Status Update: Pebble Insertion and Extraction Methods for a Pebble Bed Salt Cooled Reactor Using Surrogate Materials

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ABSTRACT

The use of buoyant fuel pebbles in salt cooled reactor designs such as the Pebble Bed Advanced High Temperature Reactor (PB-AHTR) presents new challenges for fuel handling systems. This report documents the current status of the Pebble Recirculation Experiment (PREX) 3.1, which will demonstrate aspects of pebble fuel handling systems with scaled reactor reflector geometry and flow configurations. PREX 3.1 makes use of surrogate materials that can be used to reduce safety concerns and increase modularity to test alternative injection and extraction geometries. At present, the test section and flow loop for PREX 3.1 are complete and initial flow testing is underway. Upcoming work will include operation with flow through the pebble bed and testing of injection and extraction geometries that will inform design for a future prototype reactor.

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1.0 INTRODUCTION

The use of buoyant fuel pebbles in salt cooled reactor designs such as the Pebble Bed Advanced High Temperature Reactor (PB-AHTR) [1] presents new challenges for pebble fuel handling systems. In the PB-AHTR design (Fig. 1.1), fuel pebbles in the core float up against a top reflector and must be removed through defueling chutes, the inverse of the case in helium-cooled pebble bed reactors. Fuel is added to the core by injection into the coolant flow entering the bottom of the core in order to maintain a constant inventory of pebbles in the core to ensure that the bed remains fully packed as pebbles are removed from the top of the core. Proper design of the fuel handling system is needed to assure that pebbles cannot become jammed in locations with difficult physical access. Scaled experiments provide an excellent tool to verify the effectiveness of these design approaches.

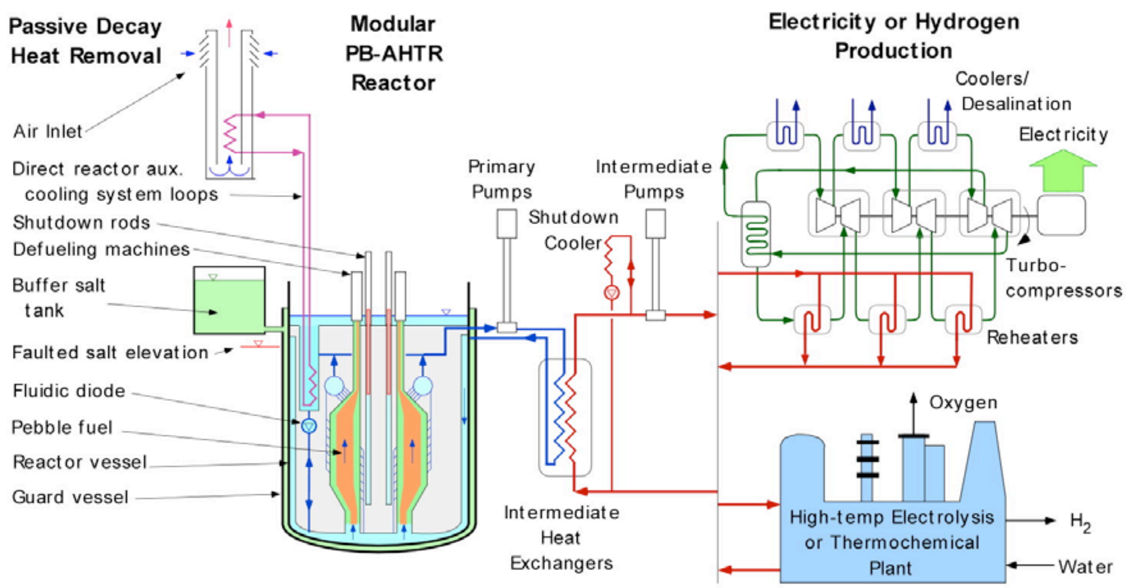


Fig. 1.1 Schematic drawing of the Pebble Bed Advanced High Temperature Reactor (PB-AHTR).

A review of the literature on granular flow shows few relevant examples for the transport of buoyant pebbles in viscous fluids and only a small number for nuclear applications. The pebble dynamics in gas-cooled reactors are better understood and show similar behavior to conventional granular transport systems such as hoppers and silos where gravity is the primary driver of pebble motion [2]. However, in gas-cooled reactors, interactions between the pebble motion and fluid flow can be decoupled since helium drag forces are negligible compared to gravity.

