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Laminar Burning Velocity of Lean Methane/Air Flames under Pulsed Microwave Irradiation

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Abstract: Laminar burning velocity of lean methane/air flames exposed to pulsed microwave irradiation is determined experimentally as part of an effort to accurately quantify the enhancement resulting from exposure of the flame to pulsed microwaves. The experimental setup consists of a heat flux burner mounted in a microwave cavity, where the microwave has an average power of up to 250 W at an E-field in the range of 350–380 kV/m. Laminar burning velocities for the investigated methane/air flames increase from 1.8 to 12.7% when exposed to microwaves. The magnitude of the enhancement is dependent on pulse sequence (duration and frequency) and the strength of the electric field. From the investigated pulse sequences, and at a constant E-field and average power, the largest effect on the flame is obtained for the longest pulse, namely 50 µs. The results presented in this work are, to the knowledge of the authors, the first direct determination of laminar burning velocity on a laminar stretch-free flame exposed to pulsed microwaves.

Keywords: pulsed microwave; electric field; heat flux method; plasma assisted combustion; laminar burning velocity

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1. Introduction

The modification of combustion processes by application of external electric fields has been investigated by scientists for more than a century. In recent decades, the efforts have intensified, since plasma-assisted combustion is considered to have potential for improving combustion efficiency and decreasing hazardous pollutants. These combustion improvements are to a large extent related to the extension of the flammability range, better allowing fuel lean combustion. External electric fields can affect the combustion process by reducing ignition delay time or by coupling with the reaction zone, resulting in increased flame propagation speed and flame stabilization, thereby preventing or delaying extinction [1–5]. In the present work, the focus is on laminar, stretch-free, premixed flames, and the increase in laminar burning velocity. For further details on the effects of plasma on ignition and extinction, we refer the reader to the review by Ju and Sun [1] and references therein.

Early studies on flame propagation speed for flames exposed to DC electric fields show contradictory results, some indicating an increase [6] while others report on virtually no effect [7,8]. Inspired by a theoretical paper by Ward [9], the effects of microwave radiation on flames were investigated, but still with ambiguous results [10,11]. More recent experimental works are, however, in agreement regarding the fact that application of external electric fields enhances flame propagation, as outlined in the introduction of the paper by Stockman et al. [12]. The origin of the effect and the magnitude of the increase does, however, vary between studies. This is a result of the fact that the studies do not cover the same conditions neither when it comes to flame properties nor electric field strength and type. In addition, experimental challenges hamper the accuracy and the interpretation of the results.

An inherent difficulty affecting the experimental design and interpretation of results is the fact that the increased flame propagation speed can be a result of three different effects [1]: ionic wind, Ohmic heating, and kinetic enhancement by non-thermal electrons. These three mechanisms commonly operate in parallel, and their relative contribution is not fully understood in most of the published experimental data. Modeling studies are used to investigate the underlaying mechanisms and attempts are made to reproduce experimental results using one-dimensional simulations [13]. While these efforts are valuable, and are important steps towards a complete understanding, a weakness is still the relatively large amount of uncertainty in published experimental data. As pointed out by Stockman et al. [12], the research progress has been constrained by the difficulty to produce an experimental set-up that allows microwave stability and the simultaneous employment of accurate combustion diagnostics.

Microwave irradiation has been proposed as a promising way to increase concentration and reactivity of ionic, atomic, and molecular species in the flame. A scientific motivation for recent focus on experimental configurations employing microwave irradiation is that, here, one of the three enhancement factors, ionic wind, is not present [1]. Ionic wind is a mechanism where ions in a flame are accelerated by an electric field and these ions transfer momentum by collisions to neutral particles. This effect is restricted to DC fields or low frequency electric fields, while an experimental design using microwaves (MW), with oscillating frequencies in the GHz range, does not induce ionic wind. Hence, merely kinetic and thermal effects are promoted using microwave stimulation. The thermal effect is here referred to as gas heating, where electrons gain energy in the electric field, and this energy is transferred to thermal energy in neutral species by collisions. Important chain branching chemical reactions in the flame are highly temperature dependent and the gas heating thus accelerates the reactivity and increases flame propagation. The kinetic, non-thermal, plasma enhancement is due to kinetic flame enhancing effects when electric stimulation creates new chemical reaction pathways and reduces the chemical time-scales [1]. The electric energy accelerates free electrons produced in background chemionization reactions. These free electrons initiate the plasma chemistry through collisions and result in electron impact ionization and dissociation reactions producing radicals and excited species.

As mentioned above, experimental data published in the open literature are scattered. Variation in results can be a result of differences in flow field induced by various flame configurations, or variations in the type and strength of the E-field. Most of the earliest studies of plasma-enhanced flames used DC electric fields [6–8,14], while, in the early 1980s, more attention was turned towards microwave-enhanced flames [9–11,15]. Most studies target electric fields at the flame front to be below the breakdown threshold.

