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Test Time Increase by Delaying Driver Gas Contamination for Reflected Shock Tunnels

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A gasdynamical detector has been applied to measure the arrival time of driver gas in a low concentration in the test section of a high-enthalpy shock tunnel. The detection determines the useful test time with uncontaminated test gas for a wide range of specific reservoir enthalpies. Effects of over- or undertailored interface condition on severe contamination have been investigated. It is experimentally demonstrated that overtailored interface operation must be avoided to achieve the test duration necessary for aerodynamic measurements, especially for high-enthalpy flow. The interface condition is optimized for the longest test time attainable. As an active method for delaying driver gas contamination, a device to trap the driver gas at the end of the shock tube has been tried for an overtailored condition. The method, however, causes the contamination to occur earlier. A modified device using a sleeve to capture driver gas upstream has been developed. Results with the longest sleeve tested show that strong contamination is dramatically delayed and that the uncontaminated test time is significantly increased. Nevertheless, improved test times are still shorter than the test time without the device at a slightly undertailored condition.

Nomenclature

h = duct height
h_0 = specific reservoir enthalpy
M_s = incident shock Mach number
M_1 = Mach number at the duct inlet
M_∞ = freestream Mach number
p_{ch} = chamber pressure
p_{duct} = static pressure in the duct of the detector
p_0 = nozzle reservoir pressure
p_1 = initial shock-tube pressure
s/L = normalized distance between the shock wave and the the shock generator wall (Fig. 4)
t = time
w = duct width
θ_w = wedge angle
θ_1 = angle of the shock generator

I. Introduction

ONE of the most severe limitations to the performance of reflected shock tunnels is the contamination of test gas by driver gas. It is widely accepted that the driver gas (normally helium or a mixture of helium and argon) passing through the bifurcated region of the reflected shock causes early contamination of the test gas in the reservoir condition. In most cases the driver gas contamination occurs before the nozzle reservoir pressure falls. The premature contamination of test gas by the monatomic driver gas changes the gas composition and temperature in the test section flow, thereby influencing measurements in the chemically reacting flowfield. Knowing when the driver gas arrives and delaying the arrival are therefore very important to increase the useful test time for reliable tests in short duration facilities.

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To detect the contamination at the test section, a simple gasdynamical method has been first developed by Paull and King[1] and Paull[2] for use in conjunction with other experimental models. It consists of a small duct and a wedge, which are arranged so that the duct is not choked for an uncontaminated test gas but is choked for a test gas contaminated by driver gas in a certain concentration. On the basis of their idea, Sudani and Hornung[3] designed similar detectors for the T5 Hypervelocity Shock Tunnel[4] and then proposed a modified configuration of the duct detector for higher sensitivity to driver gas concentration. It was demonstrated that, over a wide range of specific reservoir enthalpies, the onset of the contamination derived from pressure measurement data in the duct was in good agreement with a prediction using Davies and Wilson's simple method.[5] A two-dimensional duct detector for flow visualization was then designed and tested in T5 to obtain a better understanding of the duct internal flow for the further improvement of detector sensitivity.[6]

The contamination phenomenon is closely related to interaction among the reflected shock, the boundary layer on the shock-tube wall, and the interface between the driver and test gases. The onset of the contamination is therefore expected to be very sensitive to interface conditions. Jenkins et al.[7] explained qualitatively a relation between the p_0 constancy and the contamination onset and suggested that the choice of interface conditions be made according to the particular requirements of the experiments. Chue and Itoh[8] numerically simulated effects of over- and undertailored conditions (where M_s is greater and smaller than the tailored interface value, respectively) on driver gas contamination and showed that the driver gas jet along the shock-tube wall was very weak at an undertailored interface operation. Sudani and Hornung[9] investigated the effects experimentally at a moderate enthalpy ($h_0 \simeq 14$ MJ/kg) by measuring the arrival time of driver gas at the test section of T5. Severe contamination occurred prematurely for an overtailored condition. Obviously, the interface condition must be optimized to obtain the longest test time achievable for each facility.

To increase the useful test time, several efforts have recently been made to develop a device for removing the driver gas jet near the end of the shock tube (end plate). Dumitrescu[10] proposed a device with a slit opening at the corner of the end plate. Chue and Dumitrescu,[11] however, experimentally and numerically showed no distinct improvements in delaying the driver gas arrival at the end plate. Sudani and Hornung[9] also showed experimentally that such a device advanced both the driver gas arrival at the test section and the p_0 drop and suggested that the driver gas jet be captured farther upstream in the shock tube. Cardoso et al.[12] independently reached the same idea of capturing driver gas upstream through numerical simulations and demonstrated numerically that their proposed device improved the test time markedly for a tailored condition. A device based on the idea of capturing driver gas upstream had already been tried and evaluated by Slade[13] with mass spectrometry. The experiment showed significant delay of the contamination onset and implied the necessity of more sophisticated investigations for further improvement.

