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Effect of unequal fuel and oxidizer Lewis numbers on flame dynamics

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Abstract

The interaction of non-unity Lewis number (due to preferential diffusion and/or unequal rates of heat and mass transfer) with the coupled effect of radiation, chemistry and unsteadiness alters several characteristics of a flame. The present study numerically investigates this interaction with a particular emphasis on the effect of unequal and non-unity fuel and oxidizer Lewis numbers in a transient diffusion flame. The unsteadiness is simulated by considering the flame subjected to modulations in reactant concentration. Flames with different Lewis numbers (ranging from 0.5 to 2) and subjected to different modulating frequencies are considered. The results show that the coupled effect of Lewis number and unsteadiness strongly influences the flame dynamics. The impact is stronger at high modulating frequencies and strain rates, particularly for large values of Lewis numbers. Compared to the oxidizer side Lewis number, the fuel side Lewis number has greater influence on flame dynamics.

Keywords: Lewis number; Diffusion flame; Flame dynamics; Preferential diffusion; Simulations

1. Introduction

The structure and stability of a flame are significantly influenced by the interaction of several coupled parameters including radiation, chemistry, unsteadiness, thermo-diffusion and preferential diffusion. The presence of a large disparity of diffusion rates of various species and unequal rates of heat and mass transfer cause the Lewis number (which relates the rates of heat and mass diffusion of various species) to vary significantly in a flame. The interaction of non-unity Lewis number with the coupled effect of radiation, chemistry and unsteadiness alters several characteristics of a flame. The consideration of this interaction is important for obtaining an improved quantitative predictive understanding of turbulent flames.

Recent work by the author's group [1] shows a significant influence of Lewis number on the flame response to unsteadiness. In that study, the effect of non-unity Lewis number due to unequal mass and thermal diffusion rates was studied. Fuel and oxidizer were assumed to have *equal* Lewis numbers (thus equal mass diffusion rates). The effect of non-unity (but *equal*) Lewis number on various flame characteristics has been studied by many other investigators e.g., [2–5]. However, in actual flames, various species may have *unequal* Lewis numbers. This is particularly the case for flames, which have a large disparity of diffusion rates of various species and, hence, are subject to significant influence of preferential mass diffusion. The preferential diffusion affects both the temperature and species concentrations [6]. It also complicates the flame stretching phenomenon.

The influence of oxidizer and fuel Lewis numbers on the flame structure was investigated by Cuenot and Poinsot [7]. They studied the influence of non-unity Lewis number resulting from both preferential diffusion and thermo-diffusive effect. Their results predict that when the two (oxidizer and fuel) Lewis numbers are equal and lower than unity, higher diffusion rates of the reactants enhance the straining effects and the flame is quenched at a lower dissipation rate. For the case of Lewis numbers greater than unity, their results predict critical dissipation rate to be higher than the reference value. However, when the Lewis numbers are different, critical dissipation rate can take any value, depending on reactant temperatures and stoichiometric ratio. Liu et al. found that the fuel stream Lewis number has a much stronger impact on the flame location and heat release than the oxidizer Lewis number [8]. Their findings also showed the differences in mechanisms by which fuel

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Nomenclature

a_P	Planck mean absorption coefficient
a_λ	monochromatic absorption coefficient
A	pre-exponential factor
c_p	specific heat of the mixture at constant pressure
D_i	coefficient of diffusivity of species i
F	fuel
$(\Delta h_f^\circ)_i$	enthalpy of formation of species i
$i'_{\lambda b}$	spectral intensity of blackbody
k	thermal conductivity of the mixture
Le	Lewis number
Le_F	flame with non-unity fuel Lewis number and unity oxidizer Lewis number
Le_O	flame with non-unity oxidizer Lewis number and unity fuel Lewis number
M_i	molecular weight of species i
N	number of non-inert species
P	pressure, combustion products
$\mathbf{Q}_{RAD}$	radiant heat flux vector
r	radial coordinate
S	Strouhal number [defined as: frequency/ (2* strain rate)]
T	temperature
T_a	activation temperature of Arrhenius expression
T_{in}	reactant inlet temperature
t	time
V	velocity vector
v_r	radial velocity component
v_z	longitudinal velocity component
Y_i	mass fraction of species i
z	longitudinal coordinate

Greek variables

∇_c	del operator for cylindrical coordinates
∇_c^2	Laplacian for cylindrical coordinates
λ	wavelength
ν	kinematic viscosity for the mixture, mass based stoichiometric air/fuel ratio
ρ	density of the mixture
σ	Stefan–Boltzmann constant
ω	mass production rate
ω_i	mass production rate of species i

and oxidizer Lewis numbers affect the adiabatic flame temperature. The difference of the influence of the two Lewis numbers on steady flame burning ("flammability limits") was shown by Mills and Matalon [9]. Daou and Linan investigated the effect of unequal Lewis numbers on the propagation of the triple flame [10]. Chen et al. investigated the influence of non-unity fuel Lewis number on NO_x emission levels [11]. The inequality in Lewis numbers due to differential diffusion and its influence on flamelet formulation were investigated by Pitsch and Peters [12].

The past studies clearly established the importance of including the variable Lewis numbers in understanding the flame structure, emission and other characteristics. However, the effect of *non-unity* and *unequal* Lewis number on flame response to unsteadiness has not been explicitly studied. A better understanding of the flame response to unsteadiness is important for improving the flamelet approach of turbulent combustion modeling [13–16]. This requires investigation of the effects of several time-varying parameters on the flame. The present study is an attempt to fill the existing gap in the literature. It numerically investigates the influence of unequal fuel and oxidizer Lewis numbers and of their interaction with unsteadiness and radiant losses on diffusion flames. The unsteadiness is simulated by considering the radiating counterflow diffusion flames subjected to modulations in reactant concentration. Studying the effect of the reactant concentration modulations is important since such modulations bring about significant effect on flame structure through changes in the global equivalence ratio (which is an important parameter in flamelet modeling approach). The reactant concentration fluctuations are also important in practical combustors that are subjected to various unsteady fluctuations. The present study considers flames with different strain rates and subjected to different modulating frequencies.

2. Mathematical formulation

The problem was formulated by considering a counterflow diffusion flame stabilized near the stagnation plane of two laminar flows. The governing equations for such a configuration can be written as following:

Conservation of mass

$$\frac{\partial \rho}{\partial t} = -\nabla_c \cdot (\rho \mathbf{V})$$

Conservation of momentum

$$\frac{\partial \mathbf{V}}{\partial t} = -\mathbf{V} \cdot \nabla_c \mathbf{V} + \left[\frac{\rho_\infty}{\rho} v_r \frac{\partial v_r}{\partial r} - \frac{1}{\rho}\frac{\partial P}{\partial z}\right]^{\mathrm{T}} + \nu \nabla_c^2 \mathbf{V}$$

Conservation of energy

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla_c T + \frac{1}{\rho c_p}\left[\nabla_r \cdot (k \nabla_c T) - \sum_{i=1}^{N} (\omega \Delta h_f^\circ)_i\right] - \mathbf{Q}_{\mathrm{RAD}}$$

Conservation of species

$$\frac{\partial Y_i}{\partial t} = \frac{1}{\rho}\left[\nabla_c \cdot (\rho D_i) - \rho \mathbf{V}\right] \cdot \nabla_c Y_i + D_i \nabla_c^2 Y_i + \frac{\omega_i}{\rho}$$

