Hole to Hole Mass Distribution in Diesel Injector

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Sammanfattning

Olika exemplar av common railinsprutare har testats i avseende på fördelning av bränsle över insprutarens åtta hål. Mätutrustning har konstruerats för att samla upp varje bränslestråle var för sig i varsitt provrör som sedan vägts.

En stor del av arbetet bestod av konstruktion av mätutrustningen och anpassningar för att kunna utföra mätningarna så noggrant som möjligt.

Tre olika insprutare av samma modell och en insprutare av senare modell testades för två olika driftspunkter och resultatet jämfördes med tidigare uppmätta värden för rökemissioner. Ytterligare sex insprutare testades för en driftpunkt. Samtliga insprutare visade upp hål till hålvariationer i olika stor utsträckning. Sammantaget av alla tio testade insprutare så kan enbart hål till hålvariationerna inte förklara skillnaderna i rök.
Abstract
Different examples of common rail injectors have been tested, referring to fuel distribution over the injector’s eight nozzle holes. Measurement equipment has been constructed to collect each fuel spray separately in one test tube each, which then will be weighed.

A big part of the work has been constructing the measurement equipment and adjustments to be able to do the measurements as accurate as possible.

Three different injectors of the same model and one injector of a later model were tested at two different load points and the results were compared with earlier measured smoke emissions. Another six injectors were tested at one load point. All the tested injectors showed hole to hole variations of different size. Summarizing the test results for the ten injectors, hole to hole variations can not alone explain differences in smoke production.
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**Subject**

**Introduction**
In diesel engines, high pressurized fuel is injected into hot compressed air in the cylinder. The fuel ignites when it is mixed with the hot air and is combusted in diffusion flames. Problems with the diesel engines are that it produces emissions of smoke and NOx, among other emissions. Fuel injectors are a vital part in improving the diesel engines performance and reducing emissions, since the injector distributes the fuel into the compressed air.

**Background**
A better knowledge of fuel distribution is vital to explain the engines behavior. This work will compare variations in fuel distribution from different injectors compared with the amount of smoke produced when the injector is tested in engine. Smoke emissions are regulated worldwide in emission legislations. It is therefore important to control all components affecting the smoke number to keep emissions down.

An optical investigation of injector fuel sprays showed large variations in geometrical differences between nozzle holes [1]. This investigation made the question arose whether the injector’s eight nozzle holes delivered an even amount of fuel or if the hole to hole distribution was uneven.

**Hypothesis**
This project will study the injectors to determine if there are any differences in the fuel distribution from different examples of the injector model. The injector delivers eight sprays that are sprayed out in the combustion chamber in an umbrella form. It is interesting to know whether the eight sprays contain the same amount of fuel, or if they differ from the others. Difference in ejected quantity would give areas in the combustion chamber with leaner or richer combustion than wanted. This could affect the smoke number.
If there are differences, they could be results of geometrical differences between the holes. Or they could depend on the needle lifting. Both scenarios would affect the fuel’s possibilities of distributing evenly over the holes. Geometrical differences would give a result independent of duration, while problems with the needle probably would give a bigger effect on short duration (half load), and be less important for long duration (full load).

**Task**

The injectors will be investigated by separating the eight sprays and collect them in eight test tubes. The fuel in the tubes is weighed separately to find differences in quantity. The measurements will be done with four injectors. After the measurements are made, the result will be compared with the smoke numbers earlier measured for each injector to investigate correlation.

To do these measurements, a measurement device that collects the spray from each injector hole individually is constructed. It is designed to meet the needs of low losses and good usability to do the measurements possible.
**Study of measurement techniques**

Different techniques for measuring hole to hole differences were described by Payri [3], Kilic [4] and Kull [5]. The three described techniques differ from each other in several aspects.

Payri injects each spray in a conical chamber, which lead the spray trough a plastic hose down to a siphon. The siphon is used to separate fuel and air by making excessive fuel leave through the siphon’s other end, while air is circulated back to the nozzle tip, where it is used for the next spray. This keeps the spray air as a closed medium.

Payri’s experimental setup is modeled in Figure 2. The injector is held with a special manufactured injector holder and fuel is supported from a rail.