Previous work completed in our laboratory demonstrated advection of pebbles by a viscous fluid into a large cold leg and pebble motion under upward axial flow in a cylindrical channel with a 45° discharge cone [3]. In this experiment, the upward fluid flow effectively supplemented the buoyancy of the pebbles, except in the region immediately adjacent to the discharge cone, so that the bed defueling still largely resembled that of gravity-driven downward granular flow.

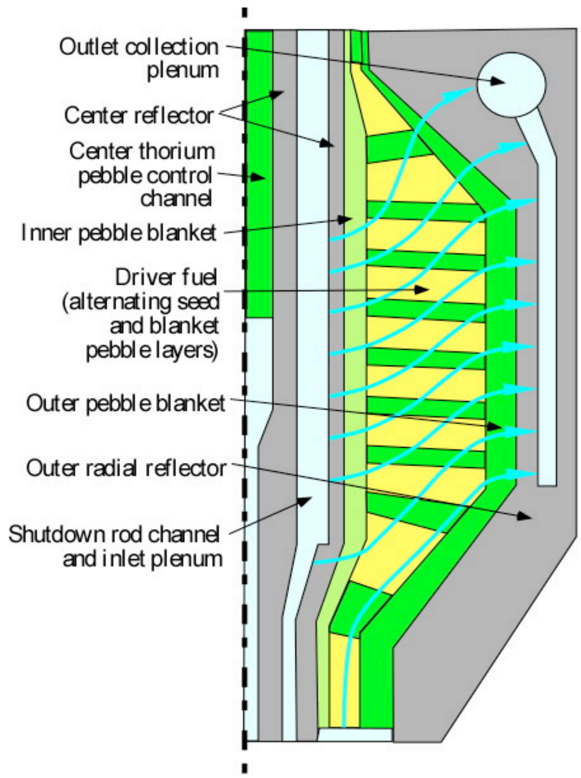


Fig. 1.2 Schematic cross-section view of PB-AHTR annular core configuration.

The current design of the PB-AHTR uses a combination of axial and radial flow in an annular core (Figure 1.2) to reduce pressure losses through the pebble bed and the required pumping power [4]. The resulting coolant flow field is significantly more complex than for cylindrical channels and a large portion of the coolant flow will be directed through the outer reflector, rather than the defueling chute. The resulting flow pattern will significantly change the forces acting on pebbles in the core, especially in the defueling region where fluid flow is diminished. A 16-MWth reduced power test reactor design, the Flouride-cooled High temperature Reactor (FHR-16) has also been proposed using a similar annular core design [5]. This design is used as the basis for the experiment geometry presented in this report.

This report presents work completed on a new experiment, the Pebble Recirculation Experiment (PREX) 3.1, which will be used to demonstrate aspects of the fuel handling system for a pebble bed salt cooled reactor using surrogate materials. Section 2 outlines the scaling methodology used in PREX 3.1 and details of the completed test section and flow loop. Several possible configurations for pebble injection and important considerations for defueling chute design are presented in Sections 3 and 4, respectively.

Finally, Section 5 presents the current status of the test loop and the initial sequence of experimental runs to be completed using PREX 3.1.

2.0 PEBBLE RECIRCULATION EXPERIMENT

Scaled test facilities are important in the development and licensing for nuclear reactors, particularly those with innovative technologies. For the purposes of demonstrating pebble recirculation dynamics for salt cooled high-temperature reactors, it is a great advantage to use surrogate materials that can be used at room temperature with fewer safety concerns and simpler instrumentation and diagnostics compared to a prototypical system. PREX 3.1 uses scaling principles to preserve fluid phenomena and pebble force dynamics based on previous work completed in the lab.

Table 2.1 shows the design parameters used in the scaling for 900-MWth PB-AHTR, 16-MWth FHR-16 and scaled PREX 3.1. Here, the core cross sectional area is taken at a horizontal section of the axisymmetric core in order to give a representative superficial, or Darcy, velocity. For proper pebble dynamics scaling, the Reynolds number, Froude number, and pebble to fluid density ratio must be matched [3]. This can be achieved with water as a simulant fluid for flibe at 650 °C by reducing length scales to 42.3% of the actual reactor system and velocity scales to 61.2%. Density ratios for fuel pebbles of density 1740 kg/m^3 are matched by using high density polyethylene (HDPE) spheres. The resulting scaled system leads to negligible distortion in the Reynolds number, a distortion of less than 2% in Froude number, and less than 1% for the density ratio. Therefore, the resulting scaled experiment should display excellent similitude to the reactor pebble bed system.

