connected to the inlet end of the pebble bed. The low-pressure side is connected to the pressure measurement point in the pebble bed via the tee connector and the pressure pipe. Helium cylinders provide the helium gas source. The gas flow rate into the pebble bed is controlled utilizing a high-precision mass flow meter. To ensure the ability to investigate the effect of the temperature of the pebble bed and the gas on the pressure drop, the entire pebble-bed-testing section was placed in a high-temperature furnace to keep the entire pebble bed at a uniformly high temperature. The maximum design temperature of the pebble bed reached 950 °C. The working temperature is ≤900 °C. The length of the pebble beds is 600 mm with 6 temperature-measurement points.

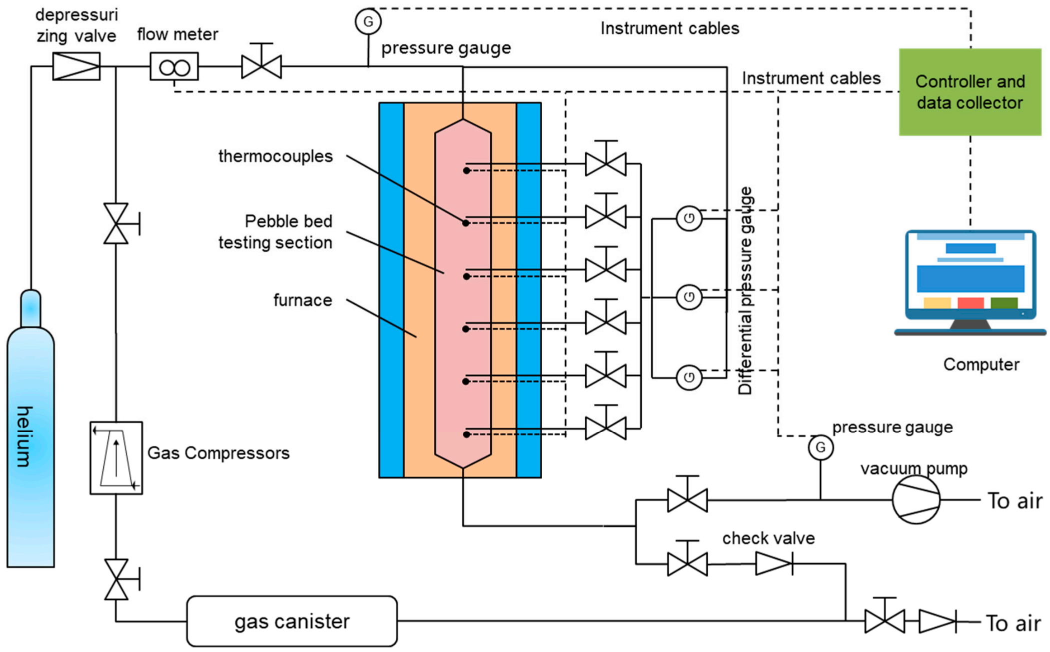


Figure 1. Schematic diagram of the measurement facility of high-temperature helium gas flow resistance in pebble beds.

2.2. Materials and Pebble Beds

In this experiment, 304 stainless-steel pebbles of different sizes were used as packing pebbles in the solid-tritium breeding blanket instead of tritium breeder ceramic pebbles and beryllium pebbles. The size and properties of the 304 stainless-steel pebbles are listed in Table 1. Figure 2 shows the morphology of the 304 stainless-steel pebbles. To investigate the pebble size effect, sizes of 0.8 mm, 1 mm, and 1.5 mm were selected. Helium gas (purity 99.99%) was used as the purge gas in this experiment. The pressure-drop-measuring experiments were conducted at room temperature.

Table 1. Properties of pebble material used in experiments.

Property	Symbols	Value
Density (kg/m^3)	ρ_p	7900
Pebble size (mm)	d_p	1 $\pm$ 0.05; 0.8 $\pm$ 0.05; 1.5 $\pm$ 0.05
Sphericity	S	0.95
Aspect ratio	A	1.01

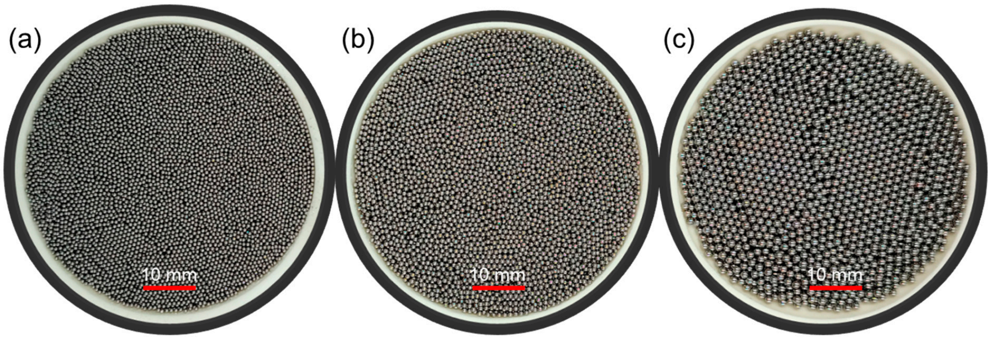


Figure 2. Steel pebbles with different pebble diameters: (**a**) 0.8 mm, (**b**) 1 mm, and (**c**) 1.5 mm.

The designed pebble-bed-testing section is shown in Figure 3a. The section view is shown in Figure 3b; the section was machined and fabricated with high-temperature alloy 310S material. The inner cross-sectional shapes inside the pebble-bed-testing section are cylindrical with different diameters; the length of the pebble bed is 600 mm. There are 6 pressure-difference-measuring points along the flow direction in the pebble bed, with steps of 100 mm. For the pebble-bed-testing section with different shapes and sizes, except for different cross-sectional shapes and sizes, all the other parameters were the same. The cross-sectional dimensions are listed in Table 2.