When using this technique, it is very important to find a way to ensure that the recirculated spray air is clean from fuel. Reused air with fuel left from previous injection would lead to fuel from one nozzle hole ending up in the wrong siphon since all air is recirculated through the same hose. Verifications also have to be made that each fuel droplet injected into the chamber also makes one fuel droplet leave the siphon, and that the air mass pushed by the fuel through the hose does not make any additional fuel leave the siphon.

![Figure 2. Experimental setup by Payri [3]](image)

Payri measures an injector with a three hole micro sac nozzle with injection pressures of 600 and 1300 bar respectively. Durations of 3 ms and 1.5 ms are tested. Hole to hole differences of ± 3.5% from average are reported.

Kilic’s measurements are done with an adapter made of plastic, leading each spray via a metallic channel to a rubber hose, down to a measurement KMM cell to measure the fuel
flow. The nozzle tip and the adapter are placed tight to each other making the spray sealed of from the surrounding air.

Placing the adapter has to be done with very high precision not to cover the nozzle holes. The smallest mismatch between nozzle hole and adapter channel could lead to measurement errors with this technique.

Figure 3 shows Kilic’s experimental setup.

![Figure 3. Experimental setup by Kilic [4]](image)

Kilic’s measurements are done on a six hole VCO nozzle with injection pressure of 100 bar. Focus is put on different needle lift and the result shows hole to hole differences of ± 3% from average for long needle lifts (h\textsubscript{N} = 0.15 mm). With extremely short needle lift (h\textsubscript{N} < 0.01 mm), differences of ± 12% from average are reported.

Kull’s measurements are done with injecting the fuel sprays into conical chambers from where the fuel is led through tubes to accumulation bins. The chambers are placed on a distance from the nozzle tip. Air circulation is not presented further. Each bin is placed on its own weighing device, which keep measurement time down. Figure 4 shows the principles for Kull’s setup. A camera is used to adjust the adapter relative the injector holes.

Kull presents measurements made with two piezo injectors with VCO nozzles with five holes. The injectors are normally installed with a 13° angle in the engine to fit under the camshaft. The nozzles are measured with both steady fuel flow and real injections. Kull’s
results shows good correlation in hole to hole measurements between the two ways of flowing fuel through the nozzles.

With this known, focus in this work will be on measurements with real injections with different duration. Measurements with steady fuel flow through the nozzles will not be done, since it would request the nozzles to be separated from the injectors. Separating nozzles and injectors shall be avoided since the injectors will be used in other projects later on.

Figure 4. Experimental setup by Kull [5]

Kull measured real injections with injection pressure of 1000 bar. For the two tested injectors, hole to hole variations of ± 6% are reported. The variations are linked to the different inclination angles of the five sprays, which is caused by the 13° installation angle.

These three techniques all have hoses that lead the spray to the fuel accumulation before measuring. Using tubes bent in different shape relative to each other can give measurement errors with different quantities of fuel left on the wall in each hose. Kull describes this problem and suggest a solution where the system is given time to build up wall films in the hoses before the real measurement begins.

Similar problems with fuel collection that this project had are not reported from these three sources. Limitation of the amount of air circulating the hoses and fuel accumulation bins together with lower injection pressures could have contributed to keep those effects down.

**Developing of measurement concepts**

The available arrangement for common rail injection testing at KTH was the so called bomb, constructed by Wickerfäldt [2]. The bomb is an arrangement for visualization (photographing) of fuel sprays in a pressurized vessel, shown in Figure 5. In its normal
version, the bomb is a closed cylindrical vessel with injections coming from the top. Windows on two sides and at the bottom of the vessel make photographing possible.

Figure 5. Pressurized vessel, "the Bomb"

A more simple spray testing rig is also available at KTH, see Figure 6. The spray rig uses a cylinder head to hold the injector. A cylinder head can be taken from Scania, instead of making a new injector holder for the bomb. The cylinder top and the circular glass tube that covers the spray area can easily be separated from each other, which give a very good access for adjustments of the measurement device.
Several concepts were considered to find a suitable solution. Doing the measurements in the spray rig was finally found to be the best solution since the geometry of the bomb would make the measurements difficult to do, due to difficulties in placing and adjusting the equipment. With four injectors to test several times each, this meant more problems than benefits.

