NASA Technical Memorandum 87642

Mass Spectrometric Gas Composition Measurements Associated With Jet Interaction Tests in a High-Enthalpy Wind Tunnel


JUNE 1986
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Beverley W. Lewis
Langley Research Center
Hampton, Virginia

Kenneth G. Brown
Old Dominion University
Norfolk, Virginia

George M. Wood, Jr., Richard L. Puster, and Patricia A. Paulin
Langley Research Center
Hampton, Virginia

Charles E. Fishel
Old Dominion University
Norfolk, Virginia

D. Alan Ellerbe
Langley Research Center
Hampton, Virginia
Summary

The need for determining gas composition is becoming increasingly important in wind-tunnel experiments to measure aerothermodynamic interactions. Mass spectrometric (MS) techniques are in development at Langley Research Center. This paper describes measurements made by continuously sampling at the top of the test section during test runs of the Langley 7-Inch High-Temperature Tunnel. The tests were performed to investigate the extent of mixing of an inert gas injected into the test stream from a jet on a flat-plate model and to monitor the combustion product results from the ignition of a high-pressure mixture of natural gas and air. The MS measurement yields the mole fraction of inert gas species (neon or helium) which reached the top of the test section as well as the carbon dioxide (CO₂) from the tunnel combustion gas test stream. The data, obtained under a variety of tunnel run conditions, are related to the pressures measured in the test section of the tunnel and the pressures measured at the gold-leak inlet of the MS. The apparent distributions of the injected gas species and tunnel gas (CO₂) are discussed in terms of the sampling technique with and without the use of an inert tracer.

Introduction

Mass spectrometric analyses were conducted in the Langley 7-Inch High-Temperature Tunnel (7-Inch HTT). The tests conducted during the analyses were designed to study the interaction of an underexpanded Mach 2.2 jet of gas that was injected from the surface of a flat plate with the hypersonic, high-enthalpy test stream. (See fig. 1(a).) The test stream is formed as a result of the high-pressure combustion of a mixture of natural gas and air expanded through a contoured conical nozzle. The tests were conducted to investigate the resultant flow field and heat distribution within the test section. They were designed to assess the need for protective measures if tests were made with high-temperature jet injections and to determine the incidence of tunnel “unstarting” due to the flow-field disturbances caused by the jet gas injection.

The mass spectrometric measurements were made during the tests to satisfy the following objectives: (1) to determine the concentration of the injected gas which reached the top of the hemispherically shaped test section, and (2) to determine the concentration of carbon dioxide (CO₂) which reached the top of the test section. Both were to be measured as they changed during the operational sequence of the tunnel runs. There were several variations in test conditions as follows: (1) hot and cold test-stream runs, (2) model in and out of the stream with jet firing, and (3) jet gas either a 1 mole percent Neon in Nitrogen (1 mole percent Ne/N₂) mixture or pure helium (He). The test conditions for each run discussed in this paper are listed in table I.

The general objective was to improve the understanding and interpretation of mass spectrometric data obtained in the dynamic and hostile environment of a high-enthalpy wind tunnel. The supersonic-jet interaction experiments described in this report are one part of an integrated investigation which includes laboratory experiments and theoretical and modeling studies of sampling integrity in severe dynamic environments. Any effect of sample inlet and gas transfer system (probe and tubing) on the composition of the sample is of prime importance, since the desired measurement is the local composition just outside the sampling inlet or probe.

Symbols

\[ I_i \] peak-height intensity measured by mass spectrometer, Hz (may be converted to amperes by factor of \( 10^{-13} \text{ A/Hz} \))

J ON jet turned on

J OFF jet turned off

MI model inserted in test stream

MO model withdrawn from test stream

\( P_i \) partial pressure of \( i \)th species, torr

\( P_{gl} \) total pressure at gold-leak inlet of MS, torr

\( P_{ts} \) total pressure in test section, torr

\( P_{tg} \) partial pressure of tunnel gas, torr

\( S_i \) MS sensitivity of \( i \)th species, Hz/torr

\( X_i \) mole fraction of \( i \)th species

Subscripts:

