Preliminary shock-tunnel experiments on liquid fragmentation and atomization in hypersonic flows

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Abstract

The present work describes the objectives, the set-up and the preliminary results of an experimental study on the fundamental mechanisms of fragmentation and atomization of a bulk of liquid in hypersonic gas flows. Additionally, we introduce a former series of experiments and calculations also carried out at ISL.

The current experiments are conducted by means of a horizontal shock tube which is operated as hypersonic wind tunnel (shock tunnel). The experimental set-up used is capable of reproducing conditions of real atmospheric flights from Mach 3 at ground-level conditions up to Mach 14 at a flight altitude of 70 km.

This work focuses on shock tunnel experiments on the fragmentation and atomization of a bulk of liquid suddenly exposed to hypersonic atmospheric flow. The liquid substance to be studied is filled into a latex balloon which is placed in front of the shock tunnel nozzle. A needle driven by a magnetic mechanism pierces the balloon shortly before the nozzle flow sets-in, so that the bulk of liquid is introduced into the flow in an almost non-intrusive way. A first series of experiments at Mach 4.5 has been conducted with the help of a high-speed camera to observe the fragmentation of a bulk of 5 ml of water, ethanol and hexane at flight altitudes of 10, 20, 30 and 40 km. The analysis of the atomization and the evolution of the drop sizes require more sophisticated optical measurement techniques. Therefore, in a series of experiments already started a special Particle Image Velocimetry (PIV) technique is used to determine the velocity of the drops. A first result is presented in this paper. Beside this, a LIF-technique is being developed and adapted to observe the evolution of drop size and liquid evaporation.

Introduction

Today the development of hypersonic flight applications is making substantial progress. Therefore, more and more flight vehicles will be able to fly through the atmosphere at Mach 5 and larger. In the case of an accident a liquid substance carried by the vehicle, e.g. propellant, could be released into the atmosphere during hypersonic flight. Following such a scenario, a bulk of a liquid substance would suddenly be exposed to the hypersonic atmospheric flow surrounding the vehicle. As a result of the instantly developed interaction between the liquid and the atmospheric flow, the liquid would be decelerated and fragmented and atomized into drops and evaporated to some extent during a very dynamic process. This process takes place in less than a second and results in a decelerated cloud of drops with a particular drop size distribution. The further mid and long term dispersion of the liquid substance within the atmosphere and its deposit on the ground, respectively, is strongly dependent on the final drop size distribution of this cloud [1]. Due to this fact, the fundamental mechanisms of fragmentation and atomization and evaporation of liquids in hypersonic flows become a key issue predicting the mid and long term dispersion of a liquid substance released during hypersonic flight into the atmosphere as well as the corresponding environmental pollution. It is worthwhile to mention that the fragmentation of liquids in hypersonic flows is also of fundamental interest for other applications, e.g. fuel injection in supersonic combustion engines or thrust vectoring of high-speed vehicles.

Since liquid fragmentation and atomization in gaseous flows has been of interest for a long time, there exists abundant literature devoted at least to some aspects of this matter, including some comprehensive reviews [2–6]. The overall transition between a bulk of liquid and its subsequent dispersion into stable drops is usually found described in the literature as a cascaded process, during which primary instabilities give birth to ligaments with a further breakup into drops [5]. Therefore, the first phase describing the formation of ligaments and of intermediate drops from a macroscopic bulk of liquid is denoted usually by initial pulverization [4], primary atomization [6] or fragmentation [5, 7]. The second phase involving the subsequent breakup of the intermediate drops in those with even smaller diameter due to an initially remaining velocity lag between the intermediate drops and the gaseous flow is in general named as secondary pulverization [4], secondary atomization [6] or simply atomization [5, 7].

