Journal of Petroleum Science and Engineering 145 (2016) 66–76

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Relationship between operational variables, fundamental physics and foamed cement properties in lab and field generated foamed cement slurries

D. Glosser [a,b], B. Kutchko [a,*], G. Benge [d], D. Crandall [c], M.T. Ley [e]

[a] United State Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA, United States
[b] Oak Ridge Institute for Science Education, Oak Ridge, TN, United States
[c] United States Department of Energy, National Energy Technology Laboratory, Morgantown, WV 26507, United States
[d] Benge Consulting, The Woodlands, TX, United States
[e] Oklahoma State University, School of Civil and Environmental Engineering, Stillwater, OK 74078, United States

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form
8 March 2016
Accepted 20 March 2016
Available online 21 March 2016

Keywords:
Energy
Foamed cement
Wellbores
Engineering

ABSTRACT

Foamed cement is a critical component for wellbore stability. The mechanical performance of a foamed cement depends on its microstructure, which in turn depends on the preparation method and attendant operational variables. Determination of cement stability for field use is based on laboratory testing protocols governed by API Recommended Practice 10B-4 (*API RP 10B-4*, 2015). However, laboratory and field operational variables contrast considerably in terms of scale, as well as slurry mixing and foaming processes. Here, laboratory and field operational processes are characterized within a physics-based framework. It is shown that the “atomization energy” imparted by the high pressure injection of nitrogen gas into the field mixed foamed cement slurry is – by a significant margin – the highest energy process, and has a major impact on the void system in the cement slurry. There is no analog for this high energy exchange in current laboratory cement preparation and testing protocols. Quantifying the energy exchanges across the laboratory and field processes provides a basis for understanding relative impacts of these variables on cement structure, and can ultimately lead to the development of practices to improve cement testing and performance.

Published by Elsevier B.V.

1. Introduction

Foamed cements offer many beneficial properties over conventional cements including: higher ductility (Benge et al., 1996; Bour and Rickard, 2000; Frisch et al., 1999), reduction of lost circulation (Bour and Rickard, 2000), improved mud displacement, and improved gas migration control (Bour and Rickard, 2000; Frisch et al., 1999; White et al., 2000). The mechanical performance of a foamed cement depends on its microstructure, which in turn depends on the preparation method and attendant operational variables (Kutchko et al., 2015). Operational variables influence cement microstructure through various physical processes which impart or convert energy in the slurry as it moves through the mixing and foaming process. Characterizing these processes within a physics-based framework can provide a basis for understanding relative impacts of these variables on cement structure, and ultimately lead to the development of practices to improve cement testing and performance.

* Corresponding author.
E-mail address: Barbara.Kutchko@netl.doe.gov (B. Kutchko).

http://dx.doi.org/10.1016/j.petrol.2016.03.014
0920-4105/Published by Elsevier B.V.

Foamed cement stability is tested under laboratory conditions according to API Recommended Practice 10B-4 (API RP 10B-4, 2015). In particular, surfactant and stabilizer packages are chosen based on the application, and laboratory tests are used to determine the relative concentration of material added to the slurry based on the stability test results. However, laboratory conditions contrast considerably from field conditions in terms of both scale of operations as well as equipment and process. Although these factors are known to influence the mechanical performance of foamed cement, little work has been done to tie laboratory and field operational variables to the energy balance across the slurry preparation processes, and consequently, the influence of energetics to foamed cement properties.

Recent experimental studies have established measurable differences in porosity, permeability, and bubble size distributions between laboratory generated and field generated cements (Kutchko et al., 2015). Stable foamed cement has a consistent density along the length of the column with a homogenous distribution of bubbles throughout the same column, commonly known as bubble size distribution (BSD). BSD of well formed foamed cement has been shown to have a uniform distribution of spherical, discreet bubbles to ensure that gas will not break out of the slurry (Nelson and Bell, 2006; Griffeth et al., 2004). Unstable foamed cements may have nonspherical and/or interconnected voids which can result in poorly contained sections caused by channelling in the well and density inhomogeneity (Nelson and Bell, 2006; Rozieres and de, Ferrier, 1991). These foams develop lower compressive strength and higher permeability than stable foamed cement (Nelson and Bell, 2006). Understanding the dynamics between operational variables; physical and mechanical processes influencing cements; and controls on the bubble size distribution is critical to understanding the stability of the foam in the well. We hope this information will lead to the development of improved laboratory testing methods, and improved field monitoring, to establish slurry design performance and further improve wellbore integrity.

This paper re-evaluates the role of operational process driven energetics in the foamed cement preparation process. In particular, we reassess the theory of mixing energy. The theory of mixing energy was first proposed in the 1980s (Hibbert et al., 1995; Orban et al., 1986; Vidick, 1990). The theory states that slurries with the same mixing energy inputs are expected to have identical properties. This would mean that if lab based mixing energy inputs matched field based mixing energy inputs, then, given the same admixture recipes, slurry properties would be identical. However, these studies did not focus on foamed cement paste and there has been minimal contemporary investigation into the influence of operational variables on foamed cement properties. Furthermore, experimental observations of lab and field cements have shown measurable differences between slurries prepared with similar mixing energies. The few peer review studies which have investigated these phenomena have primarily examined experimental relationships between cumulative mixing energy imparted to a slurry during the mixing process; and also have estimated the influence of shear rate on slurry properties (Vidick et al., 1990, Padgett et al., 1996). In these investigations, shear rate is treated as a separate phenomenon from mixing energy. These studies arrived at conflicting results with regard to the influence of cumulative mixing energy and shear rate on slurry properties. For example, some studies found no relationship between mixing energy and compressive strength (Padgett et al., 1996), while others relate compressive strength of cement directly to the mixing energy (Orban et al., 1986). The disagreement between these study results may be due to differences in experimental protocols, including differences in mixing equipment (e.g. coiled tubing versus no tubing; or different slurry volume or admixture recipes), or differences in sampling techniques, which in turn may influence slurry properties. In addition, these studies evaluate shear rate as being in contrast to energy, and not as a related quantity. Given the tight physical coupling between energy and shear rate, it is more appropriate to analyze them as dual quantities which can be altered by changes in operational processes.

Recent technological improvements that have been introduced in the field process necessitate reevaluation of the mixing energy calculations. For example, the shift from batch mixing to continuous mixing processes in the field have considerably altered both mixing apparatus geometry; and the total amount of mixing time a slurry spends in process prior to wellbore emplacement. But, perhaps the most notable operational variable in the field process which has henceforth been unquantified is the atomization energy imparted in the field foamed cement generator. During this process, nitrogen gas is injected at sonic velocity into the mixed slurry (McElfrish and Boncan, 1982). Furthermore, a qualitative accounting of the translation of the energy imparted from these processes to work; heat; and slurry kinetics is needed to better understand the energy balance in the foamed cement preparation process.

We build on prior studies by presenting a physics-based accounting for the mechanisms by which useable energy from mixing – and in the case of the field slurries – atomization, is imparted and transferred across the operational processes. Broadly speaking, the energy provided by the physical mixing, foaming, and atomization of slurry is the major input of useable energy imparted to a slurry. This energy may be translated or used for work on the slurry by a variety of processes, which are highly dependent on operational factors such as mixing time; slurry volume; and pumping pressures. While mixing and atomization energy cannot fully explain the differences observed between lab and field cements – and between cements produced with contrasting field protocols, it is nevertheless established as a critical parameter in the development of slurry microstructure and ultimately cement performance. This paper does not attempt to provide a full accounting of all of the physiochemical factors which could influence slurry properties. Here, we provide a first order approximation of energetics in the API standard lab testing protocol, and a first order approximation of energetics in a representative modern field process. To simplify computations, slurry admixture design packages in the lab and field are identical. The development of a physically based mathematical model to characterize these energies can be used by operators as a data point in the development of laboratory and field processes and packages to produce better performing cements.

