Heat Loss Rates from Hydrogen-Air Turbulent Flames in Tubes

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Introduction

It is generally accepted that heat losses are very important in dynamics of combustion processes in the way they define various critical conditions for quenching and ignition phenomena, rate of pressure rise, etc. Basic considerations in classical combustion theory include essentially the problem of the heat losses. Despite of this many models developed to describe propagation of high-speed turbulent flames do not account for the heat losses to surrounding structures, or treat these important phenomena superficially (see, e.g., the review of Bray, 1996). One of the reasons for such a situation is that for high speed flames, the rate of heat losses is believed to be low in comparison with energy release rates to influence dynamic of flame propagation. Another reason is connected with the lack of experimental data on heat fluxes to surrounding structures generated by propagating turbulent flames. The objective of the present study is to obtain experimental data on the heat fluxes to tube walls, which are generated by propagation of turbulent flames in hydrogen-air mixtures.

Heat transfer from a hot gas to surrounding structures can be generally divided into two parts: convection and radiation. A relative contribution of the convective and radiant components depends on the type of confinement and on optical and thermal characteristics of combustibles. The convective component itself depends on the flow velocity and scale (Thring, 1965). The radiant component depends on the emissivity of the hot gases. For hydrogen mixtures the emissivity should depend on steam concentration, combustion temperature, and length scale (Hottel and Sarofim, 1967). The convective and radiant components of the heat losses differ significantly by their properties, and it is important to understand their relative contribution.

Experimental

Experiments were made using obstructed cylindrical explosion tubes of 174 and 520 mm id. Ring-shaped obstacles were installed in the tubes with blockage ratios 0.3 and 0.6. The obstacle plates were spaced by tube diameter. Experiments were performed using either 174-mm tube having a length of 12.2 m (Set 1), or in 520-mm tube (6.2-m long) joint to 6.2-m section of 174-mm tube (Set 2). Ignition in the Set 2 was made in the smaller tube. In the tests flame accelerated after ignition and a quasi-steady flame propagation regime was achieved in the second part of the tubes, where the measurements of heat fluxes were made.

Experiments were made at normal initial conditions (t = 20 C, P = 1 atm) using hydrogen-air mixtures with hydrogen content 10, 11.5 and 13% (vol.). Mixtures were ignited by a weak electrical spark. Measurements included germanium photodiodes, piezo-resistive pressure transducers and thermal measurements by specially designed thermal gauges. Photodiodes were used as flame time-of-arrival probes to measure speeds of flame propagation. Their readings were also used to qualify thermal radiation intensity. Piezo-resistive pressure transducers gave detailed readings of pressure rise in combustion processes and following on pressure decrease due to heat losses from combustion products.

Thermal gauges were constructed using 10-μm iron-nickel foil as a fast thermal resistive sensor. Time resolution of the gauges was less than 20 ms. Thermal gauges were calibrated by several independent methods in a range of 0.1-20 J/cm^2. Time duration of the heat pulse was changed from 10 ms to 10 s. Heat sources used in calibration included external light source with elliptic reflector, external thermal conductivity heating, and inner heating by Joule heat. Thermal gauges were mounted to the inner surface of the tubes. The overall heat flux transferred to walls, including radiative and convective components, was integrated by the thermal gauges. To compare the overall heat flux with its radiative component, the thermal gauge was located at the same cross section as a photodiode.

Results

An example of the signal of the thermal gauge is shown in Fig. 1. The integrated total energy release, E, corresponds to the maximum of the signal. The time at which the maximum was achieved was of the order of 20 sec. It was a function of the tube size, and mixture composition, and also of the history of flame acceleration. A more representative value is the time $t_{0.9}$ at which 90% of total energy is released. This parameter is almost independent on the history of flame acceleration and is defined mainly by the mixture energetic and scale.

As it is seen from a Fig. 1, the first half of the energy is lost from the combustion system during time, which is two orders of magnitude less than the time to lose the second half the energy. To characterize the intensity of the heat loss rate as a function of the flame speed the time $t_{0.5}$ was used, which gives the time of half-energy loss (see Fig. 1). The average heat flux, $q_{0.5}$, during time $t_{0.5}$ was close to the maximum heat flux from combustion processes.

