



Influence of burner surface temperature inhomogeneities on oscillation characteristics of premixed flames

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ABSTRACT

Thermo-diffusively oscillating burner-stabilized flames provide sensitive targets for the validation and improvement of detailed chemical reaction mechanisms. Because these flames are typically modeled using a one-dimensional (1D) assumption due to their computational efficiency, the validity of this assumption under realistic experimental conditions remains unclear. In this work, premixed oscillating methane–air flames are simulated using two-dimensional (2D) numerical models. The role of spatial inhomogeneities of burner surface temperatures is investigated. Both synthetic and experimentally motivated temperature profiles are imposed at the burner surface. The results show that the dominant oscillation frequency is primarily determined by the maximum burner surface temperature. In contrast, the oscillation amplitude exhibits a strong dependence on the spatial temperature profile. Nearly one-dimensional bulk oscillations at the center evolve into wave-like, phase-shifted flame fronts along the radial direction. Thus, 1D simulations can reliably predict oscillation frequencies if the maximum burner temperature is known, while multi-dimensional simulations are required to capture spatial variations in the oscillation amplitude and boundary effects at the edge.

Novelty and significance statement: This study bridges the gap between one-dimensional flame simulations and experiments on oscillating burner-stabilized flat flames by explicitly accounting for spatial inhomogeneities in inlet temperature fields. The novelty lies in incorporating measured and synthetic temperature distributions to quantitatively assess their influence on unsteady flame dynamics. Significantly, this approach unlocks transient operating regimes, such as thermo-diffusive oscillations, as a robust source of validation data. By utilizing oscillation frequencies and amplitudes alongside standard stable flame properties, this work facilitates a more rigorous validation of chemical kinetics models. Ultimately, incorporating these dynamic targets improves the predictive capability of 1D simulations and supports the development of highly accurate reaction mechanisms for complex fuel mixtures.

1. Introduction

Burner-stabilized premixed flames are widely used as well-defined configurations for the investigation of flame structure, chemical kinetics, and model validation. In particular, flat-flame burners such as the McKenna burner have become standard tools in experimental combustion research because, in principle, they are designed to provide stable, reproducible, and nearly one-dimensional flames [1]. This makes them especially attractive for comparisons with one-dimensional simulations, which remain advantageous due to their simplicity, robustness, and computational efficiency. However, the validity of this low-dimensional assumption depends critically on the homogeneity and accurate characterization of the inlet and thermal boundary conditions. Under certain operating conditions, burner-stabilized premixed flames can exhibit self-sustained thermo-diffusive oscillations. The mechanisms responsible for these oscillations have been investigated for several decades

in experimental, theoretical, and numerical studies. Classical stability analyses showed that the interaction between selective diffusion, heat release, and heat loss to the burner can destabilize steady planar flames and lead to oscillatory solutions through Hopf bifurcations [2–4]. Further numerical and nonlinear studies addressed multiplicity, stability, and rich dynamical behavior of burner-stabilized and surface-stabilized premixed flames [5,6]. Experimental investigations [7–9], together with theoretical and numerical studies [10–12], have provided essential information on stability limits, oscillation frequencies, and amplitudes. De Goey et al. [12] reviewed the propagation, dynamics, and control of laminar premixed flames and highlighted the importance of flame-burner interaction, heat-transfer processes, and the distinction between planar and multi-dimensional flame dynamics. In their interpretation, oscillations of burner-stabilized flames are linked to unsteady heat losses at the burner, which generate enthalpy perturbations that

