

BLAST WAVE PROTECTION OF AQUEOUS FOAMS

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INTRODUCTION

Whereas the plausible mechanisms of the blast wave mitigation by regular and particulate aqueous foams were the subject of many experiments and simulations [1], the basic science behind these phenomena is still not well understood. The unique features of the particulate foams as the sound and shock wave absorber were demonstrated first in the experiments conducted in open cut mines by Moxon et al (1990). For the particles size smaller than $76\ \mu\text{m}$ a principal mechanisms of sound and shock wave attenuation were explained by the increased viscous losses. There are also evidences (Hunter et al 2008) that additives of large particles (tens μm in diameter) increase the dissipation of the concomitant flow of the interstitial liquid and thus reduce drainage rate. Whereas these facts look intriguing, sparse experiments demonstrate any consensus neither on the optimal particulate materials nor on final effects caused by solid additives. For example, whereas in the experiments of Moxon et al (1990) attenuation of the sound wave increased with raised concentration of particles, in experiments of Feklistov et al (1994) aqueous foam particulated by $30\ \mu\text{m}$ particles of cork was more transparent for sound than particles-free foams of the same conditions. Unfortunately, the most recent information in this area has been rather empirical or published in patented literature where brief discussion and barring explanation to “know how” complicate the judging between the different effects.

The primary intention of the present study is to present new contribution of shock tube tests to the problem of particle related stabilization and enhanced mitigation action of the wet particulate foams. The experiments reported were designed to examine (i) the reflection of a shock wave from an air/foam face, (ii) the transmission of the shock wave through the air/foam face and (iii) propagation and dispersion of the transmitted shock wave inside the foam column.

Because wet aqueous foam of desired specification is difficult to reproduce, handle and quantitatively characterize the fact that experiments on all the above aspects were conducted in a single facility is a potentially important consideration. Moreover vertical position of shock tube simplified the issues since the gradient of the liquid fraction in draining foam coincides with the shock wave propagation. Under these, much simplified test conditions resulted flows could be treated as one-dimensional and the shock wave mitigation depends on three parameters: the intensity of the insident shock wave, M_s , the duration of the foam decay, Δt and on the particle concentration, n .

EXPERIMENTAL DETAILS

To be valuable for practical applications particles have to be harmless, cheap, hydrophilic, have proper dimension and density. On this basis as a first approach we used powder of coal fly ash as received from Ashkelon power plant (Israel). Physical properties of the coal fly ash include: specific gravity

2.1 g/cm^3 , specific surface area by BET $2.05 \text{ m}^2/\text{g}$ and PH 11.9. Mineralogical composition includes quartz, hematite, mullite, unburned carbon, calcium aluminum oxide ($\text{Ca}_3\text{Al}_2\text{O}_6$) and calcium silicate sulfate ($\text{Ca}_5\text{Si}_2\text{O}_8\text{SO}_4$). The results of MasterSize analysis in figure 1 show that powder contains about 20% of small-size fraction ($0.1 \mu\text{m} < d_p^* < 2 \mu\text{m}$) and 80% of large-size fraction ($2 \mu\text{m} < d_p^* < 80 \mu\text{m}$).

To prepare the foam, the powder was added to the foaming liquid composed of 190 ml of tap water and 10 ml of commercial surfactant ATS-787F. The foaming solutions ($m_l=200 \text{ ml}$) was mixed manually in a beaker and thereafter was stepwise added the powder ($m_p=20 \div 100 \text{ gr}$), which

concentration is $n = \frac{m_p}{m_l + m_p}$. Resulted solution was poured into a high-speed blender for whipping

during a time period about 2 min. Foam usually reached its steady height providing a constant value of liquid fraction $\alpha_0 \approx 0.2$. For the shock tube tests foam was then poured into the test section of the vertical diaphragm-less shock tube shown in Fig.2 which has a square 32 mm x 32 mm cross section made of perspex with dimensions 32mm(W)×32mm(D)×420mm(H). Shock tube generates step-wise profile of the post shock wave pressure at the foam entrance and high repeatability of the impact conditions ensures fast opening pneumatic valve that used instead of membrane between the driver and channel Britan et al (2007). The Kistler 603H series pressure transducers allowed to examine the resulted pressure field behind the reflected wave and the the wave transmission inside the foam column. When the particles are embeded inside the freshly prepared sample their initial distribution is homogeneous and foam density could be easily controled through the liquid fraction, α_0 and/or particles concentration, n.

