A COMPUTATIONAL METHODOLOGY FOR ESTIMATION OF AEROSOL RETENTION IN A SAND-BED BASED FILTERING SYSTEM FOR SEVERE ACCIDENT VENTING STRATEGIES

by

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A computational methodology to estimate the capacity of aerosol particle retention in a filtering system based on sand bed is described in this work. This methodology uses a combination of computational fluid dynamics and mechanistic models in the calculation procedure. The methodology is applied to venting actions during a severe accident in a BWR Mark II primary containment. The SALOME and OpenFoam platforms were used to generate the geometric and numerical models of a full scale model of a sand bed filtering system. The Eulerian/Lagrangian approach was used to determine the steady-state of a compressible turbulent flow through a porous media and to compute the aerosol particle transport, respectively. Collection efficiency was calculated by means of a mechanistic model based on the capture efficiency of a single grain. The obtained Eulerian results include velocity, pressure, and temperature fields inside the filtering systems. The Lagrangian tracking of aerosol particles showed that particles crossing the coarser sand tend to accumulate initially on the periphery of the filter. The parametric studies showed that mass-flows of up to 4.7 kgs^{-1} satisfy the constraint of 1.1 bar pressure drop across the sand depth. Additionally, the efficiency of 99.5 % of retention was determined for 1.0 m aerosol particles in the 0.6 mm sand grain zone, for a gas velocity of ms^{-1}.

Key words: Mark II, severe accident, openfoam, SALOME, aerosol, filtering system, efficiency

INTRODUCTION

During a severe accident, the production and accumulation of steam and gases plus the volatile fission products (noble gases and aerosols) in the primary containment induce pressure rise. Additionally, fission products constitute a heat source. If corium is already spread in the cavity or pedestal, its decay heat also contributes to containment heat rise, and consequent atmosphere pressure rise. In the fourth level of the Defense in Depth concept, accident management includes the protection of the containment [1]. If during the progression of a severe accident it is not possible to ensure maintaining of temperature and pressure within acceptable limits to avoid losing integrity, containment venting can provide a means for accident mitigation. The venting action may be filtered or not. The decision to adhere to one or the other depends on each country's regulation. If the filtered option is chosen, a significant reduction of fission product release is expected. The filtration will be through dedicated filtering engineered systems, which includes pool scrubbers, sand-bed filters, and Venturi scrubbers. Studies on the impact of implementing a filtered containment venting system have been extensively carried out [2-4].

Filtering engineering designs are currently in use in nuclear power plants in Europe and Canada, with different filtration technologies. The ones that use water in the filtration stage are called wet systems, which usually include additional devices for capturing water drops and aerosol sprays [5]. Dry systems used for aerosol retention are based on filtration through porous media. In these engineered configurations, different types of sand and gravel are used, with addition of metallic or ceramic fibers as well. Once the choice of a venting and filtering system is made, several design features have to be assessed, such as vent flow rate capacity, thermal loads, aerosol loads and their characteristics, iodine and/or hydrogen loads, and radiological protection of workers and the public,

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among others [4]. All these parameters are to be considered taking into account a broad spectrum of severe accident scenarios. The hydrodynamic performance of the venting and filtering system is the basis to assess most of the parameters mentioned.

In this paper, a computational methodology is presented for the estimation of the efficiency and aerosol transport in a sand-bed based filtering system. The application of the methodology allows studying of the impact of different venting strategies in diverse severe accident scenarios. In the computational procedure, a combination of computetional fluid dinamics (CFD) modeling and simpler mechanistic models allowed for a quick initial estimation of the overall performance of the filtering system. The freely available, open-source, packages SALOME [6] and OpenFoam [7] were used to create a full scale CFD geometric model and to carry out computations of the system performance. Pressure, temperature, and velocity fields were determined with the Eulerian approach, as well as the gas mixture distribution. Then, a Lagrangian numerical approach was used for aerosol particle tracking, transport, and distribution. Finally, the efficiency of the system was calculated by mechanistic models, thus allowing quick parametric studies of different simulation scenarios.

This paper is structured as follows: an outline of the computational methodology is presented first. Then the CFD model of a sand-bed filter is shown, and the numerical approach for calculation of pressure and velocity fields, and particle trajectories is described. The comparison with experimental data follows, and finally, discussion and conclusions are presented.