2. Laboratory operations overview

Laboratory preparation of foamed cements occurs in two stages. The first stage is the mixing stage, and the second is the foaming stage. The American Petroleum Institute (API) recommended practices are the governing standards for laboratory preparation and testing for oilfield cements.

2.1. Base slurry

In the first laboratory mixing phase, the base slurry containing all additives except for foaming surfactants is mixed in a Waring blender (Fig. 1A and B). The Waring blender has approximately an 1100 mL volume capacity (and a standard mixing volume of 600 mL). Dry cement is added to water and additives within the blender. The RPM of the blender is controlled so the slurry is mixed at 4000 RPM for 15 s. Following this initial wetting of the cement, the Waring blender is then operated at 12,000 RPM for an additional 35 s.

2.2. Foamed slurry

Once the base slurry is mixed, the cement is then transferred to a second "foaming" blender, with a blender bowl capacity of approximately 1100 mL that has a sealed top and a stacked blade assembly. The mixing blades in the foaming blender are the same as used to mix the slurry, except rather than having a single blade at the bottom of the blender bowl, there are 5 sets of stacked blades (Fig. 1C). The proportion of slurry and foaming surfactant placed in the blender bowl will depend on the desired foam quality (gas content). For example, if the foam quality is 25%, then the amount of slurry and surfactant will occupy 75% of the volume. The foaming surfactant is added to the slurry after the base cement slurry, the top put on the blender and the contents are mixed for 15 s at 12,000 RPM. Although the time and RPM to foam the system is intended to be consistent, the actual operational time and rotational speed of the blender will vary based on how much cement is in the blender. While the API protocols recommend the RPM to be as close to 12,000 as possible, slurry volume build up and viscosity changes during foaming may not allow the blender

Fig. 1. (A) Standard Waring 7 speed blender has a 1100 ml capacity; (B) impeller apparatus for Waring 7 mixing blender (C) stacked blade assembly for the laboratory foaming blender. Courtesy of Chandler Engineering.

to achieve that RPM. The geometry of the mixing device influences the effective mixing energy imparted to the cement: For the base slurry, if slurry volumes are low relative to the height of the stacked blade assemblage, the blades near the top of the blender will not be engaging all of the slurry material. To account for this, stability testing requires that if the foamed cement paste does not completely fill the blender when foamed, the system is rejected.

When the cement is foamed, the cap is removed from the blender and the foamed cement is removed. The final porosity of the sample can vary slightly due to heat generated during mixing, and in critical situations there are calculations made and new samples run to try to hone in on the desired density and thus gas content. The foamed cement is tested for stability, strength development, and any other tests desired (see API RP 10 B-4).

3. Field operations overview

A representative field operation for foamed cementing (rig-up) is shown in Fig. 2. In a field operation, the base slurry is mixed in the cement unit (Fig. 2 box 3). The dry cement is pneumatically transferred to the cement unit with air, and combined with the water in a mixing head. From there the slurry goes into a recirculation system that checks the density of the slurry, and sends part of it back around the loop for additional cement and water to be added (Fig. 2 boxes 1 and 2). The cement is recirculated with a centrifugal pump running at approximately 35 barrels per minute (1 barrel is 42 US gallons, or 0.16 m^3). The recirculating tub is about 3 barrels, so it is turned over very quickly. The recirculating tub then spills over into the mixing tub which is from 7 to 25 bbls (294–1050 US gallons, or 1.11–3.97 m^3) depending on the system. In some cases, the larger mixing tub can also be recirculated. Typically the base slurry is pumped at rates around 5 bbl/min (210 US gallons/min or 0.013 m^3 per second), though these rates vary a great deal depending on well conditions. The triplex pump has an injection port immediately before the injection point in the plungers, and it is at this point, the surfactants (sent via pipe flow) are added to the base slurry (Fig. 2 box 8). The pressure before the triplex pump is about 90–100 psi.

After the mixing process, the cement is then piped

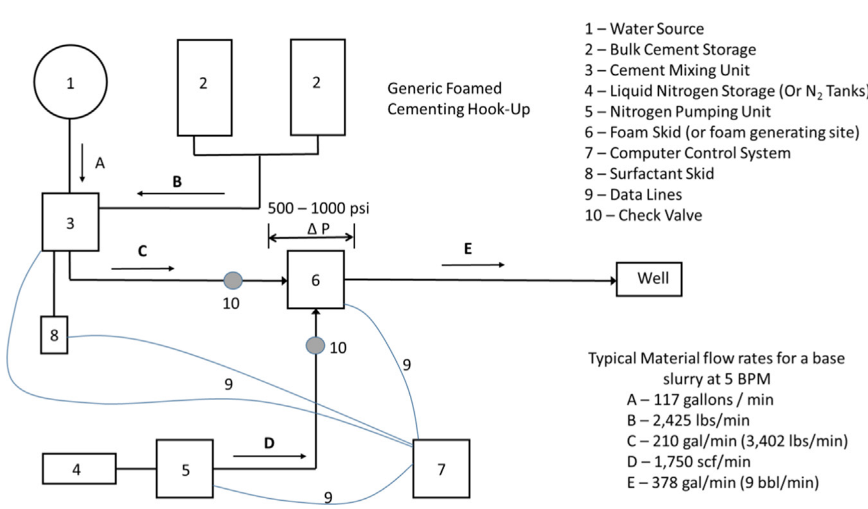

Fig. 2. Schematic overview of field operations for foamed cementing.

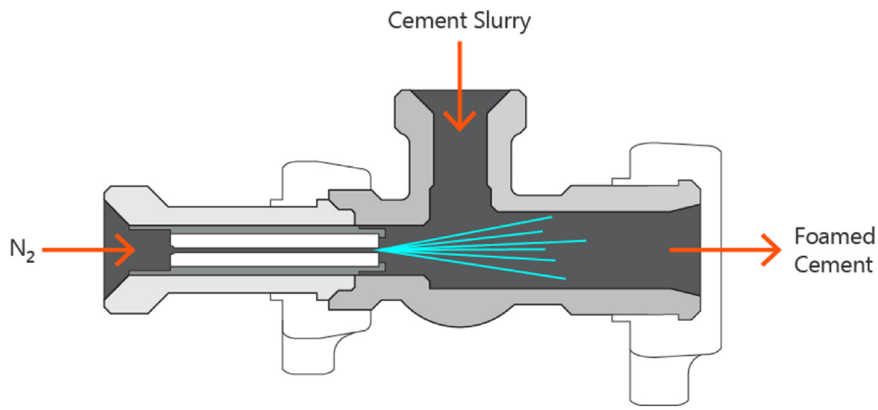

Fig. 3. Choke diagram showing atomization inside of an example foam cement generator unit, where nitrogen is atomized and injected at sonic velocity into the base slurry.

approximately 100 feet, or 30.5 m from the cement pump to the foam skid (Fig. 2 box 6). This distance will vary with logistics at the rig site. The foamed cement generator is located at the foam skid. It is here that the mixed cement slurry is intersected with the nitrogen line. At this point, the base slurry is "atomized" inside the foam cement generator (Fig. 3). The atomization process itself refers to the high pressure injection of nitrogen gas into the base slurry (McElfrish and Boncan, 1982). Sensors in line feed back to the computer to show the volume and density of slurry as well as the foam densities that are going into the well. The nitrogen is injected at a 500–1000 psi differential pressure. This is accomplished by pumping the nitrogen against a choke. Typically this choke is a 1–2 in. thick metal plate with holes drilled in it.

Downstream of the foam generator, the pressures are impacted by the friction in the pipes (referred to as the surface treating lines), and the pressures required to circulate the well. Pressure in these lines is in the range of 350 psi but can be considerably higher if smaller pipes or if pumping distances are increased. In general, the pressure will vary considerably (beyond 500 psi) depending on the well conditions and architecture.