\( i, j \) \( i \)th and \( j \)th species

msd measured

nom nominal

Abbreviations:

C cold tunnel run

H hot tunnel run

JO jet on

MS mass spectrometer

MV manual valve
was injected into the test stream from a nozzle open-
string at an angle of attack of -8°, and the flush jet
schematic of the sampling system. The nominal tun-
ing in the surface of a flat-plate wedge model. (See
fig. 1(a).) The model was mounted on a retractable
7-lnch HTT
the gas injection during a test run. Figure 2 is a
typical shadowgraph of the flow over the model with
an approximate stagnation pressure of 2200 psia and
a temperature of 3360°R. Jet chamber pressures were
varied from 20 to 135 psia. Table I gives pertinent
run conditions for the runs whose data are given and
discussed in this paper.

Mass Spectrometric Sampling and
Measurements

In these experiments, the sampling inlets
(fig. 1(a)) were located at the top of the test sec-
tion to determine the amount of injected gas that
escaped from the tunnel test stream. All inlets were
located in a line coplanar with the centerline of the
test stream, and only one inlet was open during a
run. The rake at inlet B could be rotated 180° to
increase the number of sampling points with respect
to the flat plate shown in figure 1(a). The inlets on
the rake were opened or closed with threaded plugs
and were approximately 1/4 in. in diameter. The in-
let was designed to minimize any possible sampling
effects. The sampled flow was quiescent, and the
temperature of sampled gas was near ambient; there-
fore, the gases measured were inert or unreactive un-
der these conditions. The 10 ft of 1/4-in. outside-
diameter copper-tubing transfer line connecting the
inlet to the MS has been shown in laboratory studies
to have minimal effect upon the sample composition.
(See ref. 1.) Sampling integrity was thus considered
to be good in these tests.

The simplest view of the test situation is that the
injected gas mixes with the stream gas and diffuses
from the stream boundary as a constant composition
mixture. The gas then displaces and/or mixes with
the gas in the test section and is sampled at the top
of the test section. The final mixture of the gases of
interest is not further changed when it is transported
to the mass spectrometer (MS). For purposes of
this study, effects of pumping on flow about the
inlet orifice and the species-dependent differences in
flow from within the stream to the inlet, although
undefined, were assumed to be negligible.

The MS used was a gas analysis and detection
system (GADS) that contained a small portable
hyperbolic-rod quadrupole mass analyzer. A micro-
computer provided control, data acquisition, calibra-
tion, quantitative analysis, and housekeeping func-
tions. The GADS instrument is described in refer-
ences 2 and 3. An automated analysis mode pro-
vides for the monitoring of up to 40 mass peaks in
the range of 2 to 200 atomic mass units (amu) by
peak stepping. For this study, 2 or 3 mass peaks were
monitored with a cycle time of 0.3 second for 3 peaks;
therefore, a peak-height intensity measurement was
recorded every 0.1 second. Test runs were typically
on the order of 1 to 2 minutes overall. The model
was typically in the test section about 3 seconds for
hot runs and up to 11 seconds for cold runs. The in-
jection jet was on for about 2.5 seconds for hot runs
and up to 10 seconds for cold runs. The quadrupole
MS was located adjacent to the tunnel test section
and was remotely operated from the tunnel control
room by a duplicate keyboard and an analog oscil-
locope monitor. MS data were digitally stored for
subsequent printout.

To distinguish between nitrogen injected into the
stream and the relatively large amount of nitrogen
present in the methane-air combustion products,
1 mole percent neon was added as a tracer to the
injected gas. In subsequent tests, the injected gas
was pure He, which is inert and can be sampled and
measured directly. The GADS had been previously
calibrated in the laboratory for sensitivity to Ne, He,
Ar, and CO₂ using pure gases and standard mix-
tures of these gases with air. When the jet gas was
1 mole percent Ne/N₂, the peaks monitored were Ne
at 20 amu, Ar at 40 amu, and, after a number of runs,
CO₂ at 44 amu. When He was the jet gas, He at
4 amu, Ar at 40 amu, and CO₂ at 44 amu were mon-
tored. As is discussed subsequently, the Ar 40 peak
was used as an internal standard for both cases.

