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Using shock waves to improve the sound absorbing efficiency of closed-cell foams

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ABSTRACT

Producing closed-cell foams is generally cheaper and simpler than open-cell foams. However, the acoustic and filtration efficiency of closed-cell foam materials is generally poor because it is very difficult for fluid or acoustic waves to penetrate into the material. A new method using shock waves to remove the membranes closing the cell pores (known as reticulation) and thus to improve the acoustic and filtration behavior of closed-cell foam material is presented. Various shock treatments have been carried out on polyurethane and polyimide foams and the following conclusions were drawn: (1) reticulation efficiency increased and thus the airflow resistivity and tortuosity decreased when increasing the amplitude of the shock treatment; (2) the rigidity of the foam is decreased; (3) the process is reliable and repeatable and (4) obtained acoustic performance is comparable to classical thermal reticulation.

1. Introduction

Foam microstructure can be seen as a collection of interlinked struts forming a packing of cells interconnected to others through pores. Materials with the totality of pores closed by thin membranes are called closed-cell foams. The filtration and acoustic efficiency of closed-cell foams is poor compared to open-cell foams since it is very difficult for the fluid or the acoustic waves to penetrate inside the material. To improve the filtration and acoustic behavior of closed-cell foam, the membranes closing the cell pores are removed in a process known as "foam reticulation." Materials having only open pores are called "fully reticulated," while if some of the pores are closed or partially closed, the material is "partially reticulated." Two main reticulation methods commonly used in the foam industry are thermal [1,2] and chemical [3] reticulation. The thermal method involves placing a bun of foam in a very large vessel filled with a combustible gas mixture. The gas is ignited and a controlled flame front passes through the foam, melting the window membranes. However, this method only applies to cellular material having heat destructible membranes. Moreover, it may not be applied in a continuous process and the materials must be cooled after treatment. The chemical reticulation method involves subjecting the foam to a caustic bath which dissolves the window membranes. Chemical concentration, bath temperature and time of exposition of the material in the bath may be controlled accordingly. However, this method results in an expensive process, may use hazardous materials and can produce a strong inhomogeneity of the surface and the volume of the treated material.

A reticulation method dedicated to foams comprising a flexible frame is investigated in this paper. It is based on the impact of a shock wave (i.e., a high-amplitude short-duration pressure wave) on the foam surface. This impact involves (i) the propagation of elastic and plastic waves within the porous frame and (ii) a large frame deformation [4,5]. This shock-foam interaction is used in this work to rupture the membranes closing the foam cells [6]. The shock wave reticulation method offers a number of important capabilities, as compared to the aforementioned commercially available systems: (1) the reticulation rate of the treated foam can be tuned depending on the shock strength, (2) the treatment can be varied upon the foam surface to create "acoustic patches" or transverse flow resistance variation effects, (3) it can be applied rapidly and easily in an assembly line, (4) it does not involve chemical products and/or immersion of the foam in a fluid or hot gas, and thus does not require drying or cooling the foam after treatment and (5) it is inexpensive to perform.

This paper presents an experimental validation of the proposed shock wave reticulation method. Seven different foams are reticulated using shock waves: one polyimide and six polyurethane foams. First, the experimental setup and the shock wave generator are described. The seven foams are then presented. The foams microstructures are analyzed before and after treatment from

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micrographs using light-microscopy or electron microscopy techniques. The reticulation efficiency due to the shock impact and the influence of the shock strength are evaluated from airflow resistivity, tortuosity, stiffness and sound absorption measurements. Finally, the reticulation efficiency of the proposed shock method is compared to the one of the thermal reticulation method on four polyurethane foams.

2. Experimental setup

A shock tube is used to generate controlled shock waves in a gaseous medium. Both the shock tube and the foam are in the same gaseous environment, in the present case, air at room conditions. A simple shock tube uses two tube sections and is illustrated in Fig. 1. The so-called driver section of the shock tube is filled with a high pressure gas from an external supply. A great amount of energy is thus accumulated in the driver tube. The driver tube is separated from a driven or test tube via a membrane; this driven tube is filled with low pressure gas (here, air at atmospheric conditions). When the partition is suddenly removed or ruptured, a shock wave is generated and propagates in the secondary tube toward the closed-cell material face placed at the end. A precise control of the driver pressure at rupture is required to generate shock waves of desired strength. It was found that the major controlling parameter of the shock treatment is the Mach number (M_s) of the shock wave. The amplitude of the shock (i.e., the treatment strength) increases with the Mach number. Several parameters can be modified to control the Mach number of the shock wave. They are: gas pressures, gas species, lengths of the high pressure and low pressure sections of the tube, filling time of the high pressure gas and temperature. In this work, only the gas pressure in the high pressure section is varied to change the Mach number and thus the treatment's strength. The gas used in the high pressure section is nitrogen. The pressure is varied from 50 psi to 300 psi to produce Mach numbers ranging between 1.31 and 1.86. The shock tube has circular cross-section with an inner diameter of 1.5 in. Because the effect of the impact of a shock wave with a flexible material is not homogeneous along the material thickness [4,5], all samples presented in this paper are treated on both sides with similar shock amplitude in order to get samples as homogeneous as possible.

