My Walk in the Field of Shock Waves

Ozer Igra

I entered the shock waves field in Aug. 1967 when I was accepted as a Ph.D. student at the Institute for Aerospace Studies, University of Toronto, Canada. My theses supervisor was the famous scientist Professor I. I. Glass. My knowledge in gasdynamic and especially in shock waves was almost zero. The Ph.D. research work assigned for me by my supervisor was to develop a reliable way for evaluating the recombination rate constant of ionized Argon, K_R. At that time the available data regarding K_R for Argon was to accuracy of $\pm$ 400 percent! The novel way for measuring the recombination rate constant of ionized Argon was to use a shock tube in which the driven section will contain diluted Argon. A very strong shock wave will be sent into the Argon gas and thereby raising the post shock temperature to very high level; over 9,000 °K. At such temperature, significant amount of the Argon is ionized. Generating such flow conditions was possible in the 4 by 7 inch shock tube; its photo is given in Fig. 1.

A wedge having 15° expansion was installed inside the shock tube test section; a schematic description of the expansion wedge and the expansion wave is given in Fig. 2. The required ionized Argon flow over the 15-degrees expansion corner was generated by normal shock waves having the following ranges: shock Mach numbers $13 \leq M \leq 18$; electron number densities $10^{16} \leq n_e \leq 10^{17\ \mathrm{cm}^{-3}}$ electron temperatures $9{,}000 \leq Te \leq 12{,}000$ °K. The initial (pre shock) channel pressure was $1 \leq p_i \leq 10$ Torr and the initial temperature $T_0 \approx 300$ °K.

Experiments were conducted using a Mach–Zehnder interferometer having a nine inch diameter field of view. The interferometer had a dual frequency laser light source. Typical interferograms are shown in Figs. 3 and 4. In Fig. 3 the relaxation zone prevailing behind the strong incident shock wave is shown; in Fig. 4 the expansion of the ionized Argon plasma is exhibited. In the experimental range of electron density and temperature prevailing behind the strong incident shock wave, the dominant recombination process is due to the three-body, electron–ion-electron collisions.

O. Igra (✉)
Department of Mechanical Engineering, Ben Gurion University, Jerusalem, Israel

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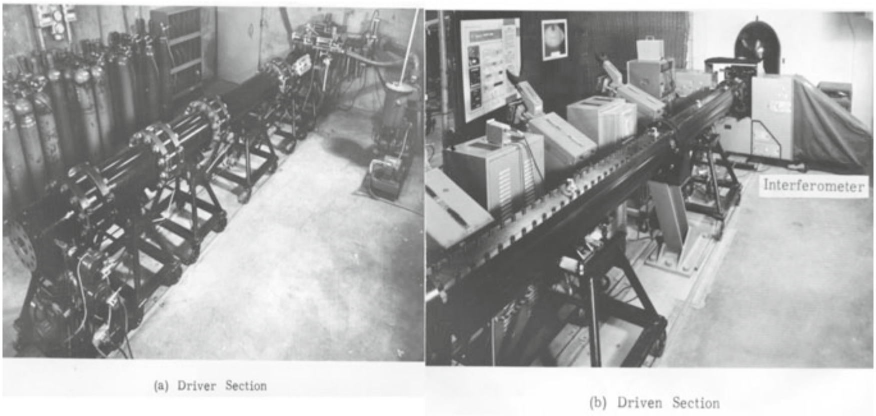

Fig. 1 Photo of the 4 × 7 inches UTIAS shock tube

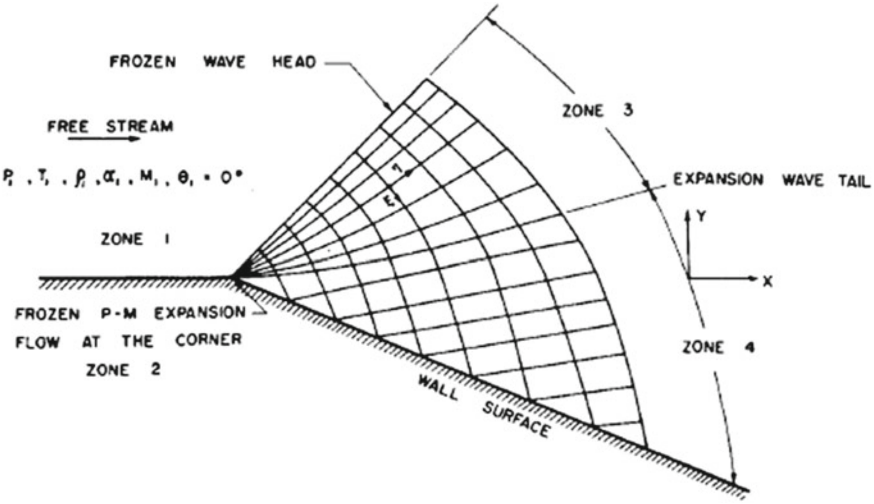

Fig. 2 Schematic diagram of characteristic net for a corner- expansion flow

That is:

$$A + e \underset{K_R}{\overset{K_I}{\longleftrightarrow}} A^+ + e + e$$

where A is a neutral Argon atom, A^+ an Argon ion, e an electron, K_I, the ionization rate constant, and K_R the recombination rate constant.

The rate equation for the production of electrons is expressed by $\frac{dn_e}{dt} = K_I n_a n_e - K_R n_e^3$.

where, n_a and n_e are number densities of neutral atoms and electrons, respectively.

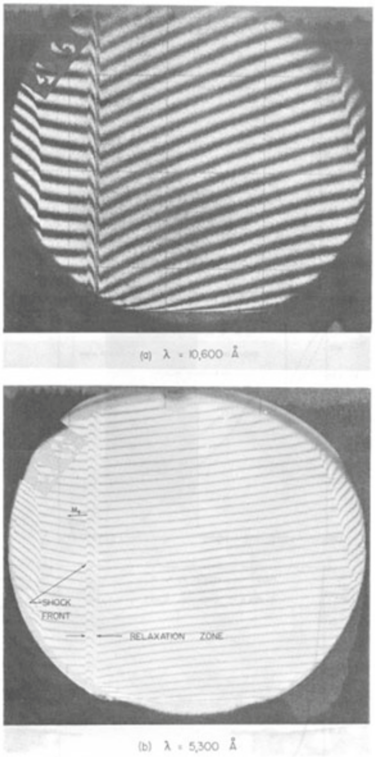

Fig. 3 Relaxation zone behind strong shock wave in Argon. P1 = 1.83 torr, T1 = 296.1 K and Ms = 19.05

