Characteristics of Propagating Tribrachial Flames in Counterflow

Young Sung Ko
Korea Aerospace Research Institute, Daejeon 305-333, Korea
Tae Man Chung, Suk Ho Chung*
School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Korea

The effect of fuel concentration gradient on the propagation characteristics of tribrachial (or triple) flames has been investigated experimentally in both two-dimensional and axisymmetric counterflows. The gradient at the stoichiometric location was controlled by the equivalence ratios at the two nozzles; one of which is maintained rich, while the other lean. Results show that the displacement speed of tribrachial flames in the two-dimensional counterflow decreases with fuel concentration gradient and has much larger speed than the maximum speed predicted previously in two-dimensional mixing layers. From an analogy with premixed flame propagation, this excessively large displacement speed can be attributed to the flame propagation with respect to burnt gas. Corresponding maximum speed in the limit of small mixture fraction gradient was estimated and the curvefit of the experimental data substantiates this limiting speed. As mixture fraction gradient approaches zero, a transition occurs, such that the propagation speed of tribrachial flame approaches stoichiometric laminar burning velocity with respect to burnt gas. Similar results have been obtained for tribrachial flames propagating in axisymmetric counterflow.

Key Words : Propagation Speed, Tribrachial Flame, Counterflow

Nomenclature

a, b, c	: Constants
t	: Time after laser shot [ms]
V_0	: Nozzle exit velocity
S_d	: Flame displacement speed
$S_L^0\|_{st}$	: Stoichiomtric laminar burning velocity
S_{tri}	: Propagation speed of tribrachial flame
Y_F	: Mass fraction of methane
z	: Axial coordinate

Greek Symbols

ϕ_R	: Equivalence ratio of rich condition
ϕ_L	: Equivalence ratio of lean condition
ρ	: Density

* Corresponding Author,
E-mail : shchung@snu.ac.kr
TEL : +82-2-880-7114; **FAX** : +82-2-883-0179
School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Korea.
(Manuscript **Received** February 4, 2002; **Revised** August 26, 2002)

Superscript

$*$	: Maximum

Subscripts

b	: Burnt
F	: Fuel
st	: Stoichiometry
u	: Unburned

1. Introduction

Tribrachial (or triple) flames play important roles in such phenomena as lifted flames in laminar jets (Cha and Chung, 1996 ; Chung and Lee, 1991 ; Lee et al., 1994 & 1997 ; Lee and Chung, 1997) and propagation in mixing layers (Buckmaster and Matalon, 1988 ; Dold, 1989 ; Echekki and Chen, 1998 ; Ghosal and Vervisch, 2000 ; Im and Chen, 1999 ; Kioni et al., 1993 ; Kioni et al., 1999 ; Ko and Chung, 1999 ; Phillips, 1965 ; Plessing et al., 1998 ; Ruetsch et al., 1995 ; Veynante et al., 1994). A tribrachial flame can be formed in a non-uniform mixture, which consists of a rich-and a lean premixed flame wings and a trailing diffusion flame, all extending from a single location.

One of the important parameters in characterizing tribrachial flames is its propagation speed. It has been demonstrated that the balance of the propagation speed of a tribrachial flame with local flow velocity along a stoichiometric contour can successfully predict lifted flame behavior in laminar free jets (Chung and Lee, 1991 ; Lee et al., 1994 & 1997 ; Lee and Chung, 1997), where the correlations of lift-off height with jet velocity, nozzle diameter, air dilution, inert dilution, and the dependence of Schmidt number of fuel have been derived.

Theoretical and numerical studies conducted in two-dimensional mixing layers demonstrated that mixture fraction gradient, which can be represented by the fuel concentration gradient at the edge of a tribrachial flame, is one of the dominant controlling factors that influence propagation speed (Buckmaster and Matalon, 1988 ; Dold, 1989 ; Echekki and Chen, 1998 ; Ghosal and Vervisch, 2000 ; Im and Chen, 1999 ; Kioni et al., 1993 ; Kioni et al., 1999 ; Ruetsch et al., 1995 ; Veynante et al., 1994). Maximum propagation speed of a tribrachial flame is predicted to be the stoichiometric laminar burning velocity multiplied by the square-root of density ratio of unburned to burnt mixtures, resulting in the maximum propagation speed of about 1 m/s for such fuels as methane and propane (Ruetsch et al., 1995).