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interact with the reaction zone after a finite convective time delay. This provides an important conceptual basis for the present study, where spatially varying burner surface temperatures are investigated as realistic thermal boundary conditions for oscillating flames. Beyond global quantities such as frequency and amplitude, previous studies have shown that flame pulsations can also strongly affect the instantaneous species fields. Nechipurenko et al. [13] reported periodic variations of radical emission and OH-related quantities in pulsating methane-air burner flames, with the maximum OH mass fraction varying by approximately 40% over one oscillation cycle, while Bykov et al. [14] found H-radical mole-fraction oscillations of about 50% in pulsating hydrogen-air burner-stabilized flames. In addition, Mislavskii et al. [15] provided time-resolved OH distributions for unsteady pulsating methane-air flames. These findings indicate that oscillatory flame motion may also influence time-averaged species profiles, motivating future detailed comparisons between pulsating flames and corresponding steady flames with matched mean thermal conditions. However, the oscillations are closely linked to the coupling between diffusive-thermal effects and heat loss to the burner surface. When the inflow velocity decreases below a critical threshold, the flame stabilizes closer to the burner, increasing conductive heat transfer to the burner surface. This enhanced heat loss reduces the local flame temperature and can destabilize the combustion front, often resulting in pulsating flames associated with a supercritical Hopf bifurcation [3]. Although methane-air mixtures have Lewis numbers close to unity, the coupling between molecular transport, heat release, and burner heat loss remains essential to understand the sensitivity of such non-adiabatic flame configurations to thermal boundary conditions [2,11]. Understanding these mechanisms is also relevant in the broader context of low-carbon combustion technologies, where alternative and hydrogen-containing fuels can exhibit combustion characteristics and thermo-diffusive sensitivities that differ substantially from conventional hydrocarbon flames [7,8,16,17].

However, in practice, the boundary conditions of flat-flame burners are not perfectly homogeneous. Recent experimental studies have shown that even nominally identical McKenna burners with stainless-steel sintered matrices can exhibit significant deviations from ideal one-dimensional conditions [18]. Hot-wire anemometry and thermography revealed strong local velocity deviations of up to $\pm 50\%$ across the burner surface, accompanied by radial temperature gradients in the matrix. Temperature differences of more than 70°C were measured between the center and the edge of the matrix. In addition, insufficient cooling of the burner housing can lead to thermal drift during operation. Such uncontrolled thermal boundary conditions and structural inhomogeneities of the sintered matrix can alter the characteristic dynamics of the system and shift the oscillation frequencies of methane-air flames by up to 50% [19].

The strong sensitivity of oscillating burner-stabilized flames to boundary conditions has also been demonstrated in related numerical and experimental studies. Moroshkina et al. [20] investigated the oscillatory behavior of H_2 - CH_4 flames and highlighted the importance of accurately prescribed inlet and boundary conditions for the physical interpretation of the results. Similarly, Li et al. [21] showed that a co-flow velocity can shift the oscillation frequency of burner-stabilized flames by up to 20%, even when the primary inflow parameters remain unchanged. These findings indicate that apparently secondary boundary effects may have a substantial influence on the dynamics of thermo-diffusively oscillating flames.

Despite this evidence, the influence of laterally varying burner surface temperature distributions on the dynamics of thermo-diffusively oscillating flames has not yet been systematically investigated. In particular, it remains unclear how such temperature inhomogeneities affect key observables such as oscillation frequency, amplitude, phase behavior, and flame-front structure. It is also unclear to what extent the commonly used one-dimensional modeling approach remains valid when the thermal boundary condition is intrinsically two-dimensional.

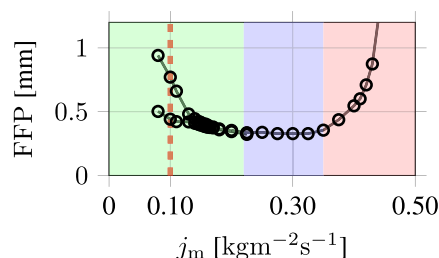


Fig. 1. Experimentally determined stability map (oscillating (green), stable (blue), blow-off limit (red)) of a burner-stabilized flame at an equivalence ratio of $\phi = 1.1$ [19].

This represents a central challenge for the interpretation of experiments and for the validation of simplified numerical models.

Recent advances in computational power and numerical modeling now enable detailed two-dimensional simulations of transient burner-stabilized flames. Building on this capability, the present work investigates how non-uniform burner surface temperature distributions influence the stability and oscillatory behavior of burner-stabilized methane-air flames using OpenFOAM [22]. Both synthetic temperature profiles and experimentally motivated profiles based on measured McKenna-burner temperature distributions [18] are considered. To assess the role of two-dimensional effects, the results are systematically compared with corresponding one-dimensional simulations performed with the in-house code INSFLA [8,23–26]. The focus is placed on how local burner temperature variations influence oscillation frequency, amplitude, and synchronization of the flame-front dynamics.

