Ducted fuel injection for compression-ignition engines

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ABSTRACT

The goal of the Ducted Combustion Chamber project is to reduce or eliminate soot emissions from diesel engines. This was done by enabling fuel to burn at a leaner mixture with a combustion strategy called Leaner Lifted-Flame Combustion (LLFC). A recent paper by Polonowski et al. [SAE Int. J. Fuels Lubr. 5(1):51-77, 2012], stated that “LLFC is defined as mixing-controlled combustion that does not produce soot because it occurs at equivalence ratios less than or equal to approximately 2.” The equivalence ratio is defined as the actual ratio of fuel over air divided by the stoichiometric ratio of fuel over air [McGraw-Hill, New York, 1988, p. 149]. Typically, diesel combustion occurs under conditions [Dec, SAE Technical Paper 970873, 1997], where the fuel inside of a diesel engine is not mixed evenly with the air. Fuel-rich regions of diffusion flames produce soot which is a pollutant. This project investigated whether injecting fuel into a duct in the combustion chamber will allow the fuel to mix more evenly with the surrounding air and produce LLFC. The process of injecting fuel into the duct should entrain (draw some of the surrounding) air into the duct. When the air and fuel are in the duct together they will mix together resulting in a more even fuel-air mixture and which will create the conditions for LLFC. Ducts of various lengths and diameters were respectively installed and tested in a constant volume combustion chamber under diesel-like conditions. High-speed imaging was used to gauge the sooting tendency of the combusting jet. This experiment shows that the duct causes a significant decrease in the amount of soot created versus a free jet in the same ambient conditions. This result suggests that the Ducted Combustion Chamber could be an effective way to reduce soot production in diesel engines. Further studies will need to be performed to optimize this technology.

INTRODUCTION

Soot is made up of small carbon particles created by the rich regions of diffusion flames commonly created inside of a diesel engine operating at medium to high load. Soot is an environmental hazard and is an emission regulated by the Environmental Protection Agency (EPA) in the United States. Currently, soot is removed from the exhaust of diesel engines by heavy and expensive filters in the exhaust system. These filters have to be maintained by the vehicle owner to continue to effectively reduce the soot emissions.

Prior research by Polonowski et al.[1] indicates that LLFC can greatly reduce the production of soot inside the engine. The challenge is to enable LLFC while maintaining adequate fuel flow to achieve high-load engine operation.

A literature review was conducted to determine if any other researchers have performed experiments similar to the Ducted Combustion Chamber experiment. The literature review did not show that anyone has published any results from experiments similar to the Ducted Combustion Chamber. Research has been conducted on encouraging mixing inside of gas turbines. However, due to the differences between gas turbines and diesel engines these strategies are not similar to the Ducted Combustion Chamber in its current configuration. The literature review did yield in the paper by Barchilon and Curtet[5] with results for the flow of jets through tubes. The paper by Barchilon and Curtet shows that the idea of injecting fuel into a duct to encourage mixing is feasible.

In this study, an attempt was made at achieving LLFC by injecting the fuel into ducts of varying dimensions, installed and tested in a constant-volume combustion vessel. Conceptually, the duct enhanced the mixing of the fuel and air before the fuel autoignites. Mixing is enhanced as the fuel is injected into the duct because injection will create a low-pressure zone inside the duct. This low-pressure zone will draw air into the duct with the fuel. The air and fuel inside the duct will mix together before the mixture exits the duct and autoignites. The resulting LLFC flame will produce less soot than the typical diesel diffusion flame that would have been created without the duct. This concept is known as a Ducted Combustion Chamber (DCC).

METHOD AND EXPERIMENTAL SETUP

The ducted fuel injection concept was tested inside of the constant-volume combustion vessel, seen in Figure 1. The combustion chamber simulated the conditions inside of a diesel engine and provided much greater freedom for testing ducts of different sizes and materials, as shown in Figure 2. The combustion chamber also provides unobstructed optical access to record the data from the experiments. The experiment was conducted using a set of operating parameters similar to what is known as ‘Spray A.’ Some of the parameters for the experiment are show in Table 1. This condition typically creates soot and was the reference condition to compare the effect on sooting behavior caused by the duct. Duct diameters of 3, 5, and 7 mm and duct lengths of 7, 14, and 21 mm were tested in this experiment. The ducts were tested at varying distances from the injector to determine what conditions give the best results. Ducts made of steel as well as quartz were tested to give optical access inside the duct and to determine the effect of material on the results of the experiment.