OUTLINE OF COMPUTATIONAL METHODOLOGY

For practical applications, the methodology requires certain simplifications in a series of quasi-steady uncoupled calculations, to lead to the desired venting mass flow rate, primary containment depressurization rate, and efficiency of the filtering system, all in acceptable intervals. The following are the necessary steps to be taken:

– *Determination of initial and boundary conditions for the containment gas and aerosol transport calculation*. The data for this step are usually arrived at by the simulation of severe accident scenarios with appropriate codes. The data include the thermodynamic conditions in the source volume (primary containment, mainly), aerosol, gas and particle mixture composition and concentrations, and the incoming velocity field to the venting system.
– *Venting pipe hydrodynamics steady state*. Once pressure, mass-flows and gas composition at the venting pipe inlet are known, a steady-state calculation (a transient calculation to reach steady-state conditions) provides the pressure, temperature, gas composition and velocity fields inside the pipe. Then an aerosol particle transport calculation is done to estimate the aerosol fractions trapped in the venting pipe walls, up to the point of the filter discharge.
– *Generation of venting pipeline pressure drop vs. mass-flow correlations*. A series of calculations are then performed to obtain curves of pressure loss *vs*. mass-flow, for diverse gas mixtures. With this approach, it is not necessary to couple the containment and the vent pipe because a quasi-static calculation approach can be used, since the venting pipe hydrodynamics reaches a steady-state condition in just a few seconds, given that one already has the hydrodynamics and thermodynamics data at the desired times of accident evolution. Thus the vent pipe outlet conditions become the boundary and initial conditions for the filtering system.
– *Filtering system hydrodynamics steady-state*. The resulting pressure, temperature, and gas mixture mass-flow computed in the previous step become the boundary and initial conditions for a new steady-state calculation, but this time for the filtering system. This calculation is carried out to determine the velocity, pressure and temperature fields inside the filter. A new series of curves of pressure loss *vs*. mass-flow for diverse gas mixtures and different types of sand, depths, *etc*., are computed, to be used later in parametric studies.
– *Estimation of filtering system efficiency*. Mechanistic models are then used for a quick estimation of the efficiency of the system, based on the results from previous steps. Moreover, results of the pressure, temperature and velocity fields in the filtering system at different states may also be employed to derive other important design parameters, such as thermal loads, mechanical impacts, and radioactive loads.

The previous procedure requires creation and/or modification of base geometric venting and filtering system models. To do this, a decision has to be made at the beginning for spatial resolution required for each specific problem, since the range of particles, drops, and sand diameters can differ by the orders of magnitude. However, it should be kept in mind that integral values of some parameters, such as pressure drop and mass-flow, can be of more practical interest. Regarding the computational process, it is necessary to determine the appropriate numerical schemes to achieve the solution of mass, momentum and energy equations, plus the closure correlations, for compressible or incompressible flow or both, for each step. For a sand-based filter, the solution involves a porous media approach. OpenFoam offers a set of generic modules that allow such a type of computations, but it is necessary to follow a series of best practices to choose the correct modules, generate specific models and achieve robust solutions.

The process just described may need an iterative approach if the overall performance of the filtering system is not the required one, or the containment depressurization rate or venting mass-flow rate do not reach the desired values. Finally, experimental or analytic solution data are required to validate the hydrodynamic performance of the filtering system. In this work, the focus is set on the determination of the hydrodynamics steady-state of a sand bed based filtering system, and its CFD modeling, and the experimental setup and data used for validation.

EXPERIMENTAL SET-UP AND DATA FOR VALIDATION

The CFD model of a sand bed filter for this study was based on the containment decompression and filtration system design described by Jouen [8]. The development of the sand bed filter part in that engineering design was supported first by laboratory scale measurements in an experimental loop set-up containing a sand column, under the PITEAS experimental program [9]. The experimental data obtained from the sand column described in that reference were used here for comparison against the numerical results obtained from a CFD model using the OpenFoam package.

The sand column in the experimental facility was 80.0 cm high and 20.0 cm in diameter. Five different sand particle sizes were used for the measurements: 0.5 mm, 0.7 mm, 1.0 mm, 1.2 mm, and 1.6 mm. The diameters were based on a lognormal distribution with a standard deviation less than 2.0. The injected aerosol particles were composed of caesium carbonate of four different aerodynamic mass median diameters: 0.66 m, 0.80 m, 1.40 m, and 1.45 m. The injected gas mixture was composed of 68 % of air, and 32 % of steam. Two gas velocities were used: 7.0 cms^{-1} and 14.0 cms^{-1}. Two test conditions were employed: steady-state and transient regime. In the first case, the gas was at 140 °C and the filter was preheated to that same temperature. In the latter case, the filter was originally at room temperature. Measurements were taken of pressure drop throughout the filtering sand column and the purification coefficient.