In the following, we provide a brief review of recent studies which reported increased laminar burning velocities as a result of microwave radiation. We focus on studies published during the last ten years, and, for overviews of earlier works, we refer to recent reviews [1–4]. Some of the experimental studies employing continuous and pulsed microwaves, presenting the detection or quantification of flame propagation speed increase, are summarized in Table 1. A summary of the results from the present study is also presented in Table 1 to allow easy comparison with previous works.

Table 1. Literature studies reporting on enhanced laminar burning velocity of methane/air flames as a result of microwave irradiation publications after 2000. LP—Laminar Premixed; SFF—Stagnation Flat Flame; SPF—Spherically Propagating Flame; PIV—Particle Image Velocimetry; LS—Laser Shadowgraphy.

Authors	Flame Config. and Diagnostics Tools	Power (W)	Microwave	E-Field Strength (kV/m)	ϕ	Flame Enhancement
Zaidi et al. [16–18]	SFF/PIV	1000–2600	Cont.	200 (max)	0.7	15–68%
Zaidi et al. [16,17]	SFF/PIV	400	Cont.		0.77	21%
Zaidi et al. [16]	SFF/PIV	700, 1200	Cont.		0.74–0.78	8–35%
Stockman et al. [19]	SFF/PIV	25 (average) 30,000 (peak)	Pulsed, 1 µs, 0.1–1 kHz		0.78–0.84	~25%
Stockman et al. [12,20]	SFF/PIV	1300	Cont.	500	0.6–0.8	5–21%
Shinohara et al. [21]	Bunsen	300	Cont.	30.2		19%
Michael et al. [22]	SPF/LS	<30 (average) 30,000 (peak)	Pulsed, 1 µs, 1 kHz		0.63–0.95	10–25%
Present work	Heat flux	<250 (average) <5000 (peak)	Pulsed, 5–50 µs, 1–10 kHz	350–380	0.65–0.75	2–13%

Before examining discussions of experimental conditions and setups, it is necessary to comment on the reliability of the quantification of the increase in flame propagation velocity. Based on the experimental evidence from the works summarized in Table 1, it is beyond doubt that microwave irradiation does enhance flame propagation speed. However, there are significant experimental challenges related to the coupling of a microwave cavity with a suitable burner design, and simultaneous measurement of flame properties without interrupting the flame or the electric field. Due to these complications, the quantification of laminar burning velocity cannot be done with the same stringency as corresponding studies in regular experimental setups. Quantification of flame propagation does instead have to be estimated or determined with a high degree of uncertainty. An example of this is that Michael et al. [22] used "estimates of the increase in the kernel growth rate" in outwardly propagating spherical flames to quantify the increase of laminar burning velocity.

Two significant works in the field include one on the effect of continuous MW by Stockman et al. [12] and another on pulsed MW by Michael et al. [22]. For the pulsed MW enhancement of laminar flame propagation in the range of equivalence ratios from 0.63 to 0.95, the increase is reported to be largest (15–25%) at the lower part of the range, and 10% closer to stoichiometry. Enhancement is achieved within three microwave pulses. Michael et al. [22] reported at least 50% microwave coupling into the flame, with 30% resulting in a direct temperature rise in the flame zone. They reported a 200–400 K increase in the reaction zone temperature, the magnitude varying with microwave pulse energy (25–50 mJ). In the study by Stockman et al. [12], using continuous microwaves at 1300 W, no temperature increase was observed in the reaction zone. Over the equivalence ratio range of 0.65–0.8, Stockman et al. [12] saw a flame speed increase of about 7% at 0.65, increasing to around 15% around 0.7, followed by a slight decrease down to 0.8. Precision in their results is $\pm$2%, but scatter in data is significant. Temperature increase in post-flame gas was measured to be in the range of 100–200 K, likely higher at the higher equivalence ratios. Flame temperature profiles indicated that the microwave energy is deposited at the flame front where electron density is at its highest, and measurements of OH radicals support the hypothesis that the increased flame propagation is a result of boosted chemical kinetics.

The goal of the research presented in this work and in future projects in the research group is to provide the reliable experimental quantification of laminar burning velocities for flames exposed to pulsed microwaves. This will enable the development of a deeper understanding, particularly when the experimental data are used for the validation of chemical kinetics models for plasma enhanced combustion.

In the present work, laminar burning velocities for lean methane/air flames subject to pulsed microwave irradiation below electric breakdown, are presented. The experiments are performed using a dedicated system, designed to allow quantitative determination of laminar burning velocities. The setup was detailed in a separate publication [23]. The present work is the first experimental campaign utilizing the new experimental configuration for a systematic investigation of laminar flames with pulsed microwave irradiation. The trends of increased laminar burning velocity with microwave irradiation are investigated with respect to equivalence ratio, duration, and repetition rate of the pulsed microwaves, as well as peak and average microwave power.

2. Materials and Methods

2.1. Burner Setup

The experimental setup consists of a perforated plate burner enclosed in a microwave cavity. The setup is described in detail in our previous work, Nilsson et al. [23], and is therefore only briefly outlined here.