The governing equations were simplified by using the assumptions of axisymmetric geometry, negligible body forces, negligible viscous dissipation, negligible Dufour effect, negligible temporal variations of pressure, and by employing the similarity transformations. The governing equations are closed by the ideal gas relations. The radiative heat flux is modeled by using the thin gas approximation. Using this assumption, the radiative heat flux at any point in the flame may be written as [17]:

$$\nabla \cdot \mathbf{Q}_{\mathrm{RAD}} = 4\pi \int_0^\infty a_\lambda(\lambda, T, p) i'_{\lambda b}(\lambda, T)\,\mathrm{d}\lambda$$

where $i'_{\lambda b}$ is the blackbody intensity and a_λ is the monochromatic absorption coefficient. By defining the Planck mean absorption coefficient as:

$$a_\mathrm{P}(T, p) = \pi \int_0^\infty a_\lambda(\lambda, T, p) i'_{\lambda b}\,\mathrm{d}\lambda / \sigma T^4$$

one obtains $\nabla \cdot \mathbf{Q}_{\mathrm{RAD}} = 4\sigma T^4 a_\mathrm{P}$. In this study, which deals with a non-sooty flame, the main contributors to radiative heat losses are the gaseous combustion products CO_2 and H_2O. Hence the radiative flux may be written as: $\nabla \cdot \mathbf{Q}_{\mathrm{RAD}} = 4\sigma T^4(a_{\mathrm{P,CO_2}} + a_{\mathrm{P,H_2O}})$; where σ is the Stefan–Boltzmann constant, and $a_{\mathrm{P,CO_2}}$, $a_{\mathrm{P,H_2O}}$ are the Planck mean absorption coefficients for CO_2 and H_2O, respectively. The values of absorption coefficients were obtained from Abu-Romia and Tien [18], and their accuracy was checked by using Grosshandler's narrow band model [19].

The study considers a diffusion flame with properties, except Lewis numbers, similar to those of a methane–air flame. The detailed kinetic mechanism of a methane–air flame is well established and documented [20]. However, in accordance with the objective of the present study (i.e., identification of the preferential diffusion effects of fuel and oxidizer streams), it employs a single step overall reaction:

$$[\mathrm{F}] + \nu[\mathrm{O_2}] + 3.76\nu[\mathrm{N_2}] \to (1+\nu)[\mathrm{P}] + 3.76\nu[\mathrm{N_2}]$$

Here, ν is the mass-based stoichiometric coefficient. Using second order Arrhenius kinetics, the reaction rate was defined as $\omega = A\rho^2 Y_\mathrm{F} Y_\mathrm{O} \exp(-T_a/T)$. The reaction rates for fuel, oxidizer, and product may then be written as $\omega_\mathrm{F} = -\omega$; $\omega_\mathrm{O} = -\nu\omega$; and $\omega_\mathrm{P} = (1+\nu)\omega$. Here, N_2 was used as an inert diluent.

The governing equations were solved by specifying the initial and boundary conditions. The initial conditions require the specification of initial flow rate, temperature and species concentration profiles. The initial steady profiles were obtained from the numerical solution of a steady-state flame. The boundary conditions require the specification of flow, temperature and species concentration at the fuel and oxidizer sides of the boundaries.

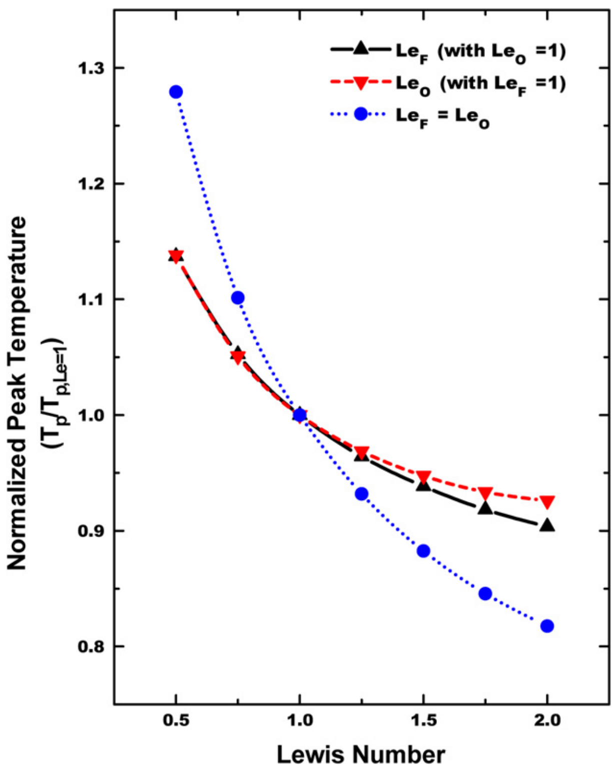
The governing equations were solved by using the numerical method of lines. A second order 3-point central difference formula was used to spatially discretize the equations and an implicit backward differentiation formula was used to integrate in the temporal direction. Based on a grid sensitivity analysis, a uniform grid with a mesh size of 0.16 mm (which is much less than the length scale of the problem) and a variable time step of the order of 1 microsecond (which is also smaller than the smallest time scale of the problem) were used in this study.

The parameter values used in the present calculations are $T_\mathrm{in} = 295$ K, $T_a = 14602$ K, pre-exponential constant $A = 9.52 \times 10^9$ ($\mathrm{m^3\,kg^{-1}\,s^{-1}}$), and fuel heating value $= 47.465 \times 10^6\ \mathrm{J\,kg^{-1}}$. These values were taken from Atreya and Agrawal [21]. The reactant mass fractions at the inlet boundaries for the steady state base case were set as: $Y_{\mathrm{F\text{-}in}} = 0.125$ and $Y_{\mathrm{N\text{-}in}} = 0.875$ on the fuel side; $Y_{\mathrm{O\text{-}in}} = 0.5$ and $Y_{\mathrm{N\text{-}in}} = 0.5$ on the oxidizer side. The corresponding Zeldovich number (defined as the ratio of diffusive length scale to reactive length scale [22]) for the steady flames was 5.4. The combustion products were assumed to be composed of one-third of CO_2 and two-third of H_2O. The details of solution procedure, code validation and the values of various constants and properties are listed elsewhere [15].

