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Investigation of the interaction between diesel spray and porous medium

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Abstract

The unique properties of porous structures have been utilised in different applications such as liquid and gaseous fuel combustors to enhance the rate of fuel air mixing and increase the thermal efficiency. There have been attempts to utilize these unique features of porous structures to improve the combustion process in direct injection diesel engines as well. In this paper the effect of porous media (PM) properties and fuel injection parameters on spray characteristics and multijet splitting effect have been investigated. The experiments were conducted in a constant volume combustion chamber (CVC) with optical access designed to achieve engine like condition. High speed camera, Shimadzu HPV-1, with a 200mm Nikon lens was used to capture impingement and interaction events at the highest possible frame rates to ensure adequate temporal and spatial resolution for imaging. The porous media employed in the experiment was a Silicon carbide (SiC) ceramic with 20ppi (pores per inch) porosity.

Introduction

Nowadays with the use of common rail fuel injection systems, diesel engines work with high injection pressures of 1800 bar or more and high local combustion temperatures of nearly 2400K. Even with these high pressures, the time required to obtain a homogenous mixture before ignition is too short. Mixture homogenization problem in conventional diesel engine becomes even more critical in the case of partially homogenous charge compression ignition engine (pHCCI) and homogenous charge compression ignition (HCCI) engines where cylinder charge must be homogenous before the start of the combustion process. Technologies such as high pressure injection, intense swirl air motions and multi-hole nozzles have been employed in conventional diesel engine combustion systems to promote fuel distribution in the chamber volume.

Highly non-homogenous mixture in a conventional diesel engine can cause non uniform temperature fields during combustion process which results in high level of engine load–dependent emissions. As a result complex and expensive after treatment systems may be required to reduce the main emissions (NOx and Soot). Even with the use of different technologies such as variable valve timing (VVT), split injection and combination thereof the problem of engine out emissions under all operating conditions cannot be solved easily. Meanwhile, it has been shown that new methods of combustion, such as homogenous charge compression ignition (HCCI) which operate with nearly homogenous air/fuel mixture, can be a possible solution to the problem of engine out emissions specially NOx and soot particles and high specific fuel consumption in low to part-load condition [1]. Application of porous media (PM) in internal combustion (IC) engine to achieve a homogenous combustion process under variable load condition, has recently become a novel new topic of combustion research [2]. The structure of porous medium is characterized by a large specific surface area; large heat capacity and transparency for gas and liquid (spray) flow. High porosity permits large transparency to gas flow, spray and flame as well as low pressure losses in fluid flow through the porous ceramic material volume. In this regards, ceramic foam with 8-30ppi (pores per inch) were found suitable for engine applications [3]. Experimental results show that unique features of porous media especially porosity and material properties can directly affect the thermodynamic properties, ignitability as well as homogenization of the mixture during the combustion process in direct injection diesel engines .

Figure 1 shows a phenomenological model representing characteristic phases of spray interaction with a porous structure compared with interaction of fuel spray with a solid surface [3]. Characteristic phases of spray interaction with a porous structure have been described as follows: Phase A free jet formation; phase B jet interaction with PM surface and partial penetration inside the PM; phase C liquid distribution throughout the porous medium volume and phase D liquid leaving the porous media [4]. It is believed that among the mentioned phases phase C is of crucial importance since it describes the homogenization effect and under hot condition fuel vaporisation of the fuel spray throughout the porous medium volume.

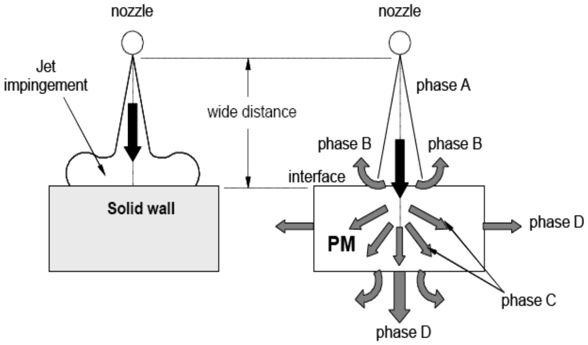

Figure 1: Four characteristic phases of jet interaction with a porous medium [2].