2. Methodology

2.1. Choice of parameters

To numerically investigate oscillations of near-stoichiometric, burner-stabilized methane-air flames, parameters ensuring operation within a stable oscillatory regime were selected based on our own experiments [19] and the literature [8,15]: $j_m = 0.1 \text{ kg}/(\text{m}^2 \text{ s})$ and $\phi = 1.10$ as indicated by the red dashed line in Fig. 1. The figure also shows stable (blue), oscillating (green), and blow-off regimes (red) in a FFP- j_m (flame front position; definition see Section 3.1) diagram. Although most studies focus on the stable region (blue), the oscillating regime (green) provides valuable insights for combustion model development.

2.2. Experimental observations

In common experimental configurations, burners that channel a gaseous premixed mixture through a porous sintered matrix are utilized to stabilize flat flames under well-defined conditions (see Fig. 2). The flame stabilizes on the burner surface, where the porous medium is intended to suppress large velocity gradients and establish highly uniform flow and temperature fields.

Consequently, in experimental setups, a perfectly homogeneous and isothermal burner surface is typically assumed. However, our recent experimental investigations [19] have demonstrated that this assumption is often far from realistic in experiments. Detailed thermographic measurements on a standard 25 mm stainless-steel McKenna burner, initially at ambient temperature and then exposed to the investigated methane-air flame, were recorded at operation durations of 30, 90, 150, and 300 s. These temporal snapshots revealed significant spatial temperature variations across the matrix surface. As depicted in Fig. 3, the spatial temperature distribution stabilizes after 150 s, demonstrating that the profile at 300 s represents a quasi-steady thermal state. Hereafter, this final 300 s temperature field is referred to as C-Exp. Specifically, characteristic non-uniform patterns were observed, with

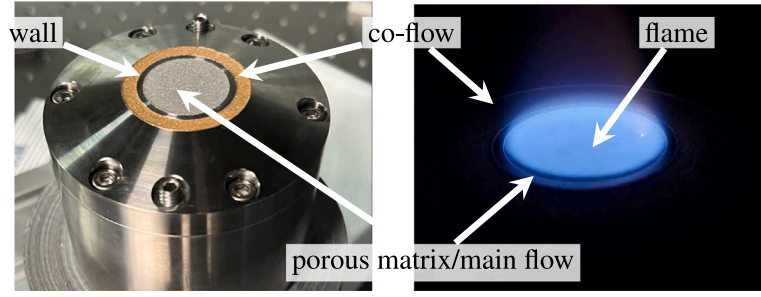


Fig. 2. Experimental setup.

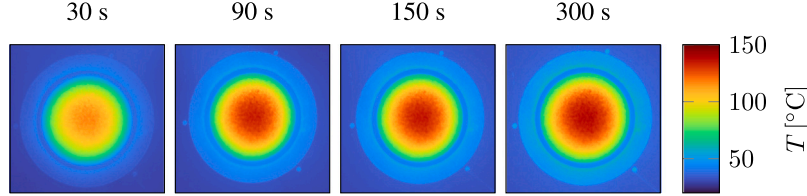


Fig. 3. Spatial temperature distribution of the burner matrix recorded 300 ms after flame blowout, following prior operation durations of 30, 90, 150, and 300 s (from left to right) [18].

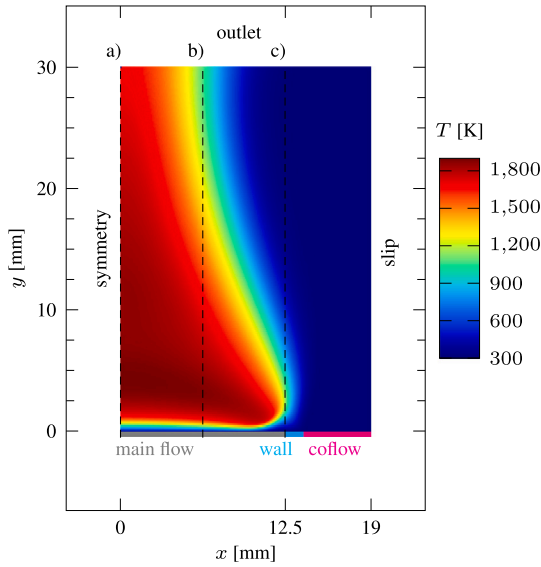
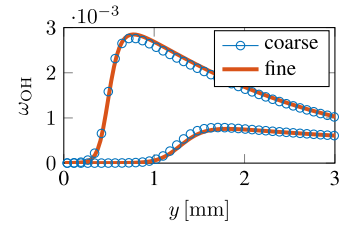


Fig. 4. 2D temperature field with boundary conditions.

temperature differences exceeding 70 K between the hot center of the matrix and its cooler outer edges. These variations can develop, for example, if the integrated cooling coil is insufficient to balance the heat input from the flame. Consequently, the unburned gas flowing through the porous matrix experiences spatially varying preheating before entering the flame zone. By applying both the measured surface temperature distributions and synthetic gradients to a simulated methane-air flame, we aim to bridge the gap between idealized one-dimensional simulations and actual experimental conditions, providing a more accurate representation of the flame structure and its stability limits.

