Pebble Flow Experiments for Pebble Bed Reactors

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Determination of Pebble Bed Reactor Dynamics through Experimentation and Modeling

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Basis of The Project

• Modeling the path of granular flow through a Pebble-Bed Reactor.

• PBMR: Pebble Bed Modular Reactor, an experimental commercial nuclear reactor design.

• A PBMR operates using 360,000 small spheres of graphite-coated uranium or pure graphite, instead of traditional fuel rod assemblies.
FUEL SPHERES

331 000 Fuel
110 000 Graphite SPHERES/CORE

5mm GRAPHITE LAYER
COATED PARTICLES IMBEDDED IN GRAPHITE MATRIX

15 000 COATED PARTICLES/FUEL SPHERE

COATED PARTICLE
TRISO COATING

- Outer isotropic Pyrolytic Carbon
- Silicon Carbide Barrier Coating
- Inner isotropic Pyrolytic Carbon
- Porous Pyrolytic Carbon Buffer

KERNEL
Uranium Dioxide

φ0,5mm

φ60mm

φ1mm
“The Problem”

- The PBMR has two types of pebbles that flow through the core: graphite reflector pebbles and U-235 fuel pebbles.
- In order to prevent power peaking in the fuel pebbles, a fixed radial distribution of these two pebble columns must be maintained throughout the height of the core as the pebbles cycle through.
Radial Fuel Distribution

- A central core of pure graphite reflector pebbles is surrounded by an annulus of a 50/50 fuel-and-reflector mix, and a larger annulus of pure fuel pebbles.
Flow Diffusion

- Several mathematical models for granular flow exist, with different amounts of diffusion and different velocity profiles.
- The neutron physics of the core relies on the assumption of laminar flow and low diffusion levels during flow down.
Dropping Diffusion

- The radial spread of pebbles dropped into the core is also an important factor in keeping the fixed radial distribution of the pebbles, as refueling is on-line during reactor operation.
The Project

- To identify key variables in both core flow and pebble dropping in the PBMR
- To formulate mathematical models which accurately describe the motion of the pebbles as a function of those key variables
- To design, build and run scaled test rigs
- To use experimental data to further develop modeling and understanding of granular flow in the PBMR
Key Objectives

• To investigate whether pebble flow in the core is characterized by well-defined streamlines or by random mixing

• To study the factors which determine the formation of graphite annulus and the degree of mixing.
Multi-Faceted Approach

- To model pebble flow through the core, we wanted a 2-D, half-core model with a flat viewing window to obtain visual confirmation of data. However, we couldn’t be sure the boundary effects of the viewing window would not change flow from real, 3-D conditions.

- Therefore we pursued in parallel a 3-D, full-core model using gamma ray imaging to track the paths of tracer balls in real 3-D conditions. These paths would be compared to the 2-D data to determine if the half-core model gave results indicative of true flow in 3-D conditions.
Multi-Faceted Approach

- In addition, detailed separate experiments were conducted on pebble-dropping to simulate the creation of a radial mixing zone during the on-line refueling process. This determined if the required radial distribution could be formed at the top of the core during operation.

- In sum, three separate experiments were conducted to obtain a complete set of data:
  - 2-D Visual Half-Model
  - 3-D Full-Model with Gamma Ray Imaging
  - Pebble-Dropping Dispersion
Key Parameters of Interest

**Core Flow:**
- Geometrical Parameters
  - Drain Hole Diameter
  - Cone Angle
  - Pebble Diameter
  - Height of the Fuel Column
- Refueling Effects
- Material Properties
  - Density
  - Young’s Modulus
  - Poisson’s Ratio
  - Friction

**Pebble-Dropping:**
- Material Properties
  - Density
  - Young’s Modulus
  - Poisson’s Ratio
  - Friction
  - Coefficient of Restitution
- Height of Drop
- Angle of Repose
- Pebble Size
Outline of Presentation