The used light source, a laser, provides a giant pulse (–30 MW) and very short exposure times (15–30 ns); it had two different wave's lengths; 6943 Å and 3471.5 Å. From two simultaneously taken interferograms the total plasma density ρ, and the degree of ionization α, or the electron number density, n_e, were evaluated. Detailed

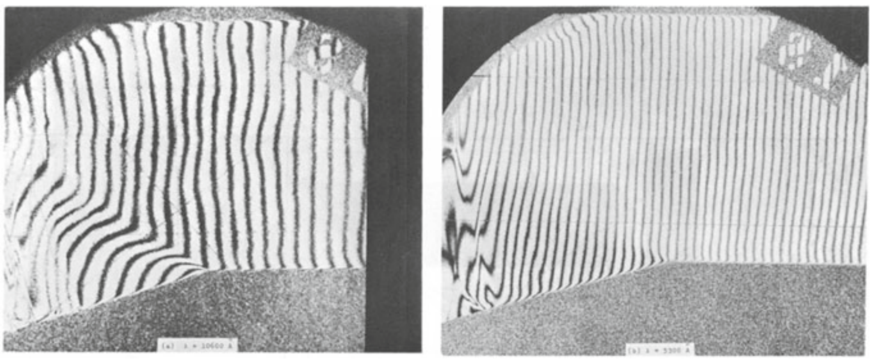

Fig. 4 Interferograms of expansion Argon plasma. P1 = 8.60 torr, T1 = 298.2 K and Ms = 13.3 taken with two different light's wave lengths

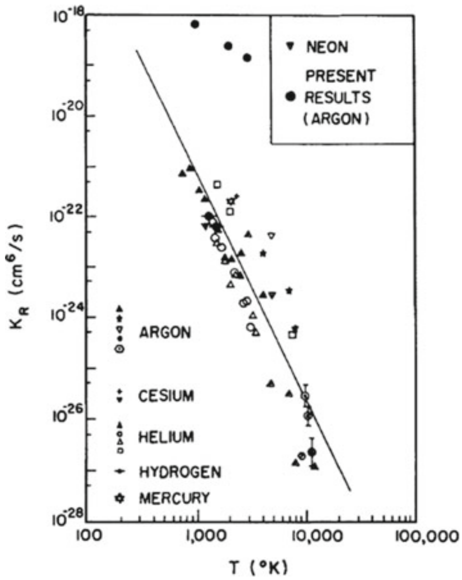

Fig. 5 Recombination rate constant variations, for a three-body collision, versus temperature

results are available in Igra and Glass [1]. Based on these findings, finally the recombination rate constant was evaluated. The obtained results are shown in Fig. 5 where results of other experimenters are also plotted.

Upon completing my Ph.D. studies I returned to Israel and I Joint the newly established Ben Gurion University. My first efforts were centered on building a respectable shock tube laboratory. At that time I was the only person among the academic staff who knows what is a shock wave or, a shock tube and therefore, could not expect any advice/support; not to mention the symbolic financial support I received from my university for this project. It is not surprising that the first shock tube in the present Shock Wave Laboratory in the Ben Gurion University was built using available material. For the driver an old British cannon from the Second World War was used, see in Fig. 6. Being a canon it was planned to be operated either by firing a piston toward the metal diaphragm separating between the driver and the driven sections of the shock tube, or just generating the required high pressure by simply exploding the explosive powder in a bullet free shell. The high pressure, generated between the moving piston and the metal diaphragm will decelerate the piston and will break/open the metal diaphragm. Once the diaphragm opened, a shock wave is transmitted into the shock tube driven section. Details describing the design of this piston driven shock tube appear in [2]. A general view of the piston driven shock tube appears in Fig. 7.

It took about 3 years to make this shock tube operational. However, for conducting experiments one needs, in addition to the shock tube, additional facilities; such as recorders, optical diagnostics, pressure gauges etc. Lack of support for purchasing such basic facilities further expanded the time needed for turning the newly build shock tube useful. It became fully operational only in the early nineties. The present

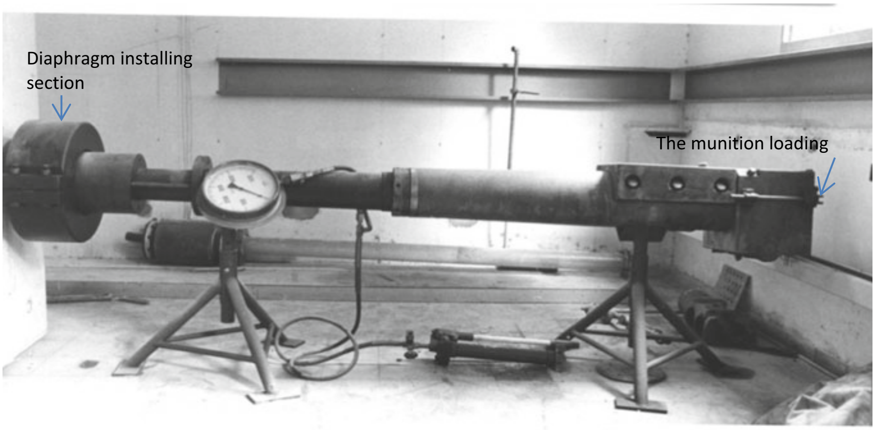

Fig. 6 The 25 lb British cannon that was modified to be used as the shock tube driver

shock tube laboratory, whose humble start is shown in Figs. 6 and 7 contains 6 different shock tubes three of the six are seen in Fig. 8. A brief description of these shock tubes is summarized in the following table.

But time was not wasted; in parallel to bringing the shock tube to be operational I used my connection with colleagues around the world for conducting joint research works. In the following my cooperation with the Shock Waves Laboratory in the institute of Fluids Science, Tohoku University, Japan; in the Ernst Mach Institute in Freiburg, Germany and with the Shock Tube Laboratory, IUSTI-CNRS, in Aix-Marseille Universit´e, Marseille, France is briefly described.