Typical foam images in Fig. 3 show that the added powder imparts a black color to the foam pictures which however not prevent the imaging and subsequent data processing of the results.

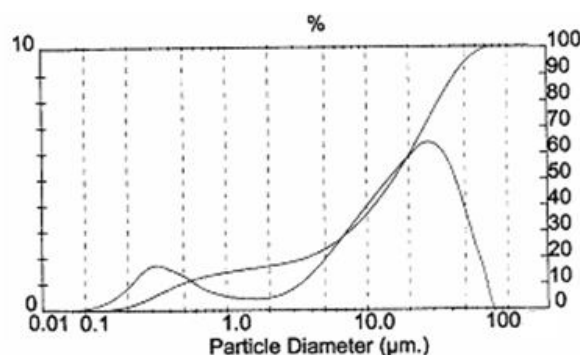


Figure 1: Size distribution of particles diameters after the special treating of row powder of coal fly ash (Mastersizer 2000).

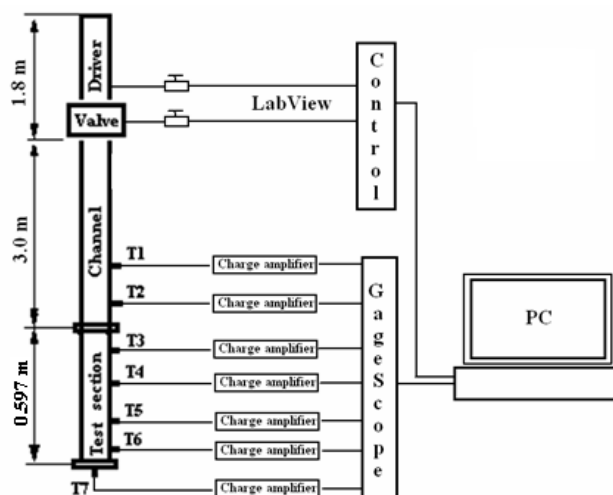


Fig.2: Schematic of the vertical shock tube and controlling equipment

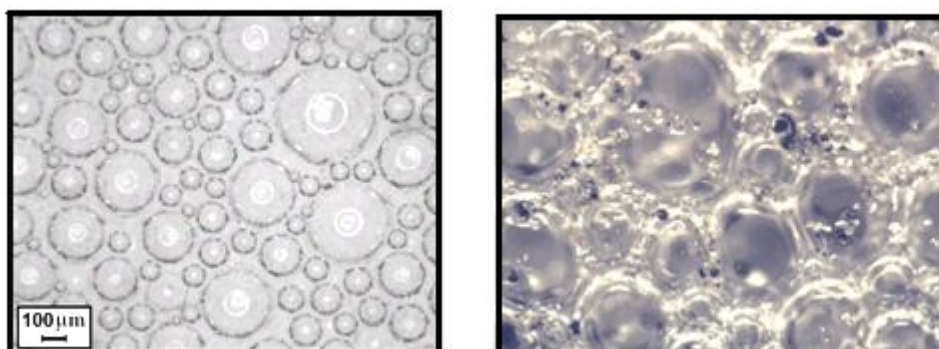


Fig.3.: Registered images of aqueous foam $\eta = 0$ (left), and particulate foam $\eta = 0.1$ (right)

The test procedure considers that the “freshly-prepared” foam samples left in a test section to drain during the controlling period, Δt and then subject to impact once the test section has 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 based software.