- Mathematical Modeling (not discussed)
- Experimental Scaling
- Fast Vs Slow Flow
- Shaping Ring for Central Column
- Results
- Summary: Conclusions and the Future
MD Simulation
Relaxed Scaling for Pebble Dispersion, Pebble Bouncing on a Hard Floor

Primary Objective:

$\left( \frac{H}{R} \right) = \left( \frac{h}{r} \right) = C$

It can be shown that the Only Condition Needed To Meet the Above Requirement, is to have the Same Coefficient of Restitution ($e_0 = e_s$) in Both Systems.
Experimental Results

• Preliminary Findings (Coke Bottle Model)
• One-Tenth Scaled Half Model with Visual Analysis
• One-Tenth Scaled Full Model with Gamma Imaging Analysis
• Ball-Dropping and Pebble Pile Formation
Preliminary Experimentation

Coke Bottle Model:

- Feasibility of Half Model
- Preliminary streamline data concerning central graphite column
- Frictional Effects
Half Model Design

Measurements in centimeters
Pebble Specifications

- AirSoft® Air Rifle Pellets
- Composed of ASB plastic, very regular
- 6 mm diameter
- 1.2 g
- Full Model: ~470,000
- Half Model: ~175,000
Half Model Runs (9 Total)

- 60° Cone Angle
  - 3.6 cm exit diameter
    - 2 runs, 1 with and 1 without refilling
    - 2 runs, 1 with and 1 without refilling, equal time steps

- 30° Cone Angle
  - 4 cm exit diameter
    - 2 runs, 1 with and 1 without refilling, equal time steps
  - 7 cm exit diameter
    - 1 run with refilling, equal time steps
    - 1 run with graphite column, no refilling, no stopping
  - 3 cm exit diameter
    - 1 run with refilling
Half Model Data Collection
3.6 cm Exit, 60°, Time Step
Effect of Exit Diameter

To Notice:
- Same Angle, different exit diameters
- Equal time steps (5 seconds)
- As expected, a larger hole means faster flow
- Straight Streamlines
Effect of Refilling

To Notice:
- Both 60°, 3.6 cm exit diameter, but 1 with refilling and 1 without refilling
- Approx. same velocities
- Straight Streamlines in both
Velocity Profile and Cone Angle

To Notice:
- Both start at linear profile
- Effect of the wall
- Unpronounced velocity profile (balls seem to move together)
- Cone angle has small contribution to velocity profile shape
Comparison to Design Profile

- Velocity Profile very similar
- Very flat until the funnel region
Friction Effects

- Bottle lined with sand paper to increase frictional effects at the wall
- Velocity profile in central region seems to remain flat until funnel area
- Very slow movement at walls
Trial with Central Column
Video Demo
Effect of Different Material Properties on Central Column

- Coke Bottle Model, filled with glass beads, was run with central column

- As with the plastic pebbles, the central column remained intact as the model was run

- Suggests streamlines are only weakly affected by friction and other material properties
Conclusions: Half Model

• From Half Model Dynamic Flow Data:
  - Laminar flow of both fuel and non-fuel pebbles
  - Little or no mixing
  - No effect with refueling on velocity or streamlines
  - Shape of velocity profile determined by cone angle

• From Half Model and Coke Bottle Model
  - Frictional effects are relatively small
Full Model Data Collection
Cross Section of Tracer

ABS Plastic Sphere
Na-24 Source
Plastic Welder Epoxy Cap

Detector Resolution Schematic

Resolution = 2D-d

d/t = D/(S+t) by similar triangle
Imaging Equipment Setup and Core Imaging Schematic

- **Gamma source**
- **Particle Count Rate Output**
- **Translator Controller**
- **Macintosh (Visual Output Translator Location)**
- **Core**
- **Detector**
- **Translator**
- **y**
- **x**

Legend:
- **Gamma source**
- **Particle**
- **Core**
- **Translator**
- **Detector**
- **Controller**
- **Macintosh (Visual Output Translator Location)**