		PB-AHTR	FHR-16	PREX 3.1
Working Fluid	-	FLiBe	FLiBe	Water
Thermal Power	MWth	900	16	0
Core Geometry	-	Axisymmetric	Axisymmetric	Quasi-2D
Inlet Temperature	[°C]	600	600	20
Outlet Temperature	[°C]	704	704	20
Fluid Density	[kg/m^3]	1990-1940	1990-1940	999
Pebble Density	[kg/m^3]	1680-1810	1680-1810	892
Pebble/Fluid Density Ratio	-	0.84-0.93	0.84-0.93	0.89
Pebble Diameter	[m]	0.03	0.03	0.0127
Core Cross Sectional Area	[m^2]	13.9	2.83	0.0375
Bed Packing Fraction	-	0.6	0.6	0.6
Re_S in Core	-	1,200	105	< 1,400

Table 2.1 Design and scaling parameters for PB-AHTR, FHR-16, and PREX 3.1.

One observation of the information Table 2.1 is that in order to maintain the same core temperature difference, the 16-MWth FHR-16 test reactor will require significantly lower total flow rates than the full-scale 900-MWth PB-AHTR. Due to the different flow length through the pebble beds, due to their different sizes, the Reynolds number difference between the two systems is greater than an order of magnitude. The difference in Reynolds number results in substantial difference in the fluid drag forces on the pebbles, when the scaling maintains the same temperature drop across both cores. Based on the flow conditions required, we will operate the PREX 3.1 experiment at a wide range of flow rates in order to study pebble dynamics under conditions where the drag forces are small compared to buoyancy to conditions where it is several times greater, comparable to the full-scale 900-MWth PB-AHTR core drag forces.

Figure 2.1 shows the test section for PREX 3.1. The experiment consists of a quasi-2D channel of constant width that matches the axisymmetric R-Z geometry of the inner and outer reflectors of the FHR-16 [5]. The loss of the radial expansion introduces one of the most important distortions for the experiment. However, since PREX 3.1 is scaled to match the significant fluid dynamics parameters for flibe, this experiment will still provide useful data on local pebble dynamics to validate models in the future.

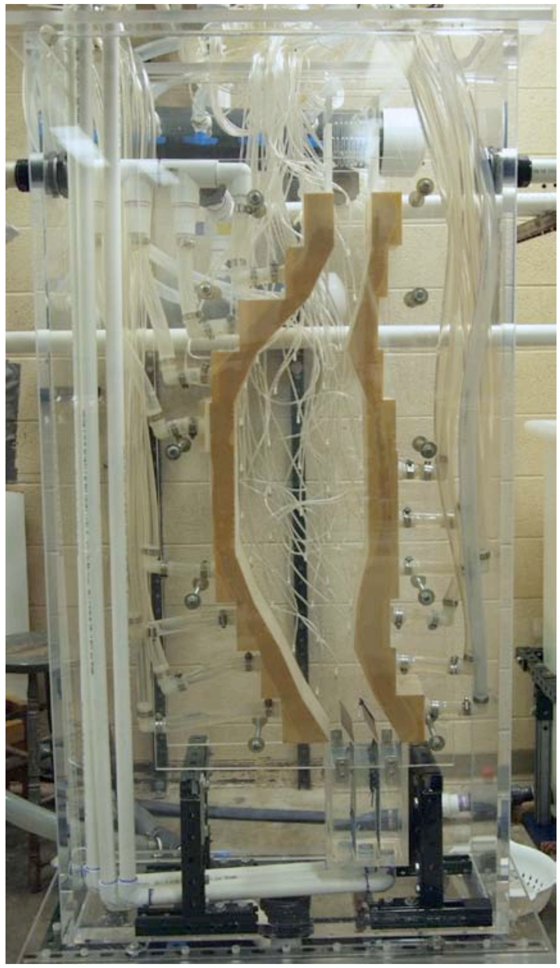


Fig. 2.1 PREX 3.1 test section in its tank. Pebbles are injected through the white piping at the right side of the test section into separate hoppers at the bottom of the bed. Flow can be directed axially through the pebble injection ports or through the faces in the lower sections of the inner (right) and outer (left) reflectors. Outlet flow can be controlled through either the top in the discharge cone or through the faces on the upper section of the outside reflector.