The first outlines of the measurement device were based on that it should be used in the bomb. It would be attached to the injector holder outside the bomb and adjusted to the injector holes there. This meant that it needed to be placed through a circular hole with a diameter of 50 mm in the top of the bomb.

An early sketch was a measurement device made from a solid piece of aluminum. This first solution gave problems with adjusting the injector holes to the channels in the device due to bad visibility. It also had systems of channels inside the aluminum which would make it rather difficult to manufacture. A second sketch was a measurement device made out of two parts, the bottom part made of aluminum and containing the channels, and an upper part made of transparent plastic, shown in Figure 7. This solution gave the possibility of doing the adjustment toward the injector by visual seeing the injector holes.
through an enlarging lens. It also made manufacturing easier since the channels became open with the top off.

Figure 7. Divided adapter concept, bottom part

The second solution still was not satisfying, since the fuel spray early after leaving the injector nozzle at high speed would hit the wall. After hitting a vertical wall there is an obvious risk that parts of the spray will bounce back to the injector instead of going down to the test tube that aggregates the fuel. Doing the measurements in this project, even small losses can affect the result badly. Therefore the wall had to be made leaning to lead all the spray down to the test tube.

The leaning wall concept was a good improvement in order to collect the spray and lead it to one place without losses. Using tubes or hoses and bending them to a good form would however do this in a better way, minimizing losses from fuel splashes.

Since the injection pressure is high, the fuel spray will affect the material it hits and may wear it down after many injections. Rubber or plastic hoses were together with copper tubes ruled out to be too fragile for this use. Steel tubes were instead selected.

The adapter is designed with some space between the openings of the pipes and the injector nozzle. This is done to have the eight sprays separated, which makes it easier to
get them into the tubes. The adapter is open underneath, which gives the possibility to photograph the sprays and the adapter for adjustment.

The solution with eight tubes attached to an adapter gives a big problem with the dimensioning 50 mm hole that the device shall be placed through. To meet this criterion the tubes have to be bent very abruptly. An abrupt bend on the tube is difficult to do without damaging the shape of the tube. Abrupt bends typically makes the tube flat in the bend, which destroys the good flow through the bend and may have cavities where fuel can be lost. An abruptly bent tube may also once again have the problem with spray hitting the wall and bounce back out to the injector.

The tubes need to be longer to fill their function. To get an adapter to continue working with, the idea of placing it all through the 50 mm hole had to be given up. Instead it would have been necessary to attach the tubes to the measurement device inside the bomb, which would be difficult. The other solution is to place the whole device from underneath, which can be quite difficult to do with good precision.

By using the spray rig the problem with placing the measurement device were solved. With good access and visibility the tubes can be attached to the measurement adapter when it is in the spray rig. The measurement device with steel tubes is shown in Figure 8.

![Figure 8. Device with long steel tubes](image-url)
The tubes are a vital part of the construction. Their objective is to collect all the spray without losses. They therefore have to be long enough to ensure that no spray can bounce back out into free air after hitting the wall in the tube bend. Rubber hoses are attached to the end of the tubes, slowing the spray down while leading it to the test tubes.

**Constructed parts**

**Figure 9 system overview**

**Measurement adapter**

The measurement adapter, (1) in Figure 9 is placed on the cylinder head with the injector nozzle tip in its center. The eight holes on the adapter are made leaning 16°, which is the same angle as the spray has. Every hole will collect one spray completely, which is why the angular adjustment of the adapter’s placement is very important. This adjustment is made visually with all the tubes, (2) in Figure 9, removed and aligning the hole to an injector hole as good as possible.

The adapter is held in place on the cylinder head by the fastening ring, (3) in Figure 9. The adapter and the fastening ring are made so that they fit each other with a conical track, (4). The fastening ring is fixed to the cylinder head with four M4 screws. With the screws fastened the adapter is fixed to the cylinder head as well, with the screws loose the
adapter can be turned in angular direction and put in an aligned position with the injector holes. The injector itself is placed fix in the cylinder head and cannot be turned. The adapter is made of steel, since the workshop is good working with steel and can build it with good precision. Steel also makes it possible to weld the tubes onto the adapter, however this was found superfluous when the adapter was manufactured.

