CHARACTERISTICS OF FLAME STABILIZATION AND COMBUSTION EFFICIENCY IN A SUDDEN EXPANSION FLOW-BASED GAS BURNER

Harinaldi
Department of Mechanical Engineering, Faculty of Engineering University of Indonesia
Kampus Baru, UI Depok, Jawa Barat 16424 INDONESIA

Abstract
Present study investigates the behaviours of flame stabilization and combustion efficiency characteristics in a sudden expansion flow-based gas burner (dump combustor) which applies a backward-facing step configuration. The study focusses on parameters closely relevant to the governing condition of the mixing effectiveness, which enhance the flame stabilization and combustion efficiency including the geometry of the flow field and injection scheme. The investigations are made with experimental approach utilizing flame visualization, flow measurement and exhaust gas analysis using a gas analyzer. Some parameters of interests including the step height \( h \) and the distance of injection location from the step edge \( L_f \) are varied in order to elucidate their influence to the combustion process. Detailed discussions regarding the flame configuration types, the extinction characteristics and combustion efficiency are given in order to elucidate the complex mechanisms affecting the relations among the amounts of burned fuel in the combustion reaction, flow geometry and the dynamical condition within the recirculation flow field where the combustion process takes place.

1 Introduction
In many studies of propulsion system, the most significant problems in the combustion process at high-speed environment are related to the large stagnation pressure loss and entropy rise associated with the heating of a high-speed stream and the interaction of fuel jets and the air stream. If it is seen from flame holding characteristics point of view, the fact that the flow velocities in the high-speed combustor are extremely high, imposes the requirement that the reaction between fuel and air takes place quickly, with combustion process takes place as complete as possible in a relatively short distance due to the limited geometrical size of the combustor. Among the standard flame holding techniques employed in subsonic combustion chambers, most involve the formation of recirculation zones in the flow field which assist in stabilizing the flame structures.

In the past a huge number of theoretical and experimental works were published dealing with the role of flow field structure behind the step and injection and mixing of gaseous types of fuel into the flow field to the flame holding mechanism, focusing on propulsion system application. Bradshaw et al. [1] had done some investigation on the basic characteristics of recirculation flow behind the step. Later, Eaton and Johnston [2] also made a review of typical flow characteristics in the turbulent circulating flow. Haibel and Mayinger [3] conducted investigation on isothermal (Helium gas) and reactive (Hydrogen gas) mixing into high speed air streams with the existence of a step compromising normal and parallel injection by using inclined injection with injection angle \( \theta \), and made a qualitative examination with holographic interferometry technique. Their result showed that the interaction between pair of vortical structure which is common in a jet flow and the flow field condition in backward
facing step which is dominated by recirculation flow induced the effect of skewed vortex generation jets from the injector. Smith [4] examined total pressure distribution, mean velocity, turbulence intensity and velocity cross correlation, gas composition, static temperature and wall static pressure distribution in a coaxial-sudden expansion cylindrical combustor which formed diffusion flame of hydrogen gas. The result showed that the size and location of the recirculation zone were appreciably altered by the presence of chemical reactions. Pitz and Daily [5] made a visualization of the reacting flow of a propane/air mixture by high-speed Schlieren photography and done measurements of the mean and rms. averages of the turbulent velocity flow field at a backward facing step using laser velocimetry method. They found that the linear growth rate of the reacting mixing layer defined by mean velocity profile was unchanged by combustion. Reaction took place largely in the two-dimensional eddies which were not confined to the velocity gradient region.

Considering the important role of flow field of a sudden expansion flow such in a backward facing step for combustion application, the present study is trying to give contribution to the continuing investigation on the flame holding mechanism using a backward facing step method. The investigation is aimed to establish a new experimental database on the flame stabilization characteristics and combustion efficiency in a sudden-expansion flow-based gas burner (dump combustor) model. Furthermore, the study investigates – within practical range – parameters closely relevant to the governing condition of the mixing effectiveness, which enhance the flame stabilization and combustion efficiency including the geometry of the flow field and injection scheme and fluid dynamics of injection flow. This research is expected to enrich the empirical results at fundamental level, to provide justification basis of some modeling resulted from computational works which are currently being studied by many researchers around the world, and to establish a general correlation (or correlations) of fluid dynamics and chemo-physical parameters, which could be shared to improve the effectiveness of mixing. These experimental works will lead to the development of mature criteria for combustor design. This is of scientific and industrial interests.

