Sensitivity analysis of instantaneous fuel injection rate determination for detailed Diesel combustion models

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Abstract

This paper will discuss the fundamentals of a detailed injector and injection rate meter simulation model, and their use in a sensitivity analysis of a Bosch rate of injection meter. The Bosch- and Zeuch-methods for instantaneous injection rate measuring are going to be discussed and a practical comparison will be presented.

The injector model is simulating a common rail injector, which will be later used as an input for a detailed Diesel combustion model. The purpose of the injection meter is to validate the injector model.

The influence of geometric parameters showed changes in the calculated instantaneous injection volumetric flow rate, due to the modified pressure waves. These geometric features contain the diameters and length of bench pipes, the size of throttle valve, the positioning of the pressure sensor. From these the best trade off parameter set shall be chosen.

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1 Introduction

Stricter worldwide emission standards put pressure onto the research in combustion development. In Diesel combustion processes injection plays an exceptionally important role, this is why more emphasis was put on injection development for last decades. Many new high pressure systems have been designed and it was realized that not only growing injection pressure can refine combustion, but injection rate shape as well. It has been shown more than two decades ago, that the mass flow versus time curve of an injection has an essential effect on combustion processes and throughout this on the emissions, efficiency and power output of the engine.

This is the reason why now it is so important to know the rate shape as well as the injection pressure when attempting to optimize the combustion. For this purpose two methods have spread on the field of research to accurately measure the injection rate shapes under variable conditions. The first and older was developed by Zeuch and published in 1961 [6]. He invented a relatively small device, on which the tested injectors can be quickly changed, therefore more suitable for larger test numbers. The other was Wilhelm Bosch, who published his work in 1966 [2]. His method became known and used more widely, although this injection meter requires more space.

The purpose of an injection meter set up in this case is not to improve injectors, but to validate an injector simulation model. The model will be used as an input for a predictive detailed Diesel combustion model, so it is essential to make it as accurate as possible in a wide variety of operating points. In order to carry out the validation, a suitable injection meter shall be constructed, this why a sensitivity analysis is performed.

2 Description of measurement methods

The principle of the Bosch method lies on recording the pressure waves during an injection event. The pressure wave is produced by the injector when it injects into a length of compressible fluid, typically diesel fuel. The concept is based on the pressure-velocity equation valid for a single pressure wave in an

instationary flow, which is shown in equation (1).

$$p = c \cdot \rho \cdot u \qquad (1)$$

p = pressure
c = speed of sound in the fluid
ρ = density of fluid
u = flow velocity

If it is combined with the continuity equation, the governing equation of the Bosch method is derived:

$$\frac{dq}{dt} = \frac{A \cdot p}{c \cdot \rho} \qquad (2)$$

q = volume of fuel
t = time
A = cross sectional area of the tube

Equation (2) shows that the volumetric flow rate of the fuel can be calculated from the pressure, speed of sound and the density of the fuel and the cross sectional area of the tube in which the fuel is injected to.

Figure 1 shows the schematic of the Bosch type injection meter. It consists of the examined injector, the injector mount on which the pressure sensor is mounted, the measuring and following tube and an orifice plate separating them. On the end of the whole system a check valve is placed. The injector mount is the most complicated unit of the system, it holds the injector concentric to the measuring tube and contains the pressure sensor. The length and diameter of the measuring tube depends on the size of the examined injector. It shall be long enough to prevent the pressure sensor from noise of the reflected pressure wave. The inner diameter of the tube affects the pressure magnitude created by the injection, while the length determines the attenuation. The size of the adjustable orifice determines the portion of the reflected pressure wave. This can vary depending on the injected amount. It is usually a ball or throttle valve to enable quick adjustments. If the orifice diameter is too large, the majority of the pressure wave will enter the following tube creating a negative wave after reflection. In order to adjust the back pressure of the system, a variable check valve is mounted on the end of the following tube. This is important, because this way typical injection pressure can be used while testing an injector.