These propagation characteristics have been substantiated experimentally by investigating the propagation of tribrachial flames in laminar jets (Ko and Chung, 1999), where the experimentally extrapolated maximum speed was 0.96 m/s for methane fuel, which is comparable to the theoretically predicted maximum value of 1.09 m/s (Ruetsch et al., 1995).

One point concerning the propagation speed of tribrachial flame is that its speed much larger than the predicted maximum value has been observed, especially in stagnant mixing layers. The observed speed reported was up to 1.8 m/s for methane (Phillips, 1965 ; Mielenz et al., 1999). The objective of the present study is to examine this discrepancy. For this, propagation characteristics of tribrachial flames in strained flow field are investigated experimentally by adopting two-dimensional and axisymmetric counterflows, which have been investigated numerically (Kioni et al., 1993 ; Daou and Linan, 1998). These systems have relevance to the propagation of autoignition front in turbulent inhomogeneous mixtures (Domingo and Vervisch, 1996).

2. Experiment

The apparatus consists of a counterflow burner, a flow controller, a visualization system, and an ignition setup. Two types of counterflow burners are investigated, as schematically shown in Fig. 1. A two-dimensional (2-D) counterflow burner has two nozzles with 10 mm × 100 mm exit area with the separation distance of 8 mm. Each nozzle is surrounded by a channel having width of 10 mm through which nitrogen is supplied for shielding from ambient air. The gap between the fuel nozzle and the nitrogen shield channel is 7 mm. The nozzle exits are covered with a porous plate to ensure uniform flow. An axisymmetric counterflow burner has nozzles with exit diameter of 21 mm and separation distance of 20 mm. The

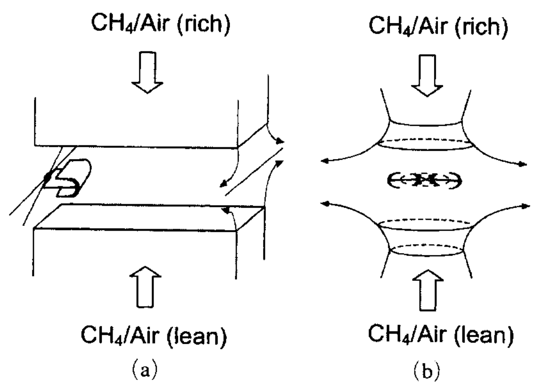

Fig. 1 Schematic of tribrachial flame propagation in two-dimensional (a) and axisymmetric (b) counterflows

nozzles are divergent-convergent types with the area contraction ratio of 40 : 1 for the exit flow to be nearly uniform.

Either C. P. grade methane or rich methane/air mixture is supplied through the upper nozzle and air or lean methane/air mixture through the lower nozzle. Flow rates are controlled by mass flow controllers (MKS) and the nozzle exit velocity is varied in the range of 5-20 cm/s for the 2-D and is fixed at 50 cm/s for the axisymmetric counterflow burners. Nitrogen flow is adjusted to have a near planar flame shape under stationary condition, which can be achieved sufficient time after transient propagation following ignition.

A Q-switched Nd : YAG laser (Spectra-Physics, GCR-150) generates laser-induced spark to ignite mixtures at 532 nm with 360 mJ maximum energy and 7 ns duration. Ignition location is adjusted by traversing f 200 mm convex lens. The laser is synchronized with the flow visualization system, including a shadowgraphy setup, a high-speed CCD camera (Kodak, EktaPro), and a planer laser-induced fluorescence (PLIF) system. The PLIF system consists of a Nd : YAG laser (Continuum, Powerlite 8000), a dye laser (Continuum, ND 6000), and a frequency modulator (Continuum, UVT). Excitation frequency for OH radical probing is $Q_1(6)$ line of 282.95 nm with $A^2\Sigma^+ - X^2\Pi$ (1, 0) transition and the fluorescence signal is detected using an ICCD camera (Princeton Instruments, EEV 02-06) through UG-11 and WG-305 optical filters.

3. Results and Discussion

When rich and lean methane/air mixtures are supplied, triple-layer flames (Lockett et al., 1999) can be formed under stationary conditions, which consist of near planar lean and rich premixed flames and a diffusion flame in between. Under the cold condition igniting at a certain location, a tribrachial flame can propagate through the counterflow. The transient behavior of propagating tribrachial flames has been investigated.

