The Development and Application of Kinetic Models for the Resuspension of Small Particles in Turbulent Boundary Layers

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Acknowledgments

- Jim Reed, CEGB/Edf Energy, UK
- Duncan Hall, CEGB/SERCO, UK
- Luigi Biasi, JRC Ispra, It
- Martin Kissane, IRSN, Fr
- Fred Zhang, NCL, UK
- Richard Perkins, ECL, Lyon, Fr
Background

- Important in a range of environmental and industrial processes
  - Clean air technology,
  - Dust storms on Earth and Mars (wave of darkening)
  - Spreading of pollen and crops diseases by fungal spores
- Release of radioactive particles in a nuclear accident
  - Focus on resuspension particles < 5microns in size
  - Principle adhesive forces – Van der Waals intermolecular forces
- Import of safety assessment of nuclear reactors
  - Development and validation of computer codes
Kinetic Models for Resuspension

- Stochastic models which take account of the role of turbulence in particle resuspension
- Focus on resuspension rates as well as fraction resuspension
- Calculation of a rate constant for resuspension
  - analogous to the rate constant for desorption of molecules from a surface $\omega e^{-E/kT}$ (relationship to kinetic theory)
  - Computational very efficient compared to simulation (particle tracking)
  - Ideally suited for incorporation into severe accident codes e.g. SOPHAEROS -> ASTEC
History and Motivation

- Radioactive particles released in severe accidents
  - PWRs - steam spikes (primary circuit), hydrogen deflagration (containment)
  - AGRS dropped stringer –accident
  - HTRs Accumulation of contaminated dust in the coolant circuit – loss of coolant accident (LOCA)
  - International Thermonuclear Experimental Reactor (ITER) Accumulation of contaminated dust in the vacuum vessel Coolant-water-ingress or Loss of vacuum accident (LOVA)

- SARNET
  - Development of SA Codes / Sophaeros
  - IRSN
ASTEC integrates the technical knowledge in SARNET

Database:
- DIVA
- ELSA
- CESAR
- SOPHAEROS
- RUPUICUV
- MEDICIS/WEX
- CPA-THY
- CPA-AFP
- IODE
- ISODOP
- SYSINT

Safety system management
- IODE
- MOL
core concrete interaction
- SOPHAEROS
- Aerosols and FP in the reactor circuits

Radioactivity in Containment
- ISODOP

Containment Thermal hydraulics
- CPA-THY

FP release
- ELSA

Core degradation
- DIVA

Circuit Thermal hydraulics
- CESAR

Molten core ejection and direct heating of containment
- RUPUICUV

Molten core concrete interaction
- MEDICIS/WEX

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OUTLINE

- Early model RRH model
  - Escape of particles from surface adhesive potential well
  - Role of adhesive and aerodynamic removal forces
  - Mechanisms for removal
    - Quasi static
    - Energy accumulation
- Rock n roll Model
- Decay of gas-borne radioactive in a reactor circuit
- Model improvements based non-Gaussian removal forces
- Extension resuspension from multilayer deposits
Reeks Reed & Hall Kinetic Model (1987)

\[ \ddot{y} + \beta \dot{y} + \omega_n^2 y = m^{-1} f_R(t) \]

very stiff lightly damped harmonic oscillator

\[ F_R = \langle F_R \rangle + f_R(t); \ \text{mean} \ \langle F_R \rangle; \ \text{fluctuating} \ f_R(t) \]

\[ \omega_n = \text{natural frequency of oscillations} \]

\[ p = n \exp\left(-\frac{Q}{2\langle \text{PE} \rangle}\right) \]
Resonant energy transfer / energy accumulation

\[ p = n \exp \left( -\frac{Q}{2\langle PE \rangle} \right) \]

- \( p \) is the rate constant for removal \( \text{s}^{-1} \)
- \( n \) typical frequency of the deformation with potential
- \( Q \) the height of potential barrier (depends on difference of adhesive removal forces)
- \( \langle PE \rangle \) average Potential Energy in well

\[ \eta = \frac{\pi}{2\beta} \omega \tilde{E}_R(\omega_n) \]