In the present paper pressure data of the two-dimensional duct detector calibrated more elaborately at a higher enthalpy ($h_0 \simeq 20$ MJ/kg) are presented for demonstrating the applicability of the detector to a different enthalpy and for the reader to understand easily the gasdynamical detection. Effects of off-tailored (over- or undertailored) interface condition on driver gas contamination are then again discussed in more detail using results of the high-enthalpy case to find out the best operating condition. A modification of the driver gas capturing device is proposed, and experimental results with the modified device in T5 are presented.

II. Gasdynamical Detection

A. Detector Calibrations

The two-dimensional duct detector for T5 is illustrated in Fig. 1. Three major modifications were made to Paull's detector[2] as reported in Ref. 6:

1) A shock generator is placed upstream of the duct to generate a two-dimensional strong oblique shock. This lowers the Mach number ($M_1 \simeq 2$ for $M_\infty \simeq 5$), and the decrease in inlet Mach number gives a dramatic improvement of sensitivity, which is then directly related to the effect of the ratio of specific heats on wedge shock angle. The inclination of the duct detector yields both higher sensitivity and weaker shock/boundary-layer interaction than in the case of no inclination.

2) The duct has a cross section with an aspect ratio of 12 and no sidewalls to enable flow visualization. The visualization data are extremely useful for the interpretation of pressure histories in the duct.

3) The position of the wedge in the duct is adjustable in the duct-axis direction. The wedge shock should impinge on the opposite duct wall on the arrival of a certain amount of driver gas so that the duct flow chokes. For the detector to be applicable to various test conditions and to have high sensitivity, this adjustment is very important.

The disadvantage of the gasdynamical duct detector is that several shots are required for the wedge adjustment and the calibration. Experiments described in this paper were conducted at a main-diaphragm burst pressure of approximately 32 MPa, which is the lowest for T5, in consideration of data productivity. A more efficient way of the calibration is under development. Air was used as the test gas and a mixture of 96% helium and 4% argon (by volume) as the driver gas for all of the cases. A conical nozzle was used, and the nozzle exit Mach number was approximately 5.1 for $h_0 \simeq 20$ MJ/kg.

Pressure traces obtained with the downstream transducer in the duct detector for an unseeded test gas and for driver-gas-seeded test gases are shown in Fig. 2. Argon or a mixture of argon and

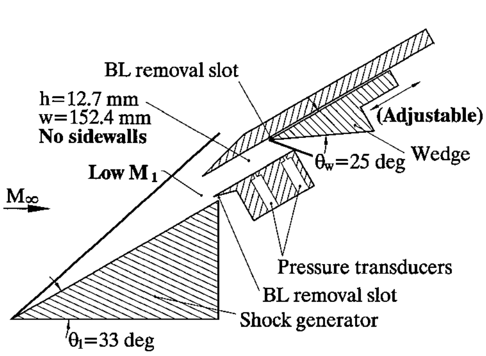


Fig. 1 Schematic of a two-dimensional duct detector allowing flow visualization.

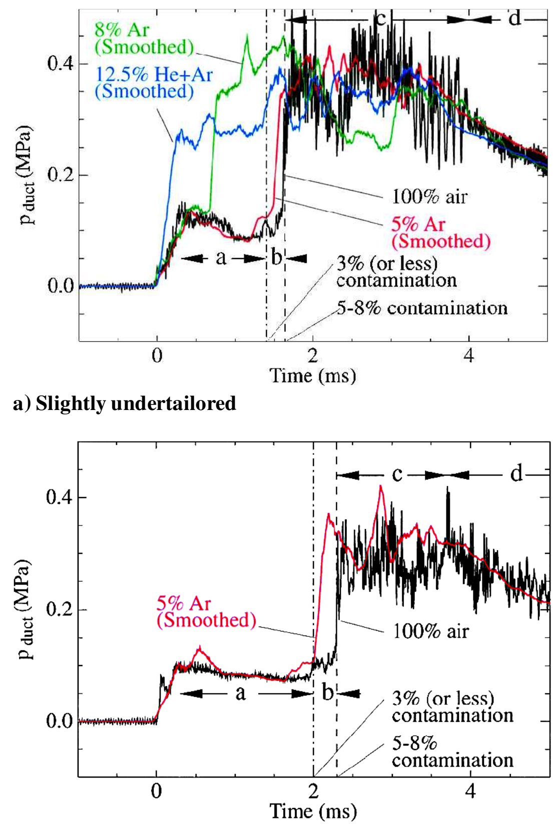
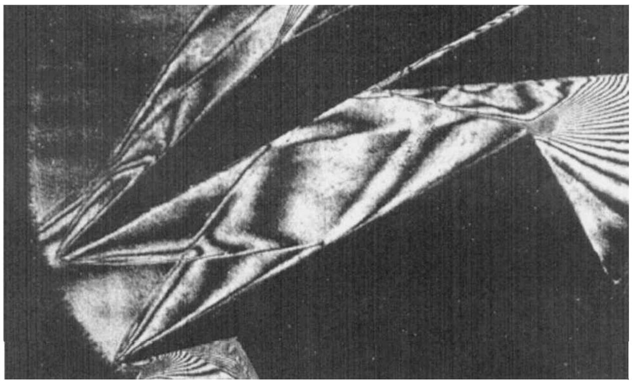


