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Description of Test Facility for Dust Remobilisation in Pebble Beds

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Summary

In this report the design of a small-scale test facility for the experimental investigation of the aerosol particle deposition and resuspension behaviour in a pebble bed is presented. It is foreseen to study the spatiotemporal distribution of particle deposits in a pebble bed by means of Positron Emission Tomography (PET).
The test facility design is mainly determined by the fluid dynamic downscaling of the turbulent flow field conditions typically found in a pebble bed High Temperature Reactor (HTR). The gas phase velocities and the size of the aerosol particles are chosen to match the Reynolds and Stokes numbers related to the graphite dust transport in an HTR. The diameters of the pebbles and the diameter of the pebble bed core are adapted in a way that an optimal use of the available PET scanner for dust deposition measurements is possible and to allow the application of analytical pressure drop correlations. Due to radiation protection reasons, the piping system is a closed loop design in order to minimize the risk of the escape of radio nuclides during the experiments. The turbulent flow field is generated by means of a high pressure radial fan controlled by a frequency inverter and the aerosol particles are injected upstream of the pebble bed using an aerosol generator. The fluid velocities and the pressure drops are measured by means of an inclined tube manometer determining the static wall pressure and/or the total pressure in channel centre. The aerosol particle concentration and size distribution is determined by isokinetic sampling technique. The geometry of the pebble bed is captured by a gamma-ray tomography computed scan (GCT). It is planned to split the experimental scheme into two parts. First, there will be a general feasibility study for the PET measurement of particle deposits under simplified conditions (polypropylene spheres, monodisperse liquid aerosol particles) in order to qualify PET for precise 3D measurement of the particle deposits. The detailed boundary conditions for a successful PET measurement shall be identified. In the second part the experimental setup shall be modified (graphite spheres, graphite dust) to come as close as possible to the fluid dynamic boundary conditions of a HTR pebble bed flow.

Approval

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1 Carbonaceous dust in the HTR primary circuit

1.1 Literature review on dust in the HTR

The transport behaviour of carbonaceous dust in the primary circuit of a High Temperature Reactor (HTR) plays an important role for the safety assessment for Design Basis Accidents (DBA). Carbonaceous dust is formed mainly due to friction between graphite components (Kissane, 2009). Especially in a pebble bed type the bulk of the dust arises due to abrasion of graphite material between the pebbles. Furthermore, dust is created as consequence of oxidation processes due to air, water and oil ingresses. During the reactor operation fission products diffuse through the graphite matrix and the graphite dust becomes a carrier of these fission products. The dust production of the German 46 MWth AVR pebble bed reactor was estimated to be approximately 5 kg/y. Results of cold gas filter experiments during standard service in the AVR showed a dust concentration up to 5 µg/m³ (Ziermann and Ivens, 1997). During cleaning transients of the primary circuit the airborne dust concentration rose up to 2 mg/m³. The particle size ranged between 0.1 and 30 µm in diameter and the modal of the number weighed size distribution was about 0.6 µm.
The spatial distribution of the carbonaceous dust in the primary circuit was estimated for a 500 MWth Pebble Bed Modular Reactor (PBMR) by means of the system code SPECTRA (Stempniewicz, 2010). According to these results most of the dust deposits at the bottom of the reactor vessel, a smaller amount in the intermediate heat exchanger and the residual dust accumulates in the piping and helium purification system. Furthermore, dust also accumulates in the pebble bed. The linear dust layer build-up was computed for stationary conditions and the results can be takes as a general estimate of the overall dust distribution in the primary circuit during standard service. To the author's knowledge, the resuspension behaviour of the dust during a DBA is yet rather unknown. One important part of the coolant circuit is the pebble bed, which is an irregular formation of thousands of single graphite pebbles. Here dust deposits and resuspension is expected to be considerable.