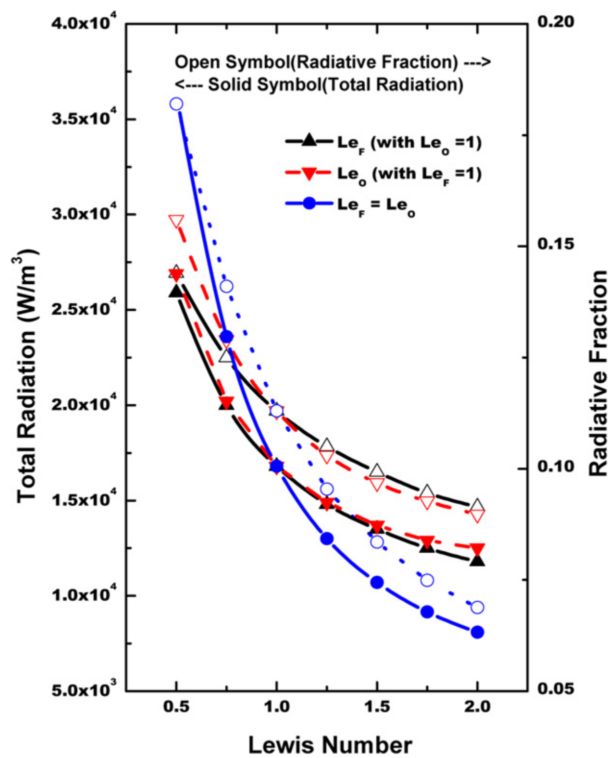
3. Results and discussion

In this study, the Lewis number was varied by changing the mass diffusion coefficients of fuel and oxidizer streams while keeping the thermal diffusivities of various species constant at values corresponding to unity Lewis number. Thus any change in Lewis number was due to variation in mass diffusion rates ($Le \sim 1/D_i$). The range of Lewis number values investigated was from 0.5 to 2, which is not realistic for methane–air flames. However, as mentioned earlier, the arbitrarily different values of Lewis numbers were used to highlight the effects of Lewis numbers. The influence of Lewis number and its interaction with unsteadiness can be better understood by first reviewing the effect of Lewis number on flame temperature and radiation characteristics under steady state conditions. Fig. 1(a) shows the projected normalized peak temperatures of flames subjected to a strain rate of $10\ \mathrm{s^{-1}}$ with various values of Lewis numbers. The normalization was done by using the peak temperature of flame with equal and unity Lewis number. Flames with equal and unequal fuel and oxidizer Lewis numbers were studied. Flames with unequal Lewis numbers (marked as Le_F and Le_O) show the effect of preferential diffusion. In these flames, Lewis number of one reactant was varied by varying the corresponding mass diffusion rate and keeping the other reactant Lewis number constant at unity.

As expected, the results show that peak temperatures increase with a decrease in Lewis number for all three cases. The effect of Lewis number on peak temperature is greater for the case of equal Lewis numbers. Compared to the case of unity Lewis number, the peak temperature is 28% higher for Lewis number of 0.5 and is 18% lower for Lewis number of 2. The peak temperatures of unequal Lewis number flames are relatively less sensitive to Lewis number values. For Lewis numbers below unity, flames with unequal fuel and oxidizer Lewis number have similar peak temperatures. Compared to the case of unity Lewis number, the peak temperature is 14% higher for unequal fuel and oxidizer Lewis number flames with a non-unity reactant (either fuel or oxidizer) Lewis number of 0.5. However, with an increase of Lewis number, the fuel stream Lewis number has gradually stronger impact on the flame temperature than the oxidizer stream Lewis number. This result is in agreement with the findings of Liu et al. [8]. For flames with the fuel and oxidizer Lewis numbers of 2, the peak temperatures are re-



(a)



(b)

Fig. 1. (a) Effect of Lewis number on steady flame temperature; (b) Effect of Lewis number on radiative heat loss and radiative fraction. (strain rate = 10 s^{-1}; boundary temperature = 295 K; reactant mass fractions = 12.5% CH_4 + 87.5% N_2 on the fuel side and 50% O_2 + 50% N_2 on the oxidizer side).

spectively 10% and 7.5% lower compared to the case of unity Lewis number.

The radiative heat loss, shown in Fig. 1(b), follows a similar trend as temperature. The radiative heat losses are maximum at low Lewis numbers, which is due to corresponding high flame temperatures. Similar to the temperatures, the radiative heat losses for flames with equal Lewis numbers are also very sensitive to Lewis number. The predicted radiative heat losses for flames with unequal Lewis numbers are relatively less sensitive to Lewis number. The radiative heat losses for low oxidizer Lewis number flames are slightly higher than those for the corresponding low fuel Lewis number flames. It is interesting to note that these flames have similar peak temperatures. Radiative fraction (defined as instantaneous ratio of the total heat radiated to the total amount of heat released) also shows similar trends. A higher value of radiative fraction for a low oxidizer Lewis number flame indicates that such a flame loses by radiation a higher fraction of the total heat released than a flame with the corresponding low fuel Lewis number. For the calculations presented here, the radiative heat losses for a flame with a uniform Lewis number of 0.5 are 18.2% of the total heat released. These losses are 14.4% and 15.6% for flames with unequal fuel and oxidizer Lewis numbers of 0.5, respectively. The radiative losses decrease to 6.9% for flames with equal Lewis numbers of 2, and to 9.1% and 9% for flames with unequal fuel and oxidizer Lewis numbers of 2, respectively.

The coupling effects of Lewis number with unsteadiness were studied by considering flames subjected to temporal modulations in fuel concentrations, for flames with equal and unequal Lewis numbers. The simulations were carried out by considering initially steady flames that were later subjected to sinusoidal modulations in fuel concentrations. During the simulations, all flame properties and parameters except Lewis numbers were considered to be time-dependent. Fig. 2 shows the results for flames with a strain rate of 10 s^{-1}, which were subjected to sinusoidal fluctuations in fuel concentration of 20 Hz and 50% amplitude. The modulation amplitude results in fuel concentration variations from 0.0625 to 0.1875. This value of modulation amplitude was selected since it covers a sufficient range with the extreme values of fuel concentration not too far from the mean value. The modulation amplitude only affects the response amplitude [15] and hence the findings of the present study are not exclusive for the selected modulation amplitude. The selected value of modulation frequency falls into a regime where the flame response is influenced by the transient effects. According to our previous studies the flame responds quasi-steadily to fluctuations at low frequencies and become insensitive at high frequencies [15,16]. The transient effects are important in a moderate frequency regime (which is determined based on a modified Strouhal number to be 2–20 Hz for a strain rate of 10 s^{-1}). It is this moderate frequency range, in which we anticipate to find a greater influence of Lewis number. Fig. 2 shows the variations of peak flame temperature (normalized with the corresponding steady-state value for the stoichiometric conditions) as a function of fluctuation time period. Results are shown after the response becomes periodic. Results for six different cases of Lewis numbers are presented: flames with

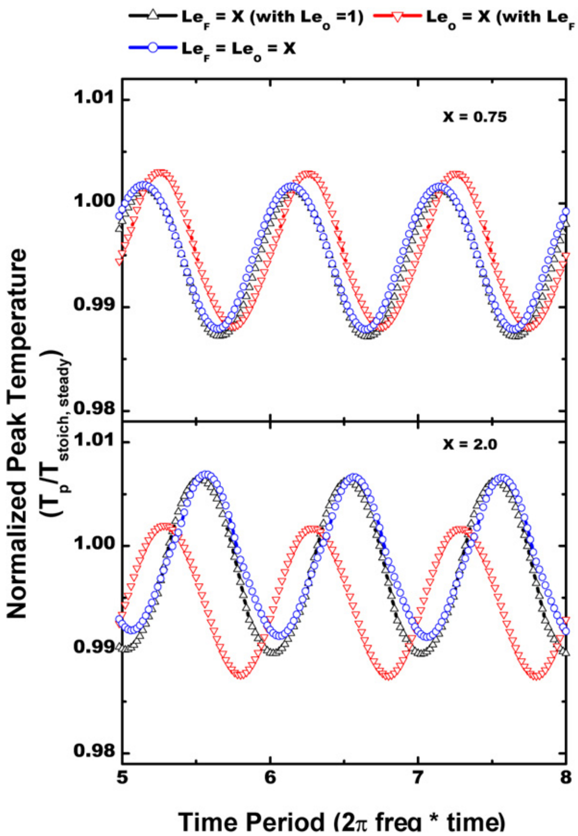


Fig. 2. Effect of equal and unequal Lewis number on flame response to sinusoidal fluctuations in fuel concentrations (amplitude = 50%; frequency = 20 Hz; strain rate = 10 s^{-1}).