- Resonant energy contribution contribution
- \( \beta \) damping constant
- \( E_R \) normaled energy spectrum of \( f_R(t) \)

\[ p = n \exp \left( -\frac{1}{2} \frac{(f_a - \langle F_R \rangle)^2}{\langle f_R^2 \rangle (1+\eta)} \right) \]

\[ n = \frac{\omega_n}{2\pi} \frac{\left( \eta + \frac{\langle f_R \rangle^2}{\langle f_R^2 \rangle} \omega_n^2 \right)^{1/2}}{\eta + 1} \]

adhesive force \( f_a = \frac{3}{2} \pi \gamma r \) (JKR, \( \gamma \) = surface energy, \( r \) = radius of curvature)

- \( \eta \to 0 \) quasi static
- \( \eta \gg 1 \) resonant energy transfer

\[ p = \frac{1}{2\pi} \frac{\langle f_R^2 \rangle}{\langle f_R^2 \rangle} \exp \left( -\frac{1}{2} \frac{(f_a - \langle F_R \rangle)^2}{\langle f_R^2 \rangle} \right) \]

\[ p = \frac{\omega_n}{2\pi} \exp \left( -\frac{1}{2} \frac{f_a^2}{\langle f_R^2 \rangle} \right) \]
Influence of surface micro roughness

- Particle surface adhesive force

\[ f_a = \frac{3}{2} \pi \gamma r_a \text{ JKR } r_a = \text{asperity radius}, \quad r'_a = \frac{r_a}{r} \]

- Distribution of adhesive forces

\[ \phi(r'_a) = \frac{1}{\sqrt{2\pi}} \frac{1}{r'_a \ln \sigma'_a} \exp \left( - \frac{\ln(r'_a/\bar{r}'_a)^2}{2(\ln \sigma'_a)^2} \right) \]

\[ \bar{r}'_a \sim 0.01 \text{ reduction in adhesion for smooth contact} \]

- Fraction remaining after resuspension

\[ f_R = \int_{0}^{\infty} e^{-p(r'_a)^t} \phi(r'_a) dr'_a \]

- Fractional resuspension rate

\[ \Lambda(t) = \int_{0}^{\infty} p(r'_a) e^{-p(r'_a)^t} \phi(r'_a) dr'_a \]
Short and Long term Resuspension Rate

Hinkley B CAGR gas flow

\[ \mu_f = 2.2 \text{ m s}^{-1} \]
\[ \rho_f = 1.2 \text{ kg m}^{-3} \]
\[ \mu_f = 1.82 \times 10^{-5} \text{ kg m}^{-1} \text{s}^{-1} \]
\[ r_a' = 0.1 ; \sigma_a = 4 \]
\[ \gamma = 0.15 \text{ J m}^{-2} \]
Measurements of resuspension factor

Silt from grass at wind speeds of 5m/s or 10m/s in a wind tunnel Garland 1979
Hall’s measurements of Lift Force

\[ \frac{\langle F_L \rangle}{\rho \nu^2} \approx 20.9 \left( \frac{r u_\tau}{\nu} \right)^{2.31} \]

\[ \hat{E}(n) = \left( \frac{v}{u_\tau^2} \right) E^+(n^+) \]

\[ E^+(n^+) = 58.06, \quad n^+ \leq 0.0054, \]
\[ E^+(n^+) = 0.0812(n^+)^{-1.26}, \quad 0.0054 < n^+ < 0.104, \]
\[ E^+(n^+) = 0.0000173(n^+)^{-5}, \quad n^+ \geq 0.104. \]

\[ \chi(P_0) = \frac{9}{2} K^{2/3} r_a^{1/3} P_1^{1/3} \left( \frac{P_1 + P_0}{5P_1 + P_0} \right), \]
\[ K = \frac{4}{3} \left( \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right)^{-1} \]
\[ P_1 = P_0 + 3\pi \gamma r_a + \left[ 6\pi \gamma r_a P_0 + (3\pi \gamma r_a)^2 \right]^{1/2}, \]
\[ \frac{\langle \dot{f}^2 \rangle}{2\pi} = 0.00658 \left( \frac{u_\tau^2}{\nu} \right), \]