The BGU Shock Tube Laboratory consists of the following six shock tubes:

Shock tube	Cross-section [mm × mm]	Driver length [m]	Driven length [m]	Driver/driven separation	Vacuum Sealed?	Shock mach number range
ST-I[a]	80 × 80	2	3.6	Mylar diaphragm	Yes	$1 < M_S \leq 6$
ST-II	80 × 80	2	3.5	Mylar diaphragm	No	$1 < M_S \leq 2$
ST-III	56 × 56	2	3	Fast valve	No	$1 < M_S \leq 2.5$
ST-IV	32 × 32	1.8	3	Fast valve	No	$1 < M_S \leq 2$
ST-V[b]	31 × 31	1	2	Mylar diaphragm	No	$1 < M_S \leq 1.4$
ST-VI[c]	200	2	10	Mylar diaphragm	No	$1 < M_S \leq 2$

[a]This is a vertical shock tube

[b]The test section of this shock tube is transparent

[c]The cross section of this shock tube is round. The walls of all the shock tubes are equipped with numerous flush-mounted piezoelectric pressure transducers (PCB, Kistler, Endevco) that are used for both pressure history and shock wave velocity measurements and triggering purposes. Schlieren and shadowgraph photography methods are used to record the various shock wave related phenomena. High-speed photography is applied using a shutter-less rotating-prism camera (Vivitro Hi-Spin) that is coupled with the following lasers: I. A 25-Watt Nd:YAG frequency doubled laser, which can be pulsed at intervals of about 20 to 200 μs. II. A 1-Watt Nd:YAG frequency doubled laser, which can be pulsed at intervals of about 10 to 200 μs or operated in a continues mode. III. A 2-Watt copper-vapor laser, which can be pulsed at intervals of about 100 μs

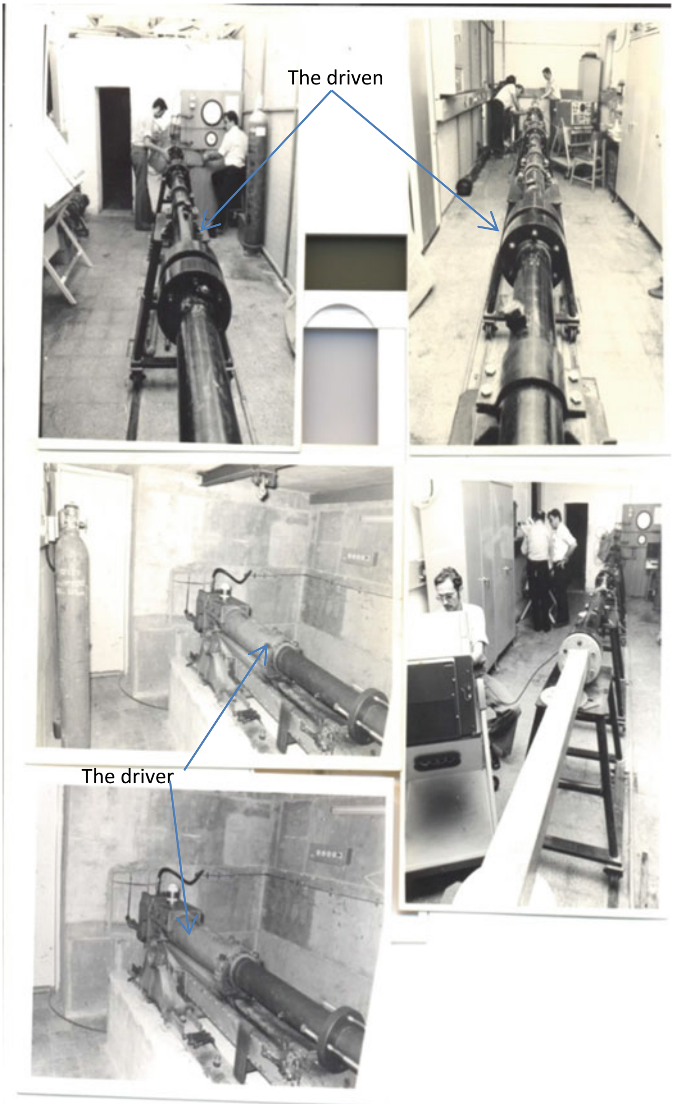

Fig. 7 The piston driven shock tube

With Professor K. Takayama from the institute of Fluids Science, Tohoku University, Japan the following topics were investigated: Experimental study checking the influence of surface roughness on the transition from regular to Mach reflection in pseudo-steady flows [3]; shock tube investigation of the drag coefficient of a sphere in a nonstationary flow [4] and experimental and theoretical studies of shock wave propagation through double-bend ducts [5]. In the following some highlights/results from this cooperation is briefly presented. In [3] the effect of the wedge surface

Fig. 8 Photo showing 3 out of 6 different shock tubes in the shock tube laboratory of the Dept. Mech. Eng., Ben Gurion University

roughness on the transition from regular reflection (RR) to Mach reflection (MR) in pseudo-steady flows was investigated both experimentally and analytically. A model for predicting the RR ↔ MR transition in the (M_i, θ_w)-plane was developed (M_i is the incident shock wave Mach number and θ_w, is the reflecting wedge angle). Its validity was checked against experimental results. Summary of obtained results are shown in Fig. 9.

Another fruitful cooperation with Professor Takayama was in evaluating the drag coefficient of a sphere in a non-steady flow. While variations in the drag coefficient of a sphere as function of Reynolds number, in a steady flow is well known and it appears in textbooks, there was no reliable information regarding its magnitude in a non-steady flow. In order to offer a reliable estimate for the Sphere's drag coefficient in a non-steady flow the following experiments were conducted. A small sphere or a few small spheres of different diameters were placed on the floor of the shock tube test-section. Their motion, induced by the passing incident shock wave was recorded and from the available sphere's trajectories the appropriate sphere's drag coefficient was evaluated; for details see in Ref. 4. As is apparent from Fig. 10 there is a significant difference between the drag coefficient in a steady and a non-steady flows.

A third joint research work conducted with Professor Takayama was studying shock wave propagation inside a double-bent duct. The aim of this work was evaluating the efficiency in using such geometry for reaching quick shock attenuation. For investigating the effect played by the duct's wall roughness, experiments were conducted by using two similar models. One had a smooth surface while the second had a very rough surface. A sample of recorded interferograms, obtained for the smooth surface duct is shown in Fig. 11a. In Fig. 11b, results obtained while using the rough surface duct are shown. A detailed description of this research is available in [5]. It is clear from Fig. 11 that the conducted simulations accurately reconstructed the recorded wave patterns. Based on this good agreement we were able to compute the pressure distribution inside the duct for the two cases, smooth and rough duct's walls. Obtained results are shown in Fig. 12.

