Vessel Geometry and Fluid Properties Influencing Mix Behavior for ResonantAcoustic® Mixing Processes

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ABSTRACT

Mixing of viscous high-solids-loaded materials such as filled HTPB was demonstrated using the ResonantAcoustic® Mixing (RAM) technology. The experimental results illustrate how thorough material mixing is a function of RAM operating parameters (namely acceleration), material viscosity and vessel diameter.

Introduction

ResonantAcoustic® Mixing (RAM) technology is being used to mix difficult-to-process materials with high viscosities and high solids loadings. These are typical conditions for processing polymer bonded explosives (PBX) and composite solid propellant. In the past, Resodyn Corporation has demonstrated RAM as a very effective method for mixing HTPB/Al/KCl inert formulations of composite propellant. Anecdotal evidence suggests that as mix vessel diameters decreases (< 25 mm) it is more difficult, if not impossible, to achieve the same mixing conditions that exist in larger diameter vessels. Small scale experiments were performed to help define the capabilities and limitations of using RAM to mix viscous, high solids loaded materials as a function of vessel diameter and material viscosity.

Experimental Procedure

When appropriately operated, the RAM produces both bulk mixing and micro-mixing regimes. The result for composite solid propellant is a highly uniform product.[1] Figure 1 illustrates the toroidal bulk flow that occurs during well coupled mixing. Simultaneously, the acoustic pressure waves passing through the mixture enhance diffusion of the small particles in the mixture. The result is rapid, uniform mixing. This mixing action has been demonstrated over a range of vessel diameters from 25 to 430 mm.[2,3] This work is in progress, thus the limits of this range have not been fully investigated. A test method was devised to evaluate geometric limitations of mix vessels with diminishing diameters.

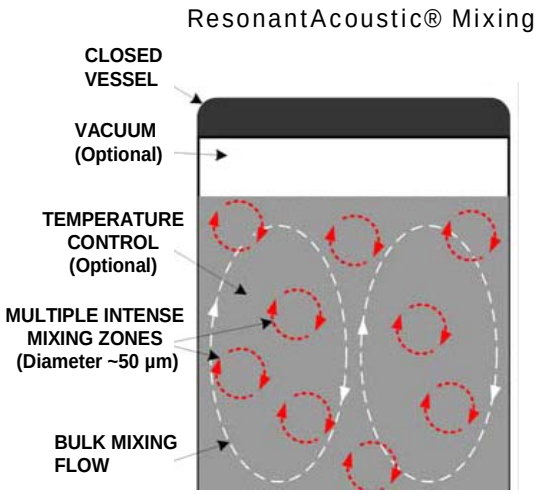

Figure 1. Mix material motion schematic.

A high viscosity, solids filled HTPB based material was used as the mix material. Table 1 lists the experimental formulation which was an inert simulation of uncured PBX explosive used to evaluate processing equipment. This formulation was used because the premix is white and would allow the use of a colored marker to track mix behavior. The formulation listed does not include any curative. Rather, DOA was substituted in a quantity similar to the amount of isocyanate curative in order to replicate the uncured viscosity over a long period of time. The

DOA substitute was combined with blue pigment and added last, just prior to mixing, to serve as a mix tracer.

Table 1. Inert PBXN Explosive Formulation

Weight %	Ingredient	Characteristics
Premix		
7.117	HTPB (polybutadiene)	Hydroxyl Value (Acetyl meq/g) = 0.80
0.271	Lecithin/DOA (50/50)	Thickening agent
0.030	DBTDL	Catalyst
7.12	DOA	Plasticizer
39.21	Gypsum	Fine Powder, Simulant Oxidizer
37.32	Sugar	Granular, Simulant Energetic
8.17	Hollow Glass	Density Adjustment
Curative		
0.710	DOA substituted for curative	Plasticizer
0.050	Zulu Blue	Powder Pigment

The experimental mix vessels consisted of clear polycarbonate tubes with the various diameters as listed in Figure 2. The mixing experiments utilized a set of the four smallest diameter vessels mounted together using a manifold lid to provide vaccum to each container. This allowed mixing to occur simultaneously for each vessel size under identical RAM equipment operating parameters and vaccuum. The two larger diameter vessels were used independently to determine mix parameters. The mix ingrediants and laboratory environment was at 30.6°C for the four small vessels and 20.7°C for the two largest vessels. This corresponds to a PBX absolute viscosity of 223,000 cP and 478,000 cP, respectivly. , 38 mm deep, with the inert PBX premix material. A small amount of colored DOA, the tracer, was then placed on top of the material as shown in Figure 3. The manifold lid was clamped in place and vaccum was applied prior to mixing. An identical procedure was used for the two larger diameter vessels, except each vessel mixed independently of the other.

