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Self-Mixing Phenomenology in Hypothetical Core-Disruptive Accidents

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SELF-MIXING PHENOMENOLOGY IN HYPOTHETICAL CORE-DISRUPTIVE ACCIDENTS

by

E. J. Chapyak

ABSTRACT

Physical processes are investigated that lead to the thermal equilibration of a disrupted liquid metal fast breeder reactor (LMFBR) core following a hypothetical core-disruptive accident (HCDA). Their impact is assessed, particularly as relating to the SIMMER code. The turbulent structure in the core region is characterized and bounding estimates are derived of thermal equilibration ("self-mixing") times. The implication of these results for LMFBR safety research is discussed briefly.

I. INTRODUCTION

A major area of investigation in liquid metal fast breeder reactor (LMFBR) safety research is the so-called hypothetical core-disruptive accident (HCDA). Of particular importance is the possibility that a loss of initial core geometry could lead, through an energetic disassembly transient, to a core region filled with high-temperature, high-pressure multiphase fuel, steel, and coolant.

Following the initial disassembly motion in the core region, the mixture can expand and progress through the intact upper core structure (UCS), flashing and interacting with the steel structure and any liquid sodium films that may be present. Finally, a portion of the mixture may come in contact with the sodium pool above the UCS (possibly generating extensive sodium vaporization) and drive a liquid sodium slug against the head of the containment vessel.¹ This sequence is illustrated in Fig. 1.

The term self-mixing has been used to describe the HCDA process where the hot, expanding, disrupted core region mixes and equilibrates with the colder surrounding core material and suppresses any further driving pressures against the containment structure. SIMMER,² because of its Eulerian construction, performs some numerical (that is, artificial) mixing, but does not model actual mixing processes; this has prompted concern over possible inaccuracies because of these modeling deficiencies. Accordingly, we have performed some limited analyses to estimate, or at least bound, physical mixing times under HCDA conditions. Rapid thermal equilibration times (≤ 50 ms) would support the contention that the SIMMER calculations of this problem are realistic or at least conservative as they relate to the late vessel energetics. Long equilibration times (≥ 100 ms) conversely would imply some nonconservatism in the SIMMER vessel energetics calculations.

In Sec. II we suggest that self-mixing is addressed adequately in turbulent-diffusion theory. We then provide upper and lower bound estimates of self-mixing times in Sec. III. Section IV presents our conclusions.

Fig. 1.
HCDA bubble expansion sequence.

II. PRELIMINARY ANALYSIS

A. Introduction

To characterize a passive scalar (for example, temperature) in a turbulent mixing environment, we normally specify (at least) a mean value and a peak-to-mean ratio.³ Whereas changes in the mean value are associated with turbulent diffusion, changes in the peak values are related more to the decay of turbulent fluctuations. An essential first step in the analysis of self-mixing is therefore to determine whether the mixing process is controlled by the decay of turbulent temperature fluctuations or by the decay of mean temperature (the slowest decaying feature will control the self-mixing time). For example, the mean temperature in the core could fall below dangerous levels, while peak temperatures (in isolated eddies) remain excessive.

The analysis below suggests that the thermal equilibration of the turbulent fine structure occurs on a somewhat faster time scale than turbulent diffusion time scales and that, therefore, the mixing process can be adequately characterized by the latter. This is fortunate because the description of turbulent diffusion is much simpler than that of turbulent fluctuations.⁴

B. Analysis

Two basic features constitute the fine structure of a material undergoing steady-state turbulent agitation. First, maximum drop or bubble size depends on whether the liquid or vapor phase is viewed as continuous. Second, in the continuous phase, eddies can range from a minimum size⁵ (the Kolmogorov microscale), at which energy feeding the turbulence is dissipated ultimately by viscosity, to a size limit dictated by the flow geometry. The maximum drop/bubble sizes and the minimum eddy size have been measured in situations where a mechanical mixer is used to induce turbulence in two-phase materials.⁶ However, to apply these steady-state correlations to the self-mixing problem, we must assume that the large eddies (which are created first) transfer their energy to the smallest eddies on a time scale that is much faster than the self-mixing time. We may then view the turbulent spectrum in quasi-steady-state terms.