Table 2. Parameters of the testing section of cylindrical pebble beds.

Testing Section ID	Bed Diameter/mm	Bed Length/mm	Pebble Diameter/mm
1	D = 28	L = 600	d_p = 0.8, 1, 1.5
2	D = 40	L = 600	d_p = 1
3	D = 50	L = 600	d_p = 1

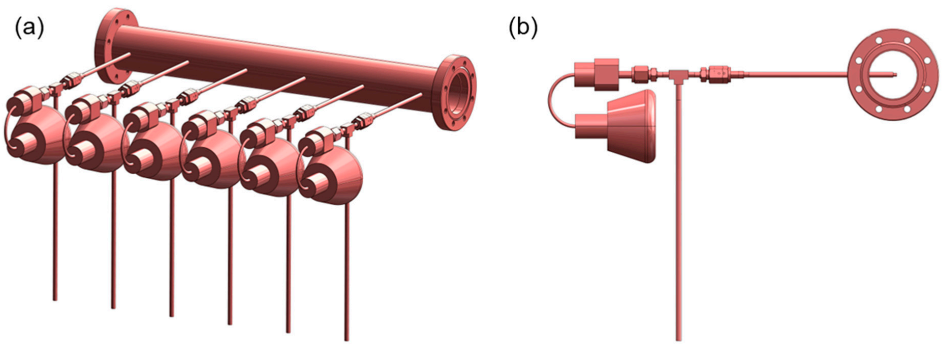


Figure 3. Testing section of pebble beds: (**a**) 3D view, (**b**) side view.

It is well known from previous studies that there is a wall effect in the region near the fixed wall in randomly packed pebble beds. The wall effect affects the packing structure characteristics of pebble beds. Radial porosity will oscillate violently in the region near the fixed wall. The average porosity is relatively large, and there is a bypass flow in the wall-affected region. Thus, to reduce the wall effect on the pressure drop, the pressure-inducing tube was extended inside the spherical bed, as shown in Figure 3b. In addition, to prevent the loosening of pebbles at both ends of the pebble bed, filters were added at both ends of the experimental section and fixed by variable-diameter flanges.

2.3. Experimental Procedure and Data Processing

The experimental procedure for measuring the pressure drop and flow resistance is shown in Figure 4. There are four main steps to the experimental process.

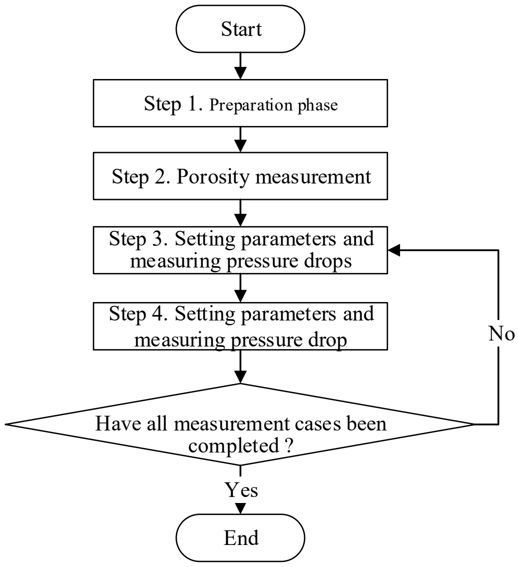


Figure 4. Procedure of pressure-drop-measuring experiment.

Step 1. Preparation: The equipment status is checked and the granular materials and experimental gas are prepared.

Step 2. Porosity measurement: The cavity of the designed pebble-bed-testing section is filled with granular pebbles. Two filters are added at both ends of the testing section and fixed by a variable-diameter flange to prevent the loosening of the granular pebbles. The porosity of the pebble bed inside the testing section is measured using the weighing method. Figure 5 shows the pebble packing in the pebble-bed-testing section. After the pebbles are packed in the pebble bed, the measuring chamber of the test section is be installed at the experiment facility. Then, a leak check is performed.

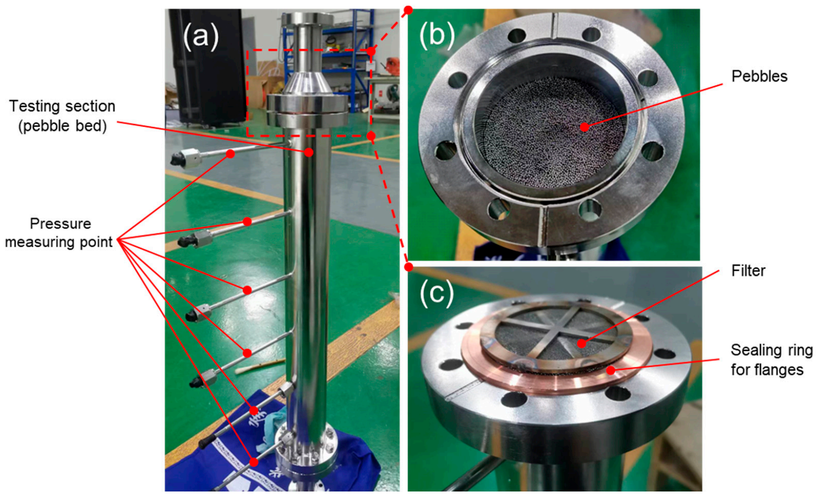


Figure 5. Packing of pebbles in pebble-bed-testing section. (**a**) Measuring chamber of the test section. (**b**) Pebble-packing process. (**c**) Installation of filter.