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Measurements of adhesion

Table 2
Fitted values for the adhesive force distribution

<table>
<thead>
<tr>
<th>Particle</th>
<th>Force</th>
<th>Measurement</th>
<th>Spread $\sigma_a$</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm alumina</td>
<td>Normal</td>
<td>Set 1</td>
<td>49</td>
<td>592</td>
</tr>
<tr>
<td>10 µm alumina</td>
<td>Normal</td>
<td>Set 2</td>
<td>208</td>
<td>56</td>
</tr>
<tr>
<td>10 µm alumina</td>
<td>Normal</td>
<td>Reed and Rochowiak (1988)</td>
<td>2.55</td>
<td>37</td>
</tr>
<tr>
<td>10 µm alumina</td>
<td>Tangential</td>
<td>Set 1</td>
<td>10.4</td>
<td>848</td>
</tr>
<tr>
<td>10 µm alumina</td>
<td>Tangential</td>
<td>Set 2</td>
<td>2.95</td>
<td>1053</td>
</tr>
<tr>
<td>20 µm alumina</td>
<td>Normal</td>
<td></td>
<td>78</td>
<td>56</td>
</tr>
<tr>
<td>Graphite</td>
<td>Normal</td>
<td></td>
<td>489</td>
<td>1.55</td>
</tr>
<tr>
<td>Graphite</td>
<td>Tangential</td>
<td></td>
<td>19</td>
<td>16</td>
</tr>
</tbody>
</table>

Material properties required to calculate particle resuspension using the RRH model

<table>
<thead>
<tr>
<th>Material</th>
<th>Graphite</th>
<th>Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interfacial surface energy, Jm$^{-2}$</td>
<td>0.15</td>
<td>0.56</td>
</tr>
<tr>
<td>Substrate density (steel), Kg m$^{-3}$</td>
<td>7830</td>
<td>7830</td>
</tr>
<tr>
<td>Substrate Young’s modulus, Pa</td>
<td>$2.1 \times 10^{11}$</td>
<td>$2.1 \times 10^{11}$</td>
</tr>
<tr>
<td>Particle Young's modulus, Pa</td>
<td>$2.0 \times 10^{10}$</td>
<td>$3.5 \times 10^{11}$</td>
</tr>
<tr>
<td>Substrate Poissons ratio</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Particle Poissons ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle density, Kg m$^{-3}$</td>
<td>2300</td>
<td>1600</td>
</tr>
</tbody>
</table>

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Resuspension measurements / model predictions

nominal 10 micron alumina spherical particles
No resonant energy contribution predictions
Rock’n’Roll model for particle resuspension

\[ \Gamma = \frac{a}{2} F_L + r F_D \quad \Rightarrow \quad F = \frac{1}{2} F_L + \frac{r}{a} F_D \]

\[ \langle F \rangle + f(t) + F_A(y) = 0 \]

At the point of detachment \((y_{dh})\) the adhesive ‘pull off’ force \(f_a = -F_A\) at \((y_{dh})\),

\[ f_{dh} = f_a - \langle F \rangle \]
Rate constant for Rock’n’Roll model

Rate constant

\[
\begin{align*}
\rho &= \frac{\int_0^\infty vW(v, y_d)dv}{\int_{-\infty}^\infty \int_{-\infty}^\infty W(v, y)dydv} \\
&= \frac{\int_0^\infty fW(f_d, f)df}{\int_{-\infty}^\infty \int_{-\infty}^\infty W(f, f)dfdf}
\end{align*}
\]

number of particles released per sec / number of particles attached to surface

\(y(t) = \psi(f)\) and so \(\dot{y}(t) = f\dot{\psi}(f)\)

Gaussian statistically independent pdf

\[
W(f, \dot{f}) = 2\pi \sqrt{\langle f^2 \rangle \langle \dot{f}^2 \rangle} \exp\left(-\frac{f^2}{2\langle f^2 \rangle}\right) \exp\left(-\frac{\dot{f}^2}{2\langle \dot{f}^2 \rangle}\right)
\]

\[
p = \frac{1}{2\pi} \sqrt{\frac{\langle \dot{f}^2 \rangle}{\langle f^2 \rangle}} \exp\left(-\frac{f_d^2}{2\langle f^2 \rangle}\right) \left[1 + \text{erf}\left(\frac{f_d}{\sqrt{2\langle f^2 \rangle}}\right)\right]
\]
Resuspension measurements / model predictions

nominal 10 micron alumina spherical particles
No resonant energy contribution predictions
Decay of particle concentration in a recirculating flow

