ResonantAcoustic® Mixing

TECHNOLOGY INTRODUCTION

ResonantAcoustic® Mixing (RAM) is a non-contact low-frequency acoustic field to facilitate mixing. This newly introduced, emerging technology has demonstrated mixing performance advantages for many complex and multiphase systems. RAM technology is delivering significant cost and time savings across a broad range of industries through dramatic reductions in mixing times and the elimination of time and costs associated with cleanup.

TECHNOLOGY APPROACH

The RAM technology approach for acoustic mixing works on the principle of creating micro-mixing zones throughout the entire mixing vessel. This approach differs from conventional mixing technology where mixing is localized at the tips of the impeller blades, at discrete locations along the baffles, or by co-mingling products induced by tumbling materials. This new technology provides faster, more uniform mixing throughout a vessel than can be created by conventional, state-of-the-art mixing systems. RAM technology has the added advantage that it does not use impellers, or other intrusive devices to mix, nor does it require unique vessel designs for a broad range of mixing applications.

RAM technology is compatible with many types of materials, which include liquid-liquid, liquid-solid, gas-liquid, and solid-solid systems. The technology can be utilized to mix low viscosity, highly viscous and non-Newtonian systems, as well as solid-solid systems in the same types of vessels, without changes to impeller design, baffles, or other complicated, intrusive components, such as injectors, nozzles, etc.

RAM technology is designed to operate at mechanical resonance. At this operating condition the RAM technology results in a virtually lossless transfer of the mixer systems' mechanical energy into the materials being mixed created by the propagation of an acoustic pressure wave in the mixing vessel. This condition is achieved by matching the mechanical operation of the mixer with the properties and characteristics of the range of materials to be mixed. The operating characteristics of the mixer are automatically sensed and controlled to keep the system at the mixing condition established to provide the best mixing performance.

Achievement of these mixing conditions requires a methodology that is patented and unique to RAM and RAM control technology, that is unachievable by any other mixing technology in the industry. For example, in conventional mixers the mechanical systems are typically designed to specifically avoid operating at resonance, as this condition can quickly cause violent motions and even lead to catastrophic failure of the system. However, when designed correctly a mechanical system operating at resonance enables even small periodic driving forces to produce large amplitude vibrations that can be harnessed to produce useful work. For RAM this operating methodology is enabled through a system designed to store vibrational energy by balancing kinetic and potential energy in a controlled resonant operating condition.

The RAM potential energy is stored in the springs and the kinetic energy is provided by plates, or masses, that are connected to the springs and are translated in a vertical motion. See Figure 1. The resonant frequency is defined as the frequency at which the mechanical energy in the system can be perfectly transferred between potential energy stored in the springs and as kinetic energy in the moving masses.

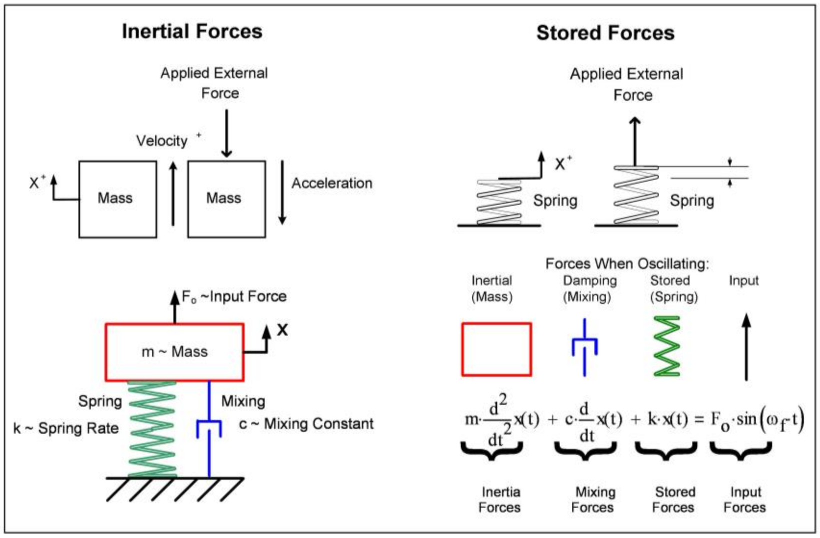


Figure 1. Simplified representation of the mass, spring and damper (mixing media) system that is in resonance.

