Remarks on the FAI Correlation-based Aerosol Model for SALUS Accident Analysis

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Introduction

- **SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR)**
  - KAERI is developing a design and analysis technique for a pool-type sodium-cooled fast reactor called **SALUS** (Small, Advanced, Long-cycled and Ultimate Safe SFR), which will generate 100MWe with a long refueling period more than 20 years.
  - Despite the extremely low probability of a severe accident expected in SALUS NPPs (Nuclear Power Plants), the analytical capabilities and tools to predict radioactive fission products (FPs) releases to the environment under postulated nuclear power plant accidents are required for public acceptance and licensing.

- **ISFRA (Integrated SFR Analysis Program for PSA)**
  - KAERI and Fauske & Associates, LLC (FAI), jointly developed ISFRA computer program to simulate the response of the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) pool design with metal fuel during a severe accident.
  - ISFRA was designed to be a fast-running simulation software, used for the Level II PSA of PGSFRs.
  - ISFRA adapted **FAI’s correlation-based aerosol analysis model**, as like MAAP or APRIL code.
Ultimate Goal: Improvement in Confidence in the ISFRA Severe Accident Source Term Analysis Tool for SALUS NPPs

Purpose of this study: To characterize the transition behavior between the steady-state and the decaying modes, and to compare the CPU times between the correlation-based model and the MAEROS sectional numerical method.

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- Introduction
- Purposes & Contents
- Correlation-based Aerosol Model
- Transition between Steady-State and Decaying modes
- CPU Time Comparison
- Conclusions
FAI’s Correlation-based Aerosol Model

- Aerosol similarity assumed.
  - As time increase, the particle size distribution becomes the same, independent of the initial distribution of sizes.
  - Two steady-state aerosols or two aging aerosols (after the initial conditions are forgotten) are similar, if their dimensionless densities \( M \) are the same. (See Figure I)
  - By similarity analysis, variables concerning aerosol behavior can be non-dimensionalized, as in Table 1.

Table 1: Dimensionless major variables for aerosols undergoing Brownian and gravitational coagulation and settling

<table>
<thead>
<tr>
<th>Time, ( \tau )</th>
<th>Particle volume, ( V )</th>
<th>Particle number density, ( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \left( \frac{\alpha g \rho K_0}{\chi^2 \mu h^2} \right)^{\frac{1}{2}} \cdot t )</td>
<td>( \left( \frac{\gamma g \rho}{\alpha^{\frac{1}{3}} \mu K_0} \right)^{\frac{2}{3}} \cdot v )</td>
<td>( \left( \frac{\gamma^3 K_0^{\frac{5}{4}} \mu^2 h^4}{\alpha g \rho^5} \right)^{\frac{1}{4}} \cdot n )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass density, ( M )</th>
<th>Decay constant, ( A )</th>
<th>Particle production rate, ( \dot{N}_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\gamma^2 \rho h^4}{\alpha^2 K_0 \mu \rho^3} \cdot m )</td>
<td>( \frac{\gamma^2 \rho h^2}{\alpha K_0 g \rho} \cdot \lambda )</td>
<td>( \frac{\gamma^4 \chi^4 K_0^3 \mu^2 h^8}{\alpha^3 g^7 \rho^2} \cdot \dot{n}_p )</td>
</tr>
</tbody>
</table>

- Fig. I: Particle mass distribution of two different aging aerosols undergoing Brownian and gravitational coagulation and settling

- \( h \): effective height for aerosol deposition [m]
- \( k \): Boltzmann constant
- \( K(v, \bar{v}) \): kernel representing the frequency of binary collisions between particles of volume \( v \) and \( \bar{v} \)
- \( K_0 \): normalized Brownian collision coefficient
- \( m \): total mass concentration of the suspended aerosols [kg/m\(^3\)]
- \( M \): dimensionless total suspended aerosol
- \( M_p \): mass dimensionless source rate
- \( N \): particle size distribution function [m\(^3\)]
- \( \dot{n}_p \): source rate of particles [m\(^3\)s\(^{-1}\)]
FAI’s Correlation-based Aerosol Model

- Aerosol dynamic equation is transformed into a simpler equation by using dimensionless parameters.