Step 3. Setting parameters and measuring pressure drop: All components of the facility are checked again to make sure that they are working well and that the installation of the pebble-bed-testing section is completed. Then, the helium gas is controlled to enter the pebble bed stably by valves and flow meters. Differential pressure tests are carried out at different positions of the pebble bed along the gas flow direction by switching valves. The inlet pressure to the pebble bed is controlled in the range of 0.1 to 0.2 MPa. The gas flow rate is controlled by a flow meter. The temperature of the pebble bed is controlled by the high-temperature tube furnace. Measurement under different conditions is completed by adjusting each parameter.

Step 4. Data acquisition and processing: In each measurement, the final experimental results are recorded after the collected real-time data are stabilized. Porosity and pressure drop rate are calculated separately at the end of a set of experiments. The experiments are concluded when all the measurements under different parameters in the experimental program are complete.

In this work, the experiments were conducted to measure the differential pressure inside the pebble bed at different locations along the flow direction from the inlet of the pebble bed. In addition, the end effects and filter's influence were excluded by subtracting the differential pressure data. Then, the pressure drop per unit length was determined by fitting the slope of the pressure loss along the flow direction.

3. Results and Discussions

3.1. Effect of Bed Length on Pressure Loss

Figure 6 shows the pressure loss of helium gas at various positions in the pebble bed along the flow direction. In these measurements, pebbles with diameters of 1 mm were packed in a cylindrical container with an inner diameter of 28 mm. The packing factor was 0.627. Figure 6 shows that the pressure loss, Δp, along the flow direction increased linearly and gradually with the increase in the length of the pebble bed. When the inlet helium flow rate was 0.5 m/s, the pressure loss 150 mm from the inlet of the bed was 1.15 kPa; this increased to 6.036 kPa at 550 mm from the inlet of the bed. The pressure loss increased to 6.036 kPa when the inlet flow rate was 1 m/s; the pressure loss at 150 mm from the inlet of the pebble bed was about 2.50 kPa; when the distance increased to 350 mm, the pressure loss increased to 7.829 kPa; when the distance increased to 550 mm, the total pressure drop reached 13.806 kPa. When increasing the superficial velocity of helium, the slope of the pressure loss along the axial direction increased significantly. By comparing the results obtained in this work with the experimental data measured by Liu et al. [20], it was found that the increasing trends are in agreement; this indicates that the results obtained in this work are reliable and the pebble-packing structures were uniform along the axial direction. The total pressure loss increased with the increase in the distance to the pebble bed inlet end. The results in this work were slightly lower at the position near the pebble bed inlet than those in the literature [20], which may be due to the slightly different packing factors of the different kinds of pebble beds.

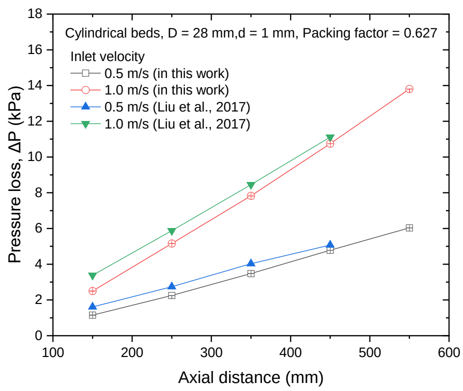


Figure 6. Pressure loss along the flow direction in pebble bed with different velocity [20].

3.2. Effect of Superficial Velocity on Pressure Loss

To analyze the effect of the inlet helium gas's superficial velocity on the pressure drop and helium gas flow resistance in randomly packed pebble beds, the pressure loss along the flow direction in the bed at a velocity of 0.5~1.0 m/s was measured, as shown in Figure 7. The inner diameter of the pebble bed is 28 mm; stainless-steel pebbles with a size of 1 mm were selected and packed in the bed container. The packing factor was 0.627 and the porosity was 0.373. The results indicated that the pressure loss along the flow direction and pressure drop gradient increased with increases in the inlet helium gas velocity. This is mainly because, as the gas flow rate increased, the collisions between the gas molecules and the surfaces of the pebbles inside the spherical bed become more and more violent, resulting in a gradual increase in the pressure loss.

In addition, the pressure drop per length unit was calculated and compared with Ergun's model [30]. Ergun's model has been widely used to estimate the pressure drop in packed-particle beds. According to the Ergun model [30], the pressure drop is predicted by the following formula:

$$\frac{|\Delta P|}{L} = k_1 \frac{(1-\varepsilon)^2}{d_p^2 \varepsilon^3} v\mu + k_2 \frac{1-\varepsilon}{d_p \varepsilon^3} \rho_f v^2 \quad (1)$$

where ΔP is the pressure loss and L is the pebble bed length. μ is the hydrodynamic viscosity of helium gas. d_p is the pebble diameters. ε is the porosity. v is the gas's superficial velocity. ρ_f is the density of the fluid. k_1 and k_2 are Ergun's constants. The original empirical constants have values of 150 and 1.75.

However, Ergun's empirical constants need to be determined for each bed because, after repacking, they may change from a macroscopic bed to another type of bed due to the changes in the packing structures within the pebble bed [31]. The second constant was adjusted to (k_2 = 2) for the best fitting with their experimental values in Abou-sena's experiment about the helium gas through the pebble beds [16]. In this work, Ergun's constants were adjusted to k_1 = 147 and k_2 = 3. The results and comparison are shown in Figure 7. It can be seen that, in the flow rate range of this paper (0.5~1.0 m/s), the helium pressure drop gradient was almost linearly related to the flow rate, as shown in Figure 7b; this is in good agreement with the prediction of Ergun's model with different Ergun's constants [16,30]. This is because, for the gas flow in porous media consisting of a packed-particle bed, the pressure drop usually consists of both the viscous term and the inertial terms. When the gas flows with relatively low superficial velocity, the pressure drop is mainly determined by the viscous term, exhibiting a linear relationship between the pressure drop and the superficial velocity, as shown in Figure 7b.