For the RAM technology, it is the mixing system as a whole, which includes the three-mass system, the spring assembly and the loaded mixing vessel, that is operated at mechanical resonance, which is nominally at 60 Hz for the RAM technology in its current configuration. The exact frequency of mechanical resonance during mixing is only affected by the payload vessel (plus contents), the equivalent mass, and how well the mix media couples to the vessel and absorbs energy as it is motivated.

The principal of Resonance in ResonantAcoustic® Mixing is illustrated in both Figures 1 and 2. ResonantAcoustic® mixers are comprised of multiple masses and multiple springs, known as a three-mass system, that are simultaneously moving during mixing. The basic behavior of the mixer is best understood by considering the simplified case shown in Figure 1, above.

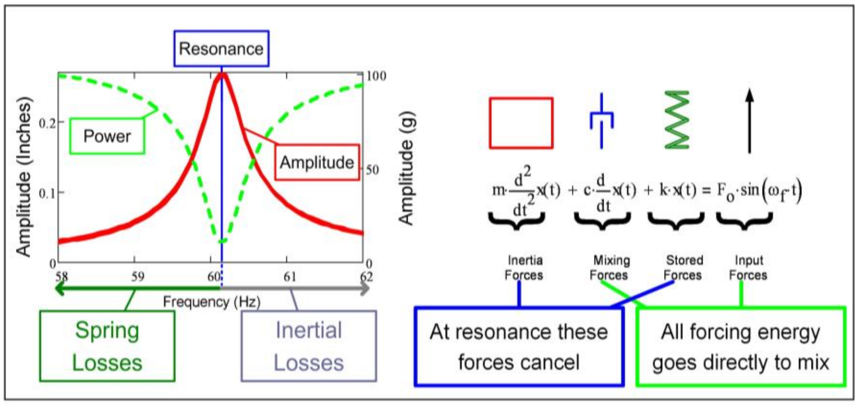


Figure 2. Differential equation and plots of oscillation amplitude and power vs. frequency showing the benefit of operating at resonance.

The diagram in Figure 1, upper left, shows a mass moving with some velocity. In order to slow down the mass (decelerate) there needs to be an applied external force. When the mass decelerates, the lower velocity results in it having lower kinetic energy. Figure 1, upper right diagram, shows that a spring can store potential energy when an applied external force compresses, or stretches the spring. The energy stored in the spring is greater when the deflection is large and reduces to zero when the spring is not distorted. The lower left diagram in Figure 1 shows a representation of a spring-mass system. In this case, the "mixing" function is modeled as a damper, which absorbs energy when the system is in motion. A second order differential equation that describes the forces present during oscillation is shown in Figure 1, lower right. This equation shows the relationship between the forces due to the moving masses, the deflected springs, and the mixing process. The expression shows that these forces sum to be equal to the mechanical force driving the system.

The differential equation is repeated in Figure 2 and is coupled with the diagram (plot) to the left, as a means to illustrate how resonance occurs. At a particular oscillation frequency, the resonant frequency, the stored forces in the springs are directly offset by the inertia forces of the masses and cancel over one period of oscillation. Thus, the system can oscillate without the need for charging the spring or providing energy to the mass during the cycles. The plot on the left of Figure 2 graphically illustrates that for frequencies below resonance, energy is lost in charging the springs, and above resonance energy has to be added to maintain the inertial energy. The result of operating at resonance, as shown by the red and green curves, is that the amplitude of the oscillations reaches a maximum, while the power required is at a minimum. The power consumed by the system is transferred directly into the mixing media.

With the system oscillating at resonance, the acceleration of the load-plate imparts a boundary condition on the vessel contents that is transmitted through the vessel contents as a low-frequency acoustic wave. Energy used in creating the mixing movement will add to the damping of the overall system, and the material contents will add to the mass. However, the amount of energy that must be transferred into the materials in order to satisfy the boundary condition will be dependent on a combination of many material and vessel geometry constraints. Some of these constraints are: the height of column of material to be moved (vessel fill height), the compressibility of the material, and its stickiness, or coupling of the material to the vessel walls, material density, vessel geometry, internal vessel pressure, vessel percent fill, and mixing regime.

