Blast Wave Mitigation by Particulate Foams

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1. Introduction

The unique features of particulate foams as blast wave absorbers were demonstrated first in the experiments [1] and explained by the increased viscous losses. There are also evidences that additives of large particles (tens μm in diameter) reduce the drainage rate [2]. While these facts look intriguing, the available information in this area was mainly published in patented literature, which complicates the judgment between the different effects.

The primary intention of the present study is to examine the (i) reflection of a shock wave and a blast wave pressure, from the foam face; (ii) transmission through the foam face; and (iii) mitigation inside the particulate foam. Since wet aqueous foams of desired specification are difficult to reproduce, handle, and quantitatively characterize the fact that experiments were conducted in a single facility is a potentially important consideration. A vertical position of the shock tube simplified the issues since the gradient of the liquid fraction in the draining foam coincides with the direction of the shock wave propagation. Under these, much simplified test conditions, the resulted flows could be treated as one-dimensional and the shock wave mitigation depends on the intensity and profile of the incident shock wave, M_s, the duration of the foam decay, Δt, and on the particle concentration, n.

2. Experimental details

To be valuable for practical applications, particles have to be harmless, cheap, hydrophilic, and have proper dimension and density. On this basis as a first approach, we used a powder of coal fly ash containing about 20% of small-size fraction ($0.1 < d_p^* < 2\ \mu m$) and 80% of large-size fraction ($2 < d_p^* < 80\ \mu m$). The foaming liquid (m_l=200 ml) was composed of 190 *ml* of tap water and 10 *ml* of commercial surfactant ATS-787F, which were mixed manually in a beaker. The powder, whose mass concentration was varied from n=0 to n=0.33 was stepwise added to the foaming liquid and further whipping during 2 min provided the foam with liquid fraction $\alpha_0 \approx 0.2$. Then, this foam was poured into the *420-mm* long test section of a vertical Perspex made diaphragm-less shock tube, shown in Fig. 1a, which has a square 32 *mm* x 32 *mm* cross section. The shock wave or blast wave profiles of high repeatability were generated by a fast opening pneumatic valve [3]. Kistler 603H series pressure transducers allowed examining the resulted pressure field.

Typical foam images in Fig. 1c show that the added powder imparts a black color to the foam pictures, which does not prevent the imaging and subsequent data processing of the results.

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The test procedure implied that the “freshly-prepared” foam samples were left in the test section to drain during the controlling period, Δt, and then were subject to impact once the test section was bolted back to the channel. Full PC control over the driver pressure, running the valve and triggering the data acquisition system (GagesScope C-220) was supported by a Lab View code.

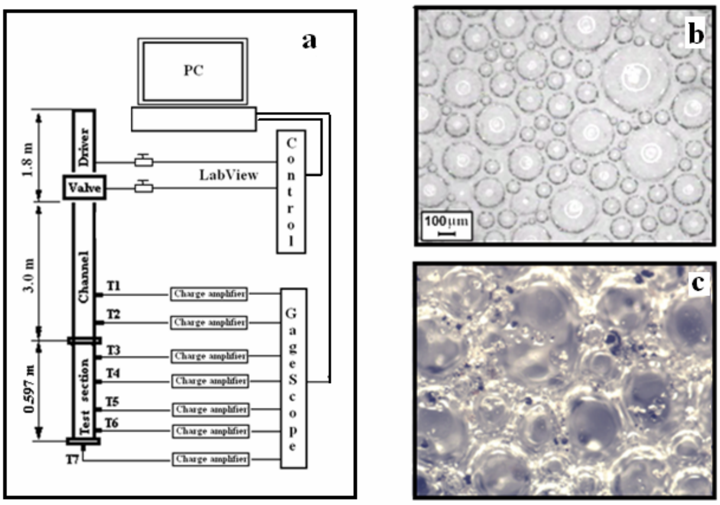


Figure 1: Schematic of the vertical shock tube (a) and typical images of conventional, $n = 0$, (b) and particulate, $n = 0.1$ (c) aqueous foams.

