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Review of PSI studies on reactor physics and thermal fluid dynamics of pebble bed reactors

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Abstract – *Switzerland is member of the Generation IV International Forum (GIF). The related work takes entirely place at PSI in the working groups of Gas-Cooled Fast Reactors and Very High Temperature Reactors. In the past, PSI has performed experimental and theoretical studies on criticality issues of pebble beds at the PROTEUS reactor, as well as a preliminary risk assessment of a prototypal HTR as an input for a comparison of energy supply options. PROTEUS was a critical assembly with an annular driver zone. The central region was filled by arrangements of fuel spheres. The reactivity effect of a water ingress was investigated by simulating the water by polyethylene rods of different diameter inserted into the gaps of a regular package. For sub-criticality measurements in pebble beds, a built-in pulsed neutron source was used. The experimental results were used to validate diffusion and higher order neutron transport models.*

Concerning thermal hydraulics of gas flows, the vast experience of PSI is focused on hydrogen transport, accumulation, and dispersion in containments of light water reactors. The phenomena are comparable in many aspects to the fluid dynamic issues relevant to HTR. Experiments on hydrogen flows are performed for numerous scenarios in the large-scale containment test facility PANDA. Hydrogen is substituted by helium as a model fluid. An important generic aspect is turbulent mixing in the presence of strong stratification, which is relevant for HTR as well. In a parallel project, generic small-scale mixing experiments with a high density ratio of 1:7 are carried out in a horizontal rectangular channel, where helium and nitrogen flows are brought into contact downstream of the rear edge of a splitter plate. Due to the high density ratio, turbulent mixing is affected by strong non-Boussinesq effects. The measurements taken by Particle Imaging Velocimetry (PIV) and Laser Induced Fluorescence techniques are compared to RANS and LES simulations. Similar large density ratios are expected in air ingress scenarios at an HTR.

As a spin-off from aerosol studies for severe accidents, theoretical studies were started on graphite dust in pebble bed reactors. Wear and tear of the fuel spheres can produce significant quantities of graphite dust. Simulations of the pebble flow in a random package have been carried out in a generic full-size reactor geometry (440'000 pebbles) using the discrete-element method (DEM). The simulations provide the residence time distribution of the pebbles and the spatial distribution of wear. The model is ready for an implementation of a dust production term. In parallel, preliminary results on dust deposition were obtained for a particle laden flow around a single sphere and a linear arrangement of spheres. For this purpose a RANS turbulence model was coupled with a continuous random walk model for the integration of the particle trajectories in Lagrangian coordinates. Based on the outlined expertise, PSI plans to intensify the work on HTR in the future.

I. INTRODUCTION

The Paul Scherrer Institute (PSI) is a multi-disciplinary research institute which belongs, together with both federal technical universities, the ETH Zurich and the EPFL, to the Swiss Federal Institutes of Technology, the so-called "ETH Domain" directly subordinated to the Federal Department of Economic Affairs, Education and Research (EAER) of Switzerland. It is the largest Swiss national research institute with about 1,900 employees, and is the only one of its kind in Switzerland. The fields of activity of PSI are solid state physics, materials sciences, elementary particle physics, life sciences, nuclear and non-nuclear energy research, and energy-related ecology. PSI operates a number of large scale facilities, which are open to external research groups. A 590 MeV cyclotron, with its 72 MeV companion pre-accelerator, is used to drive numerous beam lines, as well as the spallation neutron source complex SINQ. The proton beams are also used for cancer therapy. The latest accelerator of PSI is the Swiss Light Source (SLS), built in 2001, a synchrotron light source with a 2.4 GeV electron storage ring.

Fig. 1: Bird's eyes view of the Paul Scherrer Institute.

PSI (Fig. 1) was established in 1988 by merging the Federal Institute of Reactor Research (Eidgenössisches Institut für Reaktorforschung = EIR) founded in 1960 with the Swiss Institute for Nuclear Physics (Schweizerisches Institut für Nuklearphysik = SIN) founded 8 years later in 1968. Historically, the Federal Institute of Reactor Research was established to pave the road towards a safe and efficient use of nuclear energy in Switzerland by fundamental and applied research in the fields of reactor physics, reactor technology, nuclear thermal hydraulics and nuclear materials. Today, research activities concerning safety and efficiency of nuclear power generation are bundled in the Department of Nuclear Energy and Safety (NES) of PSI with a staff of about 180 employees and numerous PhD and postdoctoral students, which is one out of six departments of PSI. The department has six laboratories: Reactor Physics and Systems Behavior LRS, Thermal Hydraulics LTH, Hot Laboratory AHL, Waste Management LES, Energy Systems Analysis LEA and Nuclear Materials LNM.

NES is the national competence center for Nuclear Safety and maintains and develops its competences in the fields of reactor physics, nuclear thermal-hydraulics and nuclear materials and fuels. It supports the national activities directed towards a safe disposal of nuclear waste by research in repository geochemistry and mass transport of radio-nuclides in the barrier system and in the environment. In order to contribute to the high level of safety of the Swiss NPPs, NES cooperates extensively with academic institutions, national authorities as well as with the nuclear industry in Switzerland and abroad. As organic part of its activities, it supports the Federal Universities ETHZ and EPFL in conducting the Swiss master program in Nuclear Engineering established in 2008, by research infrastructure, teaching assignments of senior researchers and the supervision of master and PhD theses. The professors of Nuclear Energy Systems of ETHZ and Reactor Physics of EPFL are heads of the laboratories LTH and LRS, respectively. The present summary paper provides an overview on the activities of NES at PSI in the field of Gas-cooled High-Temperature Reactors (HTR).

