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Relationship between pore geometry and flame dynamics in porous media burners

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ABSTRACT

This work investigates the dynamics of lean premixed methane–air flames stabilized in two-dimensional, regular porous media using Direct Pore-Level Simulations (DPLS). The analysis is conducted in two stages: first, unforced flame dynamics are examined, and second, the response to externally imposed broadband velocity perturbations is assessed. Simulations are performed across multiple porous media, and a decoupling between the gas and solid thermal states is adopted to enable a systematic evaluation of the effect of porous properties on flame response. Results of unforced simulations show that, above a critical Reynolds number, vortex shedding from the solid obstacles generates coherent flame fluctuations characterized by a hydrodynamic Strouhal number $St_h \approx 0.2$, which is largely independent of porosity. Hydrodynamic Transfer Function (HTF) analysis further shows that the porous structure acts as a hydrodynamic filter, selectively amplifying perturbations associated with these intrinsic flow dynamics while attenuating other frequencies as perturbations propagate through the medium. The flame response to the imposed forcing is characterized using inlet- and locally-evaluated Flame Transfer Functions (FTFs). The inlet FTF exhibits a non-monotonic behavior reflecting modulation by hydrodynamic structures generated within the porous medium. In contrast, as the location where the FTF is evaluated approaches the flame front, the influence of hydrodynamic modulation progressively weakens and the response tends toward the low-pass behavior typical of premixed flames. When the response is represented using a Strouhal number based on geometrical properties of the porous medium related to the flame surface area, similar trends are observed across the different porous media. Overall, the present modeling framework shows that the global flame response in porous media results from the combined effect of hydrodynamic modulation within the porous structure and the intrinsic flame response to local velocity fluctuations.

Novelty and significance

This study provides a pore-scale modeling framework for premixed flame dynamics in porous media, combining unforced and forced flame analyses through Direct Pore-Level Simulations. It reveals how intrinsic vortex shedding generates coherent flow structures that selectively modulate flame response, and how porous media act as hydrodynamic filters for inlet perturbations. By decoupling hydrodynamic modulation from the intrinsic flame response, the work demonstrates a largely consistent flame behavior across different porosities, offering a framework built on dimensionless quantities for modeling flame dynamics in more complex porous configurations. These insights advance the understanding of flame–flow interactions and support the development of predictive models.

1. Introduction

Previous studies have highlighted the potential of porous media combustion to advance the design of efficient and stable combustion systems [1]. While the steady-state behavior of porous burners has

been extensively investigated [2], a detailed understanding of flame stabilization mechanisms at the pore scale — an inherently unsteady phenomenon [3] — remains limited. Gaining such insight is crucial for characterizing the dynamic response of porous burners and assessing

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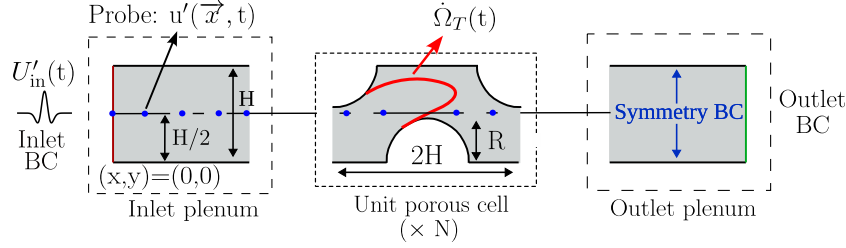


Fig. 1. Schematic illustration of the simulated computational domain, including boundary conditions.

their potential to mitigate combustion instabilities in lean-premixed combustors and high-energy-density systems [4]. Porous materials, well known for their acoustic absorption properties [5], have been primarily explored as passive strategies to control combustion instabilities. For instance, porous inserts have been shown to attenuate combustion noise and instabilities in swirl-stabilized turbulent flames [6–8] by redistributing acoustic energy across a broader range of dynamic modes. Strategic placement of porous plugs can further suppress thermoacoustic instabilities in tubular flames by modifying the natural acoustic modes and enhancing viscous dissipation [9]. Nonetheless, under certain operating conditions, porous burners themselves may act as acoustic sources. Experimental studies have reported sound emission and self-excited oscillations in porous burners, which may be associated with combustion instabilities [10–12]. In addition, experimental and numerical investigations have highlighted the occurrence of localized oscillatory flame dynamics, including pulsating regimes analogous to repetitive flame extinctions and ignitions, which have been associated with acoustic emissions [13,14]. However, detailed experimental characterization of these phenomena remains challenging due to the opacity and geometric complexity of most porous materials, which limit optical access and restrict the use of intrusive diagnostics [15,16]. In this context, high-fidelity numerical simulations can provide complementary insight by enabling controlled access to local flow and flame dynamics that are difficult to probe experimentally. The present study therefore employs Direct Pore-Level Simulations (DPLS) to investigate the dynamics of premixed methane–air flames stabilized within porous media. The objective is not to reproduce a specific porous burner in all its geometrical complexity, but rather to consider a canonical pore-scale configuration in which the mechanisms governing intrinsic flame dynamics and the response to imposed velocity perturbations can be isolated and analyzed. In particular, the study focuses on the role of pore-scale flow–flame interactions and on the hydrodynamic filtering effect induced by the porous geometry. The results are thus interpreted in relation to structural and transport properties of the medium, such as porosity and permeability. The paper is organized as follows. Section 2 presents the numerical methodology, including the DPLS framework and the modeling of heat transfer and boundary conditions. Section 3 analyzes the unforced flame dynamics and identifies intrinsic oscillatory behavior. Section 4 extends the analysis to forced flames under broadband inlet perturbations, focusing on Hydrodynamic Transfer Functions and Flame Transfer Functions. Finally, Section 5 summarizes the main findings, discusses their implications, and outlines possible directions for future work.

