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A study on enhancing gaseous effluent treatment for severe accident consequence management

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1. Introduction

During a severe accident, the complex chemical and physical reactions among molten core and coolant, or concrete will produce large amounts of gas, vapor and aerosols, thus increasing the containment pressure and threatening containment integrity. Typical ventilation systems' (high efficiency particulate arresting/air (HEPA) or charcoal) efficiency may be reduced due to large flow rate, large amount of vapor and aerosols which may result in a significant radioactive release. After the Fukushima Daiichi accident, researchers paid more attention to containment filtered venting system (CFVS). CFVS is designed to allow a controlled reduction in containment pressure through more efficient filtration and venting to reduce off-site radiological impact. For CFVS, there are mainly two types. Wet system contains washed water scrubber with droplet separator, or deep bed fine aerosol filter [1] and dry system are consisted of deep metal fiber filters. However, CFVS is very expensive.

Currently not all nuclear power plants (NPPs) have installed CFVS. Hence under the worst accident scenario, containment may lose its integrity and lead to a direct release of radioactivity to the environment. So far no methods are capable of mitigating this kind of direct release. In KAIST, several ways to capture or mitigate these radioactive source term are under investigation. These technologies are based on advanced concepts such as a vortex-like air curtain, a chemical spray and a suction arm. Treatment of the radioactive material captured by these systems would be required before release to the environment. Therefore, an alternative filtration system having a lower price, reduced maintenance requirements and flexibility will be a good replacement or complement to the more prevalent CFVSs.

It may be to the benefit of the nuclear industry if filtration systems traditionally used in other industries are investigated. Filtration systems reviewed in this study include: electrostatic collector, baghouse and cyclone etc. However, an electrostatic collector is expensive and requires considerable maintenance. A baghouse requires an extra anti-explosion system, which can introduce a safety issue to NPPs operation. As a result these systems were not investigated further in this study.

Currently cyclone based filtration system are not used in NPPs. Considering the dimension flexibility and considerably high efficiency for removing particles, [2] a cyclone combined with novel absorbents filtration system is being proposed in this paper.

2. Conceptual design

The radionuclides that could be released from an NPP are assumed to be a mixture of noble gases, gaseous iodine, cesium particulate and other particulates. [3] For the purposes of accident management, the risk significance is determined using both the element's radiological significance and elements (iodine, cesium, etc.) release fraction.. [4] I-131 has a short half-life but significant radioactive hazard to humans. Cs-134 and -137 are the main radionuclides contributing to environmental pollution because of their relatively long half-life and water solubility. [5]Therefore, CsI aerosols with gases (air and gaseous I_2) comprise the simplified source term used in this paper.

The source term is introduced into the system via a tangential inlet (Fig 3(c)). Centrifugal forces act on aerosols suspended in the gas and draw them towards the cyclone wall. The heavier CsI aerosols will pass through the lower outlet where they then come in contact with a cesium absorbent. Similarly the gaseous part will pass the upper outlet and then come in contact with an iodine absorbent. Effluents meeting regulatory release criteria will ultimately be released to the environment.

Beyond the lower outlet, the novel absorbent used to remove cesium ions is potassium copper hexacyanoferrate (KCuHCF) immobilized in a cellulose-based hydrogel (HCF-gels).. KCuHCF has a high removal efficiency and high kinetics. Iodine absorbent can be added if necessary. [6] Beyond the upper outlet the Bismuth- embedded SBA-15 is used for I_2 absorption. The advantages of Bismuth- embedded SBA-15 include high efficiency, low material price and capture stability. Further efficiency enhancer like HEPA can also be added if needed.

One feature of the design is the absorbent module material can be changed according to the requirements. The whole system is as shown in Figure 1.

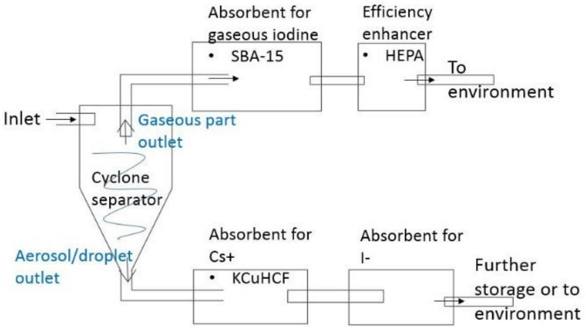

Fig. 1. Conceptual design of the whole system

The preliminary investigations of system efficiency is calculated by theoretical calculation as well as CFD approach.