Dividing the intensity of the MS peak of a par-
ticular molecular species by the intensity of the MS
peak of a species of known concentration which re-
mains chemically unchanged by the combustion pro-
cess yields quantitative information about the com-
position of the mixture. In combustion processes,
the MS peak at 40 amu, due to the inert gas Ar
present in the original fuel-air mixture, provides a
convenient and easily identifiable reference. Since
the reference gas is present in the original combus-
tor mixture, all the physical processes which occur in the combustor and at the nozzle should affect $I_{\text{Ar}}$ and all other species relatively. Dividing the peak intensity of a combustion product, such as CO$_2$, by that of Ar should then eliminate most of the interference and reduce the pressure-dependent uncertainty in the measurement. Therefore, any observed change in $I_{\text{CO}_2}/I_{\text{Ar}}$ from the nominal value must be the result of some physical or chemical change occurring in the combustor, nozzle, test stream, or sampling system that affects the CO$_2$ concentration. If one of the gases being ratioed to Ar does not originate in the combustor (gases injected from the flat-plate model), some of the combustor-nozzle physical processes may be superimposed upon the ratio and can be measured.

Intensity ratios are also used with other tracers of known composition, such as the Ne in the N$_2$ jet gas used in these studies. Here, $I_{\text{Ne}}/I_{\text{Ar}}$ is an effective ratio of the gas injection to combustion process and is used to trace the mixing of the jet gas with the combustion test gas at the top of the test section. This ratio uses the assumed constant concentration of Ar in the tunnel test gas and the constant concentration of Ne in the N$_2$ jet gas to indicate a changing mixture ratio of jet gas to tunnel gas during a tunnel run. This ratio can be made quantitative by applying calibrated sensitivity factors $S_i$ which relate peak-height intensity to partial pressure of the appropriate species. Thus, the mixing ratio of the 1 mole percent Ne/N$_2$ jet gas with hot tunnel gas is given by

$$\frac{P_{\text{N}_2\text{-jet}}}{P_{\text{tg}}} = \left( \frac{I_{\text{Ne}}}{I_{\text{Ar}}} \right) \left( \frac{S_{\text{Ar}}}{S_{\text{Ne}}} \right) \left( \frac{0.86}{1.00} \right)$$

where

- $S_{\text{Ar}} = 5.64 \times 10^4$ Hz/torr
- $S_{\text{Ne}} = 6.82 \times 10^4$ Hz/torr
- 0.86 = Mole percent Ar in tunnel gas
- 1.00 = Mole percent Ne in jet gas

For cold tunnel gas runs (standard dry air),

$$\frac{P_{\text{N}_2\text{-jet}}}{P_{\text{Air}}} = \left( \frac{I_{\text{Ne}}}{I_{\text{Ar}}} \right) \left( \frac{S_{\text{Ar}}}{S_{\text{Ne}}} \right) \left( \frac{0.93}{1.00} \right)$$

where 0.93 = Mole percent Ar in standard dry air. When He is the jet gas, the equations are as follows:

$$\frac{P_{\text{He\text{-jet}}}}{P_{\text{tg}}} = \left( \frac{I_{\text{He}}}{I_{\text{Ar}}} \right) \left( \frac{S_{\text{Ar}}}{S_{\text{He}}} \right) \left( \frac{0.86}{100} \right)$$

(Hot tunnel gas condition runs)

and

$$\frac{P_{\text{He\text{-jet}}}}{P_{\text{Air}}} = \left( \frac{I_{\text{He}}}{I_{\text{Ar}}} \right) \left( \frac{S_{\text{Ar}}}{S_{\text{He}}} \right) \left( \frac{0.93}{100} \right)$$

(Cold tunnel gas condition runs)