OBTAINED RESULTS AND DISCUSSION

Common features

Prior to the discussion the experimental results, it is worthwhile to describe the appropriate findings inferred from the results of numerical simulations of the shock wave/foam interaction in shock tube shown in Fig. 4. The waves collisions and their interactions with solid walls simulated within the limits of so-called ideal shock tube theory assuming that the driver and the channel at $t=0$ contain air with adiabatic indexes $\gamma_4 = \gamma_1 = 1.4$ and molecular weight $m = 29 \text{ g/mole}$. A wet foam (

$\alpha_0 = 0.2$) filling the test section was represented as a homogeneous single component pseudo-gas with $\gamma_f = 1.0003$, $m = 5774 \text{ g/mole}$. The initial conditions are:

$$\left. \begin{aligned} P_4 &= 4.0 \text{ bar}, \quad T_4 = 300 \text{ K}, \quad V_4 = 0 \text{ along } x \leq 1.8 \text{ m} \\ P_1 &= 1.0 \text{ bar}, \quad T_1 = 300 \text{ K}, \quad V_1 = 0 \text{ along } 1.8 < x \leq 5.397 \text{ m} \end{aligned} \right\} \quad (1)$$

where the subscripts 1 and 4 correspond to the related areas of Fig 4 (see for details Britan et al (1994)). The initial flow pattern inside the shock tube mainly controlled by the three events: 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 in Fig. 4 as (2), (3) and (5), respectively. In the period immediately following the formation of the reflected shock wave Rf, strong limitations on the flow pattern imposes the length of the foam sample (height H). Due to the high acoustic impedance and low sound speed specific for wet foam the propagation of transmitted shock wave Tr over the sample takes about 16ms. During this slow travel two subsequent events restrict its the quasi-steady moving. The first is the reflected shock Rf which hits the contact surface CS and 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 event that causes the stronger changes in the flow pattern 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 pseudo-gas model considers only acoustic characteristics of foam while ignores surface tension and internal dissipation, the wave diagram of Fig. 8b is only a reference guide explaining the key points of the flow pattern. In the real test, freshly prepared sample of wet foam quickly decays and resulted distribution of liquid fraction $\alpha(z)$ changes in time. For this reason the controlled duration of the foam decay before the test, Δt becomes a crucial parameter responsible for any distinguish between the real and simulated flow pattern. Essential information on this process could be inferred from the careful examination of the pressure readings registered behind the reflected Rf and the transmitted Tr shock waves Britan et al. (2007).

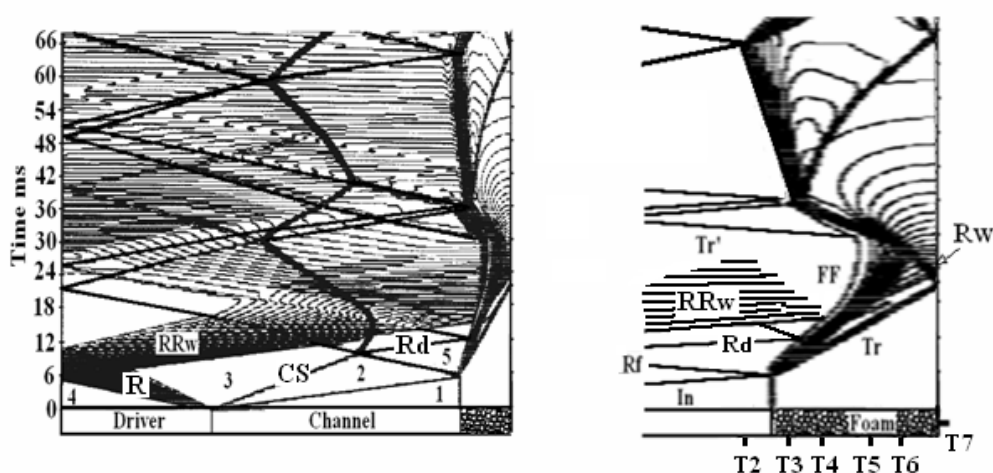


Fig. 4. Full scale diagram of the shock tube flow (a) and zoomed fragment of the wave pattern inside the test section (b) filled with the aqueous foam of high liquid fraction $\alpha_0 \approx 0.2$, $M_s = 1.3$.