II. SWISS MEMBERSHIP IN THE GENERATION IV INTERNATIONAL FORUM

Switzerland joined the Generation IV International Forum (GIF) in the year 2002 and has signed system agreements for the GFR and the VHTR. The related work takes entirely place at PSI. PSI scientists act as Swiss representative in the Very High Temperature Reactor (VHTR) Systems Steering Committee as well as co-chair of the VHTR Project Management Board Materials. Substantial own work was carried out within the PSI project "High Temperature Materials for Advanced Nuclear Plants" (HT-MAT). This includes SiC and SiC composite as constructional and cladding material, e.g. for the Gas Cooled Fast (GFR) reactor and for applications in Accelerator Driven Systems (ADS). The studies on constructional materials cover all classes of materials, steels, ceramic and refractory materials, Oxide Dispersion Strengthened (ODS) materials as well as MAX phases for all systems [1]. Additionally to all relevant standard methods of material testing, the Hot Laboratory AHL, and Nuclear Materials Laboratory LNM are equipped with or have access to numerous advanced testing and analysis methods, like in-situ creep measurements during ion irradiation, neutron diffraction and the use of synchrotron radiation, e.g. for EXAFS [2]. It is also possible to prepare micro-samples from irradiated nuclear fuel in hot cells and to transfer it to a dedicated active beam-line of the SLS. For studies of radiation damages, material samples are exposed to controlled irradiation at the SINQ and at external facilities with protons and neutrons. Nano-indentation and testing on micro-pillars were developed for small quantities of novel material [3]. The mentioned experimental capabilities are accompanied by theoretical modeling on different scales down to the molecular [4]. Contributions are made for the development of Minor Actinide (MA-MOX) fuel and mixed carbides [5].

In the field of reactor physics and safety analyses, the Fast Group of the Laboratory of Reactor Physics and Systems Behavior LRS is contributing by selected research efforts concerning Sodium cooled Fast Reactors (SFR), Gas cooed Fast Reactors (GFR) and Molten Salt Reactors (MSR). For the study of safety issues of the SFR a coupled 3-D neutronics/thermal-hydraulics code system has been developed. It is in particular used for improving the response of SFR cores to an unprotected loss-of-flow accident [6, 7]. LRS took part in the PHEBUS natural convection analysis benchmark [8]. For the GFR, a heavy gas injection method for emergency decay heat removal has been developed and analyzed [9]. Different fuel cycle options with fast reactors are analyzed with regard to actinide burning [10, 11]. Dynamics of different core concepts of thermal and fast Molten Salt Reactors (MSR) are studied [12]. Recently, efforts on the coupling of reactor physics codes to Open Source CFD for Uranium and Thorium Closed Fuel Cycle and Safety Analysis of SFR and MSR (OpenFoam) have been started. Some singular contributions were made for Supercritical Water Reactors (SCWR) and Lead-cooled systems as well. A definite highlight is successful test of the first large liquid metal target for an Accelerator Driven System worldwide. PSI hosted the MEGAPIE experiment, which replaced the solid lead target of the spallation neutron source SINQ for a period of 4 months [13].

III. NEUTRONICS OF PEBBLE BEDS

In 1990, the International Atomic Energy Agency established a Coordinated Research Project (CRP) on the Validation of Safety Related Physics Calculations for Low-Enriched High Temperature Gas Cooled Reactors (HTGRs) with the main objective to provide safety-related neutron physics data for low-enriched uranium (LEU) fueled HTGRs. The main experimental activities were conducted at the PROTEUS facility at the Paul Scherrer Institute, Villigen, Switzerland. The project served to enhance confidence in predictions of neutron physics behavior of pebble bed reactors. Different core configurations composed from spherical fuel elements with coated particles (below shortly referred to as pebbles) were studied. The fuel for the experiments (LEU pebble-type fuel with an enrichment of 16.7 % U-235) was made available by the KFA Research Center, Jülich, Germany. First criticality was achieved on July 7, 1992 [14].

PROTEUS (Fig. 2) is a zero power reactor with maximum thermal power of 1 kW commissioned in February 1968. It features a cylindrical central cavity that is driven critical by a surrounding graphite region equipped with fuel pins containing UO_2 with an enrichment of 5 %.

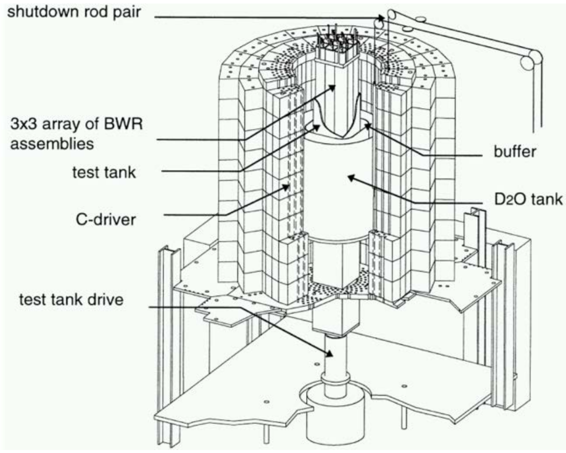

Fig. 2: The PROTEUS reactor at PSI with an insert of 9 BWR fuel elements, source: http://proteus.web.psi.ch/facility/

The central cavity has a diameter of 1.2 m. It can be filled with different sub-critical fuel arrangements (k_∞ down to 0.7) and made critical to measure neutronics properties of the inserted fuel configurations. Control organs are located in the graphite driver region not to perturb the central lattice to be investigated. PROTEUS has been shutdown in April 2011 for strategic reasons. A large amount of unique experimental data has been created in this research program. It is used for code validation purposes and can be made available to external partners.