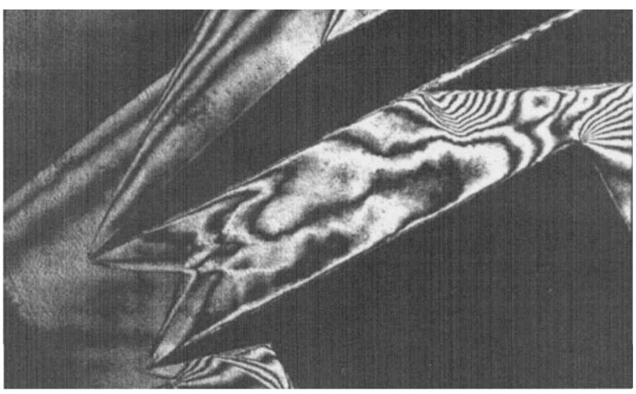
Fig. 2 Pressure traces obtained with the downstream transducer in the duct of the detector for an unseeded test gas and driver-gas-seeded test gases: $h_0 \simeq$ 20 MJ/kg and $p_0 \simeq$ 14 MPa.

helium (2:1 by volume) was used for seeding test gas because the variation in M_s was smaller than when only helium was used. Undertailored conditions were selected for these calibration shots because a large amount of contamination is expected to occur late enough for easy interpretation of the experimental data obtained. Effects of off-tailored conditions will be discussed in the following section. With an unseeded test gas the duct is first unchoked during period a. The freestream is considered to be uncontaminated or contaminated by a very low concentration of driver gas. The pressure then rises slightly during period b. A small amount of contamination occurs and causes slight interaction of the wedge shock with the boundary layer in the duct because of a slight increase in wedge shock angle.[6] When the concentration of driver gas coming into the duct becomes higher, the wedge shock impinges on the duct inner wall and starts to travel upstream. In this detector the shock stays near the wedge leading edge (period c) until a large amount of driver gas arrives (period d) because the duct has no sidewalls. As long as the pressure tap is located close enough to the duct end, the trace indicates an abrupt rise as soon as the duct exit is choked. The transition from c to d is no longer important from the viewpoint of the detection of a small amount of contamination.

Results of calibration tests in which test gas in the shock tube is deliberately seeded with driver gas are also plotted in color in Fig. 2. For a test gas seeded with 8% of monatomic gas by volume (Fig. 2a), it takes approximately 0.6 ms for the duct to be choked, whereas the duct is choked immediately after the flow arrives for a 12.5%-seeded test gas. No plateau, however, can be observed before choking, and this indicates that steady unchoked duct flow is not well established. Accordingly, the detector configuration in this case is considered to have a sensitivity to 8% or less of driver gas. Because the duct flow does not choke from the beginning for a 5%-seeded test gas, the sharp pressure rise for an unseeded test gas therefore represents the time of contamination by 5–8% of driver gas. The point of the sharp pressure rise for a 5%-seeded test gas is in accordance with that of the slight pressure rise for the unseeded test gas. This means that not more than 3% of driver gas additionally arrives at the detector at 1.4 ms.



a) Before choking



b) After choking

Fig. 3 Holographic interferograms of the duct internal flow before and after choking for an unseeded test gas: $h_0 \simeq$ 20 MJ/kg.

Similarly, the conclusion can be made that contamination by 5–8% of driver gas occurs approximately at 2.3 ms and contamination by 3% or less of driver gas does at 2.0 ms for a fully undertailored condition (Fig. 2b). In Sec. III, the time with a contamination level of 5–8% will be focused on because it can be easily detected without driver-gas-seeded data once the detector is calibrated.

B. Flow Visualization

Figure 3 shows holographic interferograms of the duct internal flow before and after choking. The wedge is adjusted so that the wedge shock just misses the end of the opposite duct wall before the contamination occurs (Fig. 3a). This is the best wedge setup for achieving sensitivity to a small amount of driver gas. However, a close observation of Fig. 3a reveals that the wedge shock is slightly bent by the interaction with the weak shocks that emanate from the duct leading edge and reflect on the inner walls. Results obtained very recently in the HIEST shock tunnel (at the Kakuda Research Center at the National Aerospace Laboratory in Japan) indicated that, in some cases, the interaction decreased the detector sensitivity and, moreover, caused the repeatability of calibration results to deteriorate.[14] Further modifications are being attempted to remove the interaction and to achieve higher sensitivity.

