Effect of Bluff Body Geometry on Flame Stabilization with the Assist of Langmuir probe

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ABSTRACT
Bluff bodies are common method used as flame holders or stabilizers in many applications such as jet engines augmenters for reasons of safety, providing excellent turbulent mixing characteristics, improvement in flame stability, and ease of combustion control.
The effects of using 12 different bluff body shapes (cylindrical and triangular with different dimensions) are examined with respect to their influence on downstream flow field. The present work offers a study to compare different bluff body geometries and their effect on the flame characteristics and its stability using two main techniques; Experimental measurements using visualization and Langmuir probe techniques and simulation technique using CFD method.

Key words: Flame holder, Flame Ionization, Langmuir probe, CFD flame holder

INTRODUCTION
Bluff bodies as flame stabilization method are widely used to stabilize flames for high velocity flow in different industrial combustion applications. Many shapes of bluff bodies are offered and supported by many researchers such as, cylindrical rods, discs, cones or vee gutters [1]. The investigation of the flame stability using bluff bodies was the target for researchers for decades [2-7].
Different results have been reported by Mishra and Kumar [8-10] to investigate the effect of coaxial air velocity, lip-thickness and preheating the reactants of the bluff-body on flame stability limits and emission levels using LPG and (LPG)-H_2 blend.
Combustion is a highly non-linear and complex process in which chemistry, fluid mechanics, thermodynamics, radiation and phase change are deeply coupled. Different techniques were used to study and examine the stabilization region resulted from using bluff bodies. Photographic [11], Doppler velocimetry [12], and particle image velocimetry [13, 14], are examples for these techniques. Although experimental data is preferred in such studies but the level of details that is now needed requires new tools of investigation. Accordingly, numerical simulation is now recognized as a powerful and reliable mean to better understand the complexity of industrial combustion systems.
A high-resolution, two-dimensional (2-D), vortex particle method is implemented, and simulations of flows around various bluff bodies are presented by Liu and Kopp [15].
Erickson et al. [16] investigated the impact of increased reactant temperature on the dynamics of bluff-body stabilized premixed flows using numerical simulation.
The large eddy simulations (LES) conditional moment closure (CMC) method with detailed chemistry is applied to a bluff-body stabilized flame by Navarro-Martinez et al. [17]. Computations of the velocity and mixture fraction fields show good agreement with the experiments. Temperature and major species are well-predicted throughout the flame with the exception of the flow regions in the outer shear layer close to the nozzle.
Large eddy simulations (LES) using a subgrid mixing and combustion model are carried out by El-Asrag et al. [18] to study two bluff-body stabilized swirling non-premixed flames.

In a study offered by Parsons et al. [19], a lean premixed combustion of methane in a bluff-body combustor is simulated using two different reduced chemical mechanisms (the first is a 9 species 5 step reduced mechanism known as ARM9 while The second is a 19 species 15 step reduced mechanism called ARM19) combined with the Probability Density Function (PDF) transport combustion model in the commercial code FLUENT. Two different turbulence flow models, namely the RNG k-ε model and the Reynolds Stress Model (RSM) are used and the results of the simulations are compared to experimental data. Good agreement between the model and experiments was observed.

Langmuir Probe and Ionization Process in Combustion

The ionization process is defined as any process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules. By applying a constant DC volt between two electrodes in a flame, ion current which reflects the amount of these species (electrons and ions) can be measured. Earlier studies used the same principle which is known as “Langmuir Probe” to study ions in flames [20]. Langmuir Probe is simply a bare wire inserted into the flame and a negative or positive voltage is applied. Accordingly, a small but detectable current will flow; this is the so-called “Ion Current”. This current contains a lot of information about the state of the gas and the combustion process. This technique is under investigation nowadays for combustion control in internal combustion engines. More details about this technique are offered by the author in [21].

At an early stage of the investigations on ions formation in hydrocarbon flames, the thermal process of ionization was the most popular explanation for the high concentration of ions, along with the process of ionization on the collision of the excited species, etc. Reviews of the earliest studies on "ions in flames" were made by Wilson [22], Thomson and Thomson [**23**], and followed by Calcote [24, 25]. More recently, Fialkov[26] published a comprehensive review on the same subject.

Calcote [24] stated that the ionization was not accomplished by thermal ionization, but rather by chemi-ionization process and the commutative excitation process of molecules, atoms or radicals lead to ionization. He suggested that nitric oxide (NO) by itself is responsible for about 95% of the available free electrons in the post-flame gases and the major species like water (H_2O), nitrogen (N_2), carbon dioxide (CO_2) and carbon monoxide (CO) contributes only slightly.