Drawings of the measurement adapter and the fastening ring can be found in Appendix A.

**Tubes**
The eight steel tubes has one 74° bend each, which is 180° minus the inclination angle of 106° to lead the spray to the test tubes. The tubes have an inner diameter of 8 mm.

The tubes are well fitted into the countersunk holes on the adapter and are easily pressed in position and need no further attachment.

**Modification of cylinder head**
The device is fastened at the bottom of a cylinder head with four M4 screws through the fastening ring. Four tapered holes for the M4 screws are made in the cylinder head. To collect the spray properly the center of the spray need to come in the center of the tube, so that nothing hits the edge or ends up outside the tube. To be able to use the whole diameter of the tube, 2 mm of material from the bottom of the cylinder head is milled away, which gives a correct position for the adapter in the z-direction, relative the injector. The modified cylinder head is shown in Figure 10.

Figure 10. Modified cylinder head
**Fuel system**

Fuel is taken from a rail supplied by a Ganzer pump. The Ganzer pump provides the rail with enough pressure to measure the points that the smoke numbers were measured at. Pressurized fuel is delivered from the pump to the rail. The pressure in the rail is measured with a Trafag pressure sensor. A solenoid valve controls the flow of pressurized fuel from the pump to the rail, maintaining a set pressure value in the rail. The pump uses its own software BSG AP 1.2 and the labs software CRSpray 1.39 to maintain the rail pressure.

The tests are made with standard MK1 diesel, which is the fuel normally used in the spray lab. The fuel is of room temperature when it enters the Ganzer pump. It is supplied to the Ganzer pump with a feeding pump of 2.5 bar.

**Controlling the injector**

The injector is controlled with the software CRSpray 1.39, which allows injection series. Duration, number of injections and time between injections can be regulated with the software.

**Spray rig**

The spray rig uses a cylinder head to hold the injector. The cylinder head is fastened to the rig with two M14 bolts. A glass tube of 140 mm diameter and 300 mm height seals of the volume around the injector, so that no fuel slips out to the surrounding air in the room, see Figure 6. The glass tube also isolates the noise, which is too loud without isolation. The spray rig collects the fuel that has been used, as well as returned fuel from the injector, and the fuel is collected in a bucket and can be returned to the fuel tank after the test.

The bottom of the spray rig is made of glass, enabling photographing of the spray. Photographing is a good insurance that the sprays are collected in a correct way. The risk with this equipment is that a small part of the spray misses the tube, giving uncertainty to the result. A photo confirming that this is not the case is a good base before continuing with the measurements. System test measurements with the equipment later showed that this was not necessary to obtain high precision.

When taking pictures of the spray, the flash light has to be positioned underneath, from where the picture also will be taken from. This is achieved with a mirror, reflecting the flash and the picture. Figure 11 shows a picture taken this way.
Figure 11. Photo of measurement device from spray rig. Note the eight sprays (2) leaving the injector nozzle tip (1), going to the tubes (4). The tubes are held by the adapter (3). Fuel leaves the tubes in gas form (5). The black circle (6) is a joint in the glass lens, and not a part of the measurement equipment.

**Measurement**

**Angular adjustment**

The injector is fixed to the cylinder head while the measurement adapter is adjusted such that the tubes collect the sprays completely. This is done with at least one of the tubes removed, enabling adjustment with visual control of the angle.

When the adapter is placed around the injector the light is affected, leaving the injector nozzle tip obscured. The small holes can therefore be difficult to detect on the black
injector nozzle tip. Therefore good light from underneath is needed to do the angular adjustment. Figure 12 shows the adapter being adjusted.

When the adjustment is done the fastening ring is fastened with its screws, such that the adapter cannot move anymore. Thereafter, the tubes are attached and the system is ready for measurements.