2.3. Simulation setup

The present study performs axisymmetric 2D simulations. The computational domain is rectangular, with a width of $L_x = 19$ mm and a

Fig. 5. Near burner ω_{OH} profiles at $x = 0$ (C-Exp): Comparison of coarse vs. fine mesh for min/max flame distances.

length of $L_y = 30$ mm, as shown in Fig. 4. The main jet, consisting of a CH_4/air mixture, has a width of $L_{x,m} = 12.5$ mm. A coflow of pure N_2 is employed to shield the flame from the surrounding atmosphere, with a width of $L_{x,c} = 5$ mm. The main jet and the coflow are separated by a wall of thickness $L_{x,w} = 1.5$ mm. A uniform mesh with a grid spacing of $75 \mu\text{m}$, approximately 7 grid points resolution of a planar CH_4/air premixed flame at equivalence ratio $\phi = 1.1$ is applied in the considered reaction zone, covering $0 \leq y \leq 10$ mm and $0 \leq x \leq 14$ mm (where the wall and the main jet are located). A grid independence study is also performed with a finer mesh of size $30 \mu\text{m}$, which shows less than 2 % difference in the resulting oscillation frequency. Furthermore, other relevant scalars exhibit excellent agreement between the two resolutions, as demonstrated by the OH mass fraction ω_{OH} profiles in Fig. 5. Therefore, in this study, $75 \mu\text{m}$ is considered sufficient to capture the important flame dynamics. Outside the reaction zone, the mesh size increases non-uniformly.

At the CH_4/air jet inlet, located at the burner surface ($y = 0$, $0 \leq x \leq 12.5$ mm), a Robin-type boundary condition [14]

$$\vec{j}_{m,0} Y_k + \vec{j}_k = \vec{j}_{m,0} Y_{k,0} \quad (1)$$

is applied to all species mass fractions, consistent with [21]. Here, Y_k is the species mass fraction at the boundary face, $\vec{j}_k$ the species diffusion flux, and $\vec{j}_{m,0} = (0, j_{m,0,y})^T$ denotes the imposed inlet mass flux with $j_{m,0,y} = 0.1 \text{ kg}/(\text{m}^2 \text{ s})$. Furthermore, $Y_{k,0}$ denotes the reference species mass fraction of species k at the burner surface for the CH_4/air mixture at $\phi = 1.1$. The inlet velocity is $\vec{u}_a = \vec{j}_{m,0}/\rho_a$, where ρ_a is the density of the unburned gas. A non-reflective pressure outlet at

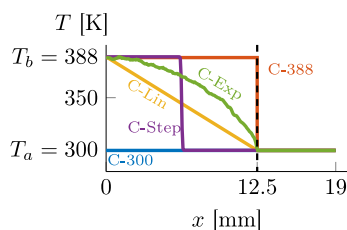


Fig. 6. Graphical illustration of the investigated temperature profiles at the burner surface.

1 bar and zero-gradient conditions for all other variables are used, while the lateral boundaries are symmetric [27] and the wall employs a no-slip condition with zero gradients for scalars. Five different types of temperature profiles are considered for the main jet inlet (see Fig. 6). In the experimental case (C-Exp), the temperature profile measured in the experiments [18] is used, with a minimum temperature T_a and a maximum temperature T_b . In all cases, co-flow is provided at fixed $T = 300$ K.

2D simulations are carried out using EBI_{ns}Foam [22], a finite-volume solver for the fully compressible Navier–Stokes equations, coupled with Cantera for detailed species diffusion. A multi-component transport model [28] is used together with the Soret effect [25]. The buoyancy effect is also considered. The finite-rate chemistry is provided through the GRI 3.0 reaction mechanism, which includes 53 species and 325 reactions [29]. The spatial discretization is performed with a second-order total variation diminishing (TVD) scheme for all the convection terms. A second-order central differencing scheme is used for the discretization of the diffusion terms. For temporal discretization, a first-order Euler scheme is applied. The adjustable time stepping is used based on the Courant number set at 0.4 for all the cases.