Accordingly, there are four main different processes in a flame that affect the ion concentration. These processes are;

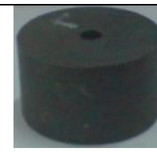
- Chemi-ionization; which is a chemical reaction that produces charged products with neutral reactants. Chemi-ionization occurs during an elementary exothermic reaction when the total energy released is large enough to ionize one of the reaction products.
- Thermal-ionization, which is a chemical reaction that is connected to the temperature of the gas
- electron attachment and
- cumulative excitation.

EXPERIMENTAL SETUP

A constant cross section area tubular combustor with 50 mm inner diameter was used to study and compare bluff-bodies with different shapes and dimensions as listed in Table (1). The experiments were conducted at atmospheric conditions in the above burner. The test rig is made of a burner with controlled air and fuel supply systems as well as the suitable measurement devices for mass flow rates and flow speeds as shown in Figures (1 and 2). A homogenous gas mixture was obtained by injecting the natural gas at sufficient distance before the bluff body position as shown in the figure.

Based on Langmuir probe technique, the ionization current was measured by a controllable ionization detection system. The system was adjusted to supply 300 DC volts across the gap between the two electrodes through a simple measurement circuit indicated in Figure (3). The ion current is then represented by the voltage drop measured across a given resistance.

Table (1) Dimensions of the twelve bluff bodies used in the present work.

Bluff body Shape	Bluff body code	Diameter (mm)	Corresponding Blockage Ratio	Sample Picture
Disc	Disk1 Disk2 Disk3 Disk4	37.5 32.5 27.5 22.5	0.5625 0.4225 0.3025 0.2024	
Cone 90^o	Cone90_1 Cone90_2 Cone90_3 Cone90_4	37.5 32.5 27.5 22.5	0.5625 0.4225 0.3025 0.2024	
Cone 120^o	Cone120_1 Cone120_2 Cone120_3 Cone120_4	37.5 32.5 27.5 22.5	0.5625 0.4225 0.3025 0.2024	

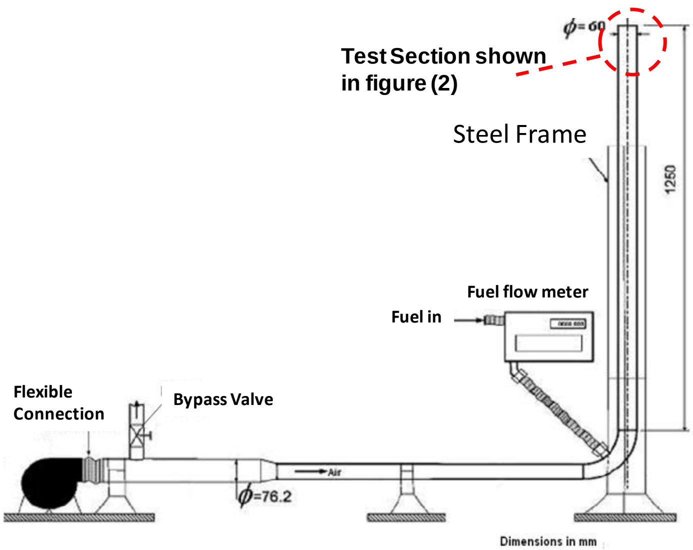


Figure (1) Layout of the experimental test rig

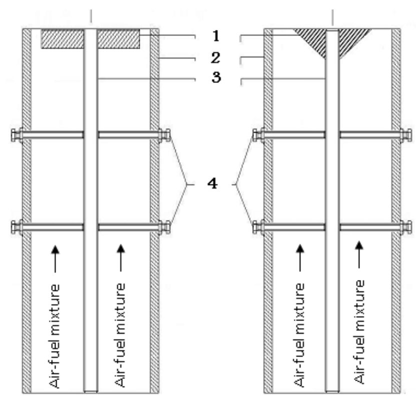


Figure (2) Test Section to show 1- Flame holder, 2- Pipe (50 mm diameter), 3- Rod (4 mm diameter), 4- Two groups of three supported bolts