This type of burner is designed to stabilize laminar flat flames for laminar burning velocity determinations using the heat flux method [24]. The burner used in the present study followed the basic design of a heat flux burner with a burner plate with a diameter of 30 mm, but with dimensions adjusted to allow coupling with the microwave cavity. The flat burner head forms an almost seamless part of the inner floor of the microwave cavity, where it was mounted at the center, electrically sealed by means of a copper gasket. Advantages of using this type of burner in the present context is the direct determination of laminar burning velocity from the temperature in the burner plate, a method that has been thoroughly characterized and for which uncertainties in measurements and data processing were well investigated [25]. Temperatures were measured during the experiment using eight type-T thermocouples located at different radii (r) in the burner plate, to determine the parabolic coefficent C, as presented by Van Maaren et al. [26]:

$$T_p(r) = T_{center} - \frac{q}{4\lambda h} r^2 = T_{center} + Cr^2 \tag{1}$$

The parabolic coefficient C includes the burner plate properties thermal conductivity (λ) and thickness (h), and the net heat transfer (q) to the burner plate. This definition yields a uniform temperature distribution in the burner plate at $C = 0$, which indicates adiabatic flame conditions. Laminar burning velocities are determined by finding the flow velocity of the unburned gas, V_g, that yields adiabatic flame conditions [25]. Temperature profiles of the burner plate are measured at four different unburned gas velocities that yield close to adiabatic conditions. These temperature profiles are then used to determine the laminar burning velocity, S_L.

The fact that the burner head was enclosed in a microwave cavity, introduced a few complications. First, the metal cavity is a large heat sink, which prolongs the time for the system to equilibrate and reach a state with zero heat flux. Second, the fact that the flame is enclosed in the relatively cold cavity results in condensation of water in the cavity ceiling. The first complication calls for a long experimental time, where the system is given time to equilibrate, while the condensation problem limits the possible experimental time, since, after some minutes, liquid water may disturb the flame. As explained by Nilsson et al. [23], these complications have been thoroughly investigated and an optimal experimental procedure has been established.

2.2. Microwave Setup

The microwave cavity had openings on the side, which were suitable for visual inspection of the flame and to enable various types of optical access. Two electric field probes were placed in the cavity roof for measurements and tuning of the electric field. The center probe was mounted in an aluminum cylinder right above the burner head and was removed and replaced by a chimney when the flame was lit. A tuner was used to match the incoming wave to the cavity and the cavity optimized for 2.45 GHz microwaves by tuning a sliding short. Pulsed microwaves were generated by an analog signal generator (Agilent N5171B), providing a continuous signal into a pulsed microwave amplifier (TMD PTC7352) in the current study. The amplifier is capable of producing 5 kW peak output power at a maximum duty cycle of 5% in the S-band (2–4 GHz), resulting in a maximum average output power of 250 W. The pulse duration and repetition rate of the microwave pulses was varied in the range of 5–50 μs and 1–10 kHz in the current investigation, both set by a waveform generator (Agilent 33500B). The signal from the amplifier was coupled to the cavity employing a circulator (Bonn Elektronik GmbH, Holzkirchen, Germany) that protects the amplifier from reflected power.

2.3. Experimental Procedure and Data Analysis

Experimental conditions for flames exposed to pulsed microwaves, visited in the present study, are listed in Table 2. In addition, laminar burning velocities were determined, without microwaves present in the cavity, for the flame conditions listed in Table 2, to validate the experimental setup and provide a baseline for quantification of laminar burning velocities with microwave stimulation. Details of this procedure are described in the next subsection. All experiments were conducted at room temperature 295 ± 1 K.

Table 2. Experimental conditions investigated in the current study. The equivalence ratio was varied in measurement 1–3, the pulse duration and repetition frequency of the microwave pulses were varied in measurements 4–6, and, in measurement 7–9, the electric field strength was increased compared to the other measurements.

Meas.	ϕ	E_{RMS} (kV/m)	Pulse Length (μs)	Frequency (kHz)	V_g (cm/s)
1	0.65	350	50	1	11.5–13.0
2	0.7	350	50	1	16.0–18.0
3	0.75	350	50	1	21.5–23.5
4	0.7	350	25	2	15.5–17.0
5	0.7	350	10	5	15.5–17.0
6	0.7	350	5	10	17.0
7	0.7	370	25	2	15.5–17.0
8	0.7	370	10	5	17.0
9	0.7	380	10	5	17.0

Figure 1 shows how the parabolic coefficient, C from Equation (1), evolves during an experiment with no microwaves present in the chamber. From the time when the flame is lit, $t = 0$ s, it takes about 25 s until the flame attaches to the burner head. This initiation phase is followed by a slow stabilizing process during which C increases towards a stable value. The leveling out of C indicates that the heat transfer in the system is equilibrating. The experiment has to be terminated after about 3 min to avoid the formation of water droplets through condensation in the microwave cavity. As evident from Figure 1, the value of C is close being levelled out after three minutes, however a fit to the data and extrapolation towards longer times (solid line in Figure 1) shows that the true value of C is slightly higher. For the flames studied in the present work, there is a trend that, at the higher equivalence ratios, the equilibration is faster, and thus the C value at the end of the experimental time is closer to the limiting value at these conditions. A fit of the data points from about 30 s (after the flame is lit) can be used to extrapolate C, as shown by the solid curve in Figure 1. From the expression derived from the fit, a limiting value of C is obtained in the following called "equilibrium value of C".