2 Experimental Works

2.1 Experimental Apparatus

The experimental work was done in Thermodynamics Laboratory, Department of Mechanical Engineering, University of Indonesia. The experimental arrangement is sketched in Fig. 1.

![Fig. 1 Experimental Apparatus](image_url)

It consisted of several main sections including air flow system (electric blower, air duct, settling chamber, and nozzle), experimental model of combustion chamber (test section, injection plate and exhaust duct), and fuel flow system. The rate of air flow supply from the blower was adjusted by some bypass valves which were installed in the bypass line, and the air sequentially entered air duct, settling chamber and a converging nozzle with contraction ratio of 9.5:1. Then the uniform air flow entered the test section. This arrangement could supply the air into the test section with maximum airflow velocity 14 m/s. At the exit of the converging nozzle, a model of combustion chamber comprises of the test section and the injection plate was attached. Test section was made from 5 mm thick brass.
plate, with entrance cross section area 80 x 80 mm; exit cross section area is 80 x 125 mm and total length of 400 mm. The step height from the base could be varied gradually in the range of 0 - 45 mm by using a laboratory jack attached to the base plate. In the base of the step, a fuel injection plate with a slit opening of 70 x 1 mm spanned across the test section was installed, and by substituting the plate, the distance from step to the injection point could be varied. In the present study two distances i.e. 40 mm and 80 mm were used. Both sides of test section were covered by aluminum plate or heat proof Pyrex glass for visualization purpose. Top surface had an open-close hole with 20 mm diameter so that it was possible to insert ignition and measurement devices. At the downstream end of the test section an exhaust duct made from flexible aluminum duct with diameter of 6 inch was attached. In the exhaust duct a port for sampling probe of gas analyzer was prepared.

2.2 Measurement Apparatus

In the flame stabilization experiment, the extinction limit was measured by varying the main airflow velocity. The variation could be made by adjusting the opening of a bypass valve and blower suction gate before the airflow enters the wind tunnel. The airflow velocity was measured with an orifice plate connected to a U tube water-filled manometer. Prior to the experiment, the manometer reading had been calibrated into the main airflow velocity \( U_0 \) at just the entrance of test section with a hot wire anemometer (Lutron AM-4204). Gas fuel injection velocity was altered by adjusting two valves in a capillary manometer system. Prior to experiment, the manometer reading has been calibrated into the gas fuel injection velocity at the slit port with a gas meter (Wet gas meter type- Shinagawa WE – 2.5 A).

The dynamical behaviour of established diffusion flames and their gradual change to extinction was examined with a visualization technique. The flame image was captured by A CCD video camera (Sony Hi8-CCD-VX1) with sufficient exposure and shutter speed to grab a clear video image.

In the experiment to determine the combustion efficiency, a gas analyzer (ECOM-AC 4-6 Gas Emission Analyzer) was used to analyse the flue gas composition as well as temperatures from which the combustion efficiency could be derived. The gas analyzer was a highly advanced portable emission analyzer for the direct measurement of combustion gas parameters incorporating electrochemical gas sensors and sample conditioning technology. Measured parameters included \( \text{O}_2 \), \( \text{CO} \), \( \text{NO} \), \( \text{NO}_2 \) and \( \text{SO}_2 \), \( \text{C}_x\text{H}_y \) temperature and pressure, stack draft, smoke and calculated parameters included combustion and emission factors including \( \text{CO}_2 \), combustion efficiency, losses and excess air.