In these equations, $S_{\text{He}} = 1.37 \times 10^6$ Hz/torr, and the jet gas is 100 mole percent He. The use of He as the jet gas allows a more direct measurement, since it is itself a single inert gas that is directly determined by mass spectrometry. Figures 3 through 7 show the model position (height) and typical run test-section and gold-leak pressure traces for five different test conditions. (See table I.) These figures also show that the pressure measured with a differential capacitance transducer at the gold-leak ($P_{\text{gl}}$), inlet of the MS followed sensibly the pressure changes in the pod ($P_{\text{tg}}$), although they were attenuated as was expected. In most of these tests, the pressure rise caused by the insertion of the model can be separated from the pressure rise caused by the firing of the jet in the model. In general, the pressure rise when the jet was fired was slightly larger than when the model was inserted for both the test-section and the gold-leak inlet locations.

Examples of the changes in the measured intensities and derived data during the course of two different test runs are shown in figures 8 through 13 for test runs 72 and 91. Figures 8 and 9 show the MS peak-height intensity curves in Hertz ($10^{-13}$ amp/Hz) for neon ($I_{\text{Ne}}$), helium ($I_{\text{He}}$), argon ($I_{\text{Ar}}$), and carbon dioxide ($I_{\text{CO}_2}$). They also show the gold-leak pressure $P_{\text{gl}}$ and the derived ratios of $I_{\text{Ne}}$ to $I_{\text{Ar}}$, or $I_{\text{He}}$ to $I_{\text{Ar}}$. The nominal static mixing ratio of 0.035 for jet-to-tunnel gases is given for comparison. From the intensity data and MS sensitivity calibration data, the partial pressures $P_i$ of Ne, He, Ar, and CO$_2$ were calculated using the equation $P_i = I_i/S_i$, where $S_i$ is in Hertz/torr. Figures 10 and 11 give the partial pressures of interest and the $P_{\text{gl}}$. From the partial pressures and the total pressure of the sample at the gold-leak $P_{\text{gl}}$, the mole fraction $X_i$ can be calculated by the equation $X_i = P_i/P_{\text{gl}}$. The mole fractions are shown in figures 12 and 13. The intensity curves of figures 8 and 9 and the partial-pressure curves of figures 10 and 11 have similar shapes for a given species in a particular run. However, the mole-fraction curves of figures 12 and 13 have shapes that differ from the $I_i$ and $P_i$ curves. The intensity-ratio
curves in figures 8 and 9 also have partially different shapes than the $I_i$ and $P_i$ curves. The $I_i$ and $P_i$ similarities are the result of their dependence on the number density of the species, which is independent of other species present. The mole-fraction curve $X_i$ is dependent on the total number density of the gas mixture. The ratio $I_i/I_j$ is relative to number densities of components $i$ and $j$ of a gas mixture.

**Results and Discussion**

**Jet Gas Interaction**

Figures 14 through 21 summarize and compare the data taken for test runs where the tunnel and instruments were operating in nominal fashion. (See table 1 for run conditions.) Figure 14 shows the variation of $I_{Ar}$ with time for hot and cold runs where the 1 mole percent Ne/N$_2$ jet was fired before or at the same time the model was inserted in the test stream. For the hot runs, $I_{Ar}$ peaked during the time the model with jet firing was in the test stream and then decreased until the model was withdrawn and the jet was stopped. For the cold runs, $I_{Ar}$ increased rapidly at first and then approached a constant level during the time the model with jet firing was in the stream. The $I_{Ar}$ trends and the difference in average peak intensity (about $5 \times 10^2$ greater in the hot runs) indicate that there was a difference in the mixing and migration of the tunnel test gas to the top of the test section between the hot and cold test streams.

Figure 15 shows $I_{Ar}$ curves for hot and cold runs with He as the jet gas and with the jet fired about 0.5 second after the model insertion. For these hot runs, the $I_{Ar}$ increased as the model was inserted; $I_{Ar}$ reached a maximum when the jet fired and dropped sharply just after the model was withdrawn and the jet was stopped. In the cold runs, $I_{Ar}$ increased with model insertion and approached a plateau that lasted until the model was withdrawn. Cold-run curves did not include model withdrawal and jet stopping data. The Ar intensities measured for both the hot and cold runs with He jet were at about the same level.