3. Materials and measurement methods

3.1. Materials

Six different polyurethane foams (N1–N6) and one polyimide foam (N7) are treated using the proposed reticulation method. Polyurethane materials consist of numerous individual cells which generally are constructed of a three dimensional skeletal structure of interconnected struts with membranes joined to the skeletal structure. The skeletal structure in these cellular materials is usually considerably thicker than the membranes or windows [1]. This 3D microstructure can be idealized as a packing of tetrakaidecahedra cells interconnected through pores [7,8]. The cell size in ppi (ppi = pore per inch) of foams N1 to N6 varies between 8 ppi and 80 ppi. The cell struts have a triangular concave cross-sectional shape which is non-uniform along the strut length; the cross section is smaller at the center of the strut. Thus, the intersections between struts, also called nodes, are zones of material concentration [9]. The cell pores can be open or closed by thin membranes as mentioned previously. The reticulation rate R_w defined in Refs. [7,8] quantifies the open pore content within the porous aggregate and can be used as an estimate of the cell interconnectivity. Fully reticulated foams have a reticulation rate of 100%. This microstructure parameter has not been estimated in this work but it is expected to be less than 10% for all base materials (i.e., untreated materials). For example, Fig. 2(a), (d) and (g) presents micrographs of the three untreated polyurethane foams N1, N2 and N4 taken with the help of a stereo-microscope Leica MZ6 or a scanning electron microscope (SEM) Hitachi S-3000N. These figures clearly show that most of the pores are closed by the thin membranes.

Material N7 is a polyimide foam, known for its unique combination of superior fire resistance, low smoke and virtually no toxic gas emission, wide operating temperature range and low density [10,11]. The microstructure of the untreated polyimide foam N7 is also captured using an SEM microscope and is presented in Fig. 3(a) and (b). The microstructure of the foam is constituted of large cells connected to each other by thin membranes (≈15 μm thick). Even if polyimide foam appears to be closed-cell type (as shown in Fig. 3(a) and (b)), the thin membranes are not connected all together which makes polyimide foams highly porous foams but with low cell-interconnectivity. Consequently, porosity and airflow resistivity of the untreated polyimide foams are $\phi = 95\%$ and $\sigma = 800\,000$ N s m^{-4} respectively.

All samples are precisely die-cut using a rotary drill press. The internal diameter of the cutter is chosen to provide samples with external diameter 0.5 mm less than the impedance tube diameter (see Section 3.2.4) as suggested in [12,13]. All treated samples are approximately 1 in. thick.

3.2. Measurement methods

3.2.1. Volume and density

The dimensions of the cylindrical samples are measured according to the standard ASTM D-3574 [14] (see Section 8 in [14]) using a sliding caliper gage. The density of the samples is simply

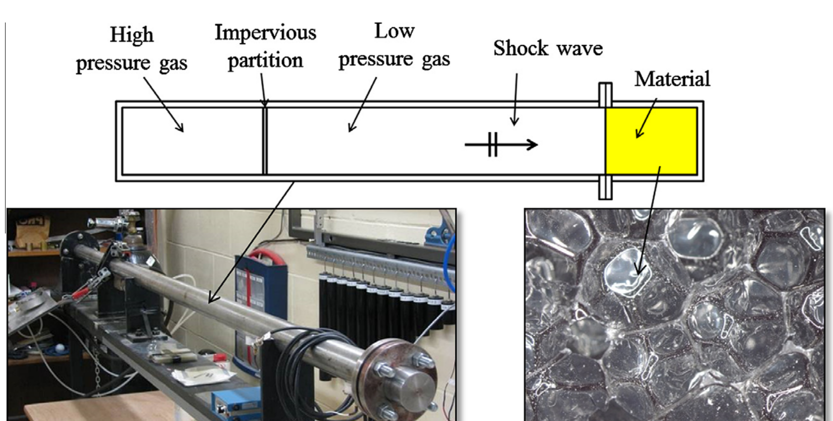

Fig. 1. Scheme of the shock tube and pictures of the experimental setup and material microstructure.