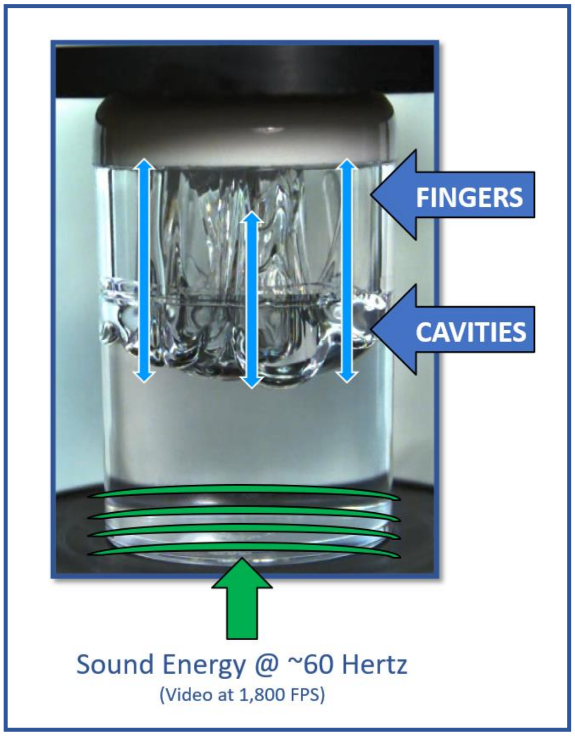


Fig. 3. Surface Disturbances Drive Mixing

Resodyn Acoustic Mixers' SmartMixing® software automatically senses the system resonance condition and adjusts the operating frequency to maintain resonance throughout the mixing process, even when state changes in the mixing ingredients cause the coupling and damping characteristics of the mix load to change.

MIXNG PROCESS

The mixing principal is illustrated in Figure 3, which shows a vessel being subjected to a low-frequency acoustic field in the axial direction resulting in disturbances at the surface of the material interface, in this case a semi-viscous liquid and the gas in the mixing vessel. The disturbances were discovered in 1831 and are known as Faraday Disturbances. The resulting intense "fingers" oscillating from the surface, and coincident cavities opening below the surface facilitate the mixing process between the two (or multiple) materials. Figure 3 shows this process within only a few microseconds of the mixing process. As the sound energy continues to create disturbances, fingers and cavities become both more intense and more pervasive throughout all the ingredients resulting in significantly faster, more thorough, and more consistent mixing results of liquid and viscous mixes like pastes and slurries. The strength of the pressure waves associated with the acoustic streaming flow is strongly correlated to the displacement of the acoustic source, e.g., the base of the vessel for the RAM technology.

The mixing phenomena in solid-solid systems do not rely upon acoustic streaming, but upon particle collisions. For the solid-solid mixing, particles in the container are excited by collisions with the vessel base and collisions with other particles in the container that can result in harmonic vibrations of the vessel with the granular material. The particle motions are dependent upon the vibration amplitude, A, frequency, ω, and the resultant accelerations that the particles undergo. The chaotic motions created within the mixing vessel by the ResonantAcoustic® Mixing cause a great degree of particle-to-particle disorder, microcell mixing, as well as creating bulk mixing flow in the solid-solid systems as depicted in Figure 3, above.

The versatility of the RAM technology is exemplified by the fact that while the phenomena causing the mixing differs between the fluid interactive and particle interactive systems, there are strong similarities in vessel design, operating conditions, thorough mixing performance, and rapid mixing times of these disparate systems.

The common thread is the RAM technology that uses an acoustic field to provide energy into the media being mixed in a manner that is uniform throughout the mixing container, rather than at discrete locations, or zones in the mixing vessel, as is accomplished by most state-of-the-art mixing technologies.

ILLUSTRATIVE EXAMPLES OF RAM MIXING CAPABILITIES

Some examples of material systems that have been mixed using the RAM technology are presented below. Experience has shown that the highest value of the RAM technology occurs with hard to mix systems, and applications where other mixing technologies are challenged, or cannot perform well without the implementation of significant engineering changes.