Focusing on Newtonian fluids, the atomization of a liquid in gaseous flows seems to be basically a strong function of the Weber number and relatively independent of other parameters such as the Ohnesorge number, Reynolds

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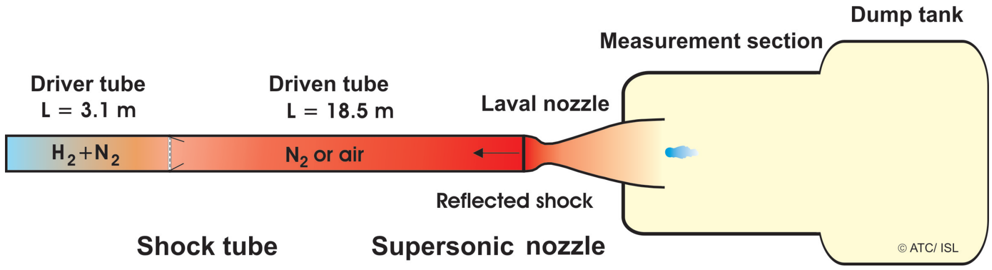


Figure 1. Principle sketch of the shock tunnel with a contoured nozzle

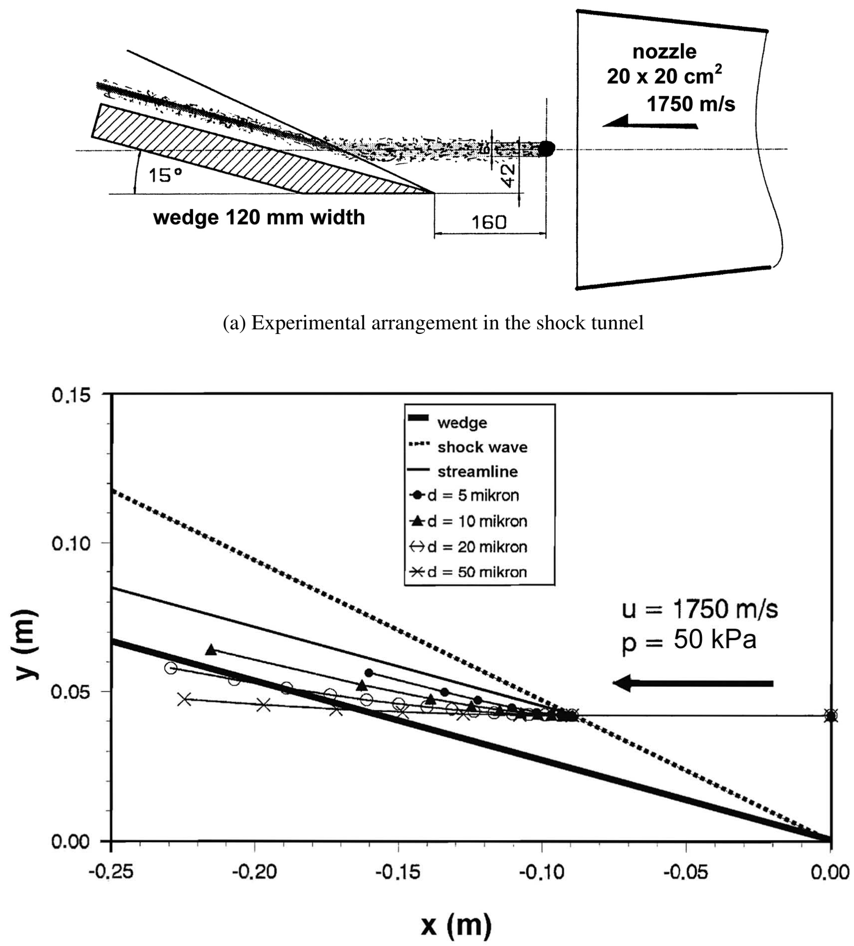
number, and the density and viscosity ratios [4,6]. The types of liquid droplet breakup according to the Weber number are classified by different modes, whereas the transition from each mode to the next one is explained mainly due to an increase of aerodynamic forces acting on a particular drop, compared to its surface tension [2, 8, 9].
Even though there have been some general modeling approaches [4, 6] of liquid atomization to overcome the disadvantages of purely empirical correlations, it is not proven so far, if the existing theory could be extrapolated to hypersonic flow regimes when strong compressibility effects come into play [10]. The lack of experimental studies focused on liquid fragmentation and atomization in hypersonic atmospheric flows is due to the difficulty of combining an experimental setup able to provide an atmospheric hypersonic flow with sophisticated measurement techniques to observe the transient liquid behavior. Many of the former studies focus on atomization of a single liquid drop, e.g. in the flow field behind a shock wave in a shock tube [11, 12].
The present work is focused on the overall process of fragmentation and atomization of a bulk of liquid in hypersonic atmospheric flows. A horizontal shock tunnel is used to duplicate atmospheric hypersonic flow conditions when a bulk of liquid is inserted into the flow in an almost non-intrusive manner. The behavior of the liquid will be observed by means of different optical measurement techniques: high-speed camera images give some insight into the fragmentation process, i.e. the formation of ligaments and intermediate drops. The subsequent atomization, i.e. the evolution of drop sizes and the mass loss due to vaporization will be measured by a Mie-LIF-technique which is currently under development. Beside this, a PIV-technique has been adopted to measure the velocity of the drops. In the following we present the experimental set-up of this ongoing study together with images taken by the high-speed camera showing the fragmentation of water, hexane and ethanol for different atmospheric flows. In addition, we show the first results originating from the PIV-measurements. This work also briefly includes the set-up and results of a former study following a different but very interesting approach to measure drop sizes in hypersonic atmospheric shock tunnel flows.