Pump rates in the field are limited by the inside diameter of the pipes. For example, the maximum rate that can be pumped through a 5.08 cm treating line as about 8 bbl/min (336 US gallons/min, or 0.021 m^3 per second). Above that metal erosion from the line has been observed (Vidick et al., 1990) Land rigs use 2 in. (5.08 cm) iron and offshore rigs typically use 3 in. (7.62 cm) treating lines, so the maximum slurry rate through them is 18 bbl/min (756 US gallons/min, or 0.047 m^3 per second).

Depending on the desired density of the foamed cement, the amount of nitrogen is adjusted. The foamed density will change with changes in pressure, temperature and initial base cement density. There are calculations and tables that help determine the amount of nitrogen needed for different pressures and temperatures. Examples can be found in API RP 10B-4.

4. Methods: main equations

4.1. Mixing energy

Mixing energy, or the amount of energy imparted to a slurry during mixing, was calculated for laboratory and field operations. For laboratory generated slurries, the mixing process can be considered to include the mixing and blending of the dry cement, water, and additives using a standard Waring blender; and the mixing in the stacked blade "foaming" blender, in Fig. 1. The specific mixing energy in the laboratory mixer is calculated as follows:

$$\frac{E}{M} = \frac{k \times \omega^2 \times t}{V} \tag{1}$$

where $\frac{E}{M}$ is the mixing energy input (kJ/kg), $\boldsymbol{k}$ is an experimental constant (N m/kg m^3/rpm), $\boldsymbol{\omega}$ is the rotational speed of the impeller blades (rpm), $\boldsymbol{t}$ is time (seconds), and $\boldsymbol{V}$ is the slurry volume (m^3). The experimental constant, k, was obtained by measuring the torque exerted by the mixer motor for slurries of varying densities, with corrections for frictional losses (Orban et al., 1986).

For the field mixer, the energy imparted to the slurries is calculated as follows:

$$\frac{E}{M} = \sum \frac{HP \times t}{\rho \times V} \tag{2}$$

where $\boldsymbol{HP}$ is horsepower (kJ/s) and $\boldsymbol{\rho}$ is slurry density. Cumulative mixing energy, expressed in kJ/kg, and instantaneous mixing energy, expressed in Joules, were computed for both laboratory and field conditions.

4.2. Atomization energy

The base slurry and nitrogen are travelling orthogonal to one another prior to atomization, as shown in Fig. 3, so their momentums do not add. For this work the nitrogen injection into the base slurry is assumed to be a perfectly inelastic collision, and is solved in 2 dimensions. The slurry mass, m_1 is calculated based on the density and volume of the base slurry and the slurry velocity, u_1 is calculated based on the pump rate and pipe diameter (assumed to be 5 barrels per minute, or 0.80 m^3/s and 2 in., or 9.1016 m, respectively). The total mass of nitrogen gas injected through the choke, m_2 is calculated based on the molecular weight and volume of gas at 100 F (310 K). The nitrogen gas velocity, u_2 is taken as 340 m/s based on experience.

Appling conservation of momentum along the x-axis:

$$P_{ix} = P_{fx}$$
$$m_1 v_{1ix} + 0 = (m_1 + m_2) v_f \cos\theta$$
$$m_1 v_{1ix} = (m_1 + m_2) v_f \cos\theta \tag{3}$$

where P_{ix} is the initial N_2 momentum along the x-axis; P_{fx} is the final momentum along the x-axis, and the angle, θ, is the angle of the momentum vector of the N_2. The variable v_f is the unknown final velocity, and *ix* subscripts refer to initial momenta magnitude and direction along the x-axis.

Following the same logic, slurry momentum along the y axis is:

$$P_{iy} = P_{fy}$$

$$0 + m_2 v_{2iy} = (m_1 + m_2) v_f \sin\theta$$

$$m_2 v_{2iy} = (m_1 + m_2) v_f \sin\theta \tag{4}$$

where P_{iy} is the initial base slurry momentum along the y-axis; P_{fy} is the final momentum along the y-axis, and the angle, θ, is the direction of the momentum vector of the base slurry. The variable v_f is the unknown final velocity, and iy subscripts refer to initial momenta magnitude and direction along the y-axis.

To solve for the angle of the final velocity vector, θ, which the direction of the mixture following atomization, divide Eq. (4) by Eq. (3) to eliminate the unknown variable, (the final velocity v_f),

$$\frac{m_2 v_{2iy}}{m_1 v_{1ix}} = \frac{(m_1 + + m_2) v_f \sin\theta}{(m_1 + + m_2) v_f \cos\theta}$$

$$\frac{m_2 v_{2iy}}{m_1 v_{1ix}} = \tan\theta$$

$$\theta = \tan^{-1} \frac{m_2 v_{2iy}}{m_1 v_{1ix}} \tag{5}$$

And to solve for the unknown variable, the final velocity, v_f of the atomized slurry, solve (Eqs. (3) and 4) and substitute variables:

$$m_2 v_{2ix} = (m_1 + m_2) v_f \sin\theta$$

$$v_f = \frac{m_2 v_{2ix}}{(m_1 + m_2)\sin\theta} \tag{6}$$

The loss of energy during the atomization – or rather, the energy from the atomization that is transferred to the slurry and used to deform the materials, and/or translated to heat, sound, or other forms is:

$$\Delta K = \left[\frac{1}{2}(m_{1+} m_2) \times v_f^2\right] - \left[\frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2\right] = K_f - K_i \tag{7}$$

where K_i and K_f are the kinetic energy of the base slurry before the foam cement generator, and the energy of the slurry following nitrogen injection. Since the process is a perfectly inelastic collision at the macro-scale, energy from the velocity of the nitrogen is not conserved following injection. Unlike the mixer and blender energy calculations, which resulted in cumulative mixing energies expressed in kJ/kg (which were then converted to instantaneous energy in Joules) the result of this calculation is an instantaneous value of the net energy transfer between the bulk nitrogen injection into bulk base slurry, as a net quantity (in Joules). It should be noted that momentum is conserved during this process, but kinetic energy is not. This means that some of the "energy expense" of this process goes to the conversion of kinetic energy to heat, sound, and deformation of the slurry or nitrogen bubbles within the slurry (Prud'homme and Khan, 1995). Some of these are described in this document.

4.3. Shear rate

Shear rate, expressed in reciprocal seconds (1/s), is a velocity gradient between two layers of fluid, as measured across the diameter of the flow channel (Rupnow et al., 2006). In the case of Non-Newtonian fluids such as foamed cement slurry, the velocity gradient is non-linear, and is challenging to be directly measured or modelled precisely. Rheometric measurements can give an approximation of the linearity of the viscosity profile, but it is important to note that these measurements are highly device dependent, and not a direct measurement of shear rate. Because no constitutive equation for foamed cement slurries exists, a phenomologically derived relationship based on that presented by Padgett et al. (1996) was used:

$$\gamma = E/(M^* t^* \mu) \tag{8}$$

where γ is shear rate (1/s), and μ is the slurry viscosity.

However, since the relationship between viscosity and shear rate is dynamic for a Non-Newtonian fluid, it is appropriate to simplify the viscosity value of a slurry based on results from an experimentally derived relationship as a first approximation.

Foam quality at a given pressure and temperature can be expressed as:

$$\Gamma = \frac{V_g}{V_L + V_g} \tag{9}$$

where V_g and V_L are the volume of gas and slurry (m^3).

The viscosity of foamed cement slurry of a given quality was approximated based on data reported by Ahmed et al. (2009), using the following relationship:

$$\frac{\mu_s}{\mu_L} = 1 + \left(2.5 - \Psi C_a^2\right)\Gamma \tag{10}$$

where μ_s is the estimated suspension viscosity and μ_L is the estimated base viscosity (Pa s). Per Ahmed, the value of the dimensionless parameter Ψ for a foamed cement is approximately 70 for their materials. When surface tension is assumed to be constant, the nonlinearity constant value is negligible. Although the surfactant package and other cement additives used may influence viscosity through alteration of bubble sizes and cement grain dispersion, this relationship provides an approximation of the relative viscosity of a foam based on cement quality. Additional experimental measurements are needed to look at how different materials impact these assumptions.