Pressure behind the reflected shock wave, R_f

As it was pointed out previously, information on formation of the reflected wave R_f as it could be obtained from the side wall pressure traces registered upstream of foam face plays an important role in the probing the foam face conditions. Two series of such traces are shown in Fig.5, 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 reflected shock wave R_f . Following the rise of the pressure to point C, there is a change in slope to reach the plateau region (D-E). Examination of the feature (C-D) shows that after the long time decay ($\Delta t = 45 \text{ min}$) this so-called rounding is smooth while in fresh prepared sample of wet regular foam ($\Delta t = 5 \text{ min}$) it is closer to angular. As noted recently Britan et al (2007) 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 initial phase of transient acceleration of the foam face. From this conclusion it would then appear that time duration of the foam decay, Δt should be a main factor in this process. To ensure this, the values t_R and the

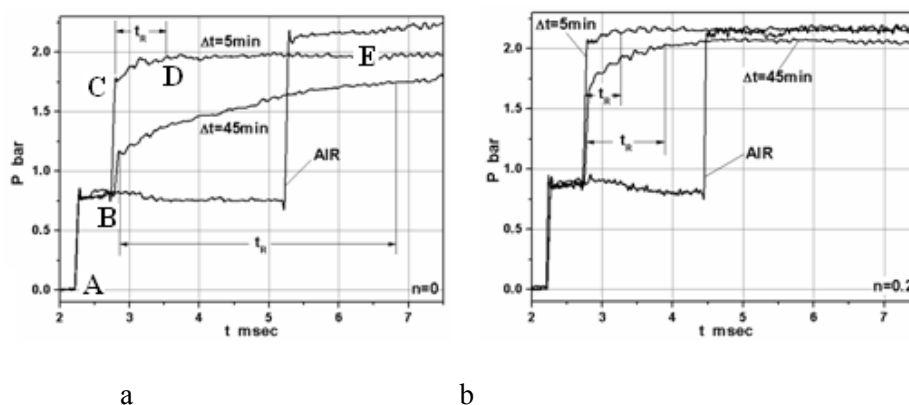


Fig. 5. Side wall pressure traces registered 90mm upstream of the regular ($n=0$) and particulate ($n=0.2$) foam face, $\alpha_0 \approx 0.2$, $M_s = 1.3$.

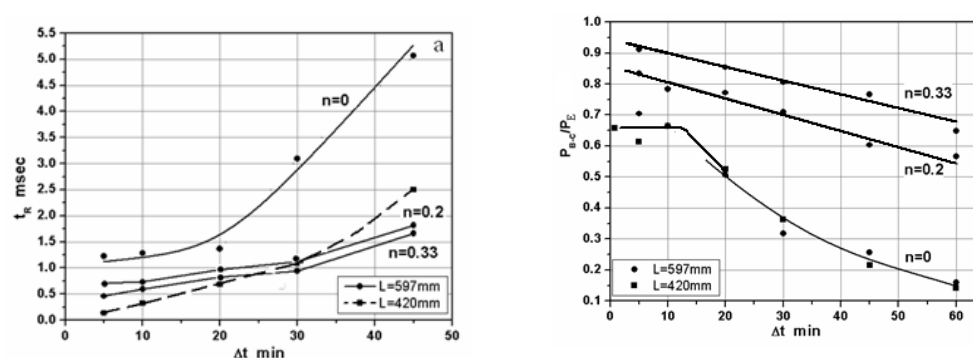


Fig. 6. Rounding t_R (a) and normalized pressure rise (B-C) (b) registered 90mm upstream of the regular ($n=0$) and particulate ($n=0.2$ and 0.33) foam face, $\alpha_0 \approx 0.2$, $M_s = 1.3$.