3.1 Two-dimensional counterflow

Two sets of experiment are conducted in 2-D counterflow ; with one end closed near ignition location and with both ends opened. The laser is focused 3 mm from the side end of the nozzle.

Shadowgraphs of typical propagating flame with both ends opened is shown in Fig. 2 for the nozzle exit velocity V_0=5 cm/s and the equivalence ratios of ϕ_R=2.0 and ϕ_L=0.3, which are supplied from the upper and lower nozzles, respectively, where the subscripts R and L indicate rich and lean conditions, respectively. After a certain initial induction period following the ignition, the front propagates nearly linearly with time. This behavior is further illustrated in Fig. 3,

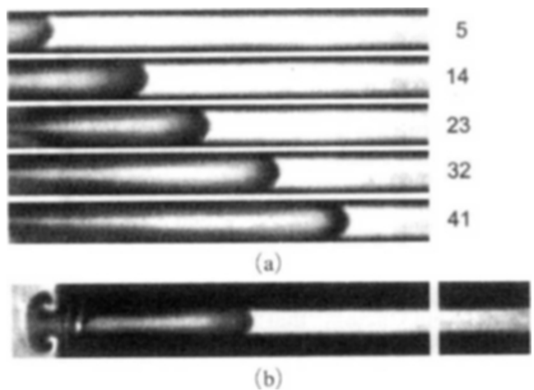

Fig. 2 Shadowgraphs of propagating flames in 2-D counterflow with open ends (a) and vortex formation by hot burnt gas ejection through open end (b) for V_0=5 cm/s, ϕ_R=2.0, and ϕ_L=0.3 (ignited at left and numbers indicate time [ms] after laser shot)

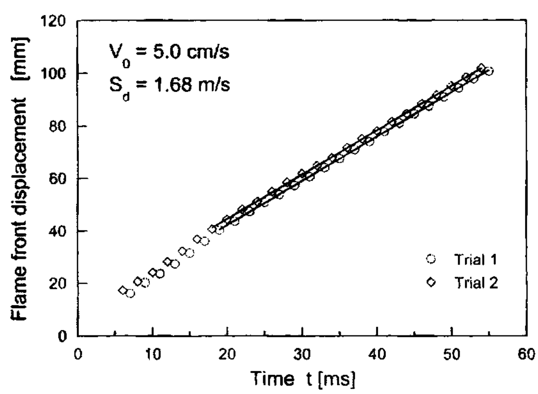

Fig. 3 Evolution of flame front displacement for ϕ_R=2.0 and ϕ_L=0.3 in 2-D counterflow with closed end

where the displacement of flame front is plotted with time for the closed end experiment. The displacement becomes linear with time at about $t=18$ ms after the laser shot and the displacement speed S_d, which is defined as the time derivative of displacement, is found to be 1.68 m/s.

This value is higher than the stoichiometric laminar burning velocity $S^o_{L,u}|_{st}$ of methane/air, which is 0.40 m/s (Law, 1993), where the subscript u indicates unburned mixture and the subscript st the stoichiometry. It is to be noted that the value is even larger than the predicted maximum propagation speed of tribrachial flames, $S^*_{tri,u}$, which has been derived to be (Ruetsch et al., 1995; Ko and Chung, 1999)

$$S^*_{tri,u}=S^o_{L,u}|_{st}(\rho_u/\rho^o_b)^{1/2} \tag{1}$$

where ρ is the density, the subscript b indicates burnt mixture, and the superscript * indicates the maximum. Note that the propagation speed is defined with respect to stagnant unburned upstream, representing intrinsic propagation behavior. The calculated value is 1.09 m/s based on the equilibrium calculation for the stoichiometric methane/air mixture. The discrepancy between the predicted and observed values will be further elaborated later.