2.3 Test Procedure and Conditions

The measurement of flame stabilization considered fluid dynamic parameters i.e. the comparison between the fuel injection velocity and airflow velocity. In this way, the stability limit to the flame extinction condition was determined. After a stable flame was formed for a certain velocity of main airflow \( U_0 \), the velocity of gas fuel injection, \( V \) was then reduced until the flame extinct. When the flame extinction happened, the extinction limit value was defined. For a certain combination of parameter, measurement of extinction limit was done more than five times to confirm the reproducibility of the obtained data. After all necessary measurement had been taken up, all the raw data was reexamined, and in case of spurious data existed, the measurements were repeated again for those parameters’ condition. Meanwhile, in the investigation of combustion efficiency, it was calculated directly by the gas analyzer based on heat release principle and the result could be obtained conveniently in printed form. The parameters of experiment were the step height \( (h) \), stream wise distance from the step to the injection slot \( (L_f) \), main airflow velocity \( (U_0) \) and the fuel gas type. Each parameter was varied in several values. Table 1 shows the summary of the experimental condition.
Table 1. Test Condition

<table>
<thead>
<tr>
<th>Step height ((h))</th>
<th>10 – 40 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the step to the injection slot ((L_f))</td>
<td>40 and 80 mm</td>
</tr>
<tr>
<td>Main airflow velocity ((U_0))</td>
<td>7.5 – 12 m/s</td>
</tr>
<tr>
<td>Fuel gas type</td>
<td>Propane ((\text{C}_3\text{H}_8))</td>
</tr>
</tbody>
</table>

3 Result and Discussion

3.1 Stable Flame Configuration

Video images obtained from flame visualization provide some qualitative information about the stabilization configurations of formed diffusion flames behind the backward-facing step and the dynamical behavior of flames structure when they approach to extinction. Fig.2 shows the video image sequence describing the configuration of diffusion flame formed at recirculation zone of the backward-facing step starting from stable condition to extinction for injection of fuel at \(L_f/h = 2\) and main air velocity, \(U_0 = 10\) m/s. Either in case of (a) \(h = 20\) mm; \(L_f = 40\) mm or (b) \(h = 40\) mm; \(L_f = 80\) mm, the figures show relatively similar trends. In a stable condition, the flame structures are very irregular. Close observation on the original video movies suggests that the flame highly fluctuates spatially and temporally. Sometimes the flame is broken down into flamelets. This flame appearance confirms that the combustion takes place mainly in the recirculation region so that the flame structure receives a strong influence from the recirculation flow. Furthermore, the yellow appearance that dominates the flame indicates that the combustion process tends to occur in fuel-rich environment. Therefore, it is supposed that in order to avoid flame extinction and to maintain the fuel burning, the gas fuel should be injected with excessive amount. When the fuel injection is decreased approaching the extinction limit, the flame start to extent its blue appearance although the structure becomes more vulnerable. The fuel injection can be continuously decreased until the flame appearance suggesting that combustion process occurs in a very fuel-lean condition and eventually the flame extinct. Hence, it is suggested that the flame extinction occurs mostly due to the weakening of chemical reactivity of the combustible mixture in the recirculation region.

Fig.2 Configuration of diffusion flame formed at recirculation zone of backstep from stable condition to extinction for injection at \(L_f/h = 2\) (\(U_0 = 10\) m/s)

On the other hand, Fig. 3 shows the video image sequence describing the configuration of diffusion flame at \(L_f/h = 4\) and main air velocity, \(U_0 = 10\) m/s. From the two series of images, either in case of (a) \(h = 10\) mm; \(L_f = 40\) mm or (b) \(h = 20\) mm; \(L_f = 80\) mm, the figures show relatively similar trends. In a stable condition, the flames are formed along the shear layer region starting from the step edge until the reattachment zone. The flame structure shows that the combustion reaction is distributed rather uniformly inside the shear layer region. Close observation on the original video movies suggests that the flame does not intensely fluctuate. This flame appearance confirms that the combustion takes place mainly in the shear-mixing layer where the injected gas fuel mixes better with main airflow that entrains into the layer. Furthermore, the bluish appearance that dominates the flame indicates that the combustion process takes place with closer to stoichiometric mixture. When the fuel injection is decreased approaching the extinction limit, the flame start to shorten and its blue appearance become less clear. The fuel injection
can only be decreased continuously until certain point when flame suddenly extinct. Hence, it is suggested that the flame extinction occurs mostly due to the hydrodynamic effect. When injected from \( L_f/h = 4 \) the flow field around the injection point is dominated by a high turbulence and high velocity reverse flow. Hence, it is suggested that the blowing effect to the flame anchor forces the flame to extinct.