The Zeuch-method is also based on pressure measuring. The fuel is injected into a constant volume chamber which makes the chamber pressure rise. The injection rate shape can be determined through the bulk modulus of the fuel:

$$K = V \cdot \frac{dp}{dV} \qquad (3)$$

K = bulk modulus of the fuel
V = chamber volume
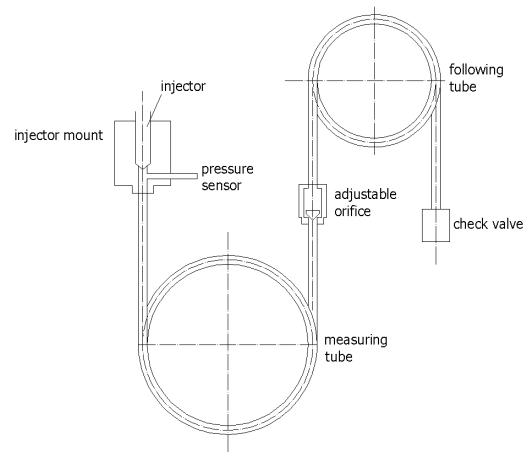p = chamber pressure

Fig. 1. Schematic of the Bosch type of injection rate meter

The bulk modulus here is analogous to the elasticity modulus of metals and exact value shall be measured for the given circumstances. Combining equation (3) with the conservation of mass gives the governing equation of the Zeuch-method:

$$\frac{dm}{dt} = \rho \cdot \frac{V}{K} \cdot \frac{dp}{dt} \qquad (4)$$

m = mass of fuel

This shows that the method determines a mass flow straight from pressure change, but the bulk modulus of the system shall be known. Takamura, et al. constructed a motor driven reciprocating piston system in their injection meter to measure this needed input [5].

The structure of the device is shown in Figure 2. It consists of an injection chamber equipped with a relief and a discharge valve. The chamber also contains the pressure and temperature sensors along with the injector. The relief valve is directly connected to the chamber volume, while the check valve is placed downstream to the relief valve. The relief valve is usually a solenoid type 2/2 valve, which is closed during injection, but immediately opens after the event. When it is opened, the pressure in the measuring chamber is controlled by the preset value of the check valve. Before the next injection the relief valve closes again. The thermocouple is used to monitor chamber temperature (to use the appropriate bulk modulus value); a pressure transducer is used to record the pressure wave.
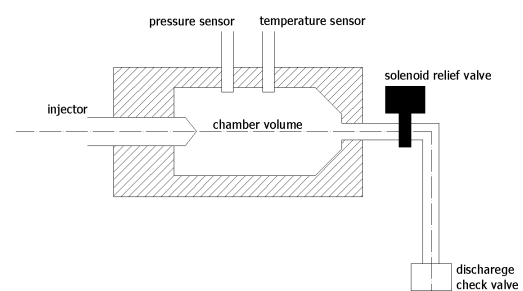

Fig. 2. Schematic of the Zeuch type of injection meter

The chamber volume shall be chosen to suit the typical quantities of the examined injector, the solenoid valve shall be a high speed type (typical response time about 0.6 ms) to meet the required injection frequency during measurement. The shape of the chamber is a cylinder with a conical contraction opposite to the injector. This contraction is needed to eliminate noise from reflected pressure waves; the angle of the cone is depending on the chamber volume.

Summarizing the two different methods it can be stated that the application of Zeuch rate of injection meter is more complicated than the Bosch type. The Zeuch type needs a complicated measuring chamber with a temperature and pressure transducer, a fast response solenoid – the operation of which shall be synchronized to the injection frequency, and the exact bulk modulus of the system (in function of the temperature). On the contrary, the Bosch type of injection meter needs only a simple injector mount with pipes and valves easy to purchase. No additional calculation and measurement is needed, the signal of the pressure transducer is directly proportional to the injection rate shape. Accuracy of both methods is satisfactory, they predict the same magnitude and shape of injection rate as Bower and Foster proved [3].
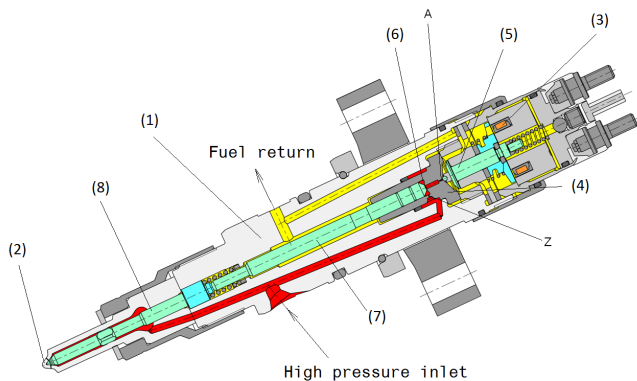