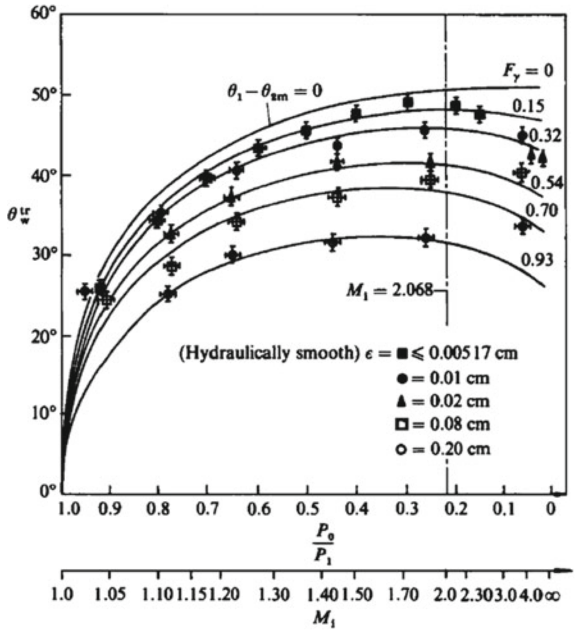

Fig. 9 The experimental results as well as the prediction of the present model for the RR ⇄ MR transition over rough wedges

It is apparent from Fig. 12 that a lower pressure is reached, at the duct exit, in the smooth surface case. This is expected, as in the rough surface case shock waves are generated at every collision of the transmitted shock wave with the steps (roughness) along its way.

I had also a fruitful cooperation with Professor Reichenbach, Drs. Heilig and Amann from the Ernst Mach Institute in Freiburg, Germany covering the following topics: An experimental and numerical study of shock wave diffraction into a square cavity [6], uni-axial strain loading of a rubber rod by planar shock waves [7], numerical simulation of the starting flow in a wedge-like nozzle [8], numerical and experimental study of shock wave propagation in a branched duct [9] and blast wave reflection from wedges [10].

Example for a research conducted jointly in three different countries is the one discussed earlier and summarized in the paper: Experimental and theoretical studies of shock wave propagation through double-bend ducts [5]. In this research the propagation of a shock wave through a double-bend duct was investigated experimentally (in Japan and in Germany) and numerically (in Israel). The German contribution, not seen in Figs. 11 and 12, checked the shock attenuation when the double bent duct had an expansion chamber as shown in Fig. 13; details in [9].

Another joint research conducted with the Ernst Mach group was investigating the starting process of the flow in a wedge-like expansion nozzle of a shock tunnel. Based on the experimental findings conducted at the Ernst Mach Institute (shadowgraphs),

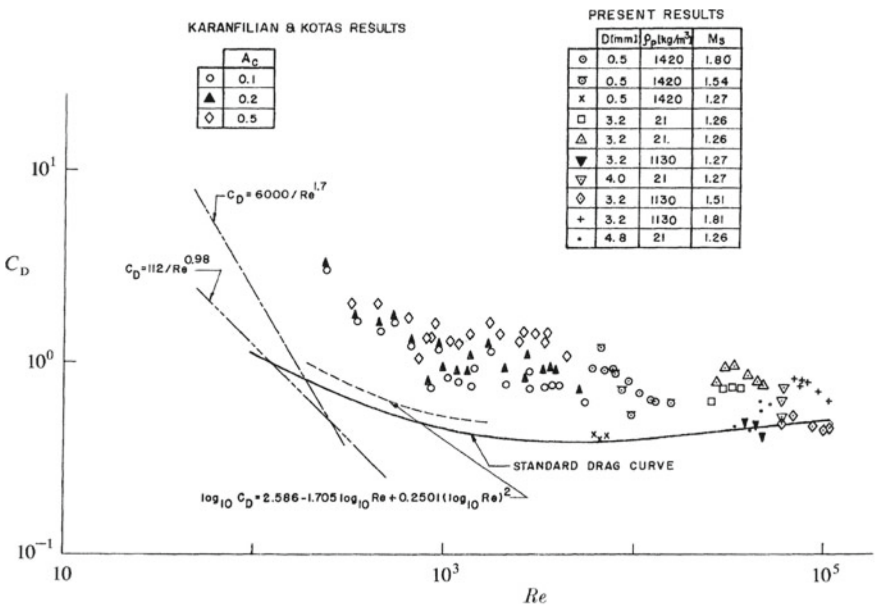

Fig. 10 The sphere drag coefficient versus Reynolds number

the flow was simulated using an un-split 2-D GRP scheme on an unstructured grid [8]. As shown in Fig. 14 the simulated pattern of reflected and transmitted shock waves in the nozzle inlet region and inside the nozzle is found to agree well with the experimental data.

Another joint research activity conducted with the Ernst Mach institute was studying blast wave reflection from wedges [10].

While a lot of attention was given to shock wave reflections from wedges, only little work was published regarding the similar case of blast wave reflection from wedges. In our joint research this subject was studied experimentally and theoretically/numerically.

Experiments where conducted in a specially arranged shock tube (detailed in [10]), a wedge was placed inside the shock tube test section, see in Fig. 15 and pressures where recorded along the wedge surface and the shock tube walls.

Typical results are shown in Fig. 16. It is apparent that the geometry of the reflected wave pattern is similar in the two cases when both incident waves have the same initial pressure jump across their fronts. However, different reflected pressure signatures (history) are observed in these two cases. The pressures obtained behind a reflected shock wave are always higher than those obtained behind the corresponding similar blast wave. In the considered case differences as high as 17% were observed, see Fig. 16.

The third research group with whom I had intensive cooperation included Dr. Lazhar Houas, Dr. Georges Jourdan and their graduate students, from the Shock

