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Efficiency of Hydrogen Combustion in a High-Temperature Supersonic Air Flow for Different Methods of Injection

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The efficiency of hydrogen burnup in a supersonic air flow is studied for different methods of fuel injection. The combustion rate and combustion efficiency were determined by detecting the emission intensity of the OH radical over the length of the flare. The distinctive features and heat release characteristics of each of the delivery methods are established, so that a desired heat release behavior can be obtained by choosing suitable injectors.

The method by which fuel is fed into an air stream is of great importance for obtaining combustion with a specified heat release distribution over the flare length. However, there is clearly not enough systematic data on the performance of different injection systems.

The purpose of this paper is to study various methods for feeding hydrogen, including combination schemes, into a supersonic air flow with fixed parameters.

The experiments were carried out on a supersonic combustion stand with electric arc air heating which has been described in detail elsewhere [1]. Figure 1 shows sketches of the injectors and the site where the fuel is delivered. Air, heated in an electric arc heater to temperatures sufficient to ensure self ignition of the hydrogen, flowed through a supersonic contoured air nozzle (Mach number M = 1.4 or 2.2) into a free space and then entered an ejector. The total pressure of the air stream was $p_0 = (3.5\text{–}5) \cdot 10^5$ Pa for M = 1.4 and $p_0 = (5\text{–}7) \cdot 10^5$ Pa for M = 2.2; in most of the experiments, $p_0 = (4.5\text{–}5) \cdot 10^5$ Pa. The injectors, which consisted of cylindrical pipes with an outer diameter of 10 mm, were arrayed along the axis of the air nozzle. Various devices were mounted inside the injectors: a cylindrical pipe with an inner diameter of 8 mm for straight-through feed (Fig. 1a), a supersonic nozzle (M = 2) (Fig. 1b), a device for swirl feed [1, 2], and a pipe with holes in it for transverse fuel feed (Fig. 1c). For counterflow feed, a setup with three pylons spaced by 120° was mostly used (see Figs. 1d and 2a). The pylons were mounted in a 20-mm-long segment that was attached directly to the nozzle. The diameter of the holes in the pylons was 0.8 mm. In most of the experiments (except for specially mentioned cases), the range of temperatures was 1300–2200 K.

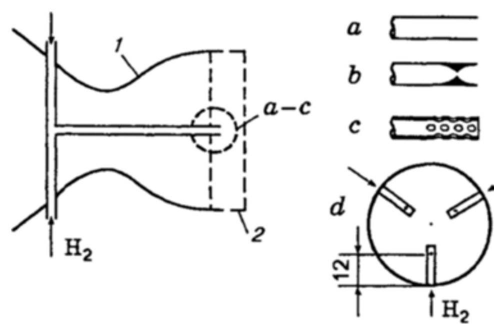

Fig. 1. Experimental arrangement and the design of the injectors: 1) air nozzle; 2) place where section d is mounted; a–c are the axial injectors and d is the section for upstream feed of fuel with three pylons (front view).

In the experiments the distribution of the intensity I of the ultraviolet emission from the OH radial was measured along the length of the flare; this made it possible to study the structure of the flare and determine the combustion efficiency [1–3]. In addition, photographs and motion pictures of the flare were taken and, in a number of experiments, shadowgrams. The light was detected along the jet

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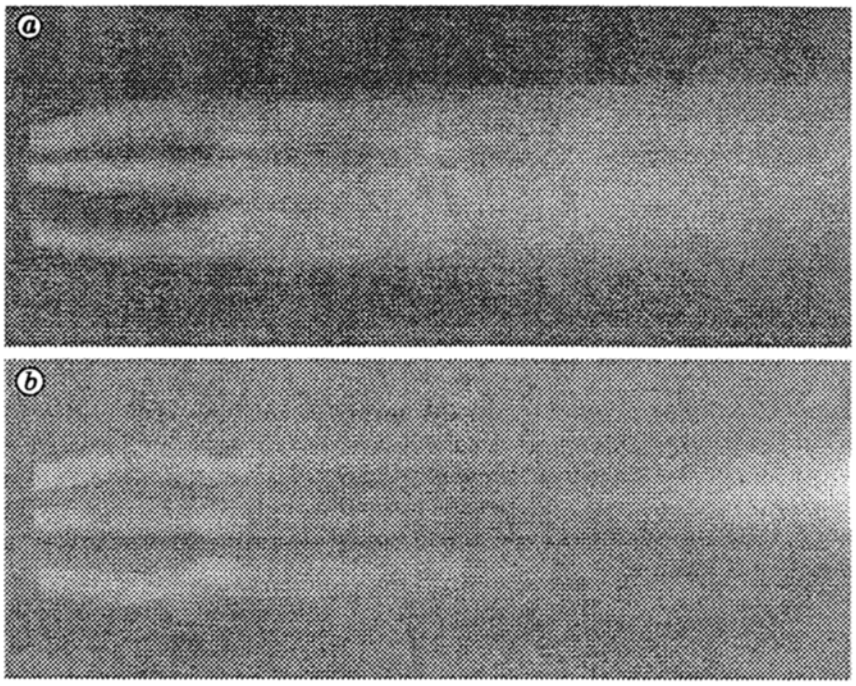