![Angular adjustment of measurement adapter](image)

**Figure 12. Angular adjustment of measurement adapter**

**Collecting fuel**

Fuel is collected in eight test tubes. Plastic hoses are attached at the end of the steel tubes, leading the fuel down to the test tubes, see Figure 13. The hoses are filled with steel wool to further slow the spray down.

The hoses do not slow the sprays down sufficiently. Therefore tests with longer hoses and more steel wool were made. However, too much steel wool appeared to raise the pressure in the hose to much during the injection, preventing fuel from entering it. Hoses of 1 m length were tried but did not improve the situation in any notable way. Too long hoses can not be used in the spray rig while keeping it sealed of. Removing the glass cylinder gives problems with diesel particles in the air and loud noise. To enable work in the lab, hose lengths had to be kept down.
A gap is left between the hose and the test tube, allowing air to leave the tube. Without a gap, pressure rises in the hose, again preventing fuel from entering the hose. The amount of steel wool and the length of the tubes were tested until a solution that generated a minimum of leakage was found.

Figure 13. Hoses attached to the steel tubes, slowing the spray down

Each test tube is marked with its own number (1 to 8). Before every measurement, each tube including its hose is weighed to get its tare. The tare cannot be estimated to be constant for all test tubes, due to differences in weight and in the amount of fuel left in the tubes from previous tests.

**Measurement routines**

The following schedule is made to ensure that all measurements are made under equal conditions. The measurements have to be repeatable to enable conclusions based on the result.

**Test plan**

Tests series will be made for both full load (2.0 ms duration) and half load (1.0 ms duration). The smoke numbers in Figure 14 were measured at those loads.
Figure 14 Smoke numbers earlier measured for the injectors by Scania.

The test contains 500 injections for full load, or 1000 injections for half load. Measurements with long and short duration are made in random order to avoid errors from the setup to interfere with the result. Each test is repeated five times for a good result.

The measurements were at the same rail pressure, 1710 bar for short duration and 2010 bar for long duration. Rail pressure and duration are determined from the smoke measurements shown in Figure 14.

**Before test**

Each measurement is given its own test number, starting with 1, to keep a good order in the results. Injector number, date, duration, number of injections and rail pressure shall also be noted in the test sheet to enable comparison and repeatability.

The test tubes are weighed before the measurement begins. Due to leakage in the measurements the outside of the tubes are cleaned before the weighing. The tare values are noted in the measurement sheet.
The injector is placed in the cylinder head carefully not to damage the nozzle tip. It is fastened with the following four steps.

1. Fasten the injector holder screw with 20 Nm.
2. Fasten the fuel spear nut with 20 Nm.
3. Fasten the injector holder screw with 56 Nm.
4. Fasten the fuel spear nut with 56 Nm.

Removing an injector is done very carefully not to damage it.

The angular adjustment of the adapter is crucial. It is important to do this step well and to be sure that the adapter is well adjusted before the tests proceeds. Good light and a positive lens are needed to visually see the injector holes.

### After test

The test tubes with hoses and content are weighed one by one and their weights are noted in the test sheet. A Sartorius scale, that measures weight with a resolution of 0.01 gram, is used for weight measurements. Fuel mass are calculated and noted for each injector hole in the test sheet. Results from each measurement are normalized with average fuel mass, according to equation (1) and (2), for the measurement and plotted in one diagram showing standard deviation for the test series.

$$X_j = \frac{X_j}{X}$$  \hspace{1cm} (1)

Where $X_j$ is measured fuel (in gram) from injector hole j. $\overline{X}$ is fuel average, according to equation (2).

$$\overline{X} = \frac{1}{8} \sum_{j=1}^{8} X_j$$  \hspace{1cm} (2)

The flow from each injector is measured 5 times for long and short duration respectively. Long and short durations are tested in random order. This gives better certainty about the test result; differences due to errors when the tests are made can be discovered and corrected.

### Tests

**Investigation of experimental errors**

Before the measurements begin the system has to be investigated to that test results can be analyzed correctly. All investigation measurements were made with injector 587 and rail pressure was 1800 bar.

