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EFFECT OF FUEL TYPE ON CONICAL FLAME INSTABILITY

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ABSTRACT: In this paper, the behaviour of conical flame in respect to the coupled perturbation of velocity and equivalence ratio has been investigated. Linearized *G*-equation is utilized to define the flame dynamics. Burning velocity of a premixed mixture plays an important role in flame dynamics. Fluctuation of burning velocity due to equivalence ratio oscillation is derived. For this purpose, an empirical model, which includes the properties of a premixed mixture, is utilized. Four governing dimensionless groups emerge in flame dynamics. Beside two well-known dimensionless groups, reduced frequency ω_* and the ratio of burning velocity to the mean axial velocity $\overline{S_u}/\bar{v}$, two others dimensionless groups emerge from the empirical model of burning velocity and the correlating coupled velocity and equivalence ratio. This analysis introduces a new parameter, c_{oc}, to study the effects of operating conditions of flame which is a function of introduced dimensionless groups. The effects of fuel type, burner geometry, and equivalence ratio are studied. The comparison is made by propane/air and methanol/air indicates the propane/air has higher sensitivity to the perturbation. This Study shows the equivalence ratio can be significantly effective on the flame response.

Keywords: linear response, velocity, equivalence ratio, coupled perturbation, flame instability.

INTRODUCTION

Combustion instability in thermal devices is a major problem with a long history of challenges. Oscillations of affecting parameters lead to unstable performance of different devices such as gas turbine and rocket motors, and low emission premixed combustors [1]. Coupling between oscillations of these parameters and the natural acoustic modes of combustor can be destructive and effects on engine hardware [2].

The involving mechanisms are mainly fluctuations of strain rate, equivalence ratio [3], velocity field [4-6]and pressure[7-10] besides large-scale coherent vortices, burner boundaries [3], convective effects[11,12], and the acoustic accelerations[13, 14]. These instability mechanisms, potentially, can be coupled or induced. Combustor structure makes some of them more effective [15] and diagnosing of the main mechanisms is important. The above mentioned mechanisms cause the flame displacement speed [3], burning rate [16,17] and flame area emerge the perturbation, which finally affecting directly on the heat release rate[1,16-18].

The instability in combustors and burners are studied using different approaches such as analytical solutions with various degrees of complexities [1,19, 20], full Navier-Stokes simulations which need computational resources[3], experimental modelling which is common due to complexity of interacting and coupling phenomenon [21-23]. Analytical approaches with some simplifying assumptions are mentioned to study or model the heat of reaction, flame speed, and flame surface area [24-26].

Two common configurations are considered in the studies; propagation of flame in tubes [17,27] or combustor ducts, and external flame stabilized above burner [28,29].Two types of stabilized flames above burner are conical flame and inverted conical flame (V-flame). Conical flame response to equivalence ratio perturbation is modelled [19] and generalized for arbitrary flame shapes [30]. Also, unification of conical and inverted conical flames was reported [3].

The level of perturbation frequency, significantly, affects the flame shape and heat release. In the case of conical flame velocity perturbation, a few hundred Hertz keeps mean conical shape [31, 32], whereas strong acoustic force changes the conical flame to hemispherical one [32] and nonlinear heat release[18] was reported.

The transfer function is a measure of flame response to the upstream perturbation of affecting parameters. It is common to define the transfer function as a ratio of normalized heat release oscillations to the normalized oscillating parameters. Most of instability mechanisms lead to heat release fluctuation whereas flame area is the source of heat release [33]. Then the alternative option is to study the flame dynamics [12].

As a general problem, the oxidizer and fuel mass flow rates can be perturbed independently as two degrees of freedom. It directly results in perturbing equivalence ratio and velocity of mixture. In this study, negligible perturbation of oxidizer mass flow rate is considered. Therefore, the degrees of freedom are reduced to one, which makes equivalence ratio and velocity coupled. Reaching these coupled perturbations to the conical flame causes disturbances in the burning velocity as well as the flame area. An equivalent definition of the transfer function is presented as the ratio of normalized flame area perturbation to the normalized oscillating parameters.