Fig. 2. Photograph of a flame with upstream fuel feed from three pylons (a) and with combination feed (b).

out to a distance of 300 mm from the cutoff of the air nozzle and, in some cases, out to 600 mm.

Straight-Through Fuel Injection. This method has been studied the most. Thus, in this paper it is used for comparison. The monotonic rise in the combustion rate with this type of feed is somewhat distorted only by the shock-wave structure of the supersonic air stream. Because of this, a periodic rise and fall in the intensity of the emission from the OH radicals is observed [1, 2]. Burnup is almost completely determined by the turbulent diffusion of hydrogen into the air stream, i.e., by mixing processes. The half aperture angle of the flame, measured form the photographs, was 3°. Töpler schlieren pictures taken under the same conditions showed that the boundary of the air stream expanded to an angle of up to 4° in this region.

In all cases with ignition of H_2 from the edge of the injector ($M = 2.2$ and $T \geqslant 1300$ K; $M = 1.4$ and $T \geqslant 2200$ K), the combustion efficiency was low at distances of up to 300 mm (up to 30% for a fuel feed rate $G_{H_2} = 6$ g/sec; Fig. 3a). When the H_2 feed rate is changed, the combustion rate of the flare at this distance does not change significantly; the initial parts of the plots of the OH emission intensity for $G_{H_2} = 2$–8 g/sec overlapped one another fairly well. This is, once again, an indication of a diffusion combustion mechanism with weak mixing of the fuel with air in the supersonic stream for this injection method. A fairly high burnup efficiency is possible in this case only over a large distance.

Downstream straight-through streams were studied with injectors of various lengths which extended beyond the nozzle cutoff by distances of 0–35 mm. In some experiments with a long injector (>20 mm), a fan of rarefaction waves from the edge of the air nozzle reached its tip. This led to the formation of a detached shock into which hydrogen flowed and combustion began at the side of the injector and not beyond it. However, the smooth burning of the entire jet, the aperture angle of the flare, and the amount of burnt H_2 remained the same as in the other cases with this feed method.

Downstream Fuel Injection at Supersonic Speeds. A supersonic flow of H_2 was produced with a conical nozzle (see Fig. 1b). This injection scheme has been used extensively in many studies [4, 5]. Under the present experimental conditions ($M_{air} = 2.2$ and $T \geqslant 1300$ K), the combustion rate with supersonic feed at distances up to 8–12 times the diameter of the hydrogen injector increases more slowly than with straight-through feed (with other conditions the same), and detachment of the flame form the injector can occur. The half aperture angle of the combustion zone is initially $\approx 2.5°$ and increases further to 3° as a distinct flare appears. The character and intensity of combustion are quite close to those observed for the straight-through flare (with a

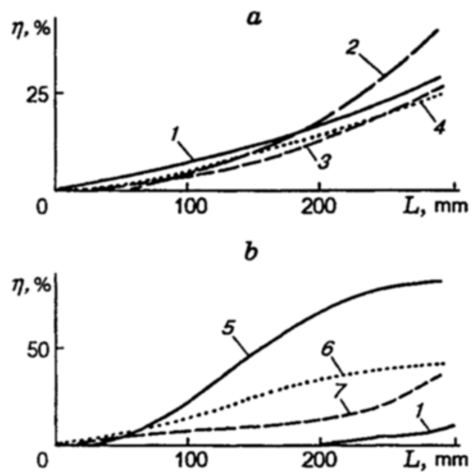

Fig. 3. Hydrogen combustion efficiency for straight-through (1), swirl (2, 3), supersonic (4), transverse (5), upstream (6), and combination (7) feeds: (a) $M = 2.2$, $T_0 = 1300$ K, and $G_{H_2} = 6$ g/sec, curves 2 and 3 refer to the degree of twist $n = 2.4$ and 1, respectively; (b) $M = 1.4$, $T_0 = 1850$ K, and $G_{H_2} = 2$ g/sec; L is the distance from the cutoff of the air nozzle.