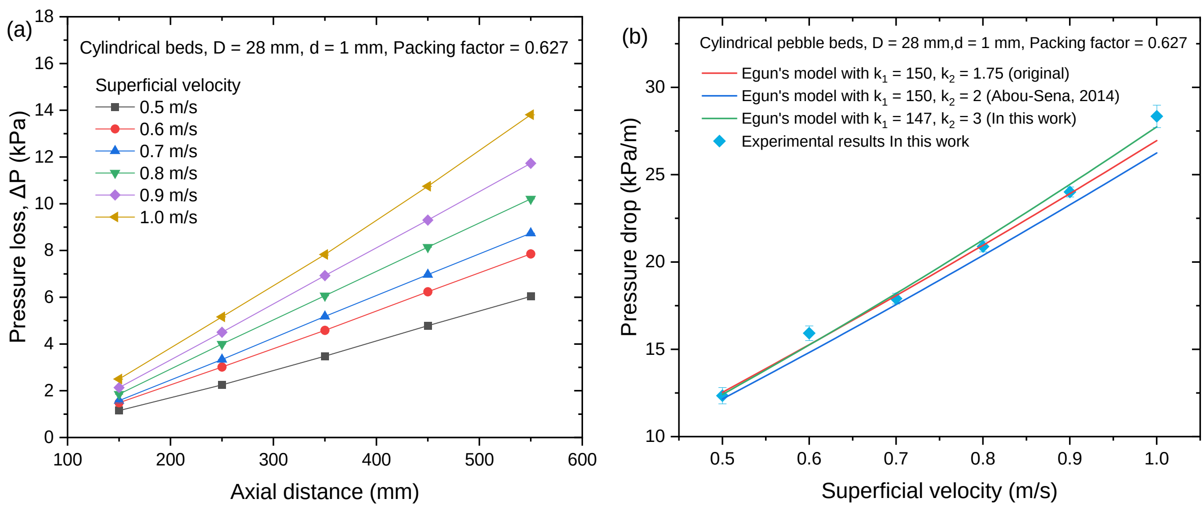


Figure 7. Effect of velocity on the pressure drops in pebble bed. (**a**) Pressure loss along the flow direction; (**b**) pressure drop per unit length [16].

3.3. Effect of Pebble Bed Dimension on Pressure Loss

The pressure drops of the helium gas flow in the pebble beds with different bed dimensions were measured. The inner diameters of the cylindrical beds were 28 mm, 40 mm, and 50 mm. The pebble diameters are all set to 1 mm. The inlet gas velocity was set to 1 m/s. The pressure drop of the helium along the flow direction inside the pebble beds is shown in Figure 8a. The results show that the pressure loss along the flow direction gradually increased linearly with the increase in the bed length; this is agreement with the previous measurement. The slope of the pressure loss is the pressure drop gradient. For the same testing section of the pebble bed, the longer the length of the bed, the more pressure is lost; however, the pressure drop gradient was essentially constant, which was due to the uniform packing structure along the axial direction. From Figure 8b, it can be seen that the change in the bed's dimensions can significantly affect the pressure drop. As the pebble bed size increases, the pressure drop per unit length gradually increases. This is mainly because changes in the dimensions of the pebble bed lead to significant changes in the packing structure (e.g., packing factor and porosity) in the pebble bed. The average packing factor gradually increased, and the porosity gradually decreased as the dimensions of the pebble bed increased, as shown in Figure 9; in turn, this affected the gas pressure distribution inside the pebble beds.

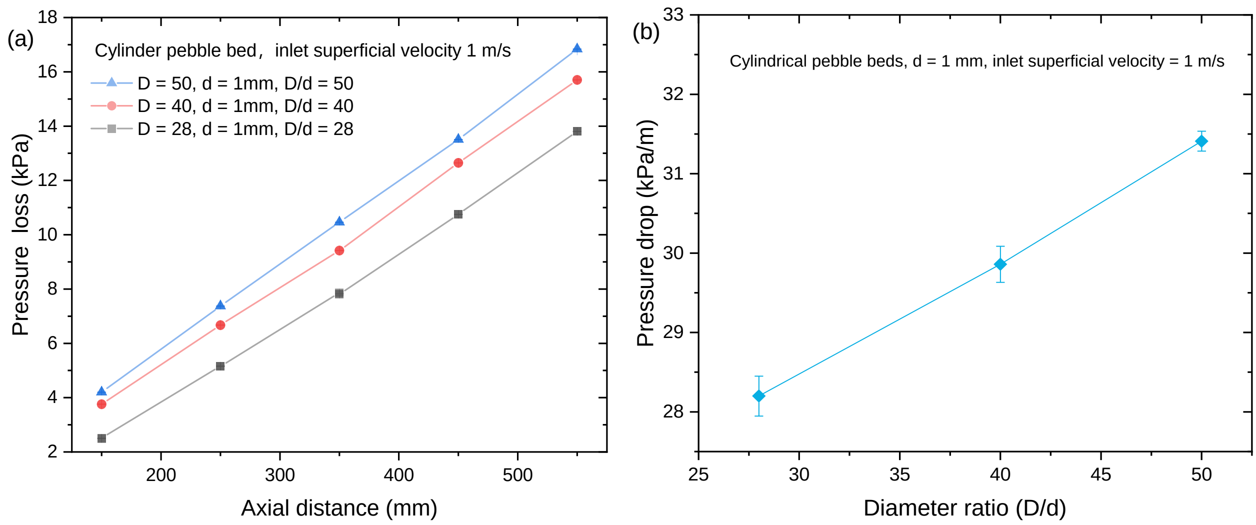


Figure 8. Effect of bed dimension on pressure loss: (**a**) pressure loss along flow direction; (**b**) pressure drop gradient at different diameter ratios.