The *G*-equation is used to study the dynamics of the flame. To solve this equation it is needed to determine the burning velocity of the premixed mixture. In this study, an empirical model [34] is utilized to define the burning velocity of a mixture as a function of equivalence ratio, fuel type, and mixture properties. Therefore, the approach facilitates studying the effects of the mixture properties on the obtained transfer functions of conical flame.

DYNAMICS OF FLAME

The presenting analysis is the model of premixed conical flame responses to the harmonic perturbation of coupled equivalence ratio and velocity of mixture. The model is based on the flame area perturbation. It is assumed the following assumptions are valid: 1) the flame is axisymmetric thin sheet which separates the cold reactant from the hot product, 2) the flame remains anchored at its initial base,3) diffusion time is assumed short compare to the period of perturbation [3], 4) the strain rate effects on the burning velocity is ignorable,5) it is assumed the flame is thin regarding perturbation wavelength, 6) it is assumed quasi-steady response to the perturbation,7) thermal expansion of flow and curvature effects[34]are negligible, and 8)negligible perturbation of oxidizer mass flow rate is considered.

Generally, the response of the flame to the upstream perturbation is called the transfer function. It is defined as the ratio of observed perturbation to the perturbation of causal parameters. The transfer function, here, is defined as normalized flame area perturbation $A'/\bar{A}$ to normalized perturbed equivalence ratio $\phi'/\bar{\phi}$, where A and ϕ are the flame surface area and the equivalence ratio, respectively. The – and 'denote the mean and the fluctuating values, respectively.

Variation in the equivalence ratio affects the burning velocity of the mixture. Burning velocity changes lead to the flame shape distortion which is described by the *G*-equation as a transport equation of the burning zone. It is indicated by an implicit function as $G(x,t)=0$. The reactants and products are located on $G<0$ and $G>0$, respectively. The transport equation for the $G=0$ is

$$\partial G/\partial t + \boldsymbol{V}.\nabla G = S_u|\nabla G| \tag{1}$$

Where t is time, $\boldsymbol{V}$ is the convective velocity field and S_u is the burning velocity of the mixture.

The burning velocity of mixture essentially is a function of mixture properties such as equivalence ratio, pressure, and initial temperature. For mixtures of some gaseous fuels and air, the burning velocities are obtained experimentally [34]. It is expressed as following:

$$S_u = S_{u0}(T_{u0}/T_0)^\alpha (P/P_0)^\beta \tag{2}$$

Where the power indexes α and β are expressed in terms of ϕ as

$$\alpha = 2.18 - 0.8(\phi - 1)$$

$$\beta = -0.16 + 0.22(\phi - 1)$$

$T_0 = 298$ K and $P_0 = 1$ atm are reference temperature and pressure, and T_{u0} and P as mixture temperature and pressure. S_{u0} is called reference burning velocity

$$S_{u0} = B_m + B_2(\phi - \phi_m)^2$$

Where B_m, B_2 and ϕ_m are constant for a given fuel. Equation (2) is reduced to

$$S_u = [B_m + B_2(\phi - \phi_m)^2](T_{u0}/T_0)^{2.18-0.8(\phi-1)}(P/P_0)^{-.16+0.22(\phi-1)} \tag{3}$$

Based on the reference [34], the burning velocity model is valid in the range of $T_{u0} = 298 - 700$ K, $P = 1 - 50$ atm and $\phi = 0.8 - 1.5$.

