SAFe and Efficient hydrocarbon oxidation processes by KINetics and Explosion eXpertise and development of computational process engineering tools

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Work Package 2
Experiments on explosion safety

Sub Package 2.2
Experimental determination of MIE (minimum ignition energy) and Markstein number

Task 2.2.1
Determination of Markstein Numbers

Deliverable No. 6
Report on experimentally determined Markstein numbers

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Responsible Partner:
Universität Karlsruhe (TH)
Engler – Bunte – Institut
Lehrstuhl und Bereich Verbrennungstechnik
Engler – Bunte – Ring 7
D–76131 Karlsruhe

Authors:
Dipl.-Ing. Maximilian Weiß
Prof. Dr.-Ing. Nikolaos Zarzalis
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1 Introduction

The effect of flame stretch on the laminar flame speed has been investigated by several authors [2, 4, 5, 6, 8, 9]. Markstein numbers, which characterize the influence of flame stretch on the laminar flame speed, have been determined experimentally and theoretically. Nevertheless, this effect has not been investigated sufficiently yet and there exist not enough data.

Moreover, it is necessary to understand the influence of stretch on the laminar flame speed, to be able to set up a universally valid theory for minimum ignition energies. Though it seems to be obvious, that the minimum ignition energy is influenced by initial stretch effects, the Markstein number has not been taken into account in theories of minimum ignition energy. Hence, to have a broad range of experiments on “explosion-safety” and to understand the influence of stretch on minimum ignition energies, it is necessary to determine Markstein numbers.

This deliverable explains the influence of stretch on the laminar flame speed. Markstein lengths are presented for methane-, ethane-, propane- and butane-air mixtures. Additionally, computed deflagrations of spherical flames of methane-air are shown, to understand the influence of stretch on the laminar flame speed and to derive Markstein lengths theoretically.

The measurements of butane-air mixtures and the computer simulations for methane-air were not part of this task and not demanded by the project plan. Nevertheless, we managed to compute spherical flames for methane-air mixtures and we think that the simulations give us valuable information about the influence of stretch on flame speed.
2 Theory

Markstein [1, 2] has been the first who described correlations between stretch effects and the laminar flame speed. He observed cellular structures at laminar flames and discovered that for some problems the stretched local laminar flame speed $S'_n$ is inversely proportional to the local cell radius $r_c$.

$$S'_n(r_c) = S_n(1 + C \frac{\delta_i}{r_c})$$

where $S_n$ is the unstretched laminar flame speed and $C$ a constant.

In the works of Clavin and Williams [4], and Clavin [3] a universally valid relationship between the change in the laminar flame speed and flame stretch rate $\alpha$, that embodies all kinds of stretch effects, has been derived theoretically. For the case of a constant pressure and single adiabatic reaction controlled by the concentration of the deficient reactant, a relationship has been introduced and can be written as

$$S_s - S_n = I_{u_b} \alpha - O(\epsilon^2 S_s)$$

where $S_s$ and $S_n$ are the unstretched and stretched laminar flame speeds, respectively, and $I_{u_b}$ is the burned gas Markstein length. It is supposed, that $\epsilon$, the ratio of laminar flame thickness $\delta_i$ and the length scale of the disturbance $\Lambda$, is much smaller than unity, and the change of the laminar flame speed due to stretch is of first order.

![Fig. 2-1 Flame speed, burning and gas velocities of a planar and spherically expanding flame.](image)

The flame stretch rate $\alpha$ takes into account different effects: strain rate, flame curvature and pressure changes. In the present paper, pressure effects are neglected and only strain and curvature are considered. This chapter explains the differences between burning velocities and flame speeds, and will shortly introduce into the
different kinds of stretch effects. Only outwardly propagating flames, or explosions, ignited from a central point, are considered. The theory explained here is basically taken from the papers of Bardley [5, 7] and Gu et al. [6].