4.4. Surface energy

Energy imparted into a foamed cement slurry is translated or converted by a variety of processes. One of several energetically expensive processes that occurs within a foamed cement is the motion and alteration of bubbles within the slurry, which in turn influences the final microstructure. The bubble size distribution, and mean bubble size, is directly related to the mechanical performance of a foamed cement (Spaulding et al., 2015). To investigate the energy cost of bubble dynamics it is useful to quantify the relative energy costs associated with alteration of bubbles, including the shearing apart and coalescence of bubbles. Calculation of the amount of surface energy of a given bubble is computed as follows:

$$\sigma_E = \sigma_\tau \times A \tag{11}$$

where σ_E is surface energy (J/m^2), σ_τ is surface tension, and A is bubble surface area.

The amount of energy needed to shear apart a bubble of an initial entrained volume of gas to a series of smaller bubbles, while conserving gas volume is accomplished by computing the volume of each of the smaller bubbles:

$$Vol_s = Vol_i n \tag{12}$$

where Vol_s is the volume of a single smaller bubble, and Vol_i is the initial gas volume of the initial bubble (m^3), and n is the number of partitioned bubbles. For ease of calculation, we assume the partitioned bubbles are of equal volume.

And then determining the radius and surface area of each of the partitioned bubbles as follows:

$$r_s = \sqrt{Vol_i} 4/3\pi \tag{13}$$

$$A_s = 4\pi r^2 \tag{14}$$

where A_s is the surface area of a partitioned bubble.

Finally the amount of energy needed to shear the bubble is computed by

$$\Delta E_{shear} = n \times A_s \times \sigma_{EP} - \sigma_E \times A \quad (15)$$

where σ_{EP} is the surface energy of a partitioned bubble, and σ_E is the surface energy of the initial bubble, and ΔE_{shear} is the energy cost in (J/m^2)

Given enough momentum, a bubble can overcome surface tension and coalesce with other bubbles, resulting in net expansion (Ley et al., 2009). The energy required to expand the surface area of a bubble by an amount δA is:

$$\Delta E_{expand} = \sigma_\tau \delta A \quad (16)$$

The surface area of a bubble is given by Eq. (14). The differential δA in Eq. (16) can be replaced with the derivative of $4\pi r^2$, which is $8\pi\delta r$. Therefore the energy required to increase the radius of the bubble by δr is:

$$\Delta E_{expand} = 8\sigma_\tau \pi r \delta r \quad (17)$$

5. Methods: experimental

Laboratory slurries were prepared in accordance with API RP 10B-4 and analyzed using multi-scale computed tomography (CT) scanning at the United States Department of Energy, National Energy Technology Laboratory (NETL). In-situ field samples of foamed cement were captured in constant pressure cylinders under field conditions and analyzed with CT, under pressure by NETL. Bubble size distributions were determined; and porosity, permeability, and other tests were performed on both lab and field cements. Mechanical properties tested include Young's modulus and compressive strength. Experimental details are described in Kutchko et al. (2015).

6. Mathematical results

6.1. Mixing energy

Calculated cumulative mixing energy inputs from the Waring blender in the lab, and the mixing tub in the field are shown in Table 1.

Cumulative mixing energy was also modelled for smaller slurry volumes to illustrate the relationship between slurry volume and mixing energy inputs. The results of this mathematical model shows that the relationship between slurry volume and mixing energy is particularly noticeable in the laboratory, where decreasing the amount of slurry relative to the Waring mixer increases the amount of energy imparted to the slurry (Fig. 4). Although laboratory testing is done with a standard volume of slurry (600 mL in a 1100 mL blender), according to the API standards.

Table 1
This table summarizes the calculated mixing energy inputs into atmospherically generated and field generated slurries. Atmospheric slurry calculations are for the Waring blending cycles and include dry cement, water, and all additives except for foaming surfactants, which are added in the stacked blade blender. Lab and Field generated cements are calculated for a Foam Quality of 40%, containing the same surfactant and admixture packages. The calculation assumes a 400HP mixer in the field, and a total mixing time of 300 s, including recirculation. See equations in Section 4.2.

Lab	Cumulative mixing energy (kJ/kg)	Instantaneous mixing energy (Joules)
Waring Blender (4000 RPM)	0.25	17.00
Waring Blender (12,000 RPM)	5.40	153.60
Stacked Blade Foaming Blender	1.20	80.30
Total Lab	6.85	250.90
Total Field Mixer	5.80	9.70

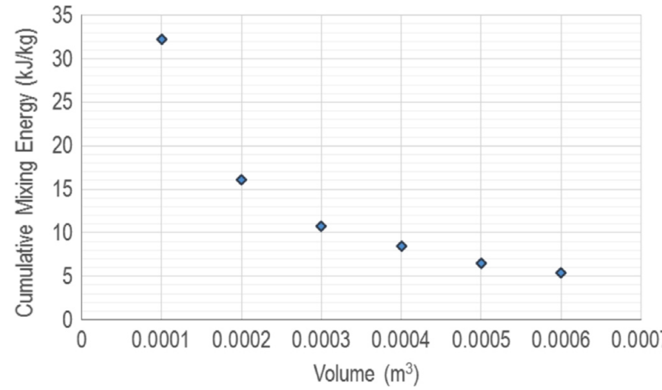

Fig. 4. Modelled cumulative mixing Energy of laboratory generated base slurry prepared using standard API recommendations of 4000 RPM for 15 s and 12,000 RPM for 35 s, but changing hypothetical slurry volume.

6.2. Shear Rate

The relative results of the calculated shear rates in lab and field mixers are in line with those of experimental studies (Teodoriu et al., 2015) (Table 2). Although the calculated shear rates are not likely to be representative of actual shear rates across the in situ slurry profiles (since the shear profile is nonlinear for a non-Newtonian mixture), the calculations do provide a reliable qualitative comparison of relative mean shear rates between processes. Field mixers operate at lower shear rates than do lab mixers. And, calculated shear rates in the lab mirror the observed trends of their mixing energies: The low speed (4000 RPM) Waring mix has the lowest shear rate; followed by the lab foaming blender; followed by the high speed (12,000 RPM) Waring mix. The field mixer has the lowest calculated shear rate (Table 2). When considering that the shear rate equation was derived based on its relationship to mixing energy and relative viscosity (both of which have kinetic, volumetric, and temporal elements), these results are reasonable. Given this logic, it is unsurprising that the shear rate of the atomization is substantially greater than any of the mixing processes in either the lab or field. The resulting energy is presented in the following section.

6.3. Atomization energy in the foamed cement generator

Energy transfer from the atomization of the base slurry by nitrogen gas in the field foamed cement generator is orders of magnitude greater than mixing energy inputs in either the lab or field mixers (Table 3). In contrast to the mixing and blending

Table 2
Calculated average shear rates in the lab mixers, field mixer; and Foamed Cement generator. Calculations are based on a 40% foam quality and use the viscosity for that quality based on the relationship reported by Ahmed. For the foamed cement generator shear rate calculation, a nitrogen pump pressure of 1000 PSI was used. See equations in Section 4.3.

Lab Waring 4000 rpm shear rate (1/s)	Lab Waring 12,000 rpm shear rate (1/s)	Lab Foaming blender shear rate (1/s)	Field mixer shear rate (1/s)	Atomizer shear rate (1/s)
450	1700	1100	0.0048	7000

Table 3
Calculated total energy transfer from atomization of base slurry with nitrogen gas in the field foamed cement generator. Calculations assume a 50 bbl job and 5 BPM base rate, and nitrogen temperature of 100–300 F. We also assume that the nitrogen acts as an ideal gas. Results were rounded to 3 significant figures. See equations in Section 4.3.