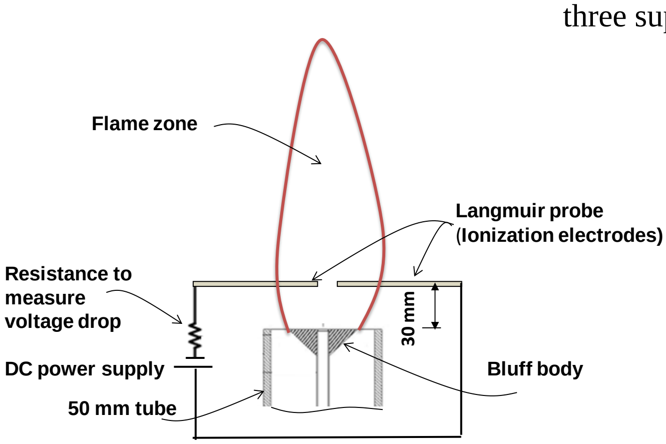


Figure (3) Langmuir probe as an ion detection method in the flame zone

Numerical model description

In the present work, premixed, stoichiometric methane/air mixtures are fed to the burner previously described. A 3D CFD mesh was created for an experimentally physical test section. A hybrid mesh is created using FLUENT's preprocessor GAMBIT with 50 mm diameter for air/methane mixture inlet and bluff body is centrally positioned at the end of 100 mm tube length. A domain for pressure outlet flow was created with a dimension of 100 mm diameter and 360 mm height. Quarter of this model was actually created and the other quarter is considered as periodically repeated. About 2,400,000 of tetrahedral cells are created. A finite volume method is used to discretize the 3D continuity, momentum, energy and species conservation equations in the fluid and the 3D energy equation. Steady-steady simulations are performed. Also a model of species is settled with eddy dissipation chemical interaction with volumetric reactions. The fluid density is calculated using the ideal gas law. The fluid viscosity, specific heat, and thermal conductivity are calculated from a mass fraction weighted average of species properties. Specific heat is calculated using a piecewise polynomial of temperature. In the present study the k-ε standard simulation model is utilized. Table (2) shows the inlet and outlet boundary conditions and assumptions that are considered in the model. Fluent 6.3 was adopted for this purpose [27].

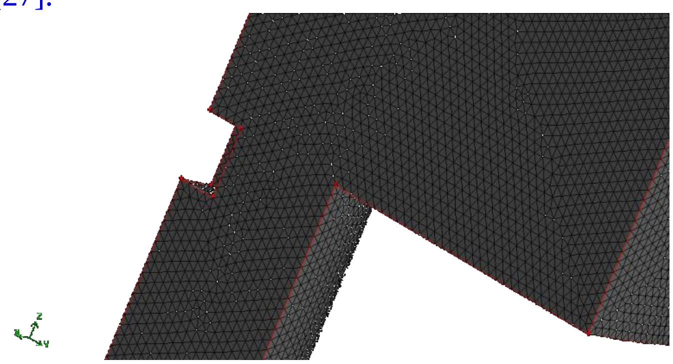


Figure (4) The mesh that created for the CFD test model

Table (2) Inlet and outlet boundary conditions which are considered in the model

	Inlet	**Outlet**
D (mm)	50	150
Turbulence index	24%	24%
Temperature (K)	450	300
Species (based on)	Velocity=10 m/sec Mass Fraction of Fuel = 0.0157 Mass Fraction of Oxygen = 0.2264	O_2 = 0.23

RESULTS AND ANALYSIS

I. Effect of bluff body shape on flame stability

It is a well-known fact that the flame holder geometry and blockage ratio (The ratio of the projected flame holder area to the total area of the burner) are the most important two factors affecting flame stability. Similarly the length of the recirculation zone is one of the parameters that usually used to define the flame stability characteristics based on the holder geometry [28]. The existence of bluff body in the flow stream creates two main zones, the recirculation zone and mixing zone as shown in Figure (5). Figure (6) shows the different combustion and velocity zones generated in downstream flame for a cone 120 with a diameter of 37.5 mm (blockage ratio is 0.5625) and velocity of 10 m/sec. The recirculation zone was determined by three different techniques as shown in the figure; by using a photograph (the lower dark area in the flame indicated by the dotted line), by observing the temperature from the temperature profile produced from the CFD model (where the temperature is the maximum in the recirculation zone and starts to decrease outside this zone) and by analyzing the fluid flow velocity distribution in the velocity profile generated from the CFD model (where the velocity starts to decrease and becomes negative in the recirculation zone)

By comparing four blockage ratios (shown in table 1) for the disk bluff body geometry as an example, Figure (7) offers the results obtained from visual inspection of the photographs and simulation results from the CFD model. There is no agreement between both methods which indicates the uncertainty in the visual observation technique. Both techniques revealed that the recirculation zone height increases by reducing the blockage ratio. By focusing on the highest temperature, Figure (8) shows that the variation in maximum temperature along the bluff body axis is not significant.