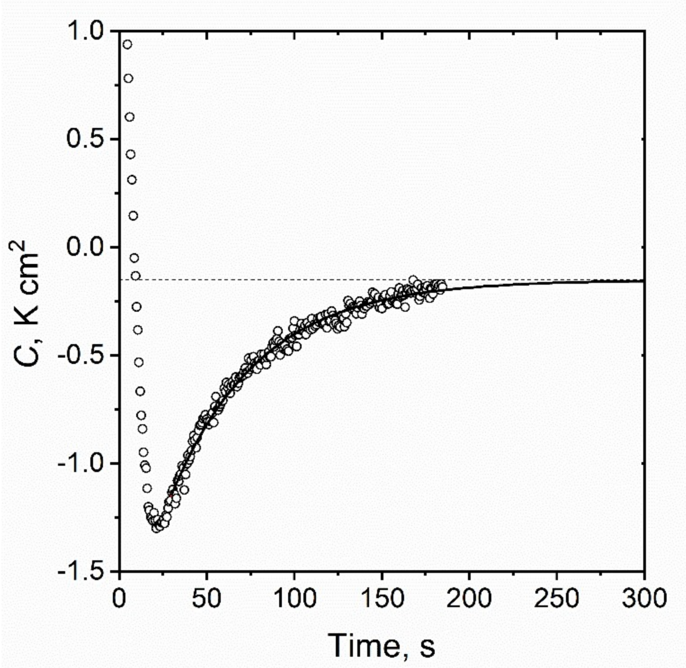

Figure 1. Evolution of coefficient *C* with time in an experiment with a flame at ϕ = 0.7 and V_g = 16.0 cm/s: Symbols represent experiments. Solid line is an exponential fit to the data, starting at *t* = 30 s, and extrapolated beyond the experimental time. Dashed line at *C* = −0.1509 K cm^2 is the value that the *C* coefficient approach according to the fitted curve.

Several experiments have been carried out with different velocities, V_g, of the unburned gas mixture. Equilibrium values of *C* from such experiments are used to find the laminar burning velocity, S_L. An example of this procedure is displayed in m for the lowest equivalence ratio, ϕ = 0.65. To reveal the possible influence of the short experimental time, two sets of symbols and two lines are presented in Figure 2, one for which the equilibrium value of *C* obtained from the extrapolation shown in Figure 1 is used, and the second, where *C* is obtained from taking the mean of the ten final data points of the experimental series (i.e., times around 175 s). Laminar burning velocities with a difference of 0.07 cm/s are obtained for this flame, where the lower value is based on the extrapolation and is therefore considered to be the true value. The difference in laminar burning velocity obtained using the two approaches is significantly smaller than the overall experimental uncertainty.

Experimental uncertainties related to the heat flux method have been thoroughly examined by Alekseev et al. [25]. A source of uncertainty taken into account in the present work is that from scatter in thermocouple reading, a burner specific uncertainty that is evaluated for each data point (*C* value) collected. This uncertainty is taken into account in the exponential fit to data as exemplified in Figure 1, where each data point is assigned a weight based on the error in *C* for that particular point. These uncertainties are in a range from about 0.1 to 0.25 K cm^2.

The laminar burning velocity increases as a flame, stabilized on the burner plate, is exposed to microwaves. This effect is revealed as a decrease in *C* when everything else is kept constant in the experiment. The response can be seen as a rapidly forming well in the *C*-trace, as exemplified by the solid line in Figure 3, where the dotted line is the corresponding experiment without microwaves. In this case, the flame has an equivalence ratio of 0.65 and the unburnt gas velocity is set to 12.0 cm/s.

