Pulsation dampers for combustion engines

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Abstract

Internal combustion engines require improved injection systems in order to meet future requirements regarding emissions. Multiple injections are applied in order to control the combustion in such a way that emissions are reduced. However, the fast openings and closings of injection valves result in pressure pulsations that penetrate through the entire common rail and injectors. The latter influence each other in this way. These pulsations need to be eliminated in order to achieve good control of the combustion processes in engines of automobiles.

The present paper summarizes developments to provide pulsation dampers for Otto engines. Theoretical considerations were carried out in order to provide an insight into the cause of the pulsations and also to understand how the interaction between the pulsations takes place. With this understanding, pulsation dampers were developed based on porous media elements inserted into the supply lines of the injectors.

Theoretically obtained results were used as a basis to produce practical injectors and these were tested for common rail systems with four injectors. The test rig for these measurements is described and the obtained results are summarized.

INTRODUCTION AND AIMS OF WORK

The present paper describes R & D work carried out by the authors to yield pressure pulsation dampers for injection systems for Otto engines. Such dampers are required to damp pressure pulsations resulting from the opening and closing of the injection valves. The faster the opening, the higher the amplitude of the pressure waves that build up inside the injectors of all combustion engines. These pulsations have amplitudes that can correspond to ±30% of the mean injection pressure. One negative effect of the pressure waves is that a good control of the combustion process inside the internal combustion engines is not feasible. Furthermore, the fast pressure fluctuations also have negative effects on the lifetime of all mechanical parts of the injection systems. Hence, their elimination is also necessary with respect to the lifetime of the entire engine.

Within their R & D project, the authors of this paper and their colleagues at FMP Technology GMBH have carried out developments to yield pressure pulsation dampers for fuel injectors employed in Otto and Diesel engines. The outcome of these developments for Otto engines are described in this paper, embracing experimental and theoretical results. The R & D work resulted in a complete theoretical treatment of pressure pulsation dampers employed in fuel injector systems for Otto engines. This treatment is based on component models of fuel injectors as a basis for AMESim simulations. The models for such simulations are described in this paper for:

- Fuel injectors consisting of a common rail, connection pipes to the injectors and the actual injectors, with opening and closing valve
- Fuel injectors with additional pressure dampers. These dampers act like parallel capillary arrays but are made up of inserted porous media elements

In addition to theoretical lay-out considerations, the authors also carried out experimental studies to verify the computed performance of the developed pulsation dampers. Hence, the present paper describes the final work of the authors regarding lay-out considerations of porous media based pulsation dampers.

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NUMERICAL STUDIES OF PRESSURE PULSATION AND DAMPING

The chosen concept of pulsation damping is based on the energy dissipation that occurs in the flow through small capillaries. This concept is already used in some applications, for the damping of pressure pulsations.

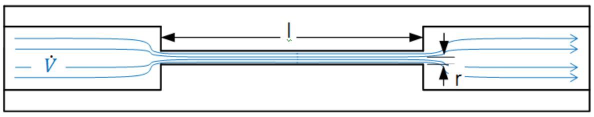

Figure 1: Schematic of the principal mechanism in a single capillary

The volume flow $\dot{V}$ through a capillary of radius r and length l is described by the law of Hagen-Poiseuille[1]. It reads:

$$\dot{V} = \frac{dV}{dt} = \frac{\pi r^4 \Delta p}{8\mu l} \tag{1}$$

Introducing

$$\Delta p = \frac{dp}{dt}\Delta t \quad and \quad \dot{V} = \frac{d\dot{V}}{dt}\Delta t \tag{2}$$

yields the following:

$$\frac{dp}{dt}\Delta t = \frac{8\mu \frac{d\dot{V}}{dt}\Delta t}{\pi r^4} l \tag{3}$$

$\frac{dp}{dt}$ describes the temporal change of the pressure profile. The pressure curve can be described by an average pressure P_m and the amplitude P_A as follows:

$$P = P_m + P_A \sin(2\pi f t) \tag{4}$$

The temporal change of pressure $\frac{dp}{dt}$ can be computed to be:

$$\frac{dp}{dt} = P_A \cos(2\pi f t) \cdot 2\pi f \tag{5}$$

Introducing this expression to the equation (3) above yields:

$$\frac{d\dot{V}}{dt} = \frac{\pi r^4 f P_A}{4\mu l} \cdot \cos(2\pi f t) \tag{6}$$