Viscous Liquid-Solid Systems

Several liquid-solid systems have been mixed for various applications with viscosities that range from 100's of cP up to 100,000,000 cP (1 MP). Figure 4 shows a typical 120 liter mix of a moderately high viscous system that was mixed in 2 minutes at nominally 80 *g* of acceleration. The temperature rise for the process was <15 ºC.

Viscous Liquid-Liquid Systems

Figure 5 shows an illustrative example of Play-Doh, a viscous compound, that was rapidly and thoroughly mixed. One-hundred *g* of acceleration was required to thoroughly mix this material which was uniformly blended after eight minutes.

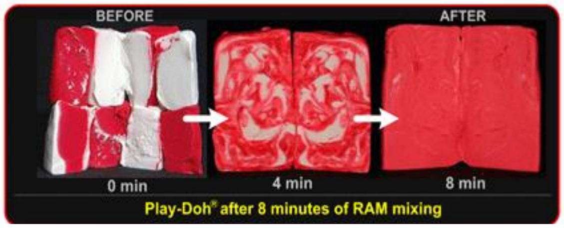
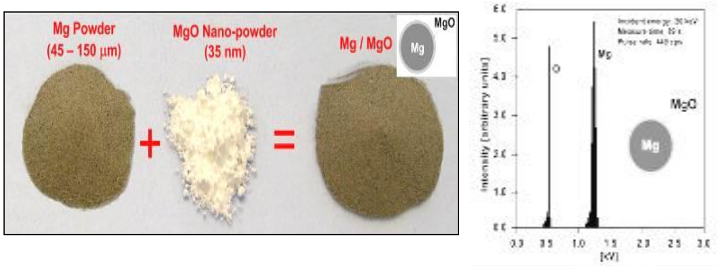


Figure 5. Mixture of Play-Doh to illustrate the mixing of two viscous liquids.

Coating of Particles with Powders or Liquids

Magnesium powder with particles sizes ranging from 45µm to 150µm, was mixed with 2 vol% MgO nanopowder, having a typical particle size of 35nm. After only ten minutes of mixing the two materials were thoroughly blended and the surface of the Mg powder was uniformly coated with the nano-sized oxide. See Figure 6.



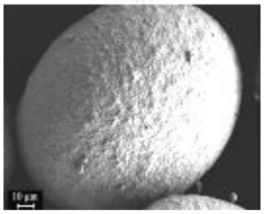


Figure 6. Micron and nano-sized particles of Mg and MgO before and after mixing. SEM micrograph of coated particle, and EDS confirmation of oxide coating.

No loose MgO nanopowder was identified anywhere in the mix volume, indicating that the entire nanopowder content is attached to the surface of the Mg particles. SEM images show the modified surface texture of the Mg powder, and the Scanning Electron Microscopy-Energy Dispersive Spectroscopy plot confirms the presence of the MgO material.

A bed of micron-sized polymer powder (nominal diameter 40 µm) was agitated in the RAM while a surfactant solution was sprayed into the bed from above. The solution was added as 1% and 5% by weight of the total mixture mass. Small samples were taken from the bulk mixture and analyzed for the coating content. The variation of the coating content was described statistically. Two mixing intensities were examined with results indicating that the higher intensity produced more uniform mixes and that the goal of <10% RSD was reached. See data in Figure 7.

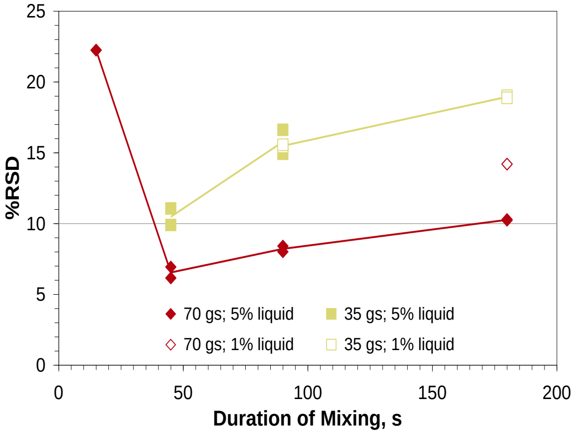


Figure 7. Plot of Relative Standard Deviation of coating content vs. mixing time for two solution concentrations and two mixing intensities.

