Expanding hydrogen–air flames over the heat absorbing substrate

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Abstract. Acceleration of hemispherical gas flames depends both on the composition of the
gas mixture and on the boundary conditions. Experimental data on the hemispherical flame
propagation in hydrogen–air mixtures with a hydrogen content of 15% were obtained at the
ignition with an energy of 5 J. The flame propagates at atmospheric pressure over a solid
aluminium wall or a layer of steel wool. To visualize the flame propagation, an ir InfraTec
ImageIR 8320 camera with spectral range 2–5.7 µm was used. It was found that the flame over
the layer of steel wool propagates 1.8 to 2.5 times more slowly than that over the surface of
an aluminium wall. Calculation of heat absorption in the steel wool layer shows that the heat
losses due to the absorption are the main phenomenon causing the flame front speed reduction,
which was observed in the experiments. Additionally, the speed of the flame was affected by
the absorption of oxygen and the release of heat during the oxidation of the steel wool, as well
as by the roughness of the layer of steel wool.

1. Introduction
Large gaseous explosions are the objects of interest both from fundamental and practical points.
The most likely scenarios for the development of a gas explosion begin with a weak initiation by
a spark or a heated surface. Under certain conditions, the flame propagates with acceleration,
generating compression waves in front of it. The character of the flame propagation is influenced
by many factors, such as the composition of the flammable mixture [1–4], the characteristics of
the surface [5–7] and the coating on the surfaces [8–14].
Experimental, theoretical and numerical studies of the propagation of premixed unconfined
or semi-confined flame in large volumes are presented in [1, 2, 15–20]. Asymptotic analyses for
spherical flame kernels (steady solutions) and slow flame expansions in mixtures near and beyond
flammability limits which correspond to a molecular diffusion coefficient of the limiting species
greater than the thermal diffusivity (Lewis number less than unity) are presented in [1]. The
author reports different regimes of flame propagation: unsteady expanding flames, with a radius
growing approximately at the square root of time; self-extinguishing flames; and accelerating
cellular flames. In [2, 16, 18–20], the acceleration of a flame in various gas mixtures in spherical
or hemispherical geometry is described by the equation:

\[ R = R_0 + A(t - t_0)^{1.5}. \]  

(1)
Such regimes are observed at the Peclet numbers of several hundreds. In each specific case, the value of the critical Pe is determined by the parameters of the flammable mixture. Karlin and Sivashinsky [17] and Kim et al [18] present the time dependence of the flame front radius as described by power equations of the form:

$$R = R_0 + B(t - t_0)\alpha,$$

where $1 < \alpha < 1.5$.

Apart the acceleration, interaction with the walls can cause a decrease in the flame velocity and complete extinguishing [5–7]. Wu and Ihme [7] considering the loss of heat in the walls that limits the combustion region. Heat losses reduce the flame velocity and are of special importance in the design of microcombustors. In [5,6,9,11,21], the propagation of a flame along a wall leads to a deceleration or complete extinguishing of the flame. The papers take into account both the thermal effect of the wall and the chemical reactions of the chain termination. Several papers [8, 10, 13, 14, 21] are devoted to the use of various coatings to prevent flame propagation, the effects of gas explosion mitigation and the suppression of smoke formation.

This work presents an experimental study of hemispherical flame propagation in a hydrogen–air mixture. The flame propagates over a solid aluminium wall or a layer of steel wool. The velocities of the flame propagation are compared at flame radii up to 0.4 m.

2. Experimental details

The experimental stand is a metal frame that confines the cylindrical envelope to a diameter of 1.5 m and 2.4 m in height of high-density polyethylene (HDPE) 100 µm thick (figure 1). The top of the cylinder was closed with a thin (100 µm) rubber shell. The bottom of the construction was closed with an aluminium plate. In the experiments with steel wool it was covered with a 50 mm layer of steel wool. The density of steel wool was 157 kg/m$^3$, the average transverse fiber size was 56 µm. The construction was placed inside an explosion chamber, VBK–2, which is part of the Moscow Regional Explosive Centre for Collective Use. The envelope was filled with a hydrogen–air mixture with a hydrogen content of 15% at normal atmospheric pressure at a temperature of $T \approx 293$ K. The filling was carried out as follows. In the shell, initially filled with air, the necessary amount of hydrogen (0.686 m$^3$) was added. The gas in the shell was mixed with a stirring fan 200 mm in diameter, providing a flow velocity of 5 m/s. After 1 hour of mixing, the fan was stopped. The error of the mixture composition was 0.3%. The flame was ignited 0.5 hours after the stirring fan was stopped. Ignition was performed with the explosion of a thin nichrome wire 0.1 mm in diameter, 10 mm in length, placed between two steel electrodes 4 mm in diameter at the bottom of the cylinder. The energy released on the wire was 5 J. In all experiments, the distance from ignition point to the surface remained unchanged and amounted to 100 mm. To measure the flame propagation speed, an ir InfraTec ImageIR 8320 camera with a spectral range of 2–5.7 µm was used. The water formed during the oxidation of hydrogen emits radiation with a characteristic maximum at a wavelength of 2.8 µm. Thus, the object captured by the ir camera is the flame front.