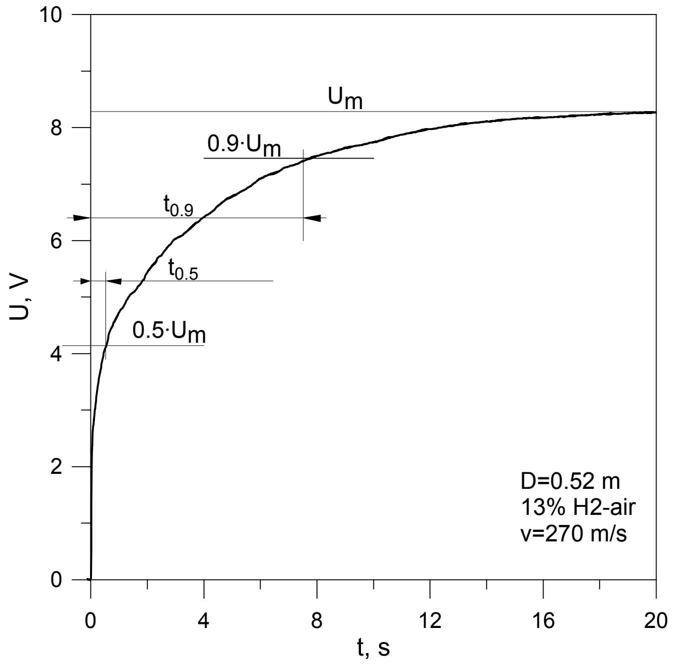

Figure 1. Typical record of thermal gauge and definition of characteristic times.

A comparison of the overall energy loss from the combustion system with the initial energy content is presented in Fig. 2. The integral of the energy loss can be determined both from the thermal gauges and from the pressure drop in the tube after combustion process. The data from the pressure drop should be considered as an average characteristic for the entire tube. The data from the thermal gauge characterize the energy loss in the location of the gage. The results show that different parts of the tube absorb different amount of energy. The deviation from the average value was usually within ± 30 %. We need to note that the thermal gauges were mounted into cylindrical part of the tubes between obstacles. It is possible to expect that other locations can give different deviations of the local heat flux values compared to the global one.

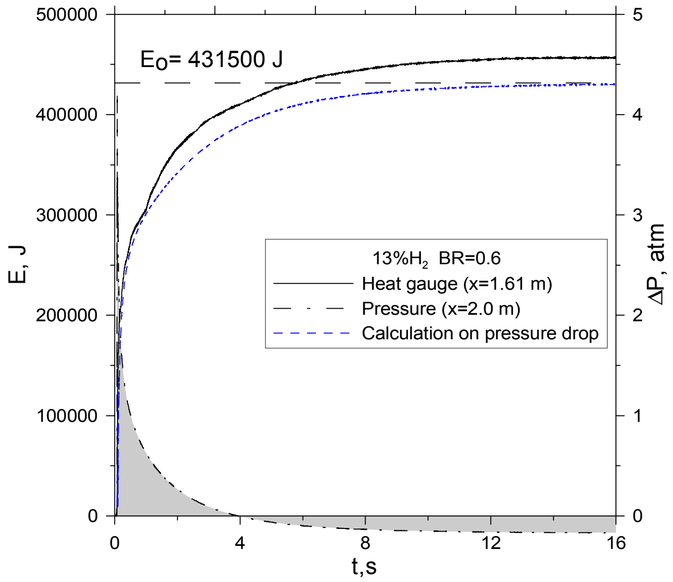

Figure 2. Comparison of the overall energy loss from combustion system with the initial energy content.

Figures 3 and 4 show dependencies of the heat flux $q_{0.5}$ on the local speed of flame propagation. It is seen that the heat flux increases sharply with the flame speed. The blockage ratio does not influence the heat flux values noticeably. The scatter of the data is rather large. This is due to different histories of flame acceleration and due to the fact that the flux depends on location. Nevertheless, the tendency and typical values of the fluxes are quite clear from Data of Figs. 3 and 4. A comparison of Fig3 and Fig. 4 shows that the value of the characteristic heat fluxes do not depend noticeably on the tube diameter.