Experimental test results showed that after single spray impingement on a large number of pore junctions of a porous media a number of secondary jets are formed according to multi-jet splitting effect [2]. Weclas and Faltermeier simulated the interaction process by a simple experiment to show the basic aspects of jet interaction with a high porous structure. They experimentally investigated the interaction of a single fuel spray with different predefined arrangements of cylindrical blocks and concluded that impingement of the high speed spray on small cylindrical obstacles causes very fast distribution of the fuel in the volume and with the resultant multijet structure higher air entrainment can be achieved compared to a free jet configuration [5].

Reported in this paper are some results of the investigation of the interaction of a diesel spray with a porous medium (PM) under different fuel injection pressures. The areas of interest at this stage are the top and bottom sides of the porous medium. The experiments were conducted in a constant volume chamber (CVC) with optical access designed to achieve engine like condition. High speed camera was also utilized to capture impingement and interaction events to ensure adequate temporal and spatial resolution for imaging. For the purpose of this experimental work, SiC ceramic disc having a diameter of 150 mm, thickness of 20mm and 20ppi porosity was selected.

Experimental analysis

Experimental set up

Among different stages of fuel interaction with a porous medium, in this analysis we report the characteristics of splitted spray structures in the bottom side of porous media. In order to analyse the spray characteristics, high speed digital imaging technique was selected. A numerical code was then developed for image processing of the resulted images. The analysis was carried out based on the intensity distribution of the recorded gray style images. Proposed measurements technique in this study offer significant improvement over the most recent published work because in contrast to previous work on capturing the time evolution of the spray interaction with porous media by phase averaging of the results or using relatively slow framing cameras, in this study sequences of spray image in each injection have been captured with high temporal and spatial resolution.

The experimental setup used in this research includes, in addition to the stainless steel CVC, a common-rail fuel injection system, trigger circuit, camera system and illumination units. The High-pressure injection system comprises a common rail connected to fuel injector mounted on top of the chamber, low pressure diesel pump which supplies fuel from a fuel reservoir to the high pressure pump and a heat exchanger to cool down the excess return flow. The equipment, including the camera, injector and flashes were synchronised using the trigger circuit which was required in order to ensure the injection occurs at the peak luminosity of the flashes and the camera began recording at the start of injection (SOI). The CVC has 8 windows from the sides and 1 window from bottom. Each window is made from a round quartz glass with 20 mm thickness and effective diameter of 40 mm. The purpose of the vessel was to allow optical access to the injection and combustion process under diesel like condition, which would be difficult to achieve with a real diesel engine [6].

During the experiments, the temperature of the fuel tank reservoir was monitored regularly to avoid running the system with excessive fuel temperature. The fuel injection event was synchronized with two flash units and the high speed camera via an array of electrical equipment. Based on the need for having a series of sequences of each individual spray and analysing its impact with porous region, appropriate camera and illumination systems were chosen and the proper setup for capturing the images was arranged. The high speed camera, Shimadzu HPV-1, with a 200mm Nikon lens was utilized to capture injection and impingement events at the highest possible frame rate. The camera was capable of capturing images up to one million frames per second however the time required between shots for the camera to sufficiently cool down makes doing so impractical [7]. A holder was used to position the porous media at different height in the CVC. Figure 2 shows the high speed camera setup and constant volume chamber (CVC). Figure 3 shows the mounted porous media inside the constant volume vessel. For investigating the interaction of the spray with porous media, in this experimental work a cylindrical shape porous ceramic beside a single hole nozzle with hole diameter of 0.3mm were employed.

