A soap film shock tube to study two-dimensional compressible flows

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Abstract A new experimental approach to the study of the two-dimensional compressible flow phenomena is presented. In this technique, a variety of compressible flows were generated by bursting plane vertical soap films. An aureole and a “shock wave” preceding the rim of the expanding hole were clearly observed using traditional high-speed flash photography and a fast line-scan charge coupled device (CCD) camera. The moving shock wave images obtained from the line-scan CCD camera were similar to the x–t diagrams in gas dynamics. The moving shock waves cause thickness jumps and induce supersonic flows. Photographs of the supersonic flows over a cylinder and a wedge are presented. The results suggest clearly the feasibility of the “soap film shock tube”.

1 Introduction

In early theoretical and experimental investigations of bursting soap films (McEntee and Mysels 1969; Frankel and Mysels 1969), it was shown that the existence of any aureole and wave preceding the rim of the expanding hole is related to large changes in surface tension as the film shrinks and thickens. This wave is referred to as the “shock wave”. More recently, Liang (1997) studied the time dependent thickness profiles of the aureole created in the bursting of vertical soap films using a fast line-scan charge coupled device (CCD) camera. The shock wave was observed very clearly. The works listed above were concerned with the physico-chemical and thermodynamical properties of soap films. Less interest has been given to their ordinary properties as a thin fluid layer.

Recently, such films have been used in classical incompressible fluid-dynamic experiments. These films, which have a thickness ranging from 0.1 to 10 μm, provide an excellent means for studying hydrodynamics in two dimensions. Previous experiments by Couder (1984), Couder et al. (1989), Gharib and Derango (1989), Beizaie and Gharib (1997), Kelly et al. (1995), and Rutgers et al. (1996) have shown certain features of turbulent flow in soap films that resemble those anticipated for a true two-dimensional system.

Our motivation in this study was different. The authors intended extending the experimental works of McEntee and Mysels (1969) and Liang (1997). Soap films were used to conduct classical “compressible” fluid-dynamic experiments. The full dynamics of soap films are in general very complex. The dynamics include chemical kinetics between multi-component phases out of global and local equilibrium. Couder et al. (1989) discussed the hydrodynamic properties of soap films built up from their very specific physics. Basically, a soap film can be thought of as a thin slab of water covered by two monolayers of surfactant. Each surfactant molecule is composed of a hydrophilic head facing the water and a hydrophobic tail directed toward the air. The structure of a soap film responds differently in different time scales. The role of compressibility in gas dynamics is played by Gibbs or Marangoni elasticity, depending on the time scales of the film stretching, and that of pressure by surface tension in the film. On short time scales, Marangoni elasticity corresponds to the relaxation process of the film and explains the films’ stability to rapid disturbances. The waves propagating in a soap film are elastic waves, and the wave speeds are only about 4 m/s in a 10-μm thick sodium dodecyl sulfate (SDS) film. At low concentration, soap films are analogous to two-dimensional perfect gases. The thickness of the film is an active scalar that responds to the dynamics of the film motion in a manner similar to shallow water flows. These properties suggest soap films as a potential candidate for producing and studying two-dimensional compressible flows.

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2 Experimental arrangement

2.1 Film formation and soap solution

The setup of the experiment shown in Fig. 1 is similar to that of Liang (1997). A film of size 60 × 30 mm was formed by pulling an acrylic frame vertically out of a soap solution with a PC-controlled stepping motor. Three nylon threads were tied to the frame to form a rectangular
boundary (the fourth side being the liquid-air interface) inside which the film was formed.

Since common soaps are made of a mixture of several surfactants, and the water is not pure, the properties of the solution are complicated. To make the future analytical work simpler, the soap solution was made by dissolving only one surfactant, SDS, in a mixture of water and glycerin (80% wt deionized water, 20% wt glycerin). Adding glycerin produced more stable films. The SDS concentration used was 0.5 critical micelle concentration (CMC) to allow the surfactant molecules to behave as two-dimensional gases. The soap container was first cleaned using alcohol and then shaken in an ultrasonic cleaner at least twice for 3 min for each sample preparation.

2.2 Bursting and high-speed flash photography

Figure 2 shows the schematic arrangement used for obtaining the high-speed flash photographs to provide qualitative flow visualization of shock wave phenomena in soap films. As the film was formed, it was punctured by an electric spark. A hand-operated micro-switch controlled the supply of current from 6 to 8 V dry cells to the primary coil. The switch opening produced a spark that initiated the film rupture.

The time delay between the initiating spark and the photographic flash was determined using a pulse generator (Philips PM 5715) triggered by a wire loop placed near the conductor connecting the electrodes to the spark coil. The synchronizing pulse delay was adjustable with a specification accuracy of 5%. The front edge of this pulse was used to trigger a stroboscope (Strobotac 1546). The pulse length of the flash was approximately 1.2 μs, which was sufficiently short to produce an instantaneous image of the flow. Kodak Ektapress type film with a speed of ASA 1600 was used for most of our work and required an f/5.6 lens opening.

2.3 Line-scan CCD imaging system

The high-speed flash photography can only capture one picture in one film burst. To reconstruct the bursting process, bursting film photographs with sequential delay times must be used. A fast line-scan CCD camera (DALSA CL-C2-0512S, 512 × 1 pixels) with 25 kHz line rate was used to facilitate the flow visualization process and to get more information during the burst of a single film.