2. Methodology

2.1. Solver setup

Two-dimensional DPLS are performed using the EBIdnsFoam solver [17], which couples OpenFOAM [18] with the open-source chemical kinetics library Cantera [19]. While fully predictive simulations of practical porous burners require three-dimensional simulations, the reduction to two-dimensional simulations is justified by the ability of such models to capture the main features of unstable flame dynamics

with a limited computational cost [20]. The fully compressible reactive Navier–Stokes equations are solved for a lean premixed methane–air mixture with an equivalence ratio of $\phi = 0.7$, inlet temperature $T_{in} = 300$ K, and pressure $p = 1$ atm. A fourth-order interpolation scheme is used for the convective and diffusive terms, while a second-order backward scheme is employed for temporal integration. Diffusive fluxes are computed using the Hirschfelder–Curtiss mixture-averaged transport model, and chemical source terms are evaluated using a one-step global reaction mechanism [21], yielding an adiabatic flame temperature of $T_{adiab} = 1840$ K. The use of the one-step mechanism was assessed through comparison with the skeletal mechanism of Kee et al. [22], which includes 17 chemical species and 58 reversible reactions, and was shown to be in good agreement with the detailed reaction mechanism in predicting temperature, heat release rate and species profiles in porous media burners [23]. The detailed comparison, reported in the Supplementary Material, shows that the one-step mechanism provides a reasonable approximation of the main global quantities relevant to the present study, including the flame response. In all simulations, the local mesh resolution within the porous region ensures approximately 15 grid points across the thermal flame thickness. The adopted resolution was selected following a mesh convergence analysis, reported in the Supplementary Material, based on both steady flame quantities and indicators of the flame dynamics. Finally, each case is simulated for a physical time of $t_{sim} = 200$ ms and flow-field quantities are sampled at a frequency of $f_{smp} \approx 10$ kHz.

2.2. Numerical domain and boundary conditions

The computational domain consists of a regular two-dimensional array of solid cylinders with radius $R = 1$ mm, forming a porous medium characterized by a macro-porosity ϵ . Three porosity values were considered, $\epsilon = \{0.6, 0.7, 0.8\}$. Each domain spans $130 \times H(\epsilon)$ mm², with a porous section of length $L_{porous} = 80$ mm. The domain height varies with porosity according to $H(\epsilon) = \sqrt{(0.5 \cdot \pi R^2)/(1 - \epsilon)}$. The major parameters of the simulated porous media, including the mean hydraulic diameter D_h , tortuosity τ , and static permeability κ , are summarized in Table 1. The computational domain and associated boundary conditions are shown in Fig. 1. Symmetry boundary conditions are imposed along the lateral boundaries, while a non-reflecting boundary condition is prescribed at the outlet. At the inlet, a fully laminar flow with uniform velocity U_{in} is imposed. Based on this velocity, a pore-level Reynolds number is defined as

$$Re_p = \frac{\langle U \rangle \cdot D_h}{\nu}, \quad (1)$$

where D_h is the average hydraulic diameter of the medium and ν is the kinematic viscosity of the mixture. D_h is an estimate of the average pore size, and is computed as $(4 \cdot A_{fluid})/P_{wetted}$, where A_{fluid} is the surface of the fluid domain, and P_{wetted} is the wetted perimeter of the solid boundaries. The quantity $\langle U \rangle = (U_{in}/2\epsilon) \cdot (1 + T_{adiab}/T_{in})$ represents the arithmetic mean of the flow velocity in the domain, which is found to provide a good estimate of the interstitial velocity at the flame front measured in the simulations. For the considered media, a large separation of time scales between potential solid temperature variation

Table 1
Properties of the simulated porous media.