correction for a shift in the point where active heat release sets in; see Fig. 3a). The aperture angle of the flare is close to that for straight-through feed and to the data of [4], where for H_2 feed at $M = 1.46$ along the axis into heated air with $M = 1.86$ the half aperture angle of the flame cone was 2–3°. This type of feed (as can straight-through feed) can be used when low heat release is required, for example, in constant cross section channels when it is necessary to avoid thermal cutoff.

Upstream Fuel Injection. In terms of burnup character, this method is also similar to the straight-through feed, but it has its advantages. First, right at the place where it enters, the upstream jet expands rapidly to occupy a cross section whose diameter exceeds that of the injector. Second, feed devices (pylons) located downstream in the flow always affect the flame stabilization. Thus, under conditions such that the flame has already detached from the injector with straight-through feed, with upstream feed no ignition delay is observed (see Fig. 3b, curves 1 and 6, for which $G_{H_2} = 2$ g/sec). Furthermore, the experiments showed that after ignition of the fuel, combustion could continue even when the temperature of the air stream had fallen to 1100 K. With straight-through feed, in this case combustion had ceased completely. This, however, is more likely related to the structural features of the injectors, rather than to the physics of the combustion process in a supersonic flow. Note that a section with three pylons will be used later for organizing joint feed from a number of axial injectors.

Delivery of Fuel by an Axial Injectorperpendicular to the Flow. This method is characterized by rapid mixing and high burning efficiency over a short length (Figs. 3b, 4a, and 5a). An injector with 28 holes (0.8 mm diameter) in a checkerboard pattern with 3–4 holes in each row, where the rows are spaced at 45° around the circumference (Fig. 1c), was used, as well as injectors with 8 and 16 holes, including ones arrayed in a row. The character of the combustion was essentially the same for all modifications of this type of injector. Combustion always began from the injector cutoff, which is facilitated by the recirculation zone beyond its end. This zone stabilizes the flame so efficiently, that combustion usually extends beyond the injector even when the air heating is shut off over a wide range of air flow velocities ranging from subsonic to supersonic. It should be noted that a checkerboard arrangement of the holes was more efficient that arranging them in a row. Thus, when the heater was turned off and the temperature of the flow fell rapidly to 270 K, sometimes the flame was seen to be cut off at the injector with the holes in a row. In the case of a checkerboard arrangement, combustion always continued.

Segner Wheel. In this design for an active injector, the part of the pipe with perpendicular feed (where the holes lie) is made to rotate. In order to make it rotate on its own, the holes are drilled at an angle to the circumference of the pipe and the escaping hydrogen spins a wheel (the principle of the Segner wheel). The rotation speed during operation is 1900–2000 rpm. Experiments showed that the observed flare is similar to that for purely transverse feed. However, rapid burning began only at some distance from the end of the injector (equal to 2–3 times the injector diameter). This can be seen especially well in comparison with transverse feed in a cold flow (see Fig. 4a and b). Using an "active" injector makes it possible to produce a flare with a short delay to the rapid combustion phase. Subsequently, combustion proceeds as with transverse feed.

Swirl Fuel Injection. In terms of combustion character, this method occupies an intermediate position between straight-through and transverse feed and has been investigated and described elsewhere [1, 2]. Recall that with swirl, the diameter of the fuel jet increases more rapidly in the initial segment than with straight-through injection. This causes the maximum in the heat release to shift toward the beginning of the flare, after which the main drop in the combustion rate sets in. The other feature of swirl feed is that the delay in ignition as the