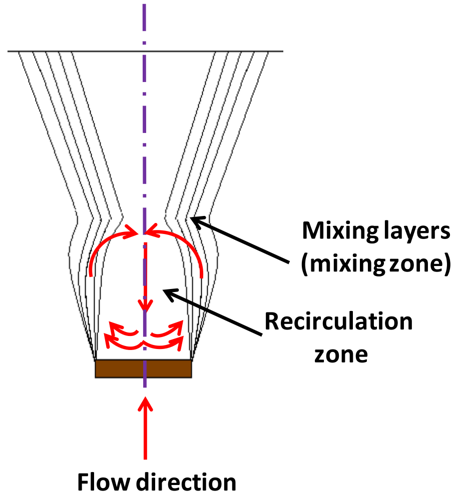


Figure (5) Schematic diagram showing the recirculation zone and the mixing zone

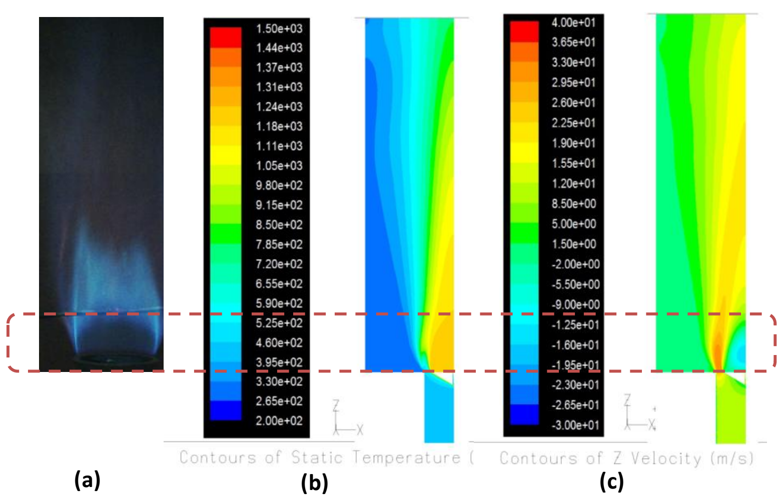


Figure (6) Comparison of (a) flame image and (b)temperature field and (c) velocity distribution calculated with CFD for Cone 120 with D=37.5 mm and at V=10 m/sec (dotted rectangle indicates the recirculation zone)

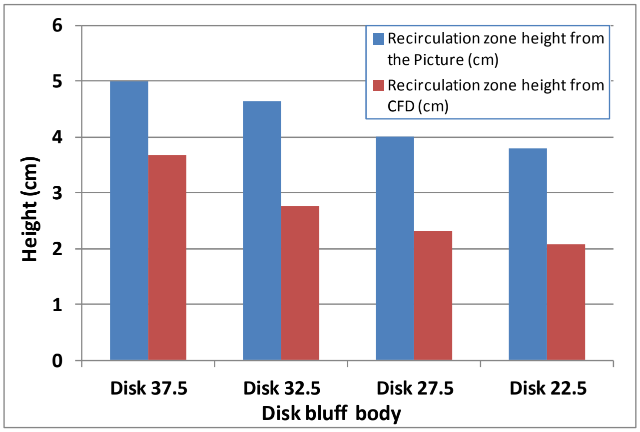


Figure (7) The recirculation zone height of four different disk bluff bodies at V=10 m/s.

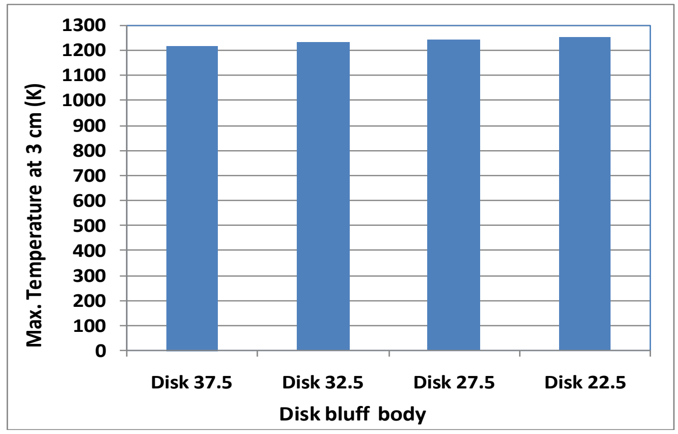


Figure (8) The maximum temperature of four different disk bluff bodies using CFD at 30 mm height from the surface and V=10 m/s.

To compare the three different geometries, constant blockage ratio of 0.5625 and inlet velocity of 10 m/sec were chosen where the temperature profile and velocity distribution are plotted as shown in Figure (9). The flame temperature distribution shows that there is no effective difference between the three geometries up to 0.25 from the center of the bluff body while the radial distance from 0.25 to 0.55 shows different behavior. Higher downstream velocity is observed from the velocity distribution for disk bluff body with less recalculated velocity (negative velocity) in the center of the recirculation zone compared to cones bluff bodies.

By comparing the maximum temperature of the three geometries, Figure (10), the disk shows the highest temperature over the other two geometries although it delivers the lowest recirculation zone height as shown in Figure (11).

Figure (12) offers a comparison of major species (CH_4, CO_2, N_2, O_2) for the three bluff bodies. As shown in the figure, the disk bluff body delivers the lowest mass fraction from CH_4, CO_2, and N_2 outside the recirculation zone, which indicates better combustion and less pollutant for this bluff body type.