3. Obtained results and discussion

Common features

The collisions of the waves and their interactions with foam were simulated within the limits of so-called ideal shock tube theory of pseudo-fluid [4]. The resulted flow pattern, shown in Fig. 2, initially is controlled by the propagation of the incident shock wave, In, contact surface, CS and rarefaction wave, R. The related flow states behind the incident shock wave (In), the contact surface (CS), and then, the shock wave (Rf) reflected at the foam face are labeled as (2), (3) and (5), respectively. During the slow travel, the shock Tr over the sample (about *16 ms*) reflected shock Rf, which hits the contact surface, CS ,gives rise to the new backward faced shock Rd. On reaching the foam face, the shock wave Rd changes the parameters inside the sample. The second important event is rarefaction fan RRw, which is just emerging as reflection of rarefaction wave R at the driver’s end. When overtaking the foam face and then, the transmitted shock wave, Tr, rarefaction fan RRw further dominates over the flow parameters in the vicinity of the end wall.

Since the pseudo-fluid code ignores any internal dissipation, the wave diagram of Fig. 2 is only a reference guide explaining the flow pattern in freshly prepared ($\Delta t = 0$) sample of conventional (n=0) foam. Further results demonstrate new details related to particle related properties observed for $0 < \Delta t > 60\,\text{min}$.

Pressure behind the reflected shock wave, Rf

The reflected wave, Rf, registered by the sidewall pressure transducer upstream of the foam face plays an important role in the probing the foam face conditions. Two series of such traces

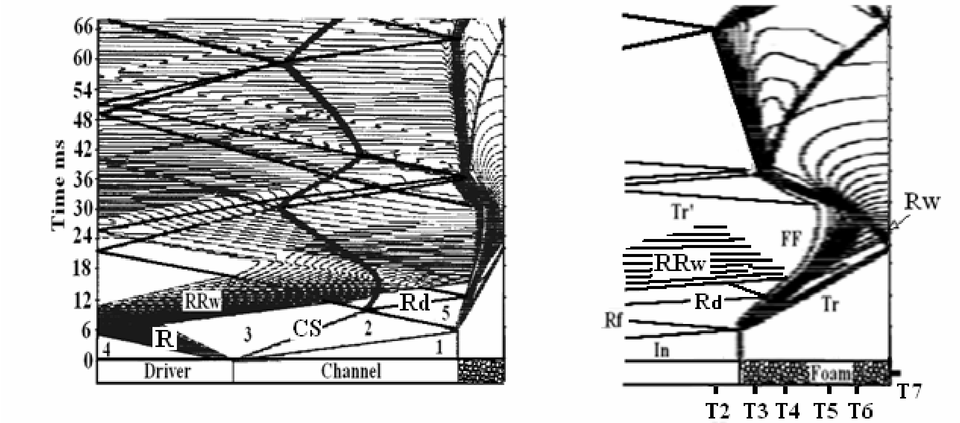
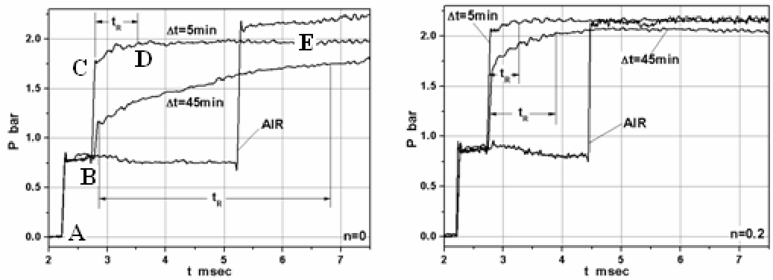


Figure 2: Full scale diagram (a) and zoomed fragment (b) of the wave pattern inside the shock tube; $\alpha_0 \approx 0.2$ and $M_s = 1.3$.

are shown in Fig. 3, where the initial pressure rise (A) is consistent with the passage of the incident shock wave, In. Similarly, the second steep rise (B-C) is typical of the reflected shock wave, R_f. Following the rise of the pressure to point C, there is a change in the slope to reach the plateau region (D-E). Examination of the feature (C-D) shows that when the decaying time is high ($\Delta t = 45\ min$) this so-called rounding is smooth, while in fresh prepared sample ($\Delta t = 5\ min$) it is closer to being angular. The reason for the pressure traces to be rounded, as well as amplitudes of the pressure rise (B-C) are both to be ascribed to the transient acceleration of the foam face [3].



a b

Figure 3: Sidewall pressure traces registered *90 mm* upstream of the regular ($n = 0$) and particulate ($n = 0.2$) foam face, $\alpha_0 \approx 0.2$ and $M_s = 1.3$.