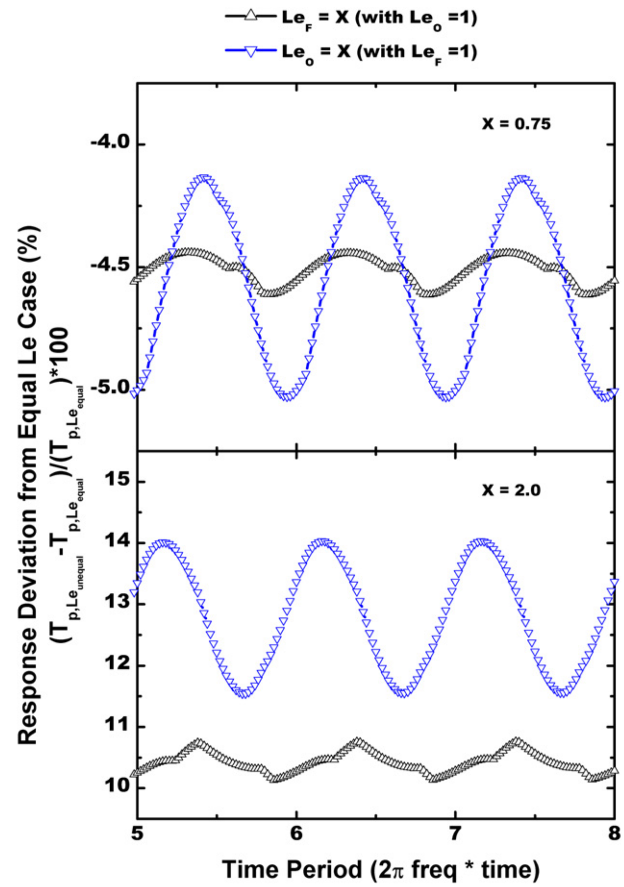


Fig. 3. Deviation in flame response to unsteadiness due to inequality in fuel and oxidizer Lewis numbers (amplitude = 50%; frequency = 20 Hz; strain rate = 10 s^{-1}).

fuel stream Lewis numbers of 0.75 and 2, and oxidizer stream Lewis number of unity (marked as Le_F); flames with oxidizer stream Lewis numbers of 0.75 and 2, and fuel stream Lewis number of unity (marked as Le_O); and flames with equal fuel and oxidizer stream Lewis numbers of 0.75 and 2 (marked as $Le_F = Le_O$). All flames respond sinusoidally to sinusoidal imposed fluctuations. However, the flame response, including the normalized response amplitude and phase shift, is different for different types of flames. The difference in response is greater at higher value of Lewis number. The response of Le_F flames is relatively similar to that of the flames with the corresponding equal Lewis numbers, whereas the response of non-unity oxidizer Lewis number flames has relatively larger deviations. At low Lewis numbers, Le_O flame is relatively more responsive to imposed modulation. However, with an increase of Lewis number above unity, the Le_F flame becomes more responsive. Similar findings were obtained by using the calculated peak product concentration as the measure of flame response (profiles are not shown in this article for the sake of brevity).

The radiative heat losses respond to unsteadiness in a similar manner as temperatures (results not shown here). At Lewis number of 0.75 (below unity), the response amplitude of radiative heat losses was higher for an Le_O flame (response amplitude = 3.5%) than for an Le_F flame (response amplitude = 3.0%) and equal Lewis number flame (response amplitude = 2.5%). This order is reversed at Lewis number of 2 (above unity), with the radiative heat loss response amplitude to be higher for an equal Lewis number flame (response amplitude = 4.5%) than for an Le_F flame (response amplitude = 4.2%) and an Le_O flame (response amplitude = 4.0%). The results show the influence of Lewis number on flame response to unsteadiness.

The difference in flame response to unsteadiness due to inequality in fuel and oxidizer Lewis numbers is more clearly shown in Fig. 3. In this figure, the flame response deviation from that of a corresponding equal Lewis number case is plotted as a function of modulation time period. The negative values at Lewis number of 0.75 indicate that the responses of unequal fuel and oxidizer Lewis number flames (Le_F and Le_O) are lower than that of the corresponding equal Lewis number case. This trend is different at higher value of Lewis number, where the response deviation is positive and is larger. The response deviation is cyclic to imposed cyclic modulations. The deviation is nearly sinusoidal for Le_O flames. The locations of peak values of response deviation are different for different Lewis number cases, which is due to differences in phase change of these flame responses. For both Lewis numbers, the response deviation is relatively greater for Le_O flames. These flames also show greater variation in their response deviation, which is due to greater responsiveness of these flames to unsteadiness.

In addition to differences in peak temperature response, the flame location and thickness are also affected by the non-

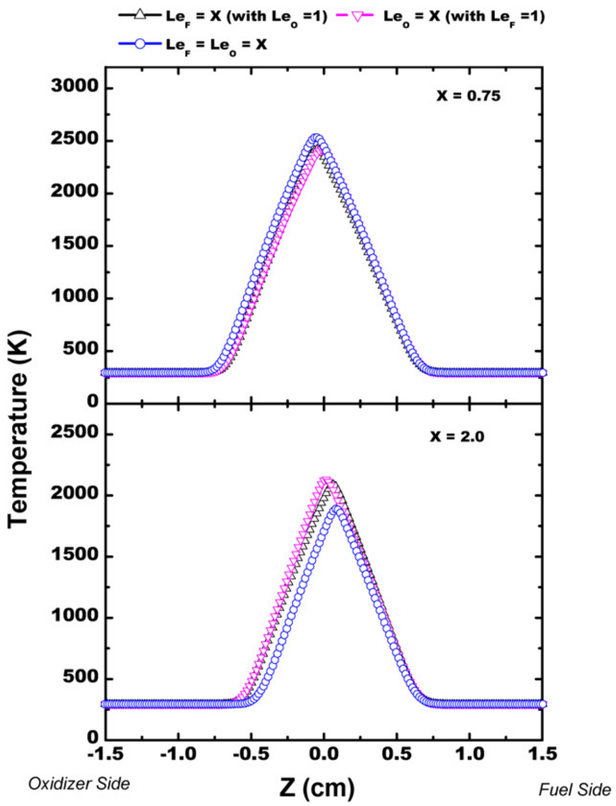


Fig. 4. Temperature profiles of flames with different Lewis numbers at the peak of their cyclic response to fuel concentration modulations (amplitude = 50%; frequency = 20 Hz; strain rate = 10 s^{-1}).