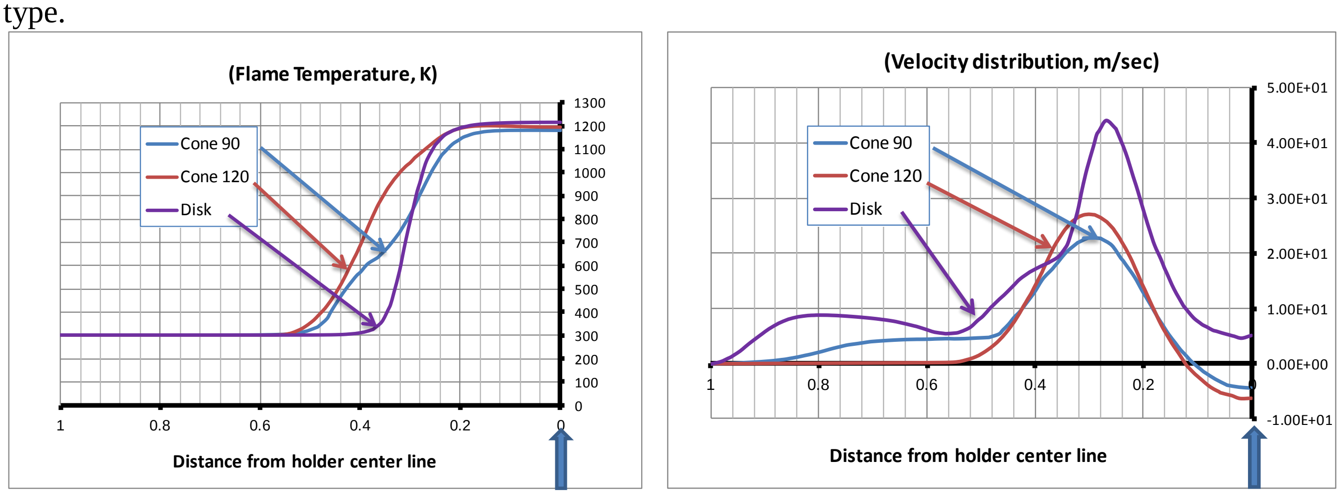


Figure (9) Simulated flame temperatures and velocity distributions over the left half of the burner for three bluff bodies with the same blockage ratio of 0.5625 and V=10 m/sec.

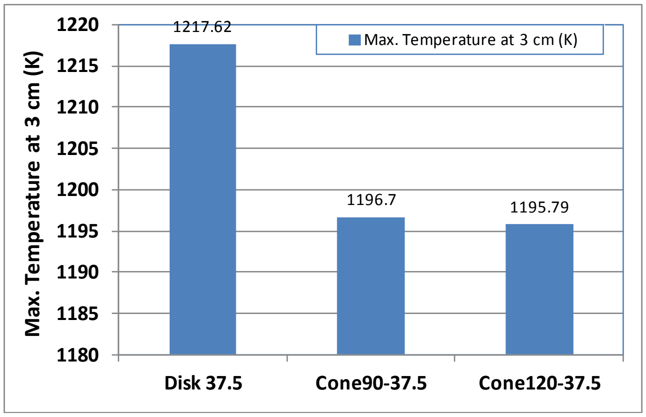


Figure (10) The maximum temperature of three different bluff body geometries measured at 30 mm height from the bluff body surface and V=10 m/s.

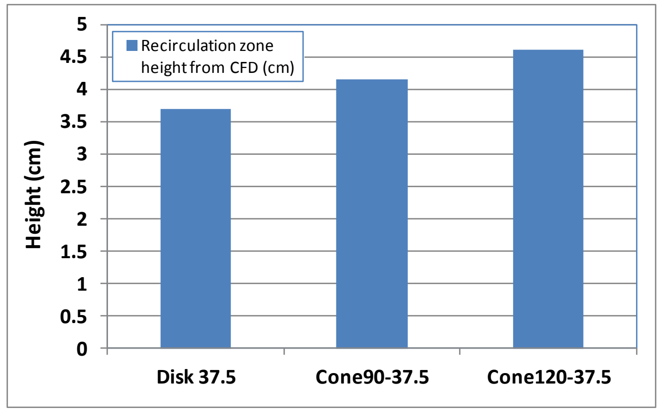


Figure (11) Recirculation zone height from CFD (cm) for three different bluff body geometries with same blockage ratio at V=10 m/s