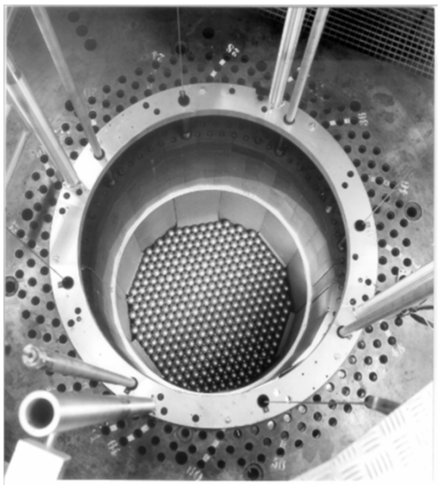

Fig. 3: The PROTEUS reactor with a regular loading pattern of pebbles, source: http://proteus.web.psi.ch/facility/

In the HTR experiments, the central region was filled with fuel and moderator spheres (Fig. 3). At

PROTEUS, ten different core configurations were used. Four types of pebble arrangements were studied. Fuel pebbles and pure graphite moderator pebbles are mixed to achieve the desired moderator-to-fuel ratio (MFR). One configuration (core 4) facilitated a random pebble bed created by feeding the spheres through a delivery tube. The fuel to moderator pellet ratio was in these tests 1:1. A repetition serving as a reproducibility test and the feed of fuel and moderator pebbles through two different tubes were further variants.

All other configurations used hand-stacked regular pebble arrangement. These lattices were either hexagonal close-packed (HCP) with a fuel to moderator pebble ratio of 1:2 or columnar hexagonal point-on-point (CHPOP) configurations, the latter with both a ratio of 1:1 and 1:2. Examples of elementary cells for two selected regular arrangements are given in Fig. 4. The theoretical pebble packing fractions for these HCP and CHPOP configurations are 0.7405 and 0.6046, respectively, whereas the latter is close to the reference value for the random packing of 0.61 (apart from the close-to-wall region, where the packing fraction decreases), which means that the results obtained with the CHPOP are representative for a realistic HTR core.

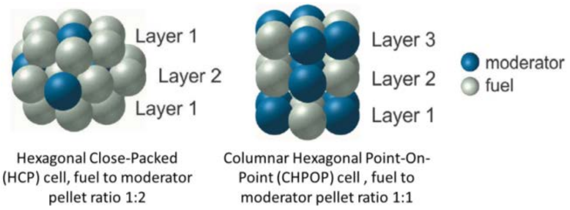

Fig. 4: Elementary cells of the regular pebble beds in the PROTEUS experiments [15]

Criticality measurements were performed by successively loading pebbles while monitoring the reading of the neutron detectors. The classical “approach-to-critical” technique was applied to determine the quantity of pebbles to be inserted in the subsequent step. For reactivity measurements, the Pulsed Neutron Source (PNS) and Inverse Kinetics (IK) techniques were employed. A miniature accelerator tube was used to produce 3 μs long pulses of 14 MeV neutrons via the D-T fusion reaction. The source was situated in the center of the lower axial reflector. Reactivity measurements were carried out as follows: (1) criticality was established using the control rods with the PNS and neutron detectors in place and the reactor start-up sources withdrawn, and the control rod positions were frozen, (2) the negative reactivity perturbation to be quantified was introduced, (3) the PNS was switched on, (4) the response of the system to the neutron pulses is recoded by a multichannel scaler system (MCA) after an equilibrium had been reached and data was acquired until the desired statistics were reached. From the transient response to the pulses, the sub-criticality was obtained by IK techniques.

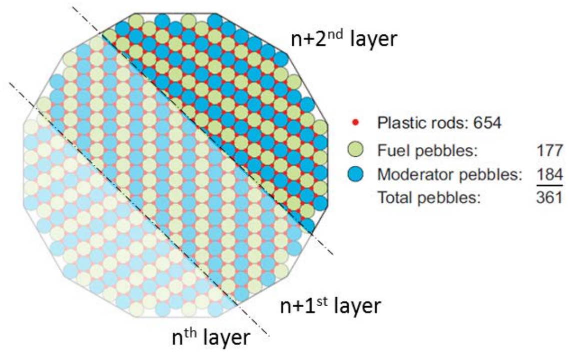

Fig. 5: Three successive layers of the core configuration of the PROTEUS core with polyethylene rods inserted in order to model moisture ingress

This technique was used to calibrate control rods in the reflector and inside the core, as well as to measure the reactivity coefficient in case of moisture ingress [16]. Water up to a density of 0.25 kg/m^3 related to the void volume between pellets (corresponds to 0.065 kg/m^3 related to the entire pebble bed volume) was modeled by the insertion of polyethylene rods with a diameter of 8.9 mm into the vertical channels between pebbles in the CHPOP packing (Fig. 5). Criticality was established with the polyethylene rods inserted. The transient response to the pulsed source was recorded after the withdrawal of a part or all polyethylene rods, which causes a negative reactivity effect. In turn, the positive reactivity insertion due to the water ingress was determined. This allowed to determine reactivity effects in the order of up to 6 $ (Fig. 6) in a safe way.