Experimental Methods

This section introduces the shock tunnels of the ISL used to reproduce real atmospheric hypersonic flow conditions. Hereafter the mentioned former study on liquid atomization which uses a wedge to determine the sizes of atomized drops in hypersonic atmospheric flows is introduced briefly. Finally the set-up of the ongoing study is described together with the method of inserting a bulk of liquid almost non-intrusively into the flow.

Shock Tunnels

The 'Aerothermodynamics and Shock-Tube' laboratory has two high-energy shock tubes (STA and STB) able to furnish up to 8 MJ/kg to perform high-speed flow experiments. The inner shock-tube diameter is 100 mm and the facility lengths are about 22 m. Nowadays, the shock tubes of the ISL are mainly used as hypersonic shock tunnels. A shock tunnel is a very short-time-duration wind-tunnel consisting of a shock tube connected to a supersonic nozzle and a test chamber. The shock tube itself is divided into a 3.1-m-long (STA) and 3.6-m-long (STB) high pressure driver tube and a 18.5-m-long low pressure driven tube as depicted in Fig. 1. The driven tube is followed by the nozzle, the measurement section and the dump tank. A preferably light driver gas is compressed in the driver tube. The steel membrane separating the high-pressure and the low-pressure parts bursts at a determined pressure depending on the experiment conditions required. At this moment a compression shock runs through the driven tube where the test gas (nitrogen in general) is contained. At the same time an expansion wave runs in the opposite direction and is reflected from the driver-tube end. The compression shock propels the gas in the driven tube in front of the entrance of the nozzle where it is compressed and heated and where it remains almost stationary for a short time. Then, the driven gas expands through the nozzle resulting in a quasi stationary hypersonic flow



(a) Experimental arrangement in the shock tunnel

(b) Deviation of sphere-shaped droplets by a velocity jump in a shock wave on a wedge

Figure 2. Former experiments

into the measurement chamber. The resulting measurement duration ranges from 1 to 4 ms. The test chamber contains the model to be studied (here the liquid bulk) and collects the shock-tube gases after the experiment. The gases are then stored in the dump tanks attached to the test chamber. The dump tanks have a volume of about 10 and 20 m^3 for STA and STB, respectively. After each shot, the free-stream flow conditions are recalculated using a one-dimensional shock-tube code which requires the measured shock-wave speed in the driven tube as an input. By varying the tube pressure, the freestream flow can be adjusted to duplicate flow conditions present in the atmosphere. Real atmospheric flight conditions can be reproduced in these facilities from ground level up to 70-km flight altitude. Experiments reported in this paper were performed either in shock tunnel STA or in shock tunnel STB at different Mach numbers and for different simulated altitudes. Nozzles having a Laval contour are available for experiments at Mach numbers of 3, 4.5, 6, 8 and 10. Divergent nozzles are used for Mach numbers of 3.5, 4, 10, 12 and 14. The nozzle-exit diameters range from 200 to 400 mm.

