

Porous Fuel Air Mixing Enhancing Nozzle (PFAMEN)

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ABSTRACT

One of the challenges with conventional diesel engines is the emission of soot. To reduce soot emission whilst maintaining fuel efficiency, an important pathway is to improve the fuel-air mixing process. This can be achieved by creating small droplets in order to enhance evaporation. Furthermore, the distribution of the droplets in the combustion chamber should be optimized, making optimal use of in-cylinder air. To deal with these requirements a new type of injector is proposed, which has a porous nozzle tip with pore diameters between 1 and 50 μm . First, because of the small pore diameters the droplets will also be small. From literature it is known that (almost) no soot is formed when orifice diameters are smaller than 50 μm . Second, the configuration of the nozzle can be chosen such that the whole cylinder can be filled with fine droplets (i.e., spray angle nearly 180°). However, injecting through a porous nozzle is not the same as an infinite number of very small holes, due to the difference in nozzle internal flow. Therefore, the nozzle tip is modeled in COMSOL Multiphysics in order to predict the outflow direction and velocity of the fuel. The Darcy-Forchheimer equation, which follows from the Navier-Stokes equation, is used for this purpose. To validate the model, experiments have been performed in the Eindhoven High Pressure Cell (EHPC) where (for vaporizing sprays) the spray is visually analyzed and (for reacting sprays) the ignition delay has been measured.

INTRODUCTION

Increasingly stringent emission legislation has lead to an intensified research on HD diesel engines to keep and

improve their fuel consumption, whilst still meeting the emission legislation. Many developments such as aftertreatment, EGR and increasingly higher fuel injection pressures were introduced to the market. Modern Heavy Duty (HD) diesel engines always have Direct Injection (DI). A high pressure pump delivers fuel at 100-250 MPa to an injector with 6-8 holes with a diameter typically around 150-200 μm . After the start of injection, the fuel forms a spray where the liquid fuel breaks up into smaller droplets. In the meantime the diesel is heated up and evaporates via entrainment of high temperature gas.

As a result of the above developments, engines have already become much cleaner. However, in order to meet EPA 10/EURO VI-like emission standards, new techniques might be required or become more interesting as costs tend to further increase. Looking at results from literature [1] and [2] there is a trend that the smaller the diameter of the injection holes gets, the less soot is formed throughout the combustion process. If the diameter of the holes becomes smaller, the total outflow area decreases, resulting in a lower volume flow. By applying more holes this issue could be overcome. However, the maximum number of holes and the minimum diameter of the holes is limited. For these reasons new solutions have to be found. One possible solution would be to inject the fuel through a porous material. The porous material contains many small pores over a large surface of the injector tip, and in this respect principally differs from injection through a conventional nozzle with straight-drilled injector holes.

To assess the technical viability of such a nozzle, a numerical model was built (using COMSOL Multiphysics)

and the flow through the material and its strength were investigated. The flow through the porous material is described by the coupled Darcy-Forchheimer equation [3]. The Darcy and Forchheimer equations are derived from the Navier-Stokes equation by Neuman [4] and Chen et.al. [5], respectively.

Besides the numerical investigation, some experimental measurements with the porous injector were performed. To test the porous injector concept, prototype nozzles were produced and the original injector tip was replaced by a porous tip. The injector was connected to two different common-rail setups, one at atmospheric conditions and one at engine-like conditions in a constant volume spray bomb. The atmospheric tests are quickly and relatively easily performed and the engine-like measurements are closer to real engine circumstances. With the atmospheric measurements the spray is analyzed visually, the volume flow of the injector is evaluated and durability tests are performed. With the engine-like tests, which are performed in the Eindhoven High Pressure Cell (EHPC, for details see [6]), again the spray is analyzed, ignition delay is determined and the combustion process is qualitatively analyzed.

In Figure 1 a typical fuel distribution is illustrated for conventional injectors and an ideal fuel distribution for porous injectors, respectively. It is expected that the quantity of oxygen that potentially takes part in the combustion process, is much larger with the porous injector since the occupied volume is larger. However, whether this is really the case will also depend on time scales (a.o. governed by exit velocity, which will be smaller due to the internal geometry of and resulting flow friction in the porous nozzle). This is one of the subjects investigated in this work.