Porosity ϵ [-]	Hydr. diam. D_h [mm]	Tortuosity τ [-]	Permeability κ [m ²]
0.6	1.55	1.21	$5.02 \cdot 10^{-8}$
0.7	2.05	1.13	$1.51 \cdot 10^{-7}$
0.8	2.88	1.10	$3.01 \cdot 10^{-7}$

and flame dynamics is observed. To give a reference, the time scale of thermal inertia in a porous silicon-carbide or alumina matrix where the average pore size is taken as characteristic length would be of the order of $10^{-1} - 10^0$ s (evaluated using average properties of the porous media [24,25]), whereas the timescales associated with flame dynamics are of the order of 10^{-3} s, as discussed later. Based on this, the solid phase energy equation is not directly solved in the present work. Instead, a steady longitudinal temperature profile is prescribed [26] varying between T_{in} and T_{adiab} according to a hyperbolic tangent function, consistent with solid temperature distributions obtained from volume-averaged simulations:

$$T_s(x) = T_{in} + \frac{\Delta T}{2} \left[1 + \tanh(s \cdot (x - x_p)) \right], \quad (2)$$

where $\Delta T = T_{adiab} - T_{in}$, s controls the steepness of the solid temperature distribution, and x_p sets the axial position of the profile center. These parameters, that indirectly control the preheating of reactants, are tuned for each porous medium to obtain a target Nusselt number, Nu_{target} , which depends only on Re_p , according to the correlation for staggered cylinders proposed by Žukauskas [27]. It is worth noting that in practical porous burners, Nu depends on the porous structure and typically varies with medium porosity. In the present study, however, the Nusselt number is intentionally kept approximately constant across the different porous media, for a given Re_p . This approach enables a controlled decoupling between porosity and interphase heat transfer, allowing the influence of porous geometry on flame dynamics to be investigated independently of thermal coupling effects. On the other hand, the prescription of a fixed solid temperature distribution entails certain limitations, including possible non-physical flame thermal anchoring, and the absence of heat recirculation due to solid radiation. To assess the impact of this approximation, additional fully coupled conjugate heat-transfer simulations were performed for selected cases and are reported in the Supplementary Material. These simulations confirm that the Reynolds-number range retained in the present study corresponds to anchored flames also when the solid temperature is solved rather than prescribed, and that the dominant flame-dynamic features discussed in the paper are qualitatively preserved. The values of s in Eq. (2) are estimated using an analytical model based on an analogy between the porous medium and a flat plate [28]. The procedure is as follows: (1) the reacting flow is initialized with solid walls modeled as adiabatic; (2) the mean axial position of the flame front is determined and assigned to x_p , i.e., the center of the solid temperature profile; (3) the solid temperature profile with steepness s , estimated from the analytical model, is imposed; (4) the prescribed Nusselt number is validated *a posteriori* by comparing the target value Nu_{target} with the probability-weighted mean of the local Nusselt numbers, evaluated using the temperature trajectory method described in [26]. For instance, Table 2 reports the steepness parameter s estimated from the analytical model, the target Nusselt number $Nu_{target} = 7$ obtained from the correlation in [27], and the resulting mean Nusselt numbers and standard deviations obtained from the DPLS, for the case $Re_p = 100$ analyzed in detail in Section 4.

3. Analysis of unforced flame dynamics

Flame dynamics are analyzed through the evolution of the flame surface area, A_f [29,30], a key parameter governing the response of premixed flames to combustion instabilities [31]. Although this

Table 2

Validation of the prescribed Nu through the imposed solid temperature profile, for $Re_p = 100$.

Porosity ϵ [-]	Profile steepness s [m ⁻¹]	Target Nu [-]	DPLS $\overline{Nu}$ $\pm \sigma$ [-]
0.6	120	7	7.19 ± 1.48
0.7	65	7	7.38 ± 1.35
0.8	40	7	6.84 ± 1.82

quantity represents a length in two-dimensional simulations, the term “flame area” is retained throughout this work for consistency with the literature. The instantaneous flame area, A_f , is evaluated by integrating the magnitude of the gradient of the progress variable [32], defined using the local mass fraction of H₂O. The time-averaged flame area, $\overline{A_f}$, is normalized by the average hydraulic diameter D_h . The resulting ratio, $\overline{A_f}/D_h$, can be interpreted as a measure of the flame surface tortuosity [30]. The values of $\overline{A_f}/D_h$ obtained for each porous configuration and for various $Re_p \in [50, 300]$ are presented in Fig. 2. For this range of Re_p , all porous media are characterized by anchored flames. Outside this interval, different regimes are observed: flash-back occurs at lower Re_p , while flame blow-off is encountered at higher Re_p . To define the bounds of the anchored regime, and to ensure that all cases considered in the analysis correspond to anchored flames, a conservative criterion is adopted based on simulations employing adiabatic walls. This choice aims at avoiding artificial stabilization effects associated with imposed solid-temperature profiles, which could promote flame anchoring by fixing the solid thermal environment. Fig. 2 shows that within the anchored flame regime, the time-averaged flame surface area, $\overline{A_f}$, displays a linear dependence on Re_p . It is worth noting that this linear trend is characteristic of the anchored-flame regime [30] and does not hold when approaching the flash-back or blow-off limits, where the flame dynamics are dominated by global displacement or extinction phenomena. Interestingly, the dependence of flame tortuosity on Re_p appears to be independent of the porosity ϵ . This suggests the existence of a geometrical similarity of the flame surface area—a key quantity influencing the flame response—across the considered values of porosity. Within the anchored flame regime, as the Reynolds number increases, the flame transitions from a steady to an unsteady, yet anchored, regime. A critical Reynolds number, $Re_{p,crit}$, illustrated in Fig. 2 by dashed vertical lines, marks the onset of flame surface oscillations. In fact, unsteady flow dynamics emerge, characterized by vortex shedding from the cylindrical solid obstacles interacting with the flame front. The resulting oscillatory flame regime is characterized by fluctuations of the flame surface area, which can be quantified using a hydrodynamic Strouhal number, St_h , defined as