Former Experiments

Comprehensive experiments and calculations on liquid fragmentation and atomization in the subsonic as well as supersonic regimes were carried out at ISL by Smeets and Patz [13]. In this paper we will just focus on one of them in the supersonic regime as an example. These experiments were carried out in shock tunnel STB with a flow rate of 1750 m/s, a static pressure of 50 kPa, a temperature of 300 K and a measuring time of 5 ms. An overview of the former work carried out at ISL on liquid fragmentation as well as a thorough introduction on the subject was given by Srulijes and Seiler [14].

Figure 2a shows the experimental arrangement. From a nozzle with a square outlet cross-section, which is connected to a reservoir under a pressure of 600 kPa, a jet beam formed by the substitute liquid hexanol perpendicularly transverses the channel. After 50 mm, the jet is collected by a funnel. In this way a cylindrical liquid beam of

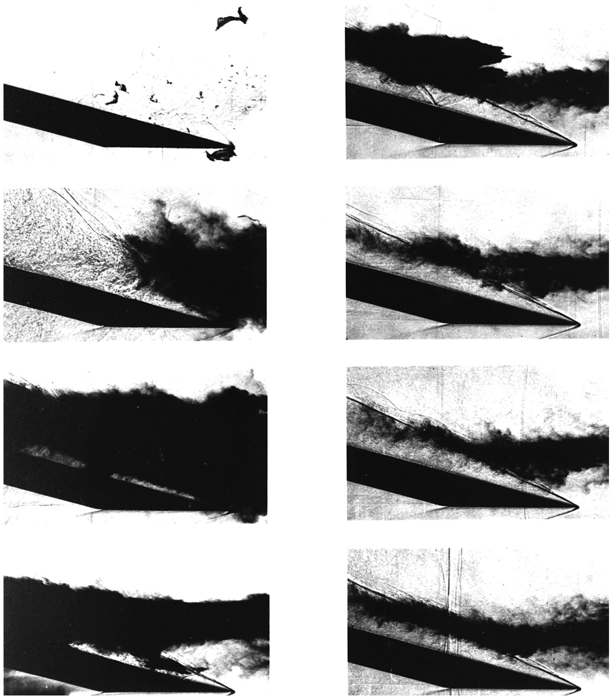


Figure 3. Former experiments – Series of shadowgrams of hexanol spraying (u = 1750 m/s, p = 50 kPa, spray pressure = 600 kPa, time interval = 0.2 ms)

6 mm in diameter and 50 mm in length is produced, which is crosswise blown by the high speed flow.
To examine the size of the droplets in the wake of the sprayed cylinder the flow is deflected over a 15°-wedge. Shadowgraph pictures show whether, and/or how, the particles follow the bending streamlines behind the inclined shock wave.
The streamlines of spherical droplets of various diameters were computed in order to determine the maximum droplet size in the spray crossing the inclined wedge shock wave with the incident flow velocity at 1750 m/s and, after their deviation behind the shock wave, following the new direction of the streamlines. The drag coefficients for spheres as a function of the Reynolds number indicated by Schlichting [15] were taken. The result in Fig. 2b shows that droplets, arriving at 42 mm distance from the wedge front edge and following the streamlines without hitting the wedge surface, must be smaller than 20 µm. For comparison, calculations done with droplets which are not flowing with the full incident flow velocity at their arrival at the inclined wedge bow wave, result in very similar streamlines so that there are no changes in this conclusion.
Figure 3 shows a series of 8 photos with 0.2 ms time interval between images. On image 1, the beginning of the flow in the shock tunnel is shown. Shortly after the start first a spray cloud (in picture 2) appears which probably consists of droplets initially surrounding the cylindrical liquid column. A large part of the liquid cylinder is torn-off and entrained by the flow. A simple calculation shows that this compact liquid reaches the measuring point approximately at the time of photo 4. The extensive cloud in picture 3 can be assigned to the strongly turbulent direct wake of this liquid. The fog in the flow coming afterwards from behind (photos 5 to 8) does not reach the wedge's surface any more. This flow comes from a shorter liquid jet escaping from the nozzle and bends immediately into the cross-flow. After reaching this stationary flow condition the droplets follow the streamlines nearly without slip. These droplets already evaporate noticeably in the heated flow behind the wedge shock. The latter is an indication that a large portion of the droplets must still be substantially smaller than 20 µm.

