1 of 1

**Dense Gas Boundary Layer Experiments:
Visualization, Pressure Measurements,
Concentration Evaluation**

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T 10 / 92

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- Visualization, Pressure Measurements, Concentration Evaluation -

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Interim Report

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SUMMARY

This technical report describes methods that were applied to investigate turbulent boundary layers generated by inviscid, baroclinic effects. The Cranz-Schardin 24-sparks camera was used to visualize the interactions of a planar shock wave with a Freon R12-layer. The shock propagates more slowly in the Freon layer than in air because of its smaller sound speed. This causes the shock front to be curved and to be reflected between the wall and the layer interface. As a consequence of the reflection process, a series of compression and expansion waves radiate from the layer. Large fluctuations in the streamwise velocity and in pressure develop for about 1 ms. These waves strongly perturb the interface shear layer, which rapidly transitions to a turbulent boundary flow.

Pressure measurements showed that the fluctuations in the Freon layer reach a peak pressure 4 times higher than in the turbulent boundary flow.

To characterize the preshock Freon boundary layer, concentration measurements were performed with a differential interferometry technique. The refraction index of Freon R12 is so high that Mach-Zehnder interferometry was not successful in these experiments. The evaluation of the concentration profile is described here in detail.

Method and results of corresponding LDV measurements under the same conditions are presented in a different report, EMI Report T 9/92.

We plan to continue the dense gas layer investigations with the gas combination helium/Freon.

TABLE OF CONTENTS

Section		Page
	SUMMARY	iii
	CONVERSION TABLE	iv
	FIGURES	vi
1	INTRODUCTION	1
2	VISUALIZATION OF THE FLOW FIELD	2
	2.1 CREATION OF THE DENSE GAS LAYER	2
	2.2 SHADOW PHOTOGRAPHS	3
3	PRESSURE MEASUREMENTS	6
	3.1 EXPERIMENTAL SET-UP	6
	3.2 RESULTS	6
4	PRESHOCK DENSE GAS LAYER PROFILE	8
	4.1 EVALUATION BY DIFFERENTIAL INTERFEROMETRY	8
	4.1.1 Experimental Set-up	8
	4.1.2 Evaluation of the Interferograms	10
	4.2 RESULTS	12
5	CONCLUSIONS	14
6	LIST OF REFERENCES	15

FIGURES

Figure

- 1 Sketch of the test set-up to create a Freon layer in the measuring chamber of the shock tube.
- 2 Sketch of the computer-controlled filling mechanism.
- 3 Timing program to operate the different valves.
- 4 Cranz-Schardin camera frame position. Test 13954.
- 5 Shock wave interaction with a dense gas layer (Freon). Shadowgram and strongly diffracted light at the same instant are shown.
Test 13954; $M_s = 1.289$
- 6 Cranz-Schardin camera frame position. Test 13955.
- 7 Shock wave interaction with a dense gas layer (Freon). Shadowgram and strongly diffracted light at the same instant are shown.
Test 13955; $M_s = 1.281$
- 8 Shadow cinematography of a planar shock wave interacting with a Freon layer. $M_s = 1.286 \pm 0.008$
sequence a: test 13956 sequence b: test 13959
sequence c: test 13957 sequence d: test 13958
- 9 Locations of the pressure gauges in the side wall of the shock tube.
- 10 Pressure records of test 14064 without Freon layer. $M_s = 1.388$
- 11 Pressure records of test 14069 without Freon layer. $M_s = 1.31$

FIGURES (CONTINUED)