For the case of sand diameter of 0.5 mm and gas velocity of 14.0 cms^{-1}, in the steady-state regime measurement, the purification coefficient value was much greater that the target value of 100, but the pressure drop in the column was higher than the targeted 100 mbar* for the engineering design. The geometric model was created in the environment of SALOME, and it consisted of a single cylinder filled with sand, with the same dimensions aforementioned. The mesh created for this sand column was formed with 5131

* 1 mbar = 100 Pa

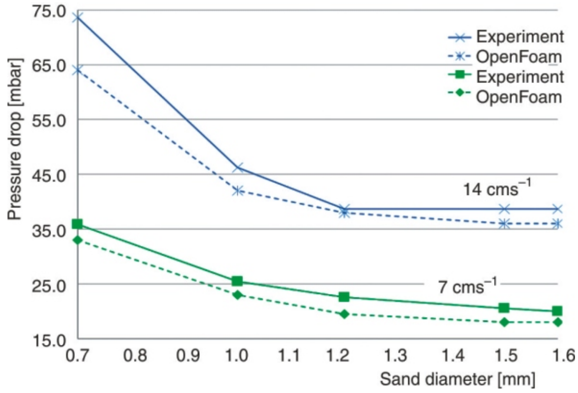

Figure 1. Pressure drop comparison between experimental data and OpenFOAM results

nodes, having 593 triangle faces, and 20984 tetrahedrons. Figure 1 shows a comparison of the pressure drops in the experimental facility and those computed with OpenFoam in this work. Unfortunately, Berlin and Delalande [9] do not present experimental values, but only profiles, and there is no other information about experimental uncertainty or data spreading bands. Thus, the values used for comparison were inferred from those plots shown in that reference, which clearly affects the accuracy of comparison results. In this case data comparison yields a maximum relative deviation of about 13 %, which was considered acceptable as a starting point to create a full scale model of the filtering system. Details of the used OpenFoam modules and the constructed SALOME geometric model are given in the following sections.

THE CDF MODEL OF FILTERING SYSTEM

Jouen [8] described an entire depressurization and filtration system, a sand-based filter, and the desired operation features for use in a PWR plant. Table 1 shows some of those design geometric and operational data.

Table 1. The PWR sand-bed filtering system as described in [8]

Diameter	7.312 m
Clay zone thickness	0.2 m
Sand zone thickness	0.8 m
Empty zone height	1.5 m
Dome-deflector zone height	0.5 m
Sand grain diameter	600.0 μm
Minimum filtering efficiency	10.0
Gas velocity	10.0 cms^{-1}
Gas mixture	Air: 33 %, steam: 29 %, CO_2: 33 %, CO: 5 %
Gas temperature	140.0 C
Maximum flow rate	3.5 kgs^{-1}
Upstream pressure	5.0 bar
Pressure drop throughout sand	0.1 bar
Aerosol particle diameter in tests	1.0 m

A 3-D geometric model and associated mesh of a sand filter with the same dimensions shown in tab. 1 was constructed for the CFD analysis. In the original design there was a polyester sheet that separated the clay and sand zones, but this interface was not included in this work. Figure 2 shows a diagram of the sequential steps in the construction of the geometric model, and fig. 3 shows the final mesh and the different zones composing the filter system. In this work, the clay was replaced by a layer of finer-grain sand. The mesh was created with 8042 nodes having 8603 triangle faces, and the full volume was divided into 39188 tetrahedrons. The filtering system inlet was a deflector device, and the outlet was the whole bottom surface. The deflector was simply modeled as an inlet tube inserted into the dome zone, without a surface wall. Thus the incoming gas stream was directed sideways instead of going straight downwards.

APPLICATION OF COMPUTATIONAL METHODOLOGY

To show how step 1 previously described in the methodology was used in this work, the severe accident scenario chosen for the analysis was a BWR station blackout, unmitigated after the assumed failure of the reactor core isolation cooling system. An initially inert Mark II primary containment design was considered as the source volume. As an accident progresses steam, hydrogen, and radioactive material (noble gases and volatile aerosols) enter the primary containment atmosphere, to encounter the inerting nitrogen. In this work, it was considered that the MCCI phenomena had not yet started, so there was no generation of CO and CO_2, and therefore only a mixture of nitrogen, hydrogen and steam were assumed to be present.