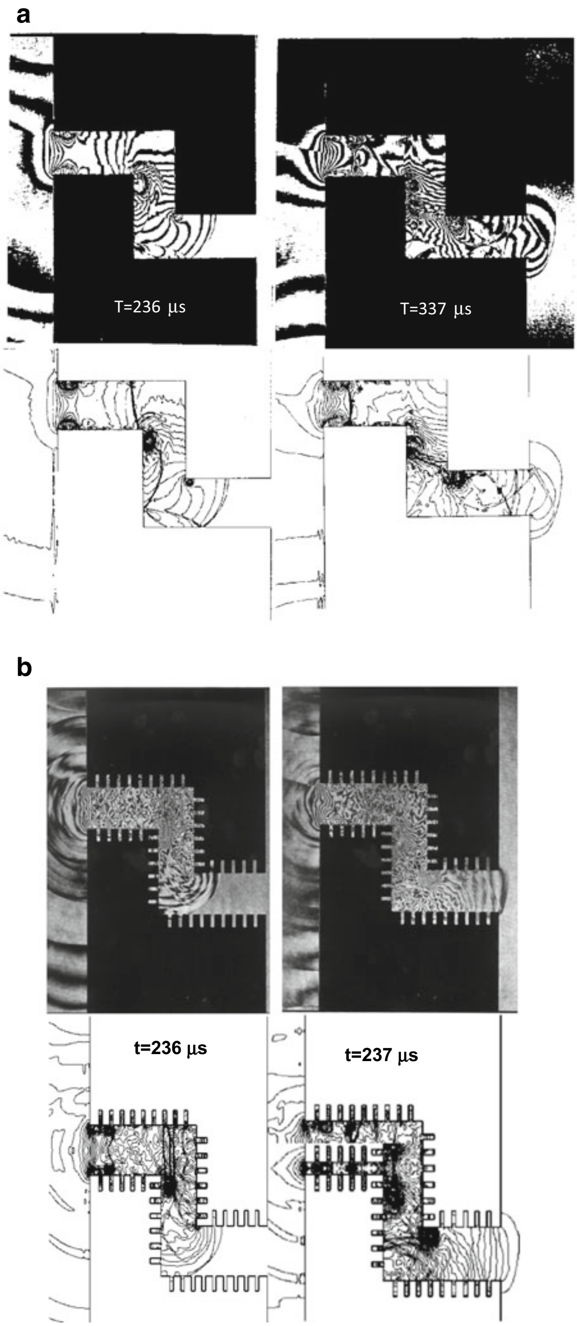

Fig. 11 **a** Shock wave propagation inside a smooth surface, double bent duct; recorded interferograms and its simulations. **b** Shock wave propagation inside a roughed surface, double bent duct; recorded interferograms and its simulations

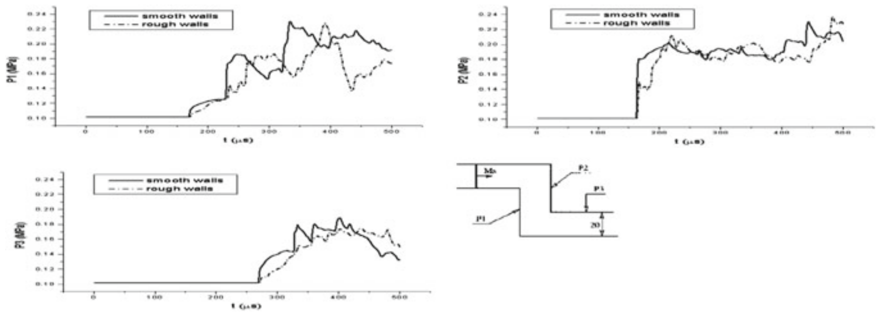

Fig. 12 Calculated pressure histories at various positions along the duct's wall

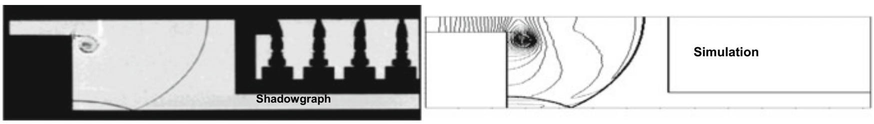

Fig. 13 The double bent model investigated in the Ernst Mach Institute

Tube Laboratory, IUSTI-CNRS, in Aix-Marseille Universit´e, Marseille, France. We were investigating the following topics: Experimental investigation of door dynamic opening caused by impinging shock wave [12]; flow generated inside a duct after it expels a shock wave [13]; effects that changes in the diaphragm aperture have on the resulting shock tube flow [14]; drag coefficient of a sphere in a non-stationary flow; new results [11]; simulation of sphere's motion induced by shock waves [15]; effect of an impinging shock wave on a partially opened door [16]; experimental investigation of shock wave propagation in a 90° branched duct [17] and investigation of blast wave interaction with a three level building [18].

As mentioned earlier, due to the lack of knowledge about the drag coefficient of a sphere in a **non-steady flow**, Professor Takayama and I recorded, in the early nineties, spheres trajectories behind on-coming shock waves; from which the appropriate drag coefficient was deduced [4]. However, in those experiments, the investigated spheres were laid on the shock tube floor and therefore they started their motion in the thin post-shock boundary layer. For eliminating the negative boundary layer effect on the sphere motion, new experiments were conducted in the Shock Tube Laboratory, of Aix-Marseille Universit´e, Marseille. In these experiments the investigated spheres were hanged at the center of the shock tube by a light wire taken from a spider web. Obtained results, including those obtained previously, in Japan [4] are shown in Fig. 17. It is clear from this figure that there is a significant difference between the drag coefficient of a sphere in a steady flow (the standard drag curve) and that obtained in non-stationary flow conditions. Based on results shown in Fig. 17, (the solid line) Jourdan et al. [11] suggested the following correlation for the sphere's drag coefficient:

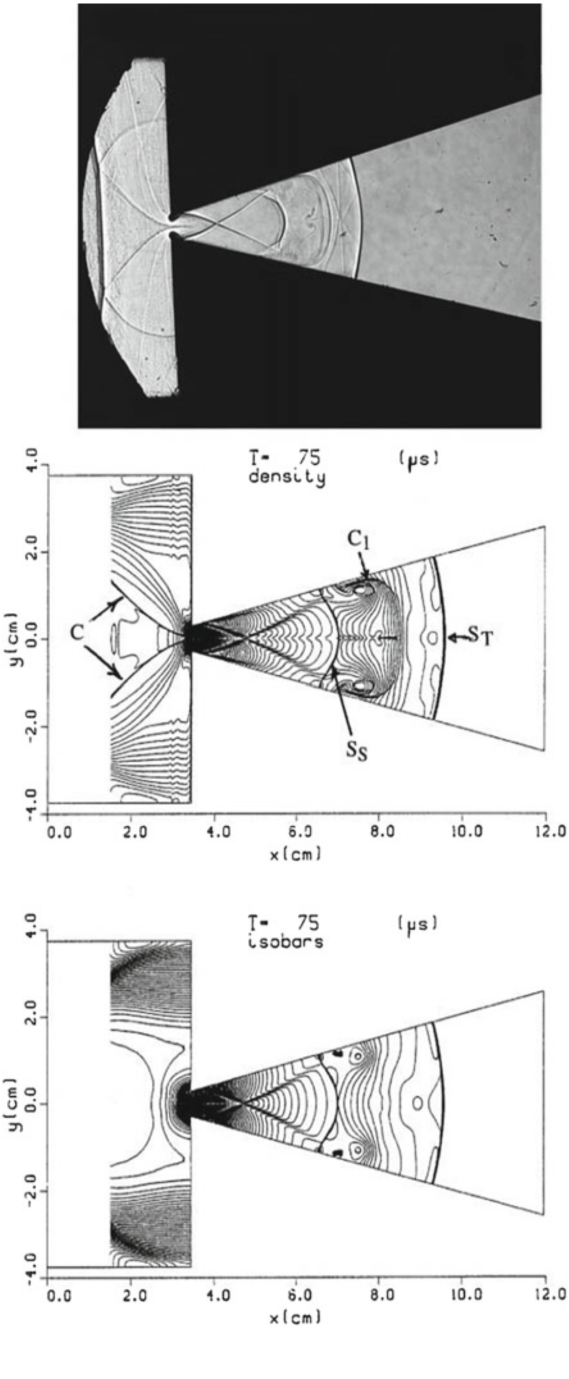

Fig. 14 The flow field inside a wedge-like nozzle at $t = 75\ \mu s$. The top is a shadowgraph photo, at the center is an isopycnic plot and on the bottom an isobar plot

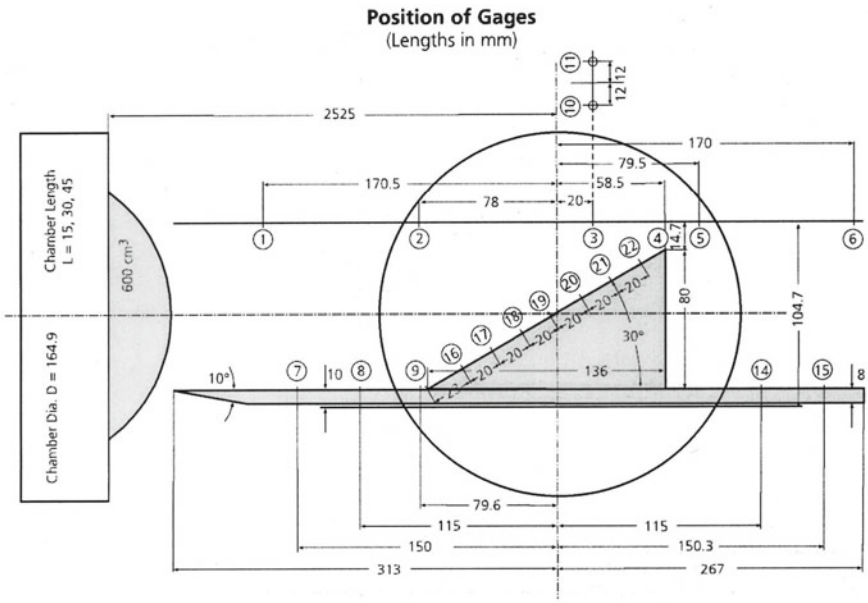

Fig. 15 Schematic description of the wedge location inside the shock tube test section

$$\log_{10}C_D = -0:696 + 1.259\,X\,\log_{10}Re_p - 0.465\,X\,\left(\log_{10}Re_p\right)^2 + 0.045\,X\,\left(\log_{10}Re_p\right)^3,$$

where Re_p stands for the Reynolds number based on the particle relative velocity.

Another example of the cooperation with the Shock Tube Laboratory, of Aix-Marseille Universit´e, Marseille is the investigation of blast wave interaction with a three level building [18]. It was shown in this investigation that weak blast waves that are considered as being harmless can turn to become fatal upon their reflections from walls and corners inside a building. In the experimental part, weak blast waves were generated by using an open-end shock tube. A three level building model was placed in vicinity to the open-end of the used shock tube; as shown in Fig. 18. The evolved wave pattern inside the building rooms was recorded by a sequence of schlieren photographs; also pressure histories were recorded on the rooms' walls. In addition, numerical simulations of the evolved flow field inside the building were conducted [18]. Typical results are shown in Fig. 19. It is apparent from the results shown in [18] that blast wave damages are higher for people standing near a wall, or even higher when near corners. Furthermore, at a late time, the overpressure behind reflected blast wave from a room corner is significantly higher than that experienced in the open atmosphere.

The good agreement obtained between numerical and experimental results shows the potential of the used code for identifying safe and dangerous places inside a building rooms penetrated by the weak blast wave.