2.1 Laminar flame speed and burning velocities

Fig. 2-1 shows a planar flame propagating within a duct, which is closed on the burned gas side, and a spherically expanding flame. The unstretched laminar flame speed \( S_s \) is the summation of the unstretched laminar burning velocity \( u_l \) and the gas velocity ahead of the flame front \( u_g \):

\[
S_s = u_l + u_g. \tag{2-3}
\]

It can also be expressed by

\[
S_s = \frac{\rho_u}{\rho_b} u_l, \tag{2-4}
\]

where \( \rho_u \) and \( \rho_b \) are the mass densities of the unburned and burned gas, respectively.

The stretched laminar flame speed \( S_n \) of a spherically expanding flame is the summation of the stretched laminar burning velocity \( u_n \) and the gas velocity ahead of the flame front \( u_g \) due to flame expansion:

\[
S_n = u_n + u_g. \tag{2-5}
\]

Considering spherical flame propagation, the rate of burning can be expressed as the rate of consumption of reactants and is written as

\[
\frac{dm_u}{dt} = -4\pi r_n^2 \rho_u u_n, \tag{2-6}
\]

where \( \rho_u \) and \( r_n \) are the initial unburned gas density and the so-called flame cold front radius, respectively, and \( m_u \) is the mass of unburned gas. The rate of consumption of reactants can also be calculated by integration over the burned gas side and can be written as

\[
\frac{dm_u}{dt} = -\frac{d}{dr} \left( \int_0^{r_n} 4\pi r^2 \rho(r) dr \right), \tag{2-7}
\]

where \( \rho \) is the density at radius \( r \).

From Eqs. (2-6) and (2-7) the equation for the stretched laminar burning velocity can be derived:

\[
u_n = \frac{1}{r_n^2 \rho_o} \frac{d}{dr} \left( \int_0^{r_n} r^2 \rho(r) dr \right). \tag{2-8}\]

As \( r_n \) is the radius of the flame cold front, the gas within the sphere of radius \( r_n \) can be regarded as a mixture of burned gas at its adiabatic temperature with a density of \( \rho_b \)
and unburned gas with a density of \( \rho_u \). The fractions of burned and unburned gas can then be written as
\[
y_{b(r)} = \frac{\rho_y - \rho_u}{\rho_y}, \quad y_{u(r)} = \frac{\rho_y - \rho_y}{\rho_y},
\]
respectively, inserted into Eq. (2-8), this yields to
\[
\frac{u}{r_u \rho_y} \frac{d}{dt} \left( \int_0^r r^2 \rho_y y_{u(r)} dr + \int_0^r r^2 \rho_y y_{b(r)} dr \right).
\]
The first term on the right represents the rate of entrainment by the flame front of gas that is as yet unburned, the second the rate of formation of burned gas. Hence, \( u_u \) is a burning velocity, which expresses the formation of completely burned gas behind the flame front and the rate of entrainment of gas by the flame front that has still to be burned.

Therefore it is necessary to define a mass burning velocity \( u_n \), which involves only the rate of formation of burned gas:
\[
\frac{u}{r_u \rho_y} \frac{d}{dt} \int_0^r r^2 \rho_y y_{b(r)} dr.
\]
The mass burning velocity \( u_n \) can be determined from measurements of pressure rises in closed vessels, whereas with schlieren photographs, as used in this work, the flame speed \( S_u \) is determined.

2.2 Flame stretch rates

The flame stretch rate is defined by the fraction of change of a flame surface element \( A \):
\[
\alpha = \frac{1}{A} \frac{dA}{dt}.
\]
For spherically symmetrical flames, the flame surface area \( A \) is identified by the flame cold front radius \( r_u \), and the total stretch rate can be calculated with the stretched flame speed \( S_u \): and the flame cold front radius \( r_u \):
\[
\alpha = \frac{1}{A} \frac{dA}{dt} = \frac{1}{4 \pi r_u^2} \frac{d}{dt} \left( \frac{4 \pi r_u^2}{4} \right) = \frac{2}{r_u} S_u \quad \text{with} \quad S_u = \frac{dr_u}{dt}.
\]
A flame front propagation in a non-uniform flow is subject to strain and curvature effects which lead to changes in flame area. These changes are measured by stretch [9]. The total stretch rate \( \alpha \) can therefore be divided into the stretch rate due to flame curvature \( \alpha_c \) and the stretch rate due to strain \( \alpha_s \) [10]:
\[
\alpha = \alpha_c + \alpha_s.
\]
The strain effect characterizes the stretch due to flame expansion and is calculated with the gas velocity \( u_g \). The curvature effect emerges from the burning velocity \( u_u \):
As experimentally only the total stretch rate $\alpha$ can be measured and a differentiation between $\alpha_c$ and $\alpha_s$ is not possible, this work will only characterize the stretch by the total stretch rate $\alpha$.