$$St_h = \frac{f \cdot R}{\langle U \rangle}, \quad (3)$$

where f is the oscillation frequency obtained from the Fast Fourier Transform of $A'_f(t)$ and R provides an estimate of the characteristic size of the hydrodynamic coherent structures interacting with the flame front. Fig. 3 presents the spectra of flame surface area fluctuations, $\widehat{A_f}$, normalized by the time-averaged value, $\overline{A_f}$, as a function of the hydrodynamic Strouhal number St_h , for $Re_p = 300$, for which a fully developed oscillating flame regime is observed. For all porous media, the peak Strouhal numbers are consistently observed at $St_h \approx 0.2$, that, depending on the medium, corresponds to a frequency range $f \in [800 - 1200]$ Hz, with the highest frequency being associated with the low-porosity medium and vice-versa. The value of $St_h \approx 0.2$ corresponds to the characteristic Strouhal number associated with vortex shedding from the solid obstacles, indicating that the unsteady flame dynamics are directly controlled by the underlying coherent vortical structures, largely independent of porosity.

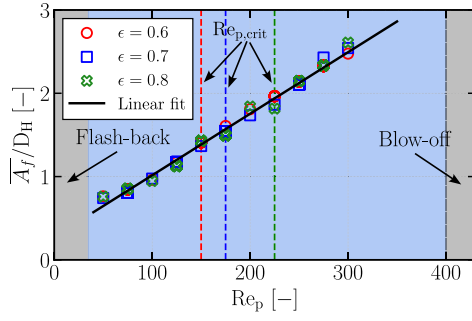


Fig. 2. Time-averaged flame surface area, $\bar{A}_f$, normalized by the average hydraulic diameter, D_h , for porous media of porosity ϵ , at various pore-level Reynolds numbers, Re_p . Dashed lines denote the transition from the steady to unsteady anchored regime for the different porous media.

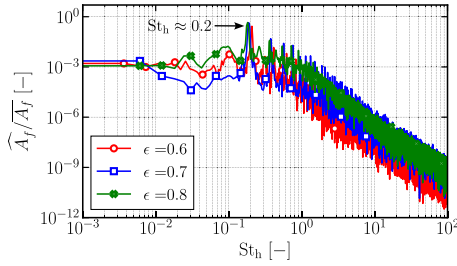


Fig. 3. Spectra of flame surface area fluctuations, $\hat{A}_f$, normalized by the time-averaged value, $\bar{A}_f$, as a function of the hydrodynamic Strouhal number St_h , for different porous media, at $Re_p = 300$.

4. Analysis of flame dynamics under inlet velocity forcing

In this section, the analysis of the unforced flame dynamics presented in Section 3 is extended by investigating how a flame immersed in a porous medium responds to externally imposed velocity perturbations at the inlet. The objective is to characterize how the porous structure modulates these perturbations and how the flame reacts to the resulting flow fluctuations across different pore-scale conditions. To achieve this, an isentropic and broadband velocity forcing was applied at the inlet in the form of a Ricker wavelet:

$$U'_{in}(t) = \eta_u [1 - 2\pi^2 f_0^2 (t - t_0)^2] e^{(-\pi^2 f_0^2 (t - t_0)^2)}, \quad (4)$$

where $\eta_u = 0.1 \cdot U_{in}$ m/s is the forcing amplitude, f_0 is the central frequency, t_0 is the time of maximum amplitude, and t denotes time. The Ricker wavelet provides a temporally localized broadband excitation with smooth spectral content centered at f_0 , while its zero mean over the excitation interval ensures that the perturbation does not introduce a steady velocity offset and therefore preserves the prescribed mean inlet velocity. For all media, the most energetic frequency f_0 was chosen so that the imposed velocity fluctuations correspond to a Strouhal number $St_h = 0.2$. This choice is motivated by the intrinsic oscillatory dynamics observed in the unforced flame simulations, where $St_h \approx 0.2$ corresponds to the characteristic frequency of vortex-flame coupling. The forcing is thus designed to target the natural flame oscillation dynamics, directly exciting the coherent structures responsible for flame surface oscillations, with the objective of quantifying and characterizing the flame dynamic response. All simulations of forced flame dynamics are conducted at $Re_p = 100$, which corresponds to a baseline steady, anchored flame regime (Fig. 2) onto which the unsteady inlet perturbation is superimposed.