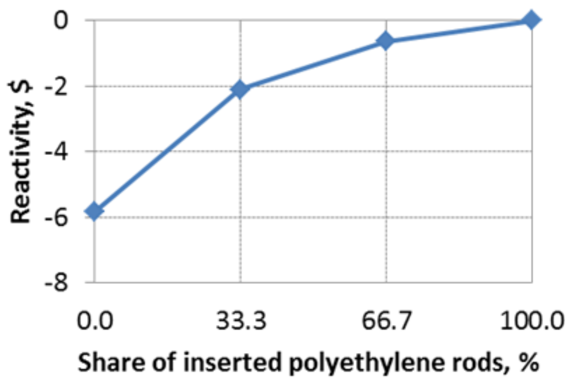

Fig. 6: Typical reactivity insert due to water ingress simulated by polyethylene rods

Besides the experiments highlight above, flux distributions and spectra were measured in the core and the side reflector. Furthermore, kinetic parameters including the prompt neutron lifetime, as well as the effect of moisture ingress on all these parameters were determined.

As a general summary, the IAEA-TECDOC-1249 [14] can be cited directly: "In total the experiments performed in the CRP produced a great amount of valuable results to be used in validation procedures of theoretical models and data bases. Together with the broad benchmark and evaluation program running parallel to the experiments a deeper insight into the safety relevant neutron physics of graphite moderated gas-cooled reactors has been obtained. The CRP has demonstrated the high quality of experimental techniques and of computational tools. Moreover it has gathered international experienced scientists around the world to define the state of the art, to identify the still existing validation deficiencies and to prescribe a way to improve the knowledge in safety related questions of gas-cooled nuclear reactors."

IV. FLUID DYNAMIC STUDIES WITH HELIUM

PSI possesses and operates the large-scale containment test facility for thermal hydraulic studies PANDA [17]. It is a multi-compartment model of a Boiling Water Reactor (BWR) containment. Initially, the work was dedicated to the qualification of passive safety systems for BWRs of the Generation III (SBWR, ESBWR, SWR1000 = KERENA). Later, the focus shifted towards hydrogen transport, accumulation and dispersion in LWR containments in a succession of several OECD and EU projects (SETH, SETH-II, HYMERES, ERCOSAM-SAMARA) with large international participation. Experiments performed at the PANDA facility of PSI use helium as a model fluid for hydrogen. The related phenomena and in particular the simulation by means of Computational Fluid Dynamics (CFD) is comparable in many aspects to the fluid dynamic issues found in HTRs. An important generic aspect is turbulent mixing in the presence of strong stratification, which is relevant for HTR as well. Due to the extensive instrumentation of PANDA, data stemming from this test facility finds increasing use for CFD code validation [18]. In this line, PANDA is being used as data source for the OECD-PSI blind benchmark exercise on erosion of a stratified layer by a buoyant jet in a large volume, which is conducted in the frame of the CFD4NRS series of international workshops [19].

The small-scale test facility MiniPanda [20], a downscaled version of the pair of drywell vessels of PANDA is available at the Laboratory of Nuclear Energy Systems at ETH Zurich. It was initially built with the intention to serve as a test object for innovative containment instrumentation. Later, it was found to be useful for code validation purposes as well. A similar jet erosion experiment like the one used for the OECD benchmark was conducted and used for a CFD code benchmark exercise with international participation under the umbrella of the Gesellschaft für Anlagen- und Reaktorsicherheit GRS of Germany [21].

The same MiniPanda was used for a generic air ingress test [22]. For this purpose, one of the vessels was filled with air, the second one with helium. A plate blocking the interconnecting pipe was removed to start the test. Due do buoyancy, helium started to flow into the air filled vessel, forming a rising plume. In turn, a counter current air flow went into the helium filled vessel and plunged down (Fig. 7).

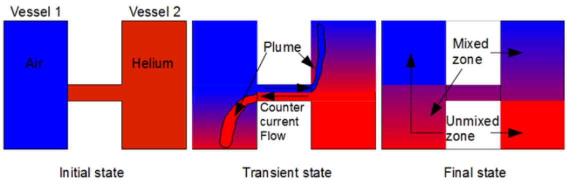

Fig. 7: Qualitative description of the generic air ingress experiment carried out at MiniPanda [22]

In this experiment, the air was heated to a higher temperature than the helium, which was left at room temperature. The transient gas exchange process was observed by thermo-resistive mesh sensors, which delivered temperature profiles across the full cross-section of both vessels and of the interconnecting pipe (Fig. 8). The data was used for CFD validation, as well, and can be made available to external users. It can be useful for the qualification of CFD models for the simulation of air ingress scenarios at gas cooled reactors despite of the significant differences in geometry and the missing pebble bed, e.g. with regard to turbulent mixing under the influence of strong density stratification.