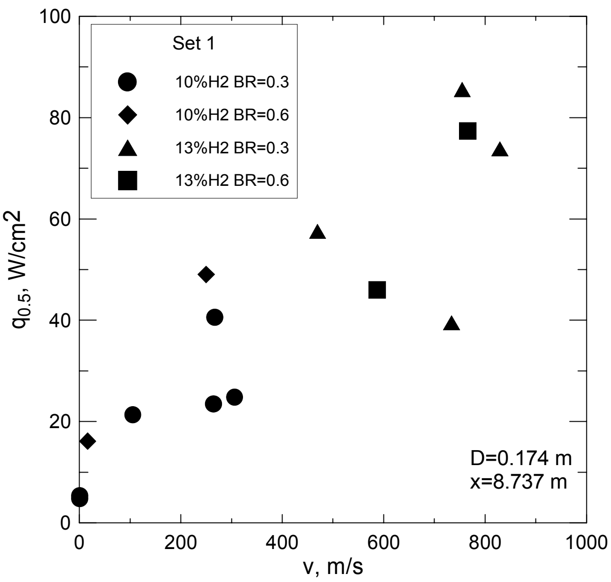

Figure 3. Dependencies of the heat flux on flame velocity in tube 174-mm

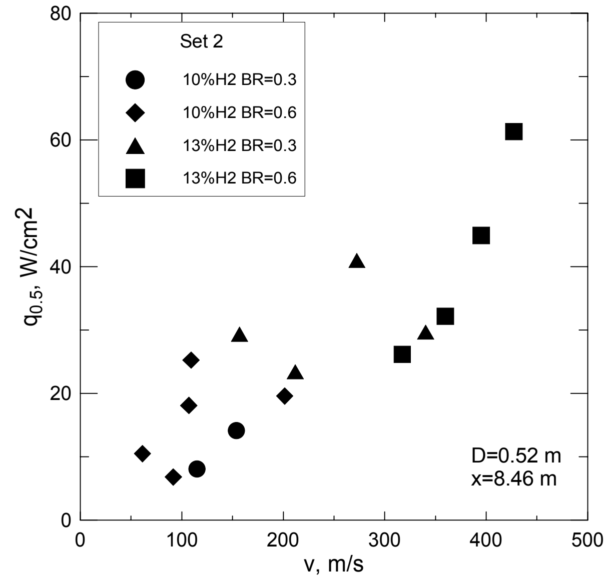

Figure 4. Dependencies of the heat flux on flame velocity in tube 520-mm

Both, the dependence of the heat flux on the flame speed (and hence on the flow speeds) and its independence on the tube diameter support a conclusion that the convective contribution to the heat losses dominates in our tests. Indeed, the heat exchange coefficient should not depend significantly on the tube size, if the flow field is similar and the gas temperature is the same. Also, it is hard to explain a strong dependence of the radiant heat flux on the flow intensity with the gas temperature being the same. To clarify further the relative contribution of the radiant and convective heat transfer, the data from the heat gauge can be compared to the readings of photodiodes. An example of such a comparison is presented in Fig. 5. It is seen that the major part of the energy is absorbed by the heat gauge during the time when the radiant heat flux recorded by photodiode is negligible.