Figure

- 12 Overpressure of the 1st maximum and the 1st minimum vs height of the measuring position in the stratified Freon-air gas. Test 14069.
- 13 Coordination of individual frames shown in Figure 8 to some pressure records of Figure 11.
- 14 Experimental setup of the differential interferometer. Circles and arrows indicate the polarisation of the incident and transmitted beam, resp. the polarisation of the ordinary beam in the prisms of the Wollaston (direction of view along the optical axis).
- 15 Preshock differential interferograms of layer 1.
upper: test DI.11, lower: test DI.28
Duration of Freon injection: 5 sec
Delay of diaphragm rupture: 2 sec
Freon pressure: 1.2 bar
- 16 Preshock differential interferograms of layer 2.
upper: test DI.8, lower: test DI.22
Duration of Freon injection: 5 sec
Delay of diaphragm rupture: 5 sec
Freon pressure: 1.2 bar
- 17 Preshock density profile of layer 2 evaluated from two inteferograms.
- 18 Preshock density profile of layer 1.
- 19 Preshock differential interferogram of layer 2 at the leading edge of the splitter plate (test DI.52).
Duration of Freon injection: 5 sec
Delay of diaphragm rupture: 5 sec
Freon pressure: 1.2 bar

SECTION 1

INTRODUCTION

Subtask 2.2 of the DNA Contract, DNA 001-91-C-0039, requires the performance of shock tube experiments to determine boundary layer heights, velocity profiles and density/concentration profiles as function of distance behind planar square wave shocks propagating over a thin, dense gas layer. The experiments are to be carried out at a flat wall where the gas layer is generated by the short-duration flow of a dense gas through a porous plate.

To characterize the flow field behind the planar square-wave shock, a four-channel Laser Doppler Velocimeter (LDV), manufactured by PRI, was used. The technique and the results of the LDV measurements are described in EMI report T 9/92 [ref. 1].

In this report, the visualization of a planar shock interacting with the gas layer is presented. The EMI Cranz-Schardin 24-spark high-speed camera was used for shadow photography. The experimental technique to produce the dense gas layer and the flow visualization methods are described in Section 2.

In addition to the specified subtask 2.2 of the contract, pressure measurements were performed at different heights inside and outside the gas layer during the interacting processes. The experimental method and results are discussed in Section 3.

To characterize the density and concentration preshock profile of the gas layer, a differential interferometry method with Wollaston prisms was applied. The high refractive index of Freon R12 prevented the use of our Mach-Zehnder interferometer. The resulting fringe shift in the Freon layer was too high and the distance of the individual fringes in some areas so small that it was impossible to resolve them optically [ref. 4]. The differential interferometry method and results of concentration evaluations are described in Section 4.

SECTION 2

VISUALIZATION OF THE FLOW FIELD

2.1 CREATION OF THE DENSE GAS LAYER.

As dense gas Freon R12 was chosen. The same technique was applied as used at previous experiments [refs. 2, 3]. The characteristic data of Freon are listed in Table 1.

Table 1. Data of Dichlorodifluoromethane (Freon R12)

Chemical formula	CCl_2F_2
Boiling point	243.4 K (= -30 °C)
Freezing point	115.2 K (= -15.8 °C)
Critical temperature	385.2 K (= 112 °C)
Molecular weight	120.92 g/mol
Density at $p_N = 1$ atm; $T_N = 273.2$ K	5.510 kg/m ³
Sound speed	150 m/s (at $T = 293$ K)
Refractive index n^{-1}	$1.18 \cdot 10^{-3}$

Figure 1 shows a sketch of the set-up installed in the test chamber of the shock tube. Four porous ceramic filter plates (FiltrokELIT; 1 FK - 4 FK) with a total length of 600 mm and two metal plates at front and rear end from the floor of the test section. Underneath the FiltrokELIT plates Freon is injected under controlled conditions. The principle of the dense gas boundary layer creation is shown in Figure 2. At first the pores of the ceramic plates are filled with Freon by rinsing and sucking out of the Freon in excess. Then the hand-operated valve V3 is closed and the pump is switched off. Immediately after that the electronic timer is triggered manually. The Freon filling valve V1 is opened after a preselected delay time. Freon is then pressed through the porous floor of the test section and creates the desired gas layer along the FiltrokELIT surface. The duration of the Freon injection and the diaphragm rupture by an airpressure-operated needle are computer-controlled. This led to reproducible dense gas layers with constant density profiles. The timing trigger program applied in the tests is shown in Figure 3.