Table 1: Data for the experimental condition

Operating parameters[4]	Temperature	Pressure	Gas Density	Ambient Gas	Nozzle Diameter	Fuel
	950K	6.0 MPA	22.8 kg/m^3	21% O_2	0.090mm	n-dodecane

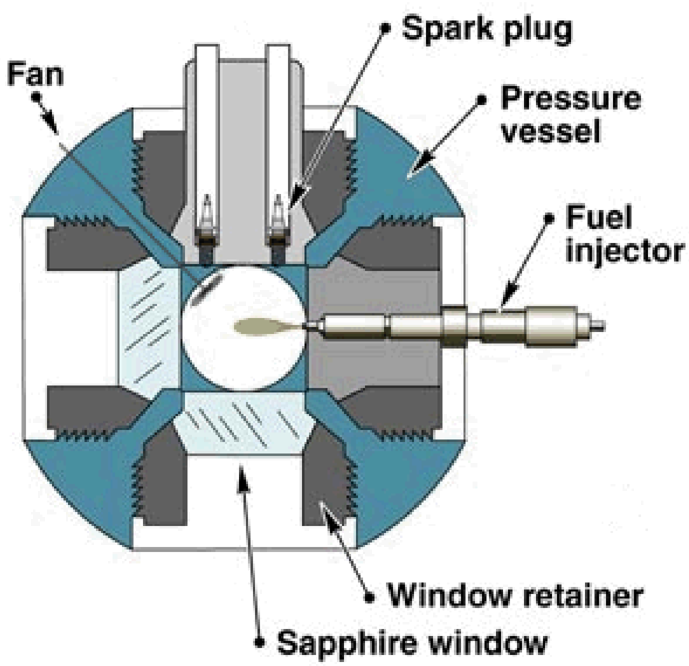

FIG. 1. Drawing of the constant-volume combustion vessel

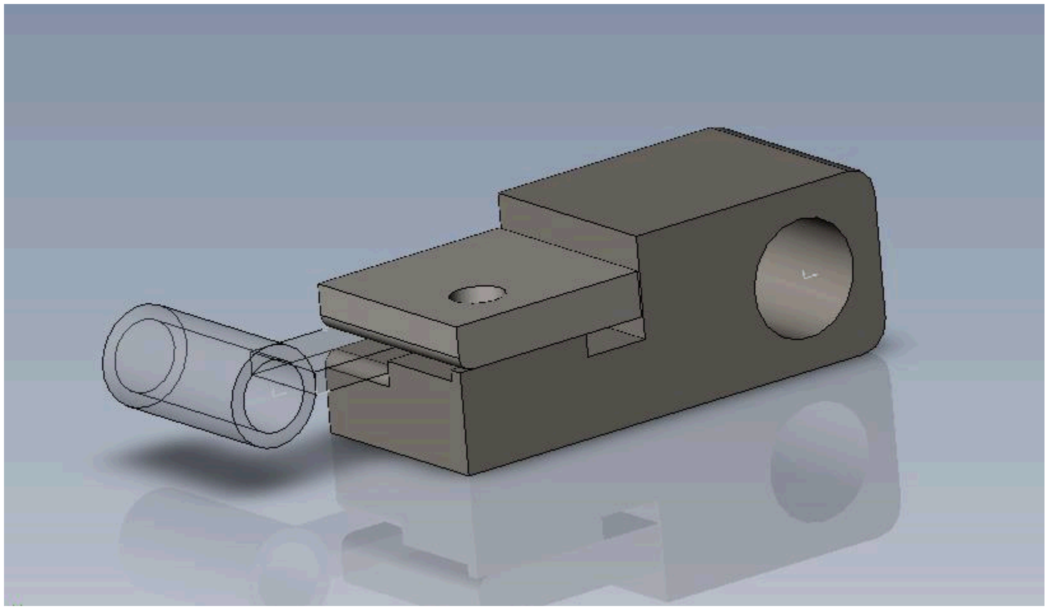

FIG. 2. Image of duct and duct holder used to test the Ducted Combustion Chamber

Soot incandescence was used to monitor the sooting behavior of the combusting jet and determine if LLFC was achieved. When little to no soot was shown in the images LLFC was successfully achieved. OH* chemiluminescence was used to measure the lift-off length of the flame (axial distance between the fuel-injector orifice exit and autoignition zone). OH* is created when fuel is ignited inside an engine; its presence indicates the axial distance from the injector where the fuel starts to burn.