Early during the investigation measurements it became clear that collected fuel quantity from two measurement series could differ. The reason was found to be due to variations
in rail pressure, due to inadequate regulation. Since the rail pressure could not be held constant, the plotted values from the measurements were normalized according to equation (1). This gives comparable results from different measurements.

The first testing of accuracy was to tell if the eight hoses with steel wool collect the fuel with a similar accuracy or if the result depends on which hose that are placed at which injector hole. Three measurement series were made with the hoses in position 0, which means that hose 1 collects the fuel from hole 1, hose 2 from hole 2 and so on. Then three measurement series were made with the tubes in position +1, hose 1 collects fuel from hole 2, hose 2 collects fuel from hole 3 and so on. The tests are summarized in Figure 15 and 13, which show average fuel x (normalized) for each injector hole, an average taken from all the tests, and standard deviation from the tests. Standard deviation is calculated with equation (3).

\[
s = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_j - \bar{x})^2}
\]  

(3)

Where \( x_j \) is fuel mass from hole \( j \) and \( \bar{x} \) is the average fuel mass for hole \( j \) in all tests, equaling \( x \) above and in the plots. The test was repeated \( n \) times.

![Figure 15. Accuracy test. Different hoses effect on result, using injector 587](image-url)
Figure 16. Accuracy test. Different hoses effect on result

Figure 15 and 16 show that fuel flow is similar regardless of which hose that is used. With this secured, hose 1 will measure hole 1 and so on in the following measurements.

Another aspect that could affect the result of the measurement is the angular adjustment of the adapter. If the spray comes inclined to the tube, parts of it could miss the tube or bounce back, which could give wrong results.

Tests are therefore made with the adapter purposely rotated about 5 degrees out of position, which is a large visible displacement, first left and then right to be compared with results from a correctly placed adapter. Results are shown in Figure 17 – 19.
Figure 17. Accuracy test. Adapter rotated to the left

Figure 18. Accuracy test. Adapter rotated to the right
Figure 19. Accuracy test. Adapter in normal position

Figure 20. Affects of angular adjustment, summary of Figure 17-19
The rotated measurements show more extreme values than the normal measurement, according to Figure 20. The difference is notable. The adapter will after this measurement only be adjusted visually with help of good light, which give precision good enough. Photo control of adjustment will not be necessary.

**Source of errors**

The high injection pressure (~ 2000 bar) affects the fuel when it enters atmospheric pressure with high speed. Collecting high pressured fuel in a tube turned out to be difficult to do completely. Smaller amounts of fuel were lost leaking out of the each tube as volatile gas. Hoses and steel wool are used to slow the spray down, minimizing losses, but the losses could not be eliminated completely with this method.

Fuel pressure could not be held constant during the injection. Average pressures were also different from injection to injection. However, this should not affect hole to hole differences.

Injecting high pressurized fuel to air of atmospheric pressure instead of air compressed in a cylinder increases the affect of cavitation on the fuel. Cavitation affects the behavior of the fluid by limiting the mass flow through the nozzle hole at a level that it can not exceed. Cavitation is calculated with equation (4).

\[
CN = \frac{P_f - P_a}{P_a - P_v}
\]  

(4)

With injection pressure \( P_f \), back pressure \( P_a \) and vapour pressure \( P_v \), which is small compared with the other pressures.

With the injector used in an engine, cavitation number will be

\[
CN_{\text{engine}} = \frac{2000 - 100}{100} \approx 12.33
\]

While cavitation number rises when the injector is tested in atmospheric pressure

\[
CN_{\text{sprayrig}} = \frac{2000 - 1}{1} = 1999
\]

Different cavitation behavior is an aspect to be ware of when evaluating these results.
Results

Three different injectors were tested, injector 582, 585, 587. Injector 707 was also tested beside these three, but results from those tests are not plotted, since it is another version of the injector.

Six injectors that had been run in long time engine test were also tested as an extra task. These injectors are called Cyl 1, Cyl 2, Cyl 3, Cyl 4, Cyl 5 and Cyl 6.

Measured data will not be presented in full in this report. This section presents data computed as average values with standard deviation data in plots. Normalization of mass is necessary to get comparable results from the measurements.