2.2 SHADOW PHOTOGRAPHS.

In exploratory test, it was discovered that the transmitted light through the shock interacting Freon layer was considerably diffracted by reason of the density gradient and the high refractive index of Freon. As a consequence, this diffracted light was not only focused onto the film by the corresponding lens of the 24-frame Cranz-Schardin camera but also by one of the adjacent camera lenses. Which lens formed a second image depended upon the direction of the density gradient in the layer. Therefore, most of the 24 frames were double exposed, namely first by the light of the corresponding spark at the correct desired time and second by the diffracted light of an adjacent spark at a different time, earlier or later, depending upon the geometrical arrangement of the frame sequence.

This is demonstrated in Figures 4 through 7. In these cases each second spark was covered. Therefore each second picture shows only the diffracted light. A simple consideration allows one to estimate the minimum angle of light deflection needed for the exposure of the second picture.

Completely black areas occur in pictures of our Cranz-Schardin camera if the deflection angle ϵ of the light is

$$\epsilon \geq \frac{r_L}{R} \cong 0.15^\circ$$

where r_L = lens radius and R = distance between test chamber and lens. In this case, the rim of the lens acts as schlieren knife. Angle ϵ is independent of the direction of the light deflection.

If light is diffracted in a second lens located in horizontal or vertical direction of the first one, the deflection angle δ must be

$$\delta \geq \frac{D_L - r_L}{R} \cong 0.21^\circ$$

where D_L = horizontal or vertical distance between the centers of two camera lenses.

Only when $\delta > 0.21^\circ$ can a second lens form an image on the film.

As shown by experiments, the density gradient in a Freon layer is favored in the vertical direction. So it is important to know in which position the 24 different frames are geometrically oriented. Figure 4 shows the arrangement and gives the chronological order in which the sparks are fired. It is obvious that - with regard to Figure 4 - the transmitted light in the dense gas is diffracted upwards. Therefore, in Figure 4, for instance, frame 3 is exposed by the diffracted light of frame 2, but frame 7 is exposed by the diffracted light of frame 8 as a result of the geometrical orientation. An analogous explanation is valid for Figure 6.

In Figure 5 and 7, respectively, individual pictures are shown together with pictures formed by their diffracted light. Some details in the dense gas layer are better detected there. Both tests in Figure 5 and 7, respectively, were performed under the same conditions. The only difference was a slight time-change of the trigger pulse for the Cranz-Schardin camera and the order of the covered sparks. So the picture sequences intersect each other. That means, the time of the first picture of Figure 5 is set between the time of pictures one and two of Figure 7. Time $t = 0$ is given where the shock front reaches the first fiducial mark.

In Figure 8 the frames of four different experiments under the same conditions but with different timing are put together in a continuous sequence. So a time duration of about 3 ms is covered. Note that the test conditions of the shown shadowgram sequences are the same as those used for the LDV measurements [see ref. 1].

By comparing for instance Figures 5a, 7a, 8a1, 8b1, one can notice that the preshock dense gas layer of the different tests are reproducible and constant over the whole visible length of the test section. The thickness of the layer remains remarkably constant.

The shock wave propagates more slowly in the Freon layer because of its smaller sound speed. This causes the shock front to be curved near the wall - as shown for instance in Figure 8 (b1 through b4). In effect, the dense gas layer acts like a waveguide, whereby the shock reflects between the wall and the interface and sets up a series of compression and expansion waves that radiate from the layer. These waves strongly perturb the interface shear layer, which acquires an undulated shape (Figure 8a4 through 8b6) and transitions rapidly to

a turbulent boundary layer flow. The shock interactions with the density gradient of the Freon layer creates vorticity by an inviscid, baroclinic mechanism. This contrasts with normal boundary layers that are generated by the viscous, no-slip condition on the wall.

SECTION 3

PRESSURE MEASUREMENTS

The fluctuations seen in the shadowgram sequences suggest that significant pressure variations are present in the dense gas layer. To quantify this assumption, pressure measurements were performed.

3.1 EXPERIMENTAL SET-UP.

One of the optical glass windows in the test section was replaced by an aluminum plate. In this plate several pressure gauges (Kistler 603 B) were installed as shown in Figure 9, so that overpressure measurements at different heights could be performed. In additions, two gauges (MK1 and MK2) were placed in the roof of the test chamber, symmetrical to the vertical measuring line MK4, MK7, MK8, MK9. Two gauges, MK3 and MK6, were installed along the same line as MK1, whereas MK5 was located along the line of MK2.

