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On the pressure buildup behind an array of perforated plates impinged by a normal shock wave

O. Ram, G. Ben-Dor, O. Sadot*

Pearlstone Center for Aeronautical Engineering Studies, Protective Technologies R&D Center, Department of Mechanical Engineering, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer Sheva, Israel

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ABSTRACT

The pressure buildup behind an array of perforated plates following a shock wave impingement was experimentally studied. The experiments were performed in a shock tube facility and the arrays were varied in the number of their perforated plates and the porosities of the plates. It was found that the pressure buildup behind all of the configurations that were examined displayed similar characteristics. Using simplified assumptions about the nature of the flow through the perforated plates array, we could account for the influence of the volume confined between the plates, and the porosity of the plates. Once accounted for, experiments were performed with argon and SF_6, in addition to air, in order to examine the effect of the gas. It was found that the pressure buildup depended on a constant parameter, which was gas-dependent. The constant parameter for each gas was found in this study experimentally. To the best of our knowledge this result has never been reported before. The large spread of different experiments performed throughout the present study enabled the separation of the effects facilitated by the perforated plates array into two distinct processes that affected the pressure buildup at the end-wall. The first was the diffraction of the incident shock wave and subsequent shock reverberations that were found to depend on the number of perforated plates in the array and their porosity. The second was the inhibition of the flow through the perforated plate that was found to depend on the confined volume, type of gas and the porosity of the plates.

1. Introduction

Porous barriers have the potential of mitigating loads that are developed behind them following the impingement of shock or blast waves [1–4]. Due to this potential, the propagation of shock waves through porous-like barriers and the developing loads behind them has been the focus of many studies in recent years. Various porous barriers have been proposed and studied, e.g., silicon carbide (SiC) filters [5–8], sets of columns with various geometries [9–11], sets of buffers [4,12–16], wire meshes [17,18], packed granular media [19–21], perforated plates [2,22–25] and more. Most of these studies consisted of an experimental investigation into the effects of the various properties of the porous barrier on the propagation of a shock wave through them, its attenuation and the developing flow field behind them. In addition, some of the studies employed numerical modeling in order to predict the developing flow fields and shock attenuation [11,26,27]. Numerically simulating the propagation of shock waves through a porous medium and the resulting flow within the porous barrier and in its vicinity is difficult. The difficulties stem both from the fact that multiple scales are involved in the solution and the need to model the small-scale fluid structure interaction and momentum transfer [27–31]. These difficulties are increased due to the fact that the flow is initiated by a shock impingement and hence is very transient. In spite of these difficulties, they presented numerical solutions that agreed quite well with the experimental results. It was shown that the interaction of the incident shock with the porous barrier structure could be simulated using inviscid tools [11–13,22,32]. However, solving the developing flow fields following the shock propagation through the barrier and the reflected shocks interactions with the developing field required the inclusion of viscosity [11,33]. Due to this fact, each study had to employ a simplified modeling approach to incorporate the microscopic interaction between the solid structure of the barrier and the flow. The modeling strategy was barrier specific and each scenario required a different approach.

Many of the studies into shock interaction with porous barriers considered a scenario at which the porous medium was placed inside a tunnel without blocking its end [3,9,11,12,24,34]. In this scenario, a constant velocity incident shock impinged head-on the front face of the

* Corresponding author.
E-mail address: sorens@bgu.ac.il (O. Sadot).

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porous medium and was partially reflected upstream and partially transmitted downstream through the porous medium. The constant velocity shock wave generated a nearly step function pressure jump on the front face of the porous medium. The transmitted shock exited at the rear face of the porous medium and propagated downstream in the tunnel. This scenario generated a constant pressure gradient between the front and the rear faces of the porous medium (far enough from the barrier itself). These studies mainly focused on the parameters that governed the strength of the transmitted shock wave and dealt with the attenuation factor, i.e., the strength of the transmitted shock wave with respect to that of the incident shock.

A more complicated case was considered in some studies where the porous medium was placed in a tunnel with a standoff distance to the end-wall thus forming a confined volume of air behind it and the end-wall [5,7,8,26,35,36]. This scenario was more complicated than the aforementioned scenario since the conditions behind the porous medium did not remain constant. The transmitted shock wave propagated into the confined volume, impinged on the end-wall, reflected upstream towards the rear face of the porous barrier and reverberated back and forth inside the confined volume. As a result, its strength declined until it subsided. In parallel to this feature, the pressure gradients that were formed on the two faces of the porous medium drive a fast mass flow into the confined volume causing its pressure to increase. The flow into the confined volume continued until the pressure inside the confined volume reached the pressure on the front face of the porous medium. As the pressure subsided, the mass flow into the confined volume subsided too. The relation between the pressure and the mass flow is inherently nonlinear. The unsteady mass flow through the porous medium increased the difficulty of predicting the pressure buildup and in turn also inhibited the ability to study the effects of various parameters such as the volume, length of the porous barrier and the properties of the porous barrier itself.