Diagram shows the setup with a core at the center, gamma source, and detector with translator controller.
Actual Measurement Setup

Movie 1

Movie 2

33.mpg

34.mpg
Determining Position

Counting Distribution

Interpolation as a Gaussian

Variation of Positions

One particle

cm

cm
Radial Dispersion of Fuel and Graphite Pebbles During Refueling in the Pebble Bed Modular Reactor
Purpose

• Investigate how pebbles behave when dropped from various heights on the surface of pebbles in the reactor core

• Examine important issues for refueling
  - Uniform formation of distinct annular rings, central graphite column and outer ring of fuel pebbles
  - Minimal mixing of two regions
Key Parameters of Interest

- Dropping rate (inner and outer locations)
- Angle of repose
- Height of drop (pebble probability distribution)
- Location of outer drop (radius)
- Height of guide ring over the surface
Experimental Design

- Vessels: 24 cm and 30 cm in diameter
- Pebble diameter 6 mm, weight 0.12 g, and density 1.06 g/cm$^3$
Drop Locations

R1 = Inner radius
= (81/175)R3

R2 = Mix zone radius
= (113/175)R3

R3 = Outer radius
R4 = Fueling radius
= R3-0.5(R3-R1)
= 0.5(R3+R1)
= (128/175)R3

R5 = center of mix zone
= (97/175)R3

Calculated from *PBMR Safety Analysis Report, Rev. B*
Dropping Rate

- Discharged in real reactor once every 30 seconds
- Experiments show that the rate of dropping affects the mixing zone
- Since pebbles on top of reactor move down at same velocity, ratio is based on area ratio:

\[
\frac{\dot{D}_f}{\dot{D}_g} = \frac{\pi \cdot (175^2 - 113^2) + \pi \cdot (113^2 - 81^2) / 2}{\pi \cdot (113^2 - 81^2) / 2 + \pi \cdot 81^2} = 2.169
\]
Angle of Repose

- Defined as the maximum angle a granular substance can make with a surface before avalanching occurs
- Experimentally found to be approximately 21° for plastic pebbles and 31° for graphite pebbles (1cm diameter)
- Angle provides some information about the profile of a pile of pebbles
Probability Distribution

- Studied by dropping pebbles onto flat surface of several layers of pebbles
- Graphite pebbles 1cm in diameter, plastic pebbles 0.6cm in diameter
- Pebble dropped from three different heights: 18.5 cm, 40 cm, and 66 cm
• Decreasing height results in a higher probability for the pebble to stop near drop location
• As drop height increases, probability increases for pebble to land further away from drop location (the wider the distribution of pebble)
Distribution of Graphite Pebbles

• PDF and CDF similar to plastic pebbles, but higher probability for graphite pebbles to stop near drop location than plastic pebbles
Variation of Outer Drop Location

- Experiments performed in vessels 24 cm and 30 cm in diameter
- Plastic pebbles dropped from height of 11 cm
- Outer drop locations roughly 0.6\(r\), 0.73\(r\), and 0.8\(r\) (\(r\) is radius of vessel)
- 0.73\(r\) is the location of the real reactor
Probability Distribution of Plastic Pebbles: 24 cm Diameter Vessel

- From equations describing specifications of real reactor, mix zone for vessel 24 cm in diameter, dropped from outer location of 8.8 cm should be **6.65 cm** (scaled linearly)

<table>
<thead>
<tr>
<th>Distance from center (cm)</th>
<th>Experimental mix zone location (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>n/a</td>
</tr>
<tr>
<td>7.0</td>
<td>3.5</td>
</tr>
<tr>
<td>8.8</td>
<td>6.2</td>
</tr>
<tr>
<td>10.0</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Probability Distribution of Plastic Pebbles: 30 cm Diameter Vessel

- Results for 30 cm diameter vessel are not conclusive because many more pebbles need to be dropped to see effect of mixing completely due to further distance from center of vessel.