1.2 Flow field and aerosol particle behaviour in a pebble bed

The transition from laminar to turbulent flow condition was explored by Jolls and Hanratty (1966) in a packed bed of spheres. The transition was visualized according to the experiment of Osborne Reynolds by seeding the flow with a tracer colour. Transition was observed at a Reynolds number of about 110 to 150 with respect to the pebble diameter.
The pressure drop over the pebble bed has been investigated by different authors. It is assumed that energy losses in the pebble bed take place due to kinetic and viscous effects. Ergun (1952) explored the pressure drop over a pebble bed, both theoretically and experimentally, and found an universal slope of pressure drop against Reynolds number. Later, Reichelt (1972) extended Ergun's approximation with respect to bed porosity and pebble-to-tube diameter ratio. Recently, Eisfeld and Schnitzlein (2001) reviewed 24 different pressure drop correlations and improved Reichelt's approach basing on the data basis, accordingly.
The flow field in a randomly packed pebble bed is characterized by local stagnation points and recirculation areas. First fluid mechanic analyses were related to the radial fluid velocity distribution and the overall pressure drop. Schwartz and Smith (1953) investigated the radial velocity distribution by means of hot wire anemometry and observed a radial velocity peak approximately one pebble diameter away from the tube wall of about 130% to 200% of the velocity in the middle of the tube. One reason for this might be the larger void fraction at 0-1 pebble diameters away from the wall.
The turbulent flow field through a pebble bed has recently been investigated by means of CFD computations as well as velocity field measurements. Calis et al. (2001) computed the flow field around columns of packed beds with very low pebble-to-tube diameter ratios of about 1 to 2. The comparison of the friction factors between the CFD computation and the Ergun's approximation leads to a poor agreement. It is assumed that the CFD RANS computation underestimates the contribution of the turbulent friction. Nevertheless, the comparison of the time averaged flow field between the CFD results and the presented Laser Doppler Anemometry (LDA) measurements show relatively good agreement. Deeper insight into the flow field was given by results of a Large Eddy Simulation (LES) through the gaps of periodically aligned pebbles (Hassan, 2008). Regarding convective heat transfer it was shown that an inhomogeneous velocity distribution leads to an inhomogeneous surface temperature distribution of the pebbles. The results of this LES were validated by means of Particle Image Velocimetry (PIV) measurements (Dominguez-Ontiveroz et al., 2008). Refractive index matching of the fluid was used to gain optical access into a packed bed of Plexiglas spheres. The formation of recirculation areas in the interspaces of the pebble bed was recorded in the Reynolds number range from 80 to approximately 551. There was a dependency between vortex formation and Reynolds number in the pores. Furthermore, spherical polymer particles with a size distribution of 80 to 120 µm are

injected into the pebble bed and the deposition rate at the contact points between the pebbles was analyzed. Dominguez-Ontiveroz et al. reported about a power law relation between particle deposition rate and Reynolds number.

2 Design of the pebble bed loop

2.1 Estimation of the characteristic numbers

The Helium Pressure Boundary (HPB) in the primary circuit of the HTR is characterized by a static pressure up to 9 MPa and a coolant temperature up to 950° C (Kissane, 2009). Considering fluid dynamic aspects of particle deposition and resuspension the aerosol particles and the flow field are scaled according to the characteristic numbers of HPB such as Reynolds number and particle relaxation time. Note, that there are many other effects (e.g. humidity, adhesiveness, electrostatics) affecting the graphite dust characteristics which might be different at standard atmospheric conditions. However, the Reynolds number is defined as:

$$\mathrm{Re}_{pb} = \frac{\bar{v}_{spb} \cdot d_{pb}}{\nu} . \qquad (2\text{-}1)$$

$\bar{v}_{spb}$ is the superficial velocity of the empty pipe containing the pebble bed, d_{pb} is the pebble diameter and ν is denoted as kinematic viscosity of the fluid. According to Tian and Ahmadi (2007) the dimensionless particle relaxation time is denoted as:

$$\tau^{+} = \frac{S \cdot d_{aero} \cdot v*_{pb}^{\;2}}{18 \cdot \nu_{air}} Q . \qquad (2\text{-}2)$$

S is the particle-to-fluid density ratio, d_{aero} is the aerosol particle diameter, $v*_{pb}$ is the shear velocity and Q is the Cunningham slip correction. Kinematic viscosity contributes to both characteristic numbers. According to the estimate shown in Table 1 helium in the HTR HPB has a three times lower kinematic viscosity than air at standard condition, but it agrees well in the order of magnitude. Thus, for economical reasons air at ambient conditions is used as fluid in the present study. Furthermore, the particle size distribution of the test aerosol particles and the fluid velocities in the pebble bed are chosen in such a manner that the deposition and resuspension phenomena of graphite dust in the HTR are scaled correctly.
The AVR pebble to pipe diameter was about 50. In the present facility we decided to choose a pebble-to-tube diameter larger than 5. Thereby, the turbulent flow field in the pebble bed can be scaled to HTR conditions and the PET scanner can resolve the spatial distribution of the particle deposits accordingly.