Three cameras were used to record the results from the experiment. The first camera was an intensified Phantom v7.1 which was filtered for OH* chemiluminescence. The second camera was an unintensified Phantom v7.1 which was used to record natural luminosity from the soot. The final camera was a Photron SA-X2 which was also used to record natural luminosity from an orthogonal viewing angle.

THEORY

The calculations of the Reynolds number of the flow of the fuel jet through the duct show that the flow through the duct should be very turbulent. Reynolds number, R_e, is calculated using the formula $R_e = \frac{\rho V L}{\mu}$ (1) where ρ is the ambient density, V is velocity, L is the duct diameter, and μ is the dynamic viscosity. The velocity V is calculated using the formula $V = \sqrt{\frac{2(p_{inj} - p_{amb})}{\rho_f}}$ (2) where ρ_f is the density of the fuel. The result of this calculation gives a Reynolds number of approximately 1×10^6, which is very turbulent. The results of previous research, by Barchilon and Curtet in 1964, on the turbulent flow of a jet through a tube[5] show that the turbulent flow of a jet through a tube causes the jet to mix with the air that was drawn in from the outside of the duct. They observed that this result occurs when the velocity of the air entering the duct is very low and the velocity of the jet is very high. The large difference in the velocities of the two substances causes the jet to draw air into the duct from the surroundings. The recirculation eddies occur when the jet in the duct is moving too quickly for the air to be entrained into the flow. The eddies slow down the flow of the jet to entrain more air into the flow. These recirculation eddies allow the air and the fuel to mix together before continuing down the duct. This research indicates that the duct will slow down the speed of the jet and that it will encourage mixing. The research performed by Barchilon and Curtet[5] focuses on incompressible flow through a larger diameter duct. It is unclear how the results will vary with the compressible flow and smaller duct in the Ducted Combustion Chamber experiment.

The liftoff length may result in the fuel igniting while it is still in some of the larger sizes of ducts. The fuel should ignite outside of the ducts, inside the combustion chamber; otherwise the duct may be damaged by the ignition of the fuel. The lift off length may be increased by the cooling effects on the fuel mixture by the duct. The duct will be cooler than the surrounding mixture inside the combustion chamber which may remove heat from the fuel mixture and decrease the temperature of the fuel, allowing the fuel to travel farther through the duct before igniting and allowing some of the larger or longer ducts to work without the fuel igniting inside of them.

RESULTS

Three cameras were used to take data. In this paper we will use the images from the Photron SA-X2 to show the reduction in natural luminosity. The images shown were taken from the east side of the combustion vessel. The saturated areas of the images are believed to be from the natural luminosity of the soot. FIG. 3 is an image taken of a free jet at the condition described earlier in this paper. The saturation in FIG. 3 indicates that a significant amount of soot was produced in this configuration. FIG. 4 is an image taken at operating conditions similar to those used in FIG. 3 with a 3x14mm steel duct positioned 2mm downstream from the injector. This flame contains very little saturation which indicates that it produced very little soot. Post processing has not been performed on either image. The flame in FIG. 4 also does not spread as it moves axially like the rich flame in FIG. 3 does. It is believed that the effect from the duct is caused by a combination of the mixing caused by the duct and the heat transfer to the steel duct. The duct was at a much lower temperature than the ambient 950 K conditions so it allows the fuel to travel in a lower temperature environment that is not present in typical diesel combustion. A quartz duct of the same size was placed in the same location.

The quartz duct did not perform as well as the steel duct. Further work will be performed to analyze the data from the three cameras and the combustion vessel itself. This additional data will reveal important information such as flame length, liftoff length, and ignition delay among other things.

