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Head-on Collision of Normal Shock Waves with Rigid Porous Materials

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Abstract. The head-on collision of a planar shock wave with a rigid porous material has been investigated experimentally. The study indicated that unlike the reflection from a flexible porous material, where the transmitted compression waves do not converge to a sharp shock wave, in the case of a rigid porous material the transmitted compression waves do converge to a sharp shock wave, which decays as it propagates along the porous material.

Key words: Porous materials, Compression wave, Reflection/interaction process

1. Introduction

The investigation of the head-on collision of normal shock waves with porous materials has increased quite intensively in the past decade due to the application of this phenomenon to many engineering fields.

Table 1. The experimental models

Material	Model	Pore per inch (ppi)	Air porosity	Model length (mm)
Silicon Carbide*	I	10	0.728±0.016	40, 60, 81
(SiC)	II	20	0.745±0.001	41, 62, 83
Alumina*	III	30	0.814±0.010	48, 93
(Al_2O_3)	IV	40	0.821±0.007	50, 99

*The structure of the material was open-cell

In the present study air-saturated rigid porous materials rather then flexible ones were used. The motivation for this study was to experimentally investigate the extent of the differences in the entire interaction/reflection process when the flexible porous material is replaced by a rigid one. In addition, Bear et al. (1992), Sorek et al. (1992), Levy et al. (1993a), have recently initiated analytical models for predicting the flowfield which is developed inside a rigid porous material under a variety of initial conditions and constrains. The study reported in this paper is also aimed at providing an experimental data base for validating their and hopefully others' analytical models.

2. Experimental set-up

The experiments were conducted in the 75 mm×75 mm shock tube of the School of Mechanical Engineering of the University of Witwatersrand in Johannesburg, South Africa. The incident shock wave Mach number range was $1.2 \leq M_i \leq 1.7$, the initial pressures and temperatures throughout this study were about 830 mbar and about 288 K, respectively.

The rigid porous materials were made of silicon carbide (SiC) and alumina (Al_2O_3). The SiC-manufactured porous material had either 10 or 20 pores per inch and the Al_2O_3-manufactured porous material has either 30 or 40 pores per inch. The air porosity of these porous materials as

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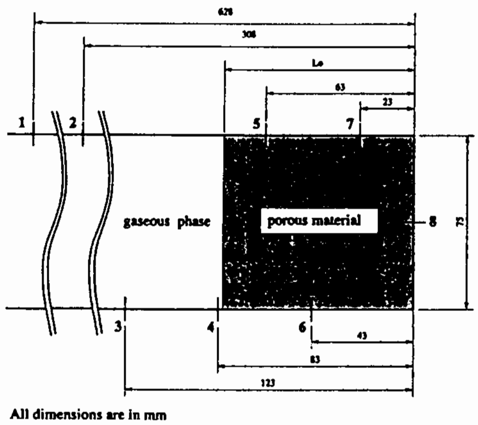

Fig. 1. Schematic illustration of the experimental set-up and the location of the pressure transducers (numbered 1 to 8)

well as the initial length, L_0, of the models which were cut from these materials are given in Table 1. The cross-section of the models was 75 mm×75 mm and hence they experienced a uni-axial strain compression. The models were mounted in such a way that their back edge was supported by the shock-tube end-wall. In order not to scratch the high-quality shock-tube windows and walls the models were enveloped by a very thin and mechanically strong cardboard.

A schematic drawing of the experimental set-up used during the present experimental study is shown in Fig.1. Although there were eight pressure transducer-ports, only seven of them were actually used in each experiment. The pressure transducers in ports 1 and 2 were used to measure the incident shock wave velocity. Pressure transducers were mounted in ports 4, 5, 6, 7 and 8 for the models having an initial length up to (inclusive) 83 mm (see Table 1). For the two alumina models with initial lengths of 93 mm and 99 mm the pressure transducer of port 4 was moved to port 3. This was done in order to have a measurement of the pressure changes that were caused by the shock wave which reflected backwards from the front edge of the porous material.

3. Experimental results

3.1. Gas pressure inside the porous material

Fig.2 illustrates the pressure histories of the gas in the pores as recorded by the various pressure transducers for an experiment with an 81 mm long model made of SiC having 10 pores per inch. The incident shock wave Mach number was M_i=1.542. The four pressure histories shown in Fig.2 were recorded by the pressure transducers which were mounted in the ports numbered 5, 6, 7 and 8 in Fig.1. It is evident from these pressure histories that:

a) The pressure jump across the compaction wave is sharp and resembled a typical pressure jump across a shock wave (note, the sharp pressure jumps are indicated by arrowheads).
b) The sharp pressure jumps are followed by continuous pressure increases which finally reach asymptotic values.
c) As the compaction wave propagates the pressure jump across it decreases, but the final pressure remains almost unchanged.