Fig. 3. Cross section of the injector

Because of the above demonstrated advantages and disadvantages, the Bosch type of injection meter was selected to use in this measurement. In order to receive accurate results, the geometric parameters shall be tuned to the meet the parameters of the examined injector. One such possibility is to perform this tuning by simulation, where an accurate meter model should be build up together with a detailed injector model.

3 Description of the simulation models

A detailed Bosch type injection meter model was built up to perform a sensitivity analysis with the geometric features. Although it would be enough to put known injection rate shapes as inputs to the model, a complete injector model was built up, because it will be needed in further simulations. The goal of this work is to set up the base for a future combustion simulation, in which case it is essential to produce a correct injection amount and rate shapes. For this reason a valid injector model

was needed. The injection rate meter is used to validate the simulation model of the injector and further on the combustion simulation. So in this case a sensitivity analysis is done to construct an injection rate meter tuned for the applied injector.

4 The injector model

A Common Rail fuel injector for commercial vehicles was modeled. Figure 3 shows the cross section of the fuel injector and Figure 4 the corresponding inner components of the simulation model.

The injector consists of five main components [1]. The injector body (1) holds together the multi hole nozzle (2) with the solenoid coil assembly (3) and contains the valve body (4). The armature of the solenoid (5) moves together with a ball. The ball is opening and closing the so called A-throttle. The valve body has two orifices (A- and Z-throttles) controlling pressure in the control chamber (6) and a corresponding control piston (7). The control piston is in direct physical connection with the nozzle needle (8).

The injector model follows this construction (see Figure 4). The multi hole nozzle (1) is in connection with the small volume of the sac (2), that is opened and closed by the needle tip (3). The needle (4) is represented by two masses connected with spring and damper parts. This allows longitudinal deformation and damping of the needle body. The control piston (5) has the same structure and its upper end is connected to the control chamber (6). The A- and Z-throttles are represented by orifices bounding the control chamber.

The upper part of the injector was built up in a subassembly, shown in Figure 5.This subassembly contains the solenoid valve with the armature (1), ball (2) and the corresponding springs. The solenoid coil assembly (3) transforms voltage to current, and current to magnetic force acting on the anchor. The fuel coming from the control chamber flows through the ball valve (4) to the low pressure side (5).

All springs, contacts and friction forces were modeled in the injector, the orifices and nozzle holes can handle cavitation. Fuel leakage from the nozzle needle and the control chamber also appear in the simulation. The complete model was implemented in GT-Suite environment [4].

