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Numerical study of influences of crosswind and additional steam on the flow field and temperature of propane non-premixed turbulence flame

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Abstract. This paper presents results of combustion of propane using computational fluid dynamics (CFD) to simulate the turbulent non-premixed flame under the influences of crosswinds and the ratio of fuel (propane) to steam, S. Configuration, discretization and boundary conditions of the flame are described using Gambit™ software and integrated with Fluent™ software for calculations of flow and reactive fields. This work focuses on the influence of various crosswind speeds (0–10 m/s) and values of S (0.14–2.35) while the velocity of fuel issued from the nozzle was kept constant at 20 m/s. A turbulence model, k-ε standard and combustion model, Eddy Dissipation model were employed for the calculation of velocity and temperature fields, respectively. The results are displayed in the form of predictive terrain profile of the propane flame at different crosswind speeds. The results of the propane flame profile demonstrated that the crosswind significantly affect the structure velocity and position of the flame which was off-center moving towards the direction of crosswind, eventually affect the temperature along the flame. As the values of S is increasing, the flame contour temperature decreases, until the flame was extinguished at S equals to 2.35. The combustion efficiency for a variety of crosswind speeds decreases with increasing values of S.

1. Introduction

Combustion is a very complex process dealing with interaction of physical and chemical phenomena including flow, turbulence, thermodynamics, chemical reaction, radiation, extinction, and ignition. Almost all burning systems in a variety of equipment such as rocket engines, aircraft engines, kilns and chimneys in industry are implemented in a turbulent environment, with the aim at increasing the rate of combustion. Heat is released from chemical reactions, but the process involves the propagation

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of heat transfer and fluid dynamics so that the theoretical interpretation can be derived using an understanding of chemistry, physics, fluid mechanics and applied mathematics [1, 14].

In accordance with the type of fuel, combustion can be divided into three types, gas, liquid and solid; while the flame generated can be classified into premix and non-premix ones. A premix flame occurs when the fuel and oxidizer are mixed before ignition, while the latter when the fuel and oxidizer are not mixed before the combustion process takes place, oxidizer merges with fuel by diffusion. In terms of safety aspects, the use of non-premix flame is better than that of premix flame. As a consequence, the non-premix flame is more widely used for industrial applications such as turbines, aircraft and furnaces [2].

Non-premix jet flames influenced by crossflow occur in several applications, such as gas turbine combustor, refinery flaring operations, and industrial burners. The characteristics of the flames under a crossflow influence are totally different from those of stable ones. Results of research found out that the combustion efficiency decreases when the crosswind speed increases. In addition, the flame will bend towards the wind direction with a smaller size, so that oxygen is diffused less into the flame. When oxygen concentration supply reduces into the flame, burning runs imperfectly and produces more pollutants, which are undesirable [3-5]. However, increased jet exit velocity makes the flame less susceptible to the effects of crosswind. The height of a flame is strongly influenced by the increase in wind speed compared to the flame length, as a result of the rising angle of inclination of the flame [6]. The difference between the combustion characteristics of the species is caused by the difference in mass, surface area, and orientation. Results of the analysis showed that the species and length of the flame are due to the influence of wind speed and humidity. At the time of ignition, a combustion material sample under windy conditions contains higher moisture than the combustion products without the influence of these conditions. The average mass loss on ignition is 13% with the effect of wind and 25% without the influence of wind [7].

A study [8] burnt fuels and removed hydrocarbon gas through a vertical hole with both diameters 0.076 m and 0.305 m. The combustion products were collected, samples were taken and analysed to determine the efficiency of combustion. If the flame is stable (i.e. the effect of exit speed and fuel value of the fuel gas), the efficiency can be greater than 98%. However, based on pilot test, it was found out that high crosswind speed significantly reduced the combustion efficiency. Other workers [9,10] demonstrated that the effect of crosswind with a range of 1–15 m/s can reduce combustion efficiency significantly. The laminar burning rate and adiabatic flame temperature increases with the addition of hydrogen into the fuel flow, thus increasing the mass and thermal diffusivity of hydrogen in the air, making it more reactive. Instead, the addition of steam into the flow of the fuel mixture of methane actually reduces the rate of air and adiabatic flame temperature of combustion [10]. Increasing mole fraction of water vapour in the fuel flow rate will further decrease a flame burning methane [11].

Addition of steam to mix with incoming air thereafter mixed with fuel will affect the combustion process inside the combustor. A research on gas turbine cogeneration systems with steam injection [12] was conducted to study the effect of NOx formation due to steam addition to a methane non-premixed flame. It was found that steam addition stimulates the production of NOx. However, because of the decrease in CH concentration with steam addition, the production rates of HCN and N radicals decrease dramatically. Another study [13] numerically investigated the effect of steam addition on the performance of the combustor. It was reported that steam injection is an effective way to reduce the temperature in the burner keeping other performance like the total pressure loss minimum.

