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Ozer Igra
Friedrich Seiler *Editors*

Experimental Methods of Shock Wave Research

Springer

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Collection Editors

Hans Grönig
Yasuyuki Horie
Kazuyoshi Takayama

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Collection Editors

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Hans Grönig is Professor emeritus at the Shock Wave Laboratory of RWTH Aachen University, Germany. He obtained his Dr. rer. nat. degree in Mechanical Engineering and then worked as postdoctoral fellow at GALCIT, Pasadena, for one year. For more than 50 years he has been engaged in many aspects of mainly experimental shock wave research including hypersonics, gaseous and dust detonations. For about 10 years he was Editorin-Chief of the journal Shock Waves.

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Professor Kazuyoshi Takayama obtained his doctoral degree from Tohoku University in 1970 and was then appointed lecturer at the Institute of High Speed Mechanics, Tohoku University, promoted to associate professor in 1975 and to professor in 1986. He was appointed director of the Shock Wave Research Center at the Institute of High Speed Mechanics in 1988. The Institute of High Speed Mechanics was restructured as the Institute of Fluid Science in 1989. He retired in 2004 and became emeritus professor of Tohoku University. In 1990 he launched Shock Waves, an international journal, taking on the role of managing editor and in 2002 became editorin-chief. He was elected president of the Japan Society for Aeronautical and Space Sciences for one year in 2000 and was chairman of the Japanese Society of Shock Wave Research in 2000. He was appointed president of the International Shock Wave Institute in 2005. His research interests range from fundamental shock wave studies to the interdisciplinary application of shock wave research.

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Experimental Methods of Shock Wave Research

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Preface

For a layman the term ‘shock wave’ may sound bizarre and completely superfluous for everyday life. However, this term is relevant in many daily events, for example the fast energy released during every lightning generates a shock wave that eventually decays to a sound wave. A shock wave accompanies every volcanic eruption, and it can be a hazardous event in coal mines; once an unexpected explosion occurs, a shock is transmitted through the mine’s shafts, enhancing its strength due to burning of the coal dust entrained behind the shock front. Attenuating such a shock/blast wave is therefore an important issue. Shock waves accompany every supersonic flight and every missile/spacecraft entering into the earth’s atmosphere. Recently, weak shock waves have been used for treating health problems. Nowadays it is normal practice to shatter kidney stones using focused weak shock waves. Shock waves are also used for returning a broken bone to its original location and there is an ongoing research on using shock waves for eliminating cancer growths. It is clear from this brief foreword that studying the physical behavior of shock and blast waves is essential for developing reliable ways for attenuating them, in the case of destructive shocks, and for proper design of supersonic airplanes and/or missiles. It is not surprising therefore that much effort has been devoted to developing laboratory facilities in which shock and blast waves can be generated and studied in a safe way. The facilities proposed, built, and used for studying shock and blast waves include shock tubes, shock tunnels, expansion tubes, ram accelerators, light gas guns, and ballistic ranges. In the present volume a variety of experimental methods which are used in shock tubes, shock tunnels, and expansion tubes facilities is presented. Details regarding ram accelerators, light gas gun, and ballistic range facilities will appear in Volume 10. When possible, in addition to the technical description of the facility, some typical results obtained using such facilities are described. In addition to descriptions of facilities mentioned above, this book includes techniques for measuring physical properties of blast waves and electrically generated shock waves.

Information about active shock wave laboratories at different locations around the world that are not described in the following chapters is given in the appendix.

This list is far from being complete. It includes only laboratories that responded favorably to our request for information. Additional information can be obtained from the research laboratories mentioned there.

The chapters in this book were written by different authors, each an expert in the described field/technique. We would like to thank all of them for their contributions to this book. Also, special thanks are due to our wives, Heidrun and Irene, for their patience and support exhibited while we spent much time bringing the book to publication.