The electrical pressure signals were stored in 9 individual transient recorders. The data handling procedure was the same as applied at earlier shock tube experiments [ref. 3].

3.2 RESULTS.

In Figure 10, pressure records are shown of a test without a Freon layer. As expected, the signals in the measuring line (MK4, MK7, MK8, MK9) are consistent and agree very well with the records of MK1, MK2, MK3 and MK6 - where the time of arrival is different due to the different position of the gauges.

In Figure 11, records are shown of a test with a Freon layer present. By comparing the corresponding records of Figure 10 (without a Freon layer), differences are obvious. The initial conditions in the shock tube tests, presented in Figure 5, 7, 8, 10, 11 respectively are the same. But the measured Mach number in tests with Freon layers are smaller (average $M_s \approx 1.30$) than in tests without the dense gas layer (average $M_s \approx 1.39$). The reason for the difference in Mach numbers, measured in the test chamber, is the attenuation of the shock wave by the expansion waves radiating from the dense gas layer. The interaction between

shock wave and Freon layer starts before the shock front enters the test chamber because of the extended Freon layer (Figure 1). Therefore the expansion waves can travel up to the roof and reduce the propagation speed of the shock front.

In the Freon layer at MK3 (see Figure 11) pressure fluctuations with several peaks were measured. The peak value of the first overpressure maximum is $\Delta p_{\max} = 4.79$ bar, whereas the following pressure maxima are reduced before the fluctuations died out after about 800 μs . The registered overpressure after this time is about $\Delta p = 1.2$ bar. The period of the pressure fluctuations is about 100 μs . This value corresponds very well with the flow speed variation measured by LDV [see Ref. 1]. The cause of the pressure fluctuations is the reflection of the curved incident shock front between wall and interface, as discussed earlier.

The pressure fluctuations get smaller with increasing height as seen in the records of MK4 through MK7 and have completely disappeared in the records of MK8 and MK9 of Figure 11. The first maximum and the first minimum, respectively, of the fluctuations are plotted vs. height in Figure 12. Whereas the pressure of the first peak rapidly decreases, the pressure of the first minimum increases with height.

In Figure 13, the frames of Figure 8 are coordinated with some pressure records. Also this comparison confirms the close connection between pressure fluctuations and reflection processes of the incident shock.

SECTION 4

PRESHOCK DENSE GAS LAYER PROFILE

4.1 EVALUATION BY DIFFERENTIAL INTERFEROMETRY

Conventional interferometry is based on the superposition of two coherent light beams in an observation plane --- one reference beam and one beam propagating through a typically transparent test object that imposes changes to the optical path length for this beam. The interference pattern in the plane of observation then reflects the difference of the path lengths to a fixed reference length. This is equivalent to a representation of the absolute path length.

In a differential interferometer, both beams propagate through the test object but at different locations. Thus the interference pattern no longer reflects the absolute path lengths. Yet it can still reveal quantitative information.

4.1.1 Experimental Set-up.

Figure 14 shows the optical set-up used for the differential interferometer. The beam of an Argon-Ion laser is coupled into the device via an optical fiber, then expanded by the microscope objective L1 and the front lens L2. The parallel bundle passes the test section of the shock tube and is focused by means of lens L3. Near the focus the light passes through a Wollaston prism W and a polarisation foil P.

The Wollaston prism serves as a beam-splitter in this simple differential interferometer. It defines a natural coordinate system; we will denote the axis parallel to the optical axis of the first prism as u and the one perpendicular to it (and thus parallel to the optical axis of the second prism) as v .

Incident light is split in v -direction into two partial beams, one of them polarized parallel to the optical axis of the first prism, the other perpendicular to it. These leave the prism deflected by small angles $\pm \varepsilon$.

In the experimental setup the polarisation of the incident beam is chosen to be 45° to the Wollaston axes. Thus the light is split up in two partial beams of equal strength.

In order to make an interference pattern visible, polarisator P is again orientated at an angle of 45° with respect to the Wollaston axes, thus transmitting only components of the partial beams that can interfere.