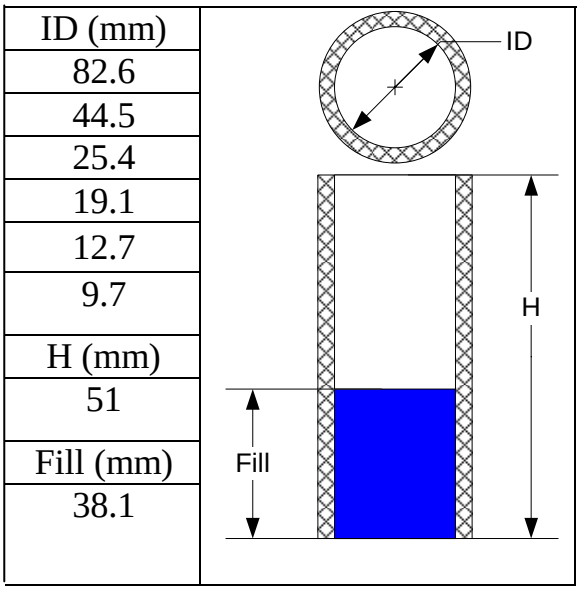

Figure 2. Mix Vessel Geometry

A LabRAM® (bench scale mixer shown in Figure 4) was used for all the experimentation. The mixing experiments consisted of exposing filled vessels to increasing acceleration levels. At each acceleration level, the LabRAM® was operated for 2 minutes to allow for difinitive identification of tracer motion. The acceleration level was recorded at the onset of mixing (defined as when the tracer was observed moving into the bulk material).

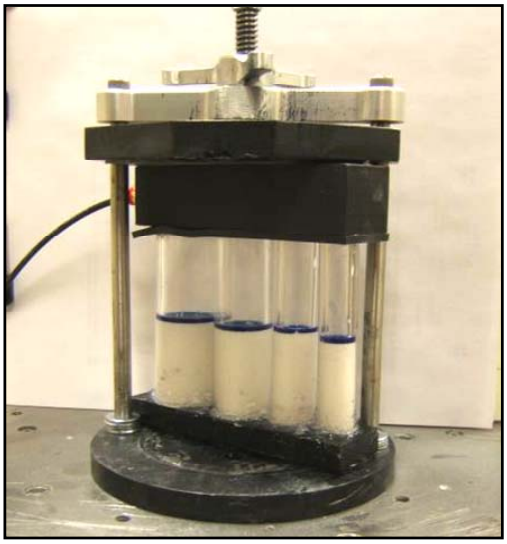

Figure 3. Four Smallest Vessels Just Prior to Mixing

Figure 4. Resodyn Corporation LabRAM®

Results and Discussion

The results of the experiments described above are summarized here. Figure 5 captures the visual results for one set of vessels during the operation of the LabRAM. The desirable mixing condition includes bulk flow. The penetration of color in Figure 5a and 5b indicates bulk flow occurring under these mixing conditions. Where bulk flow was not occurring (Figure 5c and 5d) there is only white material showing that had no exposure to the blue tracer. There is an observed limitation on bulk flow as a result of smaller vessel diameter. These conditions of mixing and not mixing appear to be defined by a relationship between material properties of the mixture and the geometry of the vessel.

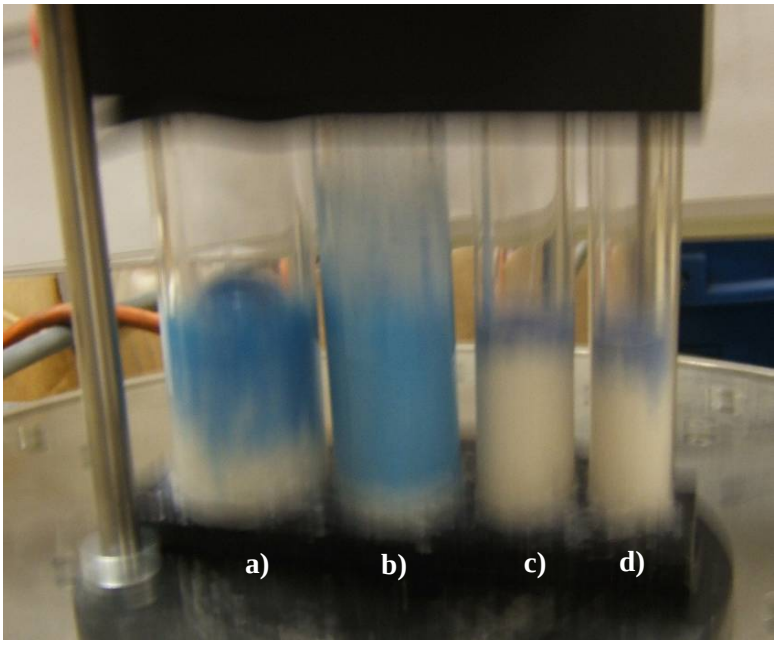

Figure 5. Mix Vessels During RAM Operation, Dye Penetration Indicates Bulk Flow for a) and b) but not for c) and d)