Pebble injection and defueling designs in PREX 3.1 are modular so that different geometric configurations can be tested. Pebble injection is handled through three separate lines that advect pebbles and then insert them into hoppers below the bottom of the bed. A detailed view of the three hoppers is given in Figure 2.2. The hoppers are necessary to ensure proper segregation of the pebbles as they enter the core and to prevent the formation of free surfaces in the bed. Free surfaces in the bed would lead to potential pebble bed instability and reorganization that would dramatically decrease confidence in the core geometry. Further discussion of considerations for pebble injection design is given in Section 3.0 of this report.

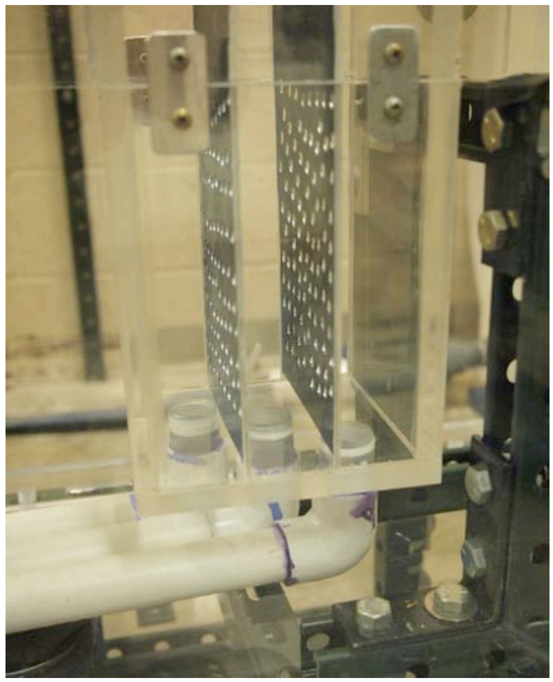


Fig. 2.2 Detail view of pebble injection locations and hoppers at the bottom of the PREX 3.1 test section.

PREX 3.1 has been constructed to allow great flexibility in controlling the fluid velocity field to observe the impact on pebble bed dynamics. In the simplest case, purely axial flow can be observed when water is injected at the bottom of the bed through the pebble injection lines. Additional injection inlets are also present on the lower portions the inner reflector (right side) and outer reflector (left side). The two sidewalls of the test section are perforated and were manufactured from detailed CAD designs with ABS plastic using fused material deposition (FDM). Figure 2.3 shows details of the inner reflector surface. The wall injection blocks are connected to a large inlet manifold (Figure 2.4) and flow to each block can be controlled by the use of a ball valve. The test section includes six injection surfaces on the inner reflector and four on the outer reflector. These connections can be seen in the PREX 3.1 flow schematic design shown in Figure 2.5. Injecting flow through thes wall surfaces will allow us to better capture the impact of radial flow for the PB-AHTR and FHR-16 designs on pebble bed dynamics.

Fig. 2.3 Detail view of inner reflector surface showing injection holes in the coolant injection blocks. Flow rates from the surface of each block can be controlled to match the desired reactor flow conditions. Manometer pressure taps on the rear surface of the test section are also visible.

Fig. 2.4 Detail view of inlet manifold for inner reflector. Ball valves are used to control the flow rate to each injection block.

Similar to the fluid injection surfaces at the bottom of the test section, coolant can be effectively removed from the upper region of the outer reflector to better represent the radial flow across the reactor core. Suction on these faces allows for greatly reduced pressure drop across the core and lowers the required pumping power. Fluid flow at the outer reflector could lead to some more complicated scenarios for pebble defueling, which is considered further in Section 4.