Foam quality	PSI	Energy from atomization (Joules)	Energy translated by atomization (Joules)	Energy "Residuals" (atomization – translated energy) (Joules)
40	300	5,140,000	5,110,000	30,000
40	500	11,700,000	11,500,000	200,000
40	1000	23,300,000	22,700,000	600,000
20	300	1,980,000	1,970,000	10,000
20	500	3,260,000	3,250,000	10,000
20	1000	6,420,000	6,380,000	40,000

processes, the atomization process in the field foam cement generator is high energy and nearly instantaneous (McElfrish and Boncan, 1982).

Atomization energy was calculated for both a 20% and a 40% foam quality slurry. Because nitrogen pressure can be controlled at the field site, the energy exchange for each slurry was computed under 3 scenarios (300 psi; 500 psi; and 1000 psi nitrogen back pressure) to better understand how injection pressure influences energetics. In all cases, almost all of the energy from the nitrogen injection is immediately transferred to the slurry. But there are still considerable energy residuals, the physical significance of which is unclear. For both the 20% and 40% slurries, the energy inputs and transfer increased with increasing pressure. The energy residual (energy from atomization – energy translated from atomization) increases with increasing pressure. Therefore, higher nitrogen pressure gives more energy into the slurry, and, while most of the energy is immediately used, the higher energy injections also leave more energy in the slurry following the atomization process (Table 3).

When higher foam qualities are created, the energy level is also higher. There are two reasons for this: First, the nitrogen must be injected at a higher velocity in order to obtain higher foam qualities. Second, the injected nitrogen makes up a larger volume of the final slurry. Since the nitrogen is more energetic, this will impart even more energy to the system. Accordingly, these calculations also show that 40% slurry injection is a higher energy system than 20%. The higher energy of the 40% foam quality slurry is due to the fact that most of the initial velocity from the process is coming from the nitrogen, not the base slurry: nitrogen is travelling at a high velocity, and by increasing its mass (relative to the 20% case, and also relative to the amount of base slurry its colliding with), there are considerably higher kinetic energies.

6.4. Surface tension

Mathematical calculations showing the energy expense of shearing and coalescing foamed cement bubbles were performed in order to illustrate the magnitude of the energetics involved with a subset of bubble dynamics. The number of bubbles coalesced and sheared were arbitrarily selected, and give preliminary insights into whether shearing versus coalescence are energetically preferred. For these illustrative calculations, surface tension is assumed to be a constant value of 0.45 J/m^2 (Wittmann, 1973). These results are illustrative of the amount of energy needed to either shear apart a bubble in a slurry, or, coalesce bubbles (Tables 4 and 5). These example calculations could be up-scaled to estimate the total energy expense for various size field jobs, or for a typical laboratory volume based on probability distributions describing the BSDs at various points in the processes. Such computations are outside the scope of this paper. However, these results are an illustration of an important physical process occurring in the slurry at various points across the mixing and/or atomization processes. It is apparent that the physical process of altering the number of bubbles and the size of the bubbles in a slurry is potentially an energetically expensive process.

7. Experimental results

Based on findings by Kutchko (2014) and Spaulding et al. (2015) field generated foamed cements tend to have, on average, smaller, less uniform bubble sizes than comparable laboratory cements. A representative example is shown in Fig. 5. These images are cross sections obtained by scanning the sample with X-ray computed tomography. The black areas are void spaces. The total volume of the field and laboratory sample voids is comparable, but the laboratory sample has voids that are much larger in size. This considerable difference in bubble size distribution can be clearly observed in the images when comparing samples of similar foam quality generated in a laboratory (Fig. 5A) vs that generated by field equipment (Fig. 5B). This figure presents the visible differences in bubble size distribution in cements prepared under the contrasting pressure and energy processes in the laboratory versus the field. There is also a relationship between void connectivity and foam quality: Backscatter Emission Scanning Electron Microscopy (SEM) analysis showed that void size and connectivity increased with increasing foam quality (Figs. 6–8). These connected void structures in the higher quality foams may partially explain the observation that foamed cement may not be stable at higher foam qualities. This greater connectivity in higher foam quality cements was also observed in the CT images as well as literature (Rozieres and de, Ferrier, 1991; Kutchko et al., 2014) It should be noted that industry does not use cements with foam qualities greater than 30% due to their lower stability.

8. Discussion

The theory of mixing energy relates the total mixing energy imparted to cement slurry during the mixing process to its physical properties. A small number of studies dating back to the 1980 s have purported to find links between mixing energy and slurry hydration rate; thickening time; free water; plastic viscosity; rheological stress/strain; and compressive strength (Orban et al., 1986; Vidick et al., 1990; Hibbert et al., 1995; Rupnow et al., 2006). API recommended mixing procedure yields a slurry mixing energy of 5.5 kJ/kg to achieve "optimal" slurry properties. The mixing energy hypothesis states that slurries of equal mixing energies are expected to have matching properties, irrespective of mixing device or scale (Padgett et al., 1996; Orban et al., 1986). Thus, if validated, the mixing energy parameter would provide a metric for comparison between lab and field generated slurries,

Table 4
Energy needed to shear a bubble into several smaller bubbles calculated from Eq. (14).

	Initial bubble area (m^2)	# of partitioned bubbles	Area per partitioned bubble (m^2)	Surface tension (J/m^2)	ΔE (J/m^2)
Shearing	5.02e−07	5	1.71e−05	.45	1.7e−07

Table 5
Energy needed to overcome surface tension for bubbles to coalesce, calculated from Eq. 16.

	Initial bubble area (m^2)	Expanded bubble area (m^2)	δr (m)	Surface tension (J/m^2)	ΔE (J/m^2)
Coalescence	5.02e−07	2.01e−06	.002	.45	4.5e−07

and allow for the design of optimal slurry recipes including surfactant and additive combinations. However, past studies linking mixing energy to slurry properties are limited insofar as they do not account for the translation of energy inputs to useable energy or heat; or the transfers of energy throughout the cement mixing, foaming, and (in the field) atomization process. Since admixture recipes are developed in the lab for application in the field, it is critical to understand how contrasting operational processes and resulting energy exchanges that occur in the field can alter a slurry.

This paper builds upon past work and provides an analysis of energy transfers that occur in the lab and field foamed cement processes. Most critically is the examination of atomization energy imparted in the field process, and how this high energy process may be influencing slurry microstructure, and resulting mechanical performance. A qualitative examination of useable energy losses and expenses during the slurry mixing and circulation process further elucidates how operational variables influence physical dynamics, and ultimately slurry stability.

Here, it is shown that:

1. Energy and shear rate are tightly coupled phenomena in both the lab and field processes. They do not stand in opposition to one another. Instead, shear rate must be considered as a function of energy, with higher energy environments yielding higher shear rates.
2. Instantaneous mixing energy inputs (Joules) are a better indicator of useable energy than cumulative mixing energy (kJ/kg) (as described in 8.2) and are greater in the lab mixer than the field mixer.
3. However, the energy imparted by nitrogen injection into the base slurry is – by a significant margin – the highest energy process in the field, and there is no analog for it in the lab protocols.
4. Higher energy (and higher shear) environments promote physical processes which deform the slurry and drive bubble dynamics by way of several mechanisms, including, but not limited to, the motion, shearing apart and coalescence of bubbles, and alteration of slurry rheology (Ahmed et al., 2009). This means that in the field process, the atomization of slurry in the foamed cement generator is the primary energy-based input for foamed cement bubble dynamics, which likely contributes to the observed smaller field bubble sizes observed prior wellbore emplacement (McElfrish and Boncan, 1982).
5. Bubble size distribution is an indicator of foamed cement stability, which directly influences mechanical performance, including compressive strength and Young's modulus (Spaulding et al., 2015). Although energy transfers resulting from lab and field operational processes cannot fully explain observed bubble size distributions, mixing and atomization energy is shown to promote the deformation and bubble dynamics in a foamed cement slurry.