### 2.3 Burned gas Markstein length and Markstein number

Markstein lengths characterize the variation in the local burning velocities or flame speed due to the influence of stretching. There exist linear relationships between stretch rates and the changes in flame speed or burning velocities. Apparently, there exist different Markstein lengths for strain rate and curvature. This work concentrates on the determination of the burned gas Markstein length $L_b$, which characterizes the linear relationship between the total stretch rate $\alpha$ and the change in the flame speed as (see also Eq. (2-2)):

$$S_v - S_u = L_b \alpha.$$  \hspace{1cm} (2-16)

The dimensionless Markstein number $Ma$ can be derived from the Markstein length $L_b$, normalized by the characteristic laminar flame thickness $\delta_l$:

$$Ma = \frac{L_b}{\delta_l}.$$  \hspace{1cm} (2-17)

The flame thickness $\delta_l$ can be calculated with the kinematic viscosity $\nu$ and the unstretched laminar burning velocity $u_l$:

$$\delta_l = \frac{\nu}{u_l}.$$  \hspace{1cm} (2-18)
3 General procedure and data analysis

Methane, ethane, propane and butane-air mixtures were studied experimentally at initial pressure of 1 bar and temperature of 294 K. The influence of pressure was investigated with methane-air mixtures. Additionally, simulations were performed with methane-air mixtures to study the influence of pressure and to determine the influence of stretch on burning velocities.

3.1 Measurement technique

Laminar flame speeds and burned gas Markstein lengths were derived from spherically expanding flames ignited by two electrodes in the centre of an explosion vessel, which has a volume of 4.2 l and optical access through two windows. The mixtures were prepared with mass-flow controllers and verified with a gas analysis. Pressure and temperature were measured immediately before the ignition. The flame progress was recorded by schlieren photography with a digital high-speed camera at 12 000 frames per second.

![Fig. 3-1 Schlieren photos of a laminar methane-air mixture deflagration ignited by electrodes.](image)

Fig. 3-1 shows schlieren photos of an explosion of a methane-air mixture recorded with a digital high-speed camera. A program was developed to analyse the pictures and to hand out the radius of the flame for each time step. The pictures show, that the explosion was influenced by the electrodes. Therefore, the radius orthogonal to the electrodes was used to analyse the progress of the deflagration. In the present study it is assumed that the schlieren front radius $r_{sch}$ is equal to the cold front radius $r_u$. This
is not absolutely correct as the schlieren front radius approximates the 450 K isotherm and not the cold front of the flame. It has been shown \[5\], that \( r_s \) is related to \( r_{sch} \) by

\[
r_v = r_{sch} + 1.95\delta \left( \frac{P_s}{P_f} \right)^{0.5}.
\] (3-1)

Nevertheless, this is neglected here, as this relation has only been proved for methane and the occurring error is small.

3.2 Simulation program

The simulation program INSFLA \[11\] was used to analyse stretch effects and to determine Markstein lengths theoretically. The simulations of INSFLA are restricted to one-dimensional geometries (infinite slab, infinite cylinder or sphere) and are simplified by using the ideal gas law. The program solves the conservation equations of continuity, species mass, momentum and energy of the corresponding system. The convective terms of the conservation equations are eliminated by a transformation to Lagrangian coordinates \[12\]. Spatial discretization using finite differences leads to a system of coupled differential and algebraic equations that are solved numerically by an extrapolation code called LIMEX \[13\]. After each time step a new grid point system is calculated and the mesh is automatically adapted to the flame front in order to have a higher density of grid points in the reaction zone.