3. Experimental results

The sequence of frames demonstrating the flame propagation is displayed in figure 2. The images presented in figure 2 demonstrate a globally hemispherical flame front with perturbations at all time moments observed. The pictures show that at the propagation of the flame in mixtures with hydrogen content of 15% the envelope does not rupture during the flame propagation. The experimental flame propagation radii time dependences can be determined from the experimental image sequences. The flame front radius was measured in a vertical direction upward and in the horizontal direction both to the left and to the right of the ignition point. At a flame front radius of 0.2 m and higher, the standard deviations from the mean values of the radius for three
Figure 1. Experimental setup scheme: 1—HDPE envelope; 2—ignition wire; 3—steel wool layer (aluminium plate); 4—flame front.

Experiments are less than 3%. For the sideways flame propagation the standard deviations from the mean values are less than 5%. Experimentally obtained mean time dependences of the flame front position for the cases with and without steel wool are presented in figure 3. Figure 4 shows the dependences of the flame velocity in two directions above the steel wool layer and a solid wall in different directions. Due to the short measurement base, the error is significant. Further conclusions about the flame velocity are made on the basis of smooth approximations of the flame propagation trajectories.

Initially, the flame propagates hemispherically. In this case, the horizontal propagation of the flame was accompanied by interaction with the boundary layer on the bottom plate. In figure 3 one can see that at the initial stage the flame along the wall propagates faster than that perpendicular to the wall, i.e., vertically upwards. At a time of 60 ms, the flame radii upward and sideways become equal and are about 450 mm. Further, the flame in the upward direction is rapidly accelerated, and in the sideways direction it slows down. To explain the reason for this difference, one should remember that the volume of combustion products exceeds the volume of the initial fuel mixture. Therefore, the expanding hemispherical front of the flame induces a flow of combustible mixture directed from the point of initiation. With the distance from the flame front, the velocity of this flow falls as the square of the radius. At small radii of the flame front, the velocity in the vicinity of the surrounding shell is small enough. Thus, the walls have practically no effect on the flow ahead of the flame front. With increasing size and velocity of
Figure 2. Infrared images sequence of the hydrogen–air flame propagation over a solid planar surface at time moments of 3.33, 16.67, 30, 43.33, 56.67 and 70 ms (left-to-right, top-to-bottom).

Figure 3. Flame front radius–time plots.

the flame front, the gas velocity near the shell also increases. Since the side walls (polyethylene shell) are not gas permeable and do not change shape up to 100 ms from the ignition (figure 5), the flow deflects and propagates along the walls.

Visible flame velocity consists of the velocity of the gas flow and the velocity of the flame with respect to this flow. When the flame approaches the polyethylene shell, the radial component of the flow velocity near the flame front decreases, and the axial component increases, which leads to deformation of the initially hemispherical flame front. The flame front stretches along
the shell axis (figure 5). In view of the above, a time interval from ignition to 60 ms, when the side walls had no appreciable effect, was considered. It can be seen from figure 4 that when the flame propagates over a layer of steel wool the flame front velocity is lower than in the absence of steel wool. According to Gostintsev [2], the free spherical or cylindrical laminar flames from a weak source of ignition in the absence of any significant external influences become unstable, turbulent and self-accelerating at Reynolds numbers of $10^3$–$10^5$. According to Bradley et al [16] and Kim et al [22] $Pe$ should be higher than the critical one at $Pe_c \sim 100$ for acceleration of the flame front. In all our experiments $Pe$ reaches the critical value at distances less than 10 mm from the ignition source.

4. Discussion

Consider the flame propagation at a segment where the influence of the shell is mild enough. In figure 6 graphs of the flame radius versus time on the specified segment are presented. One can see that in the small dimensions of the combustion products cloud, the horizontal flame size is larger than the vertical one. At the end of the investigated segment, the flame accelerates rapidly upward. At the end of the investigated segment, the radii upward and sideways are equal. The dependencies shown in figure 6 demonstrate the flame acceleration, and this acceleration cannot be described by a simple power law of the form of equation (2). To evaluate the influence of the steel wool layer on the flame acceleration, let us compare the velocities at the time point of 60 ms of the horizontal and vertical part of the flame front. The time point of 60 ms corresponds to the end of the segment under consideration. In the vertical direction, the flame accelerates above the steel wool layer to 5.4 m/s, which is 2.5 times slower than the velocity upward over the solid wall. The regions of the flame front propagating horizontally accelerate above the steel wool layer to 4.2 m/s, which is 1.8 times slower than the one over the solid wall.

