Investigation of Direct-Injection via Micro-Porous Injector Nozzle

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Abstract
The possibility to reduce soot emissions by means of injecting diesel fuel through a porous injector is investigated. From literature it is known that better oxygen entrainment into the fuel spray leads to lower soot emissions. By selection of porous material properties and geometry, the spray is tunable such that a maximum of air, present in the cylinder, is utilized. A numerical model has been created to predict the flow through the porous nozzle. Experiments are reported on the spray shape, flow rate and the durability of the porous injector under atmospheric circumstances.

Introduction
With increasing fuel prices and rising attention to environmental issues, the development of engines has gone very fast. The engines have to be cleaner and more efficient. Because of this, many changes such as turbocharging, aftertreatment, ‘downsizing’, ‘common rail’, etc. were introduced. Almost all trucks and roughly half of the passenger cars are equipped with a diesel engine, which means that this is a large part of road traffic.

Most diesel engines have Direct Injection (DI), which means that the fuel is directly injected into the cylinder. A high pressure pump delivers fuel at 100-200 MPa to an injector with 6-8 holes. Because of this high pressure, the fuel is pressed through the small holes (typically with a diameter around 150-200 µm) and forms a spray. After the start of injection, the liquid fuel breaks up into smaller droplets that in the mean time are heated and evaporated by the high temperature entrained gas. The point at which all fuel droplets have evaporated is referred to as the Liquid Length [1].

As a result of the above developments of DI diesel engines, the engines already have become much cleaner. Yet, because of the severe requirements concerning emissions and fuel consumption, new techniques are required. Looking at results from literature [2] and [3] it becomes clear 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 flow area of the holes decreases, resulting in a lower volume flow. By applying more holes this problem can be solved. However, the maximum number of holes and the minimum diameter of the holes are limited. For these reasons new solutions have to be found. A possible solution would be to inject the fuel through a porous material. The porous material contains many small pores (channels) over a large surface of the injector tip.

To assess the technical viability of such a nozzle, a numerical model was built and the flow through the material and strength of the material were investigated. The flow through the porous material is described by Darcy’s law [4]. In addition, the porous injector is tested with a common-rail setup under atmospheric conditions.

Prototypes are produced and the original injector tip is replaced by a porous tip. With a common-rail setup a number of experiments are performed. The spray is analyzed, the volume flow of the injector evaluated and durability tests are performed.

In the first section, the conventional and the new concepts are explained. Next, modeling of the porous injector is treated, respectively. Finally, the performed experiments are discussed and finally some results and conclusions are given.

Concepts
The composition of exhaust gases in diesel engines is largely governed by the spray formation and mixing process. Important parameters are the diameters of the injection holes and droplets and the degree of mixing of fuel with air. Given an injection pressure, smaller orifice diameters typically provide smaller fuel droplets and this results in a more rapid vaporization and better mixing of fuel and oxygen (air). More injector holes provide a better distribution which leads to more oxygen entrainment.

Conventional injectors for heavy-duty diesels are prepared with 6-8 holes with an orifice diameter of about 150-200 µm. The maximum common rail pressure is currently about 200 MPa and rising. However, in order to meet Euro 5 targets, trucks will still require a particle filter. This is expensive and gives rise to a higher specific fuel consumption (for example due to regeneration and extra pumping losses).

To meet the requirements of Euro 6, more measures have to be taken. Injection pressures will likely rise up to 300 MPa. This leads to a higher pump capacity and thus higher fuel consumption. Theoretically, it is also possible to meet the stricter requirements by reducing the orifice diameter of the injector, because the droplets become smaller and therefore the mixing improves. However, in practice it is very difficult to drill holes smaller than 100 µm. This has to do with focusing of the drilling laser and the energy supply to melt the material.

To overcome these problems, the idea arose to inject via porous material. The porous material contains many

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small pores, which can be seen as the limiting case of a large number of small holes.

In Figure 1 a typical fuel distribution is illustrated for conventional and porous injectors, respectively. It is clear that the quantity of oxygen, which takes part in the process, is potentially much larger with the porous injector. However, whether this is really the case will also depend on time scales (a.o. governed by exit velocity). This will be the subject of the investigation presented here.

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 hemispherical shape. How this will be achieved will be discussed in the next section.

Modeling of the porous injector

A production process known as sintering produces material that is porous and permeable. With sintering, grains are pressed 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 the permeability of the material. The definition of porosity is the volume fraction of holes in the material with respect to the total volume. The ease with which the flow travels through the material, at a certain pressure drop, is the permeability of the material. In this case, stainless steel is chosen because of the favorable properties of this material in an engine environment.