Because the vapor-void fraction in the disrupted core is estimated to be in the range of 0.3-0.5,⁷ we would expect the initial disrupted core to be "bubbly" or perhaps "foamy." The correlation for maximum bubble diameter is given as⁶

$$D \approx (\sigma/\rho)^{0.6}/(P/\rho)^{0.4} , \quad (1)$$

where σ is the vapor-liquid surface tension, ρ the density of the surrounding fluid, and P is the power density driving the turbulence. The correlation for Kolmogorov microscale is

$$L \approx (\mu/\rho)^{0.75}/(P/\rho)^{0.25} , \quad (2)$$

where μ is the liquid's dynamic viscosity. It remains, of course, to provide an estimate for P . Fortunately, neither Eq. (1) nor Eq. (2) is particularly sensitive to the choice of P . SIMMER estimates the maximum generation rate of kinetic-energy density as approximately 10^8 w/m^3 . If we assume that only 1% of this power goes into the creation of turbulence, we arrive at an estimate for P of

$$P \approx 10^6 \text{ w/m}^3 . \quad (3)$$

Using Eq. (3) to simplify Eqs. (1) and (2) and by representing uranium dioxide (UO_2) with the terms $\sigma = 0.45 \text{ Pa m}$, $\rho = 8500 \text{ kg/m}^3$, $\mu = 4 \times 10^{-3} \text{ kg/s m}$, we have $D \approx 4 \times 10^{-4} \text{ m}$, $L \approx 5.5 \times 10^{-6} \text{ m}$.

To calculate thermal equilibration rates for the bubbles, we approximate the vapor-side heat-transfer coefficient by $h_v \approx k/0.15 D$, where k is the vapor thermal conductivity ($\sim 0.03 \text{ W/m K}$ for UO_2 vapor). Thus, $h_v \approx 4.5 \times 10^2$. For the liquid (continuous)-side heat-transfer coefficient, the mixing correlation⁶

$$h_c \approx 0.13 \rho C (\text{Pr})^{-2/3} \left(\frac{P\mu}{\rho^2}\right)^{1/4}$$

is used, where C is the liquid specific heat per unit mass and Pr is the liquid's Prandtl number; or for UO_2 , $h_c \approx 4.8 \times 10^4$. Because $1/h = 1/h_v + 1/h_c$, $h \approx 4.5 \times 10^2$. Therefore the largest (hence slowest to relax thermally) bubble will lose heat according to

$$\rho_v C_{pv} \dot{T} = (6h/D) \Delta T ,$$

where ρ_v and C_{pv} are the vapor mass density and specific heat per unit mass at constant pressure respectively and ΔT is the temperature difference between vapor and liquid. Taking $\rho_v = 200 \text{ kg/m}^3$ and $C_{pv} = 140 \text{ J/kg}$, we have $\dot{T} \approx 0.25 \Delta T \text{ K/ms}$. Thus, a ΔT of 1 000 K could only maintain itself for a maximum of 4 ms.

The two remaining questions involve the molecular relaxation of the smallest eddies and the turbulent relaxation of larger eddies. In the first situation, we note that the time required for the temperature at the center of a hot fluid sphere of diameter L (the smallest eddy size) surrounded by colder fluid to decay by molecular conduction to a value midway between the hot and cold temperatures is approximately given by $\tau \approx \rho C L^2 / k_L$, where k_L is the molecular thermal conductivity of the liquid. Substituting the values $k_L = 2.5 \text{ W/m K}$, $\rho = 8\,500 \text{ kg/m}^3$, $C = 500 \text{ J/kg}$ for liquid UO_2 , we have with $L = 5.5 \times 10^{-6} \text{ m}$, $\tau = 0.05 \text{ ms}$ —a duration considerably smaller than the vapor bubble thermal equilibration times.

The larger eddies decay (lose their identity) because of the disruptive action of smaller eddies with a time scale given by L/u^* , (see Ref. 8), where L is the eddy diameter and u^* is a characteristic turbulent velocity. Consistent with the previous estimate of P , u^* should be about 10 m/s. Therefore, even the largest eddy of importance here ($\approx 0.1 \text{ m}$) should lose its uniformity in about 10 ms. In addition, high-temperature eddies simultaneously will be regions of high pressure; thus, such high-temperature "pockets" may dissipate even faster than implied in the purely kinematic considerations described above.

We suggest in the next section that the shortest possible mixing time for turbulent diffusion is approximately 10 ms. The temperature fluctuations characterized above are expected to decay at a rate equal to or greater than the decay rate of mean temperature; therefore, turbulent diffusion theory can be used to describe the self-mixing process.