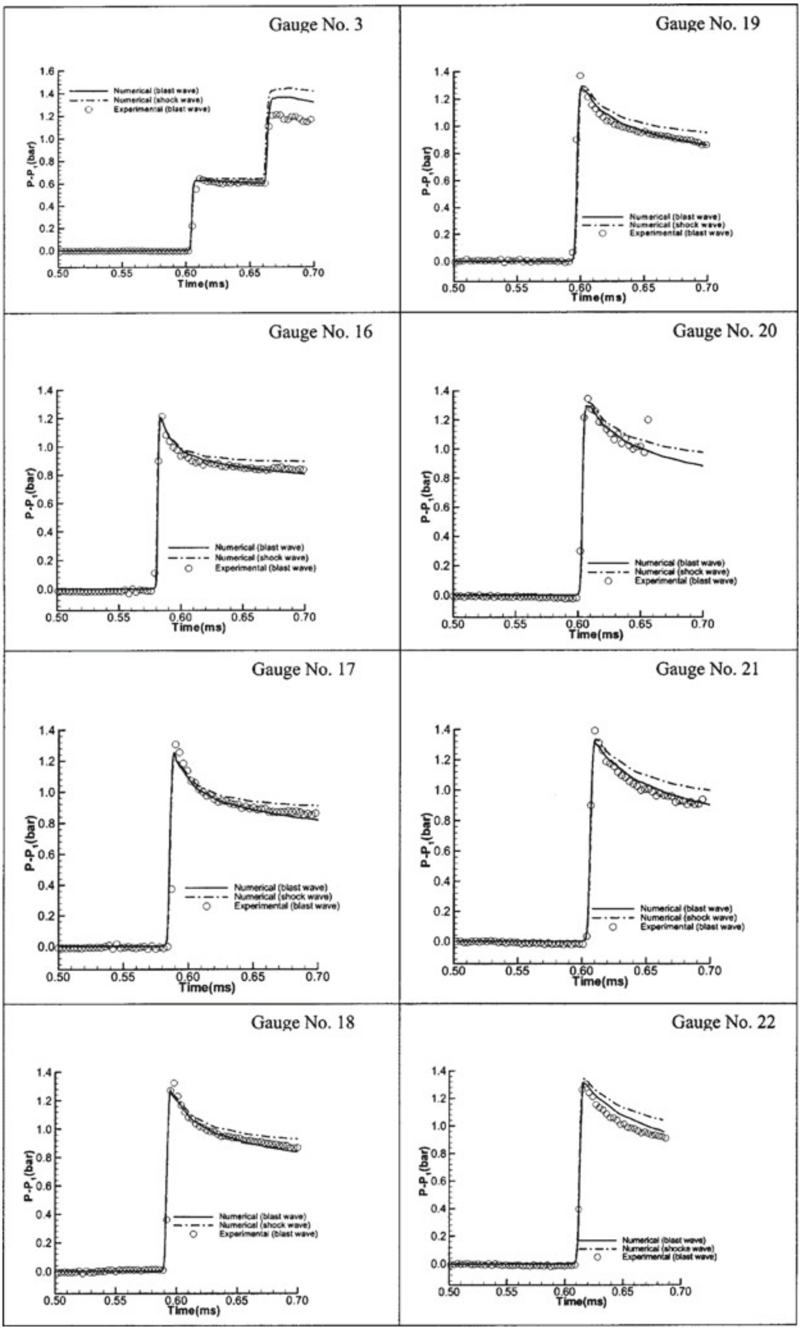

Fig. 16 Recorded and computed pressure signatures over the wedge. Initial conditions are: the driver length is 45 mm $P_4 = 5$ bars, $P_1 = 748$ torr, and $T_1 = 20.1$ °C. The driver and the driven gases are air