amplitudes of the pressure rise (B-C) registered in regular and in the particulate foams are presented as function of Δt in Fig.5. The general trend that follow these graphs supports the conclusions that when Δt increases, the rounding (C-D) lasts longer, and the pressure front (B-C) becomes smaller. Whereas initially, ($\Delta t \approx 15$ min) amplitude of the pressure front (B-C) is only about 30% weaker than equilibrium value P_E , when drainage proceeds about 30 min it becomes twice as smaller and for $\Delta t \approx 60$ min is ill defined at all. Notice that rounding t_R and overpressure P_{B-C} are both sensitive to the foam decay which in turn affects the initial stage of the foam movement. However, the rounding t_R is implicit parameter that is responsible for a number of transient phenomena that follow the moving foam face. On contrast, the overpressure P_{B-C} is explicit parameter that carries out direct information on the conditions at the foam face just before the shock tube was actuated. Different correlation of these data with our results obtained recently with the shorter sample of similar aqueous foam Britan et al (2007) supports this conjuncture. In fact, whereas both functions $P_{B-C} / P_E(\Delta t)$ in Fig. 6b overlap each other, the data for rounding $t_R(\Delta t)$ obtained recently by Britan et al (2007) fall in the range specific for particulate foam.

Time distance trajectories and side wall pressure

Since the transmitted shock wave Tr actually scans the foam sample over the full length the registered trajectories shown in Fig. 7 demonstrate that:

- (i) the role of the foam decay during the first 5 min after the foam production (left figure) is negligible small and all the trajectories are straight lined;
- (ii) added particles reduce the propagating velocity of the transmitted shock wave in particulate foam ($n=0.33$) up to 20%;
- (iii) after the 30 min of decay (right figure) spatial inhomogeneity of the regular (no-particles) foam ($n=0$) becomes significant;
- (iv) added particles improve foam stability to the point than the trajectory registered in the particulate foam ($n=0.33$) remains straight lined even for $\Delta t = 30$ min.

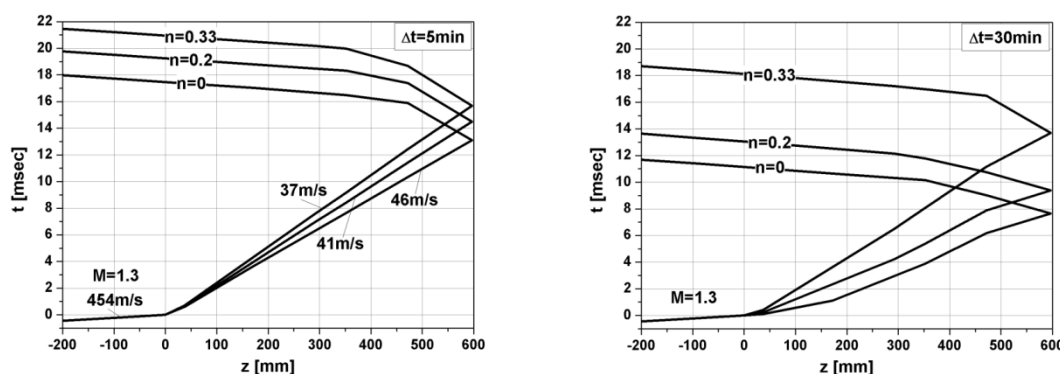


Fig.7: Time-distance trajectories of the transmitted shock waves in regular ($n=0$) and particulate ($n=0.2$ and $n=0.33$) aqueous foam of high liquid fraction $\alpha_0 \approx 0.2$, $M_s = 1.3$.