The comparative 1D simulations are conducted with the in-house code INSFLA [8,23–26]; a detailed formulation is given in [30]. It should be noted that the 1D and 2D simulations employ essentially the same set of governing equations, differing primarily in the boundary conditions dictated by the spatial dimensions. The governing equation system is treated in primitive variables with the density, the species mass fractions, the velocity as well as the temperature as dependent variables. A Lagrangian coordinate transformation is applied to handle the convective terms efficiently. The method of lines is used for numerical integration on statically adapted grids, yielding a system of coupled DAEs solved by an implicit extrapolation scheme with adaptive order, step-size control and error estimation [31]. This combination ensures sufficient resolution of gradients, for example. The boundary conditions used for the 1D simulations are consistent with the constant ones T_a and T_b given in the 2D simulations.

3. Results and discussion

3.1. Oscillatory behavior

As illustrated in the imageplot in Fig. 7, the absolute values of the OH mass fraction, ω_{OH} , exhibit significant variation during the oscillation cycle. In the state with the maximum separation distance between burner surface and the reaction zone (top row), the central part appears relatively thin, while a localized concentration of ω_{OH} is observed at the outer edge of the main flow ($x \approx 10$ – 12.5 mm). This phenomenon is attributed to the interaction between the CH_4 -air mixture and the N_2 co-flow, which induces two-dimensional effects in this region. The shear layer at the co-flow boundary causes a localized reduction in flow velocity and altered mixing gradients, allowing for a relative stabilization and intensification of the reaction zone compared to its more stretched central part. Conversely, as the reaction zone moves closer to the burner surface and reaches its minimum distance (third row), the

chemical reaction intensifies, as reflected in the contour lines of the OH radical mass fraction. Since OH is a highly reactive intermediate species primarily produced within the active reaction zone, its mass fraction serves as a reliable indicator of the local heat release rate. The surge in OH concentration during the attachment phase indicates a localized increase in reactivity, driven by the interplay between chemical kinetics and the spatially varying heat losses to the burner surface. This sudden energy release, which exceeds the heat losses, drives the flame further away from the burner surface. The reaction zone then stabilizes at an optimal position, where a balance between heat release and heat losses is established. To characterize the flame dynamics quantitatively, the flame front position (FFP) was defined as the location of the maximum OH mass fraction at each x-coordinate [8]. Since the objective of this study is not to identify an optimal flame marker, but to characterize the dominant flame dynamics, OH is used as the primary marker in the following analysis. Nevertheless, to ensure that the conclusions are not affected by this choice, an analogous heat-release-rate (HRR)-based FFP line was determined by locating the maximum HRR at each x-coordinate. The local heat release rate (HRR) represents the chemical energy released per unit volume and time and is commonly evaluated from the species production rates and their corresponding enthalpies [32]. This HRR-based line is plotted alongside the OH-derived FFP for direct comparison in Fig. 7. These definitions enable visualization of the oscillatory motion and subsequent frequency analysis by means of a Fast Fourier Transform [33]. Across all investigated cases, both definitions resulted in identical dominant frequencies, and the deviations in oscillation amplitude remained below 7.5 %. Noticeable differences were restricted to the absolute flame position, i.e., the burner-to-flame distance. Hence, the OH-based marker is retained for the subsequent analysis without affecting the conclusions regarding the flame dynamics.

Fig. 8 shows FFP- t curves for C-300 at three x-positions, from $x = 12.5$ mm (c) to the flame center at $x = 0$ mm (a). Case C-300 was selected here for illustration because it exhibits a homogeneous temperature field at the burner surface and is therefore particularly suitable for comparison with the 1D simulation, as no radial temperature gradients are present. The edge of the main flow (c) is mainly influenced by the co-flow, while farther away from the co-flow boundary, oscillation amplitude and phase become nearly identical, consistent with the spatially uniform boundary conditions. Overall, the flame behavior is largely a bulk oscillation for C-300, as confirmed by the good agreement with the 1D solution (black line).