The separation e_s of the partial beams at the screen location can be calculated from the angular separation ε :

$$e_s = 2\varepsilon(s - w) \quad (1)$$

Thus the light at a point $(-mu, -mv)$ on the viewing screen S is a superposition of the two partial beams, one having passed the object plane at $(u, v + e/2)$, the other at $(u, v - e/2)$, where $m = s/f$ denotes the magnification and e the separation in the object plane:

$$e = 2\varepsilon(f - \frac{w}{m}) \quad (2)$$

The interference pattern will reflect following phase differences:

$$\frac{\Delta\Phi(-mu, -mv)}{2\pi} = [(n(u, v + e/2) - n(u, v - e/2))] \cdot \frac{l}{\lambda} \quad (3)$$

where l denotes the depth of the test section.

For small beam separations e

$$(n(u, v + e/2) - n(u, v - e/2)) = \frac{\partial n}{\partial v}(u, v) \cdot e \quad (4)$$

is a sufficient approximation.

When the orientation v of the beam separation is inclined versus the x -axis of the test section one finds that

$$\frac{\Delta\Phi(-mx, -my)}{2\pi} = [\sin\beta \frac{\partial n}{\partial y} + \cos\beta \frac{\partial n}{\partial x}] \cdot \frac{l}{\lambda} \cdot e \quad (5)$$

where β denotes the inclination angle.

This holds true when the Wollaston is located in the focal point of lens L3. Positioning the Wollaston prism in a distance w from the focal point gives rise to a set of interference fringes that are perpendicular to the beam separation. These are due to a path length effect within the Wollaston and their spacing $\delta_{fringes}$ can be determined by

$$\delta_{fringes} = \frac{\lambda}{2\varepsilon} \frac{f}{w} \quad (6)$$

If there are no path length changes due to an index gradient in the test object the fringes will be parallel. Otherwise the fringes will be deformed by the index gradient and their displacement scaled with the fringe spacing corresponds to the phase difference due to the gradient.

The main advantage of the differential interferometer is that its sensitivity can be adjusted to large differences in the refractive index; the disadvantage is that the evaluation requires an integration starting in a region of known refractive index. The simple setup applied here has the further disadvantage that the finite fringes are perpendicular to the beam separation. Adjusting the beam separation in y -direction which makes the interferometer insensitive against a gradient in x -direction results in a poor visualization quality. Oblique fringe orientation makes the evaluation easier, but the interferometer becomes sensitive to both possible components of the gradient.

The later effect is negligible in the Freon layers of interest since the results showed an excellent stratification. In cases where both components are of the same order of magnitude one has to take two interferograms with different fringe orientations (typically perpendicular to each other).

Because optical aberrations by the Wollaston can not be totally avoided, it is advisable to take a reference interferogram previous to the injection of the Freon.

4.1.2 Evaluation of the Interferograms.

To obtain the distribution of the refractive index within the test section, the following steps (which can at least be partially automated) were taken:

1. Measurement of the fringe spacing and, by comparison of the pre-Freon and the post-Freon interferograms, determination of the fringe displacement in y -direction as a function of the position in the x - y plane of the test section.
2. Scaling of the relative fringe displacement with $\lambda/l \cdot e \cdot \sin\beta$ in order to obtain $\partial n/\partial y$.
3. Integration along a scan in y -direction, starting in a region of constant and known refractive index.

A further necessary step is to relate the refractive index to the density of the mixing layer. For homogenous gases this relation is established through

$$n - 1 = G(\nu)\rho \quad (7)$$

where $G(\nu)$ is a frequency dependant material specific constant, the Gladstone-Dale constant, that relates the optical properties of the gas to its dielectric response to electromagnetical forcing. For a mixture of gases, eg. air and Freon eq. 7 becomes

$$n_{mix} - 1 = G_{Freon}\rho_{Freon} + G_{air}\rho_{air} \quad (8)$$

where the density ρ_{mix} of the mixture is the sum of the component densities.