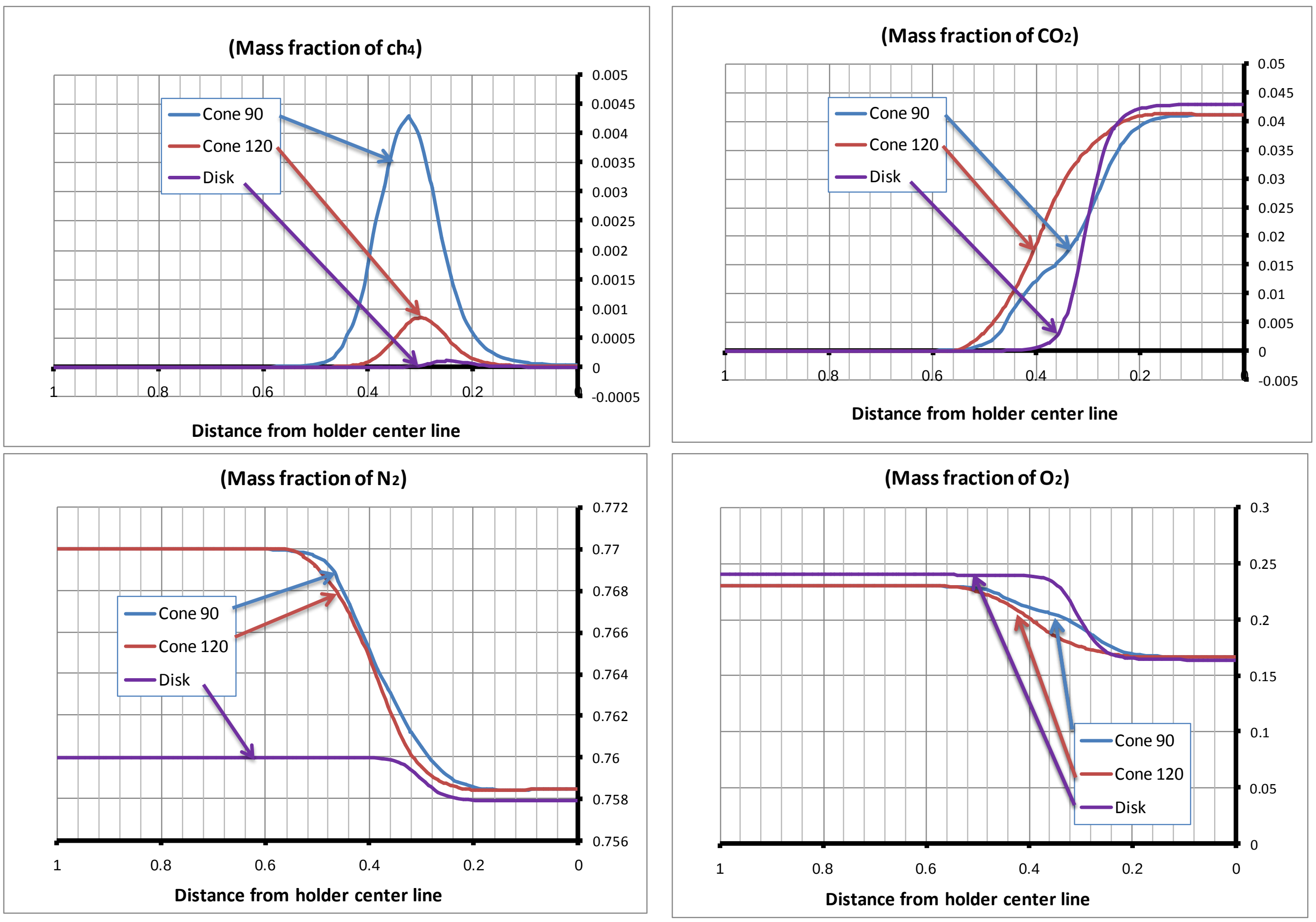


Figure (12) Some simulated output products calculated over the left half of the burner for three bluff bodies with the same blockage ratio of 0.5625 and V=10 m/sec.

II. Comparison of bluff body geometries based on ion current measurements

As mentioned earlier, the ion current was measured in the gap between two symmetric electrodes where linear relationship between the output voltage drop and the applied DC volt is observed as shown in Figure (13).

Based on this experiment a decision to apply an average volt of 300 DCV on the probe was done. To investigate how the ion current responds to the height above the burner surface, three different heights were tested based on preliminary tests done for all bluff bodies. Figure (14) shows measurements of ion currents at 10, 20, and 30 mm from the bluff body surface. The figure indicates that 30 mm above the burner is good enough to measure the ionization phenomena in the recirculation zone. This selection was confirmed by analyzing the temperature distribution at different heights for one of the bluff bodies, Figure (15). The figure shows that the temperature starts to decrease in the region above 35 mm height from the bluff body surface. The maximum temperature ensures the highest thermal ionization concentration as discussed earlier.

