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Jets of three-phase power-law fluids and foam jet mixing in gypsum slurry

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HIGHLIGHTS

- Mixing of foam with gypsum slurry can be described in the framework of the boundary layer theory.
- The smaller the diffusion coefficient, the weaker the foam mixing.
- The higher the water-stucco ratio, the better the foam mixing.
- The higher crossflow velocities and the lower obliquity angles cause poorer mixing.

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ABSTRACT

Gypsum wallboard is one of the major components of lightweight construction throughout the world. There have been significant efforts in manufacturing lightweight wallboard. One of the key elements of the manufacturing process is mixing foam in gypsum slurry. However, the dynamics of foam mixing in gypsum slurry is not fully explored and understood, which results in a trial-and-error based approach in the process optimization. In the present work, we study foam jet injection into gypsum slurry at rest and in cross-flow. The experimental part of the works reveals the foam/gypsum slurry rheological behavior. Namely, the foam-gypsum slurry mixtures are power-law fluids with the consistency and behavior indexes strongly depending on the local foam content. The submerged jet-like flows of foam/gypsum slurry mixtures belong to the class of the boundary layer problems of strongly non-linear power-law fluids of three-phase media (gypsum stucco, water and air), which is insufficiently studied in the framework of the non-Newtonian fluid mechanics. Moreover, jet propagation in cross-flow is studied here for the first time. Accordingly, a novel numerical approach to this class of problems is proposed and implemented in the theoretical part of the work, and the effect of several governing parameters [e.g., water-to-stucco ratio by mass (WSR), the Schmidt number, etc.] on the flow structure and the mixing rate is evaluated. The theoretical framework described here has a broader importance for multiple technologies related to material processing, and in particular, to formation of gypsum wallboard, since it allows one to predict the effective penetration depth of a jet, and thus, the foam/slurry mixing efficiency and the apparatus size.

1. Introduction

Boundary-layer flows of non-Newtonian, and in particular, power-law fluids have been in focus for the last 50 years due to their importance in various technologies [1–4], and because they represent themselves as a natural extension of the classical boundary layer theory of Newtonian fluids [5–7]. In particular, several self-similar solutions for jet flows of power-law fluids were proposed in [8–15]. It should be emphasized that shear-thinning power-law submerged jets reveal significant differences from their Newtonian counterparts, as well as from the other inelastic non-Newtonian fluid jets, e.g. the yield-stress Bingham fluid jets [16]. Moreover, submerged power-law fluid jets also reveal significant differences from the corresponding non-Newtonian wall-jets and the other jet-like flows restricted by walls, e.g. the coating flows and the impingement jets [17–31]. Note also that the questions of interest in relation to submerged jets of power-law fluids are

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radically different from those related to free-surface jets of power-law fluids [32–37]. Specifically, in the case of the former jets, the velocity profile development is of primary interest, whereas for the latter ones, the jet breakup into droplets is in focus, which is the surface phenomenon totally dominated by surface tension absent in submerged jets.

The solution of non-self-similar hydrodynamic problems related to power-law fluids typically requires numerical simulations of the governing equations. Several methods of numerical simulations of such non-Newtonian problems were proposed (e.g. in [38,39]), albeit none of them is specifically tailored for simulations of submerged jets of power-law fluids, even though such jet flows possess peculiarities which should be taken into account when developing numerical methods. Namely, the submerged jets always possess integral invariants and any numerical method based on a restricted domain applied to such unrestricted jet flows would inevitably preclude the required invariancy, which is unphysical. Therefore, in the framework of the theory of submerged jets of Newtonian fluids special numerical methods employing coordinate transformation which automatically guarantees a required invariancy were developed [40–44]. In the present work, this approach will be applied to submerged jets of power-law fluids for the first time as to our knowledge.

It should be emphasized that for many construction materials (e.g. cement based grout with glass powder for deep mixing) the complexity of the problem increases as a multitude of different additives can be added. In this regard, there have been significant efforts aiming at the rheological characterization of cement mixtures with additives and stabilizers, e.g. clay, lime stone, sand, etc. [45–50].