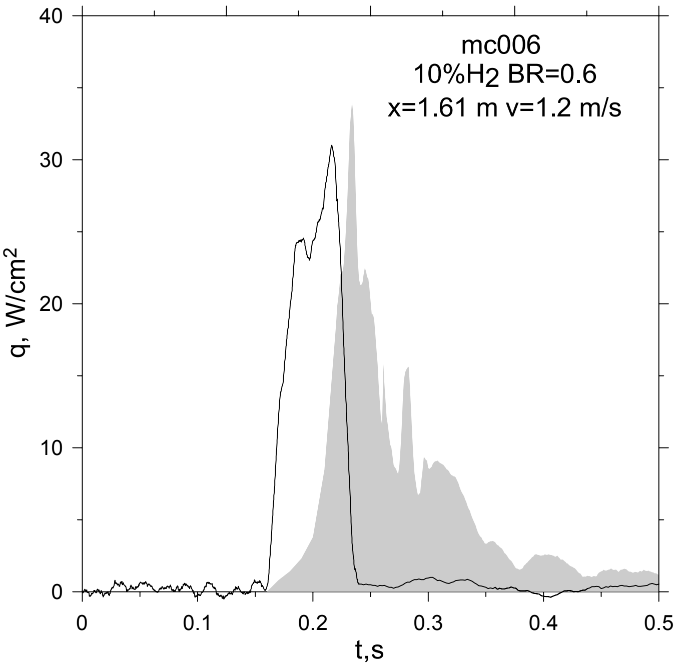

Figure 5: Comparison of the radiation intensity data from photodiode with thermal gauge signal. Line -photodiode; gray field - thermal gauge.

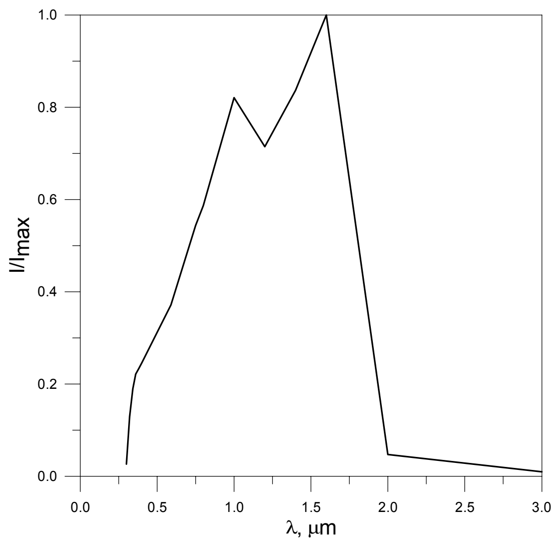

Figure 6: Spectral sensitivity of photodiode gauge.

The integral spectral sensitivity of the germanium photodiode and optical window used is shown in Fig. 6. The maximum sensitivity is in the range from 0,5 to 2 µm. The strongest lines in H2O spectrum, which should be responsible for the heat radiation in hydrogen flames, correspond to wavelengths of 1.34, 1.87, and 2.7 µm. These radiation bands are very wide under conditions of the test forming a continuos spectrum. Thus, a significant overlap exists of the photodiode gauge sensitivity and emissivity of H_2O, and the comparison presented in Fig. 5 gives an additional support to the conclusion on the dominant role of convective heat transfer in our tests.

Summary

We have presented results of experimental study of heat losses from propagating turbulent flames in obstructed tubes. Tests were made with hydrogen-air mixtures in tubes with internal diameter of 174 mm and 520 mm. Direct measurements of heat flux to tube walls versus time during flame propagation were conducted.

t was shown that total energy absorbed by the tube walls is equivalent to the mixture chemical energy for all the mixtures tested. The rate of energy losses from combustion processes was shown to depend significantly on the speed of the flame propagation. The average heat flux, q(0.5), at the time of half-energy release increases from 10 to about 80 W/sq.cm with increase of turbulent flame speed from 10 to 800 m/s. It was shown that tube diameter does not influence significantly the characteristic values of heat fluxes, while the characteristic duration of energy losses as well as total energy absorbed differ greatly in two tubes.

The main mechanism for heat losses under the conditions of present tests was shown to be convective heat transfer. This conclusion is supported by comparison of overall rate of heat losses with the measurements of its radiant component. The results suggest that qualitative and quantitative account for heat losses from combustion products is necessary to be included in turbulent combustion models to increase reliability of their predictions.

References.

Bray, K. N. C., *26th International Symposium on combustion*, The Combustion Institute, Pittsburgh, 1996, pp. 1-26.

Hottel, H.C., and Sarofim, A.F. Radiative Transfer. McGraw Hill, NY (1967).

Thring, M.W. Luminous Radiation from Flame. *Chem. Proc. Eng.* 10, pp 544-551 (1965)