Figure 2. Porosity versus permeability

In Figure 2, examples are shown of different porosities and permeabilities. In the left figure the material is non-porous and not permeable, in the middle figure the material is slightly porous and not permeable and in the right figure the material is highly porous and slightly permeable. Therefore, a porous material is not by definition permeable, but a permeable material is by definition porous.

The flow through porous material can be described with Darcy’s Law [4]. This relation is derived from the Navier-Stokes (NS) equation. If we assume stationary flow, low flow velocities, incompressible fluid and neglecting gravity, the reduced NS-equation can be written as:

\[ \nabla p = \eta \nabla^2 v. \]  \hspace{1cm} (1)

Via homogenization (Neumann, ref. [5]) we find:

\[ \frac{\eta}{\kappa_d} v = -\nabla p, \]  \hspace{1cm} (2)

which can be written in the more general form (Darcy’s Law):

\[ v = -\frac{\kappa_d}{\eta} \nabla p, \]  \hspace{1cm} (3)

where \( p \) is the pressure, \( \eta \) the dynamic viscosity of the fuel, \( v\) the velocity of the fluid and \( \kappa_d \) is the permeability defined by Darcy’s Law. Using the continuity equation and assuming a stationary situation and constant density the following equation can be derived:

\[ \nabla \cdot \left( -\frac{\kappa_d}{\eta} \nabla p \right) = 0. \]  \hspace{1cm} (4)

The above equation was implemented in COMSOL Multiphysics in order to model the internal flow in the porous injector. In this way, the optimal geometry of the porous nozzle is examined. Criteria in this optimization 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 on 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 models are made in which the inner diameter as shown in the figure, best agrees with the criteria mentioned above. First, geometry (a) is investigated.

Figure 3. Design drawing of porous nozzle concept
On the inner edge a fuel pressure of 130 MPa is prescribed, on the outer edge (cylinder) a pressure of 5 MPa, which is a typical in cylinder pressure at time of injection, is prescribed. The flow through the porous tip is calculated with equation 4 where \( \kappa_d = 3 \cdot 10^{-12} \text{ m}^2 \) (reported by manufacturer) and \( \eta = 3.8 \cdot 10^{-3} \text{ Pa} \cdot \text{s} \) (typical value for diesel). From Figure 4 follows that there is a uniform spray velocity on the outer edge which gives the spray shape as shown in figure 1b. The stresses in the material are also calculated. The maximum stresses that appear in the model are 60 N/mm\(^2\). The maximum allowable stress of the porous stainless steel is 90 N/mm\(^2\) (known from manufacturer) which means the safety factor is 1.5. This is a relative low safety factor and from experiments we have to find out whether this is sufficient.

Secondly, geometry (b) with the longer fuel channel is investigated. The pressure on the inner edge is lowered to 100 MPa to reach the same mass flow as the previous case. The other parameters are not changed. The velocity of the fluid is higher near the tip than at the sides. In a later Section, the prototype test results will be discussed. With the use of the exit velocities, the fuel spray outside the porous material can be modeled. This work is currently in progress, and falls outside the scope of the current paper.

**Experimental setup**

The first target of the experiments is to acquire a homogeneous, hemispherical spray shape. A relatively easy way to do this, is to test the spray at atmospheric conditions. Afterwards, the lifetime and the flow rate of the porous injector are examined.

To perform experiments a common-rail setup (Figure 6a) is used. A common-rail pump is powered by an electric engine. The fuel supply for the common-rail pump comes from a tank, via a low pressure pump and a filter. After the high pressure pump the fuel enters the common-rail. One exit of the common-rail is connected to the injector, the remaining connections of the common-rail are blocked. The pressure in the rail can be varied from 30 to 250 MPa. The injector is driven by a driver, which regulates start of injection, injection time and the injection frequency.

Figure 6 shows the injector where the original tip has been replaced by a porous tip. The injector is placed in a plate with several o-rings to prevent leaking. The tip is held in place against the injector by a holder and 3 bolts. The holder is fitted with an o-ring, again to prevent leakage.
Experimental results

The measurements are discussed in two parts, one part in which the spray shape of the porous injector is examined with a high speed camera and a second part in which the mass flow and durability are evaluated.

As mentioned earlier, the maximal use of the oxygen present in the cylinder is important for complete and clean combustion. To gain insight into the spray shape, measurements under atmospheric conditions are performed. Because a typical injection lasts only 5 ms (maximally), it is necessary to film the spray with a high speed camera (2500 fps).