The above review has shown that studies the effect of crosswind and steam additional is done separately. There has been limited studies was conducted to investigate simultaneous influences of crosswind and steam addition on the performance of a flame. It is the objective of this paper are to analyse the effect of various crosswind speeds and the addition of steam to the flame produced, and the combustion efficiency, using computational fluid dynamical approach.
2. Methodology

2.1. Governing Equations

In general, many equations are used in the concept of computational fluid dynamics, because the approach of fluid characteristics attempts to simulate real conditions. The basic equations involved in a laminar and turbulent flow without involving heat transfer and species are shown in Equation (1). This equation is often mentioned as the continuity equation in Cartesian coordinates that is used in computational fluid dynamics. It is also involved in the modeling of turbulent combustion including conservation of mass, momentum, enthalpy and species [1].

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  
(1)

This equation is the common equation of mass conservation and applies to any compressible and non-compressible flow. The momentum conservation equation defines the fluid motion for the forces on the particles at every certified fluid element in computational fluid dynamics modelling. Momentum conservation equations for Cartesian coordinates are shown in Equations (2)–(4):

\[
\rho g_x + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} = \rho \left[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right] 
\]  
(2)

\[
\rho g_y + \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} = \rho \left[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right] 
\]  
(3)

\[
\rho g_z + \frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = \rho \left[ \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right] 
\]  
(4)

These equations are general differential equations of fluid motion. In fact they can be applied to every continuum (solid or fluid) when moving or stationary [1].

When the combustion process involves heat transfer in the fluid or solid, the heat transfer equation needs to be changed into the form of Equation (5).

\[
\frac{\partial \varphi_h}{\partial t} + \frac{\partial \varphi h u_j}{\partial x_j} = \frac{\partial \varphi}{\partial t} + u_j \frac{\partial \varphi}{\partial x_j} - \frac{\partial \varphi h}{\partial x_j} + \frac{\partial \varphi h u_j}{\partial x_j} + \rho \varphi_h_j
\] 
(5)

Equation (6) is required for systems that involve a chemical reaction of migratory species.

\[
\frac{\partial Y \alpha}{\partial t} + \rho u_j \frac{\partial Y \alpha}{\partial x_j} = - \frac{\partial \varphi_h}{\partial x_j} + \rho \varphi_j \alpha \quad (\alpha = 1, 2, ..., N)
\]  
(6)

Solution of Equation 6 requires modelling. Eddy dissipation models (EDM) is one combustion models developed to predict the combustion reaction of gas in a turbulent flow. The combustion reaction is considered as a single reaction that is not reversed at a limited rate. EDM assumes that the reaction proceeds very quickly. When the reactants are mixed at the molecular level, in real-time directly form the product, so that the overall reaction rate is controlled by turbulent flow. The weakness of this model lies in the assumption that the combustion reaction following the one-step reaction that is not reversible. Consequently, it does not enable the combustion reaction kinetics to be
completely incorporated into the calculation. Although this model is widely used in CFD commercial software, it is only appropriate for cases where the kinetics do not play an important role, but so far is the use of this model can still be promising for prediction accuracy [1,2].

2.2. Geometry Configuration and Numerical Computation
This study starts with depicting the geometry of the flame being investigated using the Gambit software (Geometry and Building Intelligent Mesh Toolkit). The procedure is carried out drawing a cylinder in three dimensions for the nozzles and domain, followed by the process of meshing or dividing objects into small parts in order to perform the analysis on the computational fluid dynamics program. The diameter of the nozzle to issue the fuel is 2.0 mm, while the diameter of the domain is 0.7 m. Other basic data with regard to fuel are shown in Table 1. Defining the boundary conditions is performed as the velocity inlet, outlet pressure, and the interior wall. Figure 1 shows the geometry of the three-dimensional flame that has a discretized domain.

![Figure 1. Three-dimensional geometry flame domains.](image)

Calculation of flow and reactive fields, continuity, momentum, energy and species transport equations was solved by commercial CFD code Fluent 6.2.16. With regard to flow field calculation, a standard $k - \varepsilon$ turbulence model was employed to solve the momentum transport equation. As the aim of the research to study the influences of crosswind and additional steam to the fuel, the crosswind speed was varied as 0, 1, 3.77, 7.5 and 10 m/s while the mass ratio of steam to fuel (S) was varied as 0.14, 0.25, and 2.35.

| Table 1. Characteristics of the flame. |
|----------------------------------------|
| Fuel composition                      | Propane 100% |
| Speed Fuel                            | 20 m/s (Re 8800) |
| Nozel Diameter                        | 2 mm |
| Domain Diameter                       | 0.7 m |

The effects of crosswind speeds and the addition of steam to the flame were analysed to determine the efficiency of the flame combustion process. The combustion efficiency ($\eta_c$) is the mass flow rate of carbon in the form of $CO_2$ produced by flame divided by the mass flow rate of carbon in the fuel, as shown in Equation (7).
\[ \eta_c = \frac{\text{Mass flowrate of carbon in the CO}_2 \text{ produced by flame}}{\text{Mass flowrate of carbon in the C}_x\text{H}_y \text{ in the fuel gas stream}} \]  

(7)

Table 2 presented mixture of steam and fuel, starting from pure fuel to give the ratio of steam to fuel, S = 0. The amount of steam to mix with propane fuel was increased such that the maximum S value was 2.35.

