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Numerical study of a wake-stabilized propane flame in a cross-flow of air

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Predictions of flame structures, flame temperatures, and species concentrations have been numerically performed for a wake-stabilized propane flame in a cross-flow of air. The flow field has been modeled using the Reynolds-Averaged Navier-Stokes equation incorporating the Reynolds Stress turbulence closure Model (RSM) and the Large Eddy Simulation (LES) technique with the two methods compared. The combustion processes were modeled using the partially premixed and the non-premixed models and the two sets of results have also been compared. The CRECK reaction mechanism was used to model the kinetics of the propane reactions while soot in the flame was modeled with the Moss-Brookes-Hall model. Thermal radiation in the flame was modeled with the discrete ordinate method. The results of the simulation have been validated against experimental data and show that the partially premixed model performs better than the non-premixed model for wake-stabilized flames that are attached to the lee-side of the flare burner. Furthermore, the LES technique has been shown to perform better than the RSM.

1. Introduction

Environmental pollution associated with the flaring of hydrocarbon fuels has received much attention over the last few decades and most of this knowledge has been obtained from experimental studies on the laboratory scale [1,2]. This has resulted from the difficulties associated with the investigation of the full scale flares, however some work on full scale flares has been undertaken and the results from these investigations now form a central policy of the Environmental Protection Agency (EPA) on gas flaring [3]. Extensive research on full scale flares has also been performed by the Alberta Research Council (ARC) and the results of this research has helped to establish the significance of crosswinds on flare efficiencies, a factor which was not included in the EPA research [4]. On the laboratory scale, researchers have been able to probe the characteristics of flare-related diffusion flames more closely. Relationships between flame lengths and pipe internal diameters for different fuels have been established and the stability of propane flames in still air and in a cross flow of air have been investigated and reported [5,6]. Gollahalli and Nanjundappa [7] investigated propane flames in a cross-flow of air for various jet-to-cross flow momentum ratios that are related to gas flares, where they described the flow processes that control the mixing in the flame, namely a standing vortex trapped at the lee-side of the fuel pipe in the wake-stabilized regime and a pair of counter-rotating vortices downstream of the flame in a momentum-dominated regime. Huang et al. [8–10] also performed detailed experimental work on propane flames in a cross flow of air. They investigated the structure of the flames in various regimes as well as the species concentration and thermal field of the flames. They reported that for many hydrocarbon fuels, the burner-detached or lifted flame will only survive at cross-flow velocities lower than about 8 m/s while the attached flames can survive at much higher velocities. However, it has been observed that the burner tips tend to deteriorate more rapidly when flames are attached than when they are lifted due to the high temperatures at the burner tip. They also reported that if the flame was lit at a cross-flow velocity higher than a critical value, then the flame base could never leave the burner before blow-off, i.e. the flame will always attach to the burner on the leeside.

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In recent years, computational fluid dynamics studies have been made of these flames and a large body of literature is available on the simulation of methane-air flames for both straight jets and to a less extent cross-flow flames. Notable among these is the work of Escudier [11] who investigated and predicted major and minor species in methane-air flames. Castiñeira and Edgar [12] performed computational fluid dynamics simulation of wind tunnel experiments on natural gas flares using the k–ε realizable version of the eddy viscosity model; however the results obtained were not compared against experimental measurements of the species and temperature. Lawal et al. [13,14] also used the k–ε realizable version of the eddy viscosity based turbulence closure models in predicting a methane flame in a cross-flow of air and concluded that it performed better than the other variants of the k–ε turbulence models, however he too did not compare the predictions with measurements of species. Others researchers have predicted the temperatures, radiation and soot in methane-air cross flow diffusion flames with good agreements with experimental data [15–18]. Studies of cross-flow propane flames have received less attention than methane flames. However, important numerical works have been performed on propane flames among which include the work done by Botros & Brzustowski [19], where the authors numerically investigated the temperatures and radiation from a propane jet diffusion flame. Soot in cross flow propane flames has also been predicted with good agreement with experimental data [20,21]. Propane is a major constituent of gas flares both in the upstream and downstream oil and gas sectors and hence its emissions and combustion characteristics are of importance. It has been very challenging to numerically simulate the wake-stabilized flame in cross-flow. Lifted jet flames have been the topic of research for many years due to its industrial relevance and enormous complexity, and very few works has been done in the public domain for modeling wake-stabilized propane flame in cross-flow. Thus one of the main objectives of the paper is to evaluate partially premixed combustion model in the form that is available in FLUENT and the potential of the Large Eddy Simulation in simulating the propane flame in a cross-flow that is relevant to industrial flares. The present paper contributes to the previous work on the prediction of cross-flow flames by investigating the capabilities of the non-premixed and partially premixed combustion models in conjunction with the Reynolds Stress Model as well as the Large Eddy Simulation technique for predicting temperature and species concentrations in wake stabilized propane flames in a cross-flow of air.