In cases where the Gladstone-Dale constants of the components differ significantly it is more convenient to write eq. 8 in terms of the partial pressures p_{Freon} and p_{air} . Assuming the components as perfect gases one finds:

$$n_{mix} - 1 = \frac{G_{Freon} \cdot M_{Freon}}{RT} p_{Freon} + \frac{G_{air} \cdot M_{air}}{RT} p_{air} \quad (9)$$

where

R = universal gas constant

T = temperature

M_{Freon}, M_{air} = molecular weight

The interferograms of the Freon layer are compared to an interferogram where the test section was filled completely with air at the same pressure. Thus we are interested in

$$n_{mix} - n_{air} = \frac{G_{Freon} M_{Freon}}{RT} p_{Freon} + \frac{G_{air} M_{air}}{RT} p_{air} - \frac{G_{air} M_{air}}{RT} p \quad (10)$$

Substituting the pressure p by the sum of the partial pressures yields

$$n_{mix} - n_{air} = \frac{G_{Freon} M_{Freon} - G_{air} M_{air}}{RT} p_{Freon} \quad (11)$$

In preliminary experiments we obtained following values for the refraction index of air and Freon at 25° C and 1000 mbar (at a wavelength of 450 nm)

$$n_{air} - 1 = 0.284 \cdot 10^{-3}$$

$$n_{Freon} - 1 = 1.18 \cdot 10^{-3}$$

or Gladstone-Dale constants at this wavelength

$$G_{air} = 2.4 \cdot 10^{-4} \text{ m}^3/\text{kg}$$

$$G_{Freon} = 2.35 \cdot 10^{-4} \text{ m}^3/\text{kg}$$

The value for air comes out to be approximately 4 % higher than cited in literature. The difference between the value for air and the one for Freon is around 2 %. The Gladstone-Dale constant of air and Freon thus can be assumed to be equal within the range of the measuring precision. Hence the mixture of both gases can be treated like a *homogenous gas with variable density* with regard to the refractive index.

4.2 RESULTS

Following the outlined ideas, a series of interferograms were taken to examine the Freon layers created in the presented experiments. The layer profile is controlled by the duration of the Freon injection and the delay of the diaphragm rupture. Here the results for two sets of these parameters will be shown. The first layer with shorter delay is the one of which shadowgraphs are presented within this report. It will be denoted as layer 1. The other layer with longer delay -- denoted as layer 2 -- is the one in which the LDV measurements were performed that were presented in the previous report [ref. 1]. Figure 15 shows two examples for the post-injection preshock interferograms of layer 1; figure 16 gives two further examples for layer 2. The interferograms were made with laser light at a wavelength of

514.5 nm, with lenses of 1000 mm focal length and 200 mm diameter. The Wollaston provided an angular beam separation 2ϵ of $8.9 \cdot 10^{-4}$ rad and gave rise to a beam separation e of 0.65 mm.

Tests with different orientations of the beam separation indicated that the layers show no large variations in streamwise direction. Thus the effects of gradients in x -direction can be assumed neglectable in the evaluation of the interferograms.

Another result is that the layers are well reproduced from test to test. Figure 17 shows the density profile of layer 2 evaluated from two different interferograms. Though the ambient conditions and the choice of optical parameters for both interferograms differed, both results are quite comparable. Differences can be found at larger y -values; in this region the gradient of the density and the refractive index is small and causes a fringe displacement that is near the limit of detectability. Thus the deviations of the profiles might demonstrate the limitations of the differential interferometric method as well as actual differences in the profiles. This uncertainty in the resolution of small gradients can affect the absolute values of the local density because their evaluation depends on the integration of the gradient.

The longer delay time chosen for layer 2 leads to a layer where diffusion has already started to smooth out the concentration differences. This effect is less visible in layer 1 due to the shorter delay. Figure 18 shows the density profile for this layer that has a 4 mm high sublayer of nearly 100 % Freon concentration.

Further tests investigated the streamwise extension of the layer. Figure 19 shows an interferogram of the leading edge of the model. The Freon layer obviously starts immediately at the beginning of the splitter plate and soon attains the same thickness as in the test section.

SECTION 5

CONCLUSIONS

The experiments provide an excellent opportunity for studying turbulent boundary layers generated by inviscid, baroclinic effects. They are well suited for comparison and validation of computational results.