CAGR reactor coolant circuit

\[ \frac{\partial C}{\partial t} = - (\lambda_A k_A + \lambda_B k_B) C(t) + \lambda_A k_A \int_0^t \Lambda(t-s) C(s) \, ds + S(t), \]

\[ \Lambda(t) = \frac{\xi}{t^\epsilon}, \]

\[ \frac{\partial C}{\partial t} = - \alpha_{AB} C(t) + \alpha_A \int_0^{t-t_c} \frac{\xi C(s) \, ds}{(t-s)^\epsilon} + S(t), \]

where

\[ C(t) \sim \frac{\Gamma(\epsilon) \Gamma(2-\epsilon) \sin[(\epsilon-1)\pi] \alpha_A \xi}{\pi (\epsilon-1) \left[ \alpha_{AB} - \alpha_A \xi \int_{t_c}^{\infty} \frac{ds}{(s+t_0)^\epsilon} \right]^2} t^{-\epsilon}, \]

Reeks-Hall IDF Equation
Biasi Correlations adhesive force distribution

Fig. 18. Error distribution of model predictions of the fraction of resuspended particles.

\[ \phi(r'_a) = \frac{1}{\sqrt{2\pi}} \frac{1}{r'_a \ln \sigma'_a} \exp \left( - \frac{[\ln (r'_a/\bar{r}'_a)]^2}{2(\ln \sigma'_a)^2} \right) \]

geometric mean \( \bar{r}'_a = 0.016 - 0.0023r^{0.545} \)

geometric spread \( \sigma'_a = 1.8 + 0.136r^{1.4} \)
Non-Gaussian removal forces

\[ p = \int_0^\infty v P(y_d, v) \, dv / \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(y, v) \, dy \, dv \]

\[ f_a(y) + f(t) = 0 \]

\[ y(t) = \psi(f) \text{ and so } \dot{y}(t) = \dot{f} \psi'(f) \]

\[ p = \int_0^\infty \dot{f} P(f_d, \dot{f}) \, df / \int_{-\infty}^{\infty} \int_{-\infty}^{f_d} P(f, \dot{f}) \, df \, d\dot{f} \]
Distributions of $z_1 = f / \langle f^2 \rangle^{1/2}$ from DNS data

Rayleigh Distribution

Gaussian Distribution

$y_+ = 6$

$y_+ = 1$

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Distributions of $z_2 = \dot{f} / \left< \dot{f}^2 \right>$ from DNS data

**y+=6**

**y+=1**
Resuspension rate constant, $p$

Joint distribution of fluctuating aerodynamic force and its derivative

$$z_1 = \frac{f}{\sqrt{\langle f^2 \rangle}} \quad z_2 = \frac{f}{\sqrt{\langle f^2 \rangle}}$$

$$p(z_1, z_2) = \frac{z_1 + A_1}{A_2^2} \exp \left[ -\frac{1}{2} \left( \frac{z_1 + A_1}{A_2} \right)^2 \right] \cdot \frac{B_1}{B_2 \sqrt{2\pi} \sqrt{z^2 + 1}} \exp \left[ -\frac{1}{2} \left( B_3 + B_1 \ln \left( z + \sqrt{z^2 + 1} \right) \right)^2 \right]$$

where $A_1, A_2, B_1, B_2, B_3$ and $B_4$ are all constants depending on $y^+$.

$$z = \frac{z_2 - B_4}{B_2}$$

$$p = B_f \omega \frac{z_{dh} + A_1}{A_2^2} \exp \left[ -\frac{1}{2} \left( \frac{z_{dh} + A_1}{A_2} \right)^2 \right] \frac{1}{1 - \exp \left[ -\frac{1}{2} \left( \frac{z_{dh} + A_1}{A_2} \right)^2 \right]} \quad \text{Modified}$$

$$p = \frac{1}{2\pi} \omega \exp \left( -\frac{1}{2} z_{dh}^2 \right) / \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{1}{\sqrt{2}} z_{dh} \right) \right] \quad \text{Original R'n'R Model}$$

$$\omega = \sqrt{\langle \dot{f}^2 \rangle / \langle f^2 \rangle} = \omega^+ \frac{u^+_2}{\nu} \quad ; \quad z_{dh} = \frac{(f_a - \langle F \rangle) / \langle f^2 \rangle^{1/2}}{z_a = f_a / \langle f^2 \rangle^{1/2}} ; \quad B_f = \phi(B_1, B_2, B_3, B_4)$$