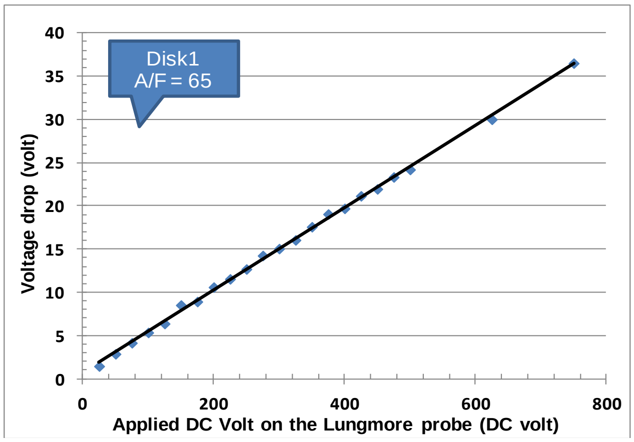


Figure (13) Impact of the applied DC volt on the voltage drop measured across the probe gap (ion current)

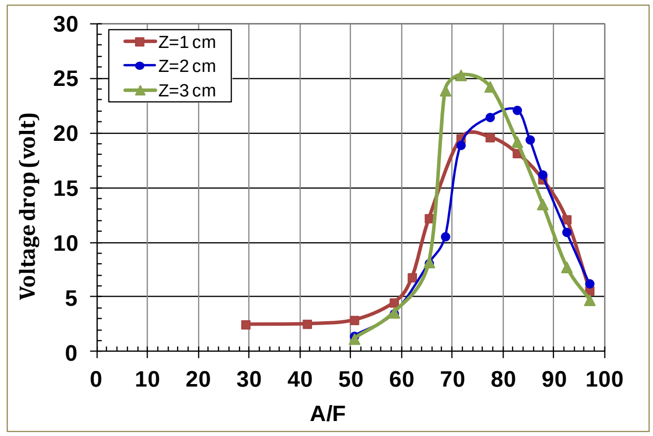


Figure (14) Voltage drop at three different heights versus A/F ratio.

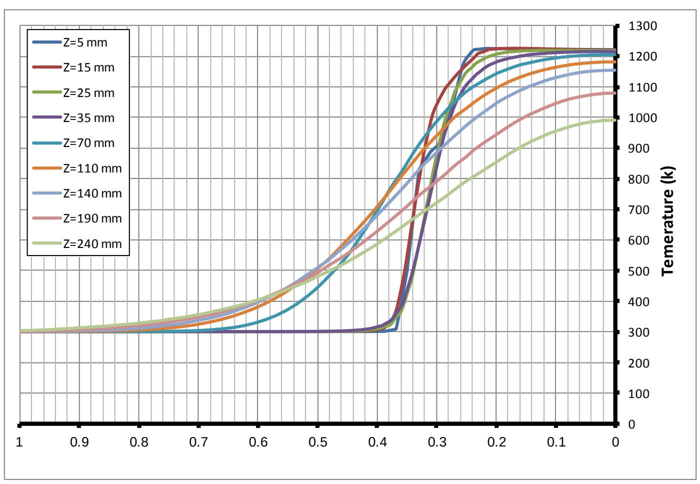


Figure (15) The temperature distribution for disk bluff body number 1 at different heights above the bluff body surface using CFD model.

Figure (16) shows a comparison of ion current for four disk shaped bluff bodies (shown in table 1), while the ion current measured across the probe for cone 90 and cone 120 are shown in Figures (17) and (18). The figures indicate that the ion current responds distinctly to the air to fuel (A/F) ratio of the premixed flame. Another observation is that the ion current signal is higher for the higher blockage ratios which coincides with the higher temperature observed from the simulation. The resolution of this fact decreases for cones especially cone 120.

By analyzing the figures, disk bluff body exhibit the maximum ionization current which validates the maximum temperature shown in Figure (10) relative to other bluff bodies. Maximum ion current coincides with an average A/F ratio of 75 for all disk bluff bodies, although increasing the blockage ratio shifts the maximum ion current peak to less A/F ratio. Cone90 and 120 exhibit almost the same trend with higher ion current peaks for cone90.
By comparing the ion current trend for the three geometries (Disk, Cone90 and Cone120) with the same blockage ratio of 0.5625, Figure (19), the disk bluff body produces higher ion current then Cone90 and finally Cone120. The ion peak position for the disk bluff body is detected at the highest A/F of 75 compared to 73 for cone90 and 66 for cone120. The comparison shows also that the disk geometry reaches higher blow off air-fuel ratio.

