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# Oscillation frequency of buoyant diffusion flame in cross-wind

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## HIGHLIGHTS

- Buoyant diffusion flame oscillation in cross-wind was investigated.
- Length of flame continuous regions increases with increasing cross-wind velocity.
- Oscillation frequency model coupling cross-wind, buoyancy and entrainment was given.
- Decay coefficient employing the entrainment deceleration on axial velocity applied.
- Flame frequency increases with increasing velocity ratio of cross-wind to jet flow.

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## ABSTRACT

Phenomenological studies relating to the oscillation of buoyant diffusion flames are very important to design flare systems in the energy and petrochemical industry or develop an image recognition algorithm for wind-aided fire detection. In this work, the oscillation frequency for the "down-wash mode" buoyant diffusion propane flames (momentum flux ratio of jet to cross-wind $< 0.1$, $6 \times 10^{-5} <$ Froude number of the fuel flow $< 2 \times 10^{-2}$, $10^2 <$ Richardson number $< 10^4$) were investigated. The experiments were conducted in a wind tunnel, and a kinematic model of the global oscillation frequency was established. The results show that: With the increasing cross-wind velocity, the flames bases are augmented by the "friction force" to cover more area of the near wake of the nozzle, with more length and area of the continuous regions of the flame. Coupling the influences of buoyancy acceleration, entrainment deceleration and "friction force" on the axial fuel velocity, the formula of the puffing frequency was deduced through introducing a buoyancy and friction force related coefficient and a decay coefficient that employs the entrainment deceleration of the axial velocity. This model was validated by the experimental results with good agreements. The flame frequency increases with increasing velocity ratio of cross-wind to jet flow. The decay coefficient is less than unity, ensuring longer flow times, enabling the theoretical model to have a good predictive capability.



## 1. Introduction

Many industrial combustion devices, such as industrial boilers and flare stacks, rely on jets in cross-wind and transverse jets to achieve mixing and prompt reactions. Combustion instability always occurs in combustion devices and destroys their structure and function. Employing flame image information related to flame oscillation, video fire detection technology has the advantages of its wide field of vision and rapid response. Phenomenological studies of such oscillations in buoyant diffusion flames are very important in designing flare systems in the energy and petrochemical industry, and in developing image recognition algorithms for wind-aided fire detection.

The oscillatory behavior of the flame is caused by the entrained flow approaching the flame induced by buoyancy, which drives the flame instabilities via the Rayleigh-Taylor (RT) instability [1]. The periodic oscillatory motion close to the base of buoyant diffusion flames is often referred to as puffing. Grant and Jones [2], Zukoski et al. [3], Weckman and Sobesiak [4], Hamins et al. [5], Malalasekera et al. [6] and others have proposed that the global oscillation frequency of the flame is inversely proportional to the square root of the source diameter as $f \propto D^{-0.5}$. The experiments of Cetegen and Ahmed [7] in 1993 further showed that the flame frequency decreased with increasing Richardson number. In 2000, Cetegen

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area that goes through the flame axis ($m^2$) |
| $a$ | acceleration of the axial velocity ($m/s^2$) |
| $b$ | half-width of flame (m) |
| $C$ | kinematic coefficient, 0.35 in this paper |
| $C_w$ | buoyancy and friction force related coefficient |
| $D$ | burner diameter (m) |
| $d_f$ | flame diameter (m) |
| $F_w$, $F_b$ | friction force and buoyancy (N) |
| $Fr$ | Froude number $Fr = u_j^2/(gD)$ |
| $f$, $\hat{f}$ | flame oscillation frequency (Hz) and its dimensionless form |
| $g$ | gravitational acceleration (9.8 $m/s^2$) |
| $K$, $K_F$ | $K = C(\rho_w/\rho_f - 1)^{1/2}$, $K_F = \frac{2}{K_G \pi g} \cdot \frac{Ri}{(1-\rho_f/\rho_w)} \cdot \frac{u_w^2}{L_f}$ |
| $K_E$ | decay coefficient, $K_E = [1 + 0.16(\rho_w/\rho_j)^{1/2}/K_G]^{-1}$ |
| $K_G$ | flame geometry factor, $K_G = d_f/L_f$ |
| $L_f$ | flame length (m) |
| $MW$ | molecular weight (g/mol) |
| $m$, $m_w$ | mass of flame column and wind column (kg) |
| $R$ | momentum flux ratio $R = (\rho_j u_j^2)/(\rho_w u_w^2)$ |
| $Ri$ | Richardson number $Ri = (\rho_w/\rho_f - 1)gD/u_j^2$ |
| $r_0$ | burner radius (m) |
| $T_f$, $T_w$ | flame temperature and cross-wind temperature (K) |
| $T_{st}$, $T_{ad}$ | stoichiometric flame temperature and adiabatic flame temperature (K) |
| $t$, $\hat{t}$ | convection time of toroidal vortices (s) and its dimensionless form |
| $t_0$, $\hat{t}_*$ | flame periodical oscillation time (s) and its dimensionless form |
| $u_f$, $\hat{u}_f$ | local axial fuel velocity at $z$ (m/s) and its dimensionless form |
| $u_j$ | fuel exit velocity (m/s) |
| $u_w$ | cross-wind velocity (m/s) |
| $z$, $\hat{z}$ | axial coordinate of flame length (m) and its dimensionless form |
| $\rho$ | density ($kg/m^3$) |