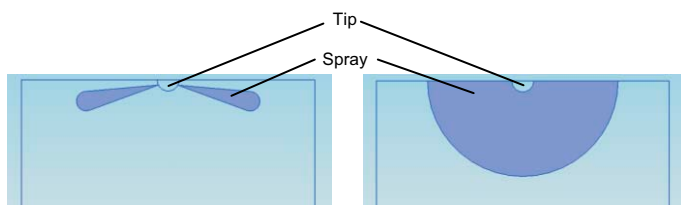


Figure 1. Fuel distribution of a conventional (a) and porous (b) injector.

As is shown in Figure 1, it is the intention to acquire a spray with a – roughly – hemispherical shape. Details of the optimal spray shape will depend on the combustion concept and the shape of the piston bowl. In the next section we will briefly discuss how this can be achieved.

The outline of this paper is as follows. In the first section, some preliminary work with regard to the porous nozzle concept is reported. The second section deals with modeling of the porous injector. In the third and fourth sections the experimental setup and experimental results

are discussed, respectively. Finally, a discussion of the results and some conclusions are presented.

PRELIMINARY WORK

In this section some preliminary work on the topic of injection through porous material is briefly discussed. To successfully inject via porous material, the properties of the material must be known. The most important are porosity and permeability. Both will be discussed here.

Porous material can be produced via sintering. With sintering, grains are pressed together at high pressure and are afterwards melted together at temperatures just beneath the melting temperature of the material. There are grains in many sizes, forms, types and materials, for example ceramics, metals, plastics, etc. The size of the grains and the pressure of the process determines for a large part the porosity and permeability of the sintered material. The porosity is defined as the volume fraction of holes in the material in relation to the total volume. The definition of permeability is the rate of flow of a liquid or gas through a porous material divided by the pressure difference that is driving the flow. In this study, stainless steel is chosen because of the favorable properties of this material in an engine environment (easy machining and high temperature resistance).

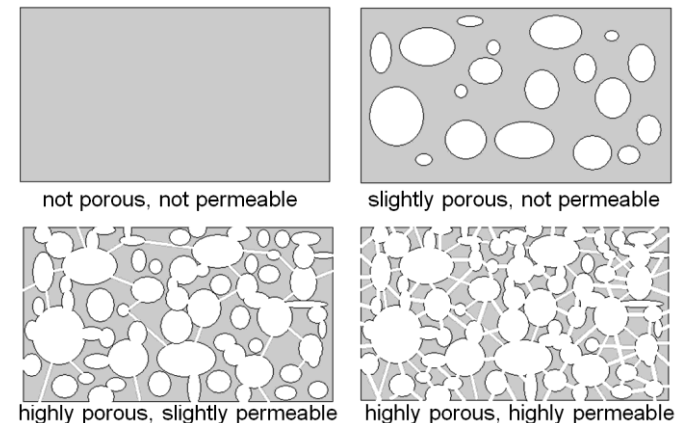


Figure 2. Four configurations with different porosities and permeabilities.

In Figure 2, examples are shown of different porosities and permeabilities. As becomes clear from the figure, a porous material is not by definition permeable, but a permeable material is by definition porous. In this study material is used that is closest to the lower left figure. Permeability and porosity depend on the internal structure of the material.

Darcy's Law [7] is a well known (empirical) relation to describe the flow through a porous material. It can be derived from the Navier-Stokes equations under certain conditions [4] and it is defined as:

$$\nabla \cdot \left(-\frac{\kappa_d}{\eta} \nabla p \right) = 0. \quad (1)$$

Here, κ_d is the permeability as defined by Darcy, η the dynamic viscosity of the fuel and p is the pressure. The equation above was implemented in COMSOL Multiphysics in order to model the internal flow in the porous injector and calculate the Reynolds number. In this way, the optimal geometry of the porous nozzle is examined and Darcy's Law can be validated. Criteria in the optimization of the porous injector are: the fuel mass flux (which should be at least equal to that of conventional injectors); the spray shape (which should resemble the hemispherical shape presented in Figure 1b); and the tensile strength (which should be larger than the tensile stresses in the nozzle, multiplied with a safety factor).

The geometries shown in Figure 3 were investigated to ascertain the influence of the length of the fuel channel. The sizes in the figures are in mm. The size of the outer diameter is chosen equal to the size of the conventional injector tip. To determine the size of the inner diameter, a few prototypes are made in which the inner diameter as shown in the figure, best agrees with the criteria mentioned above.