Following the assumption 6, the equation (3) can be used to express the temporal burning velocity dependency on the equivalence ratio. Therefore, decomposing equivalence ratio into mean and fluctuating parts $\phi = \bar{\phi} + \phi'$ yields:

$$S_u = \{B_m + B_2[(\bar{\phi} + \phi') - \phi_m]^2\}(T_{u0}/T_0)^{2.18-0.8[(\bar{\phi}+\phi')-1]}(P/P_0)^{-.16+0.22[(\bar{\phi}+\phi')-1]} \tag{4}$$

ϕ' in exponent of temperature and pressure ratios can be neglected compare to the other parts. Then equation (4) is reduced to

$$S_u = \{B_m + B_2[(\bar{\phi} + \phi') - \phi_m]^2\}(T_{u0}/T_0)^{2.18-0.8(\bar{\phi}-1)}(P/P_0)^{-.16+0.22(\bar{\phi}-1)} \quad (5)$$

In this analysis, temperature and pressure of unburned mixture are assumed constant. Also, B_m, B_2 and ϕ_m are known and constant for a given fuel [34]. For sake of simplicity in handling the equations, c_0 is defined as a constant parameter

$$c_0 = (T_{u0}/T_0)^{2.18-0.8(\bar{\phi}-1)}(P/P_0)^{-.16+0.22(\bar{\phi}-1)} \quad (6)$$

Neglecting ϕ'^2 in the equation (5) yields:

$$S_u = c_0[B_m + B_2(\bar{\phi} - \phi_m)^2] + 2c_0B_2(\bar{\phi} - \phi_m)\phi' \quad (7)$$

The first and the second terms represent the mean and fluctuating part of burning velocity as

$$S_u = \overline{S_u} + S_u' \quad (8)$$

where

$$\overline{S_u} = c_0[B_m + B_2(\bar{\phi} - \phi_m)^2]$$

$$S_u' = 2c_0B_2(\bar{\phi} - \phi_m)\phi' \quad (9)$$

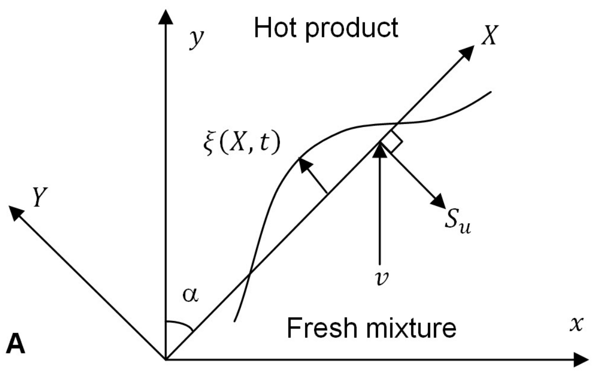


Fig. 1 (A). The steady and perturbed flame position in global (x-y) and local (X-Y) coordinates. α is half cone angle.

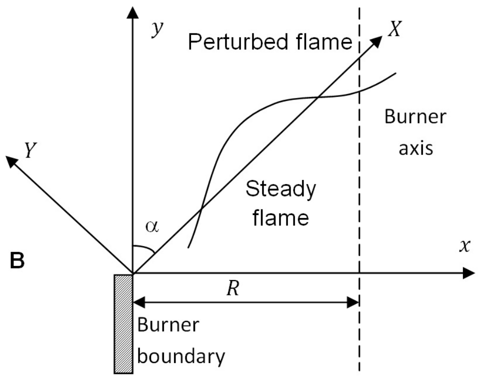


Fig. 1 (B). The conical flame above the burner with radius R.

Now, recall the equation (1); the convective velocity is assumed one dimensional with the axial component *v*. A schematic representation of the problem is shown in Fig.1 (A). Change the x-y coordinate to X-Y plane yields:

$$U = v\cos(\alpha)$$

$$V = v\sin(\alpha) \tag{10}$$

Velocities are decomposed into mean and fluctuating parts

$$\bar{U} = \bar{v}\cos(\alpha) \qquad U' = v'\cos(\alpha)$$

$$\bar{V} = \bar{v}\sin(\alpha) \qquad V' = v'\sin(\alpha) \tag{11}$$

where U' and $V'$are the tangential and normal fluctuating parts of velocity at flame front, respectively.

