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Flame structure of nozzles offsetting opposite flows

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Abstract. Effects of vortexes behind flame zone on the flame structures are investigated experimentally by nozzles offsetting opposite flows with 2D laser diagnosis. Methane air premixed gas issued from upper and lower burners with equal flow rate. An imbalanced counter flow is produced to slide the lower burner from the center axis. In our proposed flow system, the vortexes are only formed in the burnt gas region by the shear stress due to the velocity difference between the upper flow and lower flow. Three distinct flames structures, slant flames, edge shape flames, and hyperbolic flames are decided with the offsetting rate and fuel flows composition. The formed vortexes structures changed with the offsetting rate. The vortex formed behind the flame plays an important role for the flame stability.

1. Introduction

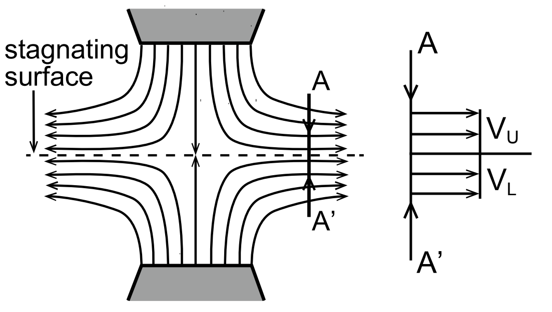
Turbulent combustions are most important issues for combustion studies as well as practical uses [1]. Up to now a lot of studies has been perform for turbulent combustion. In the most of practical combustors, the combustion phenomena preformed under low Mach number and deflagration flame regime. Then, turbulence are aggregates of wide range eddies. Turbulent flames in the wrinkled laminar flame regime, the curved flame front continuously is simultaneously moving with the incoming unburnt gas flow motion. In macroscopically, the effects of turbulence on the combustion phenomena are to wrinkle the flame front then the total reaction rate in the control volume increases as the reaction surface is increased. The wrinkled flame front structure is mainly controlled by the scale of eddies [2]. It considered as a complex curved flame [3, 4]. In microscopically, each scale curved flame locally stretched then the local reaction rate may increase or decrease. That is, the local flame propagation speed of the turbulent flame does not constant and the turbulent combustion phenomena should be discussed with the increasing reaction surface area plus local reaction rate. The important issues for the turbulent flame are to estimate the local structures within the reacting zone and the surroundings time and space. There are two studying approaches. One is directly investigated turbulent flame such as probability density function (PDF) method [5], Large Eddy Simulation (LES) [6], direct numerical simulation (DNS) [7, 8] or multi-dimensional time series laser diagnosis [9~12]. Other one is a fractionalized laminar flamelet method. A stretched flame and a curved flame are typical examples. For example, the flat formed in the wall stagnating flow is a typical stretched laminar flame for fundamental studies and a counter flow flame is also ideal not only premixed flame but also diffusion flame. As the derivation model, tubular flames are useful to study for the flamelet affecting stretch and curvature [13]. There are a lot of variations for tubular flames [3, 14]. Most of the turbulent combustion studies have been carried out in the turbulence added for the unburnt gases. The results are discussed by the initial turbulence condition and the flame front shape. However as focus in the burnt gas, the turbulence still exist and it is possible to affects turbulence in the burnt gas to the reaction zone. The effects of the vortex in the burnt gas on the flame structures have not elucidate yet.

The purpose of present study is to propose an experimental model, to introduce the flame structures in the offsetting counter flow and to investigate how the vortex behind the flame zone works the flame.