This relation shows that the pulsation of the volume flow through small diameter capillary and large length is damped. The capillary pressure drop Δp occurring through the use of a larger number N, can be reduced by splitting $\dot{V}$ into N capillaries. The total volume flow $\dot{V}$ is made up of all volume flows $\dot{v}$ through the individual capillaries.

$$\dot{V} = N\dot{v} \tag{7}$$

And hence one obtains

$$\Delta p = \frac{8\mu \dot{v}}{(\pi r^4)} l = \frac{8\mu \dot{V}}{N\pi r^4} l \tag{8}$$

The pressure loss through capillaries can therefore be reduced by a factor N when multiple capillaries are used, i.e. the needed dimensions i.e., length, diameter and the number of capillaries was computed using AMESim simulations as explained below.

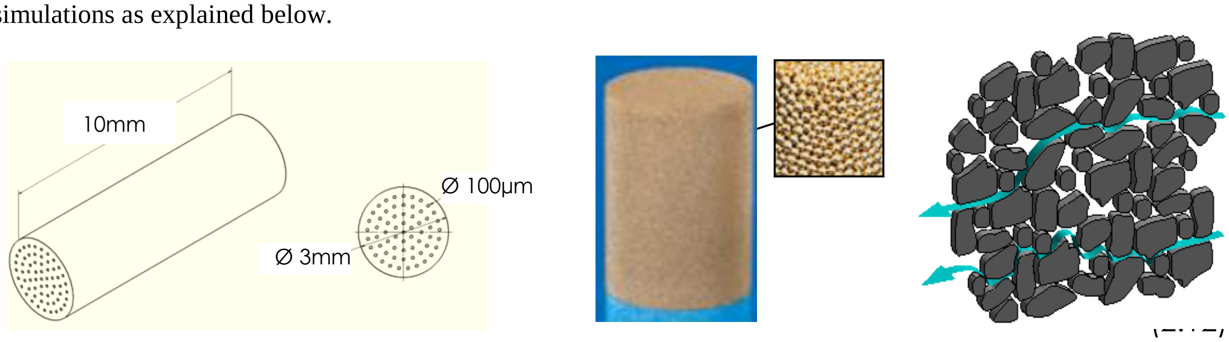

Figure 2: Schematic of standard damping devices for pressure waves

The AMESim – Program and its applications

Fluid flows, i.e. the interaction between elements of flow equipment, can often be understood by one-dimensional computations. If the integral behavior of each flow element is modified in a physically based way to permit one – dimensional simulations, numerical prediction can be performed that can support development work, which otherwise needs to be carried out only experimentally. Injection systems for Otto engines can be developed with such a numerical support. For their prediction, computational programs like AMESim, DSHplus etc. are available. In this work of the authors, AMESim was employed for their computational studies.

AMESim is a simulation software for the modeling and analysis of one – dimensional flows embracing various single elements to model the entire system. The software package AMESim consists of a 1D simulation suite to model and analyze multi-domain, combined systems and to predict their overall performance. Model components are employed in AMESim using validated analytical models that represent the system's actual hydraulic, pneumatic, electric or mechanical behavior. For the work, summarized in this paper, the modeling capabilities of the program for fluid flows were important. To create a simulation model for a system within AMESim, a set of validated libraries was used, containing pre-defined components for different physical flow phenomena. The user can compose within AMESim a physics-based flow system, provided this can be adequately described in a one-dimensional geometry representation. Choosing different library elements, the actual flow system can be modeled and made available for numerical simulation of its behavior for imposed initial conditions.

Modeling of pressure pulsations and their damping

Injectors without pressure pulsation dampers

The injector model employed by the authors to study fuel injection systems with the help of AMESim, was designed with a common rail, a connecting pipe and the actual injector, as can be seen in Figure 3. The actual injector in the model consists of a pipe-like body, followed by an opening and closing valve whose motion is guided by an electronic signal as shown in Figure 3 and a small injector volume to which a nozzle (equivalent to multiple nozzles in real case) is connected. The diameter of the equivalent nozzle has been calculated to maintain the desired flow rate while other components have been dimensioned in accordance with the injection system used for experiments in the laboratory of FMP Technology GMBH. The nozzle, as shown in Figure 3, is open to a space possessing atmospheric conditions. Hence, the entire injector tip setup is at atmospheric pressure while the common rail is loaded at 200 bar pressure initially in the simulation model. During the study of the opening and closing process, the common rail is not supplied with fuel through a pump.