From holographic interferograms the distance between the shock and the shock generator wall was measured for various driver gas concentrations (Fig. 4). Closed circles with error bars denote data with unseeded and driver-gas-seeded test gases at 0.96 ms for a slightly undertailored condition before the early contamination occurs. With the increase in the concentration of driver gas, the distance increases linearly. The solid line is derived from the closed circles by the method of least squares. A picture taken at 1.66 ms exhibited a normalized distance s/L (see the illustration of Fig. 4) of approximately 0.173. The distance indicates a contamination level of 8.5% according to the solid line. The time (1.66 ms) corresponds to the point immediately after the abrupt pressure rise in Fig. 2a (a contamination level of 5–8%). The determination of driver gas

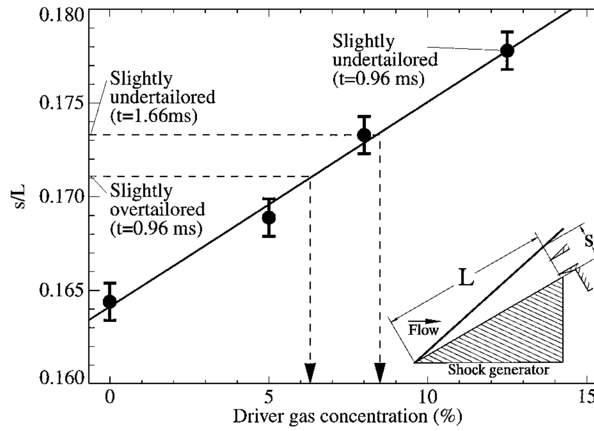


Fig. 4 Distance between the shock generator and the shock for different concentrations of driver gas: $h_0 \simeq$ 20 MJ/kg.

concentration from the flow visualization data is in good agreement with that from the pressure data.

III. Effects of Off-Tailored Conditions

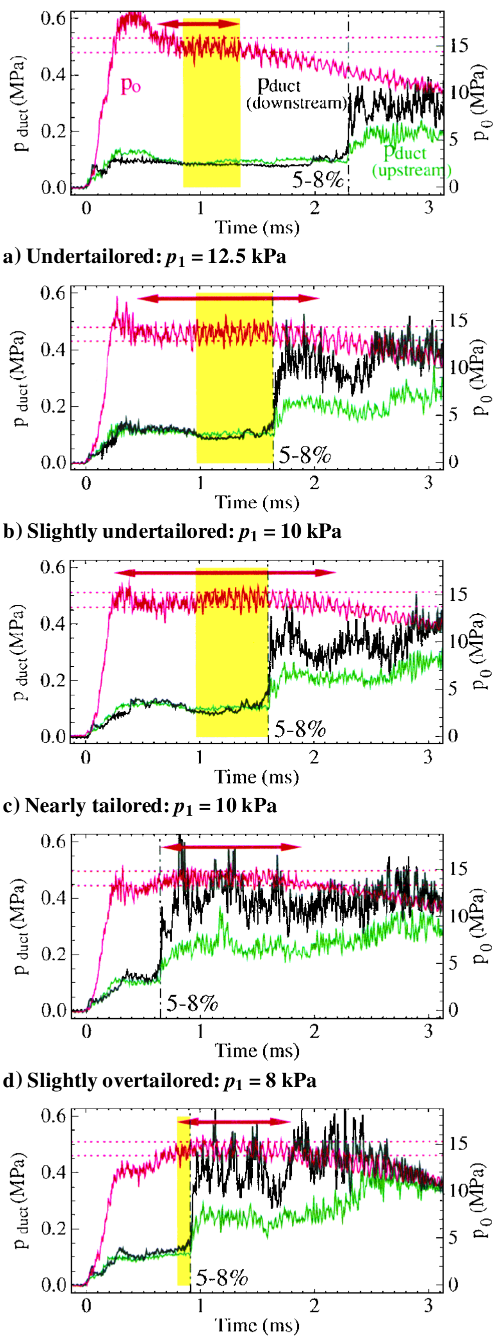
A. Pressure Traces of the Detector

As an extension of Sudani and Hornung's work,[9] effects of off-tailored interface conditions on driver gas contamination were again examined in more detail for higher-enthalpy flow. Pressure traces in the duct of the detector and in the nozzle reservoir are shown in Fig. 5. Black traces present pressure histories of the downstream transducer. Green ones present those of the upstream transducer and are helpful for determining the time for establishing steady flow. Traces of the nozzle reservoir pressure (red traces) are shifted by the time difference because of flow transport through the nozzle. Two horizontal dotted lines in each figure denote deviations of ±5% from the nearly constant value, and the arrow represents the period when the deviation of p_0 is within ±5%. Degrees of off-tailored condition were qualitatively determined by the time history of the nozzle reservoir pressure. For a fully undertailored condition (Fig. 5a) the sharp pressure rise (5–8% contamination level) is significantly delayed. The nozzle reservoir pressure, however, drops by 5% of its constant value (decreases below the lower dotted line) before the contamination occurs. Furthermore, it takes approximately 0.85 ms for both upstream and downstream static pressures to be adequately steady. Hence, in practice, the yellow period is regarded as useful test time with uncontaminated steady freestream. As the interface condition becomes tailored, the period of the p_0 plateau is extended, but the contamination occurs earlier. The useful test time for a nearly tailored condition (Fig. 5c) is actually reduced compared with that for a slightly undertailored condition (Fig. 5b). For overtailored conditions the steady flow tends to be established in a shorter period, but the period of the p_0 plateau is delayed and shorter; moreover, the contamination occurs at a considerably earlier point. Uncontaminated steady flow cannot be clearly observed, especially for a slightly overtailored condition (Fig. 5d).