In the present computations spherical geometry is calculated with usually 130 grid points. Uniform and isobar pressure is assumed. Symmetry conditions are used as the boundary conditions at \( \psi = 0 \), the centre of the reaction vessel:

\[
r = 0, \quad \frac{\partial T}{\partial \psi} = 0, \quad \frac{\partial w_i}{\partial \psi} = 0.
\]

At \( \psi = \psi_0 \), the outer boundary, conditions are simplified by assuming zero gradients of temperature and mass fraction:

\[
r = R_0, \quad \frac{\partial T}{\partial \psi} = 0, \quad \frac{\partial w_i}{\partial \psi} = 0.
\]

A full kinetic scheme for C1 with 56 species and 311 reactions was adopted for the simulations demonstrated in the present study. The spherically expanding methane-air flames were computed up to a radius of 5 cm. The mixtures were ignited by an energy source in the centre of the system. The ignition energy \( E_i \) was discharged within the ignition radius \( r_i \) and ignition time \( \tau_i \).
The temperature profile and mass fractions of CH₄, CO₂ and CH₃ of a spherical laminar methane-air flame plotted against the radius and at 1.5 ms after ignition can be seen in Fig. 3-2.

The integrations of Eq. (2-10) and Eq. (2-11) were used to get the stretched burning velocity $u_s$ and the stretched mass burning velocity $u_{mr}$ for each time step. The cold front radius $r_a$ was identified by the isotherm 5 K above the temperature of the unburned gas $T_u$. The stretched flame speed $S_a$ was found from the computed cold front radius $r_a$ versus time data and the stretch rate $\alpha$ with Eq. (2-13).

Fig. 3-3 Comparison of burned gas Markstein lengths calculated with INSFLA and values of Bradley et al. [5].
The burned gas Markstein lengths calculated with INSFLA are in good agreement with the computed values of Bradley et al. [5] (see Fig. 3-3). Only the values at an equivalence ratio of $\phi=1.33$ are unequal. Bradley et al. used for their computations a reduced mechanism whereas for the calculations in this work a complete mechanism was adopted.
3.3 Influence of ignition energy and data interpretation

Spark discharge creates an outward propagating shock wave, followed by a slower thermal wave.

![Fig. 3-4 Computed flame speeds \(S_n\) of spherical flames of methane-air plotted against radius \(r_u\) for different ignition energies \(E_i\).](image)

The thermal front has a high propagating speed, which rapidly decreases. It is necessary to know up to what radius flame propagation is influenced by the ignition. The influence of ignition energy \(E_i\) on the flame speed is demonstrated in Fig. 3-4. The flame speed \(S_n\) is plotted against \(r_u\) for spherical flames ignited with different energies \(E_i\). The ignition energy could not be increased further than 2 mJ, as the temperature of the initial plasma reached already 10 000 K and the used mechanism did not work with higher temperatures. Nevertheless, it can be seen, that the flame speed is influenced by the ignition energy but at a radius of more than approximately 6 mm the propagation speed becomes independent. This has also been shown by Bradley et al. [5]. The flame speed first decreases as the effect of the spark decays and attains a minimum before the flame chemistry is fully developed. Hence, flames with radii smaller than 6 mm were not considered to be fully developed and were not used for the determination of Markstein lengths.
Shown in Fig. 3-5 are measured values of the flame speed $S_n$ plotted against the radius $r$ and $\alpha$. The spark energy was for all experiments just sufficient to cause ignition and flames were only analysed beyond a radius of 6 mm. The values were fitted by a polynomial and plotted against the total stretch rate $\alpha$. The gradient gives the Markstein length $L_0$, and the extrapolation of the data to zero stretch rate yields $S_n$. Latter values are not presented in the present study. It has been shown [14] that the linear extrapolation to stretch rate zero is not always correct. Others have shown that the laminar flame speeds determined with the linear extrapolation to stretch rate zero of spherically expanding methane-air flames are in good agreement with the laminar flame speeds determined with other methods [6]. The laminar flame speeds are not presented in this study as this was not part of this task. The flames were observed only up to a radius of 2 cm in order to obtain Markstein lengths. Hence, the error of the laminar flame speeds obtained by a linear extrapolation can be large, as a slight error in the slope of the linear extrapolation causes a large error in the laminar flame speed.
3.4 Comparison of computed and measured burned gas Markstein lengths