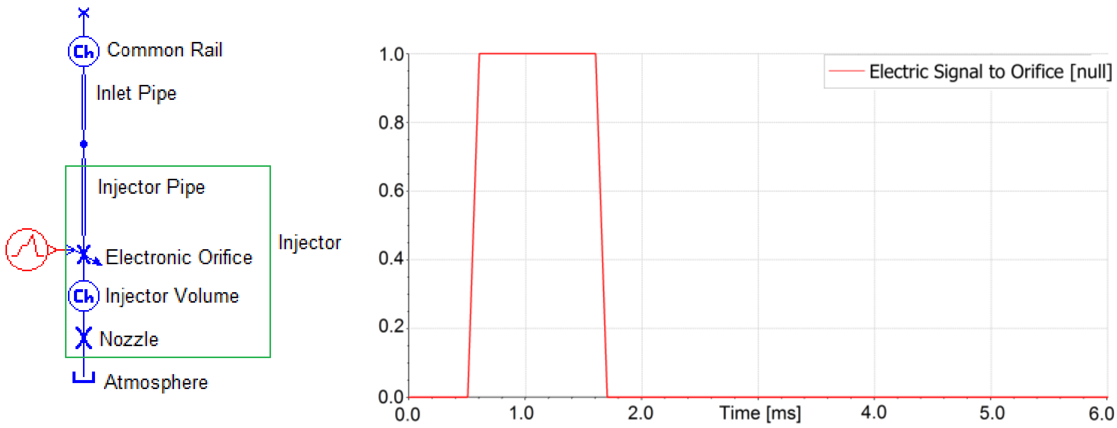

Figure 3: AMESim injector model and corresponding input signal to the orifice which controls its opening and closing

When the AMESim injector model shown in Figure 3 is activated by the opening and closing signals, shown in Figure 3, for the orifice, pressure pulsations as shown in Figure 4 are set up in the injection system. The drop in the mean pressure value in the common rail before and after the injection is due to the injected fuel. As mentioned, the computations with AMESim predict pressure pulsations occurring in the injector and a damped pressure wave is set up in the injection system. Due to the low damping amplitude of the pressure wave, the injection process is uncontrolled which also decreases the lifetime of the injector components.

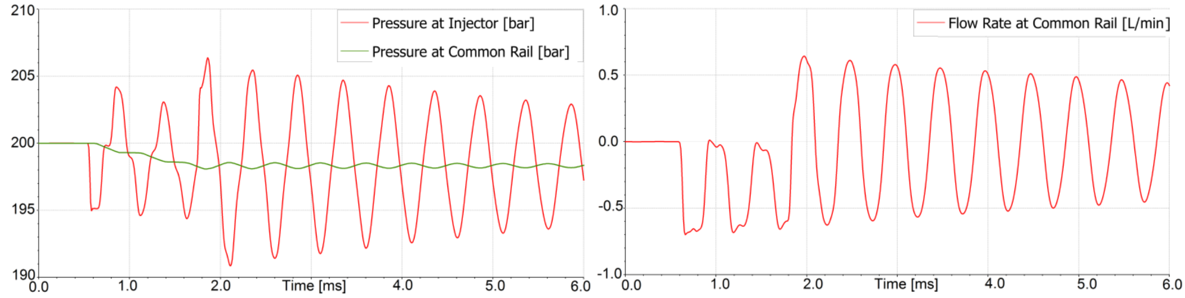

Figure 4: Pressure variation in the injector and common rail (left) and the corresponding flow rate variation in the common rail (right)

Figure 4 shows that the fluctuations in the flow rate out of the common rail have a high amplitude and a low damping rate. These flow rate fluctuations, created in the common rail, interfere with the flow rate fluctuations created by the injections by adjacent injectors. The above described process for a single injection also occurs during multiple injections. As a result, a stationary wave sets up in the entire injection system. This stationary wave of flow rate fluctuation interferes with the injection process of each injector thus making the overall process uneven and results in a failure to inject the desired amount of fuel into the combustion chamber of the system. This, as explained above, results in uneven combustion and thus decreases the overall efficiency of the combustion process and results in the increase of unwanted emissions.