**3.2 Flame Extinction**

Figure 4 shows the extinction limits of the diffusion flame in case of fuel is injected from \( L_f = 40 \text{ mm} \). In each test, the step height was varied in the range of 10 to 20 mm that gave five relative position of injection location, \( L_f/h = 2, 2.29, 2.67, 3.2, \) and 4. Each data series shown along with its best fitting plot represents the extinction limit for a certain \( L_f/h \). The figure indicates that generally for all condition, the extinction limit curves rise monotonically. In other word, the extinction limit shows relative similar characteristics with regard to the alteration of the main air flow velocity. If the main air flow velocity is increased the velocity of fuel injection should also be increased in order that the flame can be prevented to extinguish. This indicates that more amount of gas fuel is needed to provide a continuous chemical reaction in the environment with higher free stream velocity.

![Fig.4 Extinction limit in case of \( L_f = 40 \text{ mm} \)](image)

On the other hand, Fig. 5 shows the extinction limits of the diffusion flame in case of fuel is injected from \( L_f = 80 \text{ mm} \). In each test, the step height is varied in the range of 20 to 40 mm that gives five relative position of injection location, \( L_f/h = 2, 2.29, 2.67, 3.2, \) and 4.

![Fig.5 Extinction limit in case of \( L_f = 80 \text{ mm} \)](image)

Similar to the case of \( L_f = 40 \text{ mm} \), the extinction limit curves generally rise monotonically for all conditions. In other word, the extinction limit shows relative similar characteristics with regard to the alteration of the main air flow velocity. If the main air flow velocity is increased the velocity of fuel injection should also be increased in order that the flame can be prevented to extinct. However, the variation of
extinction limit curves with respect to the variation of relative position of injection distance from the step edge to the step height \((L_f/h)\) for each type of injected gas show a remarkable differences to the previous case.

From the data presented in the extinction limit curves, the characteristic of extinction can be further discussed with regard to the effect of geometrical parameter of injection represented by location of fuel injection \((L_f)\), and the size of recirculation flow field determined by the step height \((h)\). As presented in Fig. 6, the summary of the characteristics of extinction is described as the relation between the ratios of fuel injection velocity to the main airflow velocity \((V/U_0)\) and the relative distance of injection to the step height \((L_f/h)\). In each figure, the extinction characteristic is plotted for two location of injection, \(L_f = 40\) and \(80\) mm.

From the figure, it can be figured out that the ratio \(V/U_0\) at extinction for the case of injection at \(L_f = 40\) mm significantly lower than that for the case of \(L_f = 80\) mm. Furthermore, it is obvious that the flame extinction in case of \(L_f = 40\) mm shows relative constant value of \(V/U_0\) for different \(L_f/h\) with very little tendency of \(V/U_0\) to decrease when \(L_f/h\) increases. This results is indicating a weak dependent of flame extinction limit to the relative distance of injection to the step height \((L_f/h)\). On the other hand, in case of \(L_f = 80\) mm the flame extinction limit show stronger dependent to the relative distance of injection to the step height. As seen in the figure, the value \(V/U_0\) tend to increase when \(L_f/h\) is increased. It is considered that the different extinction characteristics for the two cases are related to the condition of the recirculation flow field formed behind the backstep. In case of injection at \(L_f = 40\) mm, the variation of step height is between 10 to 20 mm, meanwhile incase of injection at \(L_f = 80\) mm, the variation of step height is between 20 to 40 mm. The different height of the step is supposed to construct different fluid dynamical characteristics of the recirculation flow field behind the backstep where the gas fuel is injected and the flame is stabilized in the rim of injection hole. Some studies [1-3,6,7] had revealed that with a low step, the size of recirculation flow field is small and the reverse flow as well as the turbulent intensity is not high. With the increasing step height the recirculation flowfield will be more complex characterized by higher reverse flow velocity and higher turbulent intensity. In some instance there exist the corner Eddy due to higher pressure differential which induced when the step height is large. We attribut the characteristics of flame extinction limit as shown Fig. 6 to this recirculation flow behavior. Uno [8] had also mentioned the different characteristics of flame stabilization due to step height difference and divide the extinction limit into low step \((h < 20\) mm) and high step \((h > 20\) mm) although there was no further discussion about the flow field condition.

