Numerical Modelling of Shock-Wave Propagation in a Shock Tube Filled with Aqueous Foam

D. Counilh, E. Del Prete, A. Chinnayya, A. Hadjadj, N. Rambert, J.-F. Haas, G. Jourdan, C. Mariani, and L. Houas

1 Introduction

Aqueous foam belong to the modern protective technologies, in which the blast wave energy is transformed into less destructive forms. Several unsteady aspests of shock/foam interaction have been highlighted by Britan et al. [1],[2]. Under shock impact, the foam is shattered into a liquid spray. Thus one of the key issues is the determination of the two-phase momentum transfer between the liquid and the gaseous phases, which constitute the foam [3]. Experiments have been carried out on the T80 shock tube of IUSTI in Marseille [4] to assess the momentum transfer term of a multiphase model, that has been developped specifically for this purpose [5],[6] of blast wave mitigation by dry aqueous foam.

2 Numerical Modelling

Aqueous foams are natural but metastable states. Under high pressure load shock impact, the liquid matrix is likely to be shattered into more stable droplets [1]. This has led to model the process of shock wave attenuation in shock tubes, by a foam screen formed by a gaseous suspension of water droplets [2]. In this study, a two-fluid model is developed assuming a desequilibrium between pressure, velocity and temperature. Indeed, the travelling of shock wave over the two-phase system will cause the two phases to be brought to different mechanical and thermodynamic

D. Counilh · E. Del Prete · N. Rambert · J.-F. Haas
CEA, DAM, DIF, Arpajon, 91297, France

A. Chinnayya · A. Hadjadj
CORIA CNRS UMR 6614, Site du Madrillet, Saint-Etienne du Rouvray, 76800, France

G. Jourdan · C. Mariani · L. Houas
Aix-Marseille Université, IUSTI-CNRS UMR 7343, 5 rue Enrico Fermi,
F-13013 Marseille, France

R. Bonazza and D. Ranjan (eds.), *29th International Symposium on Shock Waves 2*,
DOI: 10.1007/978-3-319-16838-8_116

states, due to their impedance contrast. Relaxation processes will attempt to edge the phases towards equilibrium. The post-shock states will then relax to the same thermo-mechanical state at the end of a relaxation zone. The mathematical model is derived based of the eulerian balances for the volume fraction, mass, momentum and total energy of each phase. Under a compact form, the two-fluid model can be written:

$$\frac{\partial(\alpha W)_k}{\partial t} + \frac{\partial(\alpha F)_k}{\partial x} = F_k^{lag}\frac{\partial \alpha_k}{\partial x} + S_{d,k} \tag{1}$$

where α_k, ρ_k, u_k, E_k, H_k, P_k are the volume fraction, density, velocity, total energy, total enthalpy and pressure of each phase. Respectively, $W = (1, \rho, \rho u, \rho E)$ is the fluid conservative variables, $F = (0, \rho u, \rho u^2 + P, \rho E u + P u)$ the fluid eulerian flux and $F^{lag} = (-u_i, 0, P_i, P_i u_i)$ the fluid lagrangian flux. Each phase is governed by its own equation of state: Perfect Gas Law for the gas phase and Stiffened Gas for the liquid phase. The interfacial variables P_i, u_i are issued from the homogenization method *Discrete Equation Method* (DEM) [5]. These quantities play a key role on the interfaces in order to satisfy the interface conditions. S_d accounts for the momentum and energy exchanges between phases. The momentum interphase interaction is represented by the drag force of the gaseous phase on the liquid [7]. Energy exchange is associated to heat transfer. These phenomenological relations enable to close the dissipative source terms S_d. The pressure relaxation rate is infinite [8]. The mathematical well-posed properties of this model have been described in [5]. Moreover, an asymptotic derivation towards a one-velocity can be achieved and will show that the sound speed of the phase mixture is the sound speed of Wood. The resolution can be found in [5],[6].