SECTION 6
LIST OF REFERENCES

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Figure 1 Sketch of the test set-up to create a Freon layer in the measuring chamber of the shock tube.

Figure 2 Sketch of the computer-controlled filling mechanism.

Figure 3 Timing program to operate the different valves.

Figure 4

Cranz-Schardin camera frame position. Test 13 954
Spark No. 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23 were covered.
The corresponding pictures show only the diffracted light in upward
direction caused by the density gradient in the Freon layer (see
Figure 5).

Test 13954
Frame

2

3

4

5

Figure 5 Shock wave interaction with a dense gas layer (Freon). Shadowgram and strongly diffracted light at the same instant are shown. For frame position see Figure 4. $M_\infty = 1.289$. Test 13954. Frames 2-3: $t = 67 \mu s$; Frames 4-5: $t = 167 \mu s$.

Test 13954
Frame

8

7

10

9

Figure 5 continued:
Frames 8-7; $t = 367 \mu s$; Frames 10-9; $t = 4.67 \mu s$

Test 13954
Frame

12

11

14

13

Figure 5 continued:
Frames 12-11: $t = 567 \mu s$; Frames 14-13: $t = 667 \mu s$

Test 13954
Frame

16

17

20

19

Figure 5 continued:
Frames 16-17: $t = 767 \mu s$; Frames 20, 19: $t = 967 \mu s$

Test 13954
Frame

22

21

24

23

Figure 5 concluded:
Frames 22-21: $t = 1067 \mu s$; Frames 24-23: $t = 1167 \mu s$

Figure 6 Cranz-Schardin camera from position: Test 13 955
 Spark No. 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 were covered.
 The corresponding pictures show only the diffracted light in upward
 direction caused by the density gradient in the Freon layer (see
 Figure 7).

Test 13955
Frame

1

2

3

4

Figure 7 Shock wave interaction with a dense gas layer (Freon).
Shadowgram and strongly diffracted light at the same instant are
shown. For frame position see Figure 6. $M_1 = 1.281$. Test 13955
Frame 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000.

Test 13955
Frame

5

6

9

8

Figure 7 continued
Frames 5-6: $t = 226 \mu s$; Frames 9-8: $t = 426 \mu s$

Figure 7 continued
 Figure 7: $\beta = 0.57$ and $\beta_{\text{max}} = 0.33, 0.4$ and $\beta_{\text{max}} = 0.2$ (a)

Test 13955
Frame

15

16

17

18

Figure 7 continued
Frames 15-16: $t = 726 \mu s$; Frames 17/18: $t = 826 \mu s$

Test 13955
Frame

21

20

23

22

Figure 7 continued
Frames 21-20: $t = 1026 \mu s$; Frames 23-22: $t = 1126 \mu s$

Figure 8

Shadow cinematography of a planar shock wave interacting with a Freon layer.
 $M_s = 1.286 \pm 0.008$
 sequence a: test 13956; sequence b: test 13959
 a1) $t = -12.5 \mu s$; b1) $t = 46.3 \mu s$; a2) $t = 112.5 \mu s$

b 2

a 3

b 3

Figure 8

continued

b2) $t = 171.3 \mu s$;

a3) $t = 237.5 \mu s$;

b3) $t = 296.3 \mu s$

a 4

b 4

a 5

Figure 8

continued

a4) $t = 362.5 \mu s$

b4) $t = 421.3 \mu s$

a5) $t = 487.5 \mu s$

b5

a6

b6

Figure 8

continued

b5) $t = 546.3 \mu s$:

a6) $t = 612.5 \mu s$:

b6) $t = 671.3 \mu s$

a7

b7

a8

Figure 8

continued

a7) $t = 737.5 \mu s$

b7) $t = 796.3 \mu s$

a8) $t = 862.5 \mu s$

b 8

a 9

b 9

Figure 8

continued

b8) $t = 921.3 \mu s$;

a9) $t = 987.5 \mu s$;

b9) $t = 1046.3 \mu s$

a 10

b 10

a 11

Figure 8

continued

a10) $t = 1112.5 \mu s$;