Table 1 Estimation of kinematic viscosity

Parameter	Unit	Symbol		Air	Helium in HPB
Temperature	[K]	T	=	293.15	950
Pressure	[10^5 Pa]	p	=	1.013	70
Free path length	[nm]	λ	=	68	
Specific gas constant	[J/(kg*K)]	R_s	=	287.058	2077
Mass density	[kg/m³]	ρL = p/(R_s*T)	=	1.20	3.55
dynamic viscosity	[µPa*s]	µ	=	17.1	18.6
kinematic viscosity	[µm²/s]	ν = µ/ρ	=	14.2	5.2

2.2 Description of the loop components

A closed-loop design was chosen in order to meet the stringent radiation protection regulations of our PET centre. The first draft of the entire assembly is shown in Figure 1. The turbulent flow field is generated by a high pressure radial fan of 250 W electrical power. The flow is piped to the pebble bed via standard steel tubes. Upstream of the pebble bed the flow field is decelerated by a small diffuser before entering the test section. The outer diameter of the test section is adjusted to use the full size range of the PET scanner which has an inner diameter of 220 mm. Downstream of the pebble bed the particle laden flow is filtered in a HEPA (High Efficiency Particulate Airfilter) to catch the radioactive particles before entering the radial fan again.

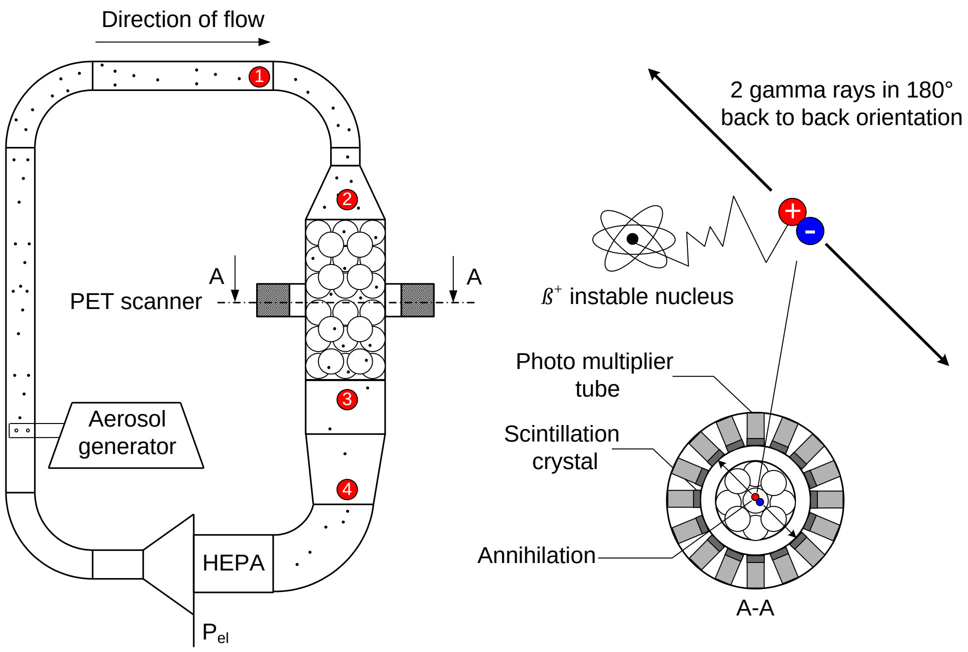

Figure 1 Scheme of the Pebble Bed Loop and the measurement principle

It is foreseen to split the entire investigation into two runs. The first run shall be conducted under simplified conditions in order to identify the right boundary conditions for the successful recording of the particle deposits. The second run shall be conducted under the improved boundary conditions identified in the first step in order to achieve more realistic data on particle deposition and resuspension in a pebble bed.
Due to the splitting of the experimental scheme into two parts the layout of the pebble bed is varied, respectively. The pebble diameter is 40 mm. In the first run, the pebble bed has a length of 4 hydraulic diameters (20 pebble layers in flow direction) and the pebbles are made of polypropylene in order to minimize the attenuation of the gamma rays. It is foreseen to use liquid aerosol particles in order to study pure particle deposition in the pebble bed. The total length of the pebble bed of 4 hydraulic diameters will comprise the possibility of the observation of the downstream progression of particle deposits.
In the second run, the polypropylene spheres will be replaced by hollow graphite spheres and the liquid particles will be changed to graphite dust. Note, the length of the pebble bed will be reduced from 4 to 2 hydraulic diameters. It is assumed to minimize the scatter radiation of gamma ray being detected which originates from the outside of the field of view. Furthermore, the determination of total pressure and particle concentration drop over the pebble bed will be harder to capture because the influence of pressure drops related to inlet/outlet formation effects will increase. The material combination of the HTR pebble bed core shall be replicated realistically and in addition particle resuspension shall also be captured by producing blower transients in the loop.