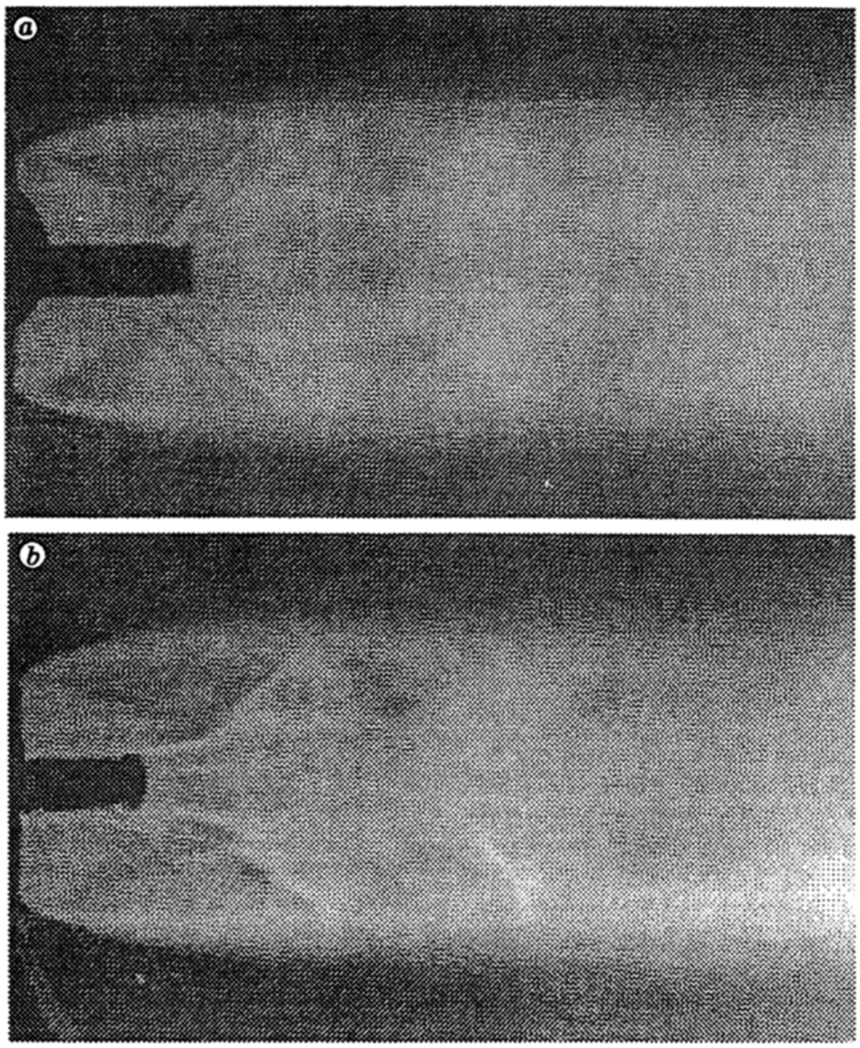

Fig. 4. Shadowgrams of a flare in a cold flow: (a) transverse feed; (b) Segner wheel.

temperature of the air feed is lowered is observed earlier than for a straight-through stream; this is also related to improved mixing of the cold hydrogen with air in the initial segment.

Additional experiments showed that these differences show up clearly only for a strong swirl. In [1, 2], the degree of twist of the injector n, defined as the ratio of the tangential and axial velocities, both averaged of the gas feed, was $\approx$2.4 (see curve 2 in Fig. 3a). When $n = 1$ is lowered to 1, the combustion rate increases more rapidly than with a straight-through stream, but the ignition delay may be retained (see curve 3 in Fig. 3a), i.e., swirl feed loses its advantages over straight-through feed.

Combined Fuel Injection. The following schemes for combined fuel injection were studied: counterflow feed from three pylons with simultaneous axial feed from a straight-through injector, swirled or transverse. The fraction of the counterflow feed in the total hydrogen feed was 15–20%. A common result for all combinations was a drop in the combustion rate compared to single injectors. Figure 3b shows plots of the hydrogen burnup for single and for combined feed (an injector with transverse feed). The combustion rate and efficiency decreased in both the combinations mentioned above, and the combustion efficiency at a distance of 280–300 mm could decrease by a factor of 2–3. A delay could appear in the ignition of the axial stream, even when an injector with transverse injection was used (see Fig. 2b). It is clear that the outer flares (peripheral streams) oppose the expansion of the axial stream and degrade its combustion; one type of feed actively acts on the other. As the hydrogen feed rate increases, the flares