3. Theoretical calculation

The system design was investigated based on OPR-1000 characteristics. Part of the parameters are listed in Table 1. Radiological Assessment System for Consequence AnaLysis (RASCAL) 4.3 is used for source term calculation and maybe further used as the filtration effect comparison.

In RASCAL 4.3, mass flow rate can be calculated as

$$\boldsymbol{Q = c \times s \times \sqrt{2\rho(p_1 - p_2)}} \qquad (1)$$

Where c is constant, s is hole area, p_1 is the pressure inside the containment and p_2 is the pressure of the external environment. ρ is the flow density and can be calculated as

$$\boldsymbol{\rho = \frac{P_1}{R'T}} \qquad (2)$$

Where T is the temperature inside the containment and R’ is constant.

According to the reference [7], flow rate at 5-10 kg/s is assumed to be suitable for CFVS evaluation.

Table 1. Parameters of OPR-1000 [8]

Parameter	Value
Reactor power	2815 [MWth]
Containment (CTMT) net free volume	2.73×10^6 [ft^3]
CTMT design pressure	0.49 [MPa]
CTMT ultimate pressure	1.01 [MPa]

The source term distribution assumption is based on PHÉBUS-FP experiment, which is lognormal distribution, r_g=3 µm, $\boldsymbol{\sigma_g = 2}$. The distribution is shown as Figure 2. [9]

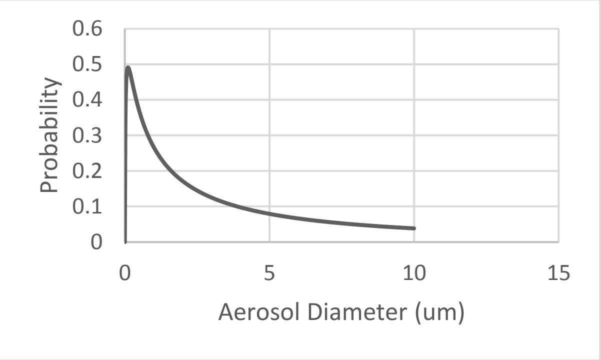

Fig 2. Aerosol size distribution

For the cyclone design, a classic high efficiency Stairmand design is applied as shown in Fig 3. The parameter as shown in Table 2.

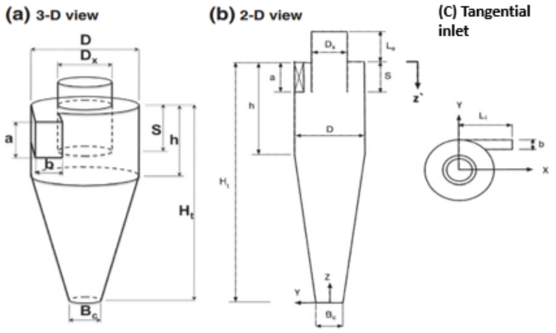

Fig 3. Stairmand cyclone design [10]

Table 2. Parameters of cyclone [10]

cyclone geometry*	a/D	b/ D	D_x/D	H_t/D	h/D	S/D	B_c/D
Staimand design	0.5	0.2	0.5	4	1.5	0.5	0.375

*Ratio

To evaluate the efficiency, cutoff diameter is very important because it defines the particle diameter corresponding to 50% collection efficiency. [10] It can be calculated as

$$D_{p50} = 3\sqrt{\frac{\mu b}{2\pi \rho_p U_i C N_t}} \qquad (3)$$

where U_i is the gas velocity at the inlet, ρ_p is the particle density, C is the the slip correction factor of the particle corresponding to Dp50, t is the residence time,$t = V/Q$, μ is the air dynamic viscosity, N_t is the number of turns, $N_t = tU_i/\pi D$, V is the volume of the cyclone and Q is the volumetric flow rate,$Q = a \times b \times U_i$.