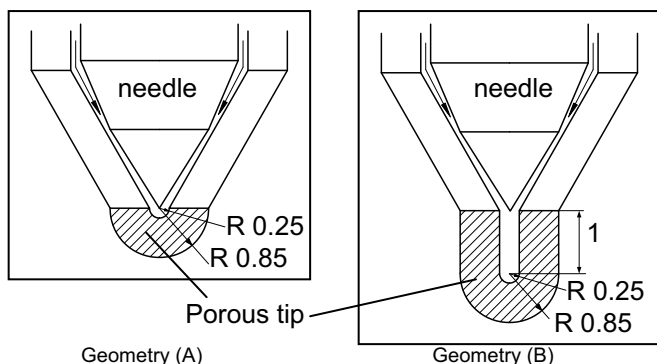


Figure 3. Technical drawing of porous nozzle concept

First, geometry (A) was investigated. On the inner edge the fuel pressure was prescribed, and on the outer edge a typical cylinder pressure at the time of injection. The flow through the porous tip is calculated with equation 1 where κ_d is reported by the manufacturer and η is a typical value of the dynamic viscosity for diesel. The values for these quantities are reported in Table 1. The "space dimension", which is used in COMSOL Multiphysics, is 2D axial symmetry. The calculations are performed for steady-state and the influence of the flow through the channel is neglected. Whether this is justified is investigated in the next section.

Table 1. Input parameters for simulations

Quantity	Value
Fuel Pressure Geometry (A)	60 MPa
Fuel Pressure Geometry (B)	25 MPa
Cylinder Pressure	5 MPa
Density (ρ) [12]	850 kg/m ³
Dynamic viscosity (η) [12]	3.8 · 10 ⁻³ Pa·s
Permeability (κ_d) [13]	3 · 10 ⁻¹² m ²
Mass flow	0.8 kg/s

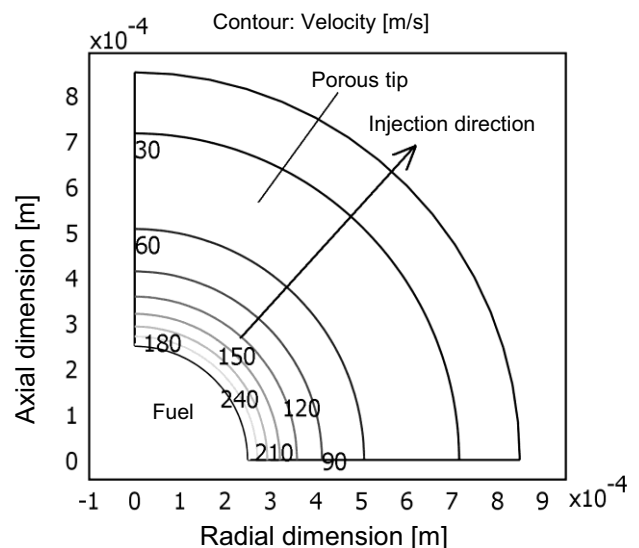


Figure 4. Simulation of prototype with geometry (A); isolines of the internal velocity in the nozzle. Exit velocity is approximately 21 m/s.

From Figure 4, showing the internal velocity profile in the nozzle, it follows that there is a uniform spray velocity at the outer edge which should result in the spray shape as shown in Figure 1b. However, experiments reveal a spray shape as is shown in Figure 5. The experiments are performed with a Dedotec COOLH light source (illuminating the spray) and Dedotec COOLT3 power supply combined with a Phantom 7.1 high speed camera.

