COMPLETENESS OF FUEL COMBUSTION IN THE SETTLING CHAMBER OF A HIGH-ENTHALPY WIND TUNNEL

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Two basic questions arise when chemical energy of fuel combustion in the settling chamber of short-duration high-enthalpy wind tunnels is used to increase the energy characteristics of the facility: What is the degree of completeness of chemical reactions in the settling chamber and what is the composition of the test gas at the nozzle exit [1]?

Gas sampling from the reacting medium for subsequent determination of the gas composition is a natural and most widespread method for estimating the degree of completeness of chemical reactions in the gas flow. Gas sampling can be performed from a supersonic or hypersonic flow at the nozzle exit in the wind-tunnel test section or directly from the settling chamber. A method of gas sampling from a hypersonic flow in the test section of the IT-302M hotshot wind tunnel is considered below.

Gas sampling in short-duration high-enthalpy wind tunnels has the following specific features.

1. The test time is ~ 100 ms. During this period, it is necessary to extract the gas sample and almost instantaneously (~ 1 ms) shut the container to ensure the absolute leak-proofness of the volume with the gas sample. To match the sample with flow parameters, operation of the gas sampler has to be rigorously synchronized with wind-tunnel operation.

2. The Mach number at the nozzle exit is \( \mathcal{M} = 5-8 \), the stagnation temperature is 1000-3000 K, and the stagnation pressure reaches several tens and hundreds of bars. If the completeness of combustion in the sample is lower than unity, these high parameters can generate conditions for afterburning of the sampled gas inside the sampler. Therefore, the sampling technique and the sampler structure have to eliminate the possibility of sample afterburning inside the system, i.e., the sample has to be “frozen.”

3. The ratio of the container (sampler) volume and its entrance area has to be chosen so that the pressure in the container during gas sampling should be several times lower than the pressure in the sampler channel to prevent rapid upstream motion of the pseudoshock in the channel and failure of the gas inflow into the sampler. In addition, as the pressure of the sampled gas is much lower than the atmospheric value (0.1-0.2 bar), a possibility should be provided to pressurize the sample to the atmospheric pressure (or higher) for a chemical analysis to be performed.

4. The mechanism of sample shutoff in the container should prevent leakage when the test section is evacuated and incoming of atmospheric air when the test section is opened.

The present study was aimed at solving the above-mentioned problems for the IT-302M hypersonic hotshot wind tunnel based at ITAM SB RAS.

Figure 1 shows the sampler in the test section of the wind tunnel. The wind-tunnel arrangement in these experiments included the discharge chamber, the settling chamber, and the nozzle designed for a Mach number \( \mathcal{M} = 6 \) with an exit diameter of 300 mm. The pressure of air pumping into the discharge (first) chamber was varied in the range \( P_{ch1}(pump) = 35-70 \) bar; the capacitor voltage was 2.5-4.8 kV. These parameters provided the following pressures and temperatures of air in the first chamber at the beginning of the test time (for combustible mixtures pumped into the first chamber, the energy released during their combustion was ignored): \( P_{ch1}(0) = 180-375 \) bar and \( T_{ch1}(0) = 700-2860 \) K.

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The beginning of the test time was assumed to be the moment of the capacitor discharge in experiments with pure air and the moment of forced opening of the diaphragm in experiments with combustible mixtures.

The layout of internal channels of one variant of the sampler and its photograph are shown in Figs. 2 and 3, respectively. The sampler proper is rather massive and is made of copper to ensure intense heat removal from the gas sample. In this part of the device, the flow should remain supersonic during the entire time of gas sampling. The sampler channel expands from 2.5-5.5 mm at the entrance to 7-9 mm at the exit (in different variants) to compensate for the growing boundary layer. At the end of the channel, there is a steel adapter containing a pseudoshock responsible for the transformation of a supersonic or hypersonic flow to a subsonic flow. After that, the sample enters the interior of the pyro-valve and then, through adapter 11, container 12. Piston 13 of the container serves for additional compression of the sample up to atmospheric pressure after the test.

The sampler is mounted on a platform connected with the strut. There are also pressure probes covered by a shield on the platform. The input orifice of the sampler is aligned along the nozzle centerline. In one variant, there were three heat-flux probes hf1-hf3 between the pressure probes p2 and p5.