2. Experimental details

Numerical predictions in the present work are validated against the experimental work performed by Huang and Yang [9], a brief description of which is as follows. The experiment was performed in a suction type, open circuit wind tunnel which had a test section of dimensions 30 × 30 × 110 cm. The burner was a stainless pipe of inner diameter $d_i = 5.0$ mm, outer diameter 6.4 mm and length 250 mm. The pipe was positioned perpendicular to the aluminum floor of the test section and protruded 180 mm into the wind tunnel. The origin was centered at the exit plane of the burner tube and the description was in terms of a rectangular coordinate system (X, Y, Z) as shown in Fig. 1. Commercial grade propane of about 95.0% C_3H_8, 3.5% C_2H_6 and 1.5% C_4H_{10} was used as the fuel and the average jet velocity, u_j was calculated (using the flow rate) to be 5.78 m/s while the fuel Reynolds number was calculated to be about 7000 for the case investigated. The cross-flow velocity u_w was fixed at 4.86 m/s, giving a jet-to-cross-flow momentum ratio R, of 2.16. The maximum turbulence intensity of the cross-flow in the wind tunnel section, as measured by a hot-wire anemometer, was less than 0.5% in the experimental range. The thermal structure of the flame was measured with a Pt–Pt/13% Rh home-made L-shaped thermocouple probe with a wire diameter of 125 ìm and a junction diameter of 150 ìm mounted on a two-dimensional traversing mechanism. Temperature measurements were not corrected for the radiative losses from the thermocouple and according to the calculation of the energy balance, the deviation of the measured temperature from the actual value was estimated to be about 50 °C at a temperature of 1600 °C. The concentrations of carbon dioxide and carbon monoxide where measured with infra-red analyzers while the concentration of oxygen was measured with a paramagnetic analyzer. Gas sampling was Q2 achieved with a stainless steel probe with a tip diameter of about 1 mm (see Fig. 2).

3. Numerical models

Mathematical models available in the commercial CFD software package ANSYS-Fluent 14.0 [22] were used to simulate the combustion. The codes solve the Favre-averaged form of the balance equations for mass, momentum, energy and the relevant scalar quantities describing

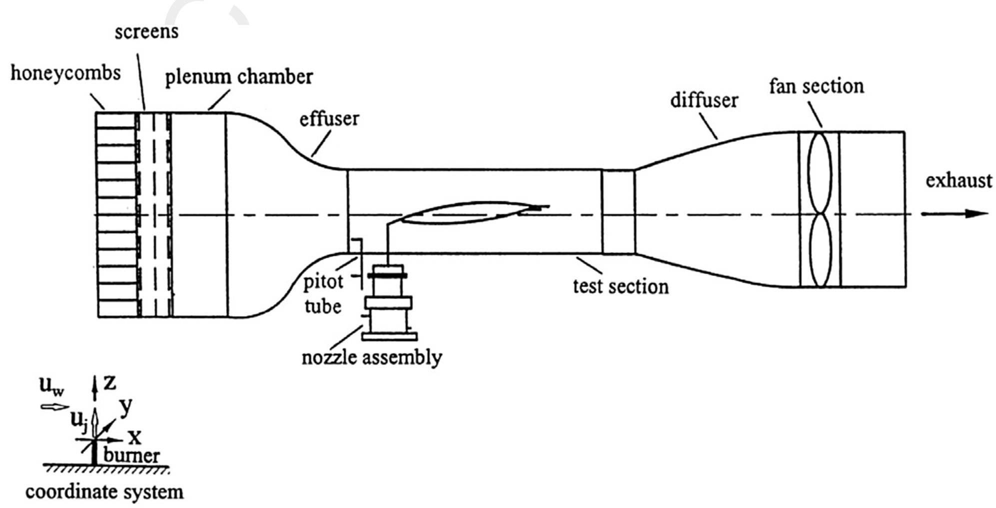

Fig. 1. Wind tunnel set-up of the experiment (based on Ref. [10]).

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