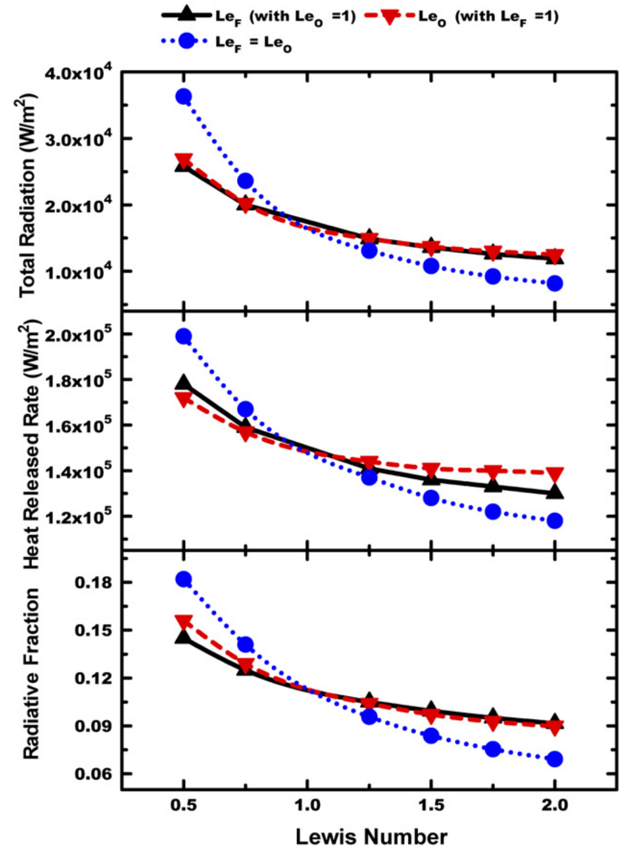


Fig. 5. Radiation and heat release characteristics of the flames subjected to modulations in fuel concentrations with different Lewis numbers (amplitude = 50%; frequency = 20 Hz; strain rate = 10 s^{-1}).

uniformity in fuel and oxidizer Lewis numbers, as shown by Fig. 4. The figure compares the temperature profiles of flames with different Lewis numbers at the peak of their cyclic response. For a Lewis number of 0.75, the results show that flames with equal Lewis numbers have higher peak temperature and larger thickness than those with unequal Lewis numbers. The figure also points out that all three flames with equal and unequal Lewis numbers move from their initial position to the oxidizer side. This location shift is due to the fact that the peak temperature profiles shown here correspond to a peak in fuel concentration. Compared to the Le_O flame, the Le_F flame is shown to move slightly more toward the oxidizer side. This is consistent with a higher fuel mass diffusion rate, which transmits the changes in fuel concentrations faster for the case of fuel Lewis number of less than unity. For a Lewis number of 2, the Le_O flame has the higher peak temperature and larger thickness than that of the Le_F flame. Compared to the non-uniform cases, the equal Lewis number case has the lower peak temperature and smaller thickness. The flames with lower fuel mass diffusion rates ($Le_F = 2$ and $Le_F = Le_O = 2$) move toward the fuel side of the stagnation plane. This movement can be explained by considering that the imposed modulation is caused by variations in fuel concentrations. The location of the flame on the fuel side has strong implications on flame dynamics [23] and pollutant emission characteristics [24]. Due to differences in thermo-chemical environment, the net production of soot and NO_x is very different for a fuel-side flame from that of an oxidizer-side flame [24]. However, the pollutant formation characteristics were not the focus of the present study, and hence, they were not investigated.

The radiation and heat release characteristics of these flames are presented in Fig. 5. The characteristics shown were obtained by averaging the instantaneous values over the modulation period. The radiation characteristics of these transient cases are very similar to those of steady state cases. With an increase of Lewis number, radiation losses decrease, which is due to a corresponding decrease in the flame temperature. Similar to the temperature response, the decrease in radiative heat losses is greater for the equal Lewis number case. Compared to the unequal fuel and oxidizer Lewis number cases, the radiative heat losses of the equal Lewis number case are greater for Lewis number below unity, but they become smaller for Lewis numbers above unity. For the range of Lewis number studied, the Le_F flame generally has lower radiative losses. However, the radiative losses for Le_F and Le_O flames are not very significantly different. The differences between different cases increase with the departure of Lewis number value from unity.

The dependence of heat released rate on Lewis number is similar to that of radiative losses. The heat release rate decreases with an increase of Lewis number, with the equal Lewis number case being more sensitive to changes in Lewis number. The heat release from an Le_O flame is relatively less sensitive to changes in Lewis numbers. Similar to radiation character-

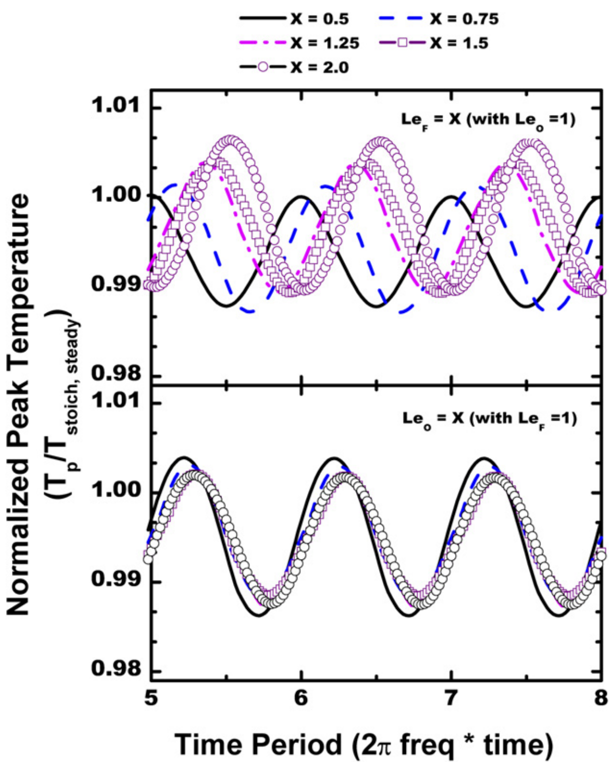


Fig. 6. Effect of fuel and oxidizer Lewis numbers on flame response to sinusoidal fluctuations in fuel concentrations (amplitude = 50%; frequency = 20 Hz; strain rate = 10 s^{-1}).

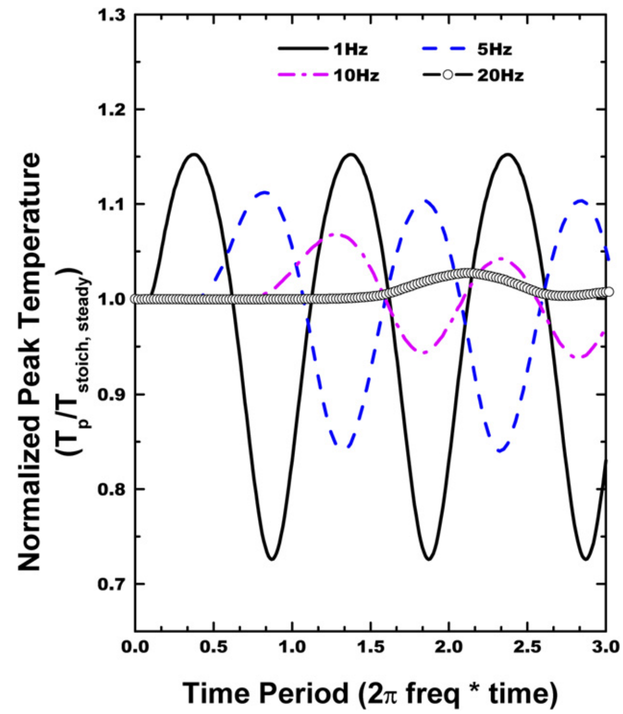


Fig. 7. Effect of modulation frequency on flame response to sinusoidal fluctuations in fuel concentrations (amplitude = 50%; frequency = 1 Hz; strain rate = 10 s^{-1}; fuel $Le = 0.75$; oxidizer $Le = 1$).

istics, the difference between different cases increases with the departure of Lewis number value from unity. The radiative fraction also decreases with an increase of Lewis number. This indicates a greater fraction of heat being lost by radiation at low Lewis numbers. Compared to unequal Lewis number cases, the radiative fraction of equal Lewis number case is higher for Lewis number below unity and lower for Lewis number above unity. Compared to an Le_F flame, the radiative fraction of an Le_O is higher for Lewis number below unity (due to a smaller amount of heat released), and lower for Lewis number above unity.