III. SELF-MIXING TIME ESTIMATES

A. Introduction

Shearing motion in a fluid is the cause of turbulence. Thus, in a pure (stable) radial expansion,⁺ we would expect little or no turbulence.⁹ However, an HCDA (or any explosive event) rarely begins with spherical symmetry. The early time behavior of such events can, therefore, lead to rather intense small-scale shearing action, which in turn can lead to turbulence. Another potentially important source of shear involves the presence of a cylindrical wall bounding the core region. Here, radially induced motion will be redirected axially by the wall, creating shear and turbulence in the process. Finally, at relatively late times (greater than ~ 1 s) gravitational forces would cause any low-density region in the core to rise, generating shear and turbulence and entraining surrounding fluid. These processes are illustrated in Fig. 2.

An important distinction must be made between the generation of turbulence by gas bubble expansion in a liquid (or for that matter, explosive discharge in the atmosphere) and HCDA core expansions. In the former cases extremely large logarithmic density gradients exist that encourage the production of turbulence during periods of positive radial acceleration and suppress turbulent fluctuations during radial deceleration. This effect is largely responsible for the observed lack of turbulence in the fluid surrounding an expanding gas bubble or in the air surrounding an explosion in the atmosphere. An HCDA core expansion, however, is characterized by rather small density gradients, so that we expect both less turbulence generated by Taylor instability and less suppression of turbulence during the deceleration phase.

The sources of turbulence described above obviously are difficult to characterize quantitatively. For this preliminary study, we have attempted to make bounding estimates of the associated mixing times. By maximizing the intensity of turbulence and mixing, we arrive at a lower-bound estimate for the time required, and by minimizing this intensity we derive an upper bound estimate.

⁺Unstable expansions, such as those characterized by Taylor instability, could create turbulence; however, these instabilities can be generated only during typically rather short periods of positive radial acceleration.

a. INITIAL STAGE

b. INTERMEDIATE STAGE

c. LATE STAGE

Fig. 2.
Possible sources of turbulent mixing in an HCDA event.

B. Lower Bound Mixing Time Estimate

We can overestimate turbulent mixing in an HCDA event by assuming that all energy goes into turbulence. As a consequence, there would be no directed motion. Further, the turbulent-velocity scale is set equal to the largest (directed) velocity calculated by SIMMER⁷ (≈ 100 m/s at $r = 0.5$ m, $t = 5$ ms). Finally, by assuming radial symmetry, we conservatively estimate the maximum eddy size as a function of radial position $\delta = kr$, where k is the Karman factor (≈ 0.4 for most applications).⁴

Additional simplifications include the assumption of homogeneous flow (which would tend to overestimate mixing tendencies), the neglect of phase changes (whose effects are probably negligible because of the initial low mass fraction of condensible vapor), and the initial condition of a hot uniform temperature sphere surrounded by a colder fluid.

The energy equation for homogeneous flow can be expressed as

$$\rho \frac{\partial e}{\partial t} + \rho u_i \frac{\partial e}{\partial x_i} = -p \frac{\partial u_i}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\partial q}{\partial x_i} , \quad (4)$$

where e is the internal energy per unit mass of material, u_i is the fluid velocity, ρ is the fluid mass per unit volume, p is the pressure, τ_{ij} is the viscous stress tensor, and q is the heat flux from molecular conduction, and cartesian tensor notation has been employed (sum over i and j). The last two terms in Eq. (4) can be ignored because they represent, respectively, viscous heat generation and molecular heat conduction, both of which are dominated by turbulent effects.

Recall that by assumption there is no directed velocity. Further, because the turbulent (fluctuating) velocity scale is taken as $u' = u_0 \approx 100$ m/s independent of position, $\partial u_i / \partial x_i = 0$. Equation (4) can then be simplified to

$$\frac{\partial}{\partial t} \langle e \rangle + \frac{\partial}{\partial x_i} \langle u_i' e' \rangle = 0 , \quad (5)$$

where the brackets denote ensemble averages and primes denote the fluctuating components of the indicated variables. In the vessel energetics (HCDA) problem, the internal energy per unit mass is dominated by the liquid phase. Taking $e = CT$ and assuming C is a constant, we have

$$\frac{\partial}{\partial t} \langle T \rangle + \frac{\partial}{\partial x_i} \langle u_i' T' \rangle = 0 . \quad (6)$$

With an eddy diffusivity approximation

$$\langle u_i' T' \rangle = -\epsilon \frac{\partial}{\partial x_i} \langle T \rangle ,$$

we can now simplify Eq. (6) to

$$\frac{\partial}{\partial t} \langle T \rangle = \frac{\partial}{\partial x_i} \epsilon \frac{\partial \langle T \rangle}{\partial x_i} , \quad (7)$$

with the eddy diffusivity given by $\epsilon = u^* \delta$, where u^* is a characteristic turbulent velocity, and δ is the largest eddy size. Conservatively, we may set $u^* = u_0$ and $\delta = kr = 0.4 r$.