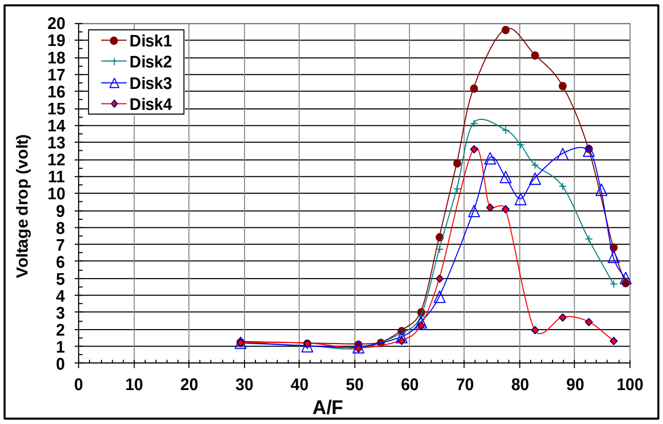


Figure (16) Effect of air to fuel ratio (A/F) on the ion current detected for Disk shape bluff body at different Blockage ratios

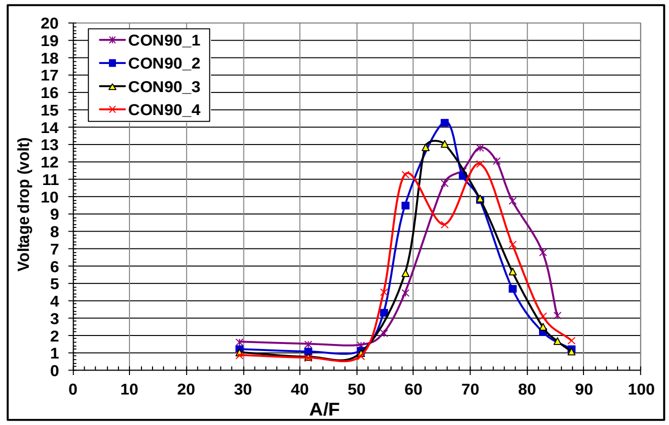


Figure (17) Effect of air to fuel ratio (A/F) on the ion current detected for cone90 bluff body at different Blockage ratios

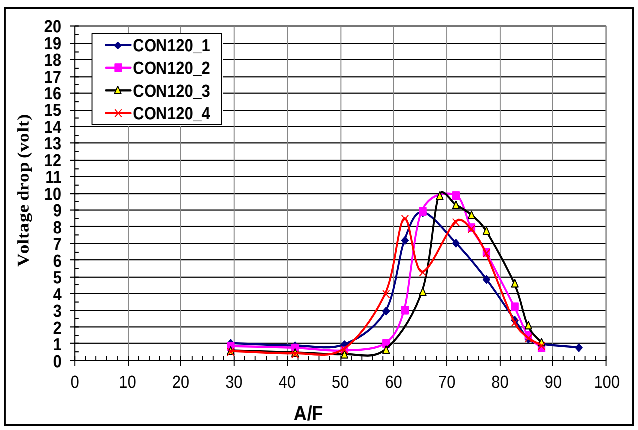


Figure (18) Effect of air to fuel ratio (A/F) on the ion current detected for cone120 bluff body at different Blockage ratios

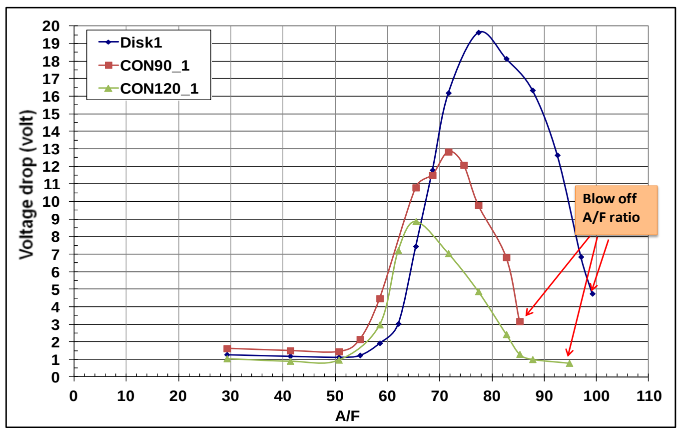


Figure (19) The voltage drop (ion current) of three bluffs body geometries with the same blockage ratio of 0.5625 and measured at 30 mm height from the bluff body surface.

CONCLUSION

In the present work three different techniques are offered to evaluate and compare some combustion characteristics of twelve bluff bodies with different geometries and dimensions. The three methods are visualization, simulation, and ionization current technique. Some key conclusions are pointed as follows:

- Vision analysis based on photographs is not accurate enough to evaluate combustion characteristics compared to other techniques.
- Increasing the blockage ratio increases the stability of flame holders and disk shaped bluff bodies behave the best compared to other shapes.
- Disk shaped bluff bodies exhibit the highest temperature in the recirculation zone and consequently the heights ionization current.
- Langmuir probe as an ion detection method is a simple and cost effective technique to evaluate flame holders and their effect on downstream combustion characteristics.
- Higher blow off A/F limit is recorded by ion current technique for disk shaped bluff bodies.

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