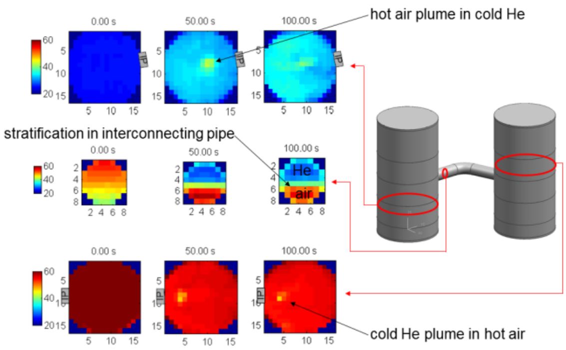

Fig. 8: MiniPanda generic air ingress experiment, temperature distributions measured by thermoresistive mesh sensors [22]

In a parallel PhD project, generic small-scale mixing experiments with a high density ratio of 1:7 are carried out in a horizontal rectangular channel, where helium and nitrogen flows are brought into contact downstream of the rear edge of a splitter plate (Fig. 9). Similar large density ratios are expected in air ingress scenarios at an HTR. The test channel HOMER (HOrizontal Mixing Experiment in a Rectangular channel) is supplied by helium and nitrogen from the GAs MIxing LOop (GAMILO). The cross-section of the channel has the dimensions of 60 x 60 mm.

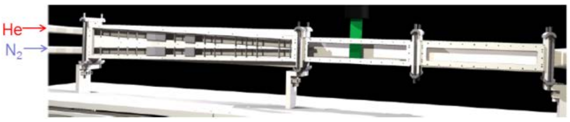

Fig. 9: HOrizontal Mixing Experiment in a Rectangular channel (HOMER)

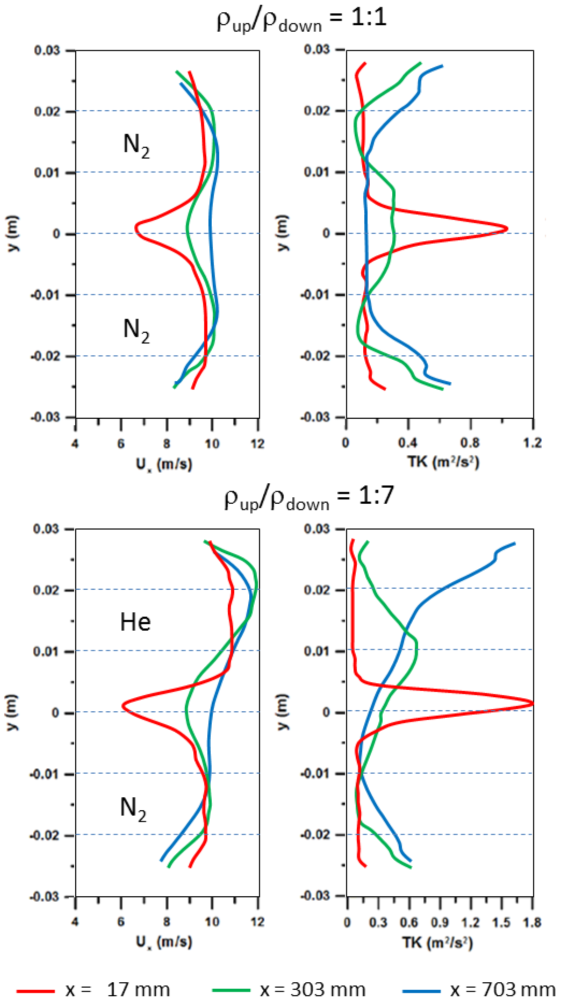

Fig. 10: Profiles of velocity (U) and turbulent kinetic energy (TK) obtained by PIV at the HOMER facility at equal velocities (8 m/s) and nitrogen in both inlets (above) and for a pure helium flow in the upper inlet and nitrogen in the lower inlet (below, density ratio 1:7), x = distance downstream of the rear edge of the splitter plate (from [23])

Due to the high density ratio, turbulent mixing is affected by strong non-Boussinesq effects. The measurements taken by Particle Imaging Velocimetry (PIV) and Laser Induced Fluorescence techniques are compared to RANS and LES simulations. We expect to be able to measure turbulent mass fluxes <u'C'> by correlating instantaneous velocities and concentrations, which can be used to validate Temperature Fluctuation Transport Models (TFTM) coupled to Reynolds Stress RANS.

Some exemplary results are shown in Fig. 10. In the case of nitrogen supplied to both inlets, symmetric profiles over the height of the channel. The peak in the center at y = 0 is caused by the boundary layer that develops on the splitter plate. With growing inlet length, the influence of the splitter plate declines, while the boundary layers grow from the top and the bottom of the channel towards the center line. In contrast to this symmetric behavior, a strong asymmetry is observed in case of the high density ratio. The upper helium stream is accelerating compared to the inlet velocity. Furthermore, the dip in the axial velocity and the peak of the turbulent kinetic energy, caused by the splitter plate, move towards the top into the light gas region.

The experimental data presented here has preliminary character. Measurements are ongoing. PIV is being validated by LDA measurements. Furthermore, the combined PIV/LIF measurements have been started. The obtained data is used for the validation of RANS and LES simulations.

V. PEBBLE MOTION AND DUST PRODUCTION BY WEAR

As a spin-off from severe accident aerosol studies, which is a strong element of the portfolio of LTH at PSI, theoretical studies were started on graphite dust in pebble bed reactors. Wear and tear of the fuel spheres can produce significant quantities of graphite dust. Limited data is available on the frictional properties of the pebble surfaces under the typical operating conditions in these reactors, which feature high temperatures, pressures, and a helium atmosphere. Simulations of the pebble flow in a random package have been carried out in different scales up to a generic full-size reactor geometry (1:6, 1:3, 1:1 corresponding to 440'000 pebbles) using the discrete-element method (DEM). For this purpose, the LargeAtomic/Molecular Massively Parallel Simulator (LAMMPS) was applied, which was developed at Sandia National Laboratories ([24]; LAMMPS, 2005). The obtained experience in the application of DEM can be used as a starting point for simulations of the pebble flow in real industrial prototypes and therefore for the optimization of the reactor geometry.