*Subscripts*

| | |
|---|---|
| $ad$ | adiabatic |
| $f$ | flame |
| $j$ | fuel |
| $st$ | stoichiometric |
| $w$ | cross-wind |

and Dong [8] found that buoyant diffusion flames originating from circular nozzles exhibit two different modes of flame instabilities, specifically, sinuous mode and varicose mode. In 2014, Hu et al. [9] investigated the instability characteristics of small-scale ethanol pool fires and arrived at three instability modes: short life RT instability, extended RT instability, and puffing instability.

To date, research on flame characteristics in cross-wind is limited to the flame angle, length, and radiation. In 1964, Pipkin and Sliepcevich [10] proposed an expression for the tilt angle of a buoyant diffusion flame assuming a cylindrically shaped flame and taking into account wind "drag" using momentum conservation. Models of bent-over jet flame with high momentum flux ratio $R$ ($R = (\rho_j u_j^2)/(\rho_w u_w^2)$) in cross-wind have been developed by several researchers such as Brzustowski [11] and Kalghatgi [12]. Some equations for predicting flame shape took into account entrainment, initial momentum and buoyancy. In 2010, Lawal et al. [13] investigated the effect of changes in the fuel exit velocity and cross-flow on the radiant fraction of a high-momentum jet flame in cross-flow with $R$ in the range of 100–800. In their study of low-momentum jet diffusion flame with a cylindrical shaped mode in cross-flow, Majesk and co-authors [14,15] investigated the functional dependence of flame length with cross-flow velocity. Their results showed a linear increase in flame length with cross-flow velocity and a linear decrease within a certain interval.

Flame flickering induced by vortices in cross-wind is different from that in still air. For flames in cross-wind, the formation and inhibition of vortices are regulated by the coupling effects of buoyancy and entrainment, particularly the momenta of shear airflow and initial jet flow. Megerian et al. [16] determined that the intrinsic self-sustained global oscillations are present for a low jet inflow ratio $R < 3.5$. However the intrinsic mechanism leading to the unsteady triggering of the vortices in these flames remains unclear. From a phenomenological perspective, entrainment has a decelerating effect upon the axial velocity that imposes complicated behavior on the convection time scale related to the puffing frequency.

In previous work, for the diffusion flames in still air, the global oscillation frequency formulas were derived by employing buoyancy only. This work focuses on the buoyancy-dominant diffusion flames in cross-wind, where the momentum flux ratio $R$ of jet flow to cross-wind is less than 0.1, which establishes a "down-wash mode" with a flammable region located around the down-washed recirculation area in the near wake of the nozzle [17]. Kinematic analysis of the global oscillation frequency formula was conducted through incorporating buoyancy, air entrainment, jet momentum, and cross-flow momentum. Furthermore, experiments were performed with Froude number of fuel flow ranging from $6 \times 10^{-5}$ to $2 \times 10^{-2}$, and the results were compared with the theoretical predictions.

## 2. Theoretical methods

To model the buoyant diffusion flame, several assumptions are introduced: the flow inside and outside the flame sheet is incompressible and inviscid; a cylindrical shape without bends prevails for small momentum flux ratio; the flame width is proportional to the flame length with a geometry factor $K_G$ [15]; the effects of the buoyancy, cross-flow and air entrainment on the axial velocity are considered separately; and the combustion efficiency of a propane diffusion flame is assumed to be 100%. According to the data presented in Kostiuk et al. [15], the combustion efficiency of a propane diffusion flame is insensitive to cross-wind under the range considered, and the lowest efficiency would be 99%. From the configuration of the flame in cross-wind (Fig. 1), the flame is seen to be tilted under the combined effects of cross-wind, buoyancy, and air entrainment. The axial velocity is accelerated by buoyancy and decelerated by air entrainment.

The mixture of the stoichiometric fuel and entrained air in an element of flame length $dL_f$ is taken as a control volume. For the friction force of the cross-wind in the horizontal direction, there is $dm_w u_w = F_w dt$, or equivalently, $\rho_w u_w dA dt u_w = F_w dt$ based on the momentum law, where $\rho_w$, $dm_w$, and $u_w$ represent cross-wind density ($kg/m^3$), mass of wind flow through $dA$ in $dt$ (kg) and cross-wind velocity (m/s), respectively. The friction is then:

$$F_w = \rho_w u_w^2 dA. \tag{1}$$