4.1. Analysis of the inlet Flame Transfer Function

The flame response to the prescribed perturbation of inlet velocity is characterized through an inlet Flame Transfer Function (IFTF) defined as

$$\text{IFTF}(f) = \frac{\hat{\Omega}_T(f)/\bar{\Omega}_T}{\hat{U}_{in}(f)/U_{in}}, \quad (5)$$

where $\hat{\Omega}_T$ denotes the volume-integrated heat release rate, and $\bar{\Omega}_T$ its time-averaged value, whereas U_{in} is the inlet velocity. In Section 3, it was shown that representing the dynamics in terms of the hydrodynamic Strouhal number, St_h , highlights the vortex–flame coupling occurring around $St_h \approx 0.2$ across all porous media. However, in studies of Flame Transfer Functions for canonical premixed flames, the characteristic length appearing in the Strouhal number is typically chosen as the flame length — or a related measure — since this quantity governs the convective time scale of perturbations that influence the flame response [33]. In the present porous configuration, the flame length is approximately proportional to the mean hydraulic diameter D_h , as it was shown in Fig. 2. For this reason, a Strouhal number based on D_h , which is a property of the porous medium, is introduced:

$$St_{\text{flame}} = \frac{f \cdot D_h}{\langle U \rangle} = St_h \cdot \frac{D_h}{R}. \quad (6)$$

Fig. 4 presents the gains (denoted as $|\cdot|$) and phases (denoted as $\angle(\cdot)$) of the IFTF for the different porous media, as a function of St_{flame} . The gain curves exhibit a non-monotonic behavior characterized by local valleys and peaks, including a pronounced maximum around $St_h \approx 0.2$, almost independently of the medium porosity. A similar behavior was initially reported by Vroemen et al. [34]. This prior observation, obtained for a significantly more complex porous burner, suggests that the phenomenon reported in the present study may have been previously encountered in experiments and deserves further investigation. Away from the local extrema, the gain and phase curves display only minor variations between the different porous media. The correspondence between the spectral peak of flame surface oscillations at $St_h \approx 0.2$ and the local maximum observed in the IFTF gain suggests that this characteristic shape may be the result of the modulation by the hydrodynamic structures generated within the porous medium, in particular by the interaction between vortex shedding and the flame front. In addition, the similarity of the curves far from the local maxima suggests that, once the effects associated with hydrodynamic modulation are removed, a similar flame response may be recovered for the different porous media. These observations suggest that the analysis of the flame response to inlet forcing may be separated into two contributions, following the approach used in [35,36]: a local Hydrodynamic Transfer Function (HTF), accounting for the hydrodynamic modulation of the velocity perturbation as it propagates through the porous medium, and a local FTF, describing the transfer between local velocity perturbations and heat release rate fluctuations. For a given position in the domain, the product of the local HTF and LFTF is strictly equal to the IFTF:

$$\text{IFTF}(f) = \text{HTF}(x, f) \times \text{LFTF}(x, f). \quad (7)$$

Since the IFTF is uniquely defined, this decomposition can be performed at any location in the domain, provided that the HTF and LFTF are evaluated at the same position.

4.2. Analysis of the HTF

To characterize how the inlet velocity perturbation propagates through the porous medium and influences flame dynamics, the HTF approach is adopted. In the frequency domain, the HTF is defined as

$$\text{HTF}(x, f) = \frac{\hat{u}(x, f)/\bar{u}(x)}{\hat{U}_{in}(f)/U_{in}}, \quad (8)$$

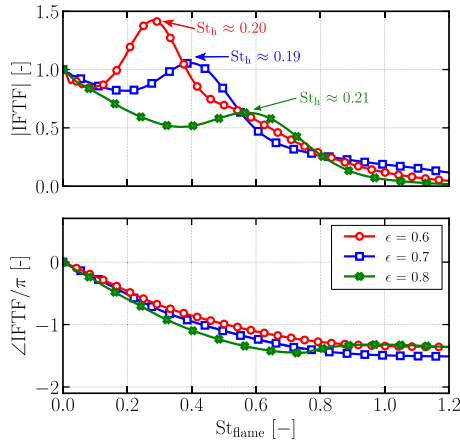


Fig. 4. Gains and phases of the IFTF, plotted as a function of St_{flame} , with local maxima of the gains indicating the effect of hydrodynamic modulation.