For step 2, a venting pipeline system model was developed for the code GASFLOW [10], which was a computational code for applications used, among other, to determine potential hydrogen deflagration and explosion risk by 3-D calculations of hydrogen distribution in primary and secondary containments and vent lines. With the GASFLOW venting line model, different hydrogen venting strategies were computed [11]. Depending on the scope of this step 2, 1-D geometrical models and calculations can be used. The GASFLOW can be used for the calculation of transport of aerosols, but to accelerate calculations, more simplified but faster CFD models in the SALOME and OpenFOAM environments were created. Either way, the steady-state calculation was performed first, and then the aerosols were injected at the pipe inlet to estimate fractions trapped in the pipeline. step 3 was then carried out, to determine if the desired conditions at the inlet of the filtering system were achievable for different venting strategies.

To satisfy step 4 of the methodology, previously described filtering system geometrical model was developed and the sets of equations determining the hydrodynamic performance of the filtering system was solved with the OpenFOAM package, in an Eulerian/Lagrangian approach. The boundary and initial conditions for the calculation are shown in tab. 2. Two solvers were employed in the computational process: rhoPorousMRSimpleFoam, to determine the steady--state of a compressible turbulent flow through a porous media; and porous Explicit Source Reacting Parcel Foam, to compute aerosol transport. The equations solved in the first step were mass, momentum and energy balances, to obtain the velocity, pressure, and temperature fields inside the whole filtering system. The momentum equation for a porous media in the solver rhoPorousMR SimpleFoam was a modified

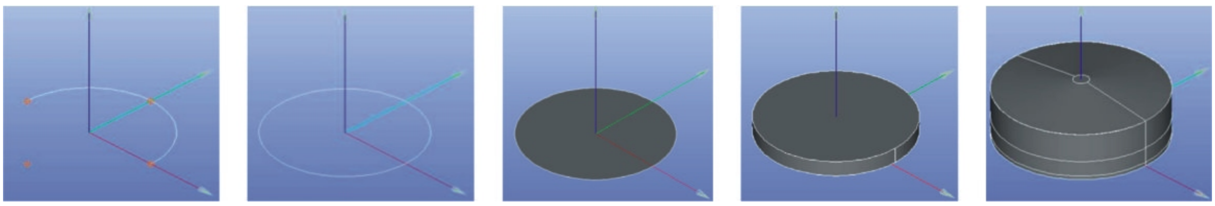

Figure 2. Development of the full scale filtering system in SALOME

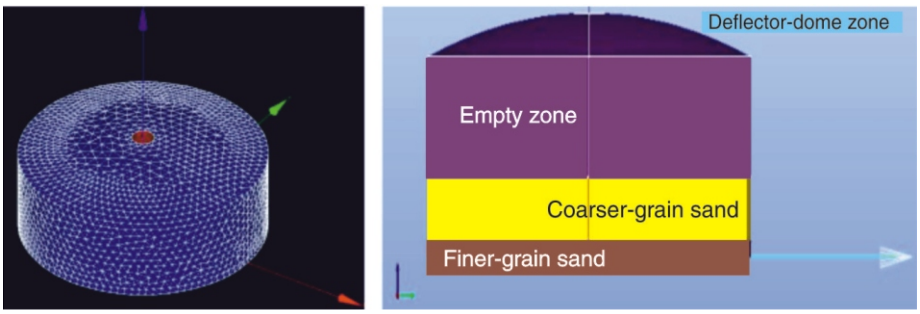

Figure 3. Mesh and different zones composing the filtering system

Table 2. Initial and boundary conditions for the steady-state calculations

Inlet flow rate	3.5 kgs^{-1}, zero gradient
Inlet gas temperature	422.0 K
Rate of dissipation of turbulence energy	0.24576
Turbulence kinetic energy	0.1617
Outlet pressure	Atmospheric, zero gradient
Finer sand grain diameter	0.5 mm
Coarser sand grain diameter	0.6 mm
Gas velocity	10.0 cms^{-1}
Gas mixture	Nitrogen: 38.7 %, steam: 57.4 %, H2: 3.9 %
Aerosol particle diameter	1.0 m

Navier-Stokes equation, where the time derivative is attenuated by adding a sink term [12]. This additional source term was the Darcy-Forchheimer equation, consisting of a viscous and inertial loss term. The viscous term led to a pressure drop proportional to velocity; while for the inertial term, the pressure drop was proportional to velocity squared.

The OpenFoam solver needs values for the tensor coefficients in the Darcy-Forchheimer equation. For the case of a homogenous porous medium, the tensor coefficient for Darcy´s Law reduces to a scalar, which is simply the inverse of the permeability of the media, and a simple equation to calculate it is the following

$$B \quad \frac{e^3 d^2}{180(1 \quad e)^2} \tag{1}$$

where B [m^2] is permeability, e – the porosity, and d [m] – the diameter of the sand particle . From this step, it is possible to obtain curves of pressure loss *vs*. mass-flow for diverse gas mixtures and different types of sand, depths, *etc*.

