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An investigation of methane and propane vertical flares

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Flame lengths, temperature, species and lift-off heights have been experimentally and numerically investigated and compared for buoyant methane and propane jet diffusion flames at Reynolds number of 5700. The flow field has been modeled using the Reynolds-Averaged Navier–Stokes equation incorporating the k–ε realizable turbulence closure model. Combustion was modeled using the unsteady Eulerian-flamelet model based on the mixture fraction approach and the heat loss by radiation was accounted for using the Discrete Ordinates Method. The GRI mech. 3.0 and the CRECK reaction mechanisms were used to model the kinetics of the methane and propane reactions, respectively. Comparison of the predicted flame length and temperature revealed good agreement with experimental data. Post-flame measurements of NO_x and CO revealed greater quantities of both pollutants in the methane flame. Furthermore, investigation of the effect of the burner nozzle thickness on the flame lift-off heights showed that the lift-off height decreased as the nozzle thickness was increased, with the methane flame displaying higher lift-off heights.

1. Introduction

The combustion of waste hydrocarbons in flares is associated with the undesirable formation of pollutants, such as CO, NO_x, unburned hydrocarbons, smoke as well as CO_2. Many studies have been made of methane and natural gas flames but relatively few have been made of propane flames. Thus many generalizations about flare behavior have been concerned only with methane flames. This investigation is concerned with the difference in behavior between methane and propane flames when compared on the basis of similar Reynolds number. Flame lengths are important in flaring applications because they determine the height of the flare stack and historically a considerable number of studies have been made of flame lengths of methane and propane flames and a number of correlations have been made based on jet properties. Semi-empirical correlations have been derived for the length of a flare flame and the radiation from the flame by representing the flame surface as the frustum of a right cone [1]. It has also been demonstrated that the flame length decreases as the enthalpy of combustion of the fuel is reduced and increases with an increase in the pipe internal diameter for a given fuel at a given flow rate [2,3]. The stability of flares is also of major importance due to the effect it has on combustion efficiency and pollutant emissions. The EPA reported that "properly operated flares achieve at least 98% combustion efficiency in the flare plume". According to the EPA, this relatively high efficiency is achieved by stable flames, with a fuel enthalpies of combustion in the flared gases of at least 7.5–9.3 MJ/m^3. The flame stability has been defined as the condition where a decrease in the flare gas heating value or an increase in flare gas exit velocity results in flame blow-out [4]. For many hydrocarbon fuels, the burner-detached (lifted) flames can only survive at cross-flow velocities lower than 8 m/s [5]. In comparison, the burner attached flames can exist at much higher crosswind velocities than lifted flames. This is important in flares where blowouts are a common problem. Research carried out by the ARC helped to establish the significance of a crosswind on flare efficiencies, a factor which was overlooked in the EPA research, where most of the studies conducted related to natural gas flares.

The advance made in computing technology has enabled researchers to model the properties of turbulent jet diffusion flames using numerical techniques. In-flame temperatures and species as well as soot have been successfully modeled by several authors with good agreements with experimental data [6–8]. A recent study of variants of the k–ε turbulence closure models has shown that the realizable

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version is superior to the other variants in modeling diffusion flames from circular pipe burners [9]. The present work is both a numerical and an experimental investigation of turbulent jet diffusion flames of propane and methane operating under similar conditions with an aim to investigate the differences that exist between the flames in terms of their flame lengths, the emission from the flames and the effect that a change in the thickness of the pipe-nozzle will have on the flame lift-off heights.

2. Experimental methods

The experimental work was performed on a laboratory scale diffusion burner with a fuel pipe with internal and external diameters of 3.25 mm and 6.4 mm respectively. The burner featured a shroud with a diameter of 102 mm, through which shroud-air was supplied at about 0.3 m/s which served to shield the flame from surrounding disturbances.

2.1. Flame length and lift-off height measurement

Both the visible flame lengths – defined as the axial distance between the burner exit plane and the tip of the visible flame, and the lift-off heights of the flames – defined as the distance between the nozzle and the base of the lifted flame, were obtained by averaging a video record of the flames over 30 frames using a 12.1 megapixels CMOS camera (Canon PowerShot SX260HS).

2.2. Flame temperature measurement

The burner was mounted on a three-dimensional (XYZ) traverse grid system, and the origin was centered at the exit plane of the burner tube. The fuel flow rate was measured using a calibrated rotameter, and the average jet velocity u_j, was calculated from the fuel flow rate. Radial measurements of the in-flame temperature were taken at 3 axial flame locations using a Pt–Pt/13-%-Rh thermocouple with a bead diameter of 216 μm. The thermocouple was coated with a thin layer of silica to avoid catalytic reactions on the bead [10]. The output of the thermocouple was processed by a computer controlled data acquisition system and the data were later corrected for radiation and convection heat transfer between the thermocouple bead and the surroundings using the method of Kaskan [11].

2.3. Species and soot measurement

Gas samples were extracted at the post flame region using a quartz probe with a 1 mm tip diameter. The samples withdrawn through the probe were then passed through a heated sample line to a Horiba VS-3000 gas conditioning system and passed into a Horiba VA 3000 chemiluminescent NO_x analyzer and an infrared CO/CO_2 analyzer. The total unburnt hydrocarbons in the post-flame region were determined using a MEXA-1170 HFID flame ionization detector (FID). The gas analyzers were calibrated with certified standard mixtures of 52 ppm, 8.02%, and 6.25% of NO, CO and CO_2 in nitrogen, respectively. Zero and span calibrations were performed before and after each measurement in order to minimize the influence of the instrument drift.

The soot mass in the post flame region was determined gravimetrically using filter papers in a holder. The filter papers were dried in an oven and weighed before soot deposition. The fuels were combusted on a basis of similar Reynolds number and the filter paper was re-weighed to determine the mass of soot collected. Several runs were carried out for each fuel, and the average mass was determined.

3. Numerical methods

3.1. Mathematical models

The mathematical models available in the commercial CFD software package ANSYS [12] were used to simulate the experimental conditions. The code solves the density-averaged form of the balance equations for mass, momentum, energy and the relevant scalar quantities describing turbulence and combustion based on the finite volume solution method. The flow field has been modeled using the RANS equation. The Reynolds stresses arising from the RANS equations were closed using the realizable k–ε turbulence model. Combustion was modeled with the laminar flamelet model [13], while the radiation was modeled with the discrete ordinate model [14].

The governing equations used for the analysis of the turbulent reacting flows are given below in Cartesian tensor notation.

Mass conservation:

$$\frac{\partial\overline{\rho}}{\partial t}+\frac{\partial}{\partial x_k}(\overline{\rho}\tilde{u}_k)=0 \tag{1}$$

Momentum conservation:

$$\frac{\partial(\overline{\rho}\tilde{u}_i)}{\partial t}+\frac{\partial}{\partial x_k}(\overline{\rho}\tilde{u}_k\tilde{u}_i)=\frac{\partial\overline{P}}{\partial x_i}+\frac{\partial\tau_{ik}}{\partial x_k}+\tilde{F}_k-\frac{\partial}{\partial x_k}\left(\rho\widetilde{u''_k u''_i}\right) \tag{2}$$

where $\overline{\rho}$ and $\overline{P}$ are the unweighted mean density and pressure; the symbol ~ represents a Favre mean or density weighted mean quantity and the symbol ″ denotes a corresponding fluctuating quantity. The two terms on the left hand side of Equation (2) represent the accumulation and convective terms respectively. The first three terms on the right hand side represent the pressure, viscous and source terms respectively, while the last term represents the turbulence or Reynolds stress.

Energy conservation:

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