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### Table of resuspension rate parameters

<table>
<thead>
<tr>
<th>DNS</th>
<th>$B_{\text{fdot}}$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$\omega^+$</th>
<th>$f_{\text{rms}} = \langle f^2 \rangle^{1/2}/\langle F \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y^+ = 6$</td>
<td>0.358568</td>
<td>1.83605</td>
<td>1.478360</td>
<td>0.12714</td>
<td>0.346</td>
</tr>
<tr>
<td>$y^+ = 2$</td>
<td>0.351181</td>
<td>1.75990</td>
<td>1.431301</td>
<td>0.13126</td>
<td>0.365</td>
</tr>
<tr>
<td>$y^+ = 0.6$</td>
<td>0.346911</td>
<td>1.78475</td>
<td>1.446609</td>
<td>0.15203</td>
<td>0.366</td>
</tr>
<tr>
<td>$y^+ = 0.1$</td>
<td>0.343658</td>
<td>1.81256</td>
<td>1.463790</td>
<td>0.16419</td>
<td>0.366</td>
</tr>
</tbody>
</table>
Resuspension Rate Constant

Normalized resuspension rate constant

- Green line: ratio
- Blue line: Gaussian case
- Purple line: non-Gaussian case

$p_{\omega} / p_{\omega}^{\text{Gaussian case}}$

$p_{\omega}^{\text{ratio of non-Gaussian to Gaussian}}$

$z_{dh}$

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

0 0.1 0.2 0.3 0.4

0 10 20 30 40

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Comparison of Original and Modified R’n’R model

Comparison with Hall’s experimental results

<table>
<thead>
<tr>
<th></th>
<th>$\omega^+$</th>
<th>$\langle f^2 \rangle^{1/2} / \langle F \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified (DNS)</td>
<td>0.164189</td>
<td>0.366</td>
</tr>
<tr>
<td>original</td>
<td>0.0413</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Comparision of fraction resuspended for 20μm Alumina

Fraction resuspended after 1s

- Modified model (DNS)
- Original R’n’R model

Run - 7
Run - 8
Run - 20
resuspension fraction after 1s modified versus original models

Hall's experimental flow and adhesion properties for 10 micron alumina particles
fractional resuspension rates for modified and original models

\[ \frac{F_f}{F} = 2.0 \]

\[ u_1 = 0.7 \text{ m/s}, 10 \mu \text{m Alumina} \]

\[ \text{Resuspension Rate (s}^{-1}) \]

\[ t(s) \]

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Newcastle University
Multilayer modelling

Suppose we let \( n_i(\xi, t) d\xi \) denote the number of particles between \( \xi, \xi + d\xi \) in the \( i-th \) layer of a deposit composed of \( L \) layers, the layers being numbered sequentially from the top layer (totally exposed to the flow) downward as \( i = 1, 2..., L \). The set of ODE equations are thus

\[
\frac{\partial n_i(\xi, t)}{\partial t} = -p(\xi)n_i(\xi, t) + \psi(\xi) \int_0^\infty p(\xi')n_{i-1}(\xi', t) d\xi'
\]

\[
= -p(\xi)n_i(\xi, t) + \psi(\xi)\Lambda_{i-1}(t)
\]

\[
\Lambda_i(t) = \sum pn_i(\xi, t) \Delta \xi
\]

\( \xi = \) adhesive force, flow etc.