Direct photographs of propagating flame fronts and their PLIF images are shown in Fig. 4 for $(\phi_R, \phi_L)=(1.4, 0.6)$, (2.0, 0.3), (5.5, 0.27), and (∞, 0), where the last case corresponds to the nonpremixed flame situation. The propagating front of the flame (a) shows a long rich premixed flame wing and a relatively short lean premixed flame wing, together with a trailing diffusion flame, demonstrating the tribrachial structure. As ϕ_R increases and ϕ_L decreases, the three different types of flames are less discernable, since the flammable region becomes narrow. Then, the leading front can have an edge flame structure (Buckmaster and Matalon, 1988). Also, the radius of curvature of propagating front decreases, due to the increase in mixture fraction gradient (Ruetsch, 1995; Ko and Chung, 1999). One point to note is that for all the combinations of (ϕ_R, ϕ_L), the predicted maximum temperatures will be the same and equal to the adiabatic flame temperature of the stoichiometric methane/air mixture once the Lewis numbers are assumed unity. PLIF images of propagating tribrachial flames demonstrate that the leading edges exhibit maximum intensity of OH fluorescence, which agrees with the previous observation (Plessing et al., 1998) for tribrachial flames.

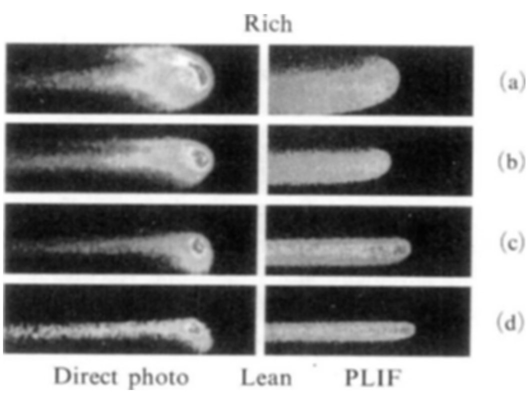

Fig. 4 Direct photographs and OH PLIF images of propagating flames in counterflow for (a) $(\phi_R, \phi_L)=(1.4, 0.6)$, (b) (2.0, 0.3), (c) (5.5, 0.27), and (d) (∞, 0)

3.2 Axisymmetric counterflow

Propagation of a tribrachial flame in the axisymmetric counterflow is observed by igniting a mixture at the stagnation point for $V_o=50$ cm/s and $(\phi_R, \phi_L)=(1.4, 0.6)$. Direct photographs using the ICCD camera are shown in Fig. 5 for the propagating tribrachial flame at $t=8$ ms (a) and corresponding stationary triple-layer flames (b). General behavior of unsteady tribrachial flames can be described as follows. After ignition, the burnt gas region grows in both vertical and horizontal directions such that it has an oval shape. A tribrachial flame formed along the periphery propagates radially. After a certain induction time, e.g., $t\approx 8$ ms, the radius of curvature of tribrachial front maintains relatively unchanged.

Evolution of the displacement of tribrachial front is shown in Fig 6, demonstrating linear increase with time after $t\approx 8$ ms. The corresponding displacement speed is 2.15 m/s, which again is much larger than either the stoichiometric laminar burning velocity or the maximum propagation speed of a tribrachial flame predicted

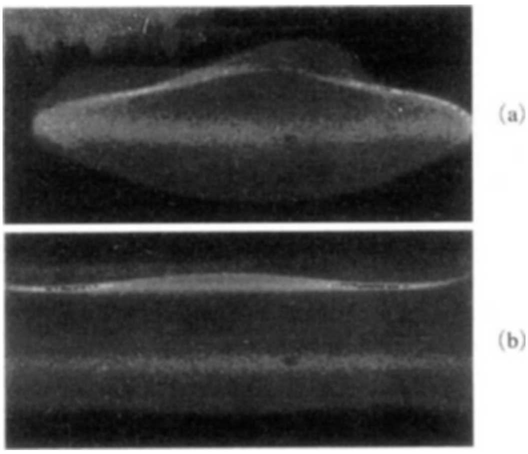

Fig. 5 ICCD images of propagating tribrachial flame at $t=8$ ms (a) and corresponding stationary flame (b) for $\phi_R=1.4$, $\phi_L=0.6$, and $V_o=50$ cm/s

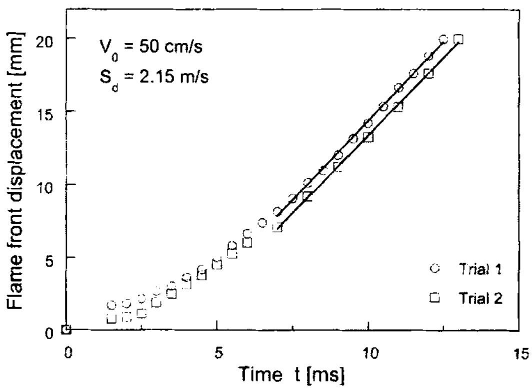

Fig. 6 Evolution of flame front displacement with time for $\phi_R=1.4$ and $\phi_L=0.6$ in axisymmetric counterflow

previously (Ruetsch et al., 1995).