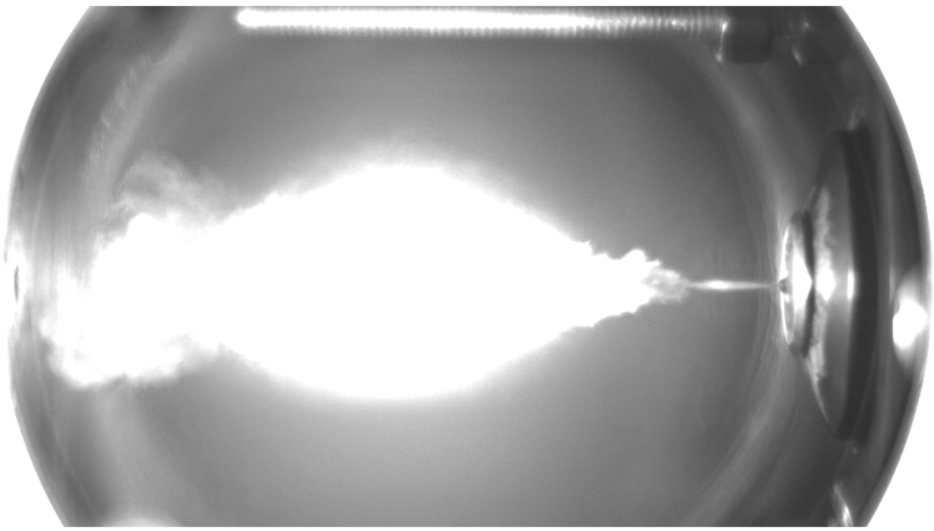

FIG. 3 Image of natural luminosity from a free jet. All saturated areas are believed to be soot.

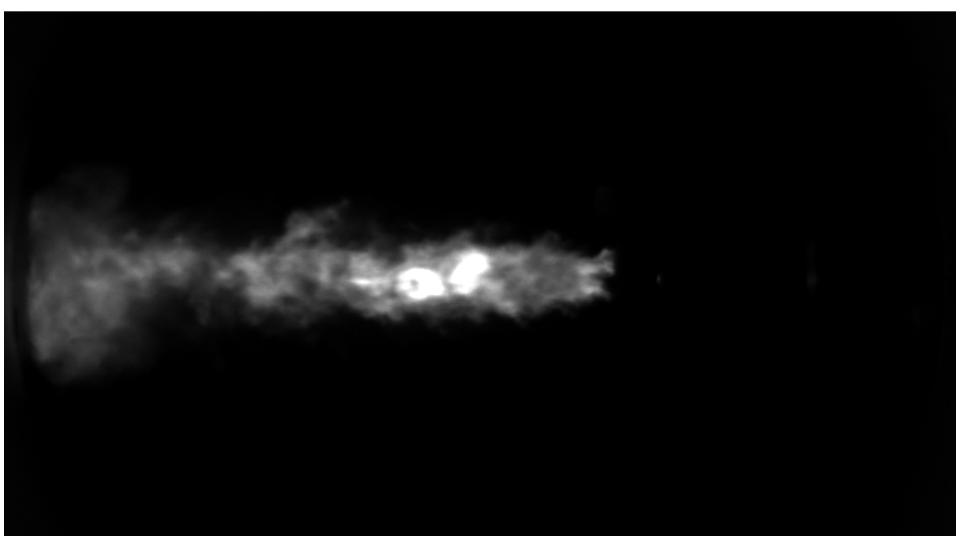

FIG. 4 Image from same camera with 3x14mm steel duct 2mm downstream from the injector.

CONCLUSIONS

In summary, a duct was placed in a constant-volume combustion vessel to determine its effect on the sooting tendency of a fuel in diesel like conditions. This experiment suggests the duct to be a very effective method of reducing soot production. However, there is still a lot of work that needs to be done to optimize the results of the duct. Parameters that could still have significant impact on the performance of the duct include location, size, shape, injection pressure, and many others. Further research and development work will need to be done with the duct before it is ready for the next step of putting it into an engine. Development of a computer model of the effect of the duct would be useful as well. Research also needs to be performed to determine how the duct works as well since little work has been done to understand compressible turbulent flow through tubes.

The Ducted Combustion Chamber has met the goals set out for it at the beginning of the experiment. It has been shown to greatly decrease the production of soot versus a free jet condition that is known to soot.

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