The changes in mole fraction $X_i$ for the N$_2$ jet gas and the He jet gas with time are shown in figures 16 and 17; $X_{Ne}$ and $X_{He}$ were obtained from the MS peak intensity data sampled from the top of the test section. The He jet runs of figure 17 show similar trends with a decrease in He background as the model was inserted, a large, sharp rise in $X_{He}$ as the jet was fired, and a slow decrease until the model was withdrawn and the jet was turned off. Differences between hot and cold runs were presumed to be due to differences in the pumping of the flows. In the case of the N$_2$ jet (fig. 16), the same trends are evident (as in fig. 17) but are not as well defined. The peaking of $X_{Ne}$ after the jet is fired is shown, as is the decrease while the model was inserted with jet firing. The N$_2$ jet runs differed from most of the He jet runs in that the jet was fired before, or at the same time that, the model was inserted; for the He runs, the jet was fired after the model was in the test stream.

Figures 18 and 19 show $I_{Ne}/I_{Ar}$ and $I_{He}/I_{Ar}$ for cold and hot runs, respectively. For the cold runs, the curves show a peaking of the intensity ratios while the jet was firing and then a decrease until the model was removed and the jet was stopped. For the hot runs with the He jet, the intensity-ratio curves tended to increase sharply when the jet was fired and either peaked or leveled off before the model was retracted. In figure 19, the peaking was more pronounced when the jet gas was N$_2$, than for He. This observation may be the result of greater diffusion rates.

Figure 20 shows the percentage of N$_2$ jet gas that was measured at the top of the test section during several runs. When the N$_2$ jet gas was injected into the hot test stream, the jet gas increased in the sample to a maximum and then decreased somewhat before the model was withdrawn and the jet was turned off. Most of the runs produced gas mixtures with between 50 and 80 mole percent jet N$_2$ at the top. One cold run (27) with the jet fired below the test stream is also shown. The N$_2$ jet gas at the top of the test section reached 60 mole percent, indicating that there was little mixing or entrainment of jet gas with the test stream under these conditions.

In figure 21 (He jet gas runs), all the runs except run 91 had mixtures of He and tunnel gas at the top which were less than 1 mole percent He. Run 91 was one in which the He jet was fired below the hot test stream and produced a gas mixture at the top of the test section. This mixture had a He concentration of about 55 mole percent, which shows that most of the He ejected from the jet traveled around the test stream to the top with minimal interaction with the test stream. The fact that He did not show up at the test-section top in any concentrations greater than 1 mole percent when injected into a hot or cold test stream indicates that most of the He was entrained with those test streams and was removed from the test section.

When a N$_2$ jet is injected into a hot or cold stream, the injected gas mixes with the test-stream gas and diffuses to the top of the test section as a mixture. When a N$_2$ jet is fired below a cold stream, there is only slight mixing with the test-stream gas, and apparently much of the jet N$_2$ gas goes directly to the top of the test section and passes around the test stream. Helium behaved the same way when fired below a hot stream. From these results, it is suggested that the molecular weight differences
between the injected gas and the test-stream gas produce significant differences in stream mixing and diffusion from the stream. Nitrogen with a molecular weight of 28 is similar to air (79 mole percent N₂) with an average molecular weight of 29 that mixes and diffuses at similar rates. Helium with a molecular weight of 4 appears to be mainly entrained in the test stream and does not diffuse out readily nor is it picked up from outside the hot stream.