DEM is based on a tracking of individual spheres according to forces caused by gravity and the contact with neighboring fuel spheres. The spherical pebbles interact according to a spring–dashpot contact model. Normal and tangential components of the contact forces are obtained as a function of normal and tangential relative velocities of both contacting surfaces and the elastic and viscoelastic components of deformation are taken into account. In our calculations presented by [25], a linear Hookean contact model was applied instead of the more realistic Hertzian contact model, which is essentially non-linear because it takes into account the complex deformation of the contact spot with increasing load. A sensibility check with both contact models in the 1:3 geometry has shown deviations below 5 % for flow rate, velocity, profile and wear. This was found to be acceptable in view of the preliminary character of the calculations and allowed a significant economy of computational costs. Another simplification consists in the assumption of equal mechanical properties for modeling pebble-to-pebble contact and pebble-wall contact, although the graphite used for the reactor internals duct is known to possess mechanical properties different from those of the pebbles. The results have therefore generic character.

The volume of worn graphite material was predicted by the model of [26], correlating it linearly to the applied load between touching pebbles and the sliding distance, i.e. the integral over the slip velocity. Wear by pebble collisions and higher order effects due to alterations in pebble sphericity are neglected. For the generic simulations the reactor vessel geometry of the MIT modular pebble-bed reactor design has been adopted.

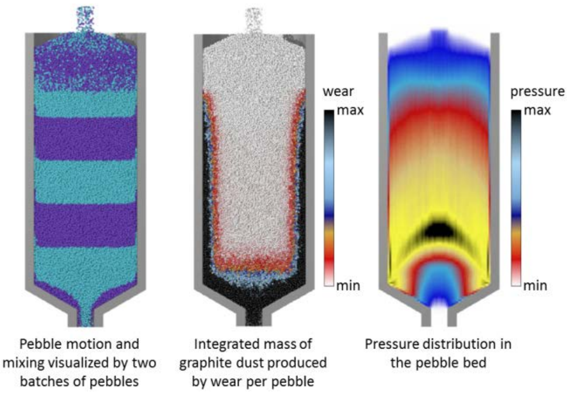

Fig. 11: Results of pebble flow and wear simulations in a generic HTR geometry (from [25])

The simulations provide details of the pebble flow and the mixing of recycled pebbles, velocity profiles close to the wall and in the inlet and outlet regions, the residence time distribution of the pebbles, the spatial distribution of wear and the pressure distribution in the pebble bed, as illustrated in Fig. 11. The simulations provided profiles of the density of the pebble bed, which is important to correctly predict neutronic properties of the core. It was possible to predict the spontaneous transition from a random package to a dense package of spheres, also called pseudo-crystallization, as a function of the friction coefficient. This phenomenon may lead to an obstruction of the pebble flow in certain, non-optimized geometries. Furthermore, the effect of growing order in the pebble bed structure in the direction towards the wall is correctly predicted (**Error! Reference source not found.**).

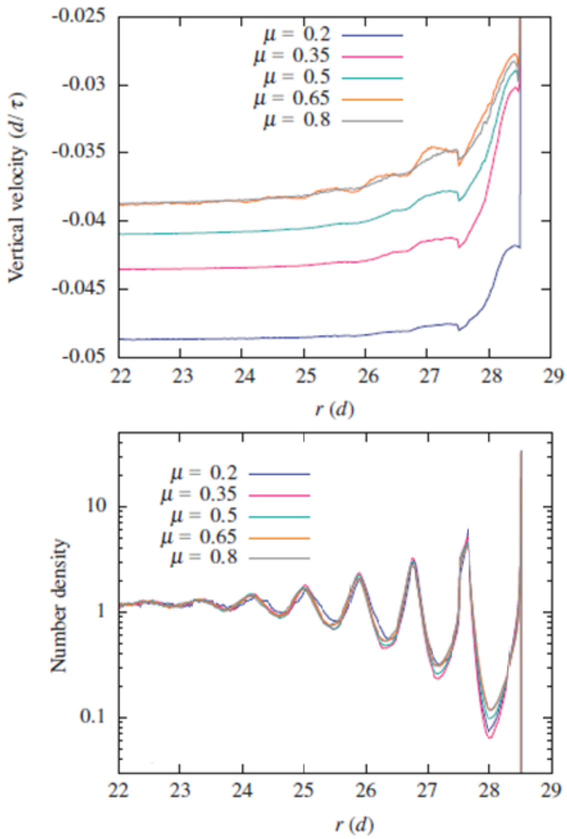

Fig. 12: Velocity profiles close to the wall (above) and growing order of pebble number density towards the wall (below), both as function of the friction coefficient μ, [25]

The main purpose of the simulations consisted in the creation of a sound fundament for the transfer of results obtained at downscaled test rigs to the real rector size in the planning phase of a new experimental facility. The results show complex behavior due to discrete pebble packing effects, although several simple scaling rules can be derived. Besides the support of a new experimental project proposal, which was finally not launched, the theoretical simulations are of generic value. The model is ready for tuning the model parameters to experimental results. The weakest point is given by the closure laws of the wear model, in particular concerning the behavior in helium at prototypal temperatures. There is still a lack of experimental data for the development of adequate model equations, calling for dedicated experiments. With an appropriate set of closure relations, the model can be potentially used for the analysis of industrial designs and their optimization.