Table 2. Species mass fraction flow fuel for various values of S.

| S  | X\text{C}_3\text{H}_8 | X\text{N}_2 | X\text{H}_2\text{O} |
|----|-----------------|------|-------------|
| 0  | 1               | 0    | 0           |
| 0.14 | 0.8          | 0.09 | 0.112       |
| 0.25 | 0.72         | 0.1  | 0.18        |
| 2.35 | 0.18         | 0.39 | 0.423       |

3. Results and Discussion

3.1. Flow field profile

Figure 2 illustrates the flow field profile in terms of axial velocity of fuel at various crosswind speeds. The highest fuel speed can be seen at a position close to the surface of the nozzle; the speed decreases with increasing distance towards the flame. Finally, flow rate decreases with increasing distance of flame area. Fluid velocity increases not only at the tip of the nozzle, but also on the downstream flow of the output of the nozzles. This phenomenon takes place because the high cross wind speeds mixing of fuel and air occurs very quickly at the base of the flame, where there is a vortex motion that moves the incoming air into the missing tip of the flame, so that the flame bends towards the direction of the cross wind. The volume of incoming air affects the magnitude of the flame’s height.

Figure 2. Flame flow field (axial velocity) against axial position for a variety of crosswind speeds.

3.2. Influences of additional steam for a variety of crosswind speeds

Figure 3 shows the relationship between the crosswind speeds and the combustion efficiency at different S values. The combustion efficiency was obtained in accordance with Equation 7. The trend of three curves of different S values is similar, the combustion efficiency tends to decrease with the increase of crosswind speeds. However, at the highest value of S (2.35), the combustion efficiency decreases sharply with respect to the increase of crosswind speeds. This finding supports the results of previous researches [8-10]. At lower values of S (0.14 and 0.25), the combustion efficiency was
almost stable up to the crosswind 7.5 m/s, and thereafter decreases slightly significant. This finding indicates that at small ration of steam to fuel, combustion efficiency is still high until particular crosswind speed (7.5 m/s). Having a fuel speed of 20 m/s is capable of suppressing the influence of crosswind flow of 7.5 m/s in speed. However, the fuel speed of 20 m/s is no longer able to maintain a stable combustion efficiency at higher crosswind speeds. Results obtained from this study indicate that the mass ratio of steam to fuel and crosswind speed play an important role in calculating the efficiency of the combustion. The highest efficiency of combustion obtained here is 99%.

![Figure 3](image)

**Figure 3.** Relationship between crosswind speed and combustion efficiency.

Crosswind speeds also greatly affected the efficiency of combustion, as seen from Figure 3. At higher speeds, the efficiency decreases significantly, which mainly due to incomplete combustion. At higher crosswind, the flame tends to bend towards wind direction and almost extinct. As in the case of value of S = 2.35, imperfect combustion took place, as indicated by low resulting combustion efficiencies even at lower crosswind speeds. At higher crosswind speeds, greater than 7.5 m/s, the flame was extinguished and consequently the combustion efficiency reached zero. This suggests that the addition high portion of steam is not recommended for burning hydrocarbons.

3.3. Flame contour temperature profile

Figure 4 shows the flame temperature contours that are generated at various cross wind speeds and for different mass ratios of steam to fuel. Differences in colour on the contour image reflects the different temperature values generated by each flame. From Figure 4, it can be seen that the value of S at various cross wind speeds greatly affects the combustion temperature. The flame temperature decreases with increasing amount of steam supplied in the fuel flow. At a large value of S (2.35), the flame was almost extinguished, resulting in the release of hydrocarbons into the atmosphere instead of combusting the fuel. Linking this contour temperature with Figure 3, now it is much easier to understand that at high value of S efficiency of the combustion is low.
As the temperature getting lower, the combustion efficiency also decreases.

**Figure 4.** Flame contour temperature at crosswind speed 0, 1.377, 5.0, 7.5 and 10 m/s and value S (0.14, 0.25 and 2.35).

### 4. Conclusion

A CFD study of a propane non-premixed flame and the impact of crosswinds as well as additional steam have been presented using the k-ε standard for the turbulent model, and eddy dissipation for the combustion model. The results of CFD study showed The addition of a quantity of steam to a combustion system influenced by crosswind lowered the flame temperature. As the temperature getting lower, the combustion efficiency also decreases. The study needs to be enhanced to further investigate the impact of steam addition on soot and NOx production by a flame.

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