3.2 Combustion Efficiency

The combustion efficiency is calculated directly by the gas analyzer based on heat release principle. The exhaust gas samplings from the combustion reaction were done in three different conditions of main air flow velocity and in each condition the fuel injection velocity is set to value of 2%, 20 % and 40 % above the extinction limit. Not like the previous results in the extinction limit measurement, in general there is no remarkable different tendency of combustion efficiency between injection with \(L_f = 40\) mm and \(L_f = 80\) mm. Hence, in the following section only representative results from the case of injection at \(L_f = 40\) mm are discussed.
The combustion efficiency of propane is shown in Fig. 7 (a)-(c).

![Graph](image)

Fig. 7 Combustion Efficiency (Propane)

Comparison of all the plots also suggest that the combustion takes place more efficiently if the fuel is supplied to the combustion chamber with the velocity near to the flame extinction limits. Increasing the injection velocity above the extinction limits will decrease the combustion efficiency. In each condition of fuel injection velocity it is observed that the curves of combustion efficiency do not decrease monotonically with an increase of $L_f/h$. Instead, the curves exhibit a plateau for $L_f/h$ in the range of between around 2 and 3.5 and then decreases substantially for $L_f/h = 4$. Meanwhile, although not too obvious, for injection with a certain $L_f/h$ the combustion efficiency will increase if the main air flow velocity is increased. The above results indicates that the mechanisms governing combustion efficiency characteristics suggest a complex relations among the amount of burned fuel, the amount of heat releases in the combustion reaction and the fluid dynamical condition within the recirculation flow field where the combustion process takes place. As shown in the figures of combustion efficiency characteristics some peculiarities such as the plateau appearance in the combustion efficiency curves seem to be better explained if attributed to the mixing effectiveness of the injected fuel and the entrained air flow. Some flow field measurement behind the backstep [2, 3, 6] has shown that the middle region of recirculation flow has relatively constant flow structure dominated by moderate reverse flow velocity as well as turbulent intensity. This proposed to provide a rather uniform mixing that result a rather constant efficiency if the fuel is injected and undergo combustion reaction in that region.

3 Concluding Remarks

The present work has studied comprehensively the behaviours of flame stabilization and combustion efficiency characteristics in a sudden expansion flow-based gas burner (dump combustor) applying a backward-facing flow step configuration. The investigations were made with experimental approach utilizing flame visualization, flow measurement and exhaust gas analysis using a gas analyzer. Some important aspects can be concluded as follows:

1. Stable flame configuration can be divided into two different types, the one stabilized within the recirculation region and another
one stabilized in the shear layer region. The former configuration highly fluctuates spatially and temporally indicates that the combustion process tends to occur in fuel-rich environment. Meanwhile the later shows that the combustion reaction is distributed rather uniformly inside the shear layer region. The flame does not intensely fluctuate and indicates that combustion process takes place with closer to stoichiometric mixture.

2. The extinction characteristics are related to the condition of the recirculation flow field formed behind the backstep yielding two different cases. With lower step height \((h\text{ less than } 20\text{ mm})\) the flame shows relative constant value of \(V/U_0\) for different \(L_f/h\) indicating a weak dependent of flame extinction limit to the relative distance of injection to the step height \((L_f/h)\). With higher step height \((h\text{ more than } 20\text{ mm})\) the flame extinction limit shows that value of \(V/U_0\) remarkably depend on the relative distance of injection to the step height \((L_f/h)\).

3. The combustion efficiency characteristics suggest complex mechanisms governing relations among the amounts of burned fuel, the amount of heat releases in the combustion reaction and the fluid dynamical condition within the recirculation flow field where the combustion process takes place. The competition between the penetration capabilities of injected gas having higher momentum when injected with higher velocity with the capability of recirculation flow to engulf the supplied fuel in the recirculation region determined the fuel consumption as well as the combustion efficiency.

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