The material properties of the mixture can be lumped into a nondimensional parameter, the vibrational Reynolds number, Re_v:

$$Re_v = \frac{\delta \omega D}{\nu} \qquad (1)$$

where: δ = amplitude = $\frac{G(g)}{4\pi^2 f^2}$ G = gravitational constant (m/s^{2}g)

ω = angular frequency = $2\pi f$ g = acceleration in g's

ν = kinematic viscosity = $\frac{\mu}{\rho}$ f = vibration frequency (1/s)

μ = absolute viscosity (kg/m s) ρ = density (kg/m^3)

D = hydraulic diameter (m)

Substituting the definitions for amplitude, angular frequency and kinematic viscosity and dividing by the vessel diameter yields the relationship:

$$\frac{Re_v}{D} = \frac{G(g)\rho}{2\pi f \mu} \qquad (2)$$

This relationship provides a method to lump all the material and RAM parameters that significantly affect mixing. The results of the mix experiments were plotted in terms of Equation 2 versus the vessel diameter and are depicted in Figure 6. The diamond symbols indicate conditions where no mixing occurred. The triangle symbols indicate a transition to mixing. The square symbols indicate visible mixing as a result of RAM parameters, vessel geometry and material properties that exist at that data point. The dashed line represents a theoretical threshold condition. When the value for Equation 2 exceeded the dashed line, mixing occurred for those experimental conditions. The theoretical threshold is represented here by the power law relationship listed on the plot.

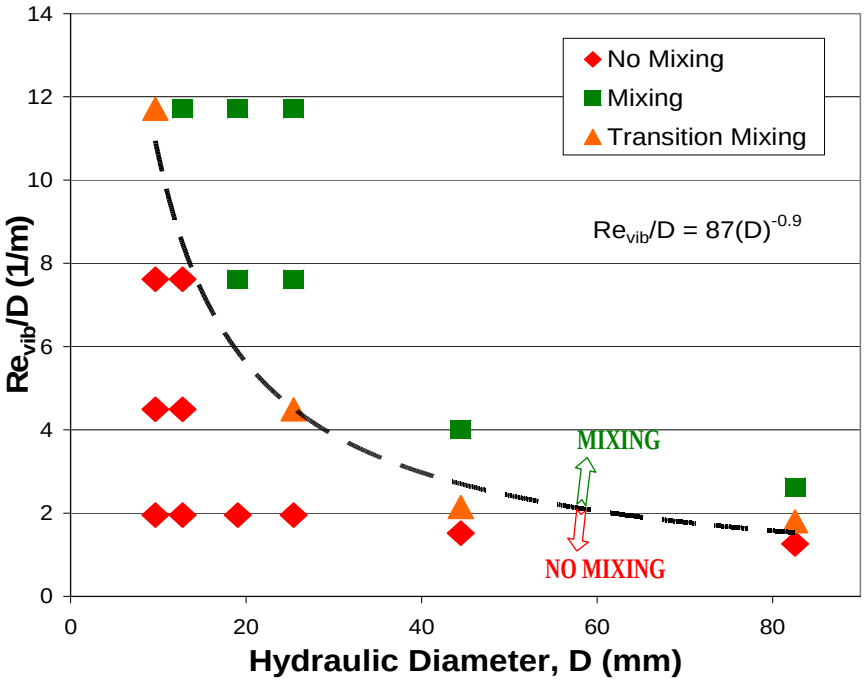

Figure 6. Well Developed Mixing as a Function of Vessel Diameter, RAM Operating Parameters and Mixture Properties

Summary and Conclusions

The experiments indicate a relationship exists that predicts desirable mixing conditions as a function of RAM operating parameters (namely acceleration), material viscosity and vessel diameter. This provides a straight forward method for evaluating the minimum requirements for the design of mix vessels based upon the mix material properties.

References

(1) Coguill, S. L.; *57th JANNAF Propulsion Meeting*, May 2010.
(2) Lucon, P.; *NAMF Mixing XXII Conference*, June 2010.
(3) Miller, J. T.; Bode, D. A.; Coguill, S.; *36th JANNAF PEDCS Meeting*, December 2010.