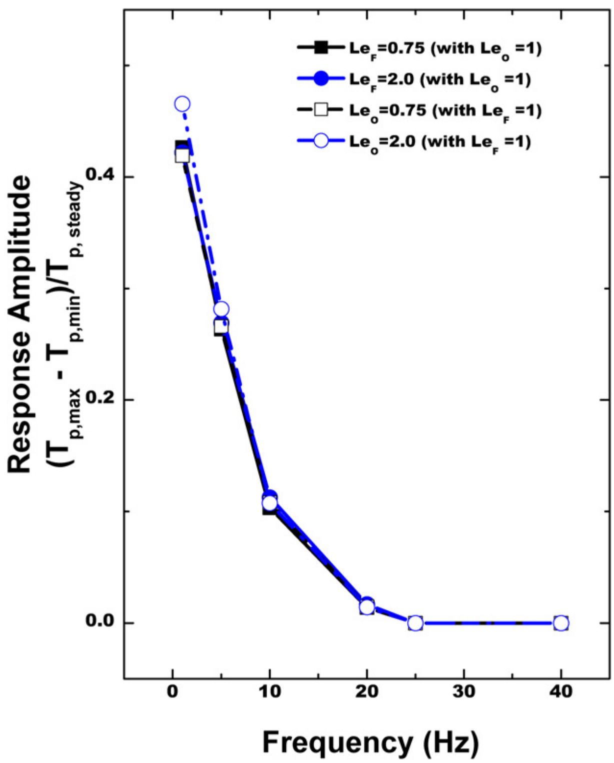
Fig. 6 shows the effect of different values of Lewis numbers (ranging from 0.5 to 2) on flame response for flames with non-unity and unequal fuel and oxidizer Lewis numbers. The results presented are for flames with a strain rate of 10 s^{-1}, which were subjected to fuel concentration fluctuations of 20 Hz and 50% amplitude. Results are shown after the response becomes periodic. These results are similar to those presented in Fig. 2. The figure depicts that the flames with non-unity fuel stream Lewis numbers are relatively more sensitive to variations in Lewis numbers. The flame response amplitude and phase shift increase with an increase of fuel Lewis number. At higher Lewis numbers, the flame response also becomes more symmetric with respect to its steady-state value. The response of non-unity oxidizer Lewis number flames is, however, found to be less dependent on Lewis number variations. For Lewis numbers ranging from 0.5 to 1.75, the flame response decreases with an increase of Lewis number. But for Lewis numbers from 1.75 to 2, the flame response increases.

The results show that, at low values of Lewis numbers, there is not much difference in response of Le_F and Le_O flames. For the flame conditions shown in the figure, the response amplitude of an Le_O flame is only 4% higher than that of an Le_F flame at a Lewis number of 0.75. However, the difference in flame response grows with an increase of Lewis number. At a Lewis number of 2, the response amplitude of an Le_O flame is 18% lower than that of an Le_F flame.

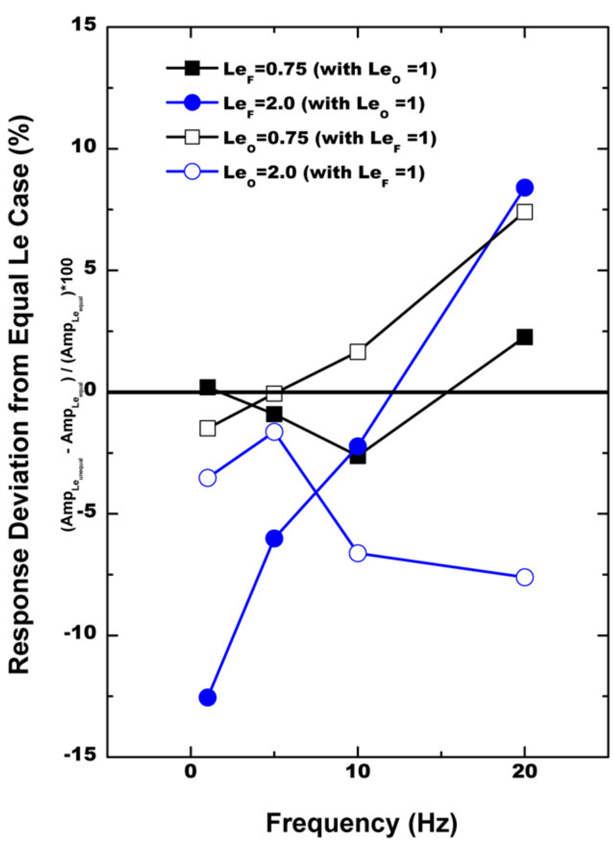
3.1. Effect of frequency

The effect of fluctuation frequency was investigated by simulating the flames subjected to variations in fuel concentration with different modulation frequencies. Fig. 7 shows the results for flames characterized by a fuel Lewis number of 0.75, which were subjected to 50% fuel concentration fluctuations at a strain rate of 10 s^{-1}. The figure shows that the flame response is maximum at low frequencies and that its amplitude decreases with an increase of the imposed frequency. For the present conditions, the flame becomes insensitive to the imposed fluctuations at frequencies higher than 25 Hz (shown in Fig. 8(a)). This insensitivity is due to effective neutralization of the high frequency concentration fluctuations by diffusion over the time period required to convect them into the reaction zone [14]. The results for flames with other Lewis numbers (not shown here) indicate similar trends. These results are in agreement with the past studies [14–16].

The effect of Lewis number on flame response to modulations at different frequencies is shown in Fig. 8. The results presented are for flames with a strain rate of 10 s^{-1}, which were subjected to fuel concentration fluctuations of 50% amplitude. Fig. 8(a) shows the flame temperature response (nor-



(a)



(b)

Fig. 8. Effect of Lewis number on flame response to imposed fluctuations at various frequencies: (a) normalized flame response; (b) response deviation from that of a flame with equal and the corresponding value of Lewis number. (amplitude = 50%; strain rate = 10 s^{-1}).

malized with the peak steady temperature corresponding to stoichiometric conditions) of four flames with different Lewis numbers. The results show that the dependence of flame response on modulation frequency is similar for different Lewis number flames. The cutoff frequency at which flame becomes insensitive to imposed modulation is also similar for different Lewis number flames. At low frequencies, the response amplitude of an Le_O flame with oxidizer Lewis number of 2 is slightly greater than that of other cases. The effect of unequal Lewis numbers on the flame response to modulations at different frequencies is more clearly shown in Fig. 8(b). In this figure, flame response deviation from that of a flame with equal and the corresponding value of Lewis numbers is plotted as a function of modulation frequency. Thus, a negative response deviation value indicates the flame response amplitude to be lower than that of the corresponding equal Lewis number flame. The differences in flame response amplitude between flames with equal and unequal Lewis numbers clearly show the influence of Lewis number on the flame response at all frequencies. The deviation varies with Lewis number and modulation frequency. At 1 Hz (quasi-steady regime), the response amplitudes of unequal Lewis number flames are lower than those of the equal Lewis number flames. For all frequencies, the response amplitude of an Le_O flame with oxidizer Lewis number of 2 is lower than that of the corresponding flame with equal Lewis number case, whereas the other flames in the figure have both lower and higher response amplitudes at different frequencies. In the transient regime (frequency range of 2–20 Hz for strain rate of 10 s^{-1}), the deviation of flame response from that of the corresponding equal Lewis number flame generally increases with an increase of frequency (with the maximum deviation remains under 10%). The deviation also increases with the increase of Lewis number. These findings indicate that, within the frequency regime where transient effects are important, inequality in Lewis number has greater influence at higher frequencies.