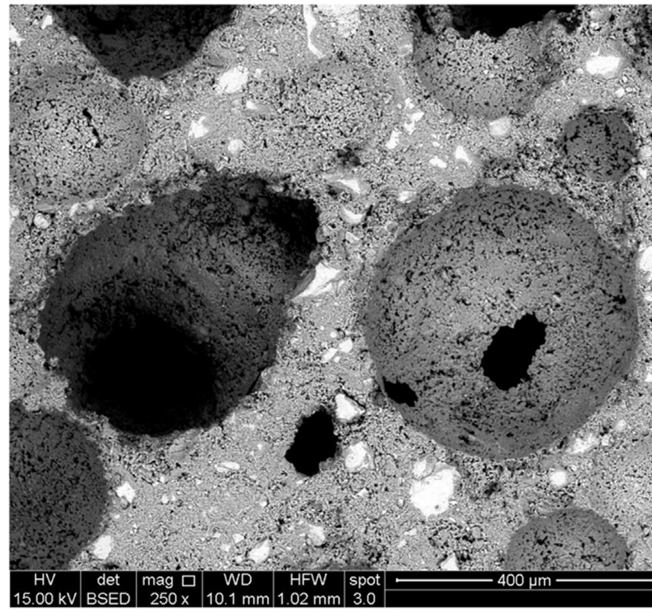

Fig. 6. Backscattered Electron (BSE) Scanning Electron Microscopy (SEM) Images of 30% foam quality foamed cement.

8.1. *Shear rate and energy are complementary quantities*

Foamed cements exhibit non-Newtonian behaviour such as

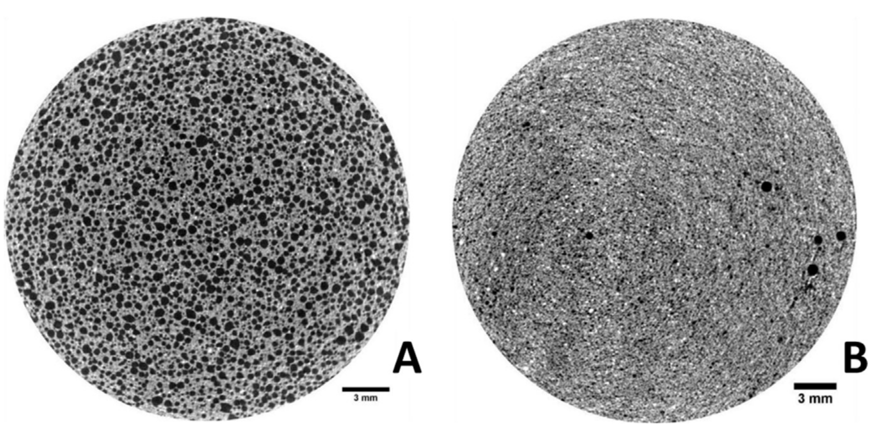

Fig. 5. CT scan images of (A) laboratory generated foamed cement of foam quality 40%, and (B) field generated foamed cement, of foam quality ~35%. From Kutchko (2014). Note the considerable difference in bubble size distribution between the cement generated in the lab blender vs cement generated using large-scale field equipment and pressurized treating lines.

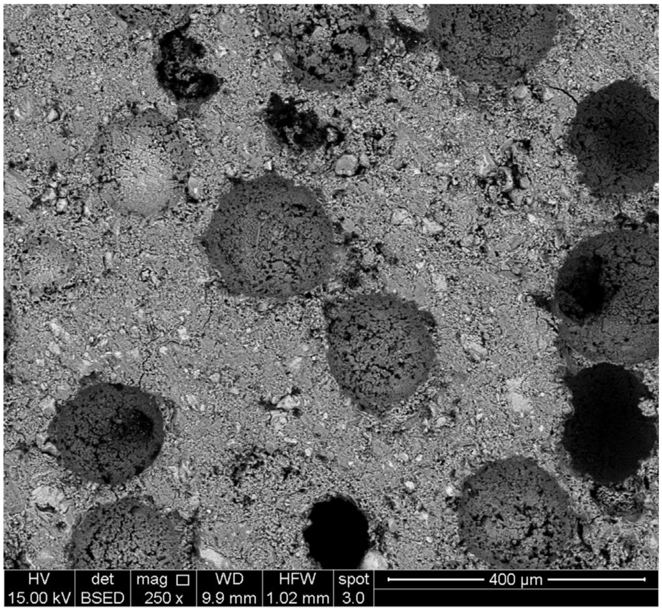

Fig. 7. Backscattered Electron (BSE) Scanning Electron Microscopy (SEM) Images of 20% foam quality foamed cement.

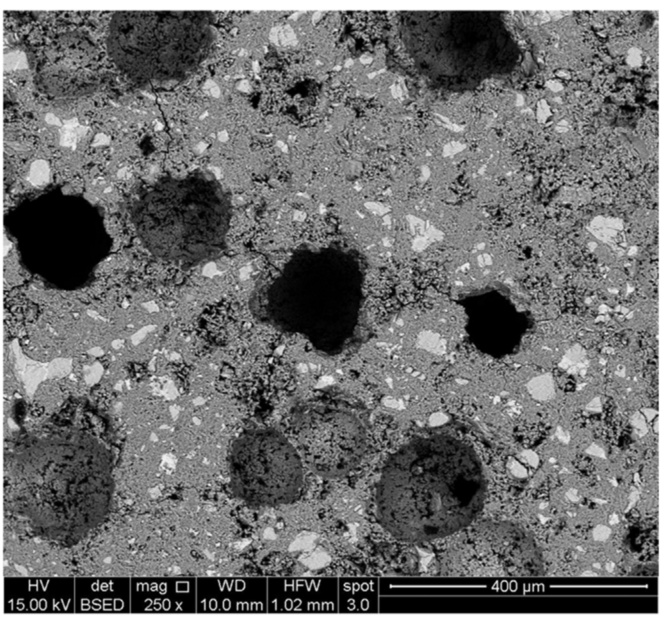

Fig. 8. Backscattered Electron (BSE) Scanning Electron Microscopy (SEM) Images of 10% foam quality foamed cement.

shear thinning and yield stress. As such, they are shear-history-dependent fluids in which the foam structure may be continuously changed. Non-Newtonian equations such as Bingham, Power Law, and Herschel–Bulkley Models are typically applied to describe foamed cement slurries (Ahmed et al., 2009).

Although it has been postulated that shear rate has a greater influence on cement slurry properties than mixing energy (Teodoriu et al., 2015), the relationship between energy and shear rate is so tightly coupled from an operational perspective, that shear rate may be properly considered a physical dual of energy. Shear rate of a slurry is highly dependent on operational variables such as impeller velocity and geometry; pumping and equipment geometry; pumping pressure and slurry velocity, and, in the field, the atomization of pressurized nitrogen into the base slurry the foamed cement generator. The energy to do the work of shearing the slurry is imparted by these operational processes through the energy provided by these processes process. In short: shear rate is a function of energy.

Foamed cement slurry is a non-Newtonian mixture (Ahmed et al., 2009). Consequently, computation of shear rate, and measurement and mathematical modelling of foam rheology is an approximate enterprise. The shear field of foamed cement slurry cannot be accurately characterized for a given volume of cement. Attempts to measure shear rate using conventional viscometry rely on the application of fluid laws (e.g. power law) to determine the velocity gradient and compare measurements across devices. Furthermore, measurements of shear rate of foamed cement slurry samples taken in the field – or in experimental procedures designed to approximate field operations – are not actual physical measurements of in situ shear rates. Instead, they are approximations of velocity at a moment, based on mathematical extrapolation of instrument torque and rotational rates.