The decrease in the pressure jump across the compaction wave as measured from Fig.2 is shown as a function of distance propagated by the compaction wave in Fig.3. The distance propagated by the compaction wave as function of time is shown in Fig.4, which indicates that the compaction wave velocity has a nearly constant value of 330 m/s. In spite of this fact, Fig.3 indicates that the initial pressure jump across the compaction wave decreases. These supposedly contradicting experimental observations suggest that the compaction wave broadens as it propagates along the porous material and develops a dispersed structure. Note, that although the initial jump across the compaction wave decreases, the overall pressure increase remains almost unchanged. It should also be noted here that the compaction wave velocity, as deduced from Fig.4, is slightly smaller than the speed of sound of the air filling the pores. (This will be further discussed in the next section). As a result of the observation that the sharp pressure jump across the transmitted compaction wave decays, it is clear that if the porous model is short enough, then the compaction wave could reach the shock-tube end-wall prior to its degeneration to either a fully dispersed or a sound wave.

The pressure histories shown in Fig.2 indicate that although a compaction wave having a sharp jump of about 105 KPa (as estimated from Fig.3) collided head-on with the shock-tube end-wall, there is no noticeable evidence of a sharp reflected compaction wave. Furthermore, the pressure history, as recorded by the pressure transducer which was mounted in port 8, at the shock-tube end-wall, clearly indicates that the pressure there does not remain uniform, as it should have been had a compaction wave reflected there. Instead, it is seen to continuously increase until it levels off at a value slightly higher than the pressure, P_5, that would have been obtained had the incident shock wave (M_i=1.542) collided head-on with the shock-tube end-wall without the presence of the porous material.

3.2. Gas pressure outside the porous material

The pressure histories, as recorded in the same experiment by the pressure transducers which were mounted in the ports numbered 1, 2 and 4 in Fig.1, are shown in Fig.5. The pressure histories, as recorded by the pressure transducers mounted in ports 1 and 2, indicate the passage of two shock waves across them. The first step jump is due to the incident shock wave, and the second one is due to the shock wave which reflects head-on from the front edge of the porous material. Since the center of the pressure transducer mounted in port 4 was only 2 mm ahead of the front edge of the porous material, and since the diameter of the transducer was 3 mm, it did not have enough resolution to clearly separate between the pressure jumps across the incident and the reflected shock waves.

The pressure jump across the reflected shock wave, S_r, is clearly seen to increase as the reflected shock wave moves away from the front edge of the porous material. In addition, following the above-mentioned pressure jump across the reflected shock wave, the pressure is seen to continuously rise to values slightly larger than the values, P_5, which would have been obtained had the incident shock wave (M_i=1.542) reflected head-on from a rigid wall.

Although Figs.2 to 5 describe the results of only one experiment, similar results were obtained in all the experiments. However, it should be mentioned that a comparison between Models I and II (see Table 1) revealed that the initial strengths of the transmitted compaction wave were almost the same when identical incident shock waves were used, in spite of the fact that the number of pores per inch in Model II was twice the number in Model I.

This was not the case when the results of Models III and IV were compared. Here the compaction wave transmitted into Model III was clearly stronger than that transmitted into Model IV. The reason for this peculiar behavior could be attributed to the fact that while the porosity of Model II is clearly larger than that of Model I, the porosities of Models III and IV are similar. Hence the larger porosity of Model II, together with the fact that the pores were smaller, could yield a response equivalent to that of Model I, where the porosity was smaller but the pores were larger.