In addition to the difference in response amplitude, the difference in response delay (phase shift) also increases at higher frequencies. Fig. 9 depicts the phase shift of various flames as a function of modulating frequency. The figure shows that the phase shifts for all flames increase almost linearly with frequency. The phase-shift for Le_O flames (with non-unity oxidizer Lewis numbers) is not sensitive to the value of Lewis number at all frequencies. However, for Le_F flames (with non-unity fuel Lewis numbers), the phase shift increases with an increase of Lewis number. The phase shift dependence of such flames on Lewis number increases with frequency. At low values of Lewis numbers, the Le_O flames have larger phase shift than the corresponding Le_F flames. This trend is reversed at higher values of Lewis numbers.

3.2. Effect of strain rate

Previous studies have shown that flames at higher strain rates are more responsive to unsteadiness [14–16]. Hence, at higher strain rates, the coupling effect of Lewis number with unsteadiness may become more pronounced and is of greater interest. Fig. 10 shows the predicted flame response to imposed fluctu-

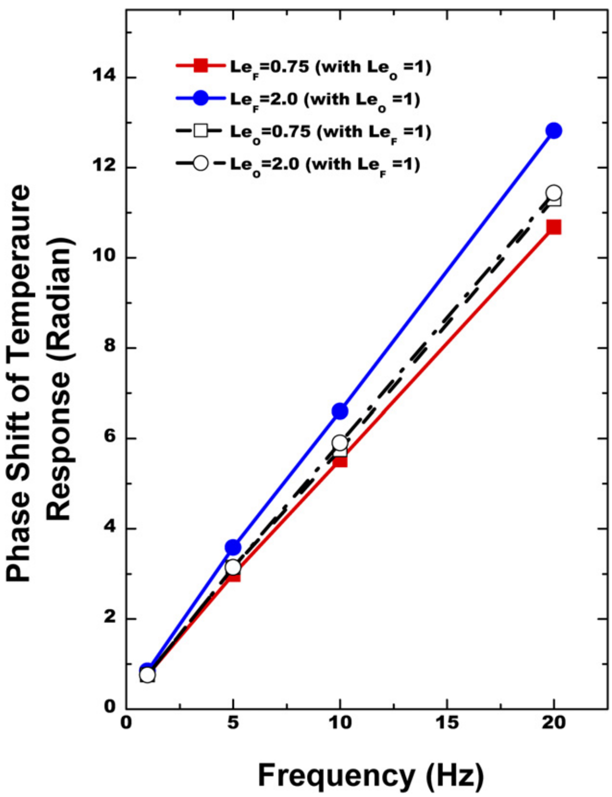


Fig. 9. Effect of Lewis number on phase shifts of flame response to imposed fluctuations at various frequencies (amplitude = 50%; strain rate = 10 s^{-1}).

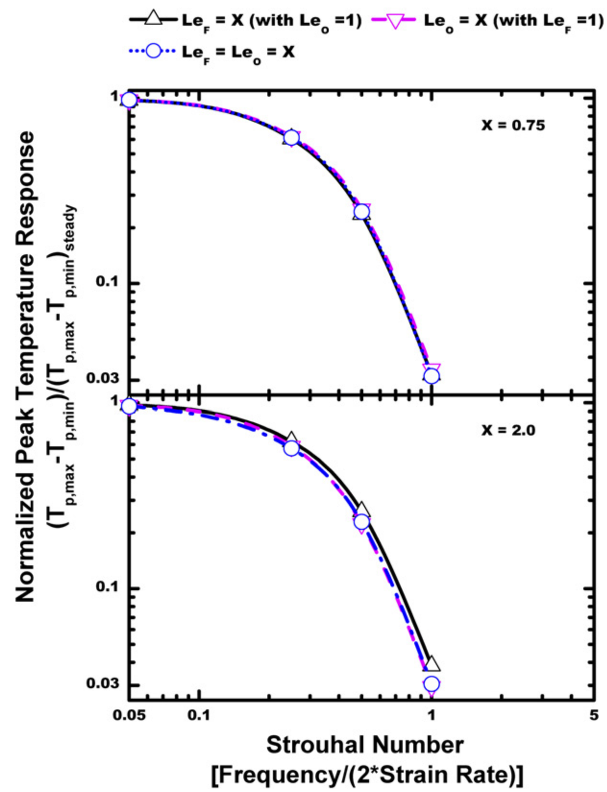


Fig. 11. Flame response to imposed fluctuations as a function of Strouhal number for various Lewis numbers (amplitude = 50%; strain rate = 10 s^{-1}).

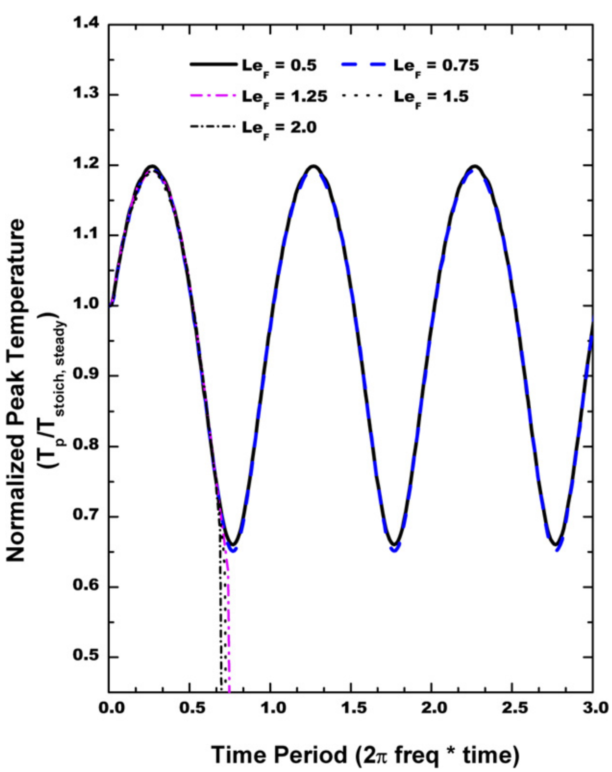


Fig. 10. Flame response to imposed fluctuations at high strain rate for various Lewis numbers (amplitude = 50%; frequency = 1 Hz; strain rate = 100 s^{-1}; oxidizer $Le = 1$).

ations at a strain rate of 100 s^{-1}. Le_F flames with fuel Lewis numbers ranging from 0.5 to 2 were considered. These flames were subjected to sinusoidal fuel concentration fluctuations of 1 Hz and 50% amplitude. The figure depicts that the flames with fuel Lewis numbers of 0.5 and 0.75 respond sinusoidally to the sinusoidal imposed fluctuations. However, the flames with fuel Lewis numbers greater than unity, are not able to survive the imposed fluctuations and suffer extinction. Similar results are found for Le_O flames (results not shown here).