b10) $t = 1171.3 \mu s$;

a11) $t = 1237.5 \mu s$

b 11

a 12

b 12

Figure 8

continued

b11) $t = 1296.3 \mu s$;

a12) $t = 1362.5 \mu s$;

b12) $t = 1421.3 \mu s$

c 1

d 1

c 2

Figure 8

continued

sequence c: test 13957; sequence d: test 13958

c1) $t \approx 1.5$ ms;

d1) $t \approx 1.56$ ms;

c2) $t \approx 1.63$ ms

d 2

c 3

d 3

Figure 8

continued

d2) $t \approx 1.69$ ms;

c3) $t \approx 1.75$ ms;

d3) $t \approx 1.81$ ms

c 4

d 4

c 5

Figure 8

continued

c4) $t \approx 1.88$ ms;

d4) $t \approx 1.94$ ms;

c5) $t \approx 2.00$ ms

d5

c6

d6

Figure 8

continued

d5) $t \approx 2.06$ ms;

c6) $t \approx 2.13$ ms;

d6) $t \approx 2.19$ ms

c 7

d 7

c 8

Figure 8

continued

c7) $t \approx 2.25$ ms;

d7) $t \approx 2.31$ ms;

c8) $t \approx 2.38$ ms

d 8

c 9

d 9

Figure 8

continued

d80.0 ~ 2.44 ms

c90.0 ~ 2.80 ms

d90.0 ~ 2.86 ms

c 10

d 10

c 11

Figure 8 continued
 c) $\lambda = 2.63 \text{ ms}$, d) $\lambda = 2.69 \text{ ms}$, e) $\lambda = 2.75 \text{ ms}$

d 11

c 12

d 12

Figures

continued

d 11 at 2.50 μm

c 12 at 2.50 μm

d 12 at 2.50 μm

Location of the pressure gauges in the side-wall of the shock tube

Figure 9 Location of the pressure gauges in the side wall of the shock tube.

a)

c)

b)

d)

Figure 10 Pressure records without Freon layer $M_s = 1.388$. Test 14064

(different pressure scales!)

- a) MK 3
- b) MK 4
- c) MK 5
- d) MK 6

g)

h)

e)

f)

Figure 10 continued.
 e) MK 7
 f) MK 8
 g) MK 9
 h) MK 2

a)

c)

b)

d)

Figure 11 Pressure records with Freon layer. $M_s = 1.31$. Test 14069

- (different pressure scales).
a) MK 3 c) MK 5
b) MK 4 d) MK 6

e)

g)

f)

h)

Figure 11 continued.
e) MK 7
f) KM 8
g) MK 9
h) MK 2

Figure 12 Overpressure of the 1st maximum and 1st minimum vs height of the measuring position in the stratified Freon-air gas. Test 14069.

a)

b)

Figure 13 Coordination of individual frames shown in Figure 8 to some pressure records of Figure 11.
a) MK 3 b) MK 4

c)

d)

Figure 13 continued.

c) MK 5

d) MK 6

Angular separation 2ε induced by the Wollaston prism

Figure 14 Experimental setup of the differential interferometer. Circles and arrows indicate the polarisation of the incident and transmitted beam, resp. the polarisation of the ordinary beam in the prisms of the Wollaston (direction of view along the optical axis).

Figure 15 Preshock differential interferograms of layer 1.
 upper: test DI.11, lower: test DI.28
 Duration of Freon injection: 5 sec
 Delay of diaphragm rupture: 2 sec
 Freon pressure: 1.2 bar

Figure 16 Preshock differential interferograms of layer 2.
 upper: test DI.8, lower: test DI.22
 Duration of Freon injection: 5 sec
 Delay of diaphragm rupture: 5 sec
 Freon pressure: 1.2 bar

Figure 17 Preshock density profile of layer 2 evaluated from two interferograms.

Figure 18 Preshock density profile of layer 1.

Figure 19 Preshock differential interferogram of layer 2 at the leading edge of the splitter plate (test DI.52).
Duration of Freon injection: 5 sec
Delay of diaphragm rupture: 5 sec
Freon pressure: 1.2 bar

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