As is known, the acceleration of free and semi-confined flames is governed by the development of the flame front surface. For this acceleration, a fractal increase in the flame surface with positive fractal excess is necessary [2]. Fractal development of the flame surface is caused
by the diffusion-thermal, hydraulic (Darrieus–Landau) and Rayleigh–Taylor instabilities. The instabilities develop faster, the higher the flame front velocity. At a self-similar flame propagation according to the power law described by (1), the coefficient determining the velocity according to Gostintsev et al [2] is described by the equation:

$$A = 2 \times 10^{-3} \sigma^2 u_n^2 \chi_m^{-0.5},$$

where $\sigma$ to be coefficient of thermal expansion equal to the ratio of densities of the fresh mixture and burnt gas, $u_n$ to be normal flame velocity, and $\chi_m$ to be fresh mixture thermal diffusivity.

This equation is not ultimate truth, e.g., in [16] for close to a stoichiometric hydrogen–air mixture, the value of $A$ differs from the calculated by (3) 1.66 times. The only indicator that can affect the layer of steel wool is the coefficient of thermal expansion. The remaining parameters are the characteristics of the combustible mixture.

Consideration of the mechanism of the steel wool layer effect on the acceleration of the flame is worth addressing beginning with the heat absorption. During flame propagation, the steel wool does not heat up instantly; therefore, we calculated the absorption of heat by the porous layer. To clarify the peculiarities of heat absorption by steel wool, it is necessary to calculate the Fourier numbers for individual fibers and for the layer as a whole:

$$F_0 = \frac{\kappa \tau}{\rho c L^2},$$

where $\kappa$ to be heat conductivity, $\tau$ to be characteristic time scale, $\rho$ to be density, $c$ to be heat capacity, and $L$ to be characteristic spatial scale.
The heat conductivity of steel wool may be estimated as
\[
\kappa_w = \left( \frac{1 - \varphi}{\kappa_s} + \frac{\varphi}{\kappa_g} \right)^{-1},
\]
where \(\kappa_w\) to be heat conductivity of the steel wool, \(\kappa_s\) to be heat conductivity of the steel, \(\kappa_g\) to be heat conductivity of gaseous phase and \(\varphi\) to be porosity of the layer [23]. Characteristics of porous media such as density and heat capacity are equal to proportional sums of the ones for composing materials. As a characteristic time scale, the flame propagation time until reaching a radius of 0.3 m was chosen. The spatial scale was the fiber thickness and the layer thickness for individual fibers and the steel wool layer, respectively.

Fourier numbers for individual fibers are \(\text{Fo}_f \approx 10^7\), for the layer as a whole are \(\text{Fo}_w \approx 10^{-4}\), and consequently, in calculating the absorption of thermal energy, the steel wool layer may be considered as a continuous medium with constant heat capacity, and thermal conductivity parameters.

To determine the dimensionality of the heat conduction problem, it is necessary to determine the heat wave in metal layer parameters. The thickness of the heated layer propagating in front of the flame is:
\[
\delta \sim \frac{\chi_w}{v},
\]
where \(\chi_w\) to be steel wool thermal diffusivity [24].

Substituting the thermal diffusivity of the steel wool \(\chi = 3.8 \times 10^{-6} \text{ m}^2/\text{s}\) and the average flame propagation velocity \(v = 5 \text{ m/s}\), we get the thickness of the heated layer \(\delta = 7.6 \times 10^{-7} \text{ m}\). The obtained value is 500 times less than the thickness of the flame front in the test mixture. Thus, for the estimate, we can neglect the propagation of heat along the radius of the layer.

Propagation of heat is calculated only in depth. Thus, for each section of the layer, the task of finding the temperature distribution reduces to solving a one-dimensional nonstationary heat

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**Figure 6.** Flame front radius–time plots and time interval under consideration (logarithmic coordinates).
Transfer equation:
\[
\frac{\partial T(x,t)}{\partial t} = \chi \frac{\partial^2 T(x,t)}{\partial x^2}.
\]
(7)

Boundary conditions are given by
\[
\begin{cases}
T(0,t) = T_{\text{out}}, \\
\frac{\partial T(l,t)}{\partial x} = 0,
\end{cases}
\]
(8)
where \(T_{\text{out}}\) to be temperature of combustion products over the layer, and \(l\) to be layer thickness.