5 The injection meter model

The injection meter model is built up following the structure shown in Figure 1. Fuel is injected into the measuring tube (1), the diameter and length of which is adjustable for the sensitivity analysis. The throttle valve between the measuring and following tubes is represented by an orifice (2); here the diameter can be changed according to the cases. The diameter and length of the following tube (3) is also adjustable, but no check valve was used at the end of it. This check valve is replaced by an infinite volume chamber (4) with a given pressure, so the excited vibration of the spring force operated valve is eliminated.
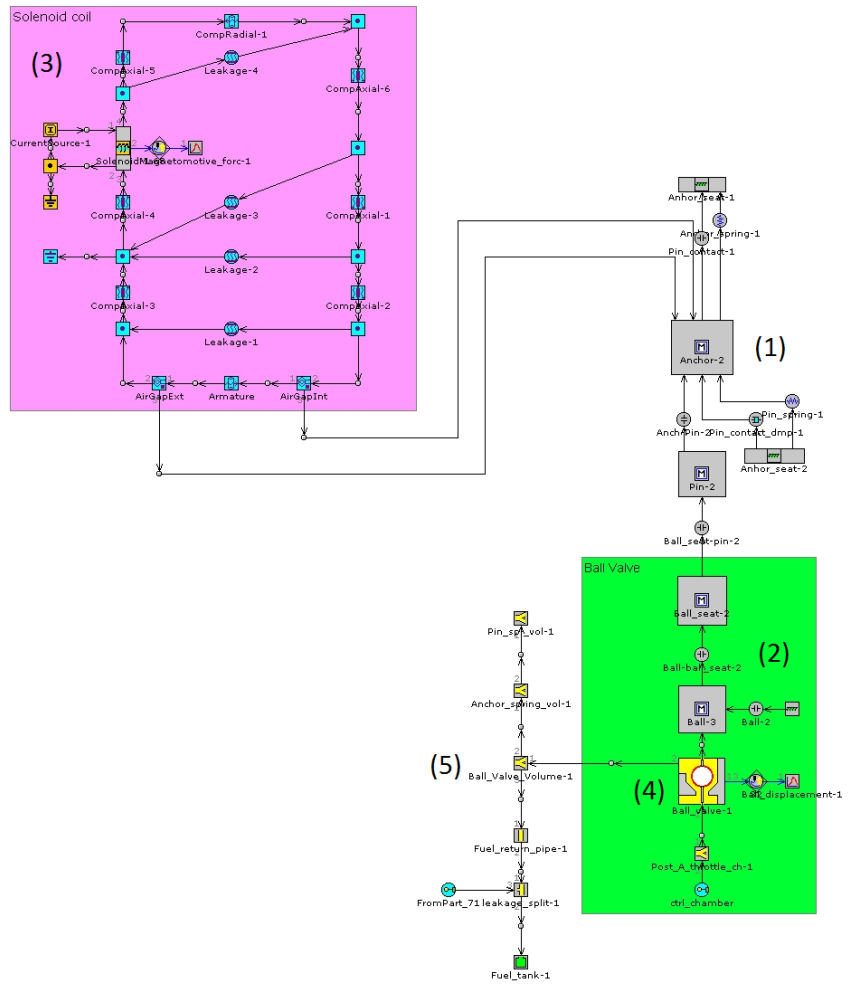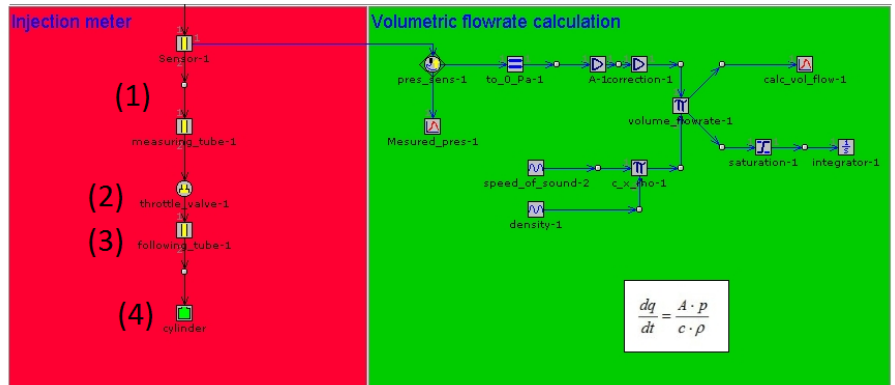
Fig. 4. Injector model

Fig. 5. Solenoid valve model

Fig. 6. Injection meter model

$$\frac{dq}{dt} = \frac{A \cdot p}{c \cdot \rho}$$

Volumetric flow rate calculation is based on Equation 2. A pressure sensor is placed in a distance of 20mm from the injector nozzle to avoid measuring the pressure oscillation caused by cavitation. The sensed pressure is multiplied by the cross section area of the tube which is constant. The actual speed of sound and density values can be taken from a lookup table or either they can be evaluated in the model in the place where the pressure sensor is.