The authors of this paper based their analysis on pressure waves and aimed at damping them because they cause the flow rate fluctuations. Damping the pressure wave pulsations is understood to damp the flow rate fluctuations. Also, an analysis of pressure wave variations in the system using AMESim is helpful, as they can be readily compared with the experimental results. Hence, the analysis in this paper primarily deals with pressure wave pulsations and their damping, although the flow rate fluctuations were the major problem and they were analyzed in all parts of the authors' studies.

Injectors with pressure pulsation dampers

It has been identified experimentally that the introduction of elements of porous media in the injection system can damp the pressure pulsations that are produced during the opening and closing of the injector valve. To simulate the influence of porous media elements in AMESim, a program was set up and employed in which the porous media was treated as a set of capillaries put together in parallel. As all the capillaries, whose number could be as high as 5000, cannot all be taken into consideration in the simulations with AMESim, due to computational time limitations, a scaling theory has been developed to scale down the entire model and in this way, to work with a single capillary. The results computed in this way can then be scaled up to find the appropriate dimensions for porous media elements for the injection system. This is the familiar bottom to top approach often chosen in numerical treatments of flow phenomena of this type. Figure 5 shows the introduction of capillaries into a model of the injection system.

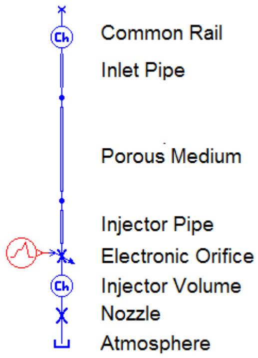

Figure 5: AMESim Capillary - Injector Model

As mentioned above, a scaling down strategy has been developed to scale down the dimensions of the components to represent them equivalently in AMESim in a way that only a single capillary can be used to represent the porous media. In other words, since the original scale components operate for a number of capillaries; their dimensional values are scaled down in such a way that the fraction of the component acting for a single capillary in the original case is equivalent to those represented in AMESim. For computations, the equivalent diameter and number of capillaries in a porous media can be calculated as follows [2]:

$$d_c = \frac{0.23 \cdot \epsilon \cdot d_p}{1 - \epsilon} \quad (9)$$

ε = Porosity

d_c = Equivalent capillary diameter

d_p = Particle diameter of porous media

$$N = \epsilon \cdot \left(\frac{D_p}{d_c}\right)^2 \quad (10)$$

D_p = Diameter of porous media

To verify the above scaling theory, two models have been developed in AMESim. Assuming that the full scale model contains 5 capillaries as shown in Figure 6, it has been scaled down to one capillary using the derived scaling matrix. Extensive computations were performed yielding the results shown in Figure 6 as one example.

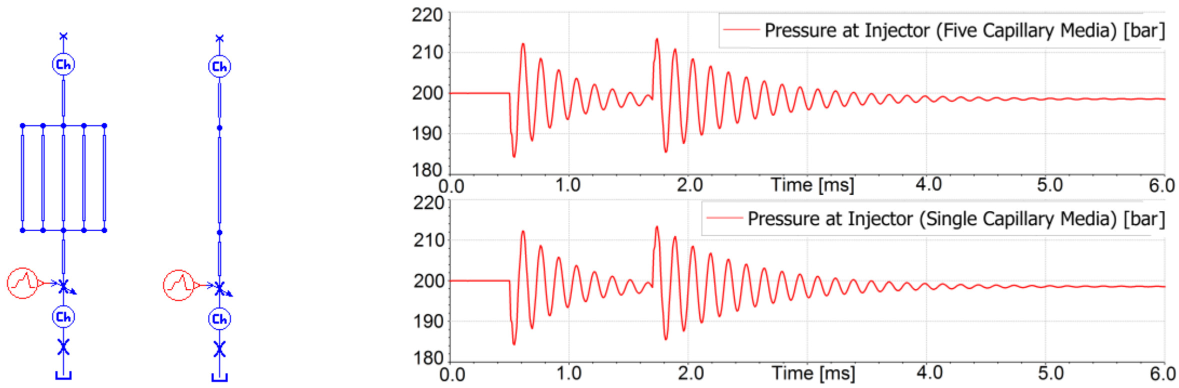

Figure 6: Left: Five capillary model; Middle: Single capillary model; Right: Comparison of pressure variation in the injector for both scaled models

As it can be observed from Figure 6, the pressure variation in the system, due to the opening and closing of the injector orifice, is the same in both cases when the dimensions of the components in AMESim are calculated using the developed scaling strategy. Thus, by using the developed scaling strategy, the original model can be scaled down to have a single capillary in AMESim and the results predicted by using this model will be the same when any number of capillaries are combined to form a porous medium and integrated into the injector system.