At about 5 ms into a typical SIMMER calculation of this problem, the core kinetic energy has reached a maximum, with a maximum velocity $u = 100$ m/s at $r = 0.5$ m.⁷ We initialize the turbulent-mixing calculation at this point with an eddy diffusivity as given above. Thus, Eq. (7) implies

$$\frac{\partial \langle T \rangle}{\partial t} = \frac{u_0^2 k}{r^2} \frac{\partial}{\partial r} r^3 \frac{\partial \langle T \rangle}{\partial r} , \quad (8)$$

subject to the initial condition

$$\langle T \rangle (t = 0) = \begin{cases} T_H & (r < a) \\ T_C & (r > a) \end{cases} ,$$

where the radius a of the hot core region is taken as 0.5 m. Letting $\langle T \rangle = T e^{-\lambda t}$, we obtain from Eq. (8)

$$u_0 k r \frac{d^2 T}{dr^2} + 3u_0 k \frac{dT}{dr} + \lambda T = 0 \quad . \quad (9)$$

Solutions to Eq. (9) can be solved by using the Hankel Transforms. The solution satisfying the appropriate initial conditions is

$$\langle T \rangle = (T_H - T_C) r \frac{a}{r} \int_0^\infty J_3(x) J_2(x \sqrt{\frac{r}{a}}) e^{-\frac{u_0 k t x^2}{4a}} dx + T_C \quad .$$

In particular,

$$\langle T \rangle (r = 0) = T_H - \frac{(T_H - T_C) u_0 k}{32a} \int_0^t \int_0^\infty x^4 J_3(x) e^{-\frac{u_0 k t' x^2}{4a}} dx dt' \quad ,$$

or

$$\langle T \rangle (r = 0) = T_H - \frac{(T_H - T_C)}{2} \left[\left(\frac{a}{k u_0 t} \right)^2 e^{-\frac{a}{k u_0 t}} + 2 \left(1 + \frac{a}{u_0 k t} \right) e^{-\frac{a}{k u_0 t}} \right] \quad .$$

The time τ when $\langle T \rangle (r=0) = 1/2(T_H + T_C)$, which serves as a convenient definition for the time required to achieve self-mixing, is given by $a/k u_0 \tau \approx 2.5$. With $k = 0.4$, $u_0 = 100$ m/s, $a = 0.5$ m, the self-mixing time $\tau = 5$ ms. Because approximately 5 ms is required to reach the initial conditions for the problem treated above, this calculation suggests that the total time for self-mixing is bounded from below by 10 ms.

C. Upper Bound Mixing Time Estimate

We can reach a rather extreme underestimation of turbulent mixing in an HCDA event by ignoring turbulence generated by nonspherical symmetry as well

as that generated by the presence of a cylindrical wall. Then the only remaining source of turbulent mixing would be entrainment associated with the buoyant rise of the low-density portion (bubble) of the disrupted core. This problem can be made tractable by ignoring any radial motion after the disrupted core has been created and by disallowing any subsequent phase changes.

Bubble volume can be determined by the equation $V = V_L + V_G(t) + V_E(t)$, where V_L is the initial volume of liquid in the bubble, $V_G(t)$ is the vapor volume in the bubble, $V_E(t)$ is the entrained volume of surrounding fluid, ρ is the mass density of the incompressible liquid, and t represents times. The vapor density is much less than the liquid density; therefore the average density in the bubble can be approximated by $\bar{\rho} = \rho(V_L + V_E)/V$. The equation of motion for the bubble then becomes

$$\frac{d}{dt} (\bar{\rho}Vu + \frac{1}{2} \rho Vu) = (\rho - \bar{\rho})gV - Cd\rho \frac{\pi R^2 u^2}{2}, \quad (10)$$

where g is the gravitational acceleration, u is the rise velocity, Cd is a drag coefficient (assumed constant), and R is the bubble radius. A rather good description of the entrainment process can be obtained by using the Taylor entrainment hypothesis

$$dV_E/dt = \alpha u \pi R^2, \quad (11)$$

where α is an empirical constant. Values of α between 0.1 and 0.3 cover a wide range of entrainment conditions, including nuclear and high-explosive fireball data.¹⁰ In view of the discussion presented in Sec. II, we shall assume that thermal equilibrium is maintained within the bubble at all times. This implies that the temperature in the bubble can be approximated by $T = (V_E T_C + V_L T_H)/(V_E + V_L)$, where T_C is the temperature of the fluid external to the bubble, T_H is the initial bubble temperature, and the effect of vapor mass in the bubble has been neglected. From the perfect gas law we may derive