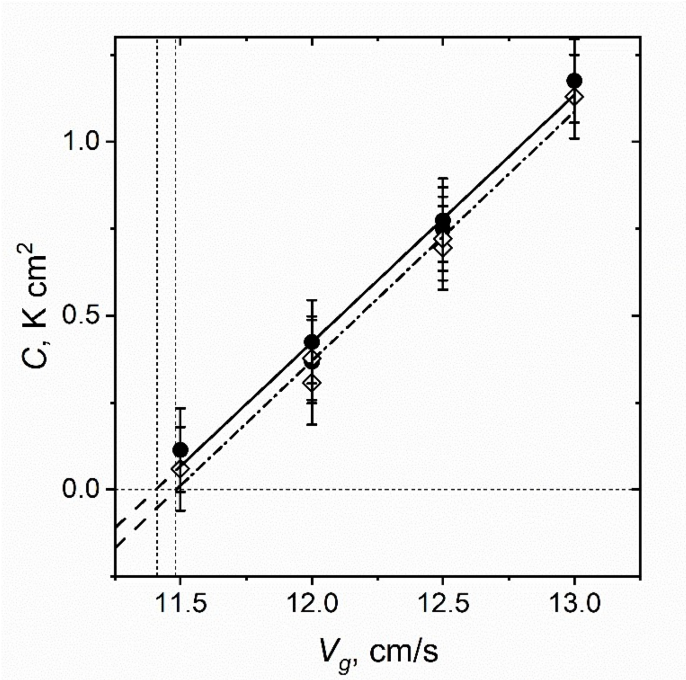

Figure 2. Determination of laminar burning velocity for a flame at ϕ = 0.65, using the mean of *C* coefficients at around 175 s (open symbols and dash-dotted line) and extrapolated *C* (closed symbols and solid line). Error bars include uncertainties in *C* as a result of thermocouple scatter.

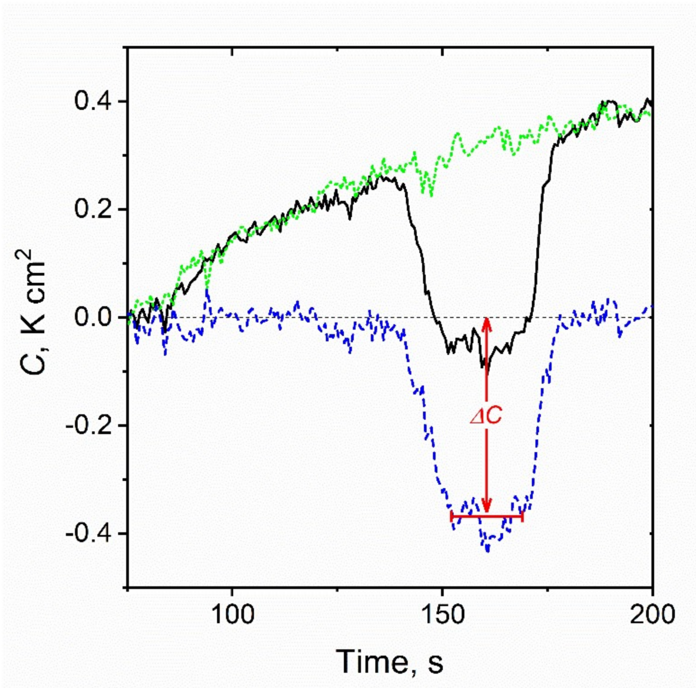

Figure 3. Trace of coefficient *C* for an experiment with a flame at ϕ = 0.65 and V_g = 12.0 cm/s. The solid black line corresponds to data from the flame exposed to pulsed microwaves with a pulse duration of 50 µs and a frequency of 1 kHz at an electric field of E_{RMS} = 350 kV/m. The dotted green line displays the *C*-trace for the corresponding experiment without microwaves and the dashed blue line is the difference between the two.

As explained in relation to Figure 1, the value of *C* is approaching a stable value, but the limitation in experimental time does not allow the heat transfer to reach an equilibrium. Due to these limitations in experimental time, microwave exposure must be done before the *C*-trace is stable, as evident from the rising baselines in the solid black and green dashed lines in Figure 3. This means that the C-values at the bottom of the well in Figure 3, at a stable microwave exposure, cannot reliably be used to quantify the laminar burning velocity. Instead, the information obtained from data, as exemplified in Figure 3, is used to quantify the difference, ΔC, between the response of flames with and without microwaves. This is then put on an absolute basis using values of C calculated from the expression for the slope for the base case without microwaves. To clarify the procedure, it is shown in Figure 3 how the baseline (no microwave case) is subtracted to present the dashed line. The red horizontal line in Figure 3 represents the time when microwaves were constant and affecting a stable flame, an average was taken for the values of ΔC in the interval. Again, ΔC, is a quantification of the decrease in C-coefficient upon microwave exposure.

The procedure is used to evaluate the parabolic coefficient for data obtained over a range of V_g and the values are plotted to obtain laminar burning velocities for the flames exposed to microwaves. An example for a flame at $\phi = 0.75$ is shown in Figure 4, where the dataset is represented by open diamonds and the solid line represents the flame exposed to microwaves.