Friess and Yadigaroglu (FY), 2001
<table>
<thead>
<tr>
<th>Average radius ($\mu$m)</th>
<th>Fluid density (kg.m$^{-3}$)</th>
<th>Fluid kinematic viscosity (m$^2$.s$^{-1}$)</th>
<th>Wall friction velocity (m.s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.227</td>
<td>0.5730</td>
<td>$5.2653 \times 10^{-5}$</td>
<td>6.25</td>
</tr>
<tr>
<td>Surface energy (J.m$^2$)</td>
<td>Adhesion reduction factor (geometric mean)</td>
<td>Adhesion spread factor (geometric standard deviation)</td>
<td>Geometric mean of normalised adhesive force $\bar{z}<em>a = \frac{3/2\pi \gamma}{f</em>{m}(F)\bar{F}}$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.015</td>
<td>1.817</td>
<td>5.94</td>
</tr>
</tbody>
</table>

– Values of parameters in STORM SR11 Phase 6. Flow properties correspond to nitrogen gas at 12 bar pressure and temperature of 370 deg C typical of a PWR severe accident
Resuspension rate of each layer for hybrid generic model

STORM Test SR11 flow conditions

Reduction in adhesion 0.0075, spread in adhesion 1.001

Reduction in adhesion 0.015, spread in adhesion 1.87
Resuspension of each layer vs. time

![Graph showing resuspension of each layer vs. time]

- Reduction in adhesion = 0.0075, spread = 1.001

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Fractional resuspension rate as a function of number of layers

(particle diameter: 0.45μm) based on STORM test (SR11) Phase 6 conditions
Resuspension half-life vs. layer thickness

- Spread factor = 1.1
- Spread factor = Biasi(1.8)
- Spread factor = 4.0
- Ratio of short-term (<10^{-4} s) to long-term resuspension fraction
Influence of size distribution

- Monodisperse model (single particle size)

\[
\frac{\partial n_1(r', t)}{\partial t} = -p(r')n_1(r', t)
\]

\[
\frac{\partial n_i(r', t)}{\partial t} = -p(r')n_i(r', t) + \varphi(r') \int_0^\infty p(\tilde{r}') n_{i-1}(\tilde{r}', t) d\tilde{r}' \quad (i \geq 2)
\]

- Polydisperse model

\[
\frac{\partial n_1(r, r_a', t)}{\partial t} = -p(r, r_a')n_1(r, r_a', t)
\]

\[
\psi(r) = \frac{1}{\sqrt{2\pi}} \frac{1}{r \ln \sigma_r} \exp \left( -\frac{[\ln(r/\bar{r})]^2}{2(\ln \sigma_r)^2} \right)
\]

\[
\frac{\partial n_i(r, r_a', t)}{\partial t} = -p(r, r_a')n_i(r, r_a', t) + \psi(r) \psi(r_a') \int_r^\infty \int_0^\infty p(\tilde{r}, \tilde{r}_a') n_{i-1}(\tilde{r}, \tilde{r}_a', t) d\tilde{r}_a' d\tilde{r} \quad (i \geq 2)
\]
STORM SR11 Test

STORM SR11 test and multilayer model result (m = 0.01, sf = 1.5)

- Experimental data
- Monolayer, monodisperse
- 5 layers, monodisperse
- 10 layers, monodisperse
- Monolayer, polydisperse
- 2 layers, polydisperse
- 3 layers, polydisperse

Resuspension fraction vs. time (s)

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Multilayer model results with BISE experiment

- Experimental data
- Monolayer, monodisperse
- 50 layers, monodisperse
- 100 layers, monodisperse
Summary & Conclusions

- Kinetic model for resuspension of particles by a turbulent boundary
  - Rate constant for removal for a particle from a surface
  - Analogy with desorption rate of molecules from a surface (Arrhenius)
  - Resonant energy transfer/quasi-static removal
  - Originally developed for removal by lift forces \(<F>, f, E_f(n)\)
  - Broad distribution of surface adhesive forces log normal, geom spread factor
  - Factor of 100 reduction in adhesion compared to perfectly smooth contact

- Short term \(e^{pt}\) and long term resuspension \(\Lambda(t) \sim \xi t^{-1}\)
  - Decay of gas borne concentration in reactor coolant circuit (deposition and resuspension)

- Model validation
  - Centrifuge measurements of surface adhesion,
  - Tangential force easier to remove particles than normal force - ‘rolling over lift off’
  - Development RnR model using moments of drag forces
    - Much better agreement with R&H resuspension measurements

- RnR treatment for non Gaussian removal forces
  - Significant increase in the resuspension rate for rough surface \(<FR> \ll g, \text{mean adhesive force}\)