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FULL LENGTH ARTICLE

A polynomial regression model for stabilized turbulent confined jet diffusion flames using bluff body burners

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Abstract Thermal structure of stabilized confined jet diffusion flames in the presence of different geometries of bluff body burners has been mathematically modeled. Two stabilizer disc burners tapered at 30° and 60° and another frusted cone of 60°/30° inclination angle were employed all having the same diameter of 80 (mm) acting as flame holders. The measured radial mean temperature profiles of the developing stabilizing flames at different normalized axial distances were considered as the model example of the physical process.

A polynomial mathematical model of fourth degree has been investigated to study this phenomenon to find the best correlation representing the experimental data. Least Squares regression analysis has been employed to estimate the coefficients of the polynomial and investigate its adequacy. High values for $R^2 > 0.9$ obtained for most of the investigated bluff burners at the various locations of x/d_j prove the adequacy of the suggested polynomial for representing the experimental results. Very small values of significance $F < (\alpha = 0.05)$ for all investigated cases indicate that there is a real relationship between the independent variable r and the dependant variable T. The low values of $p < (\alpha = 0.05)$ obtained reveal that all the recorded parameters for all the investigated cases are significant.

1. Introduction

Turbulent diffusion flames are usually used in industrial applications such as gas burners of industrial furnaces, gas turbine combustion chamber and flaring of petroleum industry. To improve the efficiency of practical burners, the design has been widely studied and received renewed attention in recent years. The co-axial jet diffusion flames have been found to be a viable method for enhancing flame stability. In such an arrangement, a flame holder such as bluff bodies is necessary to generate a recirculation zone in which the fuel and oxidizer mix thoroughly. Bluff body wakes play a very important role in stabilizing the flame [1]. It can be noted that the aerodynamic wake provides sufficient residence time for the fuel to ensure a stable flame creating a pilot flame which serves as a continuous

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ignition source to stabilize the main flame even at a higher velocity [2,3].

Several studies on bluff body flame stabilization have been reported revealing the complex flow pattern, chemistry and pressure gradient interaction which present in the reactive recirculatory flow field [4–6].

Also the effect of bluff body shape in flame stabilization was investigated experimentally [7–9]. Bluff bodies with different geometry and aerodynamic characteristics had a more obvious effect on flow structure and mixing mechanism. The flow features influenced by the different shapes of bluff bodies creating a large scale motion of the re-circulated vortices, prolong stagnation of reactants which is a key factor to flame stabilization regime.

Moreover, the effect of bluff body geometry such as lip thickness, for the LPG jet diffusion flames, on several physical parameters like flame length, gas temperature and flame stability were experimentally studied [10–12]. Results indicated that with increase in lip thickness, the flame length gets reduced, increasing the flame temperature and enhancing flame stability. This can be attributed to the enhanced reactivity and residence time of the mixture gas with increasing lip thickness of the bluff body. Also the recirculation zone formed in the wake of this bluff body allows better mixing in this region shifting the reaction zone toward the bluff body realizing an improvement in the combustion domain.

The present study analyses through mathematical modeling the previously reported experimental data of thermal structure of turbulent stabilized confined jet diffusion flames in the presence of different geometries of bluff body burners [13].

2. Experimental

The experimental setup comprised a vertical combustor of 150 (mm) diameter, 5 (mm) thickness and 1 (m) height. The combustion chamber was fitted with an arrangement of supplying the fuel and combustion air. The burner section consisted of an outer cylinder of the same diameter as the combustion chamber and a central pipe of 25 (mm) diameter. The latter holds the bluff body and the fuel supply line is connected to the fuel jet nozzle of (d_j) 2.5 (mm) inner diameter and 10 (mm) outer diameter at the centre of the bluff body at the base of the combustor. In this experimental example three bluff-bodies were used. The first stabilizer disc was tapered at 30°; the second was tapered at 60° of the same diameter of 80 (mm) and 10 (mm) high. The third bluff body was stabilizer frusted cone having inclination angles of 60°/30° and 50 (mm) high with the same surface diameter of 80 (mm) facing the jet flame. Commercial LPG fuel was used in all experiments. The developing jet flames operated at the same fuel mass flow rate ($\dot{m}_f$) of 2.6 kg/h, combustion air flow rate ($\dot{m}_a$) of 40 kg/h, air/fuel ratio (A/F) = 15.34 at the stoichiometric condition and overall flames equivalence ratio (Φ) = 1 in the presence of each bluff body geometry [13].

The mean radial temperature distribution was measured at different normalized axial distances along these developing flames over the different bluff-body burners.

3. Regression analysis and mathematical model

Regression analysis is a statistical tool for the investigation of relationships between two or more variables of which at least one is subject to random variation, and to test whether such a relation, either assumed or calculated, is statistically significant. Usually, the investigator seeks to ascertain the causal effect of one variable upon another. To explore such issues, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables upon the variable that they influence. The investigator also typically assesses the "statistical significance" of the estimated relationships, that is, the degree of confidence that the true relationship is close to the estimated relationship. The statistical tests, which normally accompany regression analysis, serve in model identification, model verification, and efficient design of the physical process. Regression analysis produces an equation that will predict a dependent variable using one or more independent variables. Numerous references dealt with the concept of Regression analysis [14–17].

When running regression, we are trying to discover whether the coefficients of the independent variables are really different from 0 (so the independent variables are having a genuine effect on the dependent variable) or if alternatively any apparent differences from 0 are just due to random chance. The null (default) hypothesis always states that each independent variable is having absolutely no effect (has a coefficient of 0) and you are looking for a reason to reject this hypothesis.

3.1. Polynomial regression

From the experimental result we assume that the behavior of the dependent variable can be explained by a polynomial, additive relationship between the dependent variable and a set of power in the independent variable. Polynomial regression models contain squared and higher order terms of the predictor variables making the response surface curvilinear.

In statistics, polynomial regression is a form of linear regression in which the relationship between the independent variable x and the dependent variable y is modeled as an nth order polynomial. Polynomial regression fits a nonlinear relationship between the value of x and the corresponding y, and has been used to describe nonlinear phenomena. Although polynomial regression fits a nonlinear model to the data, as a statistical estimation problem it is linear, in the sense that the regression function $E\ (y|x)$ is linear in the unknown parameters that are estimated from the data. In addition, it is assumed that the Ordinary Least Squares (OLS) assumptions hold that minimizes the variance of the unbiased estimators of the coefficients. We then proceed to develop a complete fourth degree polynomial model. We eliminate non-significant terms based on statistical parameter tests (if the recorded $p > (\alpha = 0.05)$ and the coefficient confidence interval spans zero) then rerun the model without these non-significant parameters. The final model should contain only significant parameters.

3.2. Goodness of fit

The *OLS* technique ensures that we find the values of coefficients which 'fit the sample data best', in the specific sense of minimizing the sum of squared residuals. To guarantee that the 'best fitting' equation fits the data well we assess the adequacy of the 'fitted' equation through the following indicators [16,17].