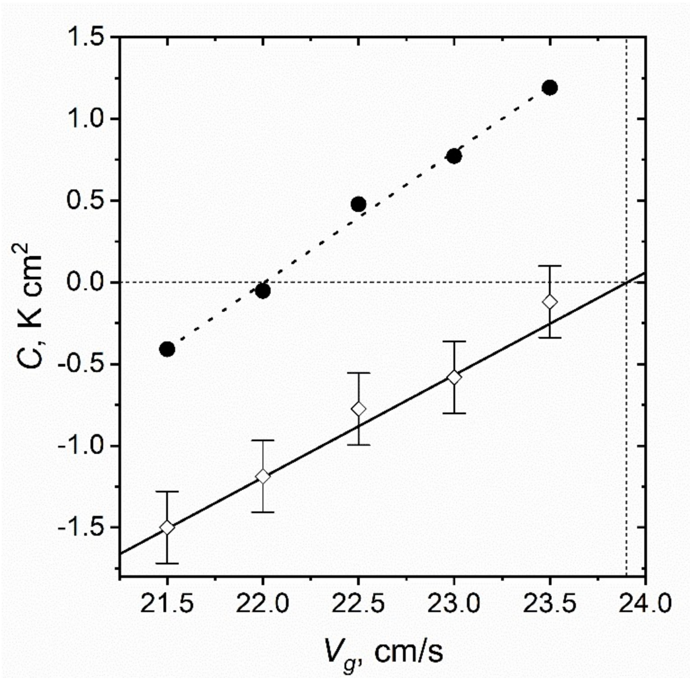

Figure 4. Determination of laminar burning velocity for a flame at $\phi = 0.75$, exposed to pulsed microwaves with a pulse duration of 50 µs and a frequency of 1 kHz at an electric field of $E_{RMS} = 350$ kV/m. Open symbols and solid line represent the data with microwaves and filled symbols and dotted line represent the corresponding flame without microwave exposure.

3. Results

3.1. S_L for Methane/Air at Standard Conditions

The experimental setup was first used to determine laminar burning velocities at standard conditions without microwave irradiation. This is an important validation of the setup and the experimental procedure, and, in addition, the results are used as baseline values for the determination of the enhancement effect in the flames affected by microwaves, presented in a later subsection.

Laminar burning velocities for flames with no microwave stimulation are plotted in Figure 5 for the three lean equivalence ratios. The figure also includes experimental data points from the literature. In general, it is difficult to determine laminar burning velocity at these low flows, which is evident from the spread in literature data. However, the results from the present study are in good agreement with the bulk of the published data. The laminar burning velocities determined here are $S_L(\phi = 0.65) = 11.4 \pm 0.2$ cm/s,

$S_L(\phi = 0.7) = 16.0 \pm 0.2$ cm/s, and $S_L(\phi = 0.75) = 22.0 \pm 0.3$ cm/s, where error bars are resulting from scatter in the thermocouple reading analyzed, as described by Sileghem et al. [27].

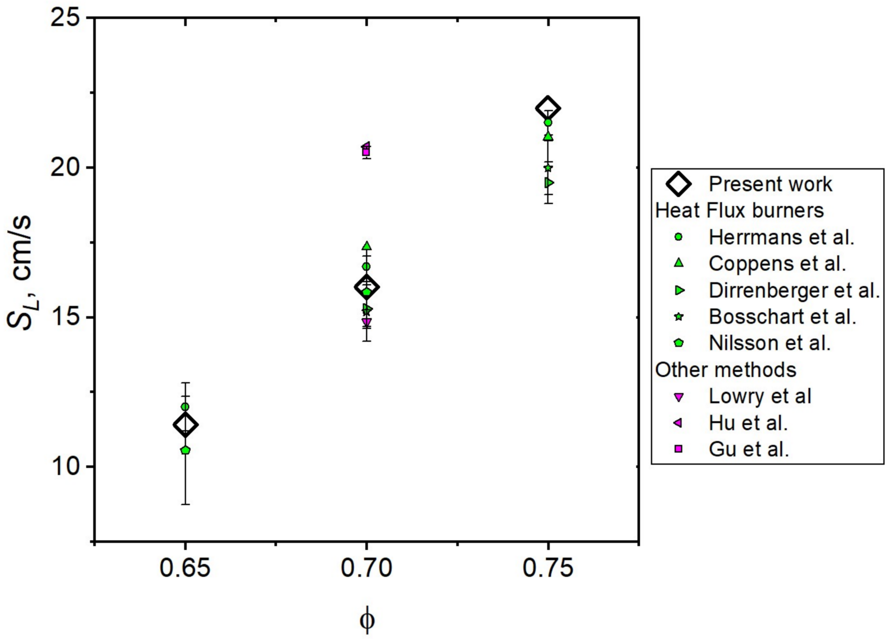

Figure 5. Laminar burning velocities at lean conditions for standard conditions methane/air flame, results from present study (open diamonds) and recent literature [28–35].

3.2. S_L for Methane/Air with Microwaves

The experimental results of laminar burning velocity with microwave stimulation are collected in Table 3 for the experimental conditions specified in Table 2. For a few cases, namely 6, 8, and 9, were the only visited conditions where there was an unburned gas velocity of 17.0 cm/s and $\phi = 0.7$. The difference in C was here directly related to a difference in S_L, with the assumption that the time-derivative, a, corresponding to the slope in Figure 2, was identical for the flame with and without microwaves, using the simple relation $\Delta S_L = \Delta C/a$. Since this is based on only a single point, it should not be considered a stringent determination of difference in laminar burning velocity, but rather as an estimate.