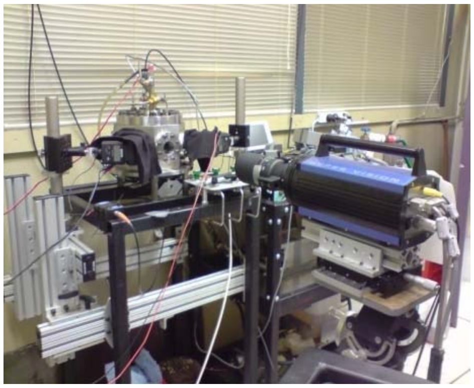

Figure 2: High speed camera with constant volume combustion chamber in the LTRAC laboratory.

Figure 3: Top view of porous medium inside CVC.

Experimental analysis

Experimental results

Figure 4 shows the results of diesel spray interaction with a solid surface at 800 bar injection pressure. The distance of the nozzle tip from the top surface of the PM was set to 20mm in all cases. In this figure, the rebound angle of the spray inside the chamber after interaction with solid surface was nearly 170 degree in 0.448 ms after SOI. Figure 5 shows the interaction of the diesel fuel spray with porous medium at the same injection pressure in 0.63 ms after SOI. The rebound angle in this case is nearly 85 degree.

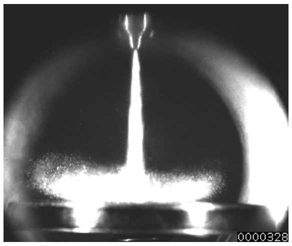

Figure 4: Interaction of fuel spray with a solid surface at 800 bar injection pressure 0.448ms after SOI.

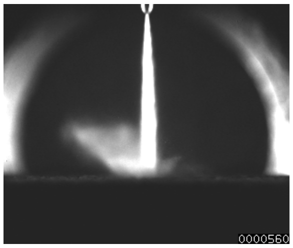

Figure 5: Interaction of fuel spray with porous media at 800bar injection pressure 0.63 ms after SOI.

Imaging results at different injection pressures of 500, 800 and 1000 bar showed narrower angle of spray distribution on top of porous media compared to the flat surface. These results also showed wider angles of dispersion between the secondary sprays (splitted sprays after interaction of the main spray with the porous medium) on top of the porous media at higher injection pressures. To analyse the effect of porous medium on the distribution of the fuel inside the CVC, a series of experimental analyses were carried out to investigate the characteristics of the multi sprays structures leaving the porous media. The investigation of the spatial distribution of these multi spray patterns inside the chamber will answer our question about the effect of porous media on fuel distribution and charge homogenization in engine application. Figures 6 and 7 show the images of multi sprays structures leaving the bottom of the porous medium at 500 bar injection pressure at two different time steps captured at 63kfps. Figures 8 and 9 show the multi sprays leaving the porous media at 800 bar injection pressure.

Figures 10 and 11 show the dispersion of the multi sprays in the chamber at 1000 bar injection pressure. All the images were taken at 63kfps and camera exposure time of ½. Measurement results of the spray angle at different time steps of the same injection pressure showed nearly constant angle during the injection process for each case. Results show wide fuel distribution inside the chamber even at low injection pressures. The time required for the spray to leave the PM was 0.23ms, 0.16ms and 0.14ms respectively for 500, 800 and 1000 bar injection pressures respectively.

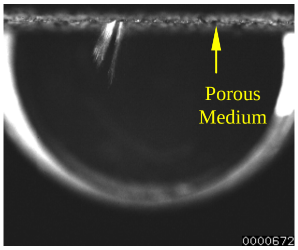

Figure 6: Multi spray formation in 0.634 ms after SOI at 500 bar injection pressure.

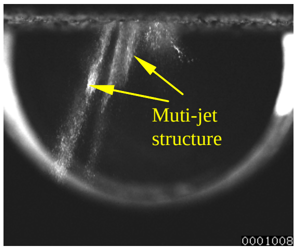

Figure 7: Multi spray formation in 1.015 ms after SOI at 500 bar injection pressure.