Experimental Set-up

Observing the fragmentation and atomization of a bulk of liquid in atmospheric hypersonic flows requires an experimental set-up capable of reproducing the relevant hypersonic atmospheric flow conditions, a method to bring the liquid into the flow and appropriate measurement techniques to observe the liquid behavior of interest. The present study employs the shock tunnels introduced above to duplicate a real atmospheric hypersonic flow with respect to velocity, density and temperature. A magnetic piercing mechanism shown in Fig. 4 has been constructed and installed at the nozzle's exit, which pierces a latex balloon filled with the particular liquid substance when

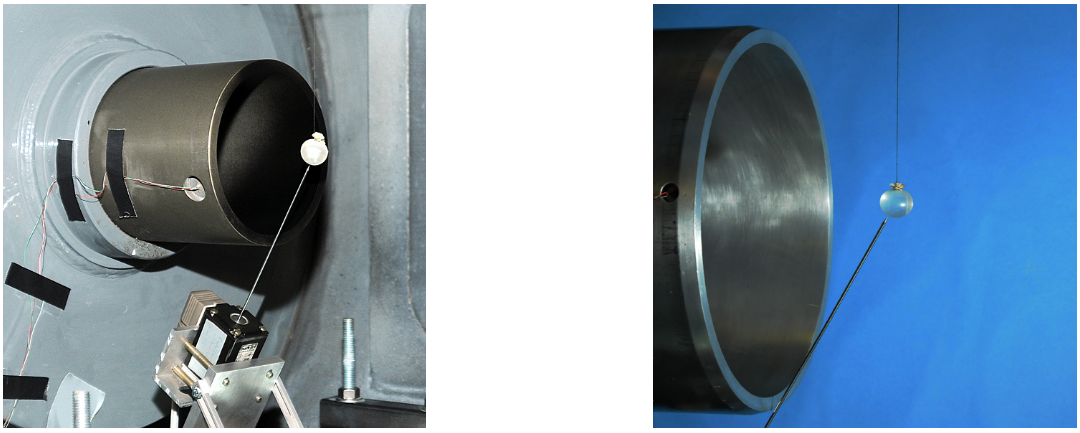
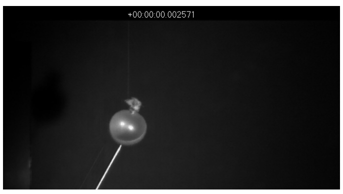


Figure 4. Experimental Setup – Piercing mechanism with balloon filled with liquid in front of the nozzle