Because only the initial pressure in the shock tube was changed to achieve off-tailored conditions in these studies, the incident shock speed was varied and, accordingly, so was the specific reservoir enthalpy. For the overtailored conditions h_0 was slightly increased because of the increase in shock speed. This effect should cause the wedge shock angle to decrease so that the duct flow would become hard to choke. It is therefore demonstrated that choking prematurely as shown in Figs. 5d or 5e is not caused by the variation in enthalpy but certainly caused by the variation in γ, i.e., the driver gas contamination. As shown in Fig. 4, the shock distance for a slightly overtailored condition also shows that contamination by more than 5% of driver gas has already occurred at 0.96 ms.

B. Useful Test Time

Figure 6 presents effects of the tailoring level, represented by incident shock Mach number, on useful test time. Shock speeds at several shots are averaged for each tailoring level. The repeatability



a) Undertailored: $p_1 = 12.5$ kPa

b) Slightly undertailored: $p_1 = 10$ kPa

c) Nearly tailored: $p_1 = 10$ kPa

d) Slightly overtailored: $p_1 = 8$ kPa

e) Overtailored: $p_1 = 6.5$ kPa

Fig. 5 Pressure traces in the duct of the detector and in the nozzle reservoir for various interface conditions: $h_0 \simeq 20$ MJ/kg (red arrows, the period during p_0 is nearly constant; and yellow regions, useful test time).

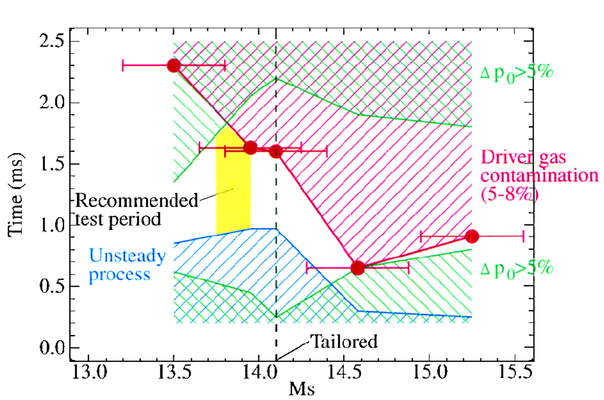


Fig. 6 Effects of off-tailored interface condition on useful test time: $h_0 \simeq 20$ MJ/kg.

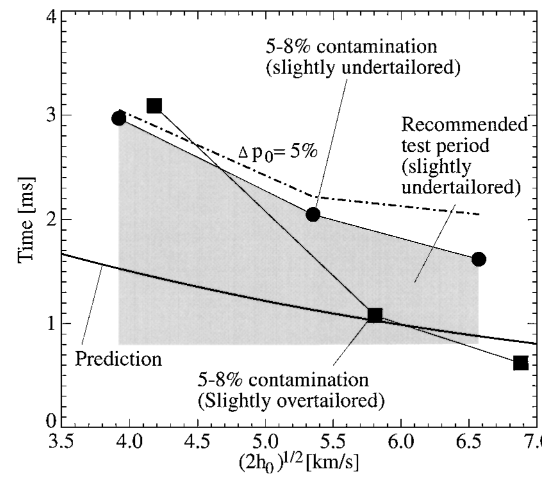


Fig. 7 Useful test time over a range of specific reservoir enthalpies attainable in T5 for slightly off-tailored interface conditions.

of M_s is indicated by error bars plotted over 5–8% contamination data. The tailoring M_s is approximately 14.1 (denoted by a dashed line). An undertailored interface operation is recommended to avoid the severe contamination for overtailored conditions. A strongly undertailored condition, however, should not be selected to avoid the early drop of p_0. The region of a recommended test period is indicated by an yellow region. The determination of the degree, however, is somewhat subjective. Data like those shown in Fig. 5 should be obtained and used as a guide for defining the tailoring level. Careful observations of the p_0 trace at every shot are also required to keep the best interface condition.

Contamination data obtained with the two-dimensional duct detector for both slightly over- and undertailored conditions are plotted as functions of freestream velocity (approximately $\sqrt{(2h_0)}$) in Fig. 7. The origin of the test time axis in this figure corresponds to the time when flow reaches the test section, i.e., when the pressure in the duct starts to rise. At a low enthalpy ($h_0 \simeq 8$ MJ/kg) no significant discrepancies between an overtailored and an undertailored condition can be observed. At higher enthalpies ($h_0 \simeq 14$ and 20 MJ/kg), however, the contamination is drastically advanced only for overtailored conditions. If the T5 shock tunnel is operated at a slightly undertailored condition, the shaded region can be used as useful test time with uncontaminated steady freestream. The test time is considered to be long enough for conventional aerodynamic measurements over a wide range of enthalpies. A prediction using Davies and Wilson's method is conservative for a slightly undertailored condition and also that 5–8% contamination occurs earlier than when p_0 drops by 5% of its nearly constant value irrespective of enthalpy. Acquiring the contamination data experimentally is therefore of importance in determining the useful test time for test conditions at which each shock tunnel is operated.