**Carbon Dioxide Distribution**

Carbon dioxide (CO₂) differs from the other gases measured in these tests in that CO₂ is a product of the combustion reaction of methane (CH₄) and oxygen (O₂). The CO₂ levels will serve, then, as a monitor of the overall combustion system efficiency. The other gases measured, Ne, He, and Ar, are all chemically inert and were introduced at constant concentration levels in the jet gas or were already present in the tunnel gas. Of the inert gases in the test section, only Ar had any concentration dependence on the combustion process, and then only if the fuel-to-air ratio changed. During a test run in which the combustor performed stably and according to the nominal conditions of fuel-to-air ratio which is 8:10 stoichiometric to CO₂ and water (H₂O), the mole ratio of CO₂ to Ar should remain constant at 8.7 if there are no physical or chemical processes taking place in the system which remove CO₂ from the hot test gas stream or sample stream. The mole ratio of 8.7 corresponds to a measured intensity ratio \( \frac{I_{CO₂}}{I_{Ar}} \) of 3.5 for the GADS in these tests. These are theoretical maximum stream values assuming complete combustion and equilibrium flow. With a cold-gas stream, the CO₂ concentration would be on the order of 0.03 mole percent (average atmospheric value), the mole ratio of CO₂ to Ar would be 0.03, and \( \frac{I_{CO₂}}{I_{Ar}} \) would be 0.014. We, however, were measuring at the top of the test section and were testing the assumption that the gases that reach this sampling point arrive without significant change in concentration or composition from average stream values except for mixing. With these considerations in mind, the CO₂ data are presented and discussed in the paragraphs that follow.

Figure 22 shows MS peak-height intensity data for CO₂ and Ar for a hot run (86) with He jet firing in the test stream. In figure 22(a), three intensity curves are shown—Ar peak intensity, CO₂ intensity, and nominal CO₂ intensity—calculated from \( I_{Ar} \) and the nominal \( \frac{I_{CO₂}}{I_{Ar}} \) ratio for the combustion-gas test-stream value of 3.5. In figure 22(b), two intensity-ratio curves are shown, \( \frac{I_{CO₂}}{I_{Ar}}_{msd} \) and \( \frac{I_{CO₂}}{I_{Ar}}_{nom} \). The latter is a constant-value straight line at 3.5. The shapes of the \( I_i \) curves are reasonable and show that the measured \( I_{CO₂} \) curve is similar to the nominal \( I_{CO₂} \) curve, although it is attenuated by about 24 percent at the peak of the curves. Some dilution \( (I_i \text{ attenuation}) \) of the test-stream gas is expected because of the jet gas injected and because of the mixing with gases already in the top of the test section.

Figures 23 through 26 show curves of the measured \( I_{CO₂} \) and \( I_{Ar} \), and the nominal \( I_{CO₂} \) and \( \frac{I_{CO₂}}{I_{Ar}}_{msd} \) as a function of time for four runs each as labeled. The agreement between the runs is good considering the complexity of the systems involved. Figures 23, 24, and 26 also show averaged measured curves (dotted lines) for these four runs. They display the trend of an increase in CO₂ intensity as the “model-in” period is approached, peaking toward the end of jet injection and dropping sharply just before the “model-out” and “jet-off” events.

Figure 27 shows curves of \( \rho_{gl} \), \( I_{CO₂} \), and \( X_{CO₂} \) for 3 different types of runs with He jet injection, cold and hot runs with model in and jet on (figs. 27(a) and 27(c)), and a hot run with model out and jet fired beneath the test stream (fig. 27(b)). In the cold run (fig. 27(a)), the measured CO₂ level was about 0.04 mole percent (compared with ambient air at 0.03 mole percent) and was somewhat oscillatory over the larger run time. The hot run with the jet fired below the test stream (fig. 27(b)) showed a drop in CO₂ concentration from about 3.6 mole percent to about 1.2 mole percent when the He jet was fired. This indicates that a large amount of the ejected He migrated directly to the top of the test section and diluted the CO₂ (tunnel test gas) by a little more than 1:1. (See fig. 21.) Figure 27(c), where the He was injected into the hot test stream, shows the \( X_{CO₂} \) peaking before the model was inserted and then generally decreasing as the jet was firing, until the model was withdrawn and the jet was shut off, after which it increased and peaked again. This trend, shown in the curves in figure 28, indicates that dilution or removal of CO₂ from the top of the test section is faster than diffusion from the test stream during the model-in, “jet-on” part of the run. The shapes of the curves in figure 28 are determined by the change of \( \rho_{CO₂}/\rho_{gl} \) with time during a run. In this case, there is a relatively constant \( \rho_{CO₂} \) with an increasing \( \rho_{gl} \) that peaks as the model is withdrawn and as the jet is turned off. The pressures, \( \rho_{CO₂} \) and \( \rho_{gl} \), are determined by the rate at which CO₂ diffuses from the test stream to the top of the test section with other test-stream and jet gas components. Changes in \( \rho_{gl} \) are the result of He jet addition and subsequent diffusion to the top of the test section. This includes any effects that the injection may have on the diffusion of all the other
species present. The MS inlet pressure $P_{gl}$ is directly related to the test-section pressure $P_{ts}$ but is smaller because of the pressure drop through the 10-ft-long transfer line.