Full load

Full load, which means long duration, showed the biggest variation in smoke numbers, according to Figure 13. Figure 21 – 23 show results for the three measured injectors at long duration.

Injector holes 6 and 8 showed two respectively one measurements with less fuel than average, which increased the standard deviation. Injector 582 shows big hole to hole differences, with very big difference between hole 5 and 6.
Injector hole eight for injector 585 showed one measured value higher than the others. Apart from that the values are good together for the repeated measurements.

![Graph showing fuel mass distribution for Injector 587.](image)

**Figure 23.** Injector 587, 2010 bar rail pressure and 2.0 ms duration.

Injector 587 is the injector with lowest smoke number. Injector holes 3 and 7 had one measurement out of five each with lower result than average. This injector shows a more even fuel distribution than the others.

Figure 21 – 23 show that all the injectors have different hole to hole variations.

Figure 24 summarizes the results for the injectors. Fuel mass is taken from an average from five repeated measurements. Injector 587 shows a more even fuel distribution than injector 582 and 585. Injector 585 shows one spray that contains 9 % more fuel than the average spray. Injector 582 has one spray with 6 % more fuel than average, while injector 587 has all eight sprays within 2 % from average.
Differences in fuel distribution from \( n = 8 \) injector holes, where \( y_j \) is measured average fuel in hole \( j \), showed in Figure 25. An ideal injector without hole to hole variations would have all eight values equaling 1. The differences will be shown as standard deviation for the injector according to (5).

\[
s_t = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (y_j - 1)^2}
\]  

Sprays diverging from average give a high standard deviation. The standard deviation should be a good measurement of the total hole to hole difference for the injector. Figure 25 plots the standard deviation and the smoke numbers for long duration.
Figure 25 shows an increasing dependence between fuel distribution variation and smoke number at full load. Bigger hole to hole variations result in a higher smoke number. Full load are the points with highest smoke numbers, making this dependence interesting. More injectors of the same model need to be measured to investigate this dependence further.

Additional full load measurements were made on six injectors that previously had been run in long time engine test. These measurements were made with a different fuel supply system than the previous measurements. Rail pressure was 2100 bar in those measurements, at which pressure the smoke numbers earlier had been measured.

A summary of these measurements are presented in Figure 26 and 27. The new fuel supply system is based on an engine and cannot deliver injections with longer time between injections than 80 ms. Previous measurements were done with 300 ms between each injection. The high injection pressure together with the short time between injections resulted in high temperature in the plastic hoses, which made them expand. The hoses ability to slow the fuel spray down is likely to decrease with expanded tubes, with larger losses as result. This could partly explain the high standard deviation seen in Figure 27.
Figure 26. Hole to hole variation for different injectors.

When testing the last injector, Cyl 6, a fuel leak from the hose measuring injector hole 8 was discovered. This affected the measurement and could also have affected previous measurements that day. Similar problems could have been affecting other hoses.
Figure 27. Smoke numbers and hole to hole standard deviation.

**Half load**

The injectors were also tested for short duration, which is called half load. Smoke numbers were lower for half load, which makes it interesting to see if half load shows a more even fuel distribution. Figure 28 - 30 plots results with standard deviation for the four injectors.

Figure 28. Injector 582, 1710 bar rail pressure and 1.0 ms duration.
At half load, injector 582 had its measured results more collected without any values diverging. Sprays 2, 3 and 5 contain less fuel than average, and sprays 1, 4, 6 and 7 contain more fuel. Especially spray 6 differs a lot from average.

![Graph](image1.png)

**Figure 29. Injector 585, 1710 bar rail pressure and 1.0 ms duration.**

Injector 585 was tested eight times for half load. Injector hole 4 had big differences in fuel quantity between the measurements, giving bigger standard deviation. Injector hole 8 had one measured value lower than average. Hole 4, 5 and 6 are diverging clearly from average, giving an uneven distribution.

![Graph](image2.png)

**Figure 30. Injector 587, 1710 bar rail pressure and 1.0 ms duration.**

As for full load, injector 587 has an even fuel distribution compared with injector 582 and 585.