The examined parameters are the diameter and length of the measuring- and following tube, the diameter of the adjustable orifice and the distance of the pressure measuring point from the nozzle holes.

6 Sensitivity analysis

The sensitivity analysis was carried out with a reference injection rate shape, measured by the manufacturer on the same type of injector. This reference was used previously to tune the injector model. The rate shape does not contain pre- or post-injection, only a main injection phase. Maximal instantaneous injection flow rate is 38.4cm^3/s, the injection length is 3.7ms, and the amount of injected fuel is 102mg.

As a starting point a geometric parameter set had to be chosen for the sensitivity analysis, to set up a baseline in simulations. The base parameters are in brackets in the listing below.

The examined parameters were the following:

• pressure sensor distance from injector nozzle (20mm)

• measuring tube length (1500mm)

• measuring tube diameter (7mm)

• throttle valve diameter (1.55mm)

• measuring tube base pressure (50bar)

• following tube length (1000mm)

When examining one parameter, all other parameters were kept constant, except for the measuring tube length; there the throttle valve diameters were tuned for each case. The reason of this was to produce comparable results; without this the rate shapes would not show the real effect of the length change. This also shows that the parameters depend from each other, choosing the best parameter set needs iteration.

7 Effect of pressure sensor distance from injector nozzle

First question is where to measure the pressure wave propagation in the measuring tube. The pressure oscillation and cavitation may influence the measurement near the injector nozzle, this area is to be avoided. As Equation 2 states, the volumetric flow rate is directly proportional to the pressure, therefore where cavitation occurs and pressure drops the calculated rate shapes will follow this process. This is also true at the end of the injection, where flow rate and pressure is decreasing quickly.

Figure 7 shows, that at 10mm distance from the injector nozzle this pressure oscillation stops and has no more effect on the pressure waves and the rate shape.
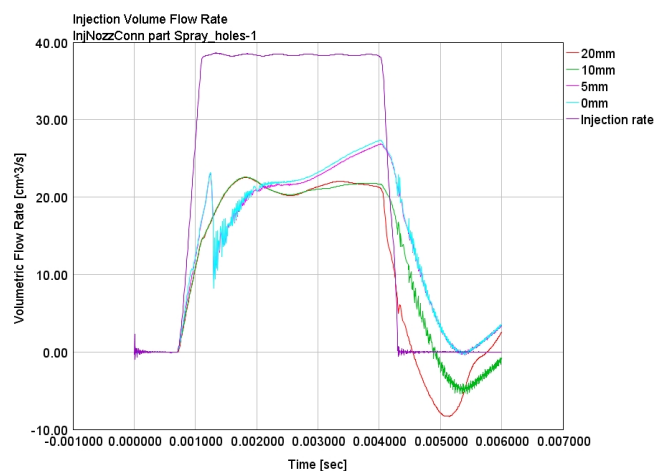

Fig. 7. Effect of pressure sensor distance from injector nozzle

8 Effect of measuring tube length

The measuring tube length is a very important parameter in the parameter set. In practice the realized measuring tubes have a length around 20 meters, but these are usually built to measure injectors for larger Diesel engines, heavy duty and naval purposes. The modeled injector is built into a medium duty commercial vehicle, so probably a shorter tube will be needed.

Tube length fundamentally affects the pressure waves, because it changes the volume of the measuring tube. When the compressible diesel fuel is injected into a larger volume, the pressure rise is smaller because the stiffness of the liquid column is smaller.

With growing length the attenuation is growing as well, so high frequency noise will not affect the measurement, but the calculated flow rates will lag behind the real injection rate, like in an overdamped system. In conclusion if a fast response measurement is needed, a shorter measuring tube shall be chosen but the effect of high frequency noise should not be neglected.

Figure 8 shows that the shortest, 1m long measuring tube gives the closes results to the real flow rate. It is surprising, that even this cannot reach the 38.4 cm3/s flow rate simulated at the injector nozzle, deviation is more than 20%. On the contrary, the 20m long tube cannot reach steady state during this injection event and the maximal calculated injection rate remains around half of the nozzle flow rate.