3 Experimental Data

These experiments were conducted into a shock tube of 379 cm length with a 8 cm by 8 cm square cross section [4]. The high pressure (HP) chamber is filled with either SF6, air or helium at various pressures. The choice depends on the desired celerity of the incident shock wave and rarefaction wave. The low pressure (LP) chamber is separated in two parts. The first one immediately after the diaphragm separating the HP and the LP chamber is filled with air at local atmospheric conditions. It allows the formation of an incident shock wave and its measurement. The second part is a test section filled with foam of different expansion ratios (ER). Two pressure transducers in air noted C_8 (177 cm) and C_7 (263 cm) and six transducers including C_6 (297 cm), C_5 (308 cm), C_4 (319 mm) in the foam are used to register the pressure histories and to analyse the effects of aqueous foams on shock waves. The pressure histories are completed by a video of the foam fragmentation under sollicitation. The experiments conducted in the campaign of IUSTI [4] concerned foam of ER 30 or 80 and shock wave Mach numbers of 1.07, 1.3, 1.5 and 1.8.

E. Del Prete [3] determines the pressure threshold at which the foam collapses, for ER 30 and 80. Here, we present the comparison between numerical and experimental results.

4 Comparison between Calculations and Experiments

In the specific case of foams of ER above 20, it is usual to consider that all the liquid of the foam is contained in the Plateau Borders (PB) which can be described as cylindrical liquid ligaments [9]. The knowledge of the cylindrical volume allows the determination of the droplet size in the numerical model. For both expansion ratios, the average droplet radius has been defined taking into account the coarsening of the foam at the instant of the shot. For ER 30 and 80, the average droplet radius is 47 and 70 μm, respectively.

In this work the fragmentation of the foam as well as the momentum transfers of liquid ligaments in the gas flow are investigated. The video animation (Fig. 1) shows that under shock loading, the liquid films are first destroyed. Then, the gas flow deforms and destroys the vertices between the PB. This conducts to a modification of the liquid structure. When each PB separates, it also deforms and accelerates due to the gas flow. It then evolves to a spherical droplet.

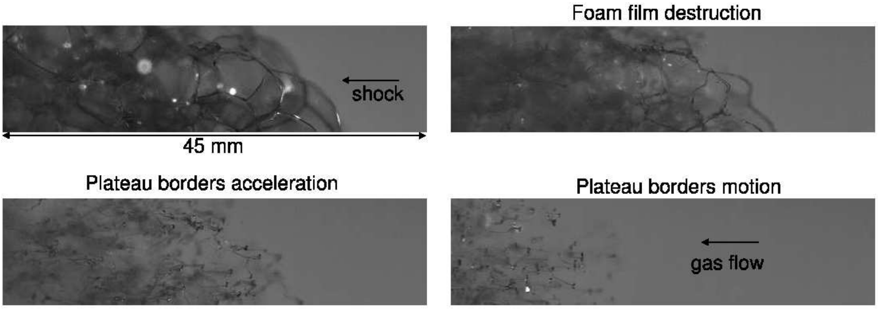

Fig. 1 Foam destruction after shock sollicitation

The experimental pressure histories show that the incident wave front is modified by the presence of aqueous foam. Moreover, the post shock evolution of the topology of the liquid phase has a deep influence on the transients of the compression wave. We identified the presence of a precursor shock wave through which the aqueous foam remains intact. The pressure threshold P_c is estimated to be between 0.1 and 0.2 bar. Below P_c, the foam is intact and the liquid and gas phases velocities are equal. Then over P_c, the foam collapses. Due to the different inertia, some momentum transfer takes place between the liquid ligaments and the gas carrier phase. This precursor shock is thus followed by a compression wave which corresponds to the liquid ligaments displacement in the gas flow and their evolution into a droplets spray. Consequently, the momentum transfers follow a modified Stokes law: $C_d = \xi \dfrac{24}{Re_p}$. The analysis of the shock wave experiments has lead to ξ=70.

The compression wave is finally followed by a rarefaction wave originating from the HP chamber. With air driver gas (Fig. 2) overpressure mitigation occurs, but with SF6 driver gas (Fig. 5) it does not occur. In the shot with SF6, the rarefaction waves originating from the HP chamber arrive too late. We can conclude that the mitigation is due to the interactions between rarefaction waves and the shock front. However, the unique use of the modified Stokes law does not allow a correct simulation of the interaction of this expansion wave with the foam. A modified version of the drag coefficient chosen in [7] for liquid droplets in a gaseous flow, C_d = 1.6, has therefore been adopted when the calculated pressure decreases, and yields a better agreement with the measurement. With this second expression, the $M^3OUSSACA$ calculation (in broken lines in figures 2 to 6) better reproduces the measured shock wave attenuation by the aqueous foam. In these figures, we show the pressure signals of transducers C_8 and C_7 in the LP chamber and C_6, C_5 and C_4 in the test section.