where $\hat{u}(x, f)$ is the complex local velocity fluctuation, and $\bar{u}$ its time-averaged value. The HTF provides a measure of the amplitude and phase response of the flow at downstream locations relative to the imposed inlet perturbation, enabling an assessment of how the porous medium filters, attenuates, or amplifies different frequency components. Local velocities are sampled by probes distributed along the longitudinal axis of the domain, as illustrated in Fig. 1. Fig. 5 presents the HTF gain as a function of the hydrodynamic Strouhal number, St_h , and the normalized axial coordinate, x/L , illustrating the evolution of the broadband inlet perturbation as it propagates through the domain. In the figure, the entry to the porous section is indicated by a solid white line, while the y - and time-averaged flame front position is highlighted by a colored box, providing a reference for the location of the reacting region. Additionally, cyan dotted lines trace the peak of the HTF gain along the axial direction, highlighting the frequencies that are most amplified throughout the domain. Upstream of the porous section, the inlet perturbation largely retains its broadband character, with a gradual amplification observed as the flow approaches the porous material. This initial increase may be attributed to enhanced local velocity fluctuations, $u'(x)$, arising from interactions with the solid obstacles. Upon entering the porous region, the HTF gains reveal that amplification becomes frequency-selective, with a narrow band centered around $St_h \approx 0.2$ being preferentially amplified. This behavior indicates that the porous medium acts as a filter, reinforcing the frequencies associated with the intrinsic vortex shedding dynamics identified in the unforced flame simulations. As the perturbation encounters the flame front, the HTF gains are abruptly damped. To further quantify how the hydrodynamic perturbation evolves along the domain, Fig. 6(a) illustrates the axial evolution of the peak HTF gain along the dotted lines represented in Fig. 5, while insets (b) and (c) show the ratios of the time-averaged local velocity to the inlet velocity along the longitudinal axis. The initial increase in time-averaged velocity at the porous entry, due to the blocking effect of the solid obstacles (Fig. 6(b)), contributes to a reduction in the HTF gain. Within the porous medium, the HTF gain exhibits an oscillatory trend associated with the presence of the solid obstacles, with the strongest amplification observed for the highest-porosity medium, $\epsilon = 0.8$. Approaching the flame front, the HTF gain gradually decreases, ultimately dropping across the flame. This attenuation is influenced by the mean flow, as shown in Fig. 6(c), and in particular is due to reactant preheating, which locally accelerates the mixture. The preheating effect is more pronounced in lower-porosity media due to closer packing of the solid obstacles. Finally, the flame itself exerts a strong attenuation on the hydrodynamic perturbation, primarily through the increase in the mean flow velocity. The frequency-selective amplification observed in Fig.

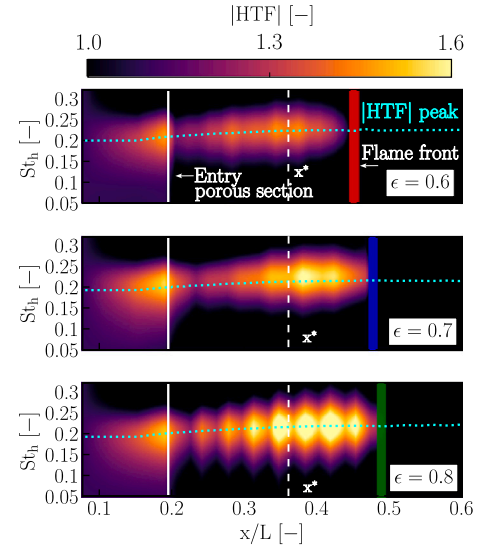


Fig. 5. Gains of HTF as a function of the axial coordinate and the hydrodynamic Strouhal number. The solid line defines the entry to the solid medium; the dashed line defines a reference position, x^* ; the dotted line follows the peak of HTF gain along the x axis. Colored bars denote the time- and y -averaged positions of the flame fronts.

5 can be further illustrated through the spectra of HTF gains and phases at a representative axial location, x^* , as shown in Fig. 7. The gain spectra exhibit a bell-shaped profile, peaking at $St_h \approx 0.2$ and attenuating lower and higher frequencies, suggesting that the porous medium behaves as a band-pass filter, selectively concentrating perturbations near the characteristic hydrodynamic Strouhal number. The phase spectra show an approximately linear trend, the slope of which can be used to estimate the local time delay of the perturbation as $\tau_{\text{phase}} = -(\angle \text{HTF} \cdot R) / (2\pi(U)St_h)$. Comparison with a characteristic convective time, $\tau_{\text{conv}} = x^* / \bar{u}$, shows good agreement with a maximum error of 3% (see the inset in Fig. 7), indicating that the perturbation is predominantly convected through the porous medium.