One possible reason for these deviations is that in this simulation a multi-hole nozzle was used and the validity of Equation 2 was only proven for single hole injector nozzles. In a multi-hole nozzle the fuel is not injected parallel with the injector longitudinal axis, so much energy of the injection can be lost when the fuel jet hits the tube wall.
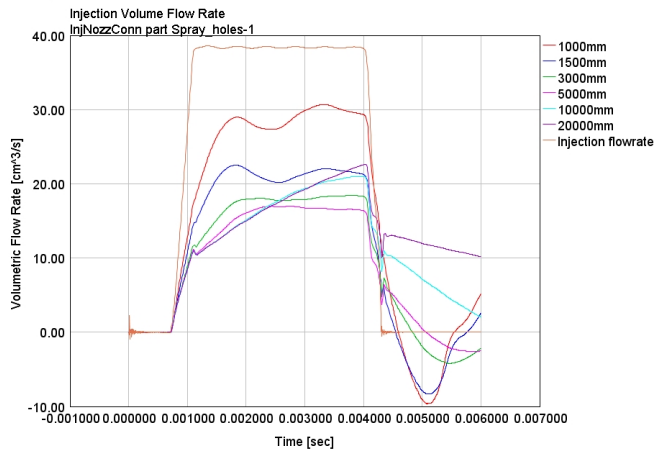
Fig. 8. Effect of measuring tube length on calculated injection rate shapes

9 Effect of measuring tube diameter

The effect of the measuring tube diameter is similar to the length effect when talking about the pressure run. Larger diameters give smaller pressure rises, but the attenuation is not changed. There is a constructional limit in our case, because the nozzle outer diameter is 7mm, so it cannot fit into smaller tubes. Nonetheless a 5mm diameter was simulated to see the effect.
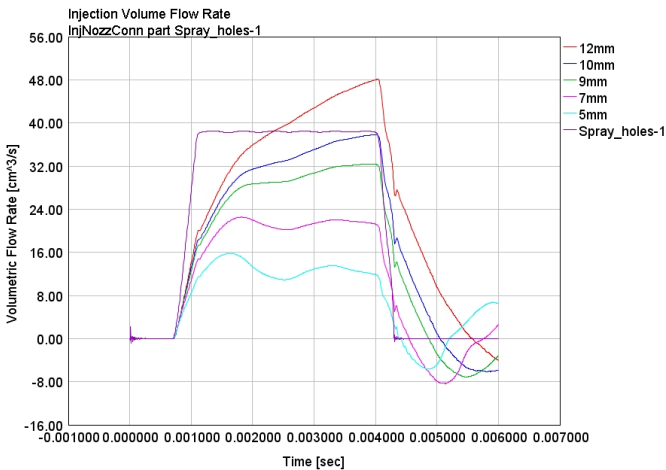

Fig. 9. Effect of measuring tube diameter on calculated injection rate shapes

The calculated rate shapes are shown in Figure 9. The 10mm diameter tube has the closest results to the real injection flow rate. In Equation (2) next to the pressure the cross sectional area of the tube stands, which gives a linear proportionality to the flow rate.

10 Effect of throttle valve diameter

The role of the throttle valve in the system is to control the reflected pressure waves and to adjust the choke. With this element the pressure waves can be shaped. Without this the injected fuel would only push the fluid column in front of it, pressure rise would be small and oscillating. This effect is shown in Figure 10, where the orifice diameter is greater than 1.6mm. Throttle valve diameter shall be changed with different injection shapes and fuel amount, so it should be adjusted in each operating point

during the measurement.

According to Figure 10, for this parameter an orifice diameter between 1.5 and 1.6 mm would be the suitable. At smaller sections, like with 1.2mm diameter the choke is too large.