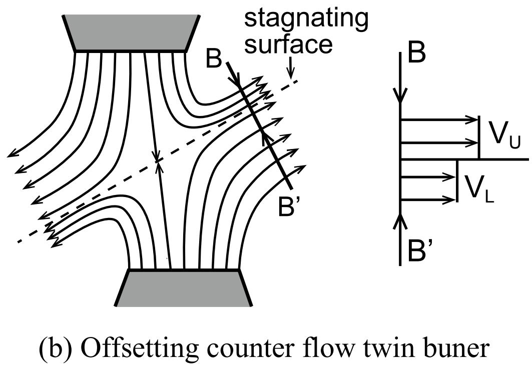
2. Experimental setup

Figure 1 shows the schematic of our proposed experimental model. The basic structure is almost same as a symmetrical counter flow twin burner. The difference is that one of the burner sided from the center axis. In a counter flow, the stagnating front formed in midway of the both of nozzles exit for the equal mass flow rate as shown in Fig. 1 (a). Then the stagnating front formed as perpendicular to the center line and there is no slip between upper flow (V_u) and lower flow (V_L) as described in the cross section A-A'. To slide the one of the nozzle from the center line as shown in the Fig. 1 (b), the stagnating front is leaning to one side. That is, the driving force is generated by the velocity difference for the outward flows between the upper and the lower as described in the cross section B-B'. The strain of the stagnating front increases with increasing the sliding amount. This is our proposed offsetting counter flow. In our study offsetting rate is defined as the sliding distance divide by the nozzle exit diameter. To increase the offset rate, the slip between upper and lower flows will gains. The shear stress in there may trigger to generating the vortex. That is the concept of the offsetting counter flow.

Figure 2 shows the specifics of the offset counter flow burner system. The burner system consists by symmetrical twin nozzle burners. The nozzles are formed by the inner nozzle and the outer nozzle. The exit diameter of the inner nozzles (D) are 10mm and the nozzles separation (L) is 20mm. The methane air premixed gas issued by the inner nozzle. The mean velocities are up to 3.6m/s at the nozzle exit. Then, the flow rate and fuel air ratio of upper and lower burners are equal conditions. In the outer nozzle, the air flows with equal flow rate of the premixed gas to minimize the turbulence due to shear stress by the surrounding air. Flow structures are obtained by particle image velocimetry. The Fine alumina



(a) Symmetrical counter flow twin burner



(b) Offsetting counter flow twin buner

Figure 1. Experimental model.