Figure 31 summarizes the results for injector 582, 585 and 587 at half load. Hole to hole variations are not significantly smaller compared to full load result presented in Figure 24. Values are an average from five measurements.
Figure 31. Hole to hole variation for different injectors.

Figure 32 shows standard deviation for hole to hole differences for half load, according to equation (4). The standard deviation is not smaller compared to the full load case in Figure 25. For half load smoke seems to be at constant level, independent of standard deviation.
Summarizing Figure 25 and 32, big differences in fuel distribution between different injector holes result in a higher smoke number at full load, for the three injectors 582, 585 and 587. Smoke number at half load is more independent of fuel distribution. This could be explained by the amount of air that is available for fuel to mix with. A larger amount of air is used to burn the fuel at full load, and an uneven fuel distribution in the cylinder raises the smoke number under these conditions, since the richest part of the cylinder doesn’t have enough air for a low smoke combustion. At half load, the cylinder has a large air surplus, why combustion can take place without increasing smoke. An injector with an even fuel distribution can therefore be used at higher load without increased problems with smoke.

Fuel distribution variation seem to be independent of duration indicate that the needle lift is not the main problem. A needle preventing fuel from reaching one or more holes in its opening and closing stage would probably give big variations for short duration, since the opening and closing stage are a larger part of where the injection takes place. For long duration, the injection part at opening and closing is smaller compared with the full injection. However, measurements with even shorter duration are needed to determine the needle’s effect on the distribution.

Figure 27 and the test of injector 707 show that other factors than fuel distribution alone probably affects smoke production.
Conclusions

The ten tested injectors all had variations in fuel distribution through the eight injector holes. This is assumed to create zones in the combustion chamber which is locally richer or leaner.

The combustion at half load is assumed to occur without any notable effects of the richer zones since there is no correlation between standard deviation and smoke. The reason for this is assumed to be due to excessive oxygen available for combustion. At full load however, the low lambda is assumed to increase the sensitivity to an uneven distribution.

This occurs for injectors with big differences between the holes, the tested injectors with 4% hole to hole difference in standard deviation had an increased smoke number at full load compared with the injector that had hole to hole difference at 1.5%, which did not show increased smoke compared with half load.

Hole to hole variations can be one of several explanations to high smoke. The six injectors from long time engine tests did not show a correlation between smoke number and hole to hole differences. These however need to be tested further before conclusions can be made due to problems during measurements.

Summarizing the full load tests, the theory of a fuel distribution and smoke production dependence could not be showed to exist for all injectors. Tendencies for this theory to be true were seen for the first tested injectors. The theory could therefore neither be accepted nor rejected.

Variations in fuel distribution are not significantly different for long duration, compared with short duration. This hints that the variations are a result of geometrical differences between the holes, rather than created by errors in the needle lift. A combination of those two and other factors is of course also possible.
**Future work**

It would be interesting to test more injectors to verify the theory. Testing injectors with higher smoke numbers than 0.5 can be done to investigate further distribution – smoke dependence. This work showed dependence between fuel distribution and smoke at full load for injectors with full load smoke numbers between 0.3 and 0.5. Further dependence was not possible to show.

Atomized fuel could not be collected into a test tube completely. Rubber hoses and steel wool were used to slow the fuel down, making it collectable. This could still not be done without small losses. New measurements with better fuel collecting would give more exact measurement data.

The present fuel collecting and weighing system requires a lot of time for placing and weighing before and after each measurement. Improvements to keep time between each measurement down would give better capacity to test more injectors.

Controlling the air flow by recirculating spray air and keeping it as an isolated medium could lower the losses by disabling air pressure to build up in the fuel collecting volume. By increasing the collecting volume, i.e. using larger test tubes or flasks, the pressure increase might be better controlled.

Variation in injection pressure made total injected mass different from test to test. A steadier rail pressure would give better repeatability in the measurements.

Test with shorter injection duration would give more information about the needle’s affect on the distribution.

Parallel with this project, injectors 582, 585, 587 and 707 are also tested in spray impulse measurement by Johan Runesson and tested in an optical engine by Mikael Lindström to investigate their diverging smoke numbers further.
References
Appendix A. Manufactured parts