The geometry of the first prototype (geometry a) was a hemisphere with inner diameter of 0.25 mm and outer diameter of 0.85 mm (see Figure 3a). This geometry is defined with use of the Comsol model. The porous tip is fixed to the injector and connected to the common-rail setup. With the high speed camera the spray is captured. In Figure 8 a picture of the spray is shown.

![Figure 8. Measured spray of the prototype with geometry (a)](image)

From the figure it becomes clear that the fuel spray is finely atomized, but the desired homogeneous hemispherical distribution is not reached. The fuel spray has a preferential axial direction, which means that geometry (a) has not the fuel distribution as shown in Figure 1b.

With a second prototype (geometry (b)) new experiments were performed. The result is shown in Figure 9. In this figure the spray distribution is more or less as shown in Figure 1b.

![Figure 9. Measured spray of the prototype with geometry (b)](image)

In the above figure, a well atomized and approximately hemispherical spray can be observed. The spray occupies a large volume which means that the fuel droplets are surrounded by a lot of oxygen. The white region (left side) is the result of overexposure during the shoot. To compare these results with a conventional injector, additional experiments are performed. Figure 10 depicts the spray of a conventional injector. In this figure, only a small fraction of the available air is entrained.

![Figure 10. Measured spray of a conventional injector](image)

The delivered power in diesel engines is controlled by the quantity of injected fuel. To ensure that the mass flow through the porous injector is the same as that of the conventional injector, mass flux measurements were performed, by applying a high injection rate into a closed reservoir. The mass of the injected fuel is weighed and divided by the number of injections.
In Figure 11 the results of the mass flow measurements of a conventional and porous injector are plotted. Under equal conditions, the mass flows of the porous injectors are higher than the mass flows of the conventional one.

To examine the lifetime of the porous injector, durability tests were performed. From experiments it is found that the injector tip breaks down at a location that is roughly indicated in Figure 12, after about 100,000 injections. This value is dependent on the geometry, size and thickness of the porous material layer.

The mass flow through the porous injectors is found to be higher than the conventional one, at least for the nozzle material and geometry used in this preliminary study. This implies that the upstream pressure of the porous injector can be set to a lower value than the conventional one, in order to inject the same mass. Another way to inject the same mass is to reduce the injection time. To inject the same mass of the porous injector at 100 MPa, the pressure of the conventional injector has to be 200 MPa. This would translate in a large fuel saving (lower pumping losses) and significant cost reduction of the fuel injection equipment.

The desired lifetime of the injector is 1,000,000 km, the average speed over the whole life is 80 km/h at an engine speed of 1500 rpm. In this case, the injector has to inject approximately 500 million times during its lifetime. From the experiments is known that the injector breaks down after about one hundred thousand injections. This means that the lifetime of the injector is far too short. To extend the lifetime, the geometry has to be optimized, other materials have to be investigated and the production process has to be improved. This requires further research, and will be investigated in a later phase of this project.

**Conclusions**

From literature it is known that the soot emissions of diesel engines reduce when the diameter of the injector holes becomes smaller and the injection pressure increases. Both of these measures have constraints. Rising the injection pressure leads to a higher pump capacity (and associated power consumption) and smaller holes are difficult to produce.

An alternative is a tip consisting of porous material, housing many small holes (with diameters in the tens of μm range). This may be advantageous for injecting diesel. The flow through the porous material was studied by building a model in Comsol Multiphysics. In a first attempt to model the flow through the porous material, Darcy’s Law was used. However, it was found that a second order (Forchheimer) term needs to be included in the model to accurately account for the momentum of the flow in the internal nozzle channel. With the use of this (extended) model, prototypes can be produced with relatively easy and at low cost.

![Figure 11. Injected mass versus opening time for conventional and porous injector](image1.png)

![Figure 12. Porous injector tip with indication of break line location](image2.png)
The mass flow and the durability of the porous nozzle were tested in experiments. At a given pressure, the mass flow was, for this specific prototype nozzle, found to be higher compared to a conventional injector. Therefore, the injection pressure can be reduced which results to lower pumping losses and costs. Yet, the durability of the porous injector does not satisfy the desired lifetime. Probably, the nozzle breaks down because of fatigue. Clearly, this durability issue needs to be investigated further.

The spray shape of some porous nozzle prototypes was also determined experimentally. Prototypes with different geometries were produced, and the Comsol model was used to optimize the geometry. The first prototype had a preference in the axial direction. Ultimately, by adapting the prototype geometry, the desired homogeneous hemispherical spray shape was realized. Overall, these results are quite encouraging in the quest for a cleaner fuel injection concept based on a porous injector nozzle.

References