This transformation changes the transport equation to $G(X,t) = Y - \xi(X,t)$. Then equation (1) is changed to

$$\partial\xi/\partial t + U\,\partial\xi/\partial X - V = -S_u\sqrt{1 + (\partial\xi/\partial X)^2} \tag{12}$$

Using first order analysis for right hand side of this equation yields:

$$\partial\xi/\partial t + (U + S_u)\partial\xi/\partial X = V - S_u \tag{13}$$

Now decomposing velocitiesU,V and S_u into the mean and fluctuating parts and perturbationU' can be neglected compare to $\bar{U}$, and $\bar{V}$cancels $\overline{S_u}$; then

$$\partial\xi/\partial t + (\bar{U} + \overline{S_u})\partial\xi/\partial X = V'(t) - S_u{}'(t) \tag{14}$$

Using the time harmonic oscillations for fluctuations of velocity, equivalence ratio, and normal flame displacement perturbations yields:

$$V'(t) = V'\exp(-i\omega t) \tag{15}$$

$$\phi'(t) = \phi'\exp(-i\omega t) \tag{16}$$

$$\xi(X,t) = \tilde{\xi}(X)\exp(-i\omega t) \tag{17}$$

Where V',ϕ',$\tilde{\xi}(X)$ are initial amplitudes of temporal oscillating part of $V'(t)$, $\phi'(t)$ and $\tilde{\xi}(X)$,respectively. Then equation (9) is expressed as

$$S_u{}'(t) = 2c_0B_2(\bar{\phi} - \phi_m)\phi'\exp(-i\omega t) \tag{18}$$

Using thermodynamics of mixture and decompose the mean and fluctuating part of velocity based on equivalence perturbation yields:

$$V' = (\dot{m}_o/A_b)(\phi_s/\rho_f)\phi' \sin(\alpha) \tag{19}$$

where $\dot{m}_o$, ρ_f and ϕ_s are mass flow rate of oxidizer, density of fuel and stoichiometric equivalence ratio of mixture, respectively.Inserting equations (15-18) in equation (14), it is reduced to

$$-i\omega\tilde{\xi}(X) + (\bar{U} + \bar{S_u})\,\partial\tilde{\xi}(X)/\partial X = V' - 2c_0B_2(\bar{\phi} - \phi_m)\phi' \tag{20}$$

To solve the above first order kinematic equation as an ordinary differential equation using a boundary condition obtained by assumption 2, zero displacement at base($\tilde{\xi}(0) = 0$), yields:

$$\tilde{\xi}(X) = \frac{V' - 2c_0B_2(\bar{\phi} - \phi_m)\phi'}{i\omega}\left[\exp\left(\frac{i\omega X}{\bar{U} + \bar{S_u}}\right) - 1\right] \tag{21}$$

Now change the local coordinate back to global one by $x = X\sin(\alpha)$, yields:

$$\tilde{\xi}(x) = \frac{V' - 2c_0B_2(\bar{\phi} - \phi_m)\phi'}{i\omega}\left[\exp\left(\frac{i\omega x}{(\bar{U} + \bar{S_u})\sin(\alpha)}\right) - 1\right] \tag{22}$$

FLAME TRANSFER FUNCTION

Using the dimensionless group called reduced frequency $\omega_* = 2\omega R/\bar{v}\sin(2\alpha)(1+\tan(\alpha))$. Now equation (22) can be reduced to

$$\tilde{\xi}(x) = \frac{V' - 2c_0B_2(\bar{\phi} - \phi_m)\phi'}{i\omega_*\bar{v}\sin(\alpha)\cos(\alpha)\,(1+\tan(\alpha))/R}\left[\exp\left(i\omega_*\frac{x}{R}\right) - 1\right] \tag{23}$$

As a bench mark if $\phi'$is going to zero in the equation (23), resultant equation is identical to velocity perturbation which derived by reference [3].Now to calculate transfer function, the area fluctuations of conical flame is needed.