Beer Sheva, Israel — Ozer Igra
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About the Editors

Ozer Igra has devoted most of his research activities to studying various aspects of shock and blast waves phenomena. His studies include both experimental and numerical investigations of strong (ionizing shocks in argon) and moderate to weak shock/blast wave in gases and in suspensions. Results of his investigations can be found in his many publications available in leading professional journals dealing with gas-dynamic flows and shock waves. He received his B.Sc. and M.Sc. degrees from the Department of Aeronautical Engineering of the Technion, Israel Institute of Technology and his Ph.D. from the Institute for Aerospace Engineering, University of Toronto, Canada. He Joined the Ben Gurion University of the Negev in 1971. There he established the Shock Waves Laboratory, supervised many masters, doctorate, and postdoc students and served as the chairman of the Department of Mechanical Engineering and thereafter as the Dean of the Faculty of Engineering. He is on the International Advisory Committee of the International Symposium on Shock Waves (ISSW) and the International Symposium on Shock Interactions (ISIS), and on the editorial board of the Shock Waves Journal.

Friedrich Seiler is well-known for his studies in shock tube technology at the French-German Research Institute of Saint-Louis in France. As scientist at the ISL, from 1980 on, his research mainly deals with high-velocity flight aerodynamics, hypersonics, optical measuring techniques and fundamental research in the field of ram acceleration. Until his retirement in the year 2011, he became head of the Aerothermodynamics & Shock Tube Laboratory at ISL. He contributes in the editorial board to the progress of the “International Journal on Shock Waves” and is also a member of the International Advisory committee of the “International Symposium on Shock Waves (ISSW)” and the “International Symposium on Flow Visualization (ISFV)”. From the University of Karlsruhe in Germany he received his “Dipl.-Phys.” degree in physics and his “Dr.-Ing.” degree from the same University. Also the University of Karlsruhe, now Karlsruhe Institute of Technology (KIT), has awarded him in 1992 the rank “Professor” and since then he is Lecturing Professor for Fluid Mechanics at KIT. His current interest is focused on the dynamics of Mach waves in supersonic jets. He contributed to a theory which describes the Mach wave behavior using a new approach.

Part I
Shock Wave Generation in Gases

Shock Tubes

Ozer Igra and Lazhar Houas

1 Introduction

A shock tube is a facility that can produce transmitted shock waves in controlled laboratory conditions. The facility is a duct divided into two sections as shown schematically in Fig. 1. One part, the driver, accommodates high pressure gas (P_4) while the other section (the driven) contains the low pressure test gas (P_1). The two sections are separated by a barrier (diaphragm). Once the barrier is suddenly removed a shock wave propagates into the driven section and a rarefaction wave propagates into the driver section. By appropriate choice of the two pressures, P_4 and P_1, and gas species a desired strength of the resulting/generated shock wave (its Mach number, M_s) can be obtained. As shown subsequently, the initial thermodynamic conditions of the gases used dictate the post-shock flow i.e., the conditions behind the shock wave.

The first to describe an experimental investigation conducted in a shock tube was Vielle [30]. Thereafter shock tubes were frequently used for studying various types of compressible flows and for simulating reentry flows. For a historical description of shock wave investigations see Chap. 1 in the *Handbook of Shock Waves*, Ben-Dor et al. [4]. In the following sections a general description of the flow evolved in a shock tube is given; this is followed by descriptions of different geometries and techniques used for generating desired shock-tube-flows and the different diagnostics used for recording these flows.

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Fig. 1 Schematic description of a shock tube

2 Shock Tube Flow

The flow generated in a straight, horizontal shock tube with uniform cross-section upon removal of the barrier separating between the driver and driven sections of the tube is one-dimensional non-steady flow. It consists of a shock wave propagating into the driven section and an expansion wave, centered at the membrane position, propagating into the driver section; see schematic presentation in Fig. 2a. A contact surface, propagating into the driven section, behind the transmitted shock wave separates between the driven and the driver gases. It should be mentioned here that Fig. 2a represents the ideal case in which the incident shock wave is generated instantly after removal of the separating barrier (diaphragm) and the rarefaction wave is a centered wave. In reality this is not necessarily the case as will be shown subsequently. The prevailing pressure and temperature variations in an ideal shock tube flow are shown schematically in Fig. 2b. Symbols (1) and (4) represent the initial states in the driven and the driver sections, respectively; (2) and (3) represent the flow fields prevailing behind the transmitted shock wave and behind the contact surface, respectively, and (5) and (6) indicate flow field prevailing behind the reflected shock wave and the reflected rarefaction wave, respectively. In the following, equations relating the flow fields across these waves are presented. Indexes numbered from 1 to 6 refer to flow fields (1) to (6). A detailed derivation of these equations is available in Glass and Hall [8] and in many gasdynamic textbooks, e.g., see Sect. 5.12 in Aksel and Eralp [1].