3.3 Propagation speed

As was mentioned previously, mixture fraction gradient, which can be represented by fuel concentration gradient, is an important controlling factor that influences propagation speed of tribrachial or edge flame. In this regard, the displacement speed S_d is plotted as a function of fuel concentration gradient $dY_F/dz|_{st}$, where Y_F is the mass fraction of methane and z is the axial coordinate. It is calculated from a counterflow code (Smooke, 1982) assuming cold and plug

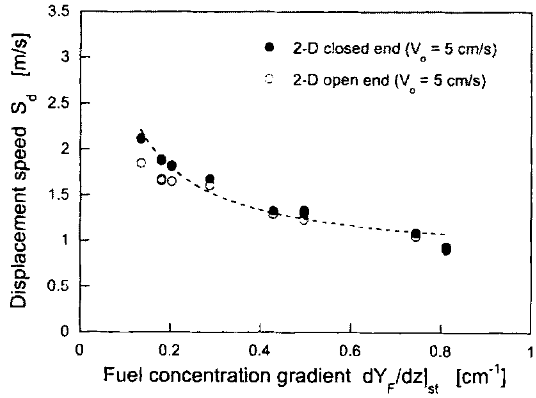

Fig. 7 Flame displacement speed with fuel concentration gradient in 2-D counterflow for closed and open end experiments with $V_o=50$ cm/s

flow conditions. The fuel concentration gradient is then determined at the axial position having stoichiometry. Details of calculation can be found elsewhere (Lee and Chung, 1994).

Displacement speeds for the 2-D counterflow burner are shown in Fig. 7 for both closed and open end experiments with $V_o=5$ cm/s. Several points are to be noted ; (1) the displacement speeds are much higher than the stoichiometric laminar burning velocity $S^o_{L,u}|_{st}$, (2) the displacement speed decreases with the fuel concentration gradient, and (3) the observed maximum displacement speed is much larger than the predicted maximum propagation speed of tribrachial flame in the limit of small $dY_F/dz|_{st}$, which is calculated to be 1.09 m/s from Eq. (1).

The flow redirection effect (Ruetsch et al., 1995 ; Veynante et al., 1994) arises from the thermal expansion behind a curved tribrachial front. When a flame front is convex toward the upstream, streamlines will diverge to satisfy the conditions of velocity jump in the normal direction across the flame front and of the continuity of tangential velocity along the front. Accordingly, the local flow velocity ahead of the convex front will decrease. Thus, even though the local flow velocity ahead of a tribrachial or edge flame may be comparable to the stoichiometric laminar burning velocity (Veynante et al., 1994 ; Plessing et al., 1998), the flame front can propagate with its speed larger than $S^o_{L,u}|_{st}$. This mechanism can be easily understood from the Landau hydrodynamic instability, which dictates that a convex flame front in a homogeneous mixture could have the displacement speed larger than the laminar burning velocity of the mixture.

The decrease in propagation speed with fuel concentration gradient can be explained as follows. Mixture fraction gradient influences the amount of burning in the premixed flame mode, since only the flammable region can be burned by a tribrachial front (Ruetsch et al., 1995 ; Veynante et al., 1994). Increase in mixture fraction gradient results in the decrease in the amount of burning in the premixed flame mode. Thus, as mixture fraction gradient increases, the flow redirection effect by a tribrachial flame front will be mitigated, resulting in the reduction in its propagation speed.

In the previous study of propagating tribrachial flames in free jets when the jet is ignited in a downstream location (Ko and Chung, 1999), it has been demonstrated that fuel concentration gradient is linearly related with the radius of curvature of a propagating tribrachial front. Thus, as fuel concentration gradient increases, the radius of curvature decreases, as exhibited in Fig. 4. Then, as the radius of curvature decreases for a convex front, propagation speed decreases. This can be understood from the behavior of a bunsen flame tip, where a concave tip toward upstream significantly increases its propagation speed. Thermal and radical diffusion in the transverse direction could also mitigate the propagation speed. These combined effects lead to the decrease in the propagation speed of a tribrachial flame with fuel concentration gradient.