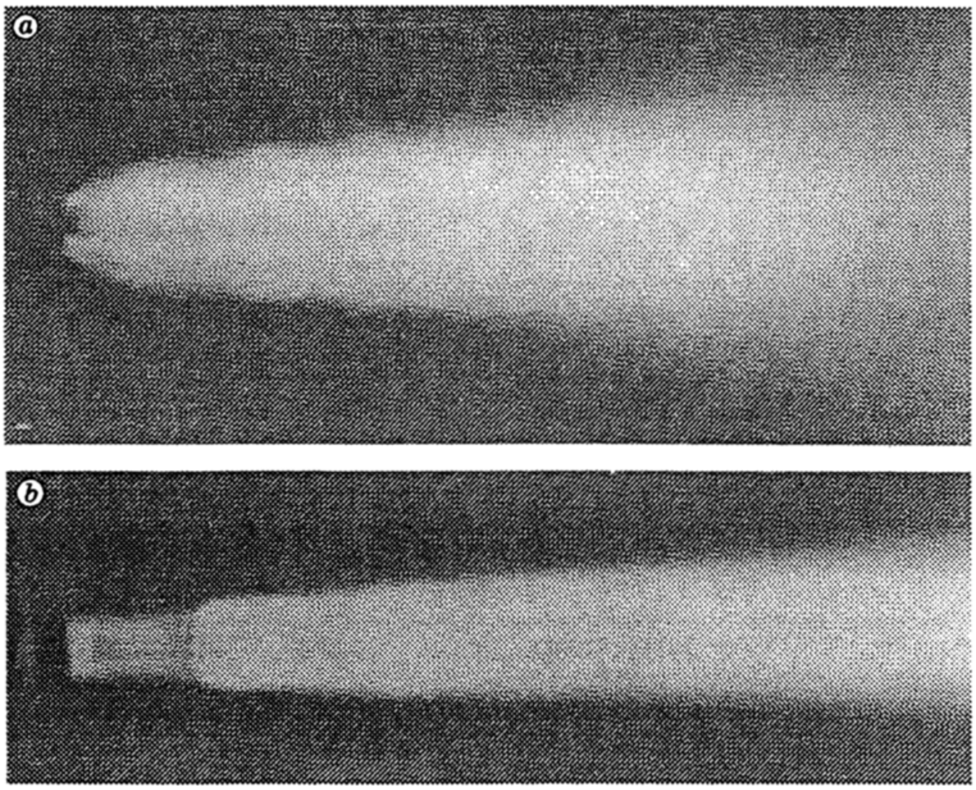

Fig. 5. The shape of an H_2 flare for transverse fuel feed: (a) injector moved into the flow; (b) injector inside the channel.

merge into a single common flare (roughly 100 mm from the injection point), but only at distances beyond 200 mm does the outer diameter of the single flare begin to increase significantly. This is consistent with the improvement in the efficiency curve recorded by the thermal vision system (see curve 7 in Fig. 3b).

Here we can make an analogy with the effect of a solid wall. This is confirmed by an experiment in which only an injector with a transverse feed is installed but a small cylindrical channel with a length equal to the protruding part of the injector (35 mm) is attached to the nozzle, so that the H_2 feed apertures were inside the channel. In this case, the individual streamlets of hydrogen no longer had the freedom to expand, but the flare changed shape and shrank in diameter, with a drop in its combustion rate along its length (see Fig. 5). Perhaps, during combination feed the burning fuel streams interact strongly with one another, in a way similar to the action of a solid surface, thereby changing the flare geometry, the combustion rate, and character of the heat release.

CONCLUSIONS

Heat release along the length of a flare has distinct features for different methods of fuel injection.

Straight-through feed and supersonic wake blow-in yield a weak monotonic rise in the combustion rate owing to poor mixing of the streams with the supersonic air flow. The flame can also detach from the injector. This feed method is appropriate when a low heat flux is needed, for example, in order to prevent thermal cutoff in constant cross section channels. The advantage of a straight-through injector is its simplicity of design.

Upstream feed is similar to straight-through flow, but combustion always begins at the feed site and the initial diameter of the flare exceeds the diameter of the feed holes because of better mixing at the injection point.

Swirl feed differs in having a more rapid rise in the combustion rate in the initial section, which is followed by the same gradual decrease as with straight-through feed.

Feed from an axial injector perpendicular to the air flow yields the highest rate of rise in the combustion rate and, therefore, the shortest length for complete burnup of the fuel. This sort of feed is recommended for obtaining especially intense combustion over a short length. Modernization of the latter method by rotating the injector (the Segner wheel) makes it possible to shift the beginning of the intense fuel burning zone away from the end of the injector.

A combination of upstream injection with axial injection when the injectors lie in a single cross section leads to a drop in the combustion rate compared to single injection. This must be taken into account during multipoint (multi-pylon) fuel injection, even if the flares do not merge with one another.

By using the features of the different fuel injection methods or combining them, it is possible to obtain the required heat release behavior and, by redistributing the feed, to control it.

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