The above figure shows measured and computed burned gas Markstein lengths for methane-air mixtures at comparable initial conditions for pressure and temperature. Both, computed and measured values show that the Markstein lengths increase with an increasing equivalence ratio and the tendencies and values are in good agreement. Therefore, measured and computed results are comparable and can together be used for the interpretation of stretch effects on the laminar flame speed and burning velocities.
4 Results

4.1 Stretched burning velocities and burned gas Markstein lengths for methane-air mixtures

The Markstein lengths $L_h$ for methane-air mixtures at an initial temperature of 294 K and initial pressures of 1 and 1.5 bar are shown in Fig. 4-1. All Markstein lengths are positive, which means, that stretch has an adverse effect on the stretched flame speed $S_n$. The Markstein length $L_h$ increases with $\Phi$, whereas increasing the pressure results in a decrease in $L_h$.

![Fig. 4-1 Experimentally determined burned gas Markstein lengths for methane-air mixtures at two different pressures.](image)

![Fig. 4-2 Computed stretched burning velocities for methane-air mixtures at different stretch rates and three different equivalence ratios.](image)
The burning velocities of three spherical flames at the equivalence ratios 0.8, 1 and 1.25 are plotted against the stretch rate \( \alpha \) in Fig. 4-2. The influence of stretch on the burning velocities is demonstrated and differences between \( u_n \) and \( u_{nr} \) can be seen clearly. The burning velocity \( u_n \), which expresses the formation of completely burned gas behind the flame front and the rate of entrainment of gas by the flame front, always increases with stretch. The mass burning velocity \( u_{nr} \), which is only related to the production of burned gas, always decreases with stretch. The differences demonstrate the influence of the flame thickness \( \delta_f \). The difference between \( u_n \) and \( u_{nr} \) increases with an increasing stretch rate, as at a large stretch rate the radius is small and the flame thickness is of comparable order as the radius. This effect can be seen at all equivalence ratios. As the influence of the flame thickness vanishes with decreasing stretch, the burning velocities \( u_n \) and \( u_{nr} \) of a flame extrapolated to zero stretch yields the same value, the unstretched laminar burning velocity \( u_l \).

![Fig. 4-3 Computed stretched burning velocities for methane-air mixtures at different stretch rates and three different pressures.](image)

The influence of pressure on the burning velocities can be seen in Fig. 4-3. The burning velocities decrease with increasing the pressure. Since the flame thickness decreases with pressure, the difference of \( u_n \) and \( u_{nr} \) decreases too.
4.2 Comparison of burned gas Markstein lengths of CH₄-, C₂H₆-, C₃H₈-, and C₄H₁₀-air mixtures

All burned gas Markstein lengths $L_b$ presented in this chapter were measured at an initial pressure of 0.998 bar and temperature of 294 K. The variation of the Markstein lengths of C₂H₆-, C₃H₈- and C₄H₁₀-air mixtures with the equivalence ratio are compared with those of CH₄-air mixtures in Fig. 4-4, Fig. 4-5 and Fig. 4-6, respectively. The symbols are the values of the measurements; the lines are polynomial fits showing the tendencies of the measurements more clearly.

![Graph showing variation of burned gas Markstein length $L_b$ for CH₄- and C₂H₆-air mixtures with equivalence ratio.]

As already explained in chapter 4.1, the Markstein length of methane-air mixtures increases with an increasing equivalence ratio. For ethane-air, propane-air and butane-air mixtures, the Markstein lengths decrease with an increasing equivalence ratio. This can be seen most clearly in Fig. 4-5 and Fig. 4-6. The Markstein lengths of ethane-, propane- and butane-air mixture at $\Phi =$1 are 3 mm, 6 mm and 12 mm, respectively, whereas the Markstein length for the methane-air mixture is 0.5 mm.
It can also be seen, that with an increasing carbon number of the fuel gas, the Markstein lengths increase for mixtures with $\Phi < 1.2$. For equivalence ratios of $\Phi > 1.3$, the Markstein lengths for methane-air mixtures become larger. At $\Phi = 1.4$, the Markstein lengths of ethane-, propane and butane-air mixtures are close together, between 1.5 and 2.5 mm, whereas the one for the methane-air mixture is about 16 mm.
Measurements with an equivalence ratio of more than 1.6 were only possible for butane-air mixture. At $\Phi = 1.7$ the Markstein length $L_{m}$ becomes negative, which means, that the flame is accelerated by stretch.