The relationship of cyclone diameter and cutoff diameter is shown in Fig. 4. The cutoff diameter increases with a corresponding increase in cyclone diameter. Aerosols with diameters less than 6 µm, require a cyclone diameter smaller than 0.5 m to reach a 50% removal efficiency. However, the proposed inlet flow rate is relatively high (5-10 kg/s), thus the diameter chosen is 1 meter. Therefore, the cyclone can only act as a pre-filter to achieve high efficiency.

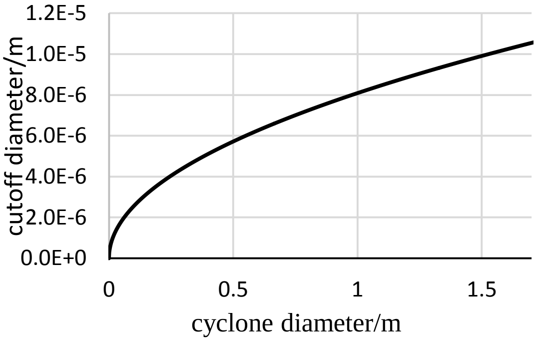

Fig 4 Relationship between cyclone diameter and cutoff diameter

4. Development of computational model

To evaluate potential efficiency of the cyclone as a pre-filter to the absorbents, a cyclone computational model was prepared in OpenFOAM. The OpenFOAM framework is based on a finite volume approach, and consists of C++ libraries, used primarily to create executable applications. The applications are either solvers or utilities. Each solver is designed to solve a specific problem, while utilities are for data manipulations [11].

3.1. Governing equations

The model was based on steady state incompressible RANS (Reynolds Averaged Navier-Stokes) equations of fluid dynamics. Reynolds Stress Model was used for the closure of RANS system of equations because of the anisotropic assumption.

For the gaseous part, the governing equation are:

$$\frac{\partial(\varepsilon_g\rho_g)}{\partial t} + \nabla\cdot\left(\varepsilon_g\rho_g u_g\right) = 0 \tag{4}$$

$$\frac{\partial(\varepsilon_g\rho_g u_g)}{\partial t} + \nabla\cdot\left(\varepsilon_g\rho_g u_g u_g\right) = -\varepsilon_g\nabla p_g + \nabla\cdot T_g + \varepsilon_g\rho_g \mathrm{g} - F_D \tag{5}$$

where $\boldsymbol{u}_g$ is gas velocity, ρ_g is gas density and ε_g is gas volume fraction, T_g is rate of momentum exchange per volume between the gas and particle phases and F_D is drag force. Equation 4 is the gaseous continuity equation and equation 5 is the gaseous momentum equation.

The Ergun-Wen Yu drag model is used, because it is suitable for all particulate volume fractions up to the closed packed condition. Drag force F_D is calculated as

$$F_D = \sum_{p=1}^{N_p}\beta_p\frac{n_pV_p}{V_m}\left(u_g\left(x_p\right) - u_p\right) \tag{6}$$

where β_p is the drag force function using the Ergun-Wen Yu drag model, n_p is the number of single particles in each calculation particle patch, V_p is the volume of a single particle, V_m is mesh volume, $u_g\left(x_p\right)$ is the gaseous virtual speed on particle patch, u_p is the calculation particle patch speed.

For the particles/aerosols part, the governing equations under Lagrange coordinates are:

$$\frac{dx_p}{dt} = u_p \tag{7}$$

$$\frac{du_p}{dt} = \frac{\beta}{\rho_p}\left(u_g\left(x_p\right) - u_p\right) - \frac{1}{\rho_p}\nabla p_g + \mathrm{g} - \frac{1}{\varepsilon_s\rho_p}\nabla\tau_p + \frac{F_{avg}}{m_p} \tag{8}$$

$$\tau_p = \frac{P_s\varepsilon_s^{\theta}}{max\left[\varepsilon_{cp} - \varepsilon_s,\ \gamma(1-\varepsilon_s)\right]} \tag{9}$$

where x_p is the particle's position coordinates, ρ_p is particle density, u_p is the local mass-averaged particle velocity, τ_p is the gradient in the interparticle stress. P_s is a parameter, θ is a constant, often ranging from 2 to 5, ε_s is the particle volume ratio. Equation 7 is the particle velocity equation, and equation 8 is particle kinetic equation.