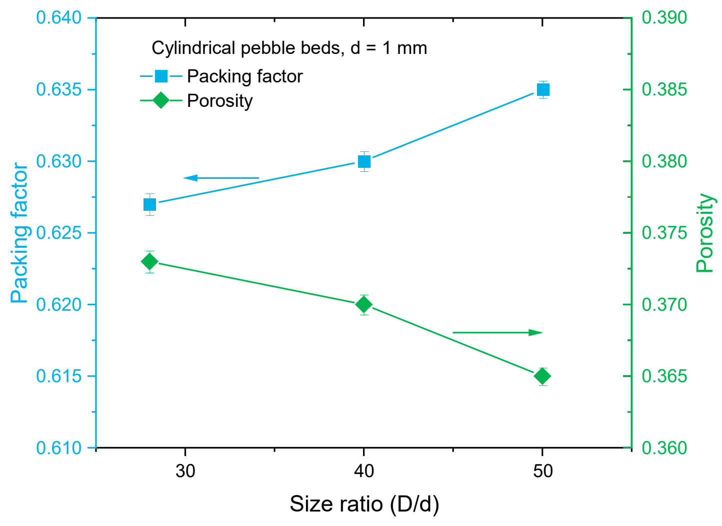


Figure 9. Packing factor and porosity of cylinder pebble beds.

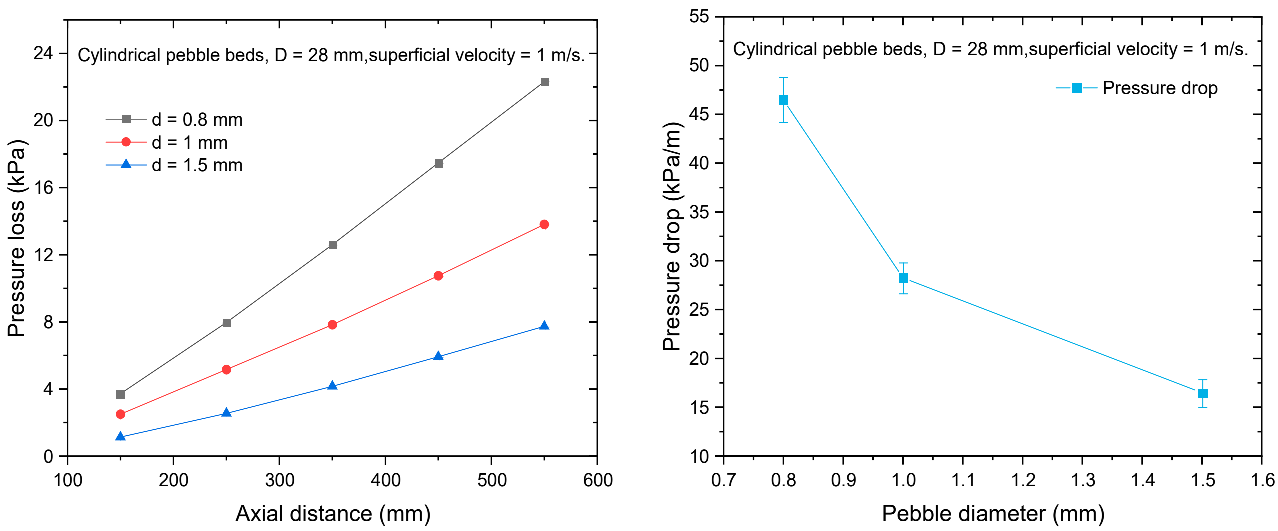
3.4. Effect of Pebble Size on Pressure Loss

There is a dispersity in the sizes of the ceramic pebbles due to the different preparation processes. The selection of pebble size and distribution will directly affect the yield of ceramic pebbles. Therefore, the effect of different pebble sizes on the flow resistance characteristics of helium in pebble beds was investigated experimentally to support the optimization of pebble size selection.

In the experiment, a cylindrical testing section with an inner diameter of 28 mm was selected and filled with 304 stainless-steel pebbles with diameters of 0.8 mm, 1 mm, and 1.5 mm, respectively. The inlet helium flow rate of the pebble bed was set to 1 m/s. When a measurement was completed, the pebble bed was unloaded and refilled with pebbles of other different sizes. Then, the measurement was repeated. Only the pebble diameters were different in each set of experiments. Other parameters were kept as consistent as possible.

The results in Figure 10 show that pebble size has a significant effect on the pressure distributions of helium gas inside the pebble beds. As the bed length increases, the pressure loss along the helium flow direction in the pebble bed increases significantly and linearly. The slope of the pressure loss curve decreases with increasing pebble size. That is to say that the pressure drop gradient of helium in the pebble bed decreases with increasing pebble size. This is mainly because the packing factor inside the pebble bed decreases and the porosity increases with increasing pebble size, as shown in Figure 11. In addition, with the increase in the pebble diameter, the flow channel dimension of the internal pore structure of the pebble bed gradually increases, which means that the flow channel tortuosity gradually decreases; thus, the pressure drop gradient gradually decreases.

For the actual fusion blanket application, the ceramic breeder pebbles and the neutron multiplier pebbles are polydisperse, e.g., binary-sized beryllium pebble bed, polydisperse ceramic breeder pebbles, etc. The effect of polydisperse pebble size on the pressure drop characteristics requires a large number of experimental measurements; these experiments have been planned and will be carried out in the near future.



(**a**) (**b**)

Figure 10. Pressure drops of helium in cylindrical pebble beds with different pebble sizes: (**a**) pressure loss along flow direction; (**b**) pressure drop gradient at different pebble diameters.