Dispersion of Nano-Materials in a Matrix of Micron-Sized Materials

A quantity of nano-sized iron oxide powder (30 nm nominal diameter) was blended with polymer powder (45 microns). The results in Figure 8 show the iron oxide material is distributed throughout the polymer powder bed and that the agglomerates of iron oxide nanoparticles were broken down to the individual particles. The distribution was quantified by analyzing small samples for iron oxide and the

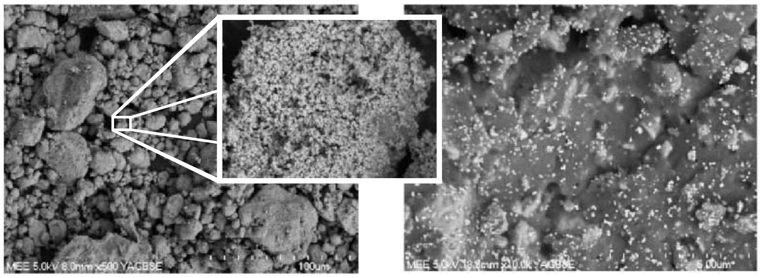


Figure 8. Iron oxide nanopowder agglomerates at 500X magnification and inset at 10,000X magnification. The oxide particles appear as small, bright spherical features and are easily distinguished from the larger, angular filler material.

breakdown of the agglomerates was assessed by SEM imaging.

Gas Dispersion into Liquids

Figure 9 shows vigorous agitation of a reactor. The system shown in the figure is air in a water mixture, where gas-liquid mass transfer measurements are being made. Typical k_La values at this condition were 3,000/hr, exceeding those obtainable in a conventional stirred reactor. Applications for this process include bioreactors and processes were high gas-liquid mass transport is of value.

Figure 9. Gas-Liquid mixing. Air and water at 20 *g* acceleration.

Hydrogenation

As a demonstration of the effectiveness of RAM technology, maleic acid was hydrogenated to form succinic acid. A 15.73 g quantity of maleic acid was dissolved in 200 ml of absolute ethanol and added to 0.238 g of Adams platinum (IV) oxide catalyst in a Pyrex tube reactor that was pressurized with hydrogen. The system was brought to resonance and hydrogen consumption calculated at 5-minute intervals. As a comparison, the experiment was repeated with mechanical agitation, but not at resonance, to simulate typical laboratory hydrogenation equipment. The results, as shown in Figure 10 confirm that the ResonantAcoustic® mixing effect is fundamentally different from mechanical stirring, and approximately seven times more efficient.

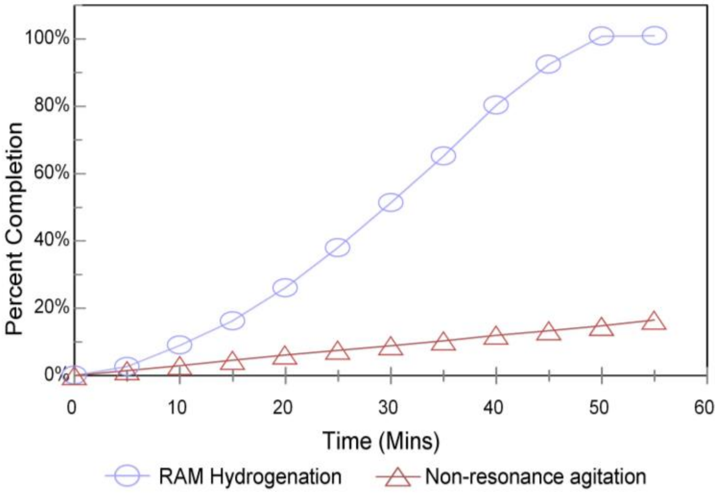


Figure 10. Hydrogen absorption rate for Resonant-Acoustic® Mixing and mechanically agitated systems.

Figure 11 provides a good view of the gas-to-liquid interfacial area that is generated during the RAM mixing and gives insight into the basis for the high level of gas-to-liquid mass transport that drives the favorable hydrogenation results that were obtained.