Initial condition is as follows:
\[T(x,t_f) = 0,\]
(9)
where \(t_f\) to be flame time of arrival moment.

A general solution of the unsteady heat transfer equation [25]:
\[
T(x,t) = T_{\text{out}} - \sum_{n=0}^{\infty} 2\frac{(T_{\text{out}} - T_0)}{\lambda_n l} \exp \left(-\chi \lambda_n^2 (t-t_f)\right) \sin \lambda_n x,
\]
(10)
where \(\lambda_n = (n + 0.5)\pi/l\).

Heat absorbed by every elementary volume is described by the equation:
\[
\delta Q_{dV} = c_w(T(x,t) - T_0)\rho_w dS dx,
\]
(11)
where \(dS\) to be steel wool area element. Substituting the experimental data and integrating throughout the volume we get an equation of heat absorbed:
\[
Q_{\text{abs}}(R) = C(R)(T(x,t) - T_0),
\]
(12)
where
\[
C(R) = \pi l c_w \rho_w \left( R^2 - \frac{4}{l^2} \sum_{n=0}^{\infty} \int_0^R \exp \left(-\chi \lambda_n^2 (t(R) - t(r))\right) \frac{dr}{\lambda_n^2} \right).
\]

Under the assumption of isobaric combustion of a mixture, the released heat during the reaction for a hemisphere of volume \(V\):
\[
\delta Q_{\text{released}} = q_m m_m,
\]
(13)
where \(q_m\) to be specific heat of the mixture burning, \(m_m = M_m P_m V_m/(9R T_{\text{out}})\) to be mass of the burned mixture, \(M_m\) to be molar mass of the burned mixture, \(P_m\) to be atmospheric pressure, \(V_m\) to be volume of the burned mixture, and \(R\) to be universal gas constant. The heat capacity of the system of combustion products and of the steel wool is equal to the sum of their heat capacities, so the final temperature:
\[
T_{\text{out}} - T_0 = \frac{Q_{\text{released}}}{C(R) - c_m m_m}.
\]
(14)
Solving the system of (12), (14) we obtain
\[
T_{\text{out}} = 0.5 \left[ (T_0 - c_m B) + \sqrt{(T_0 - c_m B)^2 + 4B(c_m T_0 + q_m)} \right],
\]
(15)
where \(B = M_m P_m V_m/(9R C)\):
\[
Q_{\text{released}} = (T_{\text{out}} - T_0) \left( C(R) + \frac{M_m P_m V_m}{9R T_{\text{out}}} \right),
\]
(16)
\[
Q_{\text{abs}} = C(R)(T_{\text{out}} - T_0).
\]
(17)
Figure 7. Dependences of released, absorbed energy and heat of iron oxidation values on the flame radius.

Figure 7 presents the estimated dependences of the released and absorbed energy values on the radius of the hemispherical flame front.

As can be seen from the graph, when the flame front reaches a distance of 0.3 m, the steel wool absorbs about 50% of the released thermal energy. This means that the coefficient of thermal expansion of the gas mixture combustion over the steel wool layer is about half the coefficient of thermal expansion when the flame propagates over the heat-insulating wall. Taking into account the quadratic dependence of the flame velocity on the coefficient of thermal expansion in (3), we obtain a 4-fold reduction of expected flame front velocity. The experiments show a decrease in the speed by a factor of 2.5.

The estimated values of the iron oxidation energy versus flame radius are shown in figure 7. The composition of the mixture becomes closer to the stoichiometric one, but nitrogen from the air remains in the mixture. At the same time, the normal flame velocity of the resulting gas mixture is lower than that of the initial hydrogen–air mixture with a hydrogen content of 15% [26], and the coefficient of thermal expansion of the combustion products is also lower. This causes a decrease in the flame propagation velocity after the consumption of a part of the oxygen on the oxidation of steel wool.

On the other hand, the rough surface of the steel wool layer turbulizes the propagating flame. This increases the surface of the flame front and hence its velocity. Then the steel wool influence should be considered as a competition between suppression and additional acceleration of the flame.

5. Conclusions
Our findings are as follows:

- The layer of steel wool reduces the velocity of hemispherical flame propagation by a factor of 1.8 to 2.5.
• Evaluative thermal calculations have shown that heat absorption by the steel wool layer is enough for the flame velocity change observed in the experiments.

• Steel wool can both slow down the flame by absorbing heat and oxygen, and accelerate it due to the turbulization of the flame at the wall and the energy release during the oxidation of iron.

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