All inlet temperature fields are compared in Fig. 9(a), where both the mean flame front position (FFP_{mean}) and the peak-to-peak oscillation amplitude a are plotted over space. As already discussed, the effect of the co-flow is clearly visible in all cases for $x > 10$ mm. A deeper discussion of that topic can be found in [21]. However, for $x < 10$ mm the FFP_{mean} remains nearly identical across all cases, with mean differences of approximately 10 %. In contrast to FFP_{mean}, the oscillation amplitude a shows a pronounced dependence on the temperature distribution, indicating a markedly higher sensitivity. This is additionally illustrated in Fig. 10, which displays the nearest and furthest positions of the flame from the burner surface for cases C-300 and C-Exp. While C-300 maintains an almost perfect one-dimensional behavior along nearly 60 % of the flame front, the flame front in C-Exp deviates from a bulk oscillation pattern already at approximately 20 % of the distance from the flame center. Consequently, the flame dynamics in the inhomogeneous temperature cases (C-Lin, C-Step, and C-Exp) exhibit distinct two-dimensional features, transitioning from an initially bulk one-dimensional mode in the constant-temperature cases (C-300/C-388) to a wave-like, phase-shifted oscillation. Near the flame centerline ($x < 3$ mm), the oscillations in all cases gradually regain their one-dimensional character. For $x > 10$ mm, a exhibits strong 2D effects. Future planned studies will aim to adjust the co-flow velocity to minimize these effects near the main-flow/co-flow boundary.

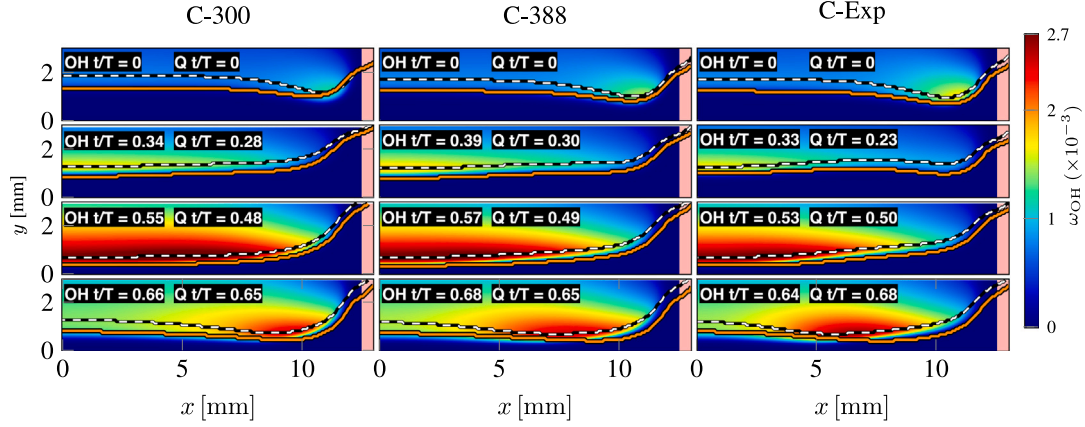


Fig. 7. OH mass fraction distributions showing four stages of the blowout and recovery cycle: (top row) maximum flame lift-off, (second row) downstream movement, (third row) maximum flame attachment/minimum distance, and (bottom row) upstream relocation. Each panel is labeled with the corresponding normalized cycle phase t/T . Columns show different cases. Flame fronts: max. OH (black/white dashed), HRR-based (orange).

Table 1

Comparison of frequencies f in Hz for investigated cases and experiments [19].

1D models		2D models					Experiment	
T_a	T_b	C-300	C-388	C-Lin	C-Step	C-Exp	T_{amb}	T_{Exp} (Fig. 3)
98.21	121.79	90.40	115.26	112.63	114.95	113.77	92	114

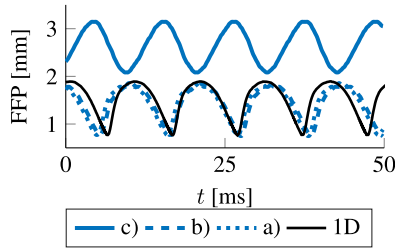


Fig. 8. Flame oscillations for C-300 at various x positions (locations a–c shown in Fig. 4); black line: 1D-300.

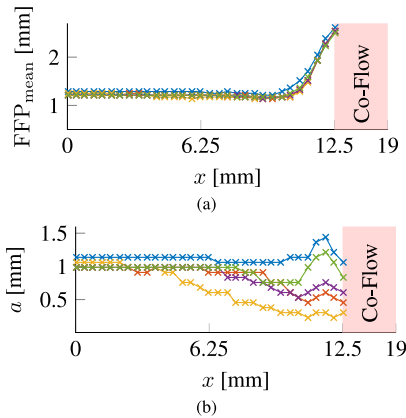


Fig. 9. Comparison of flame dynamics along the burner surface for all cases. (a) Mean flame front position (FFP_{mean}), (b) Oscillation amplitude a . (C-300: blue, C-388: red, C-Lin: yellow, C-Step: purple, C-Exp: green).