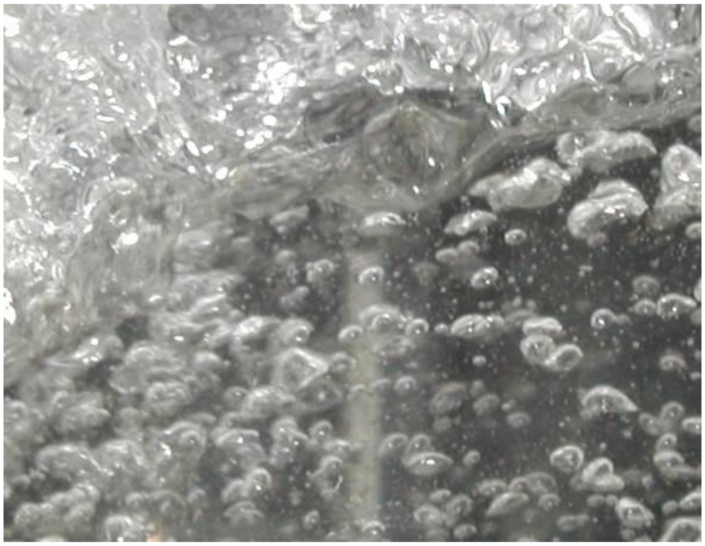


Figure 11. Close up view of gas-liquid interface at 17-g RAM acceleration.