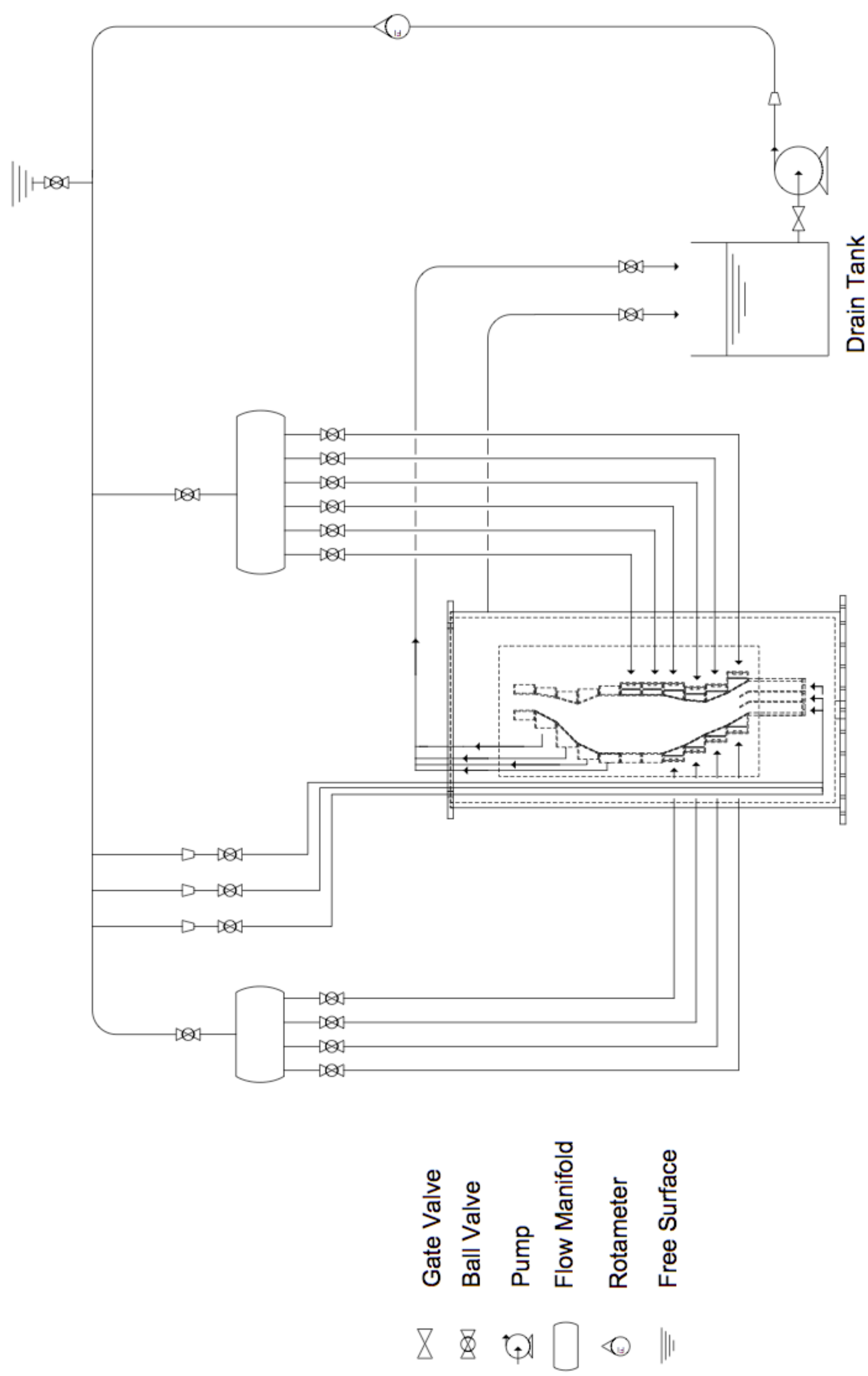


Fig. 2.5 Schematic of flow lines in PREX 3.1.

Instrumentation on PREX 3.1 will be completed to measure the pressure distributions, flow rates, and pebble motion. Pressure data will be collected for the pebble bed using an array of manometer lines connected to pressure taps on the back surface of the test section. These lines will allow for a direct measurement of local pressure in the bed, which can be used to determine the local pressure gradients and momentum transfer to the pebble bed. Versa mount flowmeters will be used to measure volumetric flow rates for all of the injection lines to an accuracy of 5%. Finally, pebble motion data will be recording using digital photo image analysis. Photographs of the pebble bed surface taken at short intervals can be analyzed to locate all pebbles in the image and track particle motion between frames [5]. Details on PREX 3.1 data collection methods will be provided in the future after completion.