Table 3. Laminar burning velocities determined in this study for the experimental conditions given in Table 2. The increase in laminar burning velocity, ΔS_L, is in relation to the values at standard conditions, given in the text and presented in Figure 5.

Meas.	S_L (cm/s)	ΔS_L (cm/s)	Increase (%)
1	11.9	0.5	4.1
2	18.1	2.0	12.7
3	23.7	1.7	7.9
4	16.5	0.4	2.7
5	16.4	0.35	2.2
6	-	0.3	1.8
7	16.8	0.7	4.6
8	-	0.4	2.3
9	-	0.6	3.5

The largest increase of S_L is seen for the longest pulse durations of 50 µs and a repetition rate frequency of 1 kHz. Several equivalence ratio conditions were investigated for this pulse sequence and the results are presented in Table 3 (Measurements 1, 2, 3).

3.3. Effect of Varied Pulse Sequence and Power

Laminar burning velocities were determined for flames with an equivalence ratio of 0.7, exposed to a constant E-field (350 kV/m), at three different pulse sequences with pulse durations of 50, 25, and 10 μs (conditions 2, 4, and 5 in Tables 2 and 3). In addition, the change in laminar burning velocity for a shorter pulse 5 μs was estimated from a single experiment at 17.0 cm/s (condition 6). A complete determination of laminar burning velocity was not possible for the shortest pulse since the microwave stimulation at these conditions showed a weak response to the flame and because data at low velocities were difficult to interpret.

Figure 6 presents *C* traces, visualizing the flame response to the different pulse sequences at the same electric field strength and unburnt gas velocity. The 50 μs pulse clearly shows a strong response of the flame while the shorter pulses result in quite weak responses. Results are presented as the increase in laminar burning velocity in Figure 7, where the open symbols represent data points that are all obtained at the same flame conditions and the electric field strength E_{RMS} = 350 kV/m, but with different pulse settings. The solid symbol in the figure display results from an identical flame exposed to a 25 μs long pulse at slightly higher E-field, namely 370 kV/m. Apparently, this small increase in field strength gives a clear increase in laminar burning velocity. The effects of electric field could, unfortunately, not be studied for the long pulse duration, because then there was breakdown. Instead, trends related to a change in E-field was investigated at a pulse duration of 10 μs, for which *C*-traces are presented in Figure 8. There is a trend in the stronger response at higher E-field, as is evident from the ΔS_L results from 5, 8, and 9 in Table 3. However, the flame enhancement at these conditions is small, 2–4%, and experimental uncertainties are not negligible. Therefore, at these conditions, the increasing trend cannot be unambiguously quantified.

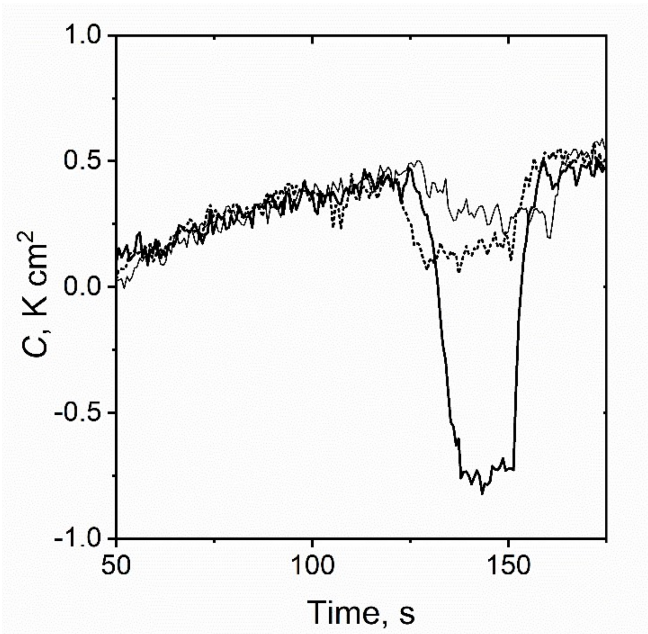

Figure 6. Trace of coefficient *C* for flames at ϕ = 0.7 and V_g = 17.0 cm/s, E_{RMS} = 350 kV/m for pulse sequences 50 μs/1 kHz (thick solid line), 25 μs/2 kHz (dashed line), and 10 μs/5 kHz (thin solid line).