Before the test, volume 8 of piston 9 is filled by a mixture of gunpowder and fine aluminum powder. Piston 9 moves to the forward stop position. The gas path of the sampler (channels of sampler 1 and adapters 4 and 10, container 12, pressure tubes and interior of the pressure probes) communicate with the test section.
Before wind-tunnel initiation, the gas-dynamic path is evacuated, except for the chamber separated from the gas-dynamic path by a diaphragm. The gas path of the model is also evacuated. When the wind tunnel starts operating, container 12 becomes filled by the sample (test gas from the wind tunnel). When a certain pressure in container 12 is reached and when a certain flow structure in channel 1 is formed (which is chosen empirically, based on the data of the pressure probes $p_1 - p_8$, depending on the combination of pressures in the test section and container 12), a signal is given for initiation of the gunpowder charge 8. Piston 9 moves to the extreme backward position and separates the interior of valve 10 and container 12 from the sampler channel. In the extreme backward position, piston 9 is automatically fixed by a special device, which prevents forward motion of the piston.

In the course of sampling due to expansion of the channel immediately behind the sampler entrance, the supersonic or hypersonic flow entering the sampler from the test section becomes accelerated. The static pressure and temperature of the sample fall down below their values at the sampling point. The sample is “frozen.” The length of the sampler channel should be such that the stagnation temperature of the sample decreased owing to heat transfer to the cold walls of the sampler to a value that prevented (after deceleration in the pseudoshock at the end of the channel) a revived reaction of the nonreacted portion of the sample. This is the physical principle of operation of the sampler part of the device [2].

**Results.**

Figures 4 and 5 show the pressures at the pressure taps $p_2$ and $p_5$ for the configuration with a sampler-entrance diameter $d = 2.5$ mm.

If the tail plug 7 is open (see Fig. 2), the pressure along the channel during the entire test time is close to the free-stream pressure, see curves 1, test No. 1142.
This shows that the flow in the sampler channel remained supersonic during the entire test time in test No. 1142, and the flow was not decelerated anywhere in the channel between the sampler entrance and the exit of adapter 4 (see Fig. 2). The pyro-valve was not actuated in this experiment, and the pressure in the container was practically equal to the static pressure at the end of the sampler channel. Thus, the sample inflow into the container did not occur during the entire test time.

In test No. 1144, the tail plug was closed, and the pyro-valve was not actuated. The results of this test are plotted by curves 2 in Figs. 4 and 5. A pseudoshock with supersonic flow deceleration is formed in adapter 4 (see Fig. 2) immediately after the beginning of the test time in the test section. The entire pseudoshock is located in adapter 4. The beginning of the pseudoshock is located near the pressure tap p6: the pressure at the pressure taps p1 – p5 is the same as the pressure in test No. 1142 with an open tail plug. The sample starts inflowing into container 12, and the pressure in the container starts increasing.
During the test time, the pseudoshock starts moving upstream in the sampler channel owing to the increase in pressure in the container. By the time $t = 40 - 45 \text{ ms}$, the pseudoshock beginning reaches the copper part 1 of the sampler channel, where heat removal from the supersonic flow is expected to occur; see the increase in pressure at $t = 40 - 45 \text{ ms}$ at the pressure tap $p_5$ on curve 2 in Fig. 5. By the time $t \sim 65 \text{ ms}$, the pseudoshock beginning reaches the pressure tap $p_2$; see the increase in pressure at $t \sim 65 \text{ ms}$ on curve 2 in Fig. 4. The pressure distribution in the channel between the pressure taps $p_2$ and $p_8$ is typical for a pseudoshock [3]. The increase in pressure at the pressure taps along the sampler channel during the test time allows us to calculate the velocity of upstream motion of the pseudoshock, caused by the increase in pressure in the container. This velocity is $\sim 3 \text{ mm/ms}$.

Based on the space and time characteristics of the flow inside the sampler, we determined the time of gas sampling $t = 45 - 50 \text{ ms}$; the gas flow along the sampler proper (its part made of copper) remains supersonic during this time. The valve should operate before this moment.

Test No. 1145 was performed with shut-off of the sampler in the container with the pyro-valve actuated at $t = 50.4 \text{ ms}$; see curve 5 in Figs. 4 and 5. It is seen that the flow in the larger part of the copper channel of the sampler really remains supersonic before the pyro-valve is actuated. Thus, the basic physical principle of gas sampling from a supersonic reacting flow is satisfied: sample cooling should occur with a supersonic flow inside the sampler. After the valve is closed, the pressure along the entire sampler becomes identical and equal to the pressure behind the normal shock $p'_0$; see curve 4 in Figs. 4 and 5. The sampler starts operating as a Pitot tube.