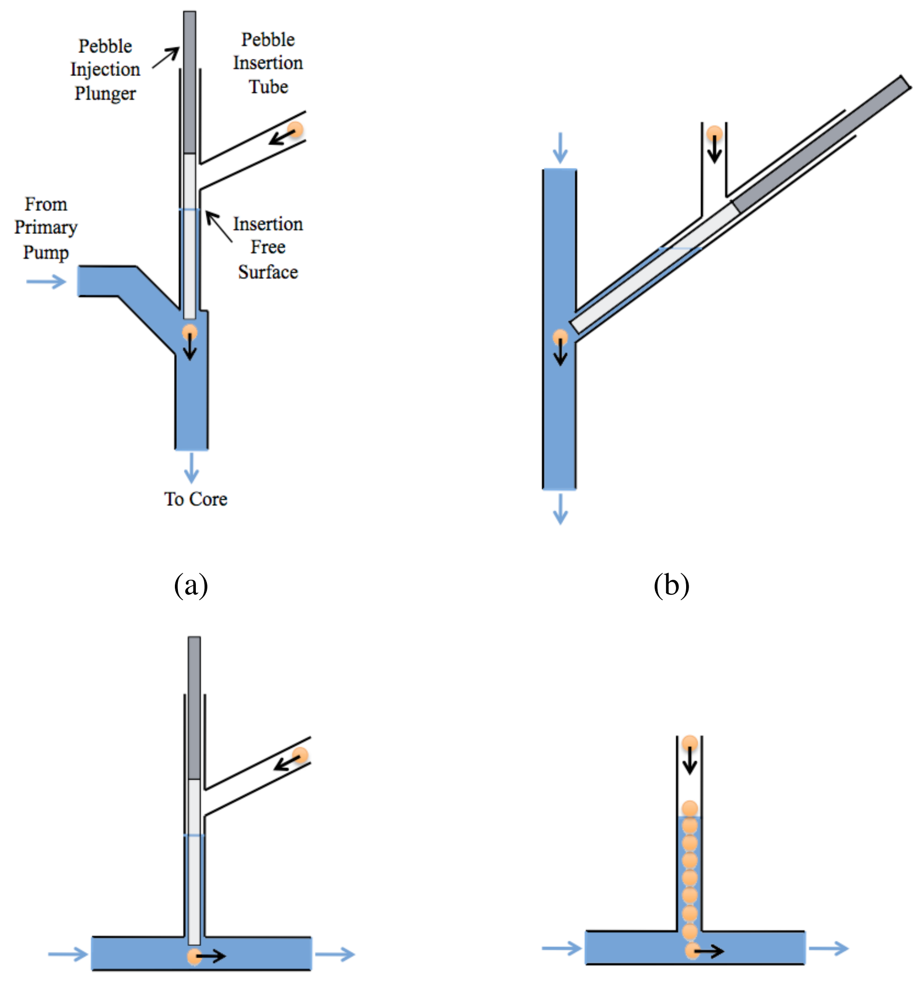
3.0 PEBBLE INJECTION DESIGN

Pebble injection and transport to the core are critical design tasks for salt cooled reactors due to the fact that reliable fuel insertion is necessary to make sure that the core remains fully packed. Blockage of one or more pebble injection pathways could elevate the free surface at the bottom of one pebble bin into the core. This scenario would lead to a rearrangement of pebbles within the core and a loss of the desired radial zoning.

Due to these concerns over the reliability of pebble insertion systems, the modular design of the PREX 3.1 injection flow lines will allow us to compare the ability to inject pebbles into several different geometric configurations. Previous work on PB-AHTR demonstrated entrainment of pebbles into a large cold leg with diameter ratio $D_{ColdLeg}/D_{Pebble} = 4$ [3], but the transport of pebbles in smaller piping systems requires further evaluation.

Small diameter piping systems for downward pebble transport will require lower flow velocities since pebbles obstruct a greater fraction of the flow channel and drag coefficients become larger [6]. However, these systems pose additional risk of pebble jamming. Future iterations of pebble injection designs for PREX 3.1 will seek to determine pebble injection rates and pipe curvatures with low jamming rates. In addition, the use of water as a simulant fluid with clear piping will enable visual inspection at locations of jamming to develop flow variation techniques that could potentially unclog pebble injection lines. These results can be used to inform the design of pebble injection systems in the salt cooled reactors where optical inspection through the coolant is possible [7].