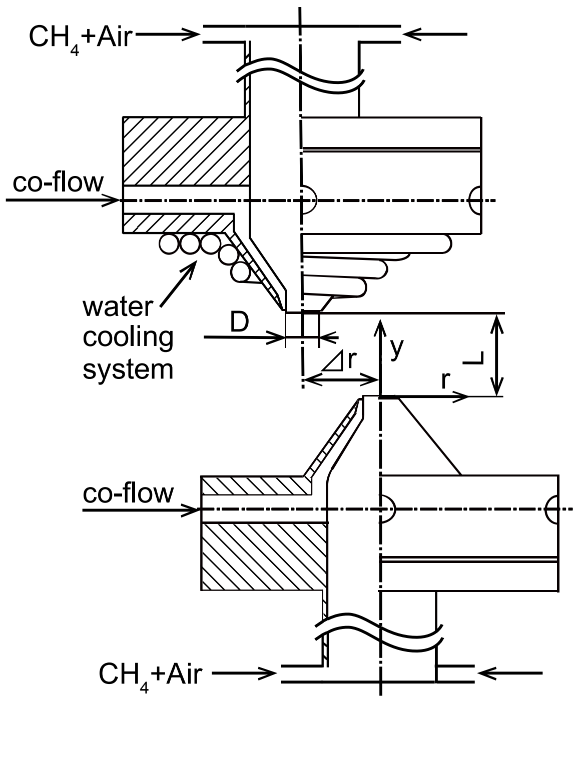


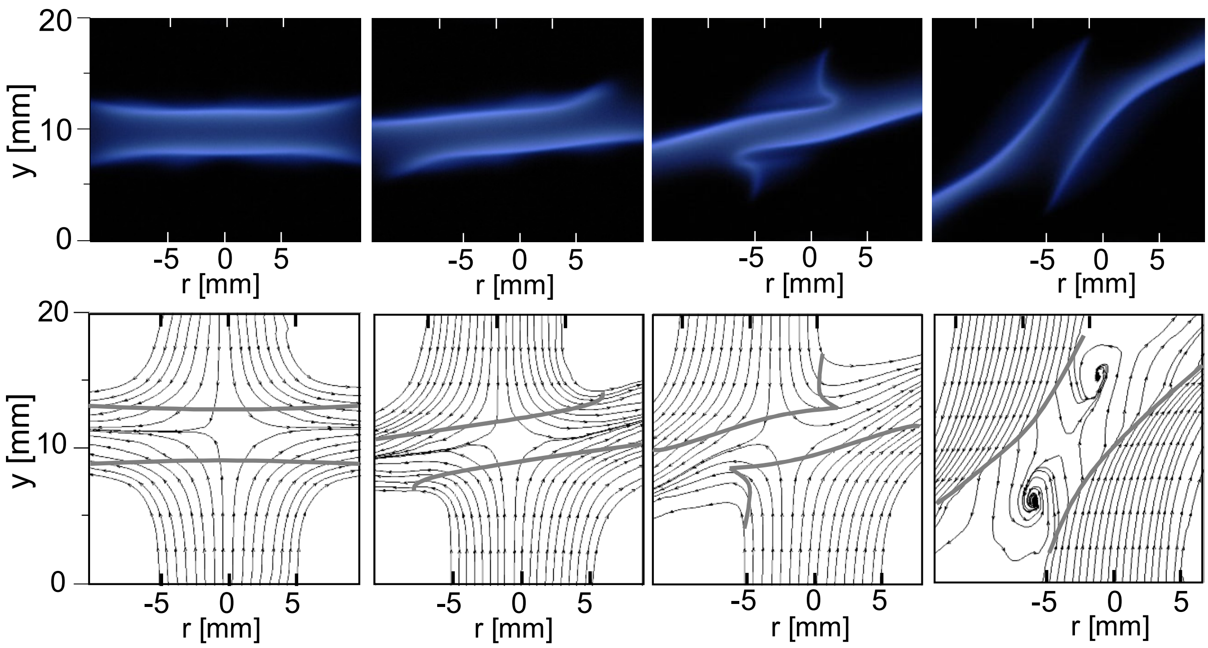
Figure 2. Offsetting burner system.

particles or silicone oil droplets are used as resolution of the digital high speed camera, Photron Fastcam 1024PCI 100K has a 1024×1024 resolution CCD at 2000 frame/sec. The coordinate y is defined as the direction from the lower nozzle. The offsetting rate r_{off} is defined as ⊿r/D where ⊿r is the offsetting distance from the origin axis.

3. Results and discussions

3.1. Basic Flames structure in the offsetting counter flows at stoichiometric

The basic flames structure for the offsetting counter flows are discussed by direct photo and PIV data. Figure 3 shows direct photos and stream lines by PIV data for the four different offsetting conditions at $\bar{U}_0$=2.0m/s and φ=1.0. From the direct photos, the flames structures can be divided into four regimes which are symmetrical parallel twin flames (see Fig. 3 (a)), slant twin flames (see Fig. 3 (b)), wedge flames (see Fig. 3 (c)) and hyperbolic flames (see Fig. 3 (d)). Initially, the structure of the symmetrical parallel twin flames shows in Fig. 3 (a). In this case, the flames are symmetrically formed in the counter flow field. This is the ordinary counter flow twin flames. The stagnating face and flames slightly shift to the upward duo to the buoyancy effect. For the slant twin flames as shown in Fig. 3 (b), the flames are slanting, however, those are formed almost parallel to the stagnating front. No vortex is formed behind the flames because the strain force is too weak to make a vortex. For the mid offset rate r_{off}=0.40 shown in Fig. 3 (c), the wedge shape twin flames formed. The flames shape of inside edge part have a right-angled hook shape. In this case, also there is no vortex behind the reaction zone. For the high offset rate condition r_{off} =0.60 shown in Fig. 3 (d), the hyperbolic curved flames formed. The no vortex conditions Fig. 3 (a) to (c) have some common in the basic flow structures. The stagnating flow and the divergent flow clearly formed even the stagnating surface is slanting with increasing offsetting rate. However, in Fig. 3 (d) at the hyperbolic flame condition, the twin vortexes are formed behind the flames zone. In this case, twin vortexes divided on either side of the stagnating line. It is worthwhile to see that the stagnating point can be observed even for the vortexes formed condition.