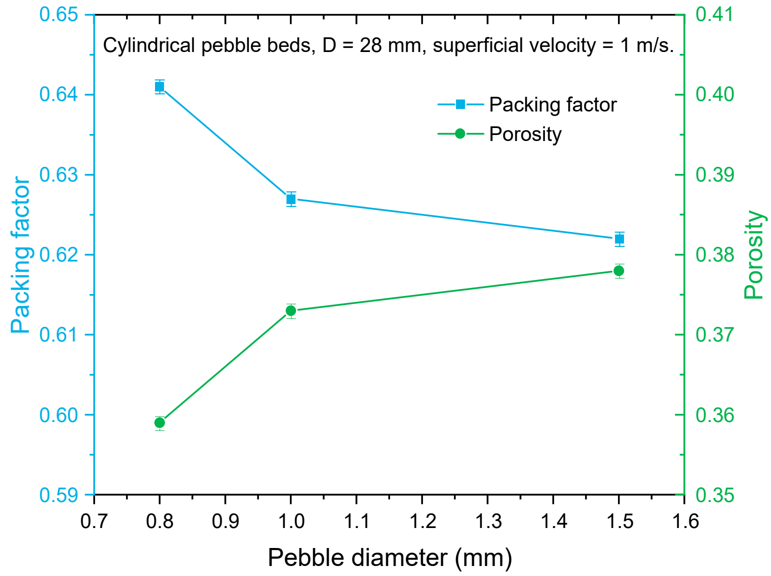


Figure 11. Packing factor and porosity of the cylindrical pebble bed with different pebble size.

3.5. Effect of Temperature of Helium and Pebble Bed on Pressure Loss

In the solid-tritium breeder blanket, both the tritium breeder pebble bed and the neutron multiplier pebble bed are in service in a high-temperature environment. The flow characteristics of helium gas in pebble beds at a high-temperature are critical for assessing the tritium-purging behaviors that occur in pebble beds. Therefore, in this study, preliminary measuring experiments of the pressure drop of helium passing through the pebble beds were conducted at room temperature, 100 °C, 300 °C, and 500 °C, respectively. The diameter of the pebble bed was 50 mm. The superficial velocity was 0.5 m/s. Pebble diameter was 1 mm.

Pressure drops for helium flowing through the pebble bed at different temperatures are shown in Figure 12. From the results, it can be seen that there is a linear increase in the pressure loss of helium along the flow direction in the pebble bed, which is consistent with the previous measurements at room temperature. In addition, it can be seen that temperature variation has a significant effect on the pressure loss of helium in the beds. The pressure drop gradient of the helium through the pebble bed gradually increases with the increase in temperature. This is largely attributable to the fact that helium is rapidly heated to a high temperature after entering the pebble bed at a high temperature. The activity of the gas molecules increases rapidly, and the collision between the gas molecules and the pebble surface is intensified. Furthermore, an increase in temperature of helium will change its physical properties, resulting in an expansion of the volume and a decrease in the helium density. After entering the pebble bed, the helium gas flow accelerates due to the temperature increase and volume expansion, leading to a gradual increase in the helium pressure drop gradient, as shown in Figure 12b.

In addition, more experiments assessing the effect of temperature on helium flow have been planned. Related experiments at high temperatures will be carried out in the near future.

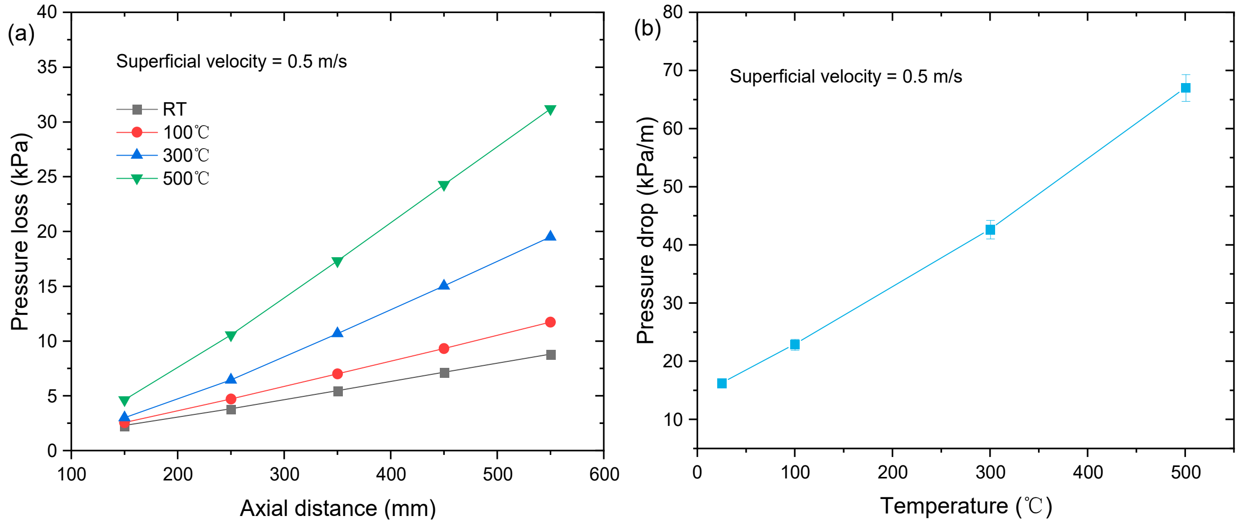


Figure 12. Pressure distribution of helium gas in pebble beds at temperature of RT~500 °C: (**a**) pressure loss along flow direction; (**b**) pressure drop gradient at different temperatures.