Figure 3.1 shows four potential pebble injection configurations that can be implemented in PREX 3.1. These design configurations include injection into downward vertical flow in (a) and (b) as well as horizontal flow in (c) and (d). Configuration (b) was demonstrated in the previous PREX experiment [3] into large diameter piping. Horizontal injection has not previously been demonstrated, but we expect pebbles will be entrained with lower flow rates since drag forces will need to overcome only rolling friction. In designs (a)-(c), a pebble injection plunger is used to force pebbles into the main flow from the stagnant fluid at the insertion free surface. One important consideration for each of these designs is that the location of pebble injection into the free stream must be below the free surface of the reactor pool and the free surface in the pebble injection line must be at an elevation so that no gas can be entrained into the coolant flow and transported into the core.



(a) (b)

(c) (d)

Fig. 3.1 Four potential pebble injection designs for PREX 3.1. Configurations (a) and (b) insert pebbles into downstream flow, where flow rates must be high enough to overcome buoyancy forces. For cases of horizontal injection, (c) and (d), only rolling friction needs to be exceeded for pebbles to enter the main flow. Methods (a)-(c) require the use of an injection plunger to force pebbles from the free surface of the injection tube into the main flow to the core. In (d), pebbles are inserted passively by the weight of the pebbles above the free surface.

Of note, in configuration (d), no plunger is needed to inject pebbles under normal operating conditions. The column of pebbles will find a neutrally buoyant configuration with some pebbles above the free surface. In this case, the addition of one more pebble to the column is sufficient to force the pebble at the bottom of the chain into the free stream. This design could be advantageous since fewer active components are needed for pebble injection and a plunger would be needed only when clearing all pebbles from the injection channel.

In all of these designs, pebbles are injected through a free surface in the liquid that changes in elevation depending upon the coolant flow rate and pressure drop through the core. The low pressure drop and head loss of the annular core design is important, because the change in free surface elevation between zero and full primary coolant flow is relatively small, around 2 m. For core configurations with significantly higher pressure drop, an alternative pressurized pebble injection method would be needed.

4.0 PEBBLE DEFUELING

Reliable defueling is also an important design consideration for pebble bed salt cooled reactors. In order to operate under its operating license, a reactor of this class will need to demonstrate that fuel can be safely removed from the core at a desired rate. It will also be necessary to show that all pebbles are cycled through the core within an acceptable residence time period. PREX 3.1 is designed to demonstrate reliable defueling rates for a pebble bed under realistic reactor flow configurations.

The PREX 3.1 test section can accommodate different defueling chute geometries easily due to the modular design. Figure 4.1 shows the first defueling chute design that will be tested. It is a simple rectangular channel of dimensions 6.8 D_{Pebble} by 11 D_{Pebble}. The channel has vertical grooves on all four faces to allow bypass flow through the chute, which can be controlled with throttling valves in return lines from the test section tank to the pump supply tank. When pebbles are loading into the test section, a small column of pebbles is expected to rise above the free surface for manual removal. In the reactor, this region would be covered completely by the coolant and a net upward force would be exerted on the defueling machine as it removes pebbles from the system. Future defueling chutes can also be tested to demonstrate fuel removal with further contraction.

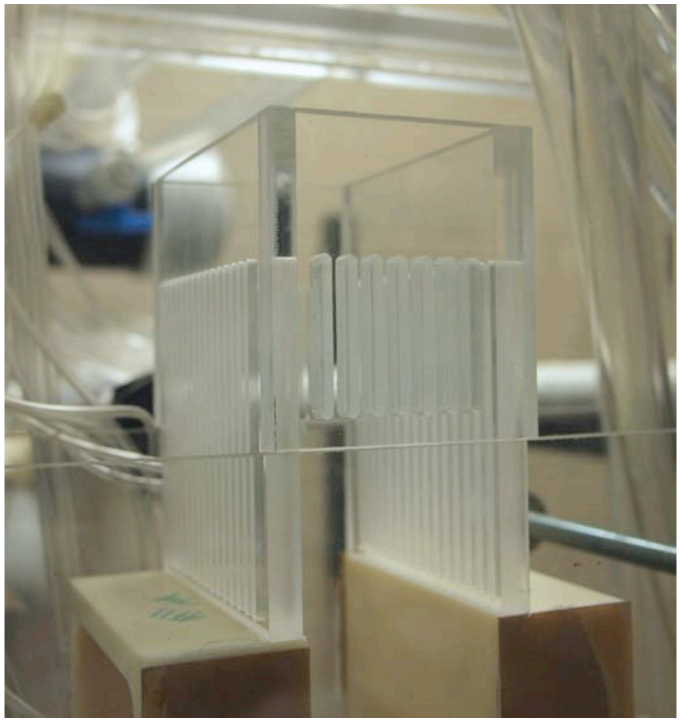


Fig. 4.1 Detail of PREX 3.1 defueling chute. The defueling chute can be easily removed and replaced with alternative geometries to observe pebble motion and potential jamming problems. Pebbles will come to rest above the free surface and are removed manually.

