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Comparing the performance of the common rail fuel injection system with the traditional injection system using computer aided modelling and simulation

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1.ABSTRACT

In