2.1 Flow Relations Across the Shock Front

For a perfect gas, which is a reasonable assumption for many gases in which the pressure and temperature jump across the shock front is moderate, the following relations can be derived from the one-dimensional conservation equations of mass, momentum and energy,

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma + 1)M_s^2}{2 + (\gamma - 1)M_s^2},$$

where M_s is the shock wave Mach number, ρ and u are the gas density and velocity, respectively, and index 1 refers to pre-shock conditions while 2 refers to post-shock conditions. γ is the gas specific heat capacity ratio.

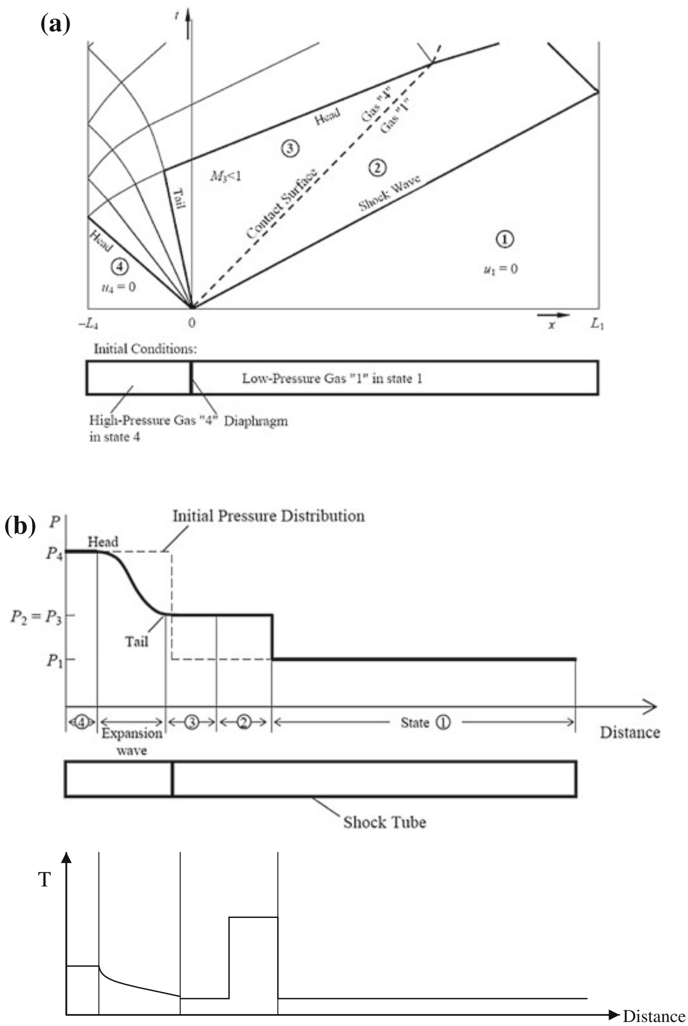

Fig. 2 **a** Schematic description of waves generated in a shock tube. **b** Schematic description showing pressure and temperature variations inside a shock tube

The pressure and temperature relations across the shock front are given in the following two equations:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{(\gamma + 1)}\left(M_s^2 - 1\right)$$

$$\frac{T_2}{T_1} = 1 + \frac{2(\gamma - 1)}{(\gamma + 1)^2}\frac{\gamma M_s^2 + 1}{M_s^2}\left(M_s^2 - 1\right)$$