Conical flame: A first order estimation of conical flame area fluctuation $A'(t)$is [3]

$$A'(t) = \frac{2\pi}{tan(\alpha)}\int_0^R (R-x)\,\frac{\partial\xi(x,t)}{\partial x}\,dx \tag{24}$$

Recall equation (17) in the global coordinate $\xi(x,t) = \tilde{\xi}(x)\exp(-i\omega t)$, Then the flame area fluctuation can be written as

$$A'(t) = A'\exp(-i\omega t) \tag{25}$$

Where A' is initial amplitude of $A'(t)$. Consequently, equation (24) is reduced to

$$A' = \frac{2\pi}{tan(\alpha)}\int_0^R (R-x)\,\frac{\partial\tilde{\xi}}{\partial x}\,dx \tag{26}$$

The mean area of conical flame is $\bar{A} = \pi R^2/\sin(\alpha)$. To obtain the transfer function, equations (19) and (23) are substituted in equation (26) and using the boundary condition $\tilde{\xi}(0) = 0$ to solve equation (26), then for sake of simplicity, the transfer function, can be written as

$$F_c = c_{oc}\tilde{F}_c(\omega_*) \tag{27}$$

Where

$$c_{oc} = \frac{\bar{\phi}}{\bar{v}\sin(\alpha)(1+\tan(\alpha))}\left[\frac{\dot{m}_o}{A_b}\frac{\phi_s}{\rho_f}\sin(\alpha) - 2c_0B_2(\bar{\phi}-\phi_m)\right] \tag{28}$$

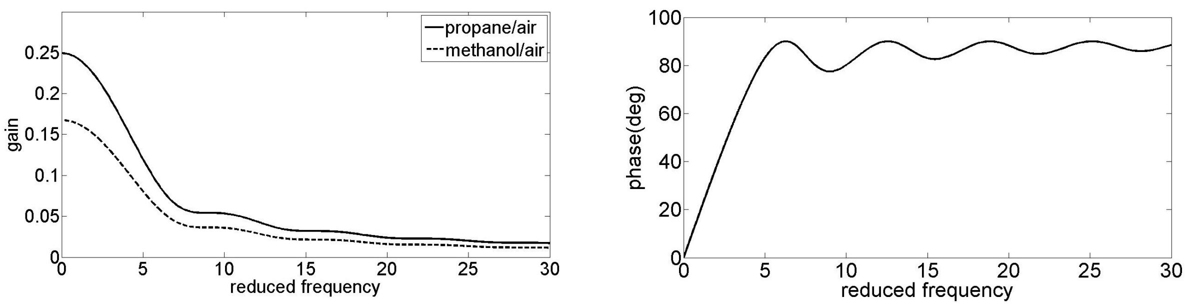
And reduced conical transfer function is

$$\tilde{F}_c(\omega_*) = \frac{2[1+i\omega_* - \exp(i\omega_*)]}{\omega_*^{\;2}} \tag{29}$$

c_{oc} is a representative of operating conditions parameters. In this form it is a function of burner geometry (A_b), fuel type ($\rho_f, \phi_s, B_2, \phi_m$) and mean values of mixture properties which are constant during an operation. This constant contains the previously mentioned non-dimensional parameters ($\overline{S_u}/\bar{v}, B_2/\bar{v}, \dot{m}_o/\rho_f\bar{v}R^2$)

RESULT AND DISCUSSION

c_{oc} causes equation (27) to differ from the transfer function of velocity perturbation obtained by reference [3] which is equal to reduced transfer functions, equations (29). Here, the c_{oc} acts like a gain amplifier. It also helps to express the transfer function for different fuels and different operating conditions. The gain and phase presentation of the conical flame response for propane/air and methanol/air, are depicted in Figs. 2. Coming Figures are calculated with R=0.1, $\bar{v}$=40 cm/s, $\bar{\phi} = 1$, at $T_{u0} = 298$ K, $P = 1$ atm the density of propane is 1.82 $\mathrm{kg/m^3}$,the density of methanol is 0.28 $\mathrm{kg/m^3}$, and the density of air is 1.201 $\mathrm{kg/m^3}$, for propane/air mixture $\phi_s = 0.0638$ and for methanol/air mixture $\phi_s = 0.1545$.