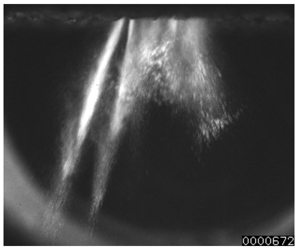

Figure 8: Multi spray formation in 0.634 ms after SOI at 800 bar injection pressure.

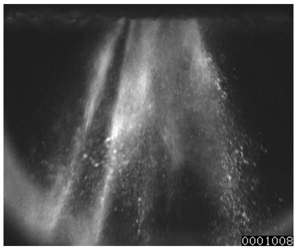

Figure 9: Multi spray formation in 1.015 ms after SOI at 800 bar injection pressure.

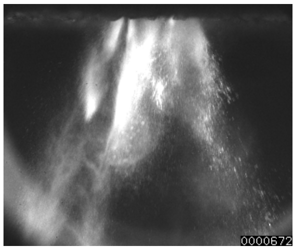

Figure 10: Multi spray formation in 0.634 ms after SOI at 1000 bar injection pressure.

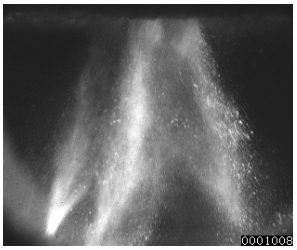

Figure 11: Multi spray formation in 1.015 ms after SOI at 1000 bar injection pressure.

In this study, the effect of different injection pressures on the spray in the presence of porous region was also investigated by examining the macroscopic properties of resulting spray patterns, e.g., projected spray area, total cone angle (angle between the outer edges of the multi spray patterns) as well as maximum penetration. A numerical code was developed to digitally analyse the multijet structure leaving the porous media. The analysis was carried out based on the intensity distribution of the recorded images. The 'background' frame without spray was used as the reference frame in the analysis. The images with injection were then subtracted from this reference image. The threshold intensity value for analysing the development of the spray area inside the chamber was chosen as 130. Figure 12 depicts comparison of the spray projected area under different injection pressures after the spray leaves the porous medium.

Significantly wider areas of fuel interaction with air inside the chamber can be achieved under higher injection pressures. Referring to Weclas phenomenological model for spray interaction with porous media and these measurement results, it appears that at lower injection pressure higher radial and lower axial fuel distribution can be achieved within the chamber, while with higher injection pressures stronger axial flow of the splitted sprays can be achieved. Figure 13 and Figure 14 show the subtracted image of the spray from background image at 0.74 ms and intensity distribution within the multi jet structure at the same time-step under 1000 bar injection pressure respectively

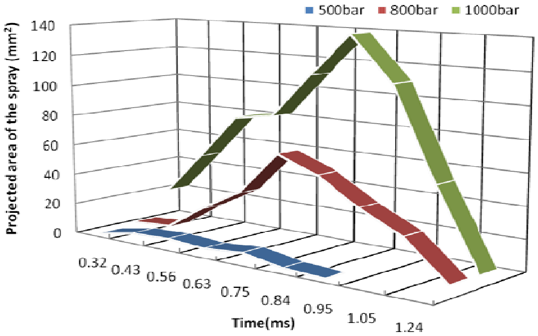

Figure 12: Projected surface area (mm^2) of the multi jet structure versus time (ms) under different injection pressures.

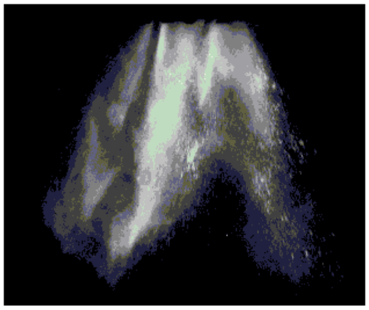

Figure 13: subtracted image of the spray from background image at 0.74 ms at 1000 bar injection pressure.