Nevertheless, relative shear rates across lab and field processes do elucidate important insights about the underlying physics of these systems. The "measurement" and computation of shear rate is possible only due to the tight physical coupling between operational variables such as device geometry; physical contact of slurry with the energy source; and the velocity of the slurry across processes. Ultimately, shear rate is important to understand only because of these relationships.

8.2. Cumulative mixing energy is roughly equivalent in the lab and field mixers, but instantaneous energy is a more reflective measurement

Mixing energy imparted to a slurry is dependent on operation specific variables in both the field and the lab. These variables include but are not limited to: Slurry volume; residence time in the mixing process; and mixing device geometry and method (such as a continuous mixer versus bath mixer in the field). Instantaneous energy inputs are more representative of useable energy that is immediately available to do work on the slurry than is cumulative mixing energy alone. Instantaneous energy, as measured in Joules, better approximates the amount of useable energy imparted into a slurry over a discrete time interval. It is the measurement of the ability to do work. From an operational perspective, cumulative mixing energy averages out the energy imparted to a volume slurry, and in doing so, underestimates the influence of slurry volume or job size on energy transfer. Unlike a continuous field mixer, where slurry volumes are evenly distributed and digitally monitored, in the case of the lab blender, cumulative mixing energy does not capture the potential for uneven physical distribution of slurry volume within the blender (ie communication between the slurry volume and mixing blades). Large instantaneous energy inputs may contribute to deflocculating cement particles, and shearing apart bubbles. In the lab particularly, where slurry volumes are low, it is straightforward to illustrate this phenomenon by calculating the mixing energy in the Waring blender for very small slurry volumes (Fig. 4).

While the calculations in this paper show that the continuous field mixer imparts cumulative mixing energy that is roughly equivalent to the lab mixing process – the actual amount of instantaneous energy, as measured in Joules – is considerably lower in the field mixer than complementary lab mixer for the unfoamed base cement slurry. Ultimately however, the influence of mixing energy (either cumulative or instantaneous), is not the primary input of energy into a slurry in the field process: Instead it is the atomization process in the foamed cement generator that is imparting the greatest transfer of energy into the slurry. The atomization process is a high shear, high energy exchange site. This phenomenon – and the coupling between shear rate and energy in the context of foamed cement generation – is discussed below.

8.3. Energy and shear rates are highest during atomization in the foamed cement generator, and there is no analog in the lab process

The calculation results (Table 2) confirm relative experimental approximations of relative shear rates in the lab and in the field. Where energy inputs are high, shear rates are high. Lab mixers operate at higher shear rates than the field mixer, but the atomizer (in the foamed cement generator) has a shear rate orders of magnitude greater than either of the mixing processes. It is not a coincidence that in addition to having the greatest shear rate, the atomizer is also, by orders of magnitude, the highest energy part of the field process.

Although the foamed cement generator process may be colloquially considered as part of the field mixing process, from a physical perspective the mechanics are quite different from a mixing operation. Consequently, the method of computation of the energy transfer must reflect this. The nitrogen injection into the base slurry is physically an inelastic collision. Because both the nitrogen and base slurry are travelling as bulk quantities, it is appropriate to assign average values for the mass and velocity of each respective system of particles for computational purposes. Furthermore, because the atomization process occurs nearly instantaneously in the foamed cement generator (McElfrish and Boncan, 1982). With these assumptions, the nitrogen gas and base slurry will be a combined quantity at a macroscopic scale and have a common velocity following atomization. Since there is only one material to deal with following atomization, conservation of momentum principles can be used to solve for the magnitude and direction of the final velocity of the slurry as a bulk quantity. The final velocity of the material is used to solve for the energy exchange.

High quality foams have higher atomization energies. Higher nitrogen pressures result in higher atomization energies (Table 3). In all cases, almost all of the energy from the nitrogen injection is immediately "lost" to the slurry, although there are considerable net residuals, the significance of the later is unclear. The amount of energy "lost" after atomization is really not "lost". It is converted to other processes, including heat; sound; and the physical processes that are deforming the slurry and driving the bubble dynamics. This calculation does not partition between energy uses: That is, it cannot resolve what proportion of energy is being used on the various slurry processes, such as the amount of energy converted to heat versus sound, slurry deformation, or to change bubble dynamics. Nevertheless, it is an important part of the field energy balance, and it provides a starting point to make inferences about how the energy transfer is going towards driving bubble dynamics.

Field generated slurries have, on average, smaller bubbles than laboratory generated slurries (Fig. 5). In both lab and field slurries, the final bubble size distribution is largely dependent on the initial distribution of bubble sizes (Kroezen and Groot Wassink, 1987). In the field, the initial, small bubble size distribution is likely caused by the high instantaneous energy imparted to the slurry in the foam cement generator. Here, nitrogen is injected at high pressures through small holes in the atomizer. This is a high velocity input through very small holes accomplished over a short time interval. Velocity is inversely proportional to diameter, so the velocity of the nitrogen is very high. The result is a steady strain field applied to the slurry, in a very high energy environment. The smaller bubbles (indicative of shearing and partial bubble coalescence, discussed below) observed in the field generated cements are reflective of these calculated results.

Between the field generated cements, there are observed differences in bubble size distribution and mean bubble size between field samples of various foam qualities (Kutchko et al., 2015). The higher quality foams have larger bubbles and display greater connectivity between, and apparent coalescence of bubbles than do the lower quality foams (Rozieres and de, Ferrier, 1991). The high atomization energy in the higher quality foams may partially explain why the higher quality foams have more apparent bubble coarsening or coalescence, and in some cases, higher connectivity in the field samples (Kutchko et al., 2015). There is more energy transferred into the slurry, which can provide the work to overcome surface tension and break apart menisci that are separating bubbles. If it were simply a matter of more gas volume yielding more void space, then the degree of interconnectedness should be the same between foam qualities, but this is not the case (Spaulding, 2015).

Because admixtures and slurry packages are designed under laboratory conditions for use in the field, prior studies have concluded that slurries designed in the high shear lab mixer might result in the wrong combinations or proportions of additives, leading to a variety of cement job problems in the field (Padgett et al., 1996; Jutten et al., 1989; Orban et al., 1986). While it is true that the lab mixers provide greater instantaneous energy inputs than the field mixers (Table 1) – and greater shear rates (Table 2) – the vast majority of the energy transfer and shear strain of a foamed cement slurry in the field process occurs in the atomizer (foamed cement generator). In other words, much of the energy and shear strain applied to a slurry is occurring downstream of the mixing process in the field, after the application of surfactant. Laboratory conditions do not approximate this particular phenomenon. The actual process of mixing the cement in the field – and the associated energy and shear rates – is not the primary energy-based input for slurry deformation, or, energy based bubble dynamics: Atomization of the base slurry by nitrogen is.

8.4. Higher energy (and higher shear) environments promote physical processes which deform the slurry and drive bubble dynamics by way of several mechanisms

Bubbles entrained within a foamed cement slurry have surface tension, and an associated surface energy based on their surface area (Eq. (11)) (Prud'homme and Khan, 1995). The energy barrier for both bubble coalescence and bubble shearing is this surface tension. As with other energetically expensive processes, there must be adequate useable energy inputs available to do the work. Tables 4 and 5 show example calculations of the energy inputs required to shear and expand bubbles, respectively. It is possible to scale these calculations up to do a fuller accounting of the energy expense, but since bubble motion, shearing, and coalescence is a dynamic and complicated process, such computations are outside the scope of this paper. However, when surface tension is reduced, the surface energy required to overcome the energy barrier for surface area expansion or shearing is likewise reduced (Eq. (15) and Eq. (17)). Surfactants are added to foamed cement slurry to lower the surface tension of bubbles, and to reduce these energy costs. Such additives are applied at the beginning of the lab and field process so that they can be mixed into the slurry material before it is impacted by downstream processes. However, if slurry properties are considerably altered downstream of this application, such as in the atomization process, then surfactants and additives influence on surface tension may be altered, although further experimental or modelling work is required to test if and how these mechanisms may altered.