4. Conclusions

The pressure loss characteristics of the purge gas helium in pebble beds were investigated experimentally with a focus on the effect of gas velocity, bed dimension, pebble diameter, and temperature. The conclusions may be summarized in the following points:

- With increases in the helium superficial velocity, the pressure drop gradient of the helium inside the pebble bed gradually increased.
- As the dimensions and the diameter ratio D/d of the pebble bed increased, the pressure drop gradient gradually increased. As the pebble size decreased, the pressure drop gradient gradually increased. This is due to the fact that, as the bed dimensions increased and the pebble size decreased, the packing factor of the pebble beds gradually increased and the porosity decreased.
- The pressure drop gradient of the helium through the pebble bed gradually increased with the increase in the helium and the bed temperature.

More experimental measurements of the flow characteristics of helium in pebble beds with polydisperse pebbles at high temperatures will be conducted in the near future.

Author Contributions: Conceptualization, H.C., B.G., B.Z., J.Y., L.W., L.Z. and Y.F.; Methodology, B.G., H.C., B.Z. and Y.F.; Data curation, H.C.; Visualization, B.G.; Formal analysis, H.C. and B.G.; Investigation, B.G. and H.C.; Writing—original draft preparation, H.C. and B.G.; Writing—review and editing, H.C., B.G., B.Z., J.Y., L.W., L.Z., Y.F. and X.W.; Supervision, Y.F. and X.W; Project administration, L.Z.; Funding acquisition, L.Z. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Chinese National Special Project for Magnetic Confined Nuclear Fusion Energy from Ministry of Science and Technology of China under grant numbers 2022YFE03210100, 2022YFE03210300 and 2017YFE0300602, the National Natural Science Foundation of China under grant numbers 52276052; the Natural Science Foundation of Sichuan, China, under grant number 2022NSFSC1216; The Innovation Program of SWIP (Grant No. 202301XWCX004).

Data Availability Statement: The data are available from the corresponding author upon reasonable requests.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

A	aspect ratio of pebbles
D	diameter of testing section of cylindrical pebble beds
d_p	diameter of pebbles
L	length of pebble beds
Δp	pressure loss
S	sphericity of pebbles
v	superficial velocity
k_1, k_2	Ergun's empirically constants
Greek symbols	
ρ_p	density of pebbles
ρ_f	density of fluid, such as helium gas.
μ	hydrodynamic viscosity
ε	porosity
γ	packing factor
Abbreviation	
BCC	body-centered cubes
CFETR	Chinese Fusion Engineering Test Reactor
FCC	face-centered cubes
HCCB TBM	helium-cooled ceramic breeder test blanket module
RP	randomized packing
SC	simple cubes
TES	tritium extraction system

References

1. Li, J.; Wan, Y. Present State of Chinese Magnetic Fusion Development and Future Plans. *J. Fusion Energy* **2018**, *38*, 113–124. [CrossRef]
2. Rubel, M. Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems. *J. Fusion Energy* **2018**, *38*, 315–329. [CrossRef]
3. Abdou, M.; Morley, N.B.; Smolentsev, S.; Ying, A.; Malang, S.; Rowcliffe, A.; Ulrickson, M. Blanket/first wall challenges and required R&D on the pathway to DEMO. *Fusion Eng. Des.* **2015**, *100*, 2–43. [CrossRef]
4. Zmitko, M.; Vladimirov, P.; Knitter, R.; Kolb, M.; Leys, O.; Heuser, J.; Schneider, H.C.; Rolli, R.; Chakin, V.; Pupeschi, S.; et al. Development and qualification of functional materials for the European HCPB TBM. *Fusion Eng. Des.* **2018**, *136*, 1376–1385. [CrossRef]
5. Feng, Y.; Gong, B.; Cheng, H.; Wang, L.; Wang, X. Effects of fixed wall and pebble size ratio on packing properties and contact force distribution in binary-sized pebble mixed beds at the maximum packing efficiency state. *Powder Technol.* **2021**, *390*, 504–520. [CrossRef]
6. Chen, L.; Chen, Y.; Huang, K.; Liu, S. Investigation of the packing structure of pebble beds by DEM for CFETR WCCB. *J. Nucl. Sci. Technol.* **2016**, *53*, 803–808. [CrossRef]
7. Gong, B.; Cheng, H.; Feng, Y.; Luo, X.; Wang, L.; Wang, X. Effect of Pebble Size Distribution and Wall Effect on Inner Packing Structure and Contact Force Distribution in Tritium Breeder Pebble Bed. *Energies* **2021**, *14*, 449. [CrossRef]
8. Wang, X.Y.; Feng, K.M.; Chen, Y.J.; Zhang, L.; Feng, Y.J.; Wu, X.H.; Liao, H.B.; Ye, X.F.; Zhao, F.C.; Cao, Q.X.; et al. Current design and R&D progress of the Chinese helium cooled ceramic breeder test blanket system. *Nucl. Fusion* **2019**, *59*, 076019. [CrossRef]
9. Giancarli, L.M.; Bravo, X.; Cho, S.; Ferrari, M.; Hayashi, T.; Kim, B.-Y.; Leal-Pereira, A.; Martins, J.-P.; Merola, M.; Pascal, R.; et al. Overview of recent ITER TBM Program activities. *Fusion Eng. Des.* **2020**, *158*, 111674. [CrossRef]
10. Lei, M.; Song, Y.; Ye, M.; Lu, K.; Pei, K.; Xu, K.; Xu, S. Conceptual Design of a Helium-Cooled Ceramic Breeder Blanket for CFETR. *Fusion Sci. Technol.* **2015**, *68*, 772–779. [CrossRef]
11. Wang, X.; Ran, G.; Wang, H.; Xiao, C.; Zhang, G.; Chen, C. Current Progress of Tritium Fuel Cycle Technology for CFETR. *J. Fusion Energy* **2018**, *38*, 125–137. [CrossRef]
12. Abdou, M.; Riva, M.; Ying, A.; Day, C.; Loarte, A.; Baylor, L.R.; Humrickhouse, P.; Fuerst, T.F.; Cho, S. Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency. *Nucl. Fusion* **2020**, *61*, 013001. [CrossRef]
13. Zhao, L.; Yang, M.; Xiao, C.; Gong, Y.; Ran, G.; Chen, X.; Li, J.; Yue, L.; Chen, C.; Hou, J.; et al. In-pile tritium release behavior and the post-irradiation experiments of Li_4SiO_4 fabricated by melting process. *Nucl. Eng. Technol.* **2023**, *56*, 106–113. [CrossRef]
14. Seki, Y.; Suzuki, S.; Enoeda, M. Experimental study of helium purge flow in pebble bed for solid breeder. In Proceedings of the 16th International Workshop on Ceramic Breeder Blanket Interactions (CBBI-16), Portland, OR, USA, 8–10 September 2011.