The side wall pressure profiles shown in Fig. 8 demonstrate interesting phenomenon of so-called double-fronted wave with slow pressure rise to a constant level which is clear evidence of a number of interrelated effects, extensively discussed in the past Weaver and Pratt (1988). Summing up the discussion Weaver and Pratt (1988), for example, suggested that four candidate explanations to be considered:

1) The nonsteady interactions emanating from the upstream air/foam boundary; 2) the non-one-dimensional behaviour of the wave system due to transverse gradients in the foam; 3) non-equilibrium relaxation of the foam in two time-dependent stages reflecting the different responses to the propagating wave of the lamellae and Plateau borders; 4) phase changes or anomalous Hugoniot. In our later Britan et al paper we first combined the side wall pressure measurements with the optical observation to show that in dry aqueous foam ($\alpha_0 \approx 0.01$) this feature reflects the dynamic of the post shock wave compression and further shuttering of the foam cells. Notice that dispersion of the leading shock in Fig. 8 increases with the distance along the foam column and with the time duration Δt . This leaves no doubts that role of the foam decay on this phenomenon is of important.

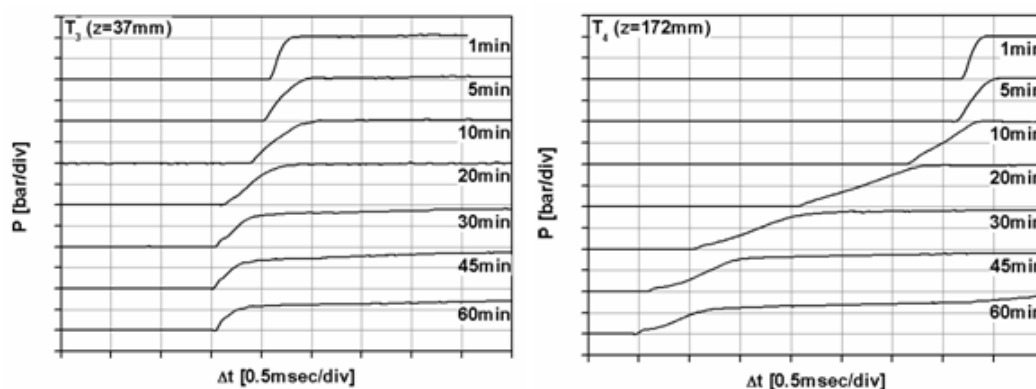


Fig. 8: Side wall pressure traces in regular foam ($n=0$) as function of the time duration Δt

Fortunately, so-called "dead time" period, about 5 min, exists when distortion of the leading fronts in Fig. 8 is small and trajectories of the transmitted shock wave T_r in Fig. 7a are straight. This period allows observing the shock wave/foam interaction under the steady foam conditions when the speed of the transmitted shock wave T_r depends only on single parameter: intensity of the impact or Mach number, M_s . As expected, data in Fig. 9 show the straight line trajectories for all range of the studied conditions demonstrating that the transmitted shock wave velocity is constant and is about ten times smaller than velocity of the impact (velocity of the incident shock wave in Air).

Interestingly that the side wall pressure traces in Fig. 10a also resemble the double-fronted wave structures demonstrated in Fig. 8. On contrast to a slow pressure rise from precursor to a peak level in the pressure traces of Fig. 8 a leading front now is sharp and followed with a pressure dip which duration, t_r , reduced with increased Mach number, M_s . Such a dip is definitely not observed in the pressure profiles of Fig. 10b registered in similar experiments while with the empty test section.

On the limited evidences collected here candidate explanation for the double-fronted wave structures in Fig. 10a is staged relaxation of the foam structure as response to the shock wave impact. However, since the final pressures after the dip and these at the shock wave front are equal, the energy losses in this area appear too small to accept the foam shattering for this case.