Figs. 2. The gain and phase of conical flame response of different fuel type.

The gains difference are caused by the c_{oc} as an amplifier which makes the same trends but different values. As is expressed in equation (28), c_{oc} is affected by fuel type, oxidizer mass flow rate, burner area, stoichiometric equivalence ratio, mean velocity and equivalence ratio. Difference in fuel density and stoichiometric equivalence ratio, make larger c_{oc} of propane/air mixture, then it shows higher sensitivity to perturbation.

To study the effect of mean equivalence ratio on the flame response, propane/air mixture is selected. The gain of the transfer function of conical flame versus different values of $\bar{\phi}$ and ω_* are shown in Fig. 3. The gain is almost monotone versus ω_* while its behaviour in respect to $\bar{\phi}$ contains a minimum value of zero. Here, $\bar{\phi} = \phi_0$ is equivalent to $c_{oc} = 0$. For propane/air mixture $\phi_0 = 1.075$ and at $\phi_0 = 1.06$ for methanol/air mixture.

Zero value of the gain means the flame is insensitive respect to perturbation. As indicated in the Fig. 3 the gain decreases and then increases versus $\bar{\phi}$ where $\bar{\phi} = \phi_0$ acts as a pivot. For $\bar{\phi} > \phi_0$ the conical flame is more sensitive to variation of $\bar{\phi}$ in comparison to $\bar{\phi} < \phi_0$.

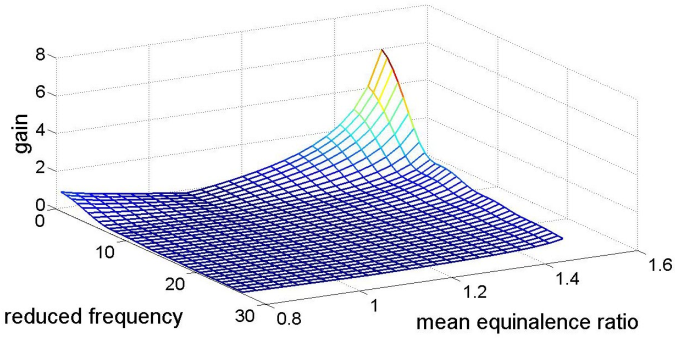


Fig.3.The gain of conical flame versus ω_* and $\bar{\phi}$.

CUNCLUDING REMARKS

The response of conical flame to coupled equivalence ratio and velocity oscillations have been obtained using the *G*-equation. In order to investigate the effects of operating conditions on the flame response an empirical burning velocity model has been used in the analysis. The quasi steady laminar flame speed of the mixture is expressed in terms of the equivalence ratio. The obtained transfer function is a function of four dimensionless groups. The reduced frequency ω_* and the ratio of burning velocity to the mean axial velocity $\overline{S_u}/\bar{v}$ are well known in the flame response studies. The third one emerges from the empirical model of burning velocity and the other new group is appeared by correlating coupled velocity and equivalence ratio. Analysis ends to define the operating conditions constant. This constant is a function of fuel type, burner geometry, and mixture properties which acts as an amplifier of transfer function.

The effect of fuel type on the flame response has been examined by comparison of response gain for propane/air and methanol/air in a broad range of ω_*. The result indicates propane/air has a higher response.

Also the effect of equivalence ratio of the mixture on the response function has been investigated. The results show the equivalence ratio does not change the dependency of the transfer function to the frequency of the perturbation. It just changes the amplitude of the gain.

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