VI. GRAPHITE DUST TRANSPORT AND DEPOSITION

A second direction of research is aerosol transport. PSI works in the field of Euler-Lagrangian particle tracking methods for the simulation of transport, sedimentation and re-suspension of radioactive aerosols in complex geometries. It has been demonstrated that CFD models, primarily developed for the analysis of core damage scenarios can be successfully applied to simulate graphite dust transport.

The transport and deposition of dust particles, which contain some amounts of radionuclides, on pebbles as well as primary circuit surfaces are of considerable safety relevance. A possible theoretical approach to predict the spatial distribution of the deposition consists in three-dimensional Euler-Lagrangian particle tracking. In the reactor scale, such CFD simulations have to resort to Reynolds Averages Navier-Stokes (RANS) turbulence models, since computer capacity for partially (LES) or fully (DNS) resolving all turbulence scales in such geometries is not in sight even in a more distant future. RANS cannot resolve the effect of turbulence on the particle motion, in particular the phenomenon of turbo-phoresis. This has therefor to be covered by additional stochastic models. [27] demonstrated the applicability of the Reynolds Stress Model (RSM) combined with the Continuous Random Walk (CRW) for this purpose.

The CRW model uses the Langevin equation. Lagrangian particle tracing is based on the solution of individual momentum equations for each particle describing particle motion by balancing inertia with drag and gravity forces. The drag force contains the fluid velocity. The time averaged part of the velocity vector is calculated in a Eulerian frame by means of solving the Navier-Stokes equation for the fluid, i.e. the gas phase, applying an RSM turbulence model. The fluctuating term is modeled on basis of the root mean square (rms) delivered by the RSM for each of each velocity component individually using successions of uncorrelated Gaussian random numbers. Special attention is required for the treatment of the boundary layer, which is not resolved below a y^+ of 100. The fluctuating term is then determined on basis of wall functions as function of the distance of the particle from the wall.

This approach automatically takes into account turbo-phoresis. An additional term for its modeling is not needed: Particles are scattered with an intensity that depends on local components of the turbulent kinetic energy. When they arrive in regions of lower turbulent kinetic energy, the process of scattering them back is less intensive, which results in a net particle flow in the opposite direction of the gradient of the turbulent kinetic energy. Particles touching the wall are taken out of the game and are considered to be deposited.

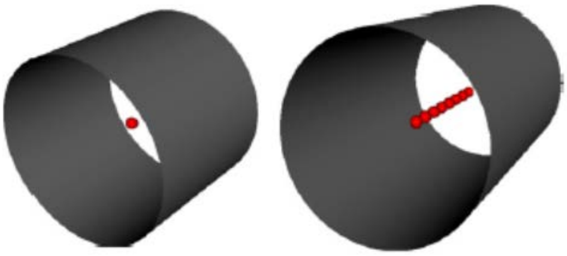

Fig. 13: Geometries used for the validation of the CRW model (from [27])

The commercial CFD code ANSYS-Fluent was used for the simulations of a particle laden gas flow around linear arrays of spheres (Fig. 13). A deposition efficiency η is defined as the ratio of the number of particles injected within the projected area of the spheres in main flow direction over the number of particles deposited. The predictions of the outlined CRW model are generally within the scatter of the available experimental data obtained by of [28] and [29], as shown in Fig. 14 and Fig. 15.

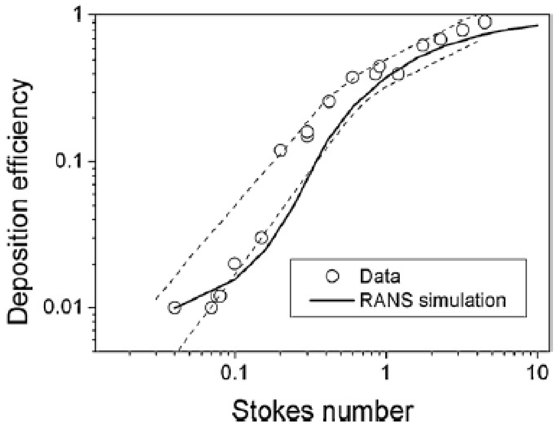

Fig. 14: Deposition of particles on a single sphere (taken from [27])

The Stokes number Stk was varied from 0.03 to 2.3 at Reynolds numbers ranging from 3000 to 8300. The spacing between the spheres L/D in the linear assembly was varied between 1.5 and 6. The deposition rate increases with growing stokes number, since particles behave more and more in a ballistic way. On a linear assembly of spheres, for medium and high Stokes numbers (0.44 and above), a shielding effect is observed, i.e. there is a minimum of deposition on the second sphere in a row. The shielding effect was found to be less pronounced at higher spacing L/D. All these qualitative effects are well predicted by the simulations and the predictions are within experimental error bands. At very low Stokes numbers (0.03–0.04), [29] experimentally observed a reverse shielding effect, i.e. deposition on the second sphere is larger than on the lead sphere. This was not reproduced by the simulations, as it can be seen from the graph in Fig. 15. For these very small Stokes numbers, more fundamental turbulence models such as LES may be required to achieve better accuracy.