$$V_G = 0.3 \frac{V_0}{T_H} \left(\frac{V_E T_C + V_L T_H}{V_E + V_L} \right), \quad (12)$$

where V_0 is the initial bubble volume and the initial vapor volume fraction is taken as 0.3. Now from Eq. (12) it is apparent that V_G varies between $0.3 V_0$ at $t = 0$ to $0.3 V_0 T_C/T_H$ at $t \rightarrow \infty$. Because $T_C/T_H \approx 0.7$ for typical HCDA applications, we may, as a reasonable approximation, neglect the time dependence of V_G . We then have

$$\frac{dV_E}{dt} = \frac{dV}{dt} = \alpha u_0 \pi R_0^2 \left(\frac{V}{V_0}\right)^{2/3}. \quad (13)$$

Differentiation of Eq. (13) leads to expressions for u and $\frac{du}{dt}$ for V and its derivatives, which, when substituted back into the equation of motion [Eq. (10)], yields

$$\left(\frac{3}{2} + \frac{Cd}{2}\right) \left(\frac{dV}{dt}\right)^2 + \left(\frac{3}{2} V - V_G\right) \left(\frac{d^2V}{dt^2} - \frac{2}{3V} \left(\frac{dV}{dt}\right)^2\right) = V_G g R_0^2 \left(\frac{V}{V_0}\right)^{2/3}. \quad (14)$$

Because V_G is always less than $0.3 V_0$ and V monotonically increases, V_G may be neglected as compared with $3/2 V$ in Eq. (14) to give

$$\frac{3}{2} V \frac{d^2V}{dt^2} + \left(\frac{dV}{dt}\right)^2 \left(1 + \frac{Cd}{2\alpha}\right) = V_G g \alpha \pi R_0^2 \left(\frac{V}{V_0}\right)^{2/3}. \quad (15)$$

Because $u = 0$ at $t = 0$, $dV/dt = 0$ at $t = 0$. Thus, from Eq. (15) we see that d^2V/dt^2 must be large initially, rapidly decaying to zero as time increases (dV/dt behaves conversely). This behavior suggests that the first term on the left of Eq. (15) can be approximated by

$$\frac{3}{2} V \frac{d^2V}{dt^2} \approx \frac{3}{2} V_0 \frac{d^2V}{dt^2}, \quad (16)$$

leading to the approximate solution

$$V = V_0 \left(1 + \frac{\log \cosh bt}{1 + Cd/2\alpha}\right)^{3/2}, \quad (17)$$

where

$$bV_o = \frac{2}{3} \sqrt{V_G \alpha g \pi R_o^2 (1 + Cd/2\alpha)} . \quad (18)$$

Taking $V_G = 0.3 V_o T_C/T_H$ to preserve the correct long time behavior of the solution we have

$$b = \frac{2}{3} \frac{\sqrt{0.3 T_C \alpha g R_o^2 (1 + Cd/2\alpha)}}{V_o T_H} . \quad (19)$$

With $Cd = 0.4$ and $0.1 \leq \alpha \leq 0.3$, $0.63 \leq b \leq 0.82$.

Thus the time τ at which $T = (T_C + T_H)/2$ ($V = 1.7 V_o$) is given by $1.5 \leq \tau \leq 3.0$ s.

IV. CONCLUSIONS

Clearly more work is warranted to reduce these bounds on self-mixing times. However, even at this relatively primitive stage, several conclusions can be made:

Mixing times of less than 10 ms can be effectively dismissed. Thus, the possibility appears remote that SIMMER calculations significantly over-estimate the work potential of an HCDA because of errors in modeling mixing processes.

Turbulence induced by the cylindrical core wall boundary is probably the most significant source of mixing. Unlike mixing with early time non-spherical flow (shear) effects or with Taylor instabilities, this source of turbulence may be amenable to quantitative analysis.

It is realistic to expect that typical self-mixing times will lie near the midrange of the two bounding estimates presented here (that is, self-mixing times on the order of 100 ms). Further, certain features of mechanical disassembly calculations appear quite sensitive to variations in mixing time in or near this range.¹¹

From these conclusions, it seems prudent for us to pursue a modest re-search program to quantify and narrow further the uncertainties in self-mixing times. In particular, rather simple experiments similar to those proposed in

Ref. 11 could be performed to increase substantially our understanding of self-mixing.

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