In Figure 14, the subtracted area of the spray in which the intensity is more than 100 is plotted in blue stars. To have an indication about the probable rich core zone of the multijet structure, the area with light intensity of more than 220 was plotted with red circles. This area was 1.88 percent of the total area of the multi jet structure which shows the distribution of the lean fuel region and reduction of the rich core zones within the body of the spray.

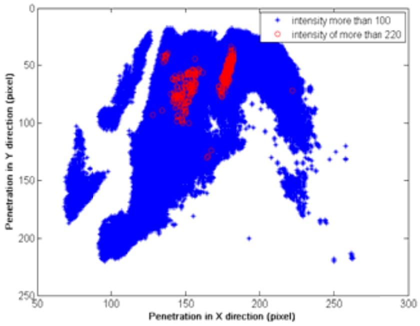

Figure 14: intensity distribution within the multi jet structure of the area development at 0.74 ms after SOI at 1000 bar injection pressure.

Destruction of the rich core zone of the spray by porous medium and high area of interaction of the fuel with air can help the formation of a homogenous charge in diesel HCCI combustion. Figure 15 shows the results of secondary spray tip penetration under different injection pressures. Since in each time step there are more than one secondary spray in the multi jet structure, the penetration of the fastest branch was considered as the reference case for comparing the spray penetration under different injection pressures.

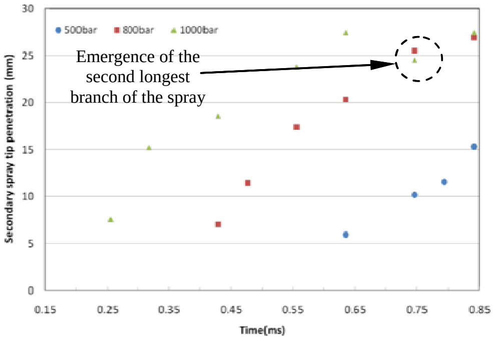

Figure 15: Penetration of the longest spray of the multi jet structure under different injection pressures

The reduction of the secondary spray tip penetration length at 0.75 ms after SOI in the case of 1000 bar injection pressure is caused because the first longest branch of the multi spray structure has passed the limit of the frame (28mm). So the tip penetration length at 0.74ms is calculated for the second longest branch of the multi jet structure under 1000 bar injection pressure. Reduction of the maximum penetration length of the spray has been highlighted by dotted line in figure 15. Figures 16 and 17 show the position of the longest tip of the secondary sprays at 0.63 ms and 0.74 ms at 1000 bar injection pressure respectively.

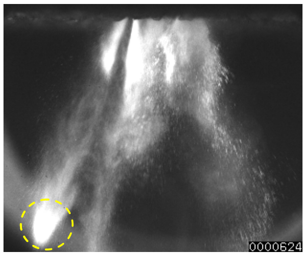

Figure 16: longest secondary spray tip at 0.63ms after SOI at 1000 bar injection pressure

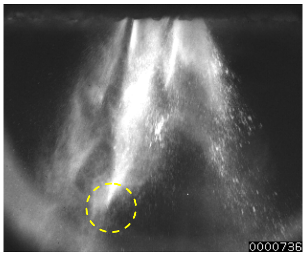

Figure 17: longest secondary spray tip at 0.74 ms after SOI at 1000 bar injection pressure

Conclusions

- An experimental set up was developed to investigate the different phases of fuel interaction with a porous medium in a constant volume chamber under ambient condition using high-speed imaging.
- Increasing the injection pressure increased the number of secondary sprays emerging from the porous medium and increased their penetration
- Maximum angle of distribution of the fuel (48 degree) leaving the porous media was achieved at 1000 bar injection pressure at 0.6ms after SOI.
- Reduction of the rich core zone of the spray by porous medium and high area of interaction of the fuel with air was achieved in different cases indicating the potential of porous media for charge homogenization.
- Experimental results show that fuel distribution inside the chamber volume was strongly affected by the characteristics of porous region

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