(a) r_{off} =0.00 (b) r_{off} =0.20 (c) r_{off} =0.40 (d) r_{off} =0.60

Figure 3. Flames structures in the offsetting counter flows at stoichiometric at $\bar{U}_0$=2.0m/s and φ=1.0.

3.2. Flow regimes and blow-off condition on the stoichiometric condition.

Figure 4 shows the map of the flow regimes and the blow-off conditions for different offsetting rate and mean velocities on the stoichiometric condition (φ=1.0). As focused on the blow-off limits, the offsetting rate at the blow-off linearly decreases with increasing mean flow velocity. No vortex regime to twin vortex regime can be divided with a straight line. In U_0 >1.2m/s the flow structure changes in the order of no vortex, twin vortex and single vortex. The boundaries no vortex to twin vortexes depend on the offsetting rate. The vortex formations order changes about U_0 =1.2m/s. In U_0 <1.2m/s the flow structure changed directly from no vortex to single vortex. It means that there is no chance to form twin vortexes for U_0 <1.2m/s condition. The offsetting rate at the single vortex to the twin vortex or no vortex almost linearly increase with decreasing the mean velocities.

3.3. Effects of mean velocities on the flow structures

In order to discuss the effects of mean velocities on the flow structures, the experiments performed under the different mean velocity condition with the fixed offsetting rate and the fixed stoichiometric. Figure 5 shows the direct photos and stream lines for three different flow conditions, $\bar{U}_0$ =1.0m/s, 1.3m/s, and 2.0m/s. As shown in direct photo, all of the flames seems in the hyperbolic regime. However, the flows structure for each velocities are totally different as shown in the PIV images. The overview of the flows structures are in the mean flow rate order. In U_0 =1.0m/s condition showing in Fig. 5 (a), any vortex dose not formed. The flow structure are a slanted counter flow and diverged flow without vortexes pattern can be observed in there. For U_0 =1.3m/s shown in Fig. 5 (b), twin vortexes are symmetrically formed in the burnt gas. In this condition, the diverged flow including a stagnating stream line can be observed between twin vortexes. The reasons of the vortexes formation are supposed to be the increased shear stress due to the gained main flows rate. In Fig. 5 (c), the flow rate increased effect becomes more and more conspicuous. It seems that to increase the main flow rate, twin vortexes merges into a single vortex. Then the single vortex formed in the center of the burnt gas region and no stagnating point observed. In this case there is no diverge flow or stagnating stream line could not observe. The burnt gas flow behind both of flames makes counter clock wise streamline. Those flow become the single vortex. Those results show that the shear stresses behind the flames zone play an important issue to form the hyperbolic flames. For the bulk structures of the hyperbolic flames that means direct image, the existence or nonexistence of the vortex dose not required point. In Fig. 5 (b), the diverged flow and stagnating point clearly observed in the twin vortexes flow field as same as discussed in Fig.3 (c). The process of twin vortexes