The solver *porousExplicitSourceReacting ParcelFoam* is the part of the Lagrangian Solvers employed for particle tracking. In this work, it was used for the tracking of the aerosol particles injected into the gas stream at the deflector zone. For the interaction wall-particle options, only the rebound interaction was used. The particle tracking allows for studies of design optimization, as for example to determine if the aerosol distribution would be homogenous in the sand zone.

AEROSOL COLLECTION EFFICIENCY

Finally, for step 5, the efficiency of the filtering system can be determined by CFD analysis, but it would require precious computation time to assess the large number of different scenarios during the progression of a severe accident (venting flow rates, gas mixtures, *etc*.). If one, additionally, needs to test different filtering system designs, clock time becomes a heavy constraint. Alternatively, in engineering practical approaches, system efficiency can be first estimated on the grounds of mechanical models. Then, if the mandatory constraining design parameters, as either operational pressure drop or temperature, are satisfied, and also if the desired efficiency is within an acceptable range, a new CFD analysis can be applied for specific promising designs. This is the approach followed in this methodology.

In a primary containment, aerosol particle rebound, adherence, and deposition on the walls are phenomena that need to be taken into account in transport calculations. In a sand filter, however, the first conservative approximation is to calculate how many particles can be trapped by sand grains, without giving credit to adherence to walls. The collection efficiency is simply as follows

$$n = 1 - P \tag{2}$$

where n is the collection efficiency and P – the total penetration in a sand filter. The first approach in this case is to consider that one grain can trap one single aerosol particle. Thus, the total penetration P_t throughout a bed of total length H, can be obtained from the following

$$P_t \quad \exp \quad \frac{3\alpha H}{2d_g}\eta_g \tag{3}$$

where η_g is the capture efficiency of a single grain, α – (= 1.0 – porosity), and d_g – the grain diameter [m]. There are different mechanisms for aerosol capture, and correlations of η_g for each of them can be found in literature, for example for low speed gas flows, Mann and Goren [13] determined the expression for the regimes of Brownian diffusion and sedimentation. The expected conditions at the inlet to the sand filter from a venting action in a BWR containment correspond to a regime dominated by inertial impact. For this case, the following correlation by Michaels and Goren [14] can be used

$$\eta_{lm} \quad \frac{1}{1 \quad 1.67(A_h Stk)^{3.55}} \tag{4}$$

where Stk is the aerosol particle Stokes number and A_h is a hydrodynamic shape factor, for particles that deviate from spherical shape, and depends on the Reynolds number. To calculate the Stokes number, one requires the velocity field computed in the previous step. Thus, one can calculate efficiencies for different sand grain sizes, porosities, and velocity fields for a particular sand filter design.

RESULTS

The design by Jouen [8] considered a PWR containment at 5.0 bar for venting action, and the design pressure of the filtering system was up to 1.5 bar in order to operate within a pressure drop of 1.1 bar. This same last value was set as the target for the model developed in this work. In a BWR Mark II containment, venting can be initiated when the pressure is between 4.0 and 4.5 $kgcm^{-2}$ (392266.0 to 441299.0 Pa), but the pressure drop through the venting pipeline can be significant. Also, devices can be used to further reduce the pressure load reaching the inlet of a filtering system. For a mass-flow rate of 3.5 kgs^{-1} (see tab. 1), the inlet pressure was 160 000.0 Pa, with atmospheric pressure (101 325.0 Pa) as the target outlet pressure (boundary condition). Figure 4 shows the results obtained for the pressure drop though the filter system. With this model, a maximum of 4.7 kgs^{-1} still satisfies the constraint of 1.1 bar.

Figure 5 shows the velocity streamlines in the filter. The incoming gas is first deflected sideways, reducing significantly the inlet velocity. The vortex zone helps in getting a more uniform distribution of the incoming aerosol particles. The streamlines clearly delineate the border between the sand and empty zones. In this area, the gas velocity has been reduced to 0.1883 ms^{-1}, which is the value used for the aerosol retention efficiency calculations.