15. Abou-Sena, A.; Arbeiter, F.; Boccaccini, L.V.; Rey, J.; Schlindwein, G. Experimental study and analysis of the purge gas pressure drop across the pebble beds for the fusion HCPB blanket. *Fusion Eng. Des.* **2013**, *88*, 243–247. [CrossRef]
16. Abou-Sena, A.; Arbeiter, F.; Boccaccini, L.V.; Schlindwein, G. Measurements of the purge helium pressure drop across pebble beds packed with lithium orthosilicate and glass pebbles. *Fusion Eng. Des.* **2014**, *89*, 1459–1463. [CrossRef]
17. Panchal, M.; Saraswat, A.; Chaudhuri, P. Experimental measurements of gas pressure drop of packed pebble beds. *Fusion Eng. Des.* **2020**, *160*, 111836. [CrossRef]
18. Mandal, D.; Sathiyamoorthy, D.; Vinjamur, M. Experimental measurement of effective thermal conductivity of packed lithium-titanate pebble bed. *Fusion Eng. Des.* **2012**, *87*, 67–76. [CrossRef]
19. Wang, M.; Liu, D.; Xiang, Y.; Cui, S.; Su, G.; Qiu, S.; Tian, W. Experimental study of the helium flow characteristics in pebble-bed under the condition of CFETR's blanket module. *Prog. Nucl. Energy* **2017**, *100*, 283–291. [CrossRef]
20. Liu, D.; Tian, W.; Su, G.H.; Qiu, S. Experimental study on helium pressure drop across randomly packed bed for fusion blanket. *Fusion Eng. Des.* **2017**, *122*, 47–51. [CrossRef]
21. Chen, Y.; Chen, L.; Liu, S.; Luo, G. Flow characteristics analysis of purge gas in unitary pebble beds by CFD simulation coupled with DEM geometry model for fusion blanket. *Fusion Eng. Des.* **2017**, *114*, 84–90. [CrossRef]
22. Cheng, H.; Fan, L.; Zhou, B.; Gong, B.; Wang, X.; Feng, Y. Numerical modeling on helium flow characteristics in tritium breeder pebble bed. *Nucl. Fusion Plasma Phys.* **2021**, *41*, 610–616. [CrossRef]
23. Choi, D.; Park, S.; Han, J.; Ahn, M.-Y.; Lee, Y.; Park, Y.-H.; Cho, S.; Sohn, D. A DEM-CFD study of the effects of size distributions and packing fractions of pebbles on purge gas flow through pebble beds. *Fusion Eng. Des.* **2019**, *143*, 24–34. [CrossRef]
24. Lee, Y.; Choi, D.; Hwang, S.-P.; Ahn, M.-Y.; Park, Y.-H.; Cho, S.; Sohn, D. Numerical investigation of purge gas flow through binary-sized pebble beds using discrete element method and computational fluid dynamics. *Fusion Eng. Des.* **2020**, *158*, 111704. [CrossRef]
25. Lei, M.; Liu, S.; Wu, Q.; Xu, S.; Li, B.; Li, C. Research on purge gas flow characteristics in different pebble bed structures for fusion blanket. *Prog. Nucl. Energy* **2023**, *155*, 104488. [CrossRef]
26. Wang, M.; Xiang, Y.; Cui, S.; Liu, D.; Tian, W.; Zhang, D.; Qiu, S.; Su, G.H. Numerical study on the purge gas flow and heat transfer characteristics in helium cooled solid breeder blanket of CFETR. *Prog. Nucl. Energy* **2018**, *105*, 114–123. [CrossRef]
27. Wu, Z.; Wu, Y.; Tang, S.; Liu, D.; Qiu, S.; Su, G.H.; Tian, W. DEM-CFD simulation of helium flow characteristics in randomly packed bed for fusion reactors. *Prog. Nucl. Energy* **2018**, *109*, 29–37. [CrossRef]
28. Zhang, H.; Li, Z.; Guo, H.; Ye, M.; Huang, H. DEM-CFD simulation of purge gas flow in a solid breeder pebble bed. *Fusion Eng. Des.* **2016**, *113*, 288–292. [CrossRef]
29. Sedani, C.; Panchal, M.; Chaudhuri, P. Simulation and experimental analysis of purge gas flow characteristic for pebble bed. *Fusion Eng. Des.* **2021**, *172*, 112778. [CrossRef]
30. Ergun, S. Fluid Flow Through Packed Columns. *Chem. Eng. Prog.* **1952**, *48*, 89–94.
31. Ozahi, E.; Gundogdu, M.Y.; Carpinlioglu, M.Ö. A Modification on Ergun's Correlation for Use in Cylindrical Packed Beds With Non-spherical Particles. *Adv. Powder Technol.* **2008**, *19*, 369–381. [CrossRef]