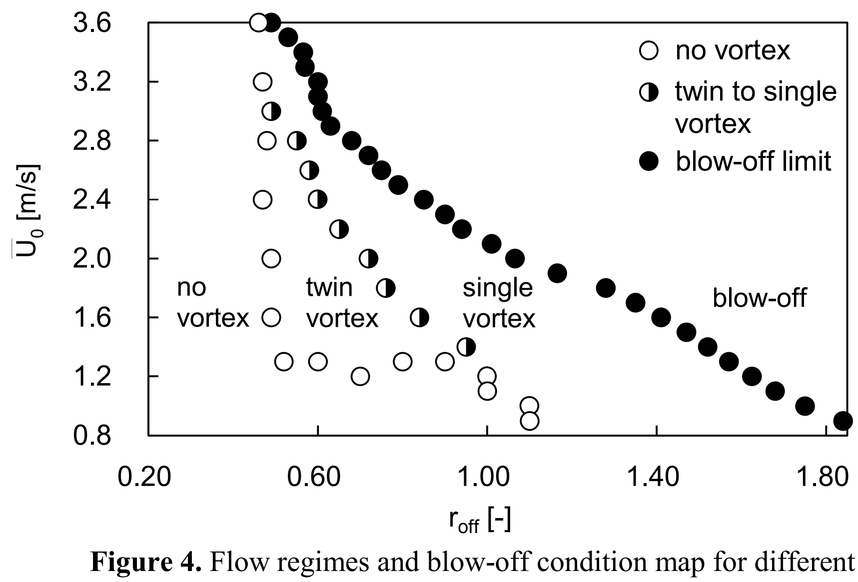
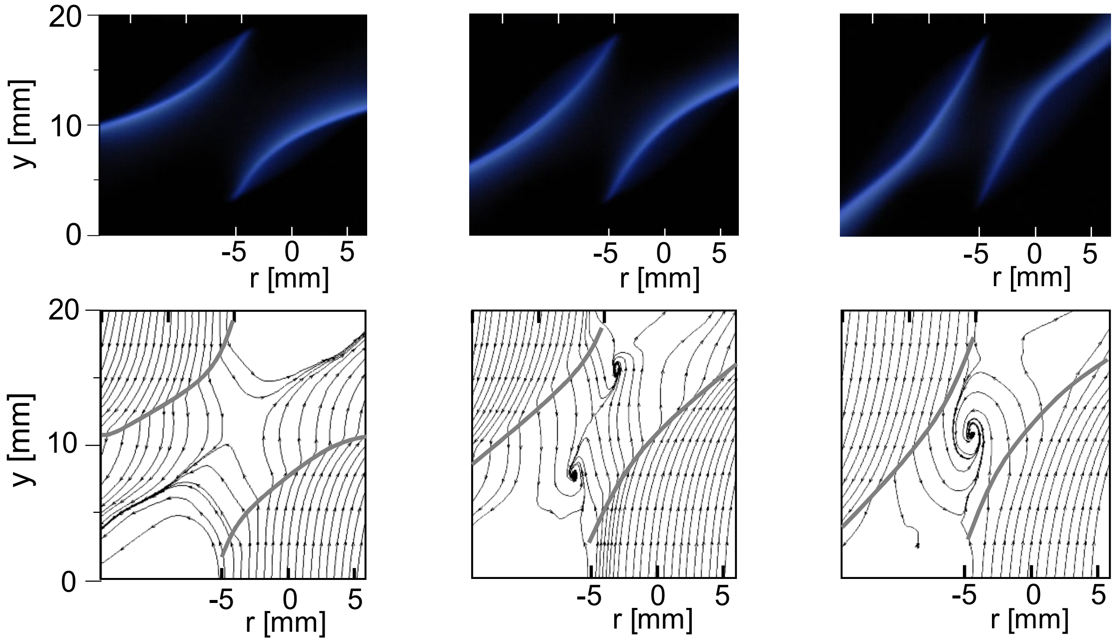
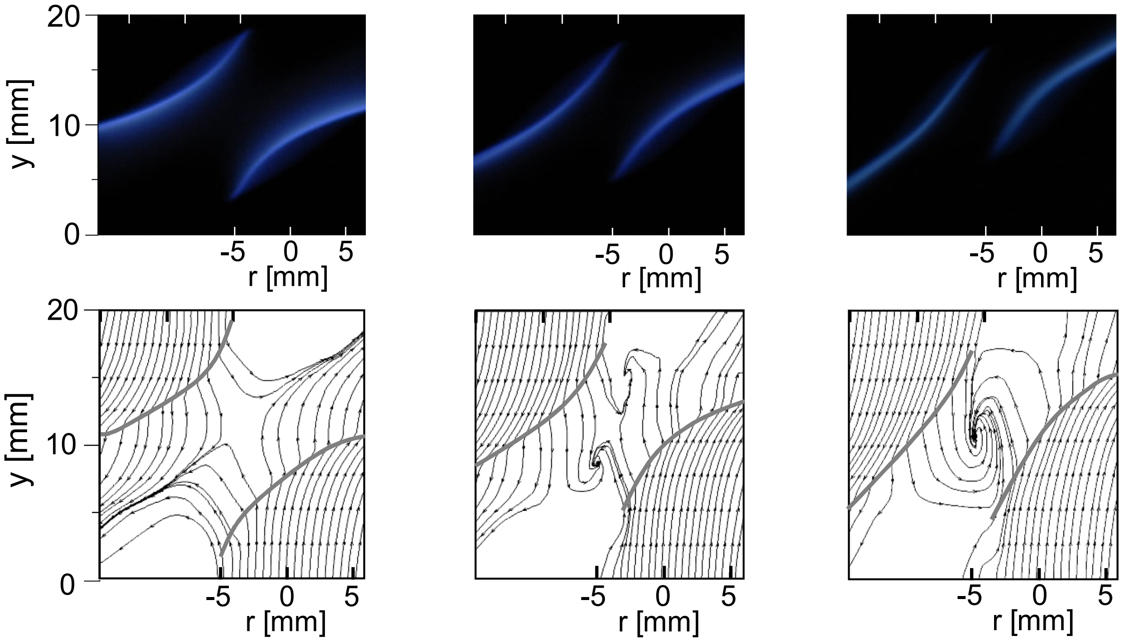