triggered just before the flow sets in.
The procedure governing an experiment is as follows: the liquid substance of interest is filled into a latex balloon which is hung in front of the nozzle. After evacuating the measurement chamber and due to the reflected shock wave, the shock tube produces a quiescent high-enthalpy gas reservoir in the region just before the end of the driven section where the nozzle is attached. This high-enthalpy gas reservoir feeds the nozzle which lets the gas expand into the measurement chamber developing a parallel flow when a contoured nozzle is used. The initial conditions of driver and driven gas before the experiment determine the temperature and the density of the gas reservoir originating from the reflected shock wave. Temperature and density of the gas expanded through the nozzle together with the initial pressure of the measurement chamber determine finally the conditions of the nozzle flow with respect to velocity, density and temperature. Just before the flow sets in the piercing mechanism is triggered destroying the latex balloon and releasing the bulk of liquid contained.
The piercing and the destruction of the balloon obviously influence the bulk of liquid contained. Preliminary tests without flow and with the help of backlight illuminated high-speed camera images have proven that this influence remains very small, i.e. the balloon vanishes in less than 1 ms and leaves the bulk of liquid in front of the nozzle. Fig. 5 presents a series of four backlight illuminated images with a delay of 3 ms between each: the first picture is taken just after the piercing took place. The next picture shows that the cover of the balloon has already collapsed and that the bulk of liquid remains unsupported in front of the nozzle. The picture series of Fig. 6 show the piercing triggered just before the onset of an atmospheric flow at Mach 3 demonstrating the applicability of the magnetic piercing mechanism.



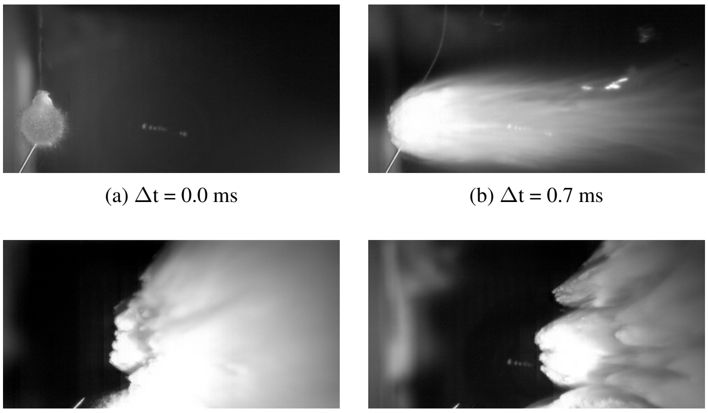
(a) Δt = 0.0 ms

(b) Δt = 3.0 ms

(c) Δt = 6.0 ms

(d) Δt = 9.0 ms

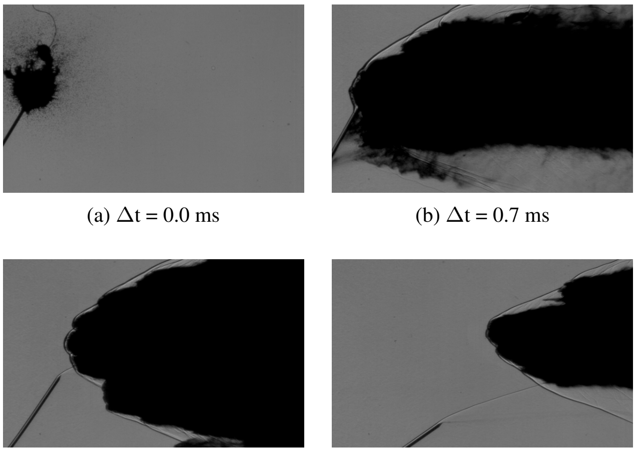
Figure 5. Insertion tests – High-speed camera images with backlight illumination



(a) Δt = 0.0 ms (b) Δt = 0.7 ms

(c) Δt = 4.8 ms (d) Δt = 5.9 ms

Figure 6. Fragmentation of water at Mach 3 in 20 km – High-speed camera images with backlight illumination