A laminar flame is maintained by molecular-diffusive transport processes. The transport processes of planar and stretched flames differ:

a) Heat transport

Heat transport takes place within the flame front from the reaction zone to the preheat zone of the laminar flame. Considering spherically expanding flames, defocusing of the heat occurs and the heat flux is increased, as the area of the preheat zone is larger than the area of the reaction zone. This leads in comparison to planar flames to a lower integral temperature within the reaction zone. Because of the exponential temperature dependency of the burning velocity, the laminar flame speed is always decelerated by positive stretch.

b) Transport of mass species

On the other hand focusing of mass species of oxygen and fuel from the preheat zone to the reaction zone takes place, as the area of the preheat zone is larger than the area of the reaction zone. The influence of the mass diffusion is more complicated than the influence of the heat transport, as the transport of oxygen and fuel are superposed and both the concentration of oxygen and the concentration of fuel in the reaction zone influence the burning velocity of the stretched flame. “Preferential diffusion” is a frequently used term for the interaction of stretch effects and molecular transport. Four cases have to be considered:

1) $\Phi < 1, \; D_{O_{2}...Air} > D_{Fuel...Air}$

The faster diffusion of oxygen from the preheat zone leads to a leaner mixture in the reaction zone. As the unstretched mixture in the reaction zone is already lean, the burning velocity of spherically expanding flames is decelerated and the Markstein length becomes larger with a decreasing equivalence ratio $\Phi$: $\Phi \downarrow \Rightarrow Ma \uparrow$.

2) $\Phi < 1, \; D_{O_{2}...Air} < D_{Fuel...Air}$

The faster diffusion of fuel from the preheat zone leads to a richer mixture in the reaction zone. As the unstretched mixture in the reaction zone is lean, the burning velocity of spherically expanding flames is accelerated and the Markstein length becomes smaller with a decreasing equivalence ratio $\Phi$: $\Phi \downarrow \Rightarrow Ma \downarrow$. 
3) $\Phi > 1$, $D_{O_2-Air} > D_{Fuel-Air}$

The faster diffusion of oxygen from the preheat zone leads to a leaner mixture in the reaction zone. As the unstretched mixture in the reaction zone is rich, the burning velocity of spherically expanding flames is accelerated and the Markstein length becomes smaller with an increasing equivalence ratio $\Phi$: $\Phi \uparrow \Rightarrow Ma \downarrow$.

4) $\Phi > 1$, $D_{O_2-Air} < D_{Fuel-Air}$

The faster diffusion of fuel from the preheat zone leads to a richer mixture in the reaction zone. As the unstretched mixture in the reaction zone is already rich, the burning velocity of spherically expanding flames is decelerated and the Markstein length becomes larger with an increasing equivalence ratio $\Phi$: $\Phi \uparrow \Rightarrow Ma \uparrow$.

To understand the measured Markstein lengths for methane-, ethane-, propane- and butane-air mixtures, it is necessary to know qualitatively the diffusion coefficients of the different species:

$$D_{CH_4-Air} > D_{O_2-Air} > D_{C_2H_6-Air} > D_{C_3H_8-Air} > D_{C_4H_{10}-Air}.$$ 

Case 1 (for lean mixtures) and case 3 (for rich mixtures) are valid for the ethane-, propane- and butane-air mixtures, whereas case 2 (for lean mixtures) and case 4 (for rich mixtures) are valid for methane-air mixtures. The described influence of the equivalence ratio on the Markstein length can be seen clearly. The Markstein lengths of methane-air mixtures increase with an increasing equivalence ratio, whereas Markstein lengths for ethane-, propane- and butane-air mixtures increase with a decreasing equivalence ratio. It can also been seen clearly, that the influence of stretch on butane flames is stronger than on ethane flames, as the diffusion of butane is much slower than the diffusion of ethane.