11 Effect of measuring tube base pressure

Measuring tube base pressure is maintained by a check valve in practice. It has dual purpose: first it ensures that the injection is occurring between the designed pressure levels. In the engine during injection the piston is near firing top dead center, pressure in the combustion chamber is around 50bar in turbocharged Diesel engines. This parameter shall be set up to get satisfactory results.
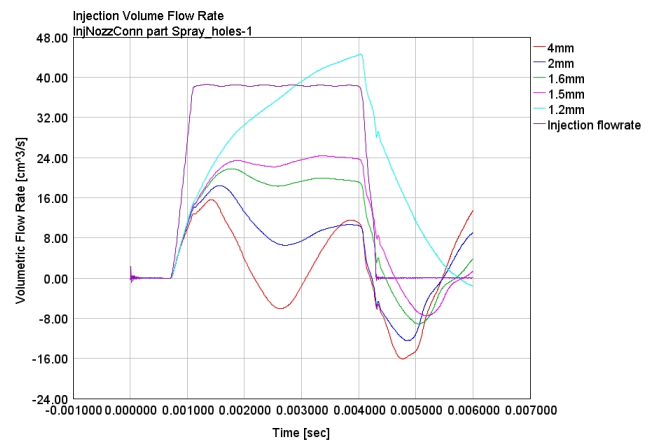

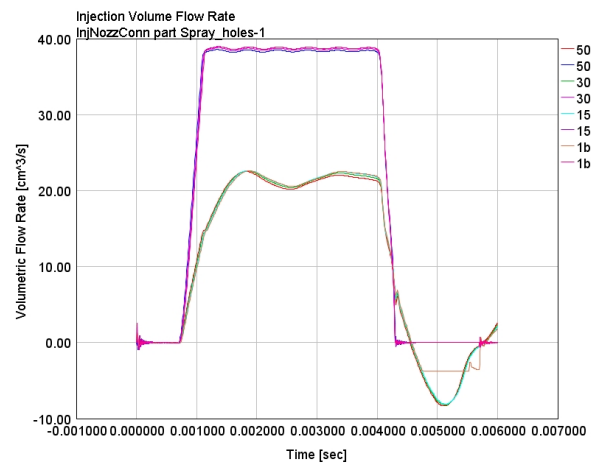**Fig. 10.** Effect of throttle valve diameter on calculated injection rate shapes

Fig. 11. Effect of measuring tube base pressure on calculated injection rate shape

The second reason for this is to avoid cavitation as much as possible. As Figure 7 showed that cavitation occurs around the nozzle at 50bar back pressure, so an analysis had to be done investigating the effect of changing the base pressure.

Observing Figure 11 it can be seen, that changing the pressure level from 1 to 50 bars does not change the results significantly. It can be stated, that back pressure level has practically no effect on injection rate shape.

12 Effect of following tube length

Following tube is needed to increase system attenuation upstream the check valve, because the check valve shall be protected from harmful high frequency pressure oscillations.

Figure 11 shows, that measuring tube length has the same kind of effect in injection rate shape like the measuring tube length, only the scale is smaller. 20 meters would over damp the system, 1 meter gives fast response, but the mentioned high frequency oscillations appear during and after injection.
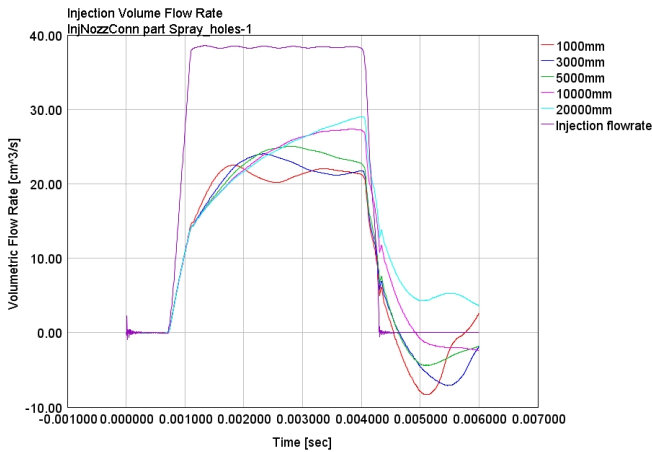

Fig. 12. Effect of following tube length on calculated injection rate shape

13 A different injection rate shape and the calculated volumetric flow rate

After examining an injection amount close to full load in a medium duty Diesel engine, some attention has to be paid on different rate shapes. It would be reasonable to see the opposite end of the load range, namely the idling.