Notice that shock wave thickening and "delay" in the wet foam particulated by different solid additives have a direct bearing on energy exchange in the foam based barriers and are under active investigation in the ongoing program in the Ben-Gurion University.

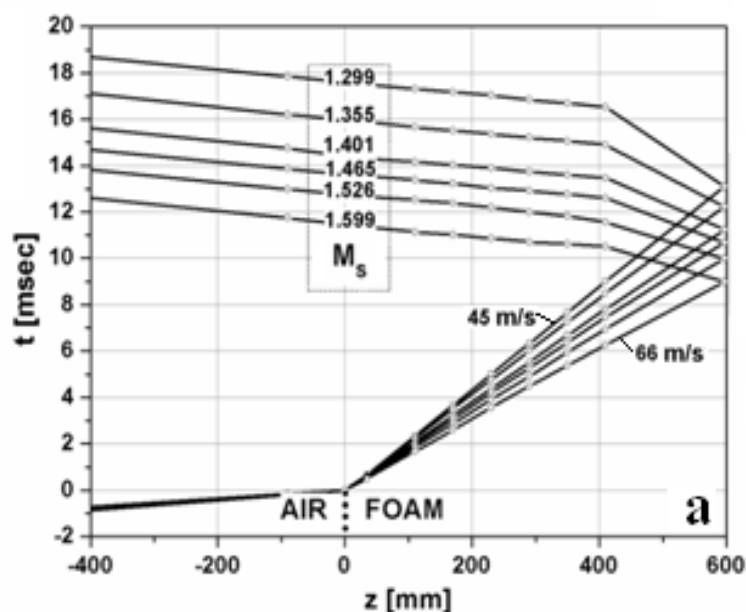


Fig.9 Time-distance trajectories of the transmitted shock waves in freshly-prepared ($\Delta t = 1$ min) regular ($n=0$) aqueous foam (a) and ratio of transmitted V_{Tr} to incident V_{In} shock wave velocities as function of M_s (b).

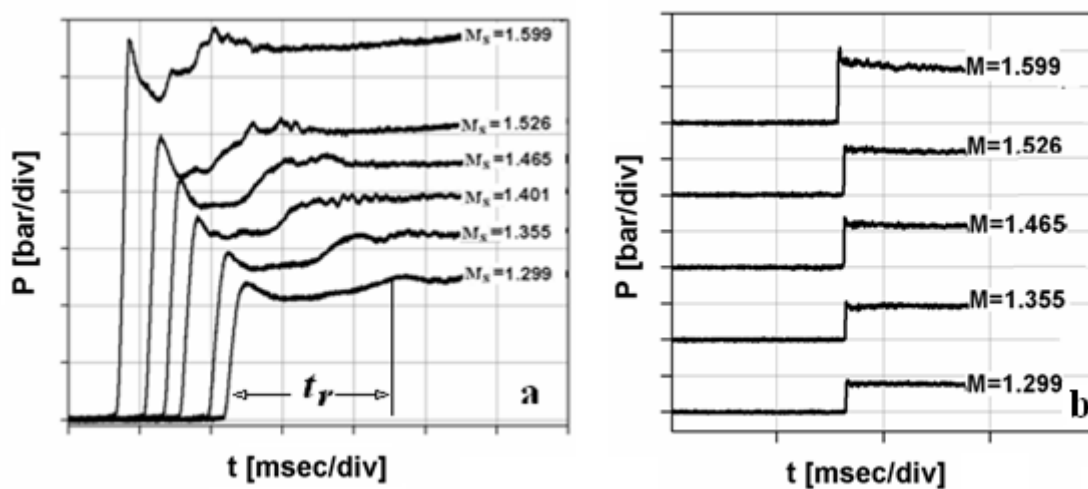


Fig.10: Side wall pressure traces registered inside the regular foam (a) and air (b), 230 mm downstream from the foam face, $\Delta t = 5$ min.

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