9. Conclusions and recommendations

For typical materials and values assumed in this work:

1. The high velocity injection of nitrogen gas into the base slurry in the field foamed cement generator during atomization transfers the greatest amount of energy of any process;
2. Cumulative mixing energy in the lab and continuous field mixers are roughly equivalent, but lab mixers impart greater instantaneous energy inputs to a base slurry;
3. Even though the lab mixers are higher energy and higher shear devices than the field mixer, most of the energy inputs driving the deformation of slurry and the contributing to bubble dynamics is produced downstream of the mixer in the foamed cement generator in the field. The lab process does not come close to approximating this environment;
4. Laboratory admixture designs do not account for the high energy exchange in the field atomization process: it is important to quantify the energy effects of atomization on the slurry, because this energy exchange is not captured in the laboratory process and may influence the cement bubble distributions;
5. Because higher quality slurries have higher atomization energies, closer monitoring of higher pressure and higher foam quality field jobs may be needed to assess the energy influence on slurry kinetics and bubble sizes following atomization;
6. Although energy transfers resulting from lab and field operational processes cannot fully explain observed bubble size distributions, mixing and atomization energy is shown to provide the physical currency that promotes the deformation and bubble dynamics in a foamed cement slurry.

Industry would benefit from having a laboratory process with better equivalence to the field processes discussed in this paper. Such a test would allow for the production of more reliable laboratory results, and ultimately better performing cements.

Acknowledgements

This work was completed as part of National Energy Technology Laboratory (NETL) research for the Department of Energy's Complementary Research Program under Section 999 of the Energy Policy Act of 2005. This research was supported in part by an appointment to the National Energy Technology Laboratory Research Participation Program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education. The authors wish to acknowledge Roy Long (NETL Strategic Center for Natural Gas and Oil) and Elena Melchert (DOE Office of Fossil Energy) for programmatic guidance, direction, and support. The authors would like to thank Bryan Tennant, Karl Jarvis and Roger Lapeer for making the CT scanner lab functional. Thanks to Rick Spaulding and Jim Fazio for superior laboratory assistance. The authors extend a special thanks to Erick Cunningham and Woody Lawrence, and to Kelly Rose and Jen Bauer. DBG would also like to thank S. Miaskeiwicz, E. Anish, the Millers, Russell Schwartz, and the Arnolds.

References

Ahmed, R.M., Takach, N.E., Khan, U.M., Taoutaou, S., James, S., Saasen, a, Godøy, R., 2009. Rheology of foamed cement. Cem. Concr. Res. 39, 353–361. http://dx.doi.org/10.1016/j.cemconres.2008.12.004.

API RP 10-B, Recommended Practice on Preparation and Testing of Foamed Cement Slurries at Atmospheric Pressure, First Edition Washington, D.C., USA, 2015.

Benge, G., Mobil, E.T.C.D., McDermott, J., Mobil, E.U.S.N.O., Langlinais, J., Halliburton, E.S.H.L., Griffith, J., Halliburton, E.S.D.O., 1996. Foamed cement job successful in deep HTHP offshore well. Oil Gas. J.

Bour, D., Rickard, B., 2000. Application of foamed cement on Hawaiian geothermal well. Geotherm. Resour. Counc. Trans., 24.

Frisch, G.J., Graham, W.L., Griffith, J., 1999. SPE 55649 Assessment of foamed - cement slurries using conventional cement evaluation logs and improved interpretation methods. In: SPE Rocky Mountain Regional Meeting. Society of Petroleum Engineers, Gillette, Wyoming.

Griffeth, J., Lende, G., Ravi, K., 2004. Foam Cement Engineering and Implementation for Cement Sheath Integrity at High Temperature and Pressure. In: IADC/SPE 87194 Drilling Conference.

Hibbert, A.P., Kellingray, D.J., Vidick, B., 1995. No Title. SPE Drill. Complet.

Jutten, J.J., Guillot, D., Parcevaux, P.A., 1989. Relationship between cement slurry composition, mechanical properties, and cement-bond-log output. SPE Prod. Eng. 4, 75–82. http://dx.doi.org/10.2118/16652-PA.

Kroezen, A., Groot Wassink, J., 1987. Bubble size distribution and energy dissipation in foam mixers. J. Soc. Dyers Colour 103, 386–394. http://dx.doi.org/10.1111/j.1478-4408.1987.tb01090.x.

Kutchko, B., Crandall, D., Moore, J., Gill, M., 2014. SPE-170298-MS Assessment of Foamed Cement Used in Deep Offshore Wells.

Kutchko, B., Crandall, D., Moore, J., Gieger, C., Gill, M., 2015. OTC-25994-MS Assessment of Pressurized Foamed Cement Used in Deep Offshore Wells.

Kutchko, B., 2014. Task 3 Cement Barriers : Assessment of Foamed Cement Systems used in Deep Offshore Wells (GOM) Improving Science-Base to Understand Wellbore Integrity & Performance of Foamed Cements.

Ley, M.T., Folliard, K.J., Hover, K.C., 2009. Observations of air-bubbles escaped from fresh cement paste. Cem. Concr. Res. 39, 409–416. http://dx.doi.org/10.1016/j.cemconres.2009.01.019.

McElfrish, P., Boncan, V., 1982. Applications of foamed cement. Soc. Pet. Eng. SPE, 11203.

Nelson, E.B., Bell, D.R., 2006. Well Cementing, 2nd ed Elsevier Science.

Orban, J. a, Parcevaux, P. a, Guillot, D.J., 1986. Specific mixing energy: a key factor for cement slurry quality. Annu. Tech. Conf. Exhib. Soc. Pet. Eng., 1–8.

Padgett, P., Energy, H., Duncan, S., 1996. Shear rate has greater influence on cement slurry properties than total mixing energy.

Prud'homme, R., Khan, S., 1995. Foams: Theory: Measurements: Applications, First Ed. CRC Press, New York.

Rozieres, J., de, Ferrier, R., 1991. Foamed-cement characterization under downhole conditions. SPE Prod. Eng.

Rupnow, T., Schaefer, V., Wang, K., Hermanson, B., 2006. Investigation of portland cement concrete mix consistency and concrete performance using a two-stage mixing process. Transp. Res. Rec. 1979, 12–20. http://dx.doi.org/10.3141/1979-04.

Spaulding, R., 2015. A Quantitative Assessment of Atmospherically generated Foam Cements: Insights, Impacts, and Implications of Wellbore Integrity and Stability, Master's Thesis. University of Pittsburgh, Pittsburgh, PA.

Spaulding, R., Haljasmaa, I., Fazio, J., Gieger, C., Kutchko, B., 2015. OTC-25776-MS An Assessment of the Dynamic Moduli of Atmospherically Generated Foam Cements.

Teodoriu, C., Okolieocha, P.A., Falcone, G., 2015. A theoretical comparison of cement slurry mixing energy in field and laboratory conditions. Environ. Earth Sci. 73, 7043–7051. http://dx.doi.org/10.1007/s12665-015-4229-6.

Vidick, B., 1990. Parameters for good control of cement slurry quality. J. Pet. Technol. 42 (07), 924–928.

Vidick, B., Nash, F.D., Hartley, I., 1990. Cementing through coiled tubing and its influence on slurry properties. Eur. Pet. Conf. 2, 157–165.

White, J., Moore, S., Miller, M., Faul, R., Services, H.E., 2000. IADC/SPE 59136 foaming cement as a deterrent to compaction damage in deepwater production. In: 2000 IADC/SPE Drilling Conference. Doi:10.2523/59136-MS.

Wittmann, F., 1973. Interaction of hardened cement paste and water. J. Am. Ceram. Soc. 56, 409–415. http://dx.doi.org/10.1111/j.1151-2916.1973.tb12711.x.