Recent studies suggested an appealing alternative to directly solving the governing equations that required the modeling of the small-scale fluid structure interactions [7,8,15]. Instead, it was shown that a macroscopic approach can be used at which the pressure profile imposed on the front face of the porous medium was studied in relation to the pressure profile that was generated on the end-wall of the tunnel. This approach was used in the past to study the pressure buildup behind stiff porous SiC filters. This methodology essentially addressed the porous medium and the confined air in it as a single mechanical system. It was shown that in these terms the function that linked the pressure imposed on the front face of the porous medium and the pressure that was developed on the end-wall of the tunnel was in fact a low-pass filter. It was found that the porous medium inhibited the propagation of fast changing pressures and the end-wall pressure profile developed behind the porous medium was much smoother and rose in a mellower fashion. It was also found that each combination of the confined volume and porous medium yielded a specific time constant that determined the pressure buildup time. In fact, it was also found by addressing the problem in this macroscopic manner that various porous media generated pressure buildups with similar overall characteristics. It was suggested that various porous media could be studied in the same manner. Using this macroscopic methodology, the pressure buildup behind the porous medium could be calculated if a parameter that defined the specific porous medium was found. Quantifying this parameter that lumped the properties of the porous medium that affected the pressure buildup such as the tortuosity and the resistance to the flow, required having the results of a single experiment. Since these studies used SiC filters that had a very complicated internal structure the direct dependence of this parameter on the structure of the porous filter could not be identified.

The present study employs the above described macroscopic methodology in order to study the propagation of shock waves through an array of perforated plates and the developing loads behind it. Perforated plates were suggested before as a means of mitigating shock and blast waves in tunnels and were proven effective by experiments. However, while being one of the simplest porous-like media, the shock interaction with the perforated plates, the transmitted shock between the plates, the reverberating shocks and the resulting flow through them is so complex that, to the best of our knowledge, no one reported on the pressure buildup behind an array of more than two perforated plates. Since the methodology that is described above does not require the solution of the microscopic interaction between the flow and the plates, an array of many perforated plates with various properties could be studied.

In the following sections the experimental apparatus and the perforated plate models that were used are presented. Followed, are the results of an experimental study that was designed to find the dependence of the pressure buildup at the end-wall on the properties of an array of perforated plates. Two different experimental configurations were used in this study. In the first configuration, the pressure buildup at the end-wall was examined with a fixed volume and different number of plates. In the second configuration, the pressure buildup at the end-wall was examined with increased number of perforated plates, different porosities and different gases. The analysis of the results is based on a method of variable reduction that is employed to find the effects of each parameter.

2. Experimental setup

2.1. Shock tube facility

The experimental investigation was performed in a shock tube located in the Shock Tube Laboratory of the Ben-Gurion University of the Negev. A horizontal, 6-m long shock tube with an internal square cross section of 32 mm by 32 mm was used. A schematic description of the experimental apparatus is shown in Fig. 1.

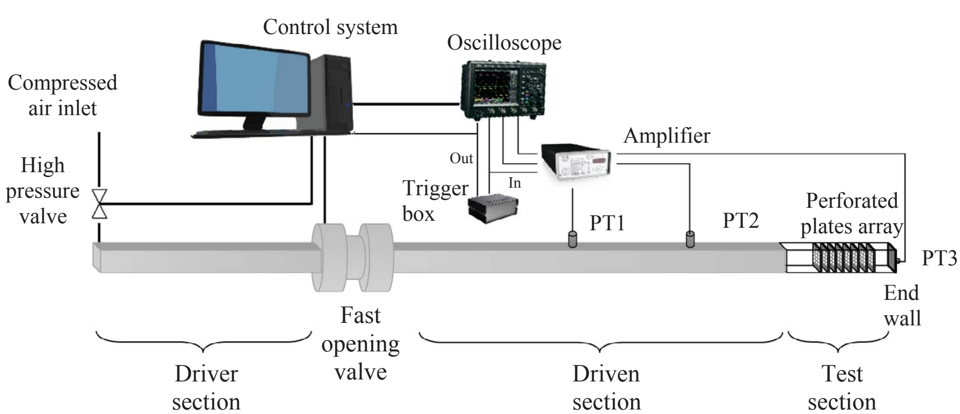

Fig. 1. A schematic description of the shock tube and the experimental apparatus that was used in the experiments.