Once the Eulerian fields had been determined, the Lagragian aerosol particle tracking calculations were carried out. One could already have the first estimation of the amount of particles trapped in the vortex zone and those capable of crossing the sand zones. The particles were injected randomly into the gas stream at the deflector entrance. Their size was 1.0 m. Figure 6 shows the aerosol particle distribution at the moment of injection, and fig. 7 shows the distribution 170.0 seconds afterwards. In these figures, the particles were enlarged to facilitate visualization, so they might appear as crossing the computational domain, but this was not the case. Figure 7 shows that the aerosols crossing the coarser sand tended to accumulate at this time on the periphery of the filter. Modifications to the geometric model, for example on the initial inclination of the deflector or when other obstacles added to change the velocity field profile, could lead to a more uniform particle distribution. This type of changes to the geometric model could be quickly carried out in SALOME.

Regarding the efficiency of the 0.6 mm (coarser grain) sand zone for collecting the 1.0 m particles, the results following the mechanistic model introduced in the previous section showed an efficiency of 99.5 % for the velocity of 0.1883 ms^{-1}.

There are still various issues to be tackled before the point of direct application of this methodology is reached and models are developed of a sand-based fission product filter in case of real severe accident scenarios. Among the main physical-chemical models that need to be added are thermal loads and the characteristics and distributions of the volatile fission products that are carried by the gas stream. In this work, for example, only one value for aerosol diameter was used (1.0 m), because it is the reference value used in the design test phase, and also as the target value for the prototype filter-