Figure 4. Flow regimes and blow-off condition map for different offsetting rate and mean velocities at stoichiometric.



(a) $\bar{U}_0$ =1.0m/s (b) $\bar{U}_0$ =1.3m/s (c) $\bar{U}_0$ =2.0m/s

Figure 5. Effects of the mean velocities on the flow structures at r_{off}=0.90 and φ=1.0.



(a) φ =1.00 (b) φ =0.90 (c) φ =0.82

Figure 6. Effects of the laminar burning velocity on the flow structures at $\bar{U}_0$ =1.0m/s and r_{off}=0.90.

to the single vortex seems that the stretching mechanism works getting strong with the increased offsetting rate and break down the stagnating point. Then the dividing force may disappear in the stagnating region. That is, the offsetting rate is an important to form a hyperbolic flame and the main flows rate works a key to depend for the vortex structures behind the flames.

3.4. Effects of mixture concentration on the flow structures

Figure 6 shows the effects of the laminar burning velocities on the vortex formation at the different stoichiometric conditions. The flow rate ($\bar{U}_0$=1.0m/s) and offsetting rate (r_{off} =0.90) are equal conditions. The flame shapes are hyperbolic flames in the all condition as showing in direct photos. The flow pattern from PIV images show that the vortex formation changes in the order of no vortex, twin, and single with changed by the equivalence rate as φ=1.00, 0.90, and 0.82. Then, the laminar burning velocities for φ=1.00, 0.90, and 0.82 are 39.3cm/s, 35.2cm/s and 31.3cm/s respectively. The laminar burning velocity data are obtained by using our counter flow burner at r_{off} =0.00 condition. Those results seem to be reasonable, because the flames distance increases with increasing burning velocity. The increased flames distance works to decrease the shear stress. Those mechanisms are the same as the previous section that is the flow structure in the burnt gas changes in the order of decreasing the flame distance, no vortex, twin vortexes and single vortex. In addition, the flame temperature also increases with increasing equivalence ratio. The dynamic viscosity in the burnt gas is also increased by the increasing flame temperature. Those are main reasons that even in the same flow rate and offsetting rate vortex formations changed.