<table>
<thead>
<tr>
<th>Distance from center (cm)</th>
<th>Experimental mix zone location (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>n/a</td>
</tr>
<tr>
<td>9.0</td>
<td>4.85</td>
</tr>
<tr>
<td>11.0</td>
<td>5.1</td>
</tr>
<tr>
<td>12.0</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Effects of Outer Drop Location

- Experiments confirm intuitive hypothesis that the location of the outer drop is important to the formation of the mixing zone.
- The further the outer drop is from the center, the further away the formation of the mixing zone.
Method to Avoid Mixing

- Cylindrical guide ring can be applied to separate the graphite and fuel zones in the upper core to guarantee no mixing.
Cylindrical Guide Ring

- Energy loss factor \((e^2 = \frac{v_2^2}{v_1^2})\): found to be 0.6 for plastic pebble against hard plastic floor and 0.4 against a pre-established bed of plastic pebbles.

- Maximum height of guide for pebble dropped into 24 cm vessel from 11 cm high at a radius of 7 cm = 1.6 cm

\[ h_{\text{max.}} = e^2 \cdot H - \frac{r^2}{4e^2 \cdot H} \]

PBMR: \(H = 100 \text{ cm}, e^2 = 0.35, \)

\(r = 60 \text{ cm} \rightarrow h_{\text{max.}} = 9.3 \text{ cm}\)
Cylindrical Guide Ring Results

• Experimentally, $e^2$ was found to be 0.2 for dropping onto bed of pebbles

• The energy loss factor ($e^2$) is much less for bed of pebbles than hard surface
Full 9-location drop
Slow Flow Experiment

- Previous Experiments were basic drain experiments - fast flow stopped.
- Need to confirm whether same behavior occurs in slower flow conditions as in pebble bed reactors.
Experimental Configuration

- Added drill like device to lower discharge hole
- Pebbles discharged at about 100 pebbles per minute
Initial Conditions

- Set up similar to first series of experiments
- Track individual pebbles with time
- Lower mixture purely fill material
- Created upper pure yellow zone to track green pebbles placed at various radii.
Results

• Similar to fast flow
• Linear streamlines
• Vertical Velocities as a function of radius are different than previously assumed
• Some surface friction observed
Shaping Ring Test - Slow

- Shaping ring inserted in top 5 inches
- Rest free - no ring
- Slow flow
Results - Shaping Ring

• Linear Behavior still observed
• Annulus maintained to within 2 to 3 pebble diameters
• Inner pebbles move faster than surface pebbles
Lower Plenum Flow

- Flow as predicted
- Suggests that a dynamic core can be created and maintained throughout reactor core.
- Peaking factors can be reduced.
Lower Plenum Discharge

- Flow shape as expected
- Need to consider rate of addition of graphite and fuel pebbles to maintain annulus based on discharge flow
Summary

• Pebble Flow Experiments

- Vertical streamlines were observed in the straight section with both 2D half model and 3D model.
- Lateral motion was limited to one pebble diameter.
- Streamlines were not significantly affected by changes in cone angle, refueling pattern, and exit diameter.
- Material properties do not appear to strongly influence the flow pattern.
- 3D model data confirms the validity of the half-model experiments. Surface effects of half-model are negligible.
Summary

• **Pebble Flow Experiments (Cont.)**

  - Once the central column is formed, mixing in the straight section is determined only by refueling and not through lateral diffusion of pebbles.

  - Overall, the data obtained, agree with the PBMR Safety Analysis Report data. Our results also comply with the data from a prior Molecular Dynamics simulation.
Summary

• Slow Flow Experiments consistent with Fast Flow - linear streamlines
• Shaping ring inserted in top of core can make a dynamic column to within 2 to 3 pebbles.
• Surface friction needs to be evaluated
Future Work

• Submitted Proposal to DOE to study details of pebble velocity with MIT math department - resolve velocity discrepancies as a function of height.
• Will examine central column bypass flow by using smaller graphite pebbles to increase flow resistance
• To study effect of pebble to pebble and surface friction on results
The Class

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