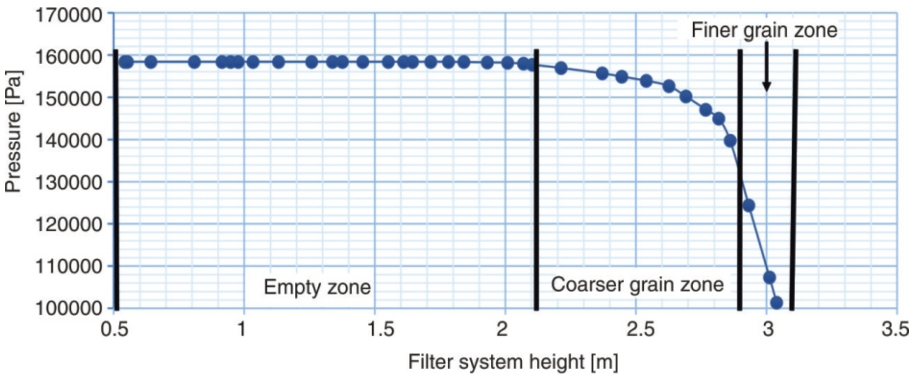

Figure 4. OpenFoam results of pressure drop across the filtering system

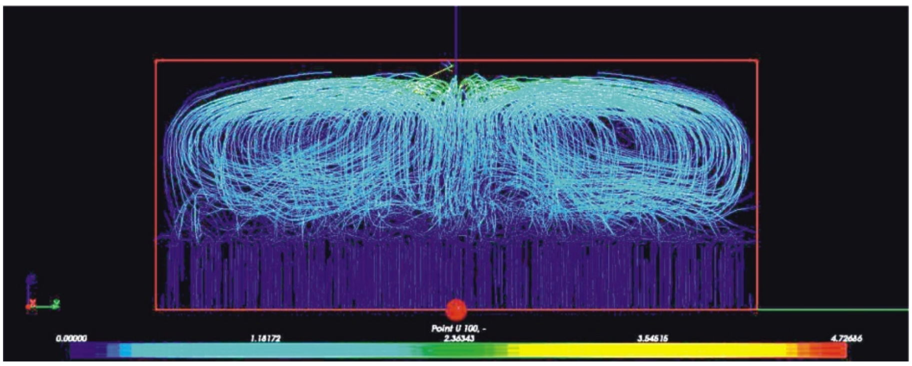

Figure 5. Velocity field on the middle plane

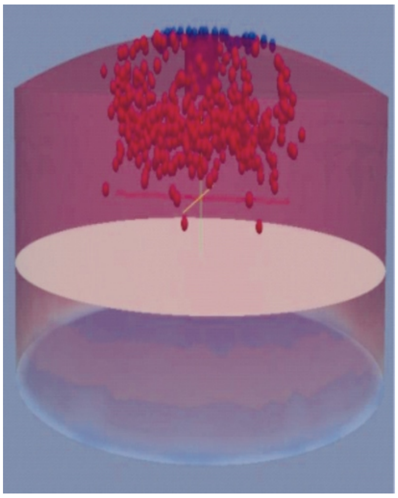

Figure 6. Aerosol particle distribution at *t* = 0.0 s

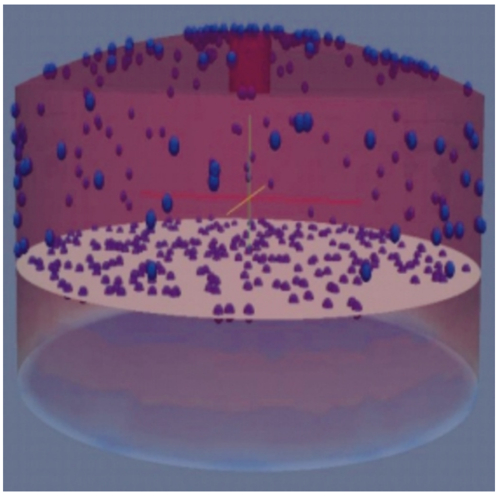

Figure 7. Aerosol particle distribution at *t* = 170.0 s

ing system design (see tabs. 1 and 2). Additionally, although one relevant issue for this type of systems is that hydrogen concentrations could reach combustion levels [15], in this work hydrogen concentration was set at 3.9 %, a value below the limit for risk consideration in plant emergency procedures. This issue, anyway, needs also to be studied for long transient events, where hydrogen concentrations could increase.

CONCLUSIONS

A computational methodology is presented for the estimation of the capacity of aerosol particle retention in venting actions during a BWR severe accident. This methodology uses a combination of CFD and mechanistic models in the calculation procedure. To show an application of the methodology, for the CFD modeling part, a full scale model of a sand bed filtering system was created. The open source, freely available, SALOME and OpenFoam platforms were used to generate the geometric and numerical models. The filtering system consisted of four sections:

– the dome, where the flow deflector was located,
– an empty zone,
– a 0.6 mm sand grain size zone; and
– a 0.5 mm sand grain size zone.

The OpenFoam solvers used were rhoPorous MRSimpleFoam and porousExplicit SourceReacting ParcelFoam to determine the steady-state of a compressible turbulent flow through a porous media and to compute the aerosol particle transport, respectively. That is, an Eulerian/Lagrangian approach was used for the CFD model. Regarding the collection efficiency, a mechanistic model based on the capture efficiency of a single grain was used for calculations.

The model of the filtering system created in this work is based on the design presented by Jouen [8] for venting from a PWR containment. In this work, the source volume was a BWR Mark II primary containment design. Velocity, pressure, and temperature fields inside the filtering systems were obtained as the first results. From the Lagrangian tracking of aerosol particles, it was noted that those particles crossing the coarser sand tend to accumulate initially at the periphery of the filter. Then, from parametric studies, it was found that mass-flows of up to 4.7 kgs^{-1} still satisfied the constraint of 1.1 bar pressure drop across the sand depth, when setting the atmospheric pressure as the target at the filtering system outlet. Additionally, from the mechanistic models used in this work, the efficiency was determined to be 99.5 % of retention for the 1.0 m aerosol particles in the 0.6 mm sand grain zone for gas velocity of 0.1883 ms^{-1}.

The CFD and mechanistic models introduced in this work can easily be modified, so a wide variety of parametric studies can be carried out, to obtain a better initial estimation of the filter efficiency depending on incoming gas flows, gas mixture proportions, sand bed depths, *etc*.

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AUTHORS' CONTRIBUTIONS

The main sand bed filter modeling and calculations were carried out by D. Cuevas Vasquez as part of her MSc Thesis research; the main developer of CFD OpenFoam models is E. Sainz-Mejia; J. Ortiz-Villafuerte was in charge of the experimental data collection, comparison with numerical results and analysis, and is also the main developer of the manuscript; and R. C. Lopez-Solis gathered and organized the data, and wrote the first version of the full manuscript. Additionally, all authors participated in the final analysis and discussion as well as the revision of the final version of the paper.

REFERENCES

[1] ***, International Atomic Energy Agency – International Nuclear Safety Advisory Group, Defence in Depth in Nuclear Safety (INSAG-10), IAEA, Vienna, 1996

[2] ***, Nuclear Energy Agency, Proceedings of the Specialists' Meeting on Filtered Containment Venting Systems. OECD/NEA/CSNI Report N° 148, Paris, May 17-18, 1988

[3] Schechtman, R., Heising, C. D., Risk Assessment of the Beneficial Impact of a Filtered Venting Containment System in a PWR with Large, Dry Containment, *Annals of Nuclear Energy, 23* (1996), May, pp. 641-661

[4] ***, Nuclear Energy Agency – Committee on the Safety of Nuclear Installations, OECD/NEA/CSNI Status Report on Filtered Containment Venting. NEA/CSNI/R, 2014, 7, 2014