  - Total Aerosol Mass Variation:
    \[ m(t) = \rho \int_0^\infty v_n(v,t)dv \]
    with \[ \dot{m}_p(t) = \rho \int_0^\infty v_n(t, v)dv \]
    \[ \dot{\lambda}(t) = \frac{\int_0^\infty v_n(v,t)u(v)dv}{h\int_0^\infty v_n(v,t)dv} \]

- In dimensionless form, steady-state and decaying conditions are expressed as follows:
  \[
  \frac{dM}{d\tau} = -\Lambda_{SED}^{SS}(M) \cdot M + \dot{M}_p = 0 \]
  \[
  \frac{dM}{d\tau} = -\Lambda_{SED}^{D}(M) \cdot M
  \]

- Functional relationships of \( \Lambda(M) \) are obtained based on many exact numerical solutions by running a sectional analysis tool, MAEROS.

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>( h ) [m]</th>
<th>( \bar{m}_p ) [kg/m²/s]</th>
<th>( \rho ) [kg/m³]</th>
<th>( \gamma )</th>
<th>( \chi )</th>
<th>( \sigma )</th>
<th>( \xi_p ) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>3.1017</td>
<td>9.1549E-7</td>
<td>2450</td>
<td>2.25</td>
<td>1.5</td>
<td>2.0</td>
<td>0.125</td>
</tr>
<tr>
<td>△</td>
<td>10.0</td>
<td>8.2160E-6</td>
<td>4000</td>
<td>2.5</td>
<td>1.0</td>
<td>1.55</td>
<td>0.136</td>
</tr>
<tr>
<td>○</td>
<td>3.1017</td>
<td>5.9638E-6</td>
<td>2130</td>
<td>2.25</td>
<td>1.5</td>
<td>2.0</td>
<td>0.25</td>
</tr>
<tr>
<td>○</td>
<td>5.0</td>
<td>2.3122E-4</td>
<td>5000</td>
<td>1.0</td>
<td>1.0</td>
<td>1.55</td>
<td>0.27</td>
</tr>
<tr>
<td>□</td>
<td>3.1017</td>
<td>1.1737E-4</td>
<td>3670</td>
<td>2.25</td>
<td>1.5</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>X</td>
<td>2.0</td>
<td>2.9343E-5</td>
<td>2000</td>
<td>1.0</td>
<td>1.0</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>○</td>
<td>1.0</td>
<td>1.1737E-4</td>
<td>1000</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. II: Dimensionless aerosol removal rate constant for sedimentation as a function of dimensionless suspended mass concentration.
Aerosol Removal Rate Constant, $\lambda_{SED}$

- **Execution procedure to calculate suspended aerosol masses**

1) Dimensionless suspended aerosol mass $M$ is calculated from the suspended aerosol mass $m$ by using the equations of Table 1,

2) The dimensionless decay constant $\lambda$ is calculated depending on the situation of steady-state or decaying aerosol,

3) Dimensionless decay constant $\lambda$ is transformed into an aerosol removal rate constant $\lambda$ by using the equations of Table 1, and

4) The suspended aerosol mass $m$ is finally calculated by

$$\frac{dm(t)}{dt} = -\lambda_{SED} m(t) + \dot{m}_p$$

- **In the ABCOVE AB5 simulation,**
  - $\lambda_{SED}$ follows $\lambda_{SED}^{SS}$ until 872s, with aerosol sources
  - $\lambda_{SED}$ jumps from $\lambda_{SED}^{SS}$ to $\lambda_{SED}^{D}$ immediately at 872s
  - then $\lambda_{SED}$ follows $\lambda_{SED}^{D}$ after 872s, without any aerosol source
How to control $\lambda_{SED}$ (or $\Lambda_{SED}$) in the transition phases?