4.3. Analysis of local Flame Transfer Functions

In Section 4.1, IFTFs were evaluated based on the velocity fluctuation measured at the inlet. More generally, the FTF depends on the spatial location at which the velocity fluctuation u' is evaluated. To account for this, LFTFs are evaluated to quantify the transfer between locally evaluated normalized velocity fluctuations and fluctuations of the volume-integrated heat release rate:

$$\text{LFTF}(x, f) = \frac{\widehat{\mathcal{Q}}_T(f) / \overline{\mathcal{Q}}_T}{\widehat{u}(x, f) / \bar{u}(x)}, \quad (9)$$

Fig. 8 presents, for the medium of porosity $\epsilon = 0.6$, the LFTF gains as a function of St_{flame} for several probe locations distributed from the inlet ($x/x_{\text{flame}} = 0\%$) to the flame front ($x/x_{\text{flame}} = 100\%$), where x_{flame} denotes the time- and y -averaged flame position. As the probe location approaches the flame, both the shape and magnitude of the gain curve progressively evolve. Moving toward the flame, the effects of hydrodynamic modulation around $St_h \approx 0.2$ progressively weaken and the gain curves tend to evolve toward a monotonic response that resembles a low-pass filter, a behavior commonly reported for premixed flames. This transition may be primarily attributed to the fact that the flame dynamics become increasingly dominated by the local response of the reaction front rather than by upstream hydrodynamic forcing, leading to the classical low-pass filtering behavior. Comparable trends were observed also for the media with porosity $\epsilon = 0.7$ and $\epsilon = 0.8$.

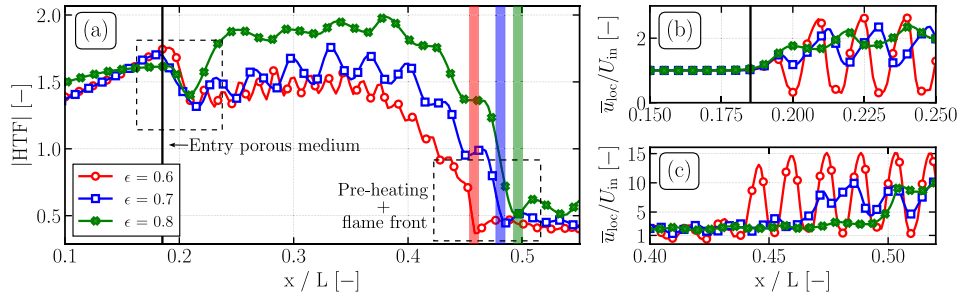


Fig. 6. (a) Peak values of HTF gains plotted as a function of the axial coordinate normalized by domain length L for different porous media. (b)–(c) Profiles of time-averaged local velocities, normalized by inlet velocity, as a function of the normalized axial coordinate, at the entry of the porous section and upstream of the flame front.

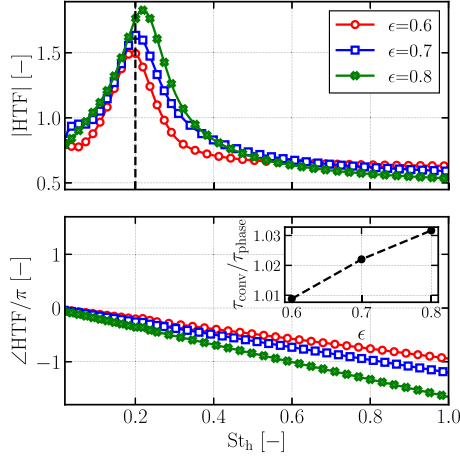


Fig. 7. HTF gains and phases for different porous media, measured at the x^* location illustrated in Fig. 5, plotted as a function of St_h . The inset illustrates the ratio between a characteristic convective time τ_{conv} and the time-delay estimated from the phase slope, τ_{phase} .

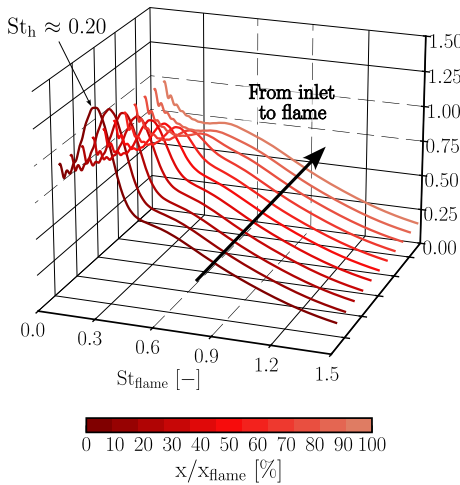


Fig. 8. Gains of the LFTF based on the local velocity fluctuation, for probes located from the inlet up to the flame front, plotted as functions of the Strouhal number St_{flame} , for the medium of porosity $\epsilon = 0.6$.