IV. Device for Delaying Contamination

A. Device for Capturing Driver Gas

To increase test time, a method to delay the driver gas contamination is required. This is essential, particularly in high-enthalpy cases where the period of the useful test time becomes critical. Dumitrescu[10] proposed an idea of capturing a driver gas jet passing through the reflected-shock bifurcation region. A device based on the idea was designed in T5 and tested with the two-dimensional duct detector. A schematic of the device installed at the shock tube end of T5 is presented in Fig. 8. The gas is sucked through the slot by means of the difference between the nozzle reservoir and initial shock tube pressures and then passes through a suction plate to the chamber. The height of the slot is 5 mm, while the radius of the shock-tube inside diameter of T5 is 45 mm. The suction rate can be varied by using suction plates with different area ratios. The volume of the chamber was determined by the filling time estimated for the largest suction area. A pressure transducer is installed in the chamber to monitor the unsteady pressure p_{ch} during a shot and to ascertain that the chamber is not filled until the contamination occurs.

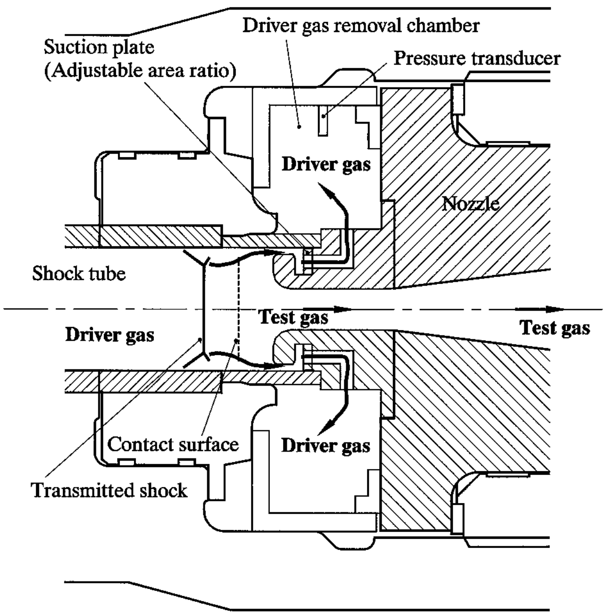


Fig. 8 Schematic of a device for capturing driver gas at the end of the shock tube.

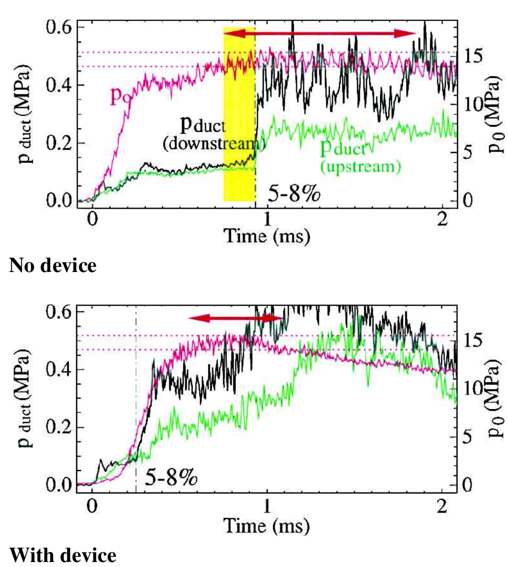


Fig. 9 Pressure traces in the duct of the detector and in the nozzle reservoir with and without a device for capturing driver gas for an overtailored condition: $h_0 \simeq 20$ MJ/kg (red arrows, the period during p_0 is nearly constant; and yellow regions, useful test time).

In the previous study[9] the device was applied to an undertailored and a nearly tailored condition. It was demonstrated that contamination onset was advanced irrespective of suction rate and that the device had opposite to the desired effect. The performance of the device, however, should be examined for an overtailored condition because a strong driver gas jet is then expected to form along the shock-tube wall, causing premature contamination.[8] Pressure traces in the duct of the detector with and without the device for an overtailored condition are shown in Fig. 9. As in the undertailored or nearly tailored condition, the application of the device never delays the contamination at the test section, and the p_0 constancy deteriorates markedly. It is possible that the driver gas is not well captured, but that a large amount of test gas is also sucked into the chamber. These results imply that, at the end of the shock tube, the driver gas jet grows to form too large a contaminated region to be completely removed.

B. Modifications of the Device

For driver gas to be efficiently removed, it should be captured before the jet along the shock-tube wall grows and is mixed with test gas on a large scale. A modified device to capture driver gas upstream of the end plate is illustrated in Fig. 10. A photograph of the suction part on the nozzle block (hatched regions in Fig. 10) is shown in Fig. 11. A sleeve is attached to the end plate of the shock tube. Four sleeves with different lengths were attempted, while the height of the gap between the sleeve and the shock tube was fixed at 4 mm. The tip of the longest sleeve is located where the reflected shock is expected to meet the contact surface. The way of the suction is basically the same as that of the device shown in Fig. 8.