Figure 7 demonstrates that the flame displacement speed with the closed end experiment has higher value compared to that with the open end. The shadowgraph with the open end case (Fig. 2b) exhibits that a mushroom-shaped rollup vortex is ejected outside of the burner by the ejection of hot burnt gas. This will reduce the displacement speed compared to the case with the closed end. Note that the difference in the displacement speeds between the open and closed end experiments is mitigated as fuel concentration gradient increases. This can be taken as granted since as displacement speed decreases, the hot burnt gas ejection in the 2-D counterflow in the direction opposite to the flame propagation will be decreased. Moreover, as fuel concentration gradient increases, the overall flame structure will change to a diffusion flame.

The observed displacement speed in general is much larger than the predicted maximum speed. The burnt gas interaction could contribute to the discrepancy between the observed displacement speed and the predicted maximum propagation speed. For a homogeneous premixture, once it is ignited at a closed end, the propagation speed will be relative to the burnt gas. In this regard, the flame in the limit of small mixture fraction gradient that corresponds to the case with stoichiometric homogeneous mixture will propagate with respect to the burnt gas when ignited at a closed end. Corresponding experiment has been conducted which results in the displacement speed of 3.08 m/s for $V_o=10$ cm/s. This is in good agreement with the calculated propagation speed with respect to the burnt gas of $S^o_{L,b}|_{st}=$ 2.97 m/s based on $S^o_{L,u}|_{st}=0.40$ cm/s. This implies that the displacement speed in the 2-D counterflow experiment with closed end can be reasonably treated as the propagation speed with respect to the bunt gas. For tribrachial flame propagation, other factors could accelerate the displacement speed. Due to the complex nature of unsteady propagation of tribrachial flame in strained counterflow, detailed study is required in the future. To qualitatively explain the displacement speed behavior, the burnt gas expansion effect is further investigated in the following.

By adopting the analogy of Eq. (1), the maximum propagation speed of tribrachial flames with respect to burnt gas $S^*_{tri,b}$ can be approximated as

$$S^*_{tri,b}=S^o_{L,b}|_{st}(\rho_u/\rho^o_b)^{1/2} \tag{2}$$

where $S^o_{L,b}|_{st}$ is the stoichiometric laminar burning velocity with respect to burnt gas. Through the balance of burning velocities, $\rho^o_b S^o_{L,b}|_{st}=\rho_u S^o_{L,b}|_{st}$, the maximum propagation speed becomes

$$S^*_{tri,b} = S^o_{L,u}|_{st} (\rho_u/\rho^o_b)^{3/2} \quad (3)$$

The magnitude is calculated to be 8.09 m/s for methane/air mixture.

Using the predicted maximum speed in the limit of $dY_F/dz|_{st} \to 0$, the experimental data for 2-D counterflow with the closed end are curve-fitted in the form of

$$\frac{S^*_{tri,b}}{S^o_{L,u}|_{st}} = a\left[\frac{dY_F}{dt}\bigg|_{st} + b\right]^{-1} + c \quad (4)$$

where z is in [cm]. The best fit is for $a=0.612$, $b=0.0334$, and $c=1.9$ when $V_o=5$ cm/s. Here, the data for $dY_F/dz|_{st} \leq 0.1$ are excluded in the curvefit since they appear in the transition regime from the propagating tribrachial flame to premixed flame, when $dY_F/dz|_{st}$ is small. The curvefit shown by the solid line in Fig. 8 represents experimental results satisfactorily, implying that the displacement speed of tribrachial flames may be regard as the propagation speed with respect to burnt gas.

For $V_o=10$ cm/s and 20 cm/s with closed end, S_d becomes higher than that of $V_o=5$ cm/s. The variation with V_o is not clear at present. Various effects can be attributed, including heat loss to porous wall. The premixed flame wings become larger and are very close to the porous wall for small V_o. Then, the heat loss can influence the propagation speed. The minimum predicted speed in the limit of large $dY_F/dz|_{st}$ is found to be about 0.76 m/s for all V_o tested.