3 Selection of measurement techniques

3.1 Basic Instrumentation

The basic instrumentation of the PBLoop consists of different static pressure ports and additional pitot tube supports at which the local fluid velocity is measured using an inclined tube manometer in order to record the volume flow. The total pressure loss over the pebble bed is determined by measuring the wall static pressure difference upstream and downstream of the pebble bed. Measurement site locations 1 to 4 are displayed in Figure 1, respectively.
In the first run, the particle number concentration of the liquid particles is measured using isokinetic sampling technique in combination with a condensational particle counter (TSI, UCPC 3025A). According to Farnsworth and Caldow (2010) the counting efficiency of the UCPC 3025A is greater than 90% for particles having an aerodynamic diameter smaller than 4 µm. Particles larger than 4 µm tend to deposit in the tubing system of the UCPC and the counting efficiency decreases, rapidly.

During the second run, the airborne mass concentration is measured by isokinetic sampling and filter experiments. The aerodynamic particle size distribution of the graphite dust is determined by an Aerodynamic Particle Sizer Spectrometer (TSI, APS 3321).
The 3D geometry of the pebble bed is recorded by means of a gamma-ray computed tomography scan further described in Hampel et al. (2007). The entire pebble bed was scanned with a resolution of 2 mm/pixel. 400 slices had to be recorded. With 5 minutes for each slice the measurement took 34 hours.
The employed PET scanner ClearPET(TM) from Raytest (Sempere, 2006) consists of 80 multi-channel photomultiplier tubes with corresponding crystal matrixes arranged in four rings with 20 cassettes arranged in a circle around the field of view (Figure 1). For a more homogeneous coverage of the volume every other module group is moved axially by a half module length. The cassettes are attached to the gantry in a way that allows different inner diameters from 135 mm to 220 mm. The resulting voxel size is 1.15 mm and the dimensions of the created intensity matrix for each scan are I=(169;169;95).

3.2 Aerosol particle generation and radioactive labelling

The aerosol particles are generated by two different devices. In the first run, the liquid aerosol particles are made of a technical oil called DEHS (Di-Ethyl-Hexyl-Sebacat) by a condensational aerosol generator (TOPAS, SLG 270). The SLG 270 uses the aerosol generation based the controlled heterogeneous condensation according to Sinclair-La Mer (Altmann and Peters, 1992). Vaporized material is recondensed in a stable process onto a well controlled number of condensation nuclei. Due to its special design the aerosol particles are fairly monodisperse and can be varied between 0.1 and 5 µm. The radioactive labelling is performed by adding ^{18}F to the atomizer liquid. Thus, the activity attaches to the condensation nuclei as further described by Prodi and Spurny (1976).
In the second run, the radioactivity dissolved in a water solution is added to the graphite dust sample. Then, the wetted dust sample is dried in an oven and will be dispersed as dry dust into the turbulent flow field by means of a solid aerosol generator (TOPAS, SAG 410).
It is foreseen to use the radioisotope ^{18}F because of its half life of about 109.77 min. This half life permits to run the PET experiments and to redo the experiment or dismantle the facility the following day because of its fast decay rate and negligible residual activity in the pebble bed.

4 Experimental scheme and test matrix

The experimental scheme is divided into two different runs. First, there will be a preliminary assessment of the turbulent flow field and the aerosol particle concentration. Second, there will be actual PET measurement itself. Regarding the splitting of the entire task into a feasibility study with liquid particles and a second study using technical graphite dust, the following test matrices were devised:

Table 2 test matrix for first run

Action	Due Date
Pressure and velocity measurements	M 14
Particle number concentration measurements	M 15
PET measurements of liquid particle deposits	M 15

Table 3 test matrix for second run

Action	Due Date
Pressure and velocity measurements	M 14
Particle number concentration measurements	M 15
PET measurements of liquid particle deposits	M 15

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