(a) Δt = 0.0 ms (b) Δt = 0.7 ms

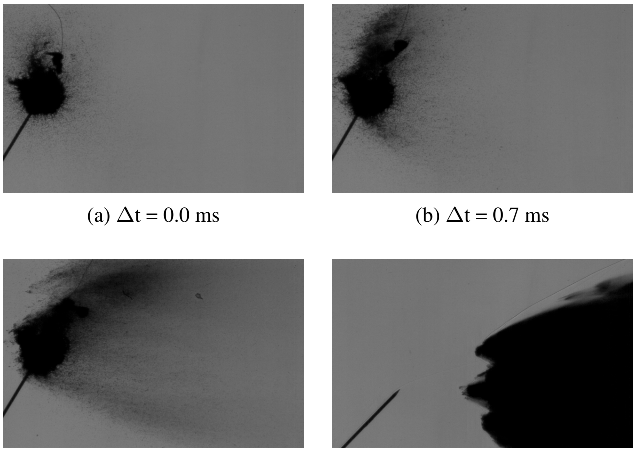
(c) Δt = 1.4 ms (d) Δt = 2.1 ms

Figure 7. Fragmentation of water at Mach 4.5 in 10 km – Series of shadowgrams taken by high-speed photography

Results and Discussion

Results and Discussion A first series of experiments observing the fragmentation of 5 ml of water, hexane and ethanol has been conducted for atmospheric flow conditions at Mach 4.5 for altitudes of 10, 20, 30 and 40 km. By means of a high-speed camera shadowgrams visualize the fragmentation of the particular liquid substance. Tab. 1 summarizes some of the experimental conditions presented in this work which have been calculated by means of a one-dimensional shock tube code – only the pressure could be measured at the end of the nozzle to validate the calculated results. In all of the experiments Hydrogen was used as driver and Nitrogen as driven gas.

Figs. 7 and 8 present a series of shadowgrams representing two experiments with water, the first at 10 km of altitude and the second at 40. A simple comparison of the temporal development of the macroscopic fragmentation effects illustrates the strong influence of the density of the gas flow on the process: The flow at 10 km of altitude exhibits a density three orders of magnitude greater than that at 40 km. Thus, the bulk of liquid at 40 km moves much slower, i.e. it would need much more time to decelerate in a real flight scenario, than at lower altitudes. In the two experiments presented in the figures, the time delay between the consecutive images is 0.7 ms except the last image of Fig. 8 which reveals a much larger delay because the water in that case needs 11 ms from the onset of the experiment to cover nearly the same distance as the water in Fig. 7 which reached it after 2.1 ms. It is obvious that due to this very different temporal behavior also the structural development of the ligaments differ. Nevertheless, a macroscopic bag building could be observed in each experiment conducted.



(a) Δt = 0.0 ms (b) Δt = 0.7 ms

(c) Δt = 1.4 ms (d) Δt = 11.0 ms

Figure 8. Fragmentation of water at Mach 4.5 in 40 km – Series of shadowgrams taken by high-speed photography