Determination logic of aerosol removal constant $\lambda_{SED}$:

I. Without aerosol source:

$$\lambda_{SED} = \lambda^D_{SED}$$

II. With aerosol sources;

II-1) If $m(t)/M_{SS} < 1.0$;

$$\lambda_{SED} = \lambda^{SS}_{SED}$$

II-2) If $m(t)/M_{SS} > 1.0$;

$$U \equiv \frac{m(t) - M_{SS}}{(f_{SS} - 1)M_{SS}}$$

Interpolation factor $FSEDDK$

$$FSEDDK = 4 \times U^3 - 6 \times U^2 + 3 \times U$$

Then,

$$\lambda_{SED} = FSEDDK \times \lambda^D_{SED} + (1 - FSEDDK) \times \lambda^{SS}_{SED}$$

Multiplier to the expected steady-state mass, above which the new source will not affect the removal rate. ($> 1.0$)

$$f_{SS} \equiv 8.0 \quad \text{in ISFRA code}$$

Fig. V: $FSEDDK$ as a function of the ratio of suspended aerosol mass $m(t)$ to the steady-state airborne aerosol mass $M_{SS}$ (with $f_{SS} = 8.0$)
CPU Time Comparison (1/2)

 Preparation of CPU Time Comparison

- FAI correlation-based aerosol model
  - Stand-alone aerosol module of ISFRA code
  - Subroutines for aerosol FP analysis were extracted from the ISFRA code, and
  - A driver (FPINTRA) was created to impose the appropriate boundary condition of the experiment

- MAEROS sectional method
  - MAEROS model was developed by Gelbard et al. in early ’80, and adapted in CONTAIN and MELCOR codes.
  - Numerical solution - the general aerosol kinetic equation is transformed into the sectionalized governing equation, assuming that coagulation and condensation occurs in series and that any two mechanisms cannot occur simultaneously.
  - MAEROS code was obtained from the IAEA code bank system.
CPU Time Comparison between AB5 Simulations by FAI & MAEROS methods

- In the ABCOVE AB5 test, performed in 1982, single-species aerosol was generated by spraying sodium at high rate for initial 872s.

- Code modification for CPU time comparison
  - Using "CPU_TIME(x)" FORTRAN subroutine - simple & primary, but robust method to measure CPU times
  - Basic logics only - unnecessary procedures were removed

- As a result, the FAI correlation-based aerosol model gives output about 80 times faster than the sectional method in the AB5 simulation
  - Both runs performed on the same PC with the 64-bit WINDOWS operating system on an Intel I7-7700 CPU
  - Simulation times = 300,000 s (for both runs)

### Table 2: Modification for CPU time measurements (in both ISFRA & MAEROS codes)

<table>
<thead>
<tr>
<th>Stand-alone aerosol module of ISFRA code</th>
<th>MAEROS sectional model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation condition</td>
<td></td>
</tr>
<tr>
<td>time_end = 3.0E+05 sec</td>
<td>28 particle size sections time_end = 3.0E+05 sec</td>
</tr>
<tr>
<td>CPU time</td>
<td>0.6250E-01 sec</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- Study on the Transition Behavior of FAI Correlation-based Aerosol Model between the Steady-state and Decaying Modes
  - Aerosol removal rate constants $\lambda_{SED}$ as a function of time were extracted, and the transition behavior from steady-state to decaying mode was tracked.
  - This transition behavior was found to be controlled by the interpolation factor $F_{SEDDK}$, which is the internal variable of ISFRA code.

- CPU Time Comparison between the AB5 Simulations by FAI Correlation-based Aerosol Model and by MAEROS Sectional Numerical Method
  - FAI correlation-based aerosol model gave output about 80 times faster than the MAEROS sectional method for the single-component aerosol analysis of the AB5 experiment.

- This is the final stage of the research series on FAI correlation-based aerosol model in the ISFRA code. The research results were summarized in the following journal paper.

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