In addition to the design of the defueling chute, reliable pebble removal for salt cooled reactors must demonstrate that all pebbles can be circulated through the core with acceptable stochastic variations in total residence time. For complex reactor flow conditions, fuel removal needs to be shown for conditions where drag forces due to the cross flow are large compared to the buoyancy forces or the drag forces due to the bypass flow in the defueling region. The region of greatest concern is that close to the fluid outlet on outside reflector, labeled in Figure 4.2. In this section or the core, a large constant pressure boundary at the reflector wall will greatly diminish tangential drag forces and local geometry could trap pebbles much longer than desired. In this case, pebbles closer to the center reflector would be channeled at great rates past the held up region, leading to further disparities in residence time. The large flexibility to control flow at the wall surfaces of the PREX 3.1 test section will enable future testing under many different flow conditions in order to evaluate the impact on pebble residence time variation and defueling rates.

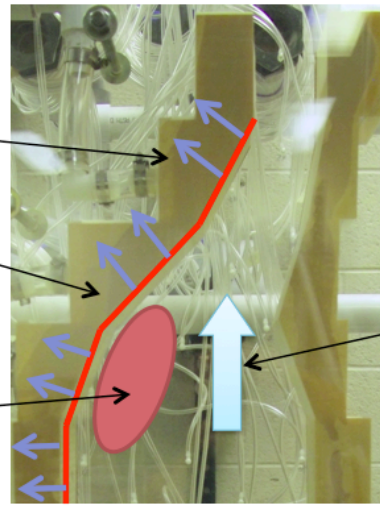


Fig. 4.2 Detail of PREX 3.1 converging region. In some cases with large drag forces on the pebbles, holdup could occur near the outer reflector at a uniform pressure boundary at the outlet. The resulting pebble bed motion could channel pebbles close to the inner reflector into the discharge chute, leading to large variances in pebble residence time.

PREX 3.1 will also be capable of evaluating the effects of bed agitation by flow alternation from the inner and outer reflectors. In this operational mode, coolant is primarily inserted from the lower portion of the inside reflector and removed through the upper potion of the outside reflector. At regular intervals, some inlet flow will be diverted to the lower portion of the outside reflector. This will serve to agitate the pebble bed so that it remains fully packed and to vary the forces on pebbles that may be held in place at the outlet region. Studies of pebble motion with PREX 3.1 will document how this flow alternation shifts pebbles locally, affects pebble packing density, and impacts the defueling rates from different regions of the core.

5.0 CONCLUSIONS AND FUTURE WORK

PREX 3.1 is a scaled experiment that will be able to demonstrate the pebble dynamics for pebble bed salt cooled reactor such as the PB-AHTR and FHR-16 using simulant fluids. The completed test section has a significant amount of flexibility in the configuration so that a large combination of different flow configurations can be studied. In addition, modularity for the pebble injection and defueling design allows for relatively simple changes to test new geometries. The use of surrogate materials greatly decreases the safety concerns associated with running such a test loop, compared to an experiment using salt under prototypical conditions, and allows easy visual inspection of the pebble injection flow lines and the surface of the pebble bed.

Initial testing of the flow loop is currently underway and operating procedures are being developed. Due to the fact that the PREX 3.1 test section sits within a large outer tank, all inlet flow lines must rise above the free surface. Care must be taken to purge air from these lines when the experiment is brought online and to make sure that these lines remain water solid during operation. This experience is also relevant for the actual reactor operation for all flow lines above the free surface while the loop is initially filled.

After procedures are completed for managing the flow loop, pebbles will be loaded into the test section through the defueling chute and measurements will be taken for a range of flow conditions from purely axial flow in the bed to cross-flow dominated conditions. Subsequently the first of the pebble injection design configurations will be installed in the loop to study the injection and transport of pebbles in small diameter piping systems. The results of these initial tests will inform how best to proceed from here.

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