Theoretical results and their implications

After a series of systematic simulations, it has been observed that the pressure pulsations were damped well with a capillary diameter of 22µm and corresponding number of capillaries as 13250. The corresponding properties of the porous media are calculated using eqn. 9 and eqn. 10. From Figure 7, it can be seen that the pressure pulsations are damped and hence, due to the absence of high frequency pulsations, the lifetime of the system components increases. From Figure 7, it can be seen that the fuel flow rate has no fluctuations in the common rail and thus, the overall injection process is smooth when a desired amount of fuel is injected into the combustion chamber.

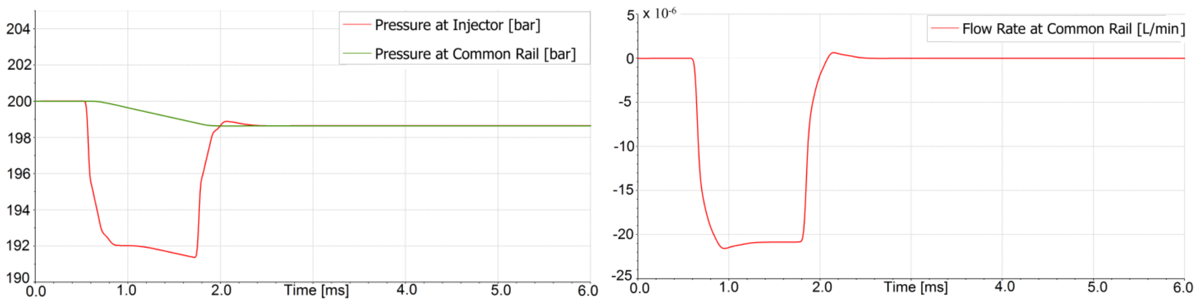

Figure 7: Pressure variation in the injector and common rail and the corresponding flow rate variation in the common rail

Multiple fuel injection system

A full model of the injection system with and without porous media, as shown in Figure 8, has been designed in AMESim to study the influence of multiple injections in a common rail system.