3.2. Frequency analysis

The oscillation frequency f is of particular interest, as it can be easily measured experimentally using Schlieren imaging or microphones, making it a suitable quantity for parameter studies. Overall, the cases

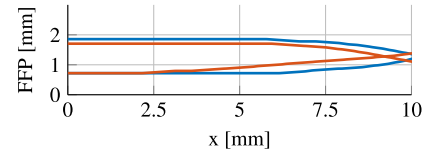


Fig. 10. The flame oscillation region for C-300 (blue) and C-Exp (red) is shown, highlighting the minimum and maximum FFP, and thereby illustrating the spatial variation of a .

with a maximum burner-surface temperature of 388 K (C-388, C-Lin, C-Step, and C-Exp) show a consistent frequency of $113 \text{ Hz} \pm 2 \text{ Hz}$, indicating no spatial variation in the oscillatory behavior (see Table 1). For C-300 with a maximum temperature of 300 K, the tracked frequency is 90 Hz. In a recent experimental study [19], we investigated a broad parameter range that includes the exact operating conditions considered here ($\phi = 1.10$, $j_m = 0.10 \text{ kg}/(\text{m}^2 \text{ s})$). We demonstrated that standard flat-flame burners undergo a significant thermal drift during operation. Specifically, as the burner housing temperature increased due to heat accumulation from ambient conditions to the temperature profile shown in Fig. 3, the experimentally observed oscillation frequency shifted from 92 Hz up to 114 Hz (see Table 1). This substantial frequency shift of over 20 % underscores the sensitivity of the flame dynamics to the matrix temperature. Consequently, the numerical findings for the operating point investigated in this work are excellently supported by these experimental observations, highlighting the necessity of accounting for realistic thermal boundary conditions.

Our numerical and experimental analysis provides quantitative validation of the hypothesis proposed by Moroshkina et al. [8]. They posited that local regions of enhanced reactivity generate perturbations along the flame front, which primarily modulate the oscillation amplitude. Conversely, the global oscillation frequency is governed by the maximum burner temperature rather than local thermal fluctuations. Although temperature variations can induce changes in inflow velocity, our observations, corroborated by 1D simulations, demonstrate that these variations exert only a marginal influence on the dominant oscillation frequency. A 1D simulation matching C-388's outflow velocity at 300 K yielded a dominant frequency of 136 Hz, approximately 20 %

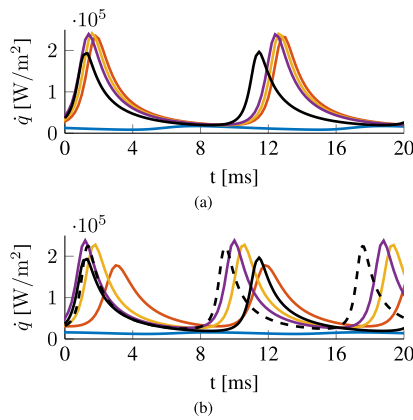


Fig. 11. Heat flux density over time (a) C-300, (b) C-Exp. purple: $x = 0$ (center); yellow: $x = 4.16$ mm; red: $x = 8.33$ mm; blue: $x = 12.5$ mm; black: 1D-300; black dashed: 1D-388.

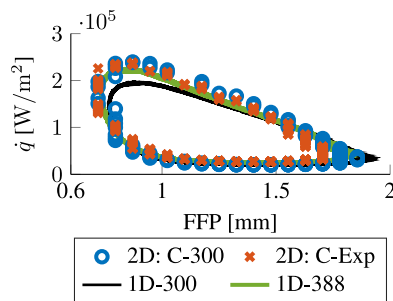


Fig. 12. Heat flux density over FFP.

higher than the reference. These results highlight the interplay of chemical kinetics, flow dynamics, diffusion, and boundary conditions in governing flame stability and oscillations.