One of the applications which would require a thorough understanding of the hydrodynamics of jets of power-law fluids propagating in medium at rest or in crossflow is related to wallboard formation from gypsum slurry, where foam jets are injected into slurry and should be uniformly mixed to guarantee a uniform distribution of voids in dry wallboard [51–53]. It should be emphasized that the installation of wallboard is still a manual process. Accordingly, voids reduce board weight and simultaneously improve their thermal and acoustic characteristics. Currently, the design and placements of foam injection ports are done based on a trial and error method. A poorly designed foam ring results in uneven distribution of foam across the wallboard, which in turn can result in weak gypsum wallboard and deterioration of other characteristics. Gypsum slurries are known to be power-law fluids [54], albeit a foam effect on the rheological behavior remains unexplored and is targeted in the experiments of the present work. Moreover, the existing models of mixing of power-law non-Newtonian fluids are mostly irrelevant in questions related to foam injection into gypsum slurries [55–58]. In this particular application our novel approach based on a combination of the rheological experiments with the numerical investigation of submerged jet propagation in the three-phase power-law fluids (gypsum slurries with foam) could greatly facilitate design and development of foam-injection ports, as well as to characterize the foam/slurry mixing efficiency and the apparatus size.

Section 2 provides the original experimental data on the material rheology. Section 3 describes the problem formulation for jets of the three-phase power-law fluids. Section 4 describes the invariant-based coordinate transformation used to develop the novel numerical method proposed in this work. Section 5 discusses the results for straight jets issued into the medium at rest, whereas Section 6 generalizes the method for the case of jets issued into cross-flow and discusses the corresponding results. Conclusions are drawn in Section 7.

2. Rheological characterization of foamed gypsum slurry

When a foam jet is issued into aqueous suspensions of gypsum stucco, a multiphase suspension is formed with the three main components, gypsum stucco, water and air being present. These are essentially the main components of gypsum slurries. Rheological characterization of foamed gypsum slurry with different foam contents is required as a foundation for any further theoretical/numerical work, which is also aimed in the present case. In this section, the rheological constitutive equation of foamed gypsum slurries with different foam content is explored and established by modifying the approach introduced by the present group in [54]. The latter work also contains the scanning electron microscopy (SEM) image of the material and sample preparation details.

2.1. Materials, sample preparation and experimental methods

In the present work stucco, dispersant, soap and climate stabilized accelerator (CSA) were obtained from USG Corporation. All the materials were used as obtained without any further purification. For preparation of stucco slurry, CSA and dispersant were blended with the stucco. In addition, 0.5% of soap was used to generate foam by maintaining the air flow rate at 1.5 L per minute, while keeping the soap flow rate of 120 g/min. The foam volume content was varied in the stucco slurry by changing the stucco content. The gypsum and foam mixing protocol are described as follows: (a) stucco is added to the gauging water (at $t = 0$ s), (b) the mixer is turned on (at $t = 15$ s), (c) foam is added (for $t = 15–40$ s), (d) foamed slurry is mixed for an additional 5 s for better blending ($t = 40–45$ s), (e) the mixer is turned off and the slurry is used for the rheological experiments described below (at $t = 45$ s). Gypsum slurry thus produced was used in the shear rheometry and also for the density measurement. For the shear rheometry, gypsum slurry was poured into a shear viscometer (TA instrument AR 2000ex). A continuous ramp procedure was conducted from the shear rate of 0.5 to 800 s^{-1} in 20 s. Another slurry sample was used for weighing to measure slurry density. The experiments were performed for two different water-stucco ratios (by mass): WSR-68:100 and 75:100 denoted as WSR 68 and WSR 75, respectively.

The gypsum slurries used had different foam contents which were from the 0% to 100% (by volume) range, with a 10% increment. Several trials were done for each slurry composition to acquire reliable statistics. The results demonstrated similar trends for WSR 68 and WSR 75, explicitly, that an increase in the foam content causes a decrease in the shear viscosity at any shear rate, except the transition from 90% to 100% foam, as shown in Fig. 1. The slopes of all the flow curves in Fig. 1 are similar but not exactly identical. For pure foam, the slope is quite different from the other cases. Fig. 1 shows that the shear viscosity for WSR 68 without foam is high, as expected, compared to WSR 75, since WSR 68 corresponds to a lower water content resulting in a lower fluidity. However, it should be emphasized that the viscosities decrease more rapidly for WSR 68 as the shear rates increases, in comparison to those of WSR 75. This can be attributed to random mixing, breakage and coalescence of air bubbles within the slurry.

Note also that Fig. 1 shows that slurry viscosity with higher water content (WSR 75) seems to be much less sensitive to additional foam content than the more concentrated one (WSR 68). This fact can be attributed to the conversion of calcium sulfate hemihydrate into calcium sulfate dihydrate in the gypsum slurry. Calcium sulfate dihydrate forms needle-like crystals. Their hydrodynamic interaction increases dramatically when water content decreases to that extent as in WSR 68, especially given the fact that the additional foam contains some additional water. This is the