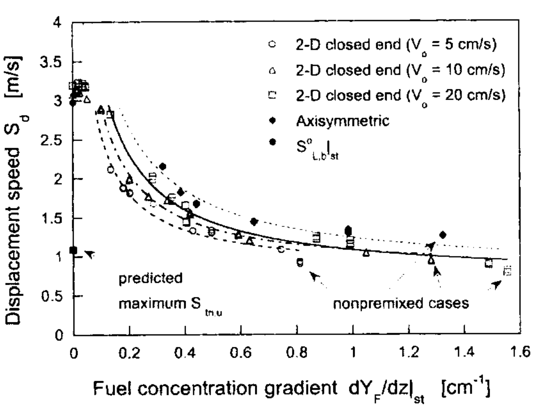

Fig. 8 Flame displacement speed with fuel concentration gradient in 2-D and axisymmetric counter flows

The displacement speed of tribrachial flame front in the axisymmetric counterflow burner is also shown in Fig. 8. Using the predicted maximum speed of 8.09 m/s, the data are curve-fitted to a $a=1.275$, $b=0.0696$, and $c=1.91$. The curvefit represented by the dotted line in Fig. 8 follows the experimental data successfully.

The tribrachial flame front in the axisymmetric counterflow has radial velocity component behind in the burnt region. Hence, the displacement speed needs to be compensated to determine the propagation speed of a tribrachial flame with respect to burnt gas. Thus, compared to the 2-D cases, the displacement speed in the axisymmetric counterflow is expected to be larger, as demonstrated in Fig. 8.

It is not clear why the displacement speed remains at a near constant value with time as shown in Fig. 6, since the radial velocity will increase linearly with radius in axisymmetric counterflow. Because of complex and unsteady nature of flow field after ignition, accurate determination of propagation speed of tribrachial flames in axisymmetric counterflow will be a subject of future study.

Finally, the implications of much larger displacement speed than $S_{tri,u}$ can be emphasized as follows. It resolves the discrepancy between the previous prediction of maximum propagation speed and the observed propagation speed (Phillips, 1965; Mielenz et al., 1999). The other is related to the propagation of autoignition front in turbulent inhomogeneous mixtures (Domingo and Vervisch, 1996). The displacement of autoignition front can be much faster than the previously expected maximum value of $S^o_{L,u}|_{st}(\rho_u/\rho^o_b)^{1/2}$.

4. Concluding Remarks

Propagation of tribrachial flames in both 2-D and axisymmetric counterflows has been investigated experimentally. By varying the equivalence ratio of mixtures, mixture fraction gradient, which is a dominant controlling factor for the propagation speed of tribrachial flames, can be effectively controlled.

The displacement speed of tribrachial flame in 2-D counterflow is found to decrease with fuel concentration gradient and the speed observed is in the range of 0.92-3.15 m/s. These values are in general much larger than the maximum propagation speed predicted previously. With a simple analogy with premixed flame, the limiting propagation speed of tribrachial flames with respective to burnt gas is expected to be $S^o_{L,u}|_{st}$ $(\rho_u/\rho^o_b)^{3/2}$. Curve-fittings of the experimental results substantiate this limiting behavior. The displacement speed in the axisymmetric counterflow also demonstrates similar behavior.

The present experimental result supports that the displacement speed in the 2-D counterflow can be regarded as the propagation speed of tribrachial flame with respect to burnt gas. However, further research is required to clarify the physical mechanism that induces large displacement speed in counterflow.

Acknowledgment

This work was supported by the Combustion Engineering Research Center.

References

Buckmaster, J. and Matalon, M., 1988, "Anomalous Lewis Number Effects in Tribrachial Flames," *Proc. Combust. Inst.*, Vol. 22, pp. 1527~1535.

Cha, M. S. and Chung, S. H., 1996, "Characteristics of Lifted Flames in Nonpremixed Turbulent Confined Jets," *Proc. Combust. Inst.*, Vol. 26, pp. 121~128.

Chung, S. H. and Lee, B. J., 1991, "On the Characteristics of Laminar Lifted Flames in a Nonpremixed Jet," *Combust. Flame*, Vol. 86, pp. 62~72.

Daou, J. and Linan, A., 1998, "The Role of Unequal Diffusivities in Ignition and Extinction Fronts in Strained Mixing Layers," *Combust. Theory Modelling*, Vol. 2, pp. 449~477.