3.2. Preparation of geometry and mesh

Salome software was use to both define the computational domain (geometry listed in Table 2) and to generate mesh (Fig. 4).

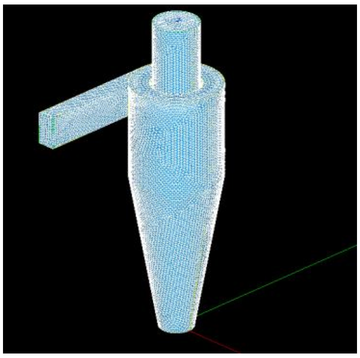

Fig 4 Mesh and geometry

3.3. Boundary conditions and discretization

The boundary conditions are listed in Table 3.

The equations for gaseous part are discretized using the finite volume method (FVM).

Table 3 Boundary conditions

Boundary	Pressure equation	Velocity equation	Reynolds stress equation	Particle /aerosols
Inlet	0 gradient	Fixed value	Fixed value	Constant velocity, flow rate and distribution
Upper outlet	Constant pressure	0 gradient	0 gradient	Flow out
Lower outlet	Constant pressure	0 gradient	0 gradient	Flow out
wall	0 gradient	No slipping	0 gradient	rebound

4. Results and Discussion

The simulation result of the aerosol separation is illustrated in Fig 5 just to provide a primary image of the separation mechanism. Further analysis of this simulation result will be discuss after additional model analyses are conducted.

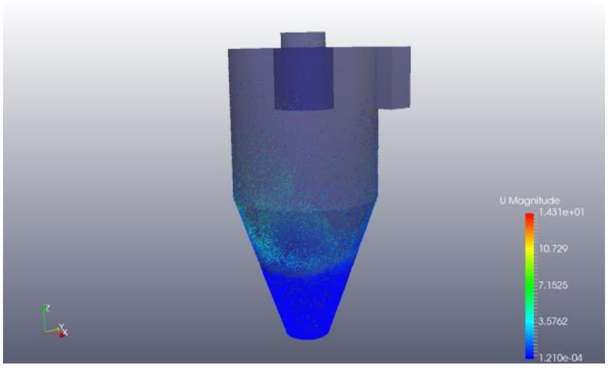

Fig 5. Simulation result to illustrate the separation mechanism

Upon exiting the pre-filtration cyclone, particles/aerosols will exit the lower part of the cyclone and enter the first absorbent module, which contains HCF-gels. In Cs^+ removal experiments, KCuHCF-cellulose hydrogel composites (HCF-gels) exhibited exceptional Cs^+ adsorption capacities (2.06- 2.32 mmol g^{-1}). The HCF-gel sample was observed to remove > 99% of Cs^+ (0.15 mmol L^{-1}) within 4 h maintaining its adsorption stability over a wide pH range of 4-11. [6] After several hours, the Cs^+ will be absorbed and effluents can enter the second stage absorbent (charcoal) for iodine ion removal. After capturing these radionuclides, the resulting waste can be removed from the tank and collected/stored for further treatment.

For the upper part, Bismuth-embeded SBA-15 will be used for gaseous iodine capture. Further efficiency enhancements, like using a HEPA, can be added if necessary. Employing additional absorbents is possible due to the modular design approach. Gaseous effluent can be released to the environment if the decontamination factor (DF) meets the regulations, thus further reducing the source term volume. Considering the entire system, using novel absorbents alone and in combination with other filtration technologies can produce promising, high efficiency enhancements.

5. Conclusions and future work

Capture efficiency of a simple cyclone separator is not ideal for particles that are smaller than 5 µm. (The cyclone diameter is 1m and therefore$D_{p50} > 8\ \mu m$.)

The current cyclone can be used as a pre-filter to separate the gaseous component and large particles.

To evaluate the whole system efficiency that can be achieved for smaller particles, CsI and I_2, KCuHCF and Bismuth- embedded SBA-15 based novel absorbents will be analyzed.

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