3.5. Flame structure regimes at the extinction and the blow-off

Figure 7 shows the extinction limits for $\bar{U}_0$=1.0m/s and 2.0m/s with different r_{off}. Based on the previous discussions, the threshold between a slant flames and a hyperbolic flames depend on the offsetting rate. That tendency clearly appears in Fig. 7. That is, in slant flames regime, both of flow rate conditions the extinction equivalence ratio slightly increases increasing with offsetting rate. On the approximately r_{off} =0.40, the extinction equivalence ratio steeply increases. In the hyperbolic flames regime, the extinction equivalence ratio increased the offsetting rate more remarkably are increased. The difference of extinction limits between $\bar{U}_0$ =1.0m/s and $\bar{U}_0$ =2.0m/s are mainly increased stretch effect due to the flow rate.

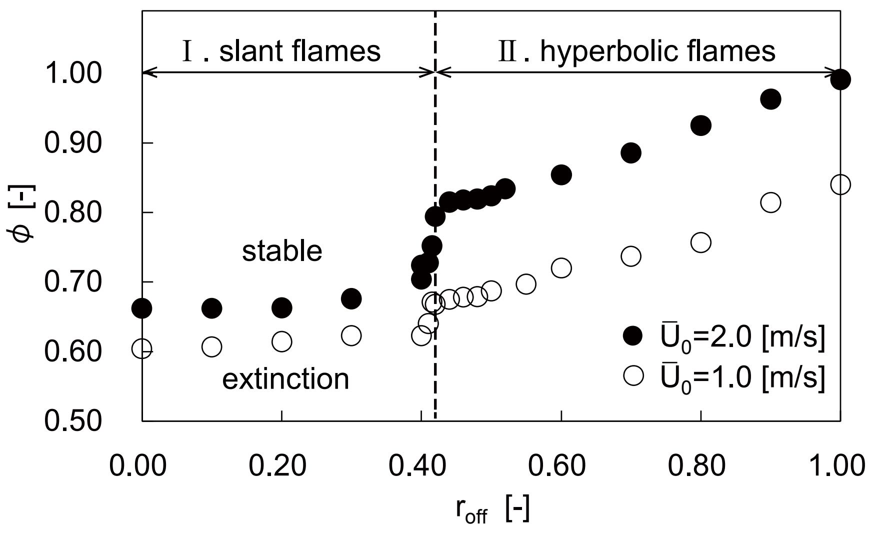


Figure 7. Flame structure regimes at the extinction and the blow-off for $\bar{U}_0$ =1.0m/s and $\bar{U}_0$ =2.0m/s.

4. Concluding Remarks

In order to discuss the laminar flamelet structure affecting with vortex only from the burnt gas side we proposed the offsetting counter flow burner. The flame and vortex structures were elucidated by a particle image velocimetry.

The flames shape in the offsetting burner can be divided in to three regimes with the offsetting rate which are slant twin flames regime, wedge flames and hyperbolic curved flames. The vortexes are only formed in the regime of the hyperbolic curved flames. The formed vortex structures have changed, in the order of increasing the offsetting rate, no vortex, twin vortexes and single vortex. As the exceptional case, in low mean velocity condition, no vortex formed even in the hyperbolic curved flame regime. The vortex structures depend on the shear stress rat impinging surface between the upper flow and the lower flow. Then, the burning velocities, the increased viscosity and the mean flow rates play an important role for the magnitude of the shear stress.

Acknowledgment

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