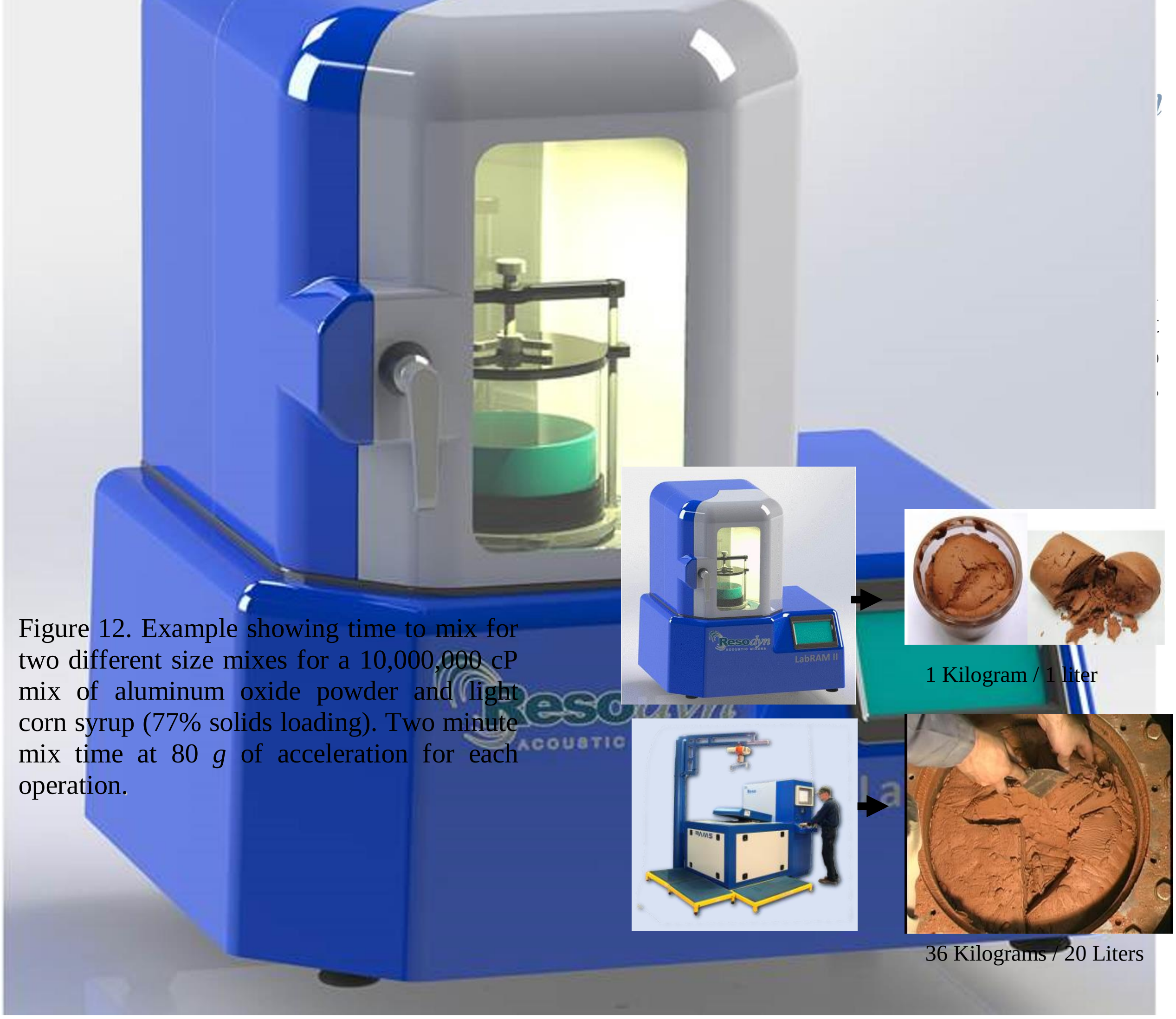


Figure 12. Example showing time to mix for two different size mixes for a 10,000,000 cP mix of aluminum oxide powder and light corn syrup (77% solids loading). Two minute mix time at 80 *g* of acceleration for each operation.

Table 1. Comparison of mixing times for increasing mix load size.

MATERIALS OF THE MIXTURE	LabRAM			RAM5			RAM30		
	Total Mass (kg)	Acc (g)	Time (sec)	Total Mass (kg)	Acc (g)	Time (sec)	Total Mass (kg)	Acc (g)	Time (sec)
Powder-Powder Mixing	0.15	17	**90**	6	17	**120***			
Epoxy Resin	0.10	30	**180**	8	30	**180***			
Base with Oil Coating	0.05	65	**40**	9	65	**80***			
Powder-Powder Mixing	0.10	80	**60**	9	80	**120***	55	80	**120***
Polymer Resin and Oil (Coating Powder with Liquid)	0.08	90	**40**	32	90	**90***	32	90	**90***
Dow 200 (20 cSt) Fluid and Joint Compound (77% Loaded)	0.10	80	**60**				44	80	**60***
Corn Syrup and AlOx (24 grit) (77% Solids Loading)	0.19	88	**120**				88	88	**120***
Corn Syrup and AlOx (180 grit) (77% Solids Loading)	0.19	88	**120**				88	88	**120***
Dow 200 (1000 cSt) Fluid and Joint Compound (67% Solids)*	0.20	70	**60**				91	70	**120***
Dow 200 (20 cSt) Fluid and Joint Compound (77% Loaded)	0.47	70	**420**				211	70	**420***

* Mix time extended to insure mixing was complete as opaque vessels precluded end-point observation.

Clearly, an increased amount of energy is required for larger material volumes. The power per mass has been characterized for a few materials and it appears that the amount of energy required for mixing is proportional to the mass of material being mixed, while the mixing time remains the same.

SUMMARY

ResonantAcoustic® Mixing technology was developed in order to reduce some of the complexities of mixer system design and to achieve key process mixing objectives. By using a low-frequency acoustic field to create both bulk motion and micro-mixing cells, the process produces uniform mixing throughout the entire mixing medium, without the need for impellers, or other intrusive components. The mixer is compatible with gas, liquid and solid phase materials, and combinations thereof, without any need for system modification.

By harnessing the power of mechanical resonance, ResonantAcoustic® Mixers achieve an unprecedented efficiency in the transfer of mechanical energy into the mixing process, resulting in blending rates that are typically 10 to 100 times faster than conventional techniques.

ResonantAcoustic® Mixers are available in three sizes: bench-top pint; as well as production scale 5 gallon and 55 gallon systems. Various applications have demonstrated that the same mixing time is required irrespective of mix load size. Moreover, this trend is consistent for applications ranging from gas-liquid hydrogenations, through powder blending and coating, to loaded resins with viscosities exceeding 10,000,000 cP.

ResonantAcoustic® Mixer users in industries as diverse as pharmaceutical manufacture to rocket propellant research are enjoying the cost savings resulting from faster, more complete mixing, the elimination of waste and clean-up, and the flexibility to switch process materials with zero set-up time.

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