PIV measurements

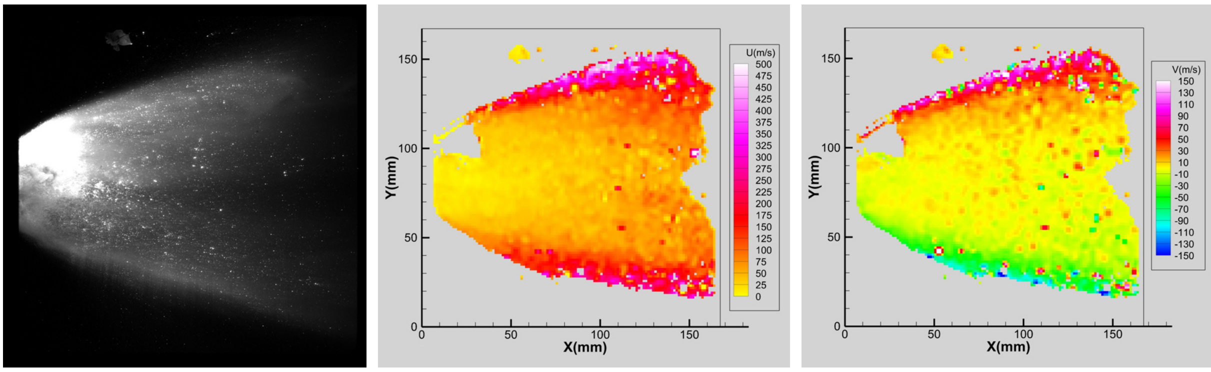
A double-frame/single-exposure digital PIV system was installed at the ISL shock tunnel STA. The light source consists of a frequency-doubled Nd:YAG double pulse laser (Quantel CFR 400 Ultra Ice) with a nominal pulse energy of 200 mJ each and a pulse duration of about 8 ns. The vertical laser-light sheet (220 mm wide, 0.6 mm thick at the waist) perpendicular to the nozzle axis was created by means of a TSI light arm and a couple of cylindrical and spherical lenses. The CCD camera was mounted on the horizontal axis to view the illuminated flow field behind the nozzle axis. The experiments were carried out with a PowerView Plus 4MP PIV camera distributed by TSI. A Zeiss objective was mounted to the camera to observe the field of view. The camera spatial resolution is of 2048 x 2048 pixels, the optical magnification is 82.3 µm/pixel, the field of view is 168 x 168 mm^2 and the delay between the two laser pulses is 2 µs. The laser and the camera are synchronized and triggered by a heat-flux sensor flush mounted in the shock-tube wall. The synchronizer separation time was checked by a fast-response photodiode and timing errors were found to be less than 1%. The PIV images were analyzed after the experiment by an inter-correlation algorithm. The width and height of the correlation windows are 48 x 48 pixels and the grid spacing step is 16 pixels. The intercorrelation function is calculated by a fast Fourier transform. Fig. 9 shows a raw image of the drops illuminated by the laser-light sheet for an experiment conducted with water at Mach 4.5 at 40 km and demonstrates the corresponding horizontal and vertical velocity profiles.

Summary and Conclusions

The objectives, the experimental set-up and preliminary results of a study on the fundamental mechanisms of fragmentation and atomization of a bulk of liquid in hypersonic atmospheric flows are presented. First tests without and those including an atmospheric flow at Mach 3.0 have been used to prove the ability of the experimental set-up to insert a bulk of liquid, in an almost non-intrusive way, into the nozzle flow generated by the shock tunnel. A first series of experiments has been conducted that visualize the fragmentation of 5 ml of water, hexane and ethanol at Mach 4.5 for altitudes of 10, 20, 30 and 40 km by means of high-speed camera shadowgraph images. Beside this,

No.	Pressure [kPa]	Density [kg/m^3]	Temperature [K]	Velocity [m/s]	a [m/s]	Mach-Number	Altitude [km]
18	30.544	0.45	228.60	1398.09	308.19	4.54	10
26	4.739	0.074373	214.69	1348.49	298.66	4.52	20
35	1.221	0.018146	226.77	1369.94	306.95	4.46	30
45	0.263	0.003626	244.31	1393.14	318.59	4.37	40

Table 1. Example of some of the experimental conditions



(a) raw image (b) horizontal velocity (c) vertical velocity

Figure 9. Fragmentation of water at Mach 4.5 at 40 km – PIV raw image and velocity profiles

the first PIV-experiments provided useful velocity profiles of the fragmented intermediate drops. A systematic discussion of the preliminary results on the basis of the shadowgrams is left, because interpreting 2D-shadowgrams of a complicated 3D-structure without any further information would not lead to fundamental insights. Nevertheless, the results give an interesting overview of the fragmentation of different liquid substances at different atmospheric flow conditions.

Future experiments will focus on the implementation and adaptation of appropriate and sophisticated optical measurement techniques: measuring the drop sizes requires an optical scattering method exploring the dependence of the light scattered from a particular drop on its surface and volume characteristics. The density of the liquid could be measured by a special LIF-technique to get reliable quantitative results on the mass loss, i.e. the mass of liquid which is lost during fragmentation and atomization through evaporation. Systematic information on the evolution of the velocity field of the drops could be gathered by further PIV-measurements. In addition to this, it would be very worthwhile to visualize the 3D-structure of the fragmentation process, e.g. by means of a tomographic method.

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