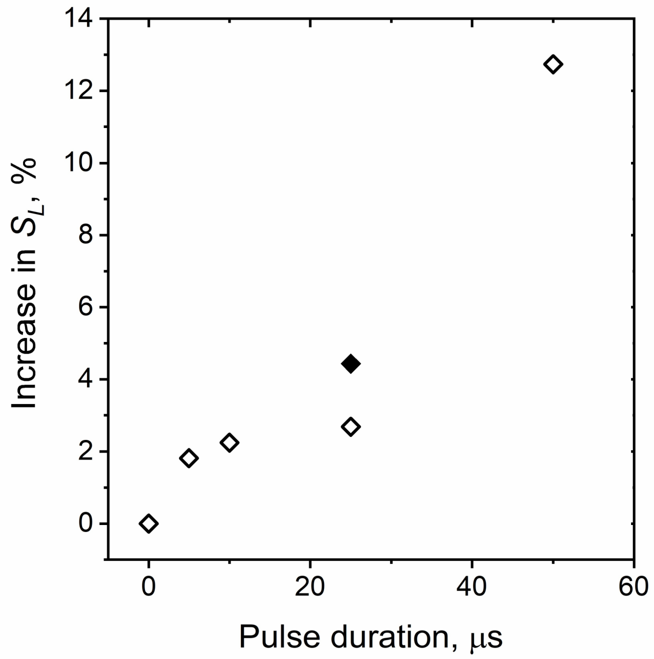

Figure 7. Percent increase in laminar burning velocity as a function of pulse duration for flames at ϕ = 0.7. Electric field strength is E_{RMS} = 350 kV/m (open symbols) and E_{RMS} = 370 kV/m (filled symbol).

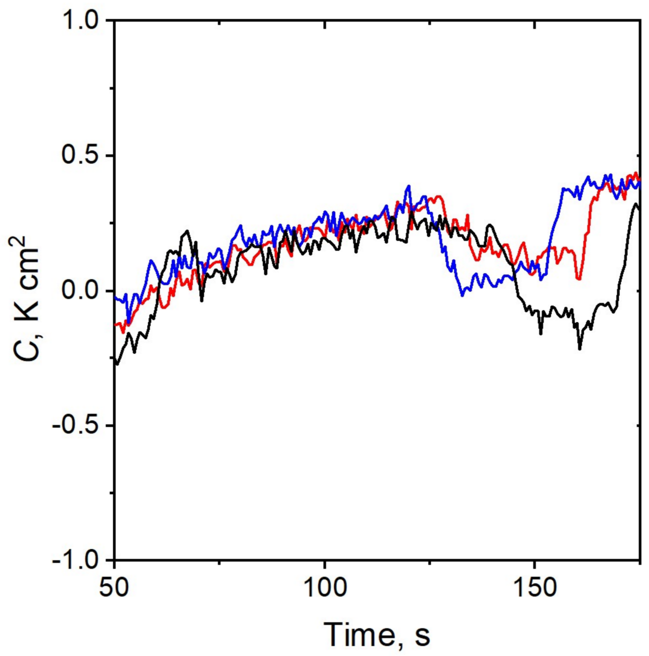

Figure 8. Trace of coefficient C for flames at ϕ = 0.7 and V_g = 17.0 cm/s, with pulse duration of 10 μs and a frequency of 5 kHz at electric fields of 350 kV/m (red), 370 kV/m (blue) and 380 kV/m (black).

4. Discussion and Conclusions

In this work, enhancement of laminar burning velocity as a result of pulsed microwave stimulation of lean methane/air flames are investigated. A dedicated setup that allows quantification of S_L at well-defined conditions has been used to study effects of equivalence ratio, pulse sequence, and strength of the E-field. It is the first study that systematically investigates the trends related to the pulse sequence of pulsed microwaves. The following conclusions can be made based on the experimental results:

- At the present conditions with a maximum average electrical power of 250 W, the increase in laminar burning velocity is in the range of 1.8–12.7%;
- From the investigated pulse sequences, and at a constant E-field and average power, the largest effect on the flame is obtained for the longest pulse, namely 50 µs;
- Increase in E-field in the range 350–380 kV/m results in a stronger enhancement of the laminar burning velocity.

The previous two studies utilizing pulsed microwaves by Stockman et al. [19] and Michael et al. [22] used a shorter pulse duration than the present work, which allowed them to apply a higher peak power. In the overlapping range of equivalence ratio, the present work showed a lower increase in flame propagation, which is likely related to the lower peak power. The present work marked the starting point for extensive investigations over a broad range of conditions. Further research should aim at investigating the flame speed enhancement at conditions identical to those studied in the cited publications. An important trend that was shown here is the increased flame propagation enhancement with increasing pulse duration at constant power.

The present work is the first determination of absolute values of laminar burning velocities for flames subject to pulsed microwaves. Together with the results from previous studies conducted at other conditions, it is possible to reveal some trends. However, the quantifications of effects and trends are far from conclusive and further systematic studies are required. Using the same experiment, the authors of the present work aim to further investigate the laminar flame enhancement at various pulse sequence and power conditions. The setup is also suitable for the investigation of several other fuels, for example, small alcohols, dimethyl ether, and potentially heavier hydrocarbons such as n-pentane and benzene. Studies of fuels with a lower flammability limit, such as the aforementioned hydrocarbons, may give important information that allows for discrimination between kinetic and thermal effects.

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