Dold, J. W., 1989, "Flame Propagation in a Nonuniform Mixture : Analysis of a Slowly Varying Triple Flame," *Combust. Flame*, Vol. 76, pp. 71~88.

Domingo, P. and Vervisch, L., 1996, "Triple Flames and Partially premixed Combustion in Autoignition of Non-premixed Turbulent Mixtures," *Proc. Combust. Inst.*, Vol. 26, pp. 233~240.

Echekki, T, Chen, J. H., 1998, "Structure and Propagation of Methanol-Air Triple Flames," *Combust. Flame*, Vo. 114, pp. 231~245.

Ghosal, S. and Vervisch, L., 2000, "Theoretical and Numerical Study of a Symmetrical Triple Flame using the Parabolic Flame Path Approximation," *J. Fluid Mech.*, Vol. 415, pp. 227~260.

Im, H. G. and Chen, J. H., 1999, "Structure and Propagation of Triple Flames in Partially Premixed Hydrogen-air Mixtures," *Combust. Flame*, Vol. 119, pp. 436~454.

Kioni, P. N., Rogg, B., Bray, K. N. C. and Linan, A., 1993, "Flame Spread in Laminar Mixing Layers : The Triple Flame," *Combust. Flame*, Vol. 95, pp. 276~290.

Kioni, P. N., Bray, K. N. C., Greenhalgh, D. A., Rogg, B., 1999, "Experimental and Numerical Studies of a Triple Flame," *Combust. Flame*, Vol. 116, pp. 192~206.

Ko, Y. S. and Chung, S. H., 1999, "Propagation of Unsteady Tribrachial Flames in Laminar Non-premixed Jets," *Combust. Flame*, Vol. 118, pp. 151~163.

Law, C. K., 1993, in *Reduced Kinetic Mechanism for Application in Combustion Systems* (N. Peters and B. Rogg, Eds.), Lecture Notes, in Physics Series m15, Springer-Verlag, Berlin, pp. 15~26.

Lee, B. J., Kim, J. S. and Chung, S. H., 1994, "Effect of Dilution of the Liftoff of Nonpremixed Jet Flames," *Proc. Combust. Inst.*, Vol. 25, pp. 1175~1181.

Lee, B. J., Cha, M. S. and Chung, S. H., 1997, "Characteristics of Laminar Lifted Flames in a Partially Premixed Jets," *Combust. Sci. Technol.*, Vol. 127, pp. 55~70.

Lee, B. J. and Chung, S. H., 1997, "Stabilization of Lifted Tribrachial Flames in a Laminar Nonpremixed Jet," *Combust. Flame*, Vol. 109, pp. 163~172.

Lee S. D. and Chung S. H., 1994, "On the Structure and Extinction of Interacting Lean Methane Air Premixed Flames," *Combust. Flame*, Vol. 98, pp. 80~92.

Lockett, R. D., Boulanger, B., Harding, S. C. and Greenhalgh, D. A., 1999, "The Structure and Stability of the Laminar Counter-flow Partially Premixed Methane/Air Triple Flame," *Combust. Flame*, Vol. 119, pp. 109~120.

Mielenz, O., Schlottmann, F. and Rogg, B., 1999, "Experimental Investigations of Laminar Triple Flames and Triplet Flames in Strained Flow Fields," *Seventeenth ICDERS*, Paper no. 215.

Phillips, H., 1965, "Flame in a Buoyant Methane Layer," *Proc. Combust. Inst.*, Vol. 10, pp. 1277~1283.

Plessing, T., Terhoeven, P., Peters, N. and Mansour, M. S., 1998, "An Experimental and Numerical Study of a Laminar Triple Flame," *Combust. Flame*, Vol. 115, pp. 335~353.

Ruetsch, G. R., Vervisch, L. and Linan, A., 1995, "Effects of Heat Release on Triple Flames," *Phys. Fluids*, Vol. 7, pp. 1447~1454.

Smooke, M. D., 1982, "Solution of Burner-Stabilized Premixed Laminar Flame by Boundary Value Methods," *J. Computat. Phys.*, Vol. 48, pp. 72~105.

Veynante, D., Vervisch, L., Poinsot, T., Linan, A. and Ruetsch, G., 1994, "Triple Flame Structure and Diffusion Flame Stabilization," *Proceedings of the Summer Program*, Center for Turbulence Research, pp. 55~73.