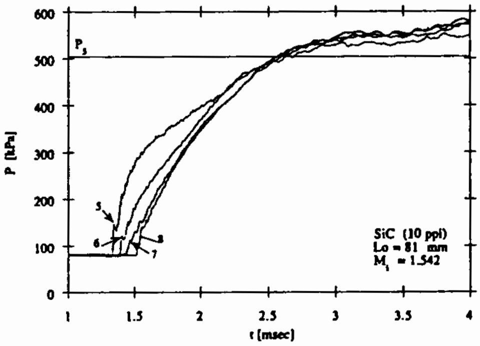

Fig. 2. The pressure history of the gas in the pores of the porous material, as recorded by the pressure transducers mounted in ports 5, 6, 7 and 8 of Fig.1

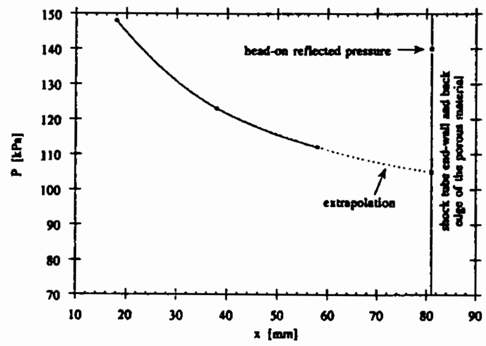

Fig. 3. The sharp pressure jump across the transmitted compaction wave as it propagates inside the porous material, as deduced from Fig.2

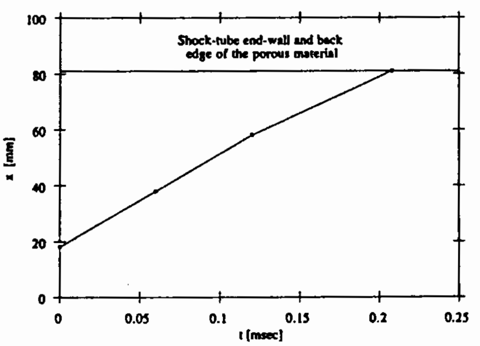

Fig. 4. The distance travelled by the transmitted compaction wave as a function of time, as deduced from Fig.2

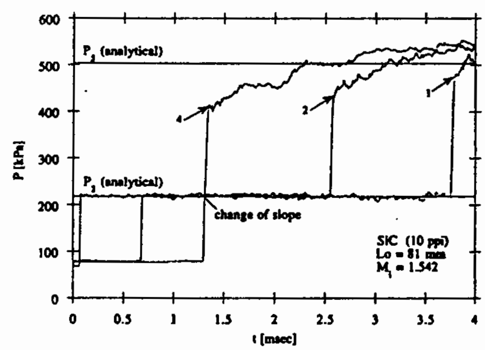

Fig. 5. The pressure history of the gaseous phase as recorded by the pressure transducers mounted in ports 1, 2, and 4 of Fig.1

4. Suggested modified phenomenological model

Based on the above-described observations, it is clear that the existing commonly accepted model for describing the investigated interaction phenomenon is insufficient, because it cannot account for the fact that the transmitted compaction wave, C_t, develops a dispersed structure, and the reflected shock wave, S_r, accelerates. Consequently, a different phenomenological model is suggested. The presently accepted model (see e.g., Skews et al. 1992) is shown in the (x,t) diagram of Fig.6. According to this model, which assumes constant velocities for all the discontinuities, the pressure, P_5, induced by the reflected shock wave, S_r, at the front edge of the porous material should remain constant until an additional shock wave, S_t, is transmitted into the gaseous phase, following the head-on reflection of the reflected compaction wave, C_r, from the front edge of the porous material. Similarly, the pressure, P_{II}, induced by the transmitted compaction wave, C_t, should also remain constant until the passage of the reflected compaction wave, C_r, which changes it from P_{II} to P_V. Furthermore, P_V should also remain constant until the reflected rarefaction wave, R_r, changes its value. The above-described model obviously cannot explain the present experimental observations in which, as mentioned earlier, the initial pressure jump across the transmitted compaction wave, C_t, decays, the reflected shock wave, S_r, accelerates, the reflected compaction wave, C_r, is not noticeable, and the pressures in states (5) and (II) are not uniform, but increase continuously until they reach a constant value long times after the initiation of the process.

Based on the observed experimental results, the continuously increasing pressure jump across the reflected shock wave, S_r, and the continuously decreasing initial pressure jump across the transmitted compaction wave, C_t, could be attributed to two processes:

a) For short times, following the instance when the incident shock wave collided head-on with the front edge of the porous material, multiple reflections, diffractions and interactions which occur inside the pores that constitute the front part of the porous material are dominant.
b) At longer times, the friction between the gaseous phase and the skeleton of the porous material becomes dominant.

The proposed phenomenological model is based on the fact that the porous materials which were investigated during the course of the present experimental study have relatively very large pores. For example the average diameter of the pores of Model I is about 2.5 mm (10 pores per inch). As a consequence, unlike the case of a head-on collision from the front-edge of the porous materials in which the size of the pores is smaller than 0.1 mm, where filtration processes are dominant, here the transmitted compaction wave propagates in a very complex geometry which forces it to undergo a variety of interaction processes at the early stages of its penetration into the porous material.