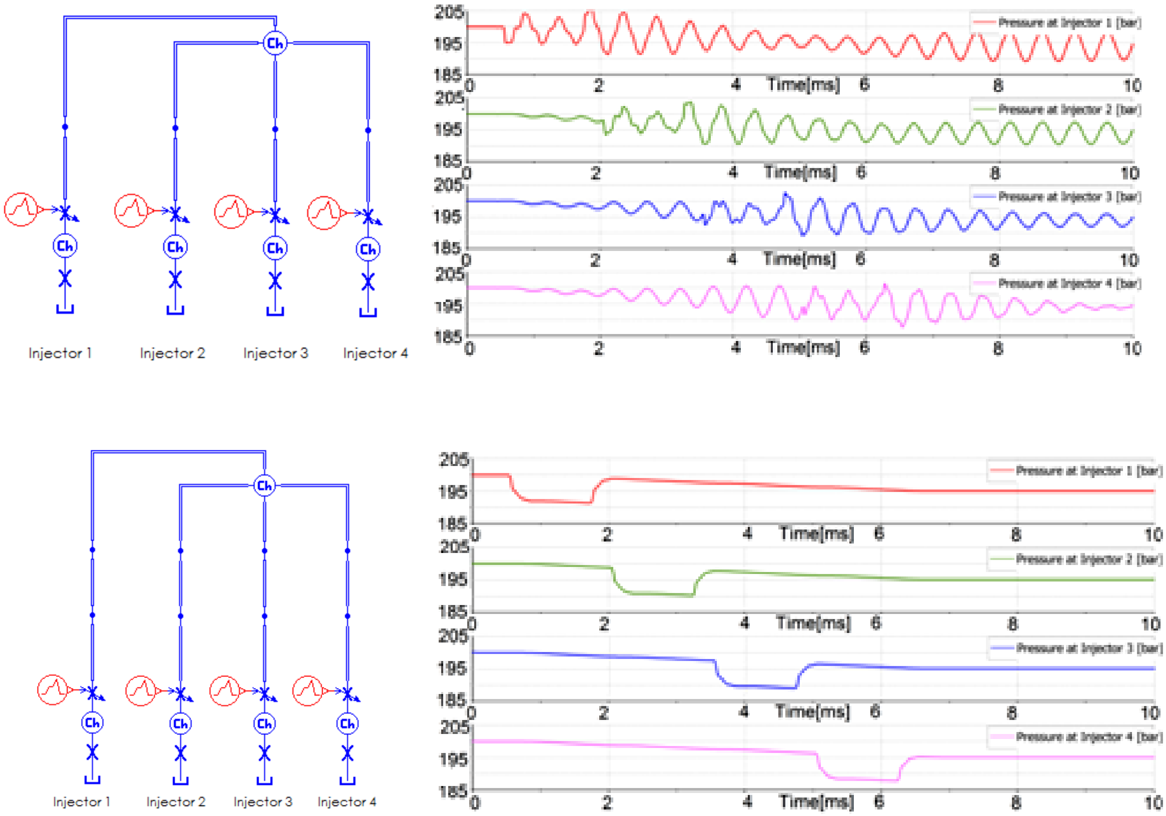

Figure 8: Pressure variation in the injectors for multiple injections: Top: Injection system without porous media; Bottom: Injection system with porous media

As it can be observed from the above figures, the pressure variation due to an injection is smooth and without fluctuations in the injection system with dampers when compared with the system without dampers. By damping the pressure pulsations, it is thus possible to inject the desired amount of fuel uniformly into the combustion chamber during the injection process, which results in increased efficiency of the combustion process. Also, as mentioned, damping of the high amplitude of pressure pulsations increases the lifetime of the components in the system.

Double porous media model

In extension of the theoretical simulation work to build pressure pulsation dampers using porous media, the authors learned from the work of Zeiser[3] that a porous medium acts as a bunch of capillaries whose diameters vary by a factor of 10 from the calculated equivalent capillary diameter using relation (10). Hence, the porous medium designed with equivalent capillary diameter of 25µm in AMESim also contains channels with equivalent diameter in the range of 2.5µm to 250µm, although these extremes occur in small numbers. Thus, when a porous medium is manufactured using the predetermined specifications; it also contains channels with large diameters which allow pressure pulsations to pass un-damped through them. Hence, when a single porous medium is used, pressure pulsations which pass un-damped through these large diameter channels result in poor damping characteristics of the designed damper element. To overcome this shortcoming of a single porous medium damper, the authors designed a damper element with two porous elements and a defined volume between them. It is expected that when a double porous medium damper is used, pressure pulsations which pass un-damped through the large diameter channels in the first porous medium will likely encounter channels with smaller diameter in the second porous medium thus resulting in an overall damping of the pressure pulsations by the exit of the damper element. To illustrate the above, simulations have been carried out in AMESim and are reported below.

Simulations have been carried out with double porous media type damper elements but with different capillary diameters within each model. Figure 9 shows the AMESim model of a double porous media but with different capillary diameters. The model has been scaled down using scaling theory and the three equivalent capillaries shown in the model have diameters of 20µm, 40µm and 80µm and a connecting pipe, equivalent to a small volume between them. Figure 9 also shows the pressure variation in the system which is observed to be an interference of pressure patterns which are produced by each of these capillaries individually. It can be observed that the pressure pattern differs from the case in Figure 7, as expected, because of the presence of the larger channels.