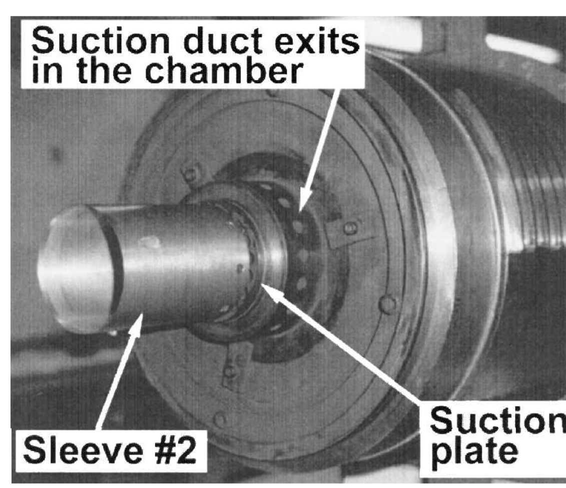


Fig. 11 Photograph of a modified device using a sleeve for capturing driver gas upstream.

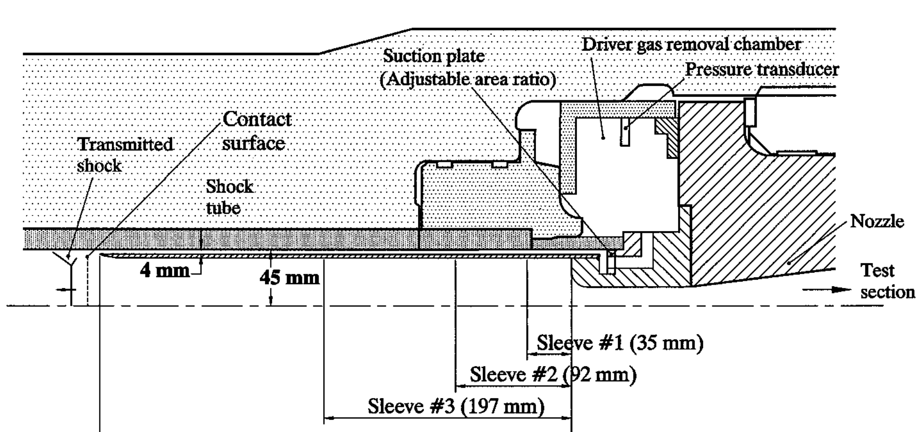
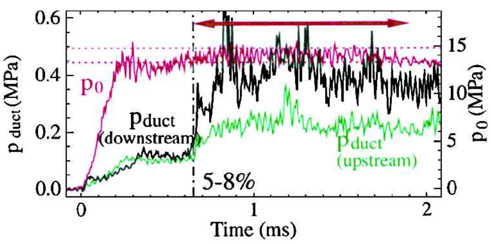
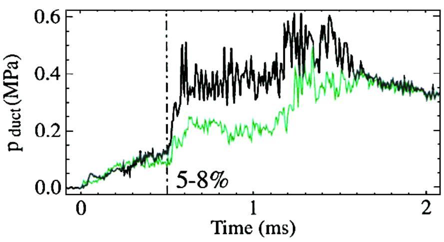


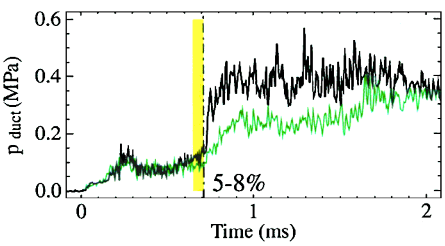
Fig. 10 Schematic of a modified device using a sleeve for capturing driver gas upstream.



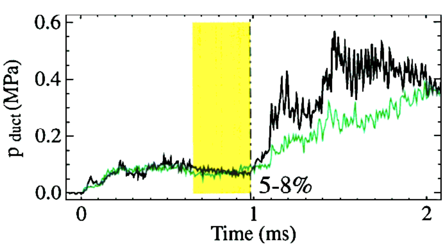
a) No sleeve



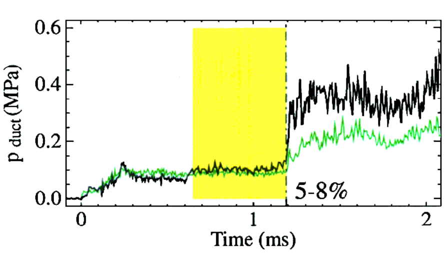
b) Sleeve 1 (35 mm)



c) Sleeve 2 (92 mm)



d) Sleeve 3 (197 mm)



e) Sleeve 4 (372 mm)

Fig. 12 Effects of the sleeve length on driver gas contamination for a slightly overtailored condition: $h_0 \simeq 20$ MJ/kg and a suction rate $\partial p_{ch}/\partial t \simeq 1$ MPa/ms (red arrows, the period during p_0 is nearly constant; yellow regions, useful test time).