The effect of strain rate and frequency is combined in Fig. 11, which shows the flame response as a function of dimensionless frequency or Strouhal number (S) (defined as frequency normalized by twice the strain rate) [15]. In this figure, the flame response amplitude is normalized by the difference of the corresponding steady state peak temperatures. Results shown are for flames with strain rate of 10 s^{-1} and Lewis numbers of 0.75 and 2. For each Lewis number, three cases are plotted: (i) Le_F; (ii) Le_O; and (iii) $Le_F = Le_O$. Figure shows that Strouhal number is a good scaling parameter for measuring the flame response to unsteadiness for different Lewis numbers. Similar to the case of unity Lewis number described by Shamim and Atreya [15], the transient effects are important for the range $0.1 \leqslant S \leqslant 1$ for different non-unity and unequal Lewis number cases. The results show that the normalized flame response of different Lewis number cases are similar for different Strouhal numbers, particularly at low Lewis numbers. At higher Lewis numbers, there is some difference between the responses of Le_F and Le_O flames. The response of Le_F flame is slightly greater than that of the Le_O flame.

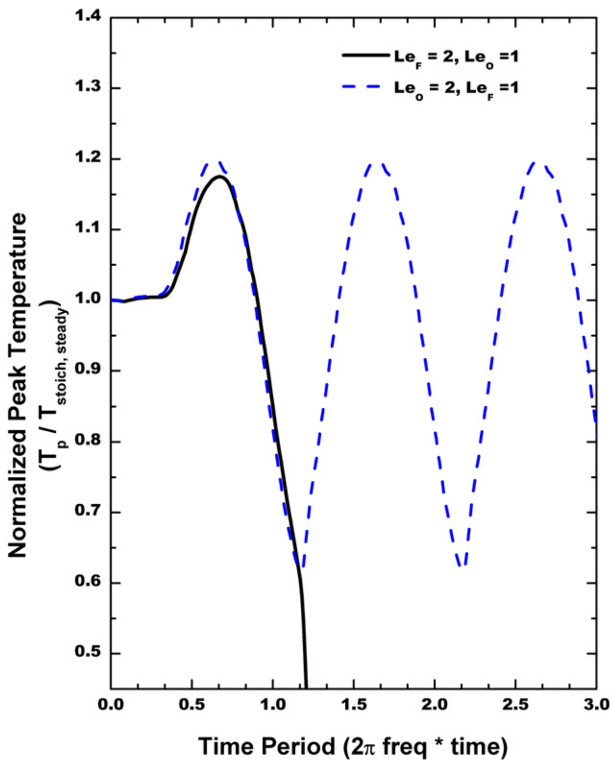


Fig. 12. Flame response to imposed fluctuations at high strain rate and moderate frequency (amplitude = 50%; frequency = 20 Hz; strain rate = 100 s^{-1}).

The extinction of large Lewis number flames at higher strain rates (shown in Fig. 10) also depends on modulating frequency. With an increase of frequency, flame response to imposed fluctuation decreases and flames with larger Lewis numbers also do not suffer extinction. For example, at 10 Hz, our investigation found that the flame with Lewis number of 1.25 also survives; and at 25 Hz, all flames with Lewis numbers ranging from 0.5 to 2 survive (results are not shown here). Considering the above results and the finding that the difference in flame response for Le_F and Le_O flames grows with the modulating frequency, there may exist frequencies at which an Le_O flame survives while the corresponding Le_F flame experiences extinction. For flames subjected to fuel concentration fluctuations at the strain rate of 100 s^{-1}, such a situation occurs at 20 Hz and Lewis number of 2 (flame with $Le_F = 2$ experiences extinction whereas flame with $Le_O = 2$ survives, see Fig. 12). This result clearly highlights the differences in flame response to unsteadiness between Le_F and Le_O flames. For different Lewis numbers, the range of modulation frequency at or below which a flame is extinguished when subjected to concentration modulations is listed in Table 1. The table shows that the extinction frequency limit is higher for Le_F than Le_O flames. For the unsteady conditions described here, the extinction frequency limit is found to be 20 Hz for Le_F flames with fuel Lewis number of 2 and 14 Hz for Le_O flames with oxidizer Lewis number of 2. The extinction frequency limit is found to be much higher (44 Hz) for flames with equal fuel and oxidizer Lewis number of 2. For the case of flames subjected to oxidizer concentration fluctuations, the extinction frequencies are lower than those of the corresponding cases of fuel concentration fluctuations. However, the

Table 1
Effect of Lewis numbers on extinction frequencies of flames subjected to concentration modulations (amplitude = 50%; strain rate = 100 s^{-1})

Lewis number	Extinction frequency [Hz]	
	Oxidizer modulations	Fuel modulations
$Le_O = 2, Le_F = 1$	17	14
$Le_F = 2, Le_O = 1$	19	20
$Le_O = Le_F = 2$	36	44

extinction frequency limit for oxidizer modulation case is also found to be higher for Le_F flames (19 Hz at a Lewis number of 2) than for Le_O flames (17 Hz at a Lewis number of 2). For oxidizer modulations, the extinction frequency limit for equal Lewis number case is 36 Hz. These results clearly demonstrate the significance of including the influence of non-uniformity of Lewis number in flame analysis and modeling. The assumption of equal, even with non-unity, Lewis numbers has been shown to result in erroneous conclusions in assessing flame dynamic response.

4. Conclusions

In this study, the effect of unequal fuel and oxidizer Lewis numbers (due to unequal mass diffusion rates) on flame dynamics has been investigated by numerical simulations. The results lead to the following conclusions:

- The steady flame temperatures of flames with unequal fuel and oxidizer Lewis numbers are generally less sensitive to Lewis numbers than those of flames with uniform Lewis numbers. The fuel Lewis number has a stronger impact on flame temperatures.
- The coupled effect of Lewis number and unsteadiness strongly influences the flame dynamics. The impact is stronger at high modulating frequencies, particularly for large values of Lewis numbers. At high frequency, flames with non-unity fuel and oxidizer Lewis numbers may be influenced differently by the coupling effect of Lewis number and unsteadiness. Non-unity fuel Lewis number flames are more sensitive to variation in Lewis number at high frequencies, whereas at low frequencies, these flames are less sensitive to Lewis number than the flames with non-unity oxidizer Lewis numbers.
- The difference of the effect of fuel and oxidizer Lewis number on the flame dynamics becomes more pronounced at high strain rates. At high strain rate, a large fuel Lewis number may cause extinction of flames subjected to unsteady changes at moderate modulating frequencies, whereas the flames with the similar conditions and the corresponding non-unity oxidizer Lewis numbers may survive. The extinction frequency, at which a flame is extinguished when subjected to concentration modulation, is higher for flames with non-unity fuel Lewis number than those with non-unity oxidizer Lewis number.

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