Indeed, when a shock wave interacts with aqueous foam, the latter undergoes a deformation which induces the rupture of liquid films and the destruction of PB into ligaments. Due to the momentum exchange with the gas flow, the liquid ligaments are progressively accelerated to the gas velocity. Due to surface tension, this acceleration leads to the breakup of the ligaments into a cloud of spherical droplets. The velocity relaxation time between the two phases can be expressed as $\tau = \frac{4}{3C_d} \frac{\rho_L}{\rho_G} \frac{d}{u_G - u_L}$ where d is the droplet diameter, L stands for the liquid phase and G the gas one. In the present situation, the velocity relaxation time between the liquid phase of the foam and the gas is about 400 μs. The analysis of the experimental signals (in continuous lines in figures 2 to 6) shows that the duration of the compression wave appearing after foam fragmentation is about 2 ms. A second expression for C_d valid for the propagation of shock and rarefaction waves in a homogeneous distribution of spherical droplets has been chosen.

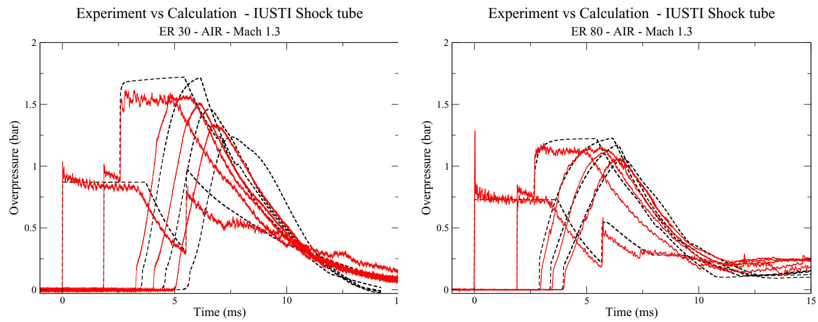

Fig. 2 Model prediction compared to experiments AIR Mach 1.3 - left: ER 30 - right: ER 80

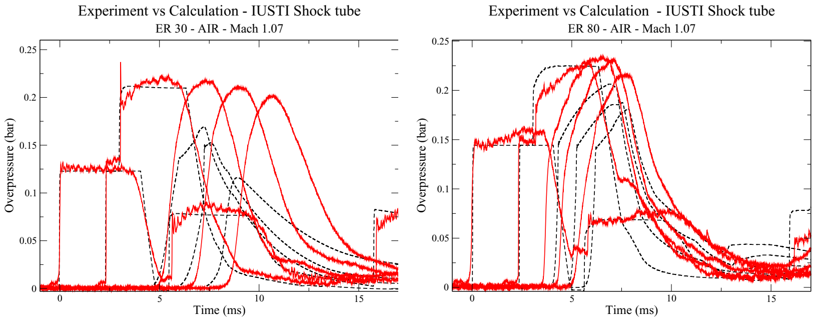

Fig. 3 Model prediction compared to experiments AIR Mach 1.07 - left: ER 30 - right: ER 80

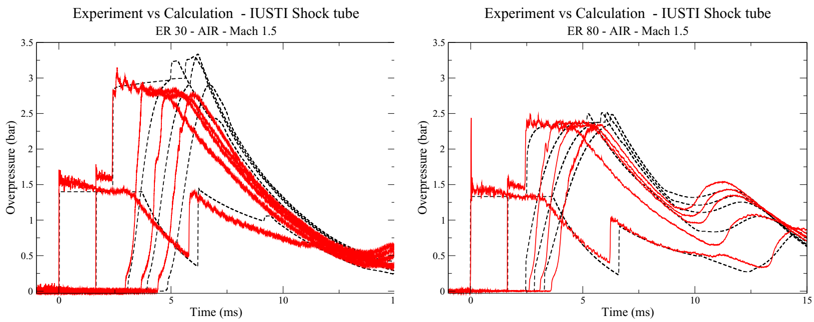

Fig. 4 Model prediction compared to experiments AIR Mach 1.5 - left: ER 30 - right: ER 80