Effects of sleeve length for a slightly overtailored condition were first examined as shown in Fig. 12. With the shortest sleeve (Fig. 12b) no uncontaminated steady flow can be observed, and the point of 5–8% contamination is advanced, as in the case of the device in Fig. 9. As the sleeve length increases, the contamination point is significantly delayed, and an uncontaminated steady flow represented by a yellow region appears (Figs. 12c–12e). It is certain that the driver gas jet which causes early contamination is captured upstream before it reaches the end plate. Especially for the longest sleeve (Fig. 12e), the 5–8% contamination is remarkably delayed, and the period of the yellow region is over 0.5 ms. Compared with traces without the device shown in Fig. 12a (a reproduction of Fig. 5d), the useful test time is dramatically improved. Chue and Eitelberg[15] numerically showed that the driver gas jet weakened rapidly after the reflected-shock/contact-surface interaction and that the vorticity generated caused the convection of the driver gas jet from the shock-tube wall toward the center of the tube. This explains satisfactorily the fact that the device of Fig. 8 is not effective, but the increase in sleeve length heightens the beneficial effect of the modified device.

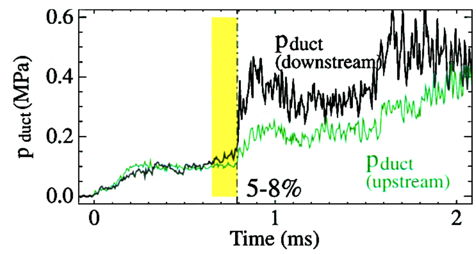


Fig. 13 Pressure traces in the duct of the detector without suction using sleeve 4 for a slightly overtailored condition: $h_0 \simeq 20$ MJ/kg (yellow region, useful test time).

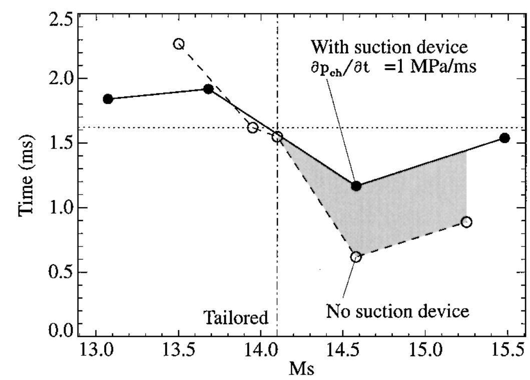


Fig. 14 Driver gas contamination with and without a modified device for various interface conditions: $h_0 \simeq 20$ MJ/kg (shaded region, useful test time).

A suction plate with the largest area ratio was applied for the cases of Fig. 12. To examine the effect of suction, a solid plate was used instead of the porous plate, and the longest sleeve (number 4) was installed. Pressure traces without suction indicate, as shown in Fig. 13, that the point of 5–8% contamination is considerably earlier than that of Fig. 12e. When the sleeves were applied, changing the area ratio of the suction plate did not significantly affect the suction rate. This was probably because the sucked flow choked somewhere before it reached the suction plate. The proper suction rate was not therefore determined in this study. It is obvious, however, that a certain amount of suction is required for the optimal performance of the device.

Figure 14 shows the contamination data obtained with the modified device for different degrees of off-tailored condition. The shaded region denotes the test time increase by using the device. For slightly undertailored and tailored conditions the device does not yield a dramatic change of test time. For overtailored conditions, on the other hand, the test time is successfully improved as already shown in Fig. 12. The improved test periods, however, never exceed values for a slightly undertailored condition recommended in Fig. 4. Moreover, the device has some problems to be solved for practical use, e.g., the strength of the sleeve for high temperature and high pressure. Hence, in the present state paying more attention to interface condition in each shot would be advisable to achieve the longest test time attainable. A new technique to delay the contamination for the tailored condition, which yields good p_0 constancy, is required to be developed.

V. Conclusions

A gasdynamical detector of driver gas contamination has been applied to a high-enthalpy flow in the T5 Hypervelocity Shock Tunnel. Several calibration shots with driver-gas-seeded test gases achieve a success in showing a satisfactory degree of detector sensitivity to a small amount of driver gas (5–8%) by detecting a sharp pressure rise by the duct flow choking.

Contamination data obtained using this detector show that the useful test time with uncontaminated steady flow largely depends on the degree of off-tailored interface condition. A slightly undertailored condition is strongly recommended to avoid severe early contamination. Under this condition the useful test time in T5 with uncontaminated and steady flow is determined and found to be sufficient for conventional aerodynamic measurements over a wide range of specific reservoir enthalpy.

A device to capture the driver gas jet at the end plate advances contamination for an overtailored condition as well as for undertailored conditions. A modification using a long sleeve for capturing driver gas upstream yields a remarkable increase of the test time only for overtailored conditions. Nevertheless, the improved times are still shorter than the test time without the device at a slightly undertailored condition. Other modifications of the device are necessary for further increase of test time. Knowing the best interface condition for each shock tunnel and repeating it precisely, however, are more essential for making reliable tests by avoiding the premature contamination.

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