Apparently, the influence of stretch on the heat transport dominates the measured flames, as the Markstein length is positive for the flames of case 2 and 3. Only the rich butane flames (case 3) have negative Markstein lengths.
5 Conclusion

The present report documents the influence of stretch on the laminar flame speed. Markstein lengths have been determined theoretically for methane-air mixtures and experimentally for methane-, ethane-, propane- and butane-air mixtures. The influence of stretch on heat and mass transport has been explained and the influence of the equivalence ratio on the Markstein length for the different fuel-air mixtures could be explained qualitatively.

The experimental results and the simulations of this report will be used to understand the influence of the Markstein number on minimum ignition energy. As the minimum ignition energy is influenced by stretch, the present results of the Markstein lengths are necessary to set up an analytical model for minimum ignition energies.

The computations which could be carried out on top of the originally planned part of the task, did show that simulation is a helpful tool to understand the influence of stretch on the laminar flame speed, and it has been demonstrated, that Markstein lengths can be predicted. They form also a first step to the tasks in Work package 3 “Modelling/Prediction of Explosion Indices”.

Listings

L.1 Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$m^2$ flame surface area</td>
</tr>
<tr>
<td>$C$</td>
<td>constant number</td>
</tr>
<tr>
<td>$E_i$</td>
<td>$J$ ignition energy</td>
</tr>
<tr>
<td>$D$</td>
<td>$m^2/s$ diffusion coefficient</td>
</tr>
<tr>
<td>$I_b$</td>
<td>$m$ burned gas Markstein length</td>
</tr>
<tr>
<td>$Le$</td>
<td>Lewis number</td>
</tr>
<tr>
<td>$Ma$</td>
<td>Markstein number</td>
</tr>
<tr>
<td>$m_u$</td>
<td>$kg$ mass of unburned gas</td>
</tr>
<tr>
<td>$r_c$</td>
<td>$m$ cell radius</td>
</tr>
<tr>
<td>$r_i$</td>
<td>$m$ radius of the ignition energy input</td>
</tr>
<tr>
<td>$r_{sch}$</td>
<td>$m$ schlieren front radius</td>
</tr>
<tr>
<td>$r_u$</td>
<td>$m$ flame cold front radius</td>
</tr>
<tr>
<td>$S_n$</td>
<td>$m/s$ stretched laminar flame speed</td>
</tr>
<tr>
<td>$S_s$</td>
<td>$m/s$ unstretched laminar flame speed</td>
</tr>
<tr>
<td>$T_b$</td>
<td>$K$ temperature of the burned gas</td>
</tr>
<tr>
<td>$T_u$</td>
<td>$K$ temperature of the unburned gas</td>
</tr>
<tr>
<td>$u_g$</td>
<td>$m/s$ gas velocity ahead of the flame front</td>
</tr>
<tr>
<td>$u_i$</td>
<td>$m/s$ unstretched laminar burning velocity</td>
</tr>
<tr>
<td>$u_n$</td>
<td>$m/s$ stretched laminar burning velocity</td>
</tr>
<tr>
<td>$u_{nr}$</td>
<td>$m/s$ stretched mass burning velocity</td>
</tr>
<tr>
<td>$w_i$</td>
<td>mass fraction of species $i$</td>
</tr>
<tr>
<td>$y_b$</td>
<td>fraction of burned gas</td>
</tr>
<tr>
<td>$y_u$</td>
<td>fraction of unburned gas</td>
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Greek

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$1/s$ flame stretch rate</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>$1/s$ stretch rate due to flame curvature</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>$1/s$ stretch rate due to strain</td>
</tr>
<tr>
<td>$\delta_i$</td>
<td>$m$ characteristic laminar flame thickness</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>ratio of flame thickness $\delta_i$ and length scale of disturbance $\Lambda$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$m$ length scale of disturbance</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>$s$ duration of the ignition energy input</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$m^2/s$ kinematic viscosity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$kg/m^3$ mass density</td>
</tr>
<tr>
<td>$\rho_b$</td>
<td>$kg/m^3$ burned gas mass density</td>
</tr>
<tr>
<td>$\rho_u$</td>
<td>$kg/m^3$ unburned gas mass density</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>equivalence ratio</td>
</tr>
</tbody>
</table>
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