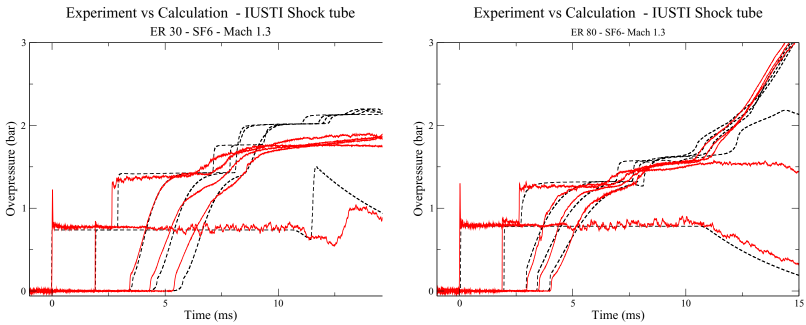

Fig. 5 Model prediction compared to experiments SF6 Mach 1.3 - left: ER 30 - right: ER 80

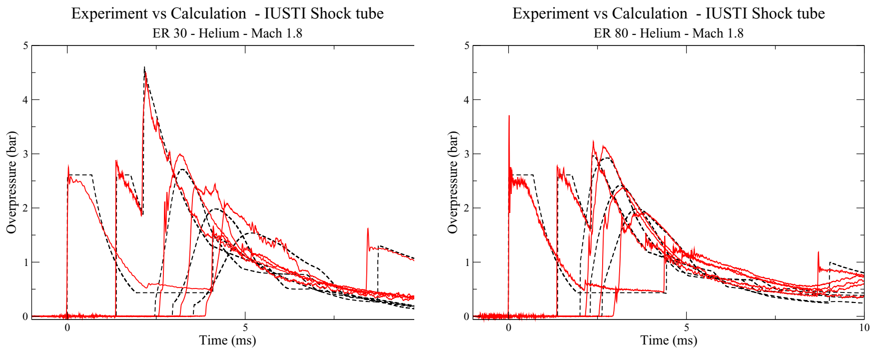

Fig. 6 Model prediction compared to experiments Helium Mach 1.8 - left: ER 30 - right: ER 80

5 Conclusion

We have examined the momentum transfer when a shock wave interacts with a dry aqueous foam. Two physical mechanisms have been pointed out. The first concerns the fragmentation model. A pressure threshold has been determined which caracterises the degree of heterogeneity of the foam. The second issue concerns the two phase-phase momentum transfer. We have shown that the momentum transfer in the foam must be treated with two different drag coefficient laws according to the different phases of the foam transformation: acceleration of the foam ligaments after fragmentation (modified Stokes law) and spherical droplets dynamics [7].

The authors thank S. Faure of CEA Marcoule for designing the foam generator.

References

1. Britan, A.B., et al.: Combustion, Explosion and Shock Waves 28, 550–557 (1992)
2. Britan, A.B., et al.: Combustion, Explosion and Shock Waves 30, 384–396 (1994)
3. Del Prete, E.: Choc et onde de souffle dans les mousses aqueuses. Etude expérimentale et modélisation numérique. PhD Thesis. University of Rouen, France (2012)
4. Jourdan, G., Houas, L., Mariani, C., Chinnayya, A., Hadjadj, A., Del Prete, E., Haas, J.F., Rambert, N., Counilh, D., Faure, S.: Experimental investigation of shock wave propagation in aqueous foam. Associated contribution to the ISSW29
5. Chinnayya, A., Daniel, E., Saurel, R.: Modelling detonation waves in heterogenous energetic materials. Journal of Computational physics 196(2), 490–538 (2004)
6. Delprete, E., Chinnayya, A., Domergue, L., Hadjadj, A., Haas, J.F.: Blast waves mitigation by dry aqueous foam. Shock Waves 23(1) (2013)
7. Ortiz, C., et al.: International Journal of Multiphase Flow 30(2), 217–224 (2004)
8. Lallemand, M.-H., et al.: International Journal for Numerical Methods in Fluids 49(1), 1–56 (2005)
9. Weaire, D., Hutzler, S.: The Physics of Foams. Oxford University Press (1999)