[5] Reyes-Garcia, A. A., *et al*., Study of Hydrodynamics Performance of a Multi-Venturi Filtering System for BWR Severe Accident Venting Strategies, *Nucl Technol Radiat, 35* (2020), 1, pp. 16-23

[6] ***, OPEN CASCADE, SALOME The Open Source Integration Platform for Numerical Simulation, https://www.salome-platform.org, (CEA, EDF & OPEN CASCADE), Copyright 2005-2019

[7] ***, OpenCFD Ltd (ESI Group), OpenFOAM: The Open Source CFD Toolbox, https://www.openfoam.com, Copyright 2004-2018

[8] Jouen, E., Containment Venting System – Sand Bed Filter: Description, Operating Procedure, Implementation Program, *Proceedings*, Specialists' Meeting on Filtered Containment Venting Systems, OECD/NEA/CSNI Report N° 148, Paris, May 17-18, 1988, pp. 257-278

[9] Berlin, M., Delalande, M., Research and Development on the Venting and Filtering System for Pressurized Water Reactor Containments (Procedure U5). *Proceedings,* Specialists' Meeting on Filtered Containment Venting Systems, OECD/NEA/CSNI Report N° 148, Paris, May 17-18, 1988, pp. 279-295

[10] Travis, J. R., *et al*., GASFLOW 3.2: A Computational Fluid Dynamics Code for Gases Aerosols, and Combustion. VOLUME 2: User's Manual, Institut für Kern- und Energietechnik, Karlsruher Institut für Technologie (KIT), Karlsruhe, 2011

[11] Solís-Alcantara, N. A., *et al*., Study of Strategies to Avoid Hydrogen Deflagration in Venting Pipelines During Severe Accident Scenarios, *Nuclear Engineering and Design, 325* (2017), Dec., pp. 57-67

[12] Hafsteinsson, H. E., *Porous Media in OpenFOAM,* Tutorial, Chalmers, Univ., Goteborg, SE 2009

[13] Mann, L. A., Goren, S. L., Aerosol Capture in Granular Beds in the Sedimentation and Diffusion Dominated Regimes, *Aerosol Science and Technology, 3* (1984), 2, pp. 195-213

[14] Michaels, C., Goren S. L., Aerosol Capture in Particle Laden Granular Beds in the Impaction Dominated Regime, *Aerosol Science and Technology, 7* (1987), 1, pp. 31-46

[15] Bal, M., *et al*., Control of Accidental Discharge of Radioactive Materials by Filtered Containment Venting System: A Review, *Nuclear Engineering and Technology, 51* (2019), 4, pp. 931-942

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РАЧУНАРСКА МЕТОДОЛОГИЈА ЗА ПРОЦЕНУ ЗАДРЖАВАЊА АЕРОСОЛА У СИСТЕМУ ФИЛТРИРАЊА НА БАЗИ ПЕСКОВИТОГ СЛОЈА ЗА СТРАТЕГИЈЕ ВЕНТИЛИРАЊА ТЕШКИХ АКЦИДЕНАТА

У овом раду описана је рачунарска методологија за процену капацитета задржавања аеросолних честица у систему филтрирања заснованом на песковитом слоју. Ова методологија користи комбинацију рачунарске динамике флуида и механичких модела у поступку израчунавања. Методологија се примењује на акције вентилације током тешког акцидента у примарном контејменту BWR Makr II реактора. Платформе SALOME и OpenFoam коришћене су за генерисање геометријских и нумеричких модела пуног опсега система за филтрирање песковитог слоја. Ојлер - Лагранжов приступ коришћен је за одређивање стационарног стања компресибилног турбулентног протока кроз порозни медијум и за израчунавање транспорта аеросолних честица. Ефикасност сакупљања израчуната је помоћу механичког модела заснованог на ефикасности захвата појединачног зрна. Добијени Ојлерови резултати укључују поља брзине, притиска и температуре унутар система за филтрирање. Лагранжово праћење аеросолних честица показало је да честице које пролазе кроз крупнији песак имају тенденцију да се иницијално акумулирају на периферији филтера. Параметарске студије показале су да протоци масе до 4.7 kgs^{-1} задовољавају ограничење пада притиска од 1.1 бара по дубини песка. Поред тога, утврђена је ефикасност задржавања од 99.5 % за честице аеросола од 1.0 μm у зони песка од 0.6 mm, за брзину гаса од 0.1883 ms^{-1}.

Кључне речи: Mark II, тежак акцидент, OpenFoam, SALOME, аеросол, систем за филтрирање, ефикасност