In Figure 13 an idle-like injection can be seen, where the pilot injection is comparable to the main phase. The calculated flow rate follows the real one with the already seen damping, both phases appear in the calculated curve.
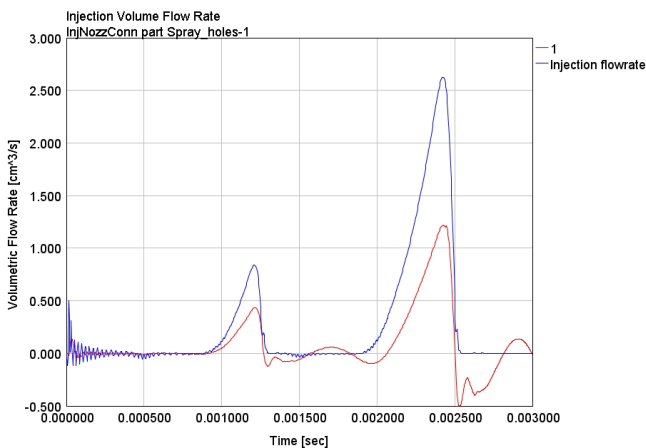

Fig. 13. Injection during idling and the calculated flow rate (1)

14 Best trade off parameter set

Although the simulations were carried out with the geometric parameters listed in chapter 4, the closest calculated injection rate to the nozzle injection shape was given by the following parameter set:

- pressure sensor distance from injector nozzle (20mm)
- measuring tube length (1500mm)
- measuring tube diameter (16mm)
- throttle valve diameter (2mm)
- measuring tube base pressure (50bar)
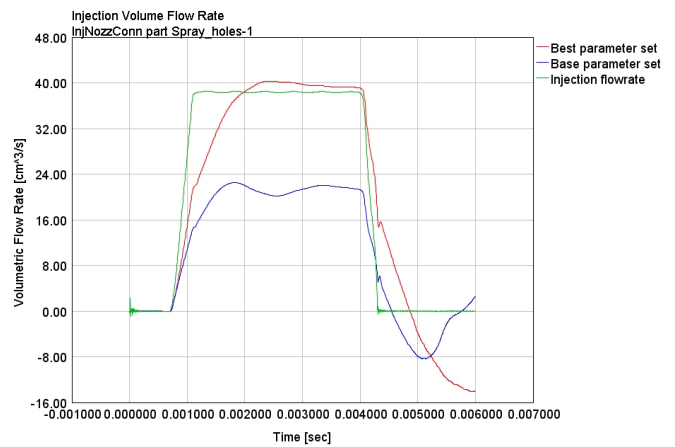- following tube length (1000mm)

Fig. 14. Injection rate shape with the best parameter set

The real injection shape and the results comparing base parameter set with the best comprise can be seen in Figure 14. The highest calculated flow rate is closer to the nozzle flow rate than with the base parameters, the curve fits the nozzle flow better.

15 Conclusion

From the sensitivity analysis the main conclusion is that the injection rate meter does not give back the exact flow rate values, only follows the shape of the injection propagation. This issue shall be the target of further consideration in the future.

Two methods can be taken into consideration in order to validate the injector model. (1) method is based on the best trade off parameter set, the injection flow rate determination would be done directly from the measured volume flow rate shape. With this method the injector model would contain the inaccuracy of the injector meter and the measurement noise.

However the injector model validation can be realized through the simulation model in another way. The idea of (2) method is that the model shall be tuned to fit the measured pres-

sure propagation even if the measured flow rate does not match the real values. If the pressure propagation in the model fits the measured one, the sought flow rate can be specified through the injector model by simulation. It would be a special model-based identification method, where the exact injection rate shape is specified through the simulation model. This way a usable output can be received for the further combustion simulations.

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