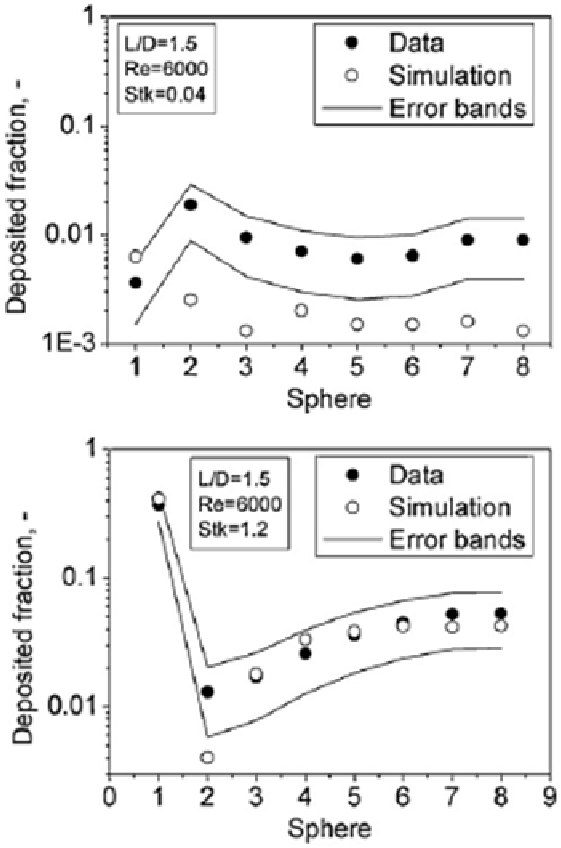

Fig. 15: Deposition of particles on a linear assembly of spheres at different Stokes numbers (from [27])

In general, it can be concluded that the application of the described CRW model to a realistic package of spheres is a logical next step, as well as a further improvement of the model itself and an implementation of closure relations for the re-suspension.

VII. UPCOMING HTR STUDIES

Recently, PSI has obtained financing for an extension of research activities in the field of modular pebble bed reactors. The interest in this reactor concept arises from its inherent safety features that are in a number of aspects superior to light water reactors. After the initial euphoric start with two prototypes of pebble bed reactors built and operated in Germany, namely the AVR and the THTR, the development was terminated mainly due to political reasons. Today, China became world leader in the field by the success of the prototype at the Tsinghua University and the launch of the twin unit project of the HTR-PM sited in Weihai in the Shandong province.

It is highly recognized in Switzerland that the Chinese concept has overcome several technological problems of the early German prototypes and that the development is in a very advanced state. Due to its simplicity compared to Light Water Reactors, this helium cooled high-temperature reactor (HTR) type is seen as an economically competitive representative of the class of small modular reactors (SMR), which otherwise often struggle with a certain contradiction to the economy of scale.

In the first step it is planned to preserve still existing know-how, consolidate a research team, establish sustainable contacts to the Chinese developers of the HTR-PM and explore the feasibility and plausibility of this innovative reactor concept in a European electricity supply environment. The proposed project involves different groups from the ETH domain. The main purpose is to build-up the specific HTR know-how in Switzerland that is necessary to provide in-depth information to decision makers and identify research needs for the future.

The goals consist in (1) a comprehensive and systematic literature study on the status of the pebble bed HTR development addressing reactor technology, plant efficiency, fuel supply and manufacturing, fuel performance, safety, economy as well as waste handling and deposition, (2) an up-to-date limited risk assessment for pebble bed reactors utilizing to the extent possible the technological input available from relevant sources including the Chinese HTR-10 and HTR-PM projects, (3) an initial assessment of the economy of power generation, (4) a preliminary study on potential technological progress on reprocessing including alternative methods for the reduction of waste volumes, (5) a preliminary analysis on the optimization of the fuel cycle to explore the feasibility of transmutation, breeding and an independent Th-U3 cycle, and finally (6) a qualitative assessment of the future development potentials of this reactor type and the identification of research needs.

It is planned to establish a close cooperation with the INET of the Tsinghua University in China. We look very much forward to future joint research activities concerning the further development and the safety assessment of the HTR-PM with this worldwide leading institution in the world.

VIII. SUMMARY

The main contribution of the Paul Scherrer Institute to the development of high-temperature gas-cooled reactors of the pebble bed type lies in the field of reactor physical experiments performed in the past with different arrangements of spherical fuel elements at the PROTEUS reactor and the related theoretical analyses. Unique data was obtained, which is of undiminished value with regard to the validation of neutronic codes. Significant contributions have been made to develop construction and fuel materials for high temperature reactor applications. Many other research activities have indirect relations to helium cooled reactors, like the work in the field of the behavior of hydrogen in the containment of LWRs in severe accidents, where helium is used as model fluids. There is room for diversification, both by a transfer of thermal hydraulic and CFD modeling methods to HTRs and by the application of experimental techniques and potentially also facilities, like PANDA for the qualification of passive HTR reactor cavern cooling systems or air ingress scenarios. Fundamental investigations of the turbulent mixing in the presence of high gas density ratios are interesting from the point of the same point of view, as well. Some dedicated theoretical studies have dealt directly with pebble flow, wear, dust generation, dust transport and deposition, which may be extended in the future. A scoping study on the feasibility and plausibility of innovative reactor concepts including the HTR-PM type reactors in a European electricity generating environment is on the way to be launched, which will explore the options for a broader participation of PSI in the development of this reactor concept and, among others, update earlier comparative probabilistic safety analyses.

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