Figure 28 shows the mole fraction of CO$_2$ plotted against time for a number of hot runs. The same trend was observed when the model was in the test stream for all runs shown, including one where the jet was fired with the model below the test stream. The trend was for the $X_{CO_2}$ to decrease during the test interval, which was about 3 seconds for these hot runs. The trend is in agreement with the assumption that CO$_2$ and other hot stream gases diffuse to the top of the test section. During the 2.5-second jet firing the test gases are diluted by and/or displaced by a mixture of jet gas and test-stream gas of decreased CO$_2$ content. For longer runs it would be expected to level off to a steady state, however, longer runs at this combustion temperature and pressure were not feasible in the 7-Inch HTT. Another factor which could affect the CO$_2$ concentration, which has not been previously discussed in this paper, is the real possibility of the formation of water droplets which can dissolve CO$_2$ and effectively remove it from the gaseous phase.

The results indicate that some previous boundary-layer CO$_2$ measurements from inlets on a conical model in the Langley 8-Foot High-Temperature Tunnel (ref. 4) have qualitative validity and, under more controlled measurement conditions, may be capable of quantitation.

Concluding Remarks

The mass spectrometric measurements made during the supersonic jet interaction tests in the Langley 7-Inch High-Temperature Tunnel provided significant information of a semiquantitative nature concerning the real-time distribution of the injected gases in the test section. The measurements of CO$_2$ and Ar diffusing to the top of the test section under several tunnel run conditions gave indications of the stability of the combustion gas test-stream composition. The quantitative aspects of the CO$_2$ measurements were well within reasonable ranges of nominal operating values. Laboratory tests indicate that the sampling system was performing well for the gas conditions being sampled; that is, there were low flow rates at the sample port, ambient temperature at the test-section wall, and out-of-stream test-section pressure in the range of 15 to 31 torr.

NASA Langley Research Center
Hampton, VA 23665-5225
February 7, 1986

References

<table>
<thead>
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<th>Run</th>
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</tr>
<tr>
<td>91 (hot)</td>
<td>He</td>
<td>62</td>
<td>MI</td>
<td>B2</td>
<td>0</td>
</tr>
<tr>
<td>93 (hot)</td>
<td>Jet off</td>
<td>Jet off</td>
<td>MI</td>
<td>&quot;B2&quot;</td>
<td>1.2</td>
</tr>
<tr>
<td>96a (cold)</td>
<td>He</td>
<td>61</td>
<td>MI</td>
<td>&quot;B2&quot;</td>
<td>11.6</td>
</tr>
<tr>
<td>96b (cold)</td>
<td>He</td>
<td>61</td>
<td>MI</td>
<td>&quot;B2&quot;</td>
<td>11.2</td>
</tr>
</tbody>
</table>

"Sample arm rotated 180°."
(a) Flat-plate model with thruster jet nozzle angled 15° forward in plate surface as mounted in 7-Inch HTT.

(b) Shadowgraph of flat-plate model in hot test stream with helium injection from plate showing typical flow patterns.

Figure 1. Flat-plate model in 7-Inch HTT.
Figure 2. Schematic of mass spectrometric sampling system for tests in 7-Inch HTT.

Figure 3. Pressure-time curves for a run where He jet was fired when model was below hot test stream.
Figure 4. Pressure-time and model rise-time curves for a run where model was inserted into hot test stream but jet was not fired.

Figure 5. Pressure-time and model rise-time curves for a run where Ne/N₂ was injected into hot test stream.
Figure 6. Pressure-time and model rise-time curves for a run where He was injected into hot test stream.

Figure 7. Pressure-time and model rise-time curves for a run where He was injected into the cold test stream.
Figure 8. MS data for run 72 where Ne/N₂ was injected into a hot test stream and an unstart occurred soon after model withdrawal. \( I_{\text{Ne}} / I_{\text{Ar}} \) for complete mixing is 0.50.
Figure 9. MS data for run 91 where He was ejected when model was below hot test stream.
Figure 10. Partial pressures derived from MS data for run 72.
Figure 11. Partial pressures derived from MS data for run 91.
Figure 12. Mole fractions derived from MS data for run 72.
Figure 13. Mole fractions derived from MS data for run 91.
Figure 14. Comparison of Ar peak intensity data for runs where Ne/N₂ was injected into several hot or cold test streams. Run 27 is included where jet was ejected below a cold test stream.
Figure 15. Comparison of Ar peak intensity data for runs where He was injected into several hot or cold test streams. Run 91 is included where jet was ejected below a hot test stream.
Figure 16. Comparison of Ne mole fraction data for several runs where 1 mole percent Ne/N₂ was injected into hot test streams. Run 27 is included where jet was ejected below a cold test stream.
Figure 17. Comparison of He mole fraction data for several runs where He was injected into hot or cold test streams.
Figure 18. Comparison of intensity-ratio curves for several cold test-stream runs.
Figure 19. Comparison of intensity-ratio curves for several hot test-stream runs.
Figure 20. Mole percent $N_2$ from injected jet gas found in gas sampled at top of test section (ports A and B1) during several runs.
Figure 21. Mole percent He from ejected jet gas found in gas sampled at top of test section from several runs using several sample port positions. Note different scale for run 91.
(a) Nominal and measured peak intensity curves.

(b) Nominal and measured intensity ratios of CO$_2$ to Ar.

Figure 22. CO$_2$ and Ar data for run 86.
Figure 23. Measured peak intensity curves for CO₂ for runs 85, 86, 88, and 89 and their average.

Figure 24. Measured peak intensity curves for Ar for runs 85, 86, 88, and 89 and their average.
Figure 25. Nominal peak intensity curves for CO₂ for runs 85, 86, 88, and 89 calculated from known composition and measured $I_{Ar}$.

Figure 26. Nominal and measured peak intensity-ratio curves for runs 85, 86, 88, and 89 and average of measured ratios.
Figure 27. CO₂ and gold-leak pressure data for three types of runs.
Figure 28. Mole fraction of CO$_2$, $X_{CO_2}$ as a function of time for several hot test-stream runs with He jet gas and one with N$_2$ jet gas.
# Mass Spectrometric Gas Composition Measurements Associated With Jet Interaction Tests in a High-Enthalpy Wind Tunnel

Knowledge of test gas composition is important in wind-tunnel experiments measuring aerothermodynamic interactions. This paper describes measurements made by sampling the top of the test section during runs of the Langley 7-Inch High-Temperature Tunnel. The tests were conducted to determine the mixing of gas injected from a flat-plate model into a combustion-heated hypervelocity test stream and to monitor the CO₂ produced in the combustion. The Mass Spectrometric (MS) measurements yield the mole fraction of N₂ or He and CO₂ reaching the sample inlets. The data obtained for several tunnel run conditions are related to the pressures measured in the tunnel test section and at the MS ionizer inlet. The apparent distributions of injected gas species and tunnel gas (CO₂) are discussed relative to the sampling techniques. The measurements provided significant real-time data for the distribution of injected gases in the test section. The jet N₂ diffused readily from the test stream, but the jet He was mostly entrained. The amounts of CO₂ and Ar diffusing upward in the test section for several run conditions indicated the variability of the combustion-gas test-stream composition.