3.3. Heat flux analysis

In order to further validate the 1D and 2D simulation results, the heat flux density at the burner surface is considered. This value is sensitive to the flame front position and can additionally be used to quantitatively describe the transient pulsating flame front behavior. Fig. 11 presents the heat flux density over time for the cases C-300 and C-Exp at 4 different x -positions as well as the 1D 300 K and 388 K case. The profile shows the characteristic flame motion. The oscillation is non-harmonic because the flame dynamics are governed by a strongly nonlinear balance between chemical heat release and heat loss to the burner. When the flame approaches the burner, the heat transfer increases sharply, so this state is only maintained for a short time. When the flame is farther away, heat losses are reduced and the flame can remain in this state for a longer part of the cycle. The resulting motion therefore resembles a relaxation-type oscillation rather than a sinusoidal one. Notably, the characteristic trends in the 1D simulations show good agreement with the 2D modeling results. Furthermore, the phase shift of the oscillation becomes apparent: for C-Exp, the oscillation exhibits a pronounced two-dimensional character, whereas for C-300 only the transition region between the flame and the co-flow deviates noticeably. For both cases, the determined maximum heat-flux values are nearly identical. In addition, Fig. 12 shows again the heat flux density, but this time plotted along the FFP. For both the 1D and 2D cases, the minimum distance between the flame front and the burner is nearly identical, reaching approximately 800 μm . Minor differences between 1D-300 and C-300 arise from the omission of the

co-flow in the 1D model, which, by definition, cannot account for such multi-dimensional effects. However, case C-300 exhibits a larger flame–burner separation, which modifies the oscillation amplitude and directly influences the dominant oscillation frequency. In simplified terms, at the same axial position, the local heat flux to the burner is higher in C-300 than in C-Exp due to the steeper temperature gradient near the burner surface. As a result, the flame stabilizes further downstream of the burner surface, leading to lower oscillation frequencies. The corresponding one-dimensional solution confirms that the 1D and 2D cases exhibit qualitatively similar behavior.

In summary, these results highlight the high complexity of thermo-diffusively oscillating flames, which are governed by the coupled effects of chemical kinetics, flow dynamics, molecular diffusion, and heat losses to the burner surface in a strongly nonlinear manner.

4. Conclusion

The present study provides a detailed numerical investigation of thermo-diffusively oscillating, burner-stabilized flames under various inlet temperature distributions. Spatial inhomogeneities in the inlet conditions primarily affect the oscillation amplitude, introducing pronounced two-dimensional modulation along the flame front. In contrast, the dominant oscillation frequency remains nearly constant across all cases and is mainly governed by the hottest regions at the burner surface.

This behavior indicates that the oscillations are governed by a coupled thermo-diffusive process linking heat release and transport. A systematic comparison between cases with identical and varied inlet conditions reveals that increasing the inflow velocity shortens the convective time scale of perturbation transport between the burner surface and the flame front, resulting in higher oscillation frequencies. Enhanced surface heat losses increase flame–burner separation and promote lower-frequency oscillations. Furthermore, the direct comparison between 1D and 2D simulations demonstrates the limitations and applicability of idealized model assumptions. While 1D models prove sufficient to accurately predict the dominant oscillation frequency, provided the maximum burner temperature is known, 2D simulations are essential to capture the spatial variation of the oscillation amplitude and edge effects induced by real-world boundary conditions. Overall, these findings show how chemical kinetics, flow dynamics, diffusion, and boundary conditions jointly govern flame stability and oscillations, supporting the design of burners with improved stability and reproducibility. Importantly, the numerical predictions, particularly the observed oscillation frequencies, show excellent quantitative agreement with our experimental measurements and the literature. This strong alignment validates the applied computational model and underscores its reliability in capturing highly sensitive, transient flame dynamics.

Building on these findings, future work will focus on an additively manufactured burner with deterministically designed internal structures. By actively controlling the aerodynamic and thermal boundary conditions, this novel setup aims to strictly minimize experimental uncertainties. Ultimately, it will provide a highly reproducible environment to investigate unsteady flame dynamics and generate high-fidelity data for the validation of combustion models.

CRediT authorship contribution statement

Philipp Golda: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Prashant Shrotriya:** Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. **Viatcheslav Bykov:** Investigation, Formal analysis, Methodology, Visualization, Writing – review & editing. **Robert Schießl:** Writing – review & editing. **Ulrich Maas:** Supervision, Writing – review & editing.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT-4/5 and Gemini 3.1 Pro to assist with spelling, grammar correction as well as tikz programming. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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