The idea of the multiple reflection process which the incident shock wave undergoes when it penetrates the front edge of the porous material is described by Levy et al. (1993b). The penetration of the shock wave through the front layer of the porous material can be viewed as a sharp front, which sweeps through the porous material, while parts of it are left behind. These parts bounce back and forth inside the cavities of the pores, parts of them interact with each other, and parts of them even find a way to emerge from the front edge of the porous material as weak compression waves, which eventually catch-up with the main reflected shock wave and increase the pressure field behind it. While penetrating the porous material, the compaction wave becomes more and more dispersed and the sharp jump across its front vanishes. Simultaneously, the friction between the gaseous phase and the rigid skeleton of the porous material becomes more and more pronounced, until it takes over and becomes the dominant mechanism. As a result of the friction interaction, the gas flowing through the open cell pores is slowed down and in turn its pressure builds up. Note that the slow-down process of the gas which flows through the pores might generate compression waves, which can also emerge from the front edge of the foam and catch up with the reflected shock wave, S_r, and further increase the pressure behind it.

Based on the above-described multi-interaction process we propose the detailed (x, t) diagram shown in Fig.7. Unlike the general (x, t) diagram shown in Fig.6, compression waves are seen to emerge from the front edge of the porous material. They eventually catch-up with the reflected shock wave, strengthen it and also increase the pressure behind it.

5. Conclusion

An experimental investigation of the head-on interaction of a planar shock wave with a rigid porous material having a large permeability has revealed that:

1. Unlike flexible porous materials, where the available experimental data indicated that the transmitted compression waves did not converge to a sharp discontinuity, here there was evidence that sharp-front transmitted waves were formed in the rigid porous models.
2. The transmitted wave velocity was found to be nearly constant and about 3-5% smaller than the speed of sound of the air filling the pores.
3. The sharp jump across the transmitted waves was found to decay as the compaction wave propagates.
4. The pressure at the shock tube end-wall, behind the reflected wave, did not remain uniform, as expected, but slightly increased. The pressure rise increased as the air porosity increased. In addition, this phenomenon became more pronounced as the length of the model increased.

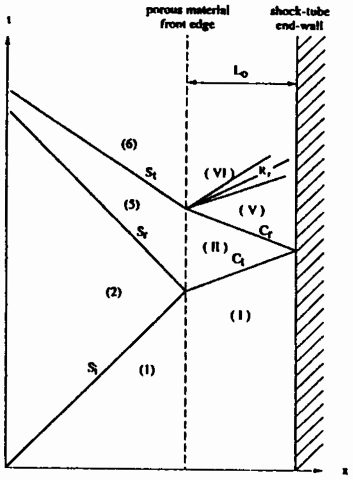

Fig. 6. The commonly accepted (x,t) diagram of the various waves involved in the interaction under consideration (see Skews et al. 1992)

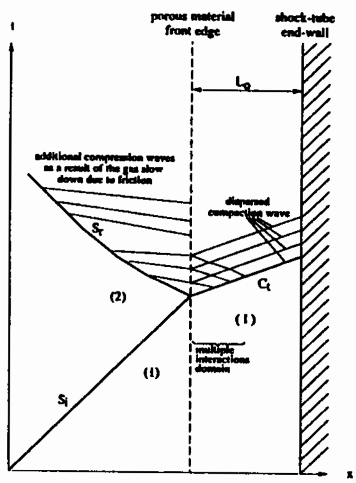

Fig. 7. The proposed detailed (x,t) diagram of the main discontinuities involved in the interaction under consideration, as suggested by our modified proposed model

5. The above-mentioned last three observations suggest that the compaction wave developed a dispersed wave structure.
6. A comparison between Models I and II (see Table 1) indicated that the strength of the transmitted compaction waves were almost identical when identical incident shock waves were used. This was not the case when the results of Models III and IV were compared.
7. The pressure jump across the reflected shock wave was found to increase as it propagated backwards.

All the above-listed observations led us to modify the generally accepted phenomenological model of this reflection/interaction process. The proposed modified model implies that the entire interaction phenomenon is probably governed at it early stages by multiple interactions of the transmitted wave with the internal walls of the pores of the porous material. Only at a later time does friction become the dominant process.

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