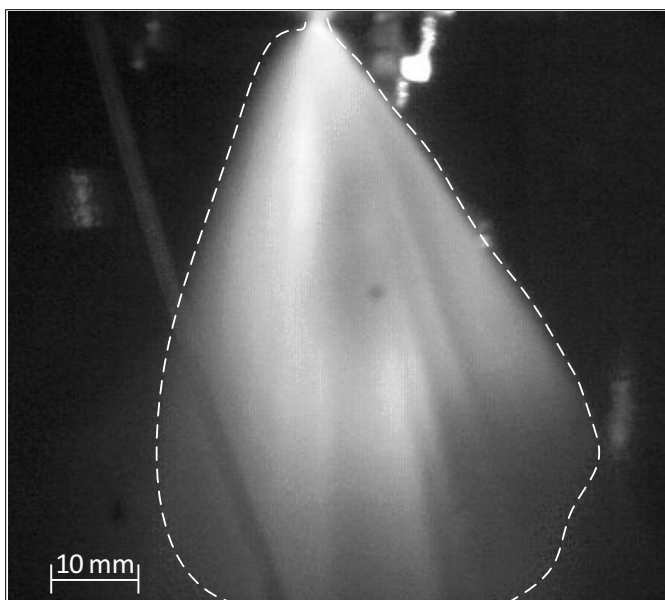


Figure 5. Experimental spray shape of injector with geometry (A). Atmospheric conditions, spray illuminated with high power light and captured with a high speed camera and experimental properties as listed in Table 2.

From Figure 5 it appears that the fuel spray is finely atomized, but the desired homogeneous hemispherical distribution is not realized. The fuel spray has a preferential axial direction, which means that geometry (A) does not have the desired fuel distribution of Figure 1b.

Table 2. Properties used for experiments

Quantity	Value
Material	Stainless steel
Mean pore size	10 μm
Porosity	32 %
Injection pressure	100 MPa
Injection time	5 ms
Shot time	4 ms

Next, geometry (B) with the longer fuel channel was investigated. The pressure on the inner edge was lowered to reach the same mass flow as in the previous case. The other parameters were not changed.

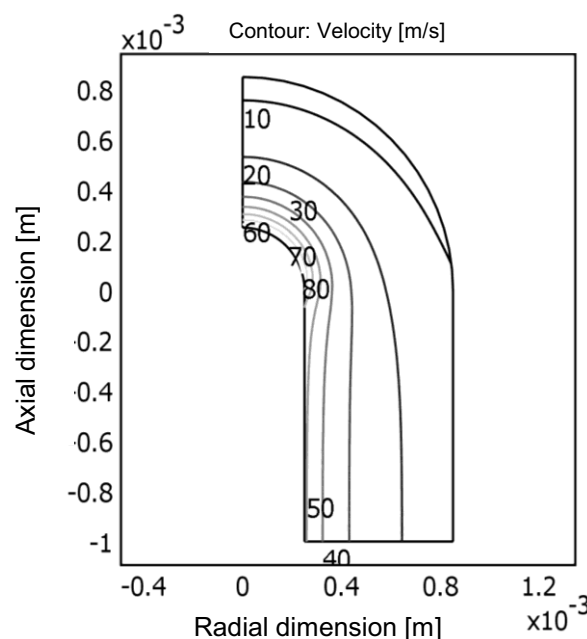


Figure 6. Simulation of prototype with geometry (B); isolines of the internal velocity in the nozzle. Exiting velocity on the tip is 8 m/s.

From Figure 6 it was concluded that again the velocity on the outer edge was almost uniform. Experiments yield the spray shape as shown in Figure 7.

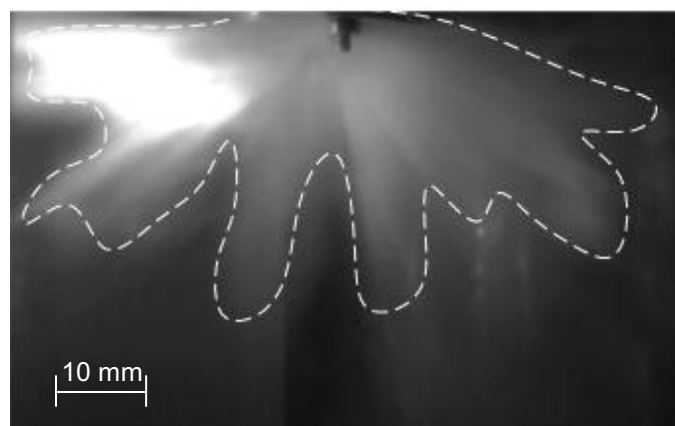


Figure 7. Experimental spray shape of injector with geometry (B); Same conditions as Figure 5.

Here, by changing the nozzle geometry, the spray shape is closer to the desired hemisphere bowl shape (Figure 1b). Of course the figure shows that the distribution locally still seems to be quite non-uniform. However, in the near future the porous material could be tuned to result in a more homogeneous distribution. This will be done by optimizing the production process. The numerical results do not (fully) correspond with the