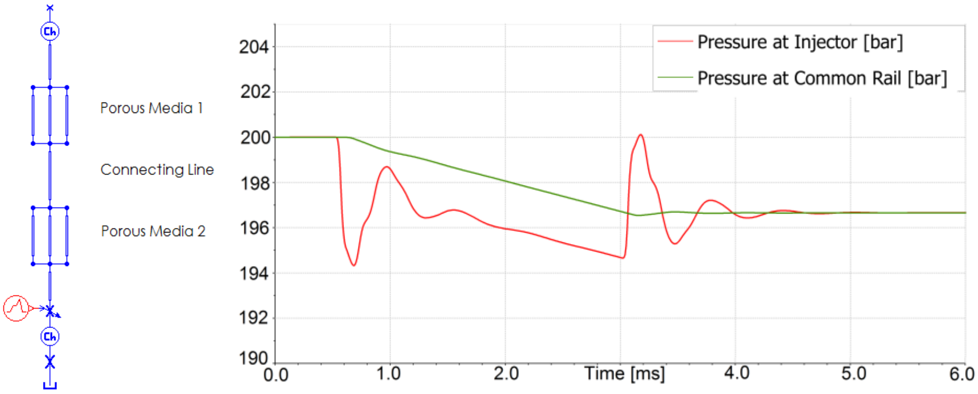

Figure 9: AMESim damper model with different capillary diameters and corresponding pressure variation in the system

Due to the presence of more channels with smaller capillary diameter, the designed double porous media type damper is expected to damp the pressure pulsations completely. Also, it has been observed that the volume between the porous media in the double damper model does not have a significant impact on the damping characteristics of the damper beyond a certain value and hence has been chosen as 1ccm for the present model.

EXPERIMETNAL INVESTIGATIONS

To validate the results of the theoretical analysis and to study the practical applicability of the designed pressure pulsation dampers, a fuel injection test-rig was built at FMP Technology GMBH. A series of experiments were carried out to study the pressure pulsations in the injector and the common rail with and without damper.

The test-rig was built with a pressure source, a fuel reservoir, a common rail and four fuel injectors as shown in Figure 10. Pressure sensors have been mounted on the injectors and the common rail as shown in the schematic. These sensors were connected to the data acquisition system to conduct further data analysis of the obtained pressure data. The set up was operated at 200 bar pressure using water as fluid in the injection system.

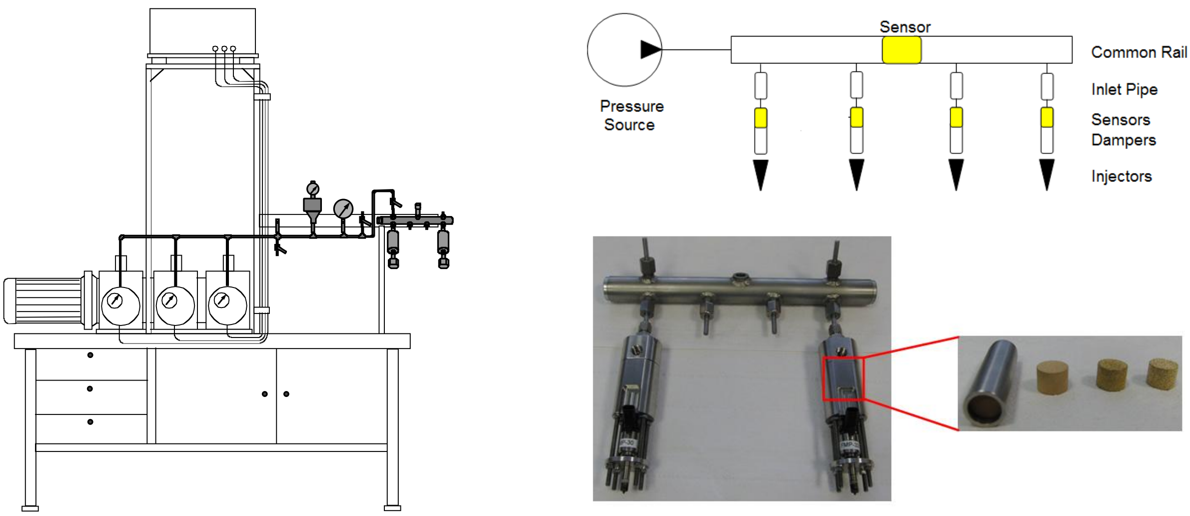

Figure 10: Fuel injection test-rig at FMP Technology GMBH and the corresponding schematic

To verify the simulation results predicted by AMESim, the test-rig has been initially run without the damper elements in the injection system. The system was initially loaded with water at 200bar. The active injector was given an electronic signal to inject fluid in intervals of 1.0ms, 3.5ms and 1.0ms consecutively. The inactive injector received no signal for injection during the test phase. Pressure sensors, as shown in Figure 10, are arranged to detect the pressure variation in the system. As it can be noticed from Figure 11, pressure fluctuations created in the active injector during the injection are carried along the common rail into the inactive injector. It can also be noticed that the pressure pulsations set up in the active injector and common rail have large amplitude and are similar to that predicted with AMESim. As discussed, these pressure pulsations with high amplitude and low damping coefficient interfere with the continuous injection process and result in uncontrolled fuel injection into the combustion chamber, thus lowering the overall efficiency of the combustion process.