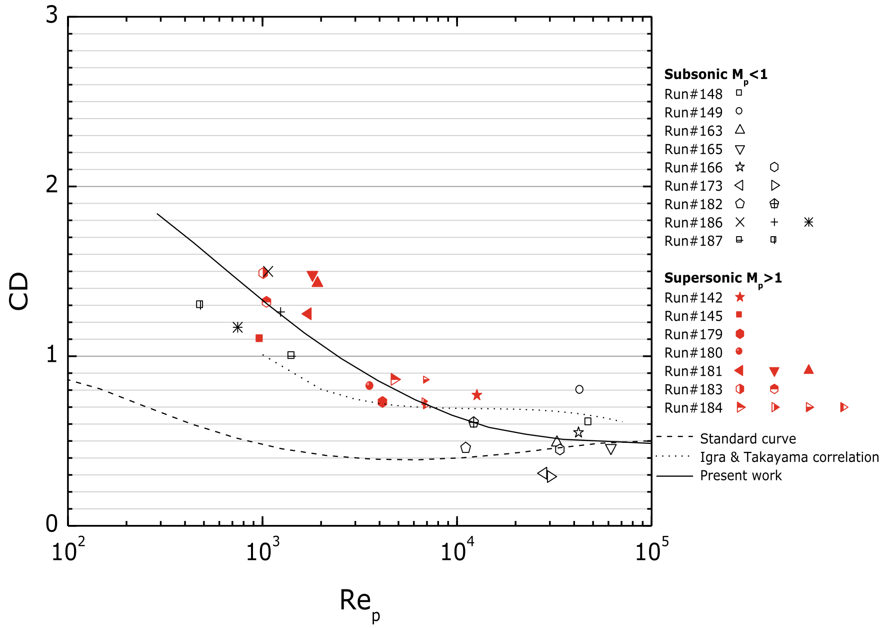

Fig. 17 Variations in the spheres' drag coefficient with Reynolds

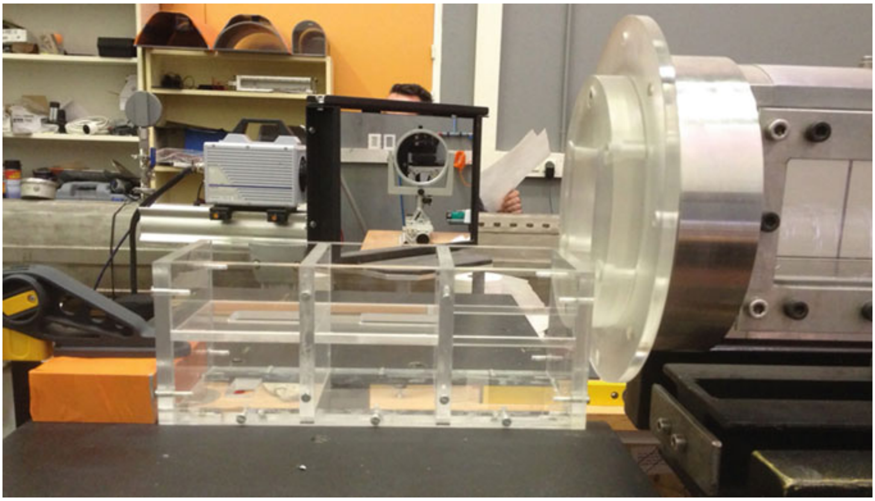

Fig. 18 View of the Plexiglas building model placed close to the shock tube exit

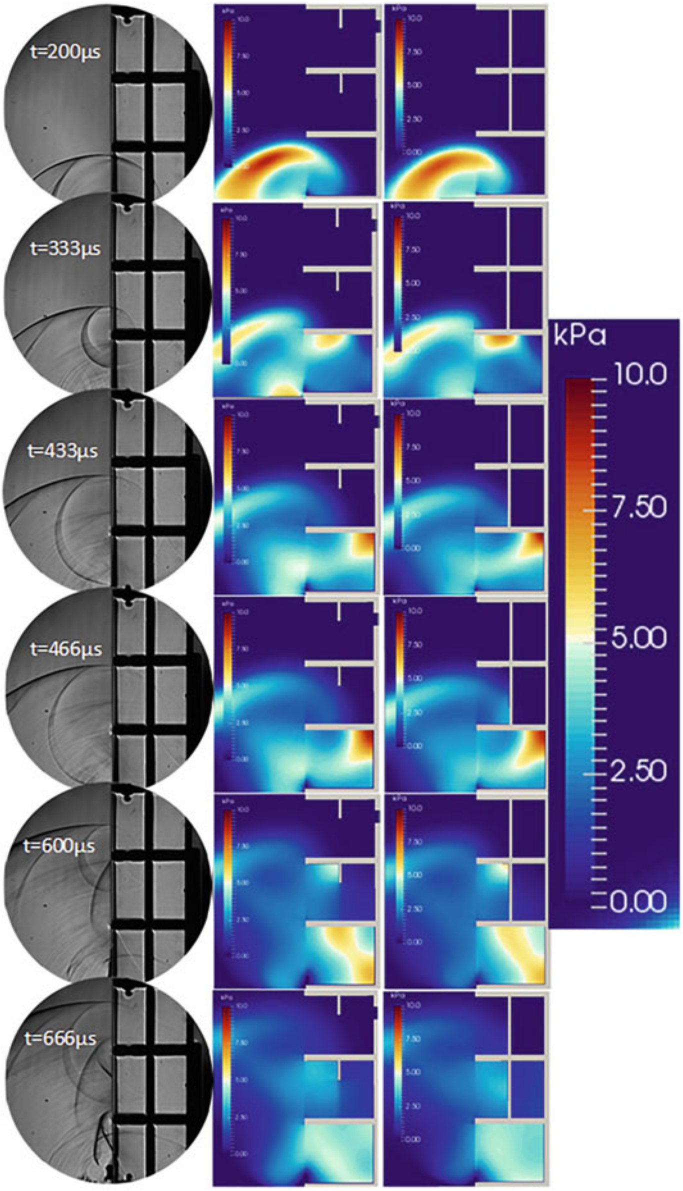

Fig. 19 Overpressure prevailing inside the three floor building model impeached by a blast wave (generated by an incident shock wave, M = 1.17). Experimental results are shown on the left and appropriate simulations appear on the right

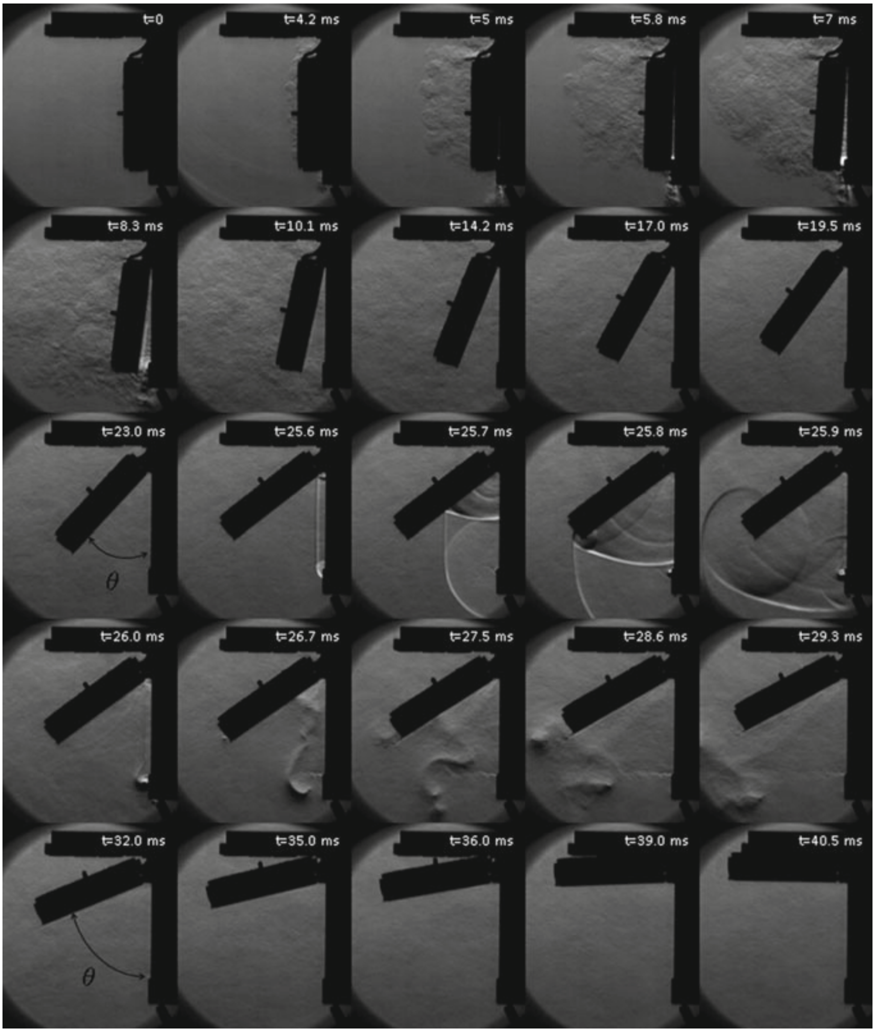

Fig. 20 Sequence of schlieren photos showing the impact of a normal shock wave ($M_{is} = 1.1$), moving initially from right to left inside the shock tube, on an aluminum door. θ is the angle between the door and its initial position

Another example of cooperation with the Shock Tube Laboratory in Marseille University was experimental investigation of door dynamic opening caused by impinging shock wave [12]. In this investigation the dynamic opening of a door, placed at the end of a shock tube driven section was checked. The door was hung on an axis and was free to rotate, thereby opening the tube. The evolved flow and wave pattern due to the door collision with the on-coming incident shock wave, causing the door opening, is studied by employing a high speed schlieren system and recording pressures at different places inside the shock tube, as well as on the rotating door. A typical schlieren records showing the interaction between the door and the on-coming shock wave is shown in Fig. 20.

Analyzing this data sheds light on the air flow evolution and the behavior of the opening door. In this research work [12], emphasis was given to understanding the complex, unsteady flow developed behind the transmitted shock wave as it diffracts over the opening door. It was shown that both the door inertia and the shock wave strength influence the opening dynamic evolution, but not in the proportions that might be expected.

So far a brief description of joint research work done with leading shock wave laboratories in Japan, Germany and France was outlined. Additionally, during the past 25 years I was involved in variety of shock wave investigations conducted in Israel. Among the covered topics were: Interaction between weak shock waves and granular layers [19]; gas filtration during the impact of weak shock waves on granular layers [20]; mechanism of compressive stress formation during weak shock waves impact with granular materials [22]; nonstationary compressible flow in ducts with varying cross-section [23]; dusty gas flow in a converging–diverging nozzle [25]; shock wave reflections in dusty-gas suspensions [26]; shock wave diffraction by a square cavity filled with dusty gas [27]; general attenuation laws for spherical shock waves in pure and particle laden gases [28]; shock wave interaction with perforated plates [30]; shock wave interaction with porous compressible foam [38]; shock wave propagation in non-uniform gas mixtures [39]; shock wave mitigation by different combination of plate barriers [42] and shock wave interaction with a polygonal bubble containing different gases [43]. Detailed description of these research activitie is available in Ref. [8, 19–44].

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