Fig. 9 illustrates the gains and phases of the LFTFs evaluated at the flame front, i.e., where the separation between hydrodynamic and flame contributions is expected to be most evident. In practice, the LFTFs in Fig. 9 are evaluated considering the velocity fluctuations measured by the probe closest to the isoline of progress variable $c =$

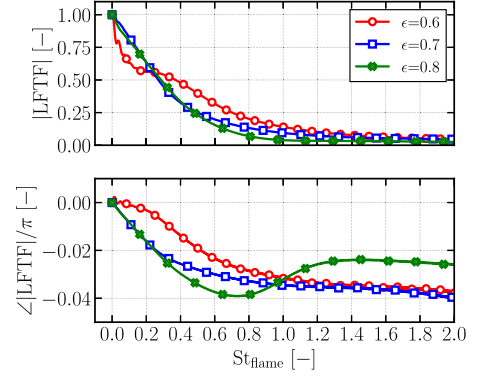


Fig. 9. Gains and phases of LFTF based on the velocity fluctuation upstream of the flame front, for different porous media, plotted as a function of St_{flame} . LFTFs are evaluated considering the velocity fluctuations measured by the probe that is closest to the isoline of progress variable $c = 0.75$.

0.75. Regarding the LFTF gains, the curves are nearly matched for the different porous media. A larger discrepancy is observed for the least porous medium ($\epsilon = 0.6$), for which the effects of hydrodynamic modulation are not fully decoupled, possibly due to stronger confinement associated with the lower porosity of the medium. These results suggest that, at the pore scale, the flame response exhibits a consistent behavior across different values of porosity. This similarity progressively disappears when the LFTF is evaluated farther upstream from the flame due to the increasing influence of hydrodynamic modulation (see Fig. 8). Indeed, the latter consistently occurs at $St_h \approx 0.2$, which, according to Eq. (6), corresponds to different values of St_{flame} depending on the porosity. As a consequence, the $IFTF = LFTF \times HTF$ exhibits a shift in the peak location for different values of St_{flame} , as observed in Fig. 4. Furthermore, the magnitude of this peak progressively decreases as the porosity increases, reflecting the lower LFTF gains observed at a given St_h . Concerning the phases, only small delays between the heat release rate and velocity fluctuations are observed in Fig. 9, which is expected given the close proximity between the velocity probes and the flame front.

5. Conclusions

This study employed two-dimensional Direct Pore-Level Simulations (DPLS) to investigate the response of premixed methane–air flames stabilized in porous media to broadband velocity perturbations. The analysis was performed in a model configuration with the objective of isolating and analyzing the mechanisms governing the flame response to external perturbations. To support the general interpretation of the results, the response was characterized using non-dimensional quantities, providing a framework that facilitates future extensions to more

complex configurations, such as irregular and three-dimensional porous media. The following main conclusions were drawn. First, the mean flame tortuosity increases linearly with Re_p and is largely independent of the medium porosity. Above a critical Reynolds number, the flow within the porous medium develops unsteady dynamics characterized by vortex shedding from the solid obstacles. This mechanism generates coherent velocity fluctuations with a Strouhal number $St_h \approx 0.2$ — a characteristic of unsteady wakes behind cylinders — which is found to be largely independent of the porosity. The flame response to broadband inlet velocity perturbations was subsequently analyzed using both inlet- and locally-evaluated Flame Transfer Functions, represented as a function of St_{flame} , a Strouhal number based on the hydraulic diameter of the medium and directly linked to the flame surface area. The inlet FTF gains exhibit a non-monotonic behavior that reflects the modulation of the flame by hydrodynamic structures generated within the porous medium at $St_h \approx 0.2$. It is shown that the global flame response to inlet forcing can be interpreted as the combined effect of two mechanisms: (1) the hydrodynamic modulation of velocity perturbations by the porous structure and (2) the intrinsic flame response to local velocity fluctuations. The first contribution was characterized using locally-evaluated Hydrodynamic Transfer Functions, which demonstrate that the porous structure acts as a hydrodynamic filter. In particular, perturbations associated with the intrinsic flow dynamics at $St_h \approx 0.2$ are selectively amplified, while other frequencies are progressively attenuated as they propagate through the medium. The analysis of locally-evaluated Flame Transfer Functions further shows that, as the evaluation location approaches the flame front, the influence of hydrodynamic modulation gradually diminishes and the flame response tends toward the low-pass behavior typically observed in premixed flames and becomes similar across the different porous media when expressed in terms of pore-scale quantities. These results should support the future development of predictive flame response models to be validated against a more extensive database (various porous Reynolds numbers, inhomogeneous porous structures, three-dimensional configurations) and support the design of porous media with enhanced flame-stabilization properties.

CRedit authorship contribution statement

Alessandro Russo: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Writing – original draft; and Writing – review & editing. **Aurelien Genot:** Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing – review & editing. **Thorsten Zirwes:** Conceptualization; Investigation; Methodology; Software; Supervision; Validation; Writing – review & editing. **Oliver T. Stein:** Conceptualization; Investigation; Methodology; Supervision; Writing – review & editing. **Rémi Roncen:** Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.proci.2026.106618>.

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