Time distance trajectories and sidewall pressure

Figure 4 demonstrate that:

(i) The role of the foam decay during the first *5 min* after the foam production (left figure) is negligibly small and all the trajectories are straight lines;

(ii) The propagating velocity of the transmitted shock wave in particulate foam ($n = 0.33$) is reduced by up to 20%;

When $\Delta t = 30\ min$ (right figure) spatial non-homogeneity of the conventional ($n = 0$) foam becomes significant while, added particles improve the foam stability and the trajectory registered in the particulate foam ($n = 0.33$) remains straight

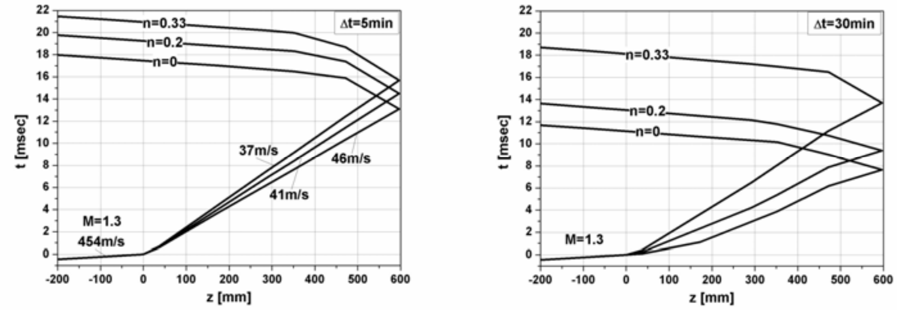


Figure 4: Time-distance trajectories of the transmitted shock waves in regular ($n = 0$) and particulate ($n = 0.2$ and $n = 0.33$) aqueous foams of high liquid fraction $\alpha_0 \approx 0.2$ and $M_s = 1.3$.

Fig. 5a demonstrates double-fronted wave structures with sharp leading front and dip which is not observed in the pressure profiles of Fig. 5b. Duration, t_r, is evidently reduced with increased Mach number, M_s and possible explanation to this effect is under active investigation in the ongoing program at the Ben-Gurion University.

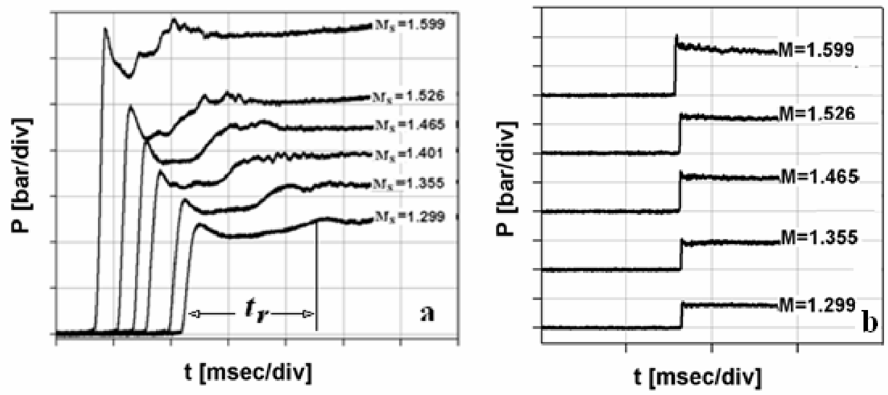


Figure 5: Sidewall pressure traces registered inside a conventional foam (a) and air (b), *230 mm* downstream from the foam face, $\Delta t = 5\ min$.

Acknowledgment

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