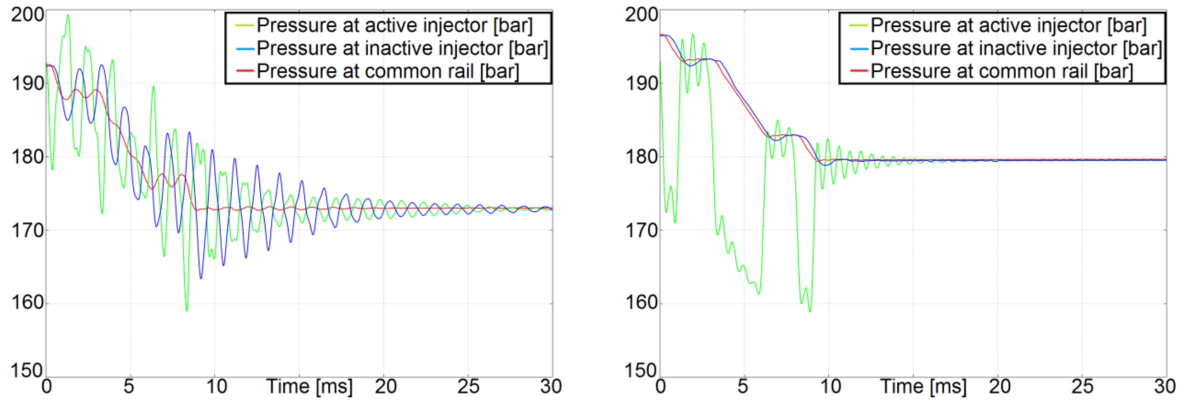

Figure 11: Pressure variation in the injection system without damper(left) and with damper (right)

Initial configuration of the test setup is maintained similar to that of the experimental setup without damper. Similar electric signal is given to the active injector for fluid injection while the inactive injector does not receive any electric signal during the test run. The only difference is that now damper elements were inserted in the inlet pipe between common-rail and connected injectors. Figure 11 shows the pressure variation in the injection system fitted with the dampers. As it can be noticed, the pressure waves are damped quickly within the active injector and are also not carried into the common rail or the inactive injector. This damping behavior of the inserted dampers not only ensure uniform injection of the fuel into the combustion chamber but also ensure that the pressure waves are damped quickly so that they are not carried to adjacent injectors and interfere in their injection process

CONCLUSIONS, FINAL RESULTS AND OUTLOOK

In this present work of the authors on pressure pulsation dampers for fuel injection systems, results of AMESim simulations and corresponding analytical work has been presented with the necessary theory and explanations. Modeling of the injection system in AMESim, based on a real injection system, has been outlined. Porous media were treated as a bundle of capillaries and a formula for finding the equivalent dimensions of capillaries based on porous media parameters has been stated A scaling method has been developed to scale down the entire injection system in AMESim to reduce computational time. The equivalence of the scaled down model to the original model has also been proven and stated in the paper. It has been observed that the porous media can be effectively used, with suitable dimensions, for a given injection system to damp the pressure pulsations. The authors also investigated single and double porous media characteristics to suggest the better damping model, taking into account the practical behavior of the porous media.

A test-rig has then been built to validate and verify the behavior of designed pressure pulsation dampers. Experiments have been carried out with and without damper elements in the fuel injection system to compare and analyze the predictions by AMESim and also study the behavior of the damper elements. It has been observed that the designed pressure pulsation dampers can be used successfully in the fuel injection systems to damp the pressure pulsations created in the system during fuel injection. With the present work, the authors have successfully designed pressure pulsation dampers for the fuel injection system which ensure controlled fuel injection into the combustion chamber and thus result in an increase in the overall efficiency of the combustion process besides increasing the lifetime of the system components.

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