Figure 6 shows the pressure in the container for different variants of sampler operation. If the tail plug is open, as was noted above, the container is not filled, and the pressure in the container does not increase during the entire test time (curve 1). If the tail plug is closed, but the valve is not actuated, the pressure in the container increases during the entire test time (curve 2). In tests with valve actuation, the pressure in the container after the sample shut-off decreases owing to heat transfer to the cold walls of the container (curve 3). This decrease in pressure is rather small: after complete cooling of the gas to room temperature, the decrease in pressure is less than 20% of the pressure at the moment of valve closing. Hence, the temperature of the sampled gas in the container at the moment of valve closing is within $350 \text{ K}$ with $p_0(0) = 300 \text{ bar}$ and $T(0) = 1600 \text{ K}$ in test No. 1145.
We can conclude, first, that the gas entering the container is already cooled and, second, that intense heat transfer from the gas to the cold walls may occur in adapters 4 and 11 (see Fig. 2), in the interior of valve 10, and in container 12. If there is a reacting gas ahead of the sampler, this second factor, combined with heat transfer from a supersonic flow in the copper part 1 of the sampler, can also favor sample freezing, if the time of container filling is smaller than the induction time depending on the sample pressure and temperature.

Another factor that favors sample freezing is the lower (as compared with $p_{\text{in}}$) pressure in the tail part of the sampler channel. At the pressure tap $p_8$, the sample pressure reaches the maximum value on its path from the sampler tip to the container. Thus, in test No. 1145, the pressure at $p_8$ immediately before the pyro-valve is closed at $t = 50$ ms is $p_8(50) = 0.14$ bar, as compared with $p_{\text{in}}(50) = 0.77$ bar. This phenomenon can be explained by two factors: 1) a higher Mach number in the sampler channel ahead of the pseudoshock than the Mach number at the nozzle exit, because of additional expansion of the channel behind the sampler entrance; 2) gas removal from the pseudoshock to the container, which was initially evacuated.

The study performed shows that the proposed system for gas sampling from a hypersonic flow in the test section ensures further acceleration of the flow in a long narrow channel and heat removal from the flow, aimed at freezing the sample and preventing afterburning, i.e., a representative sample is obtained.

The general level of pressure in the container (for wind-tunnel operation parameters used) was always much lower than the atmospheric value; hence, the sample had to be pressurized for a chemical analysis to be performed.

Using the above-described technique, we determined the content of oxygen in the test gas of the wind tunnel for the case with pure air pumped into the first chamber. Knowing the oxygen content is important if gas-dynamic models with combustion are tested [4, 5], where the heat income is provided by burning fuels in the flow of air (or another test gas) around the model.

![Fig. 7 Content of oxygen in the air flow around the model.](image)

1 – Content of hydrogen in pure air pumped into the first chamber before the test; 2 – content of oxygen in the air flow around the model.
Figure 7 shows the molar fractions of oxygen $r_{O_2}$ for tests where pure air pumped into the first chamber was used as a test gas. Curve 1 illustrates the oxygen content in air pumped from gas holders to the first chamber. The molar fraction of oxygen in pure dry air normally used in gas-thermo-dynamic calculations of gas-dynamic models with combustion is 20.95%. The presence of water vapor and carbon dioxide in real atmospheric air reduces the oxygen content (in our tests, down to 20.4%, curve 1). The symbols and curve 2 show the oxygen content in air sampled from the test section with the use of sampler 9 (see Fig. 1) versus the air temperature $T_{ch1}(0)$. The tests were performed at $p_{ch1\text{(pump)}} = 36-60$ bar, $U = 4-4.8$ kV, $p_{ch1\text{(0)}} = 330-380$ bar, sampler-entrance diameter $d = 2.5-5.5$ mm, container volume $125-570$ cm$^3$, and sampling time (between the beginning of the test time and the moment when the valve was closed) 110-40 ms depending on $d$ and container volume. The chemical analysis of the sample in container 12 (see Fig. 2) was performed on a chromatograph.

It is seen from Fig. 7 that the oxygen content in air decreases with increasing temperature of air in the first chamber. This phenomenon is caused by two factors. First, an increase in temperature is usually associated with an increase in electric discharge energy due to a greater capacitor voltage $U$, which results in a greater discharge power and, hence, greater burnout and oxidation of electrodes. Second, there are insulating fluoroplastic inserts between the electrodes and the chamber body. The greater the temperature of air contacting the end faces of the insulating inserts, the more intense burnout of the latter. This fact is additionally evidenced by the greater content of carbon dioxide in the sample at higher $T_{ch1}(0)$.

In the case of reproduction of natural stagnation enthalpies of flying vehicles at $M = 7 – 9$ (stagnation temperatures 2300-3600 K) in the IT-302M wind tunnel, the oxygen content in the air flow around the model may be expected to be reduced to 18-17%. This may require supplying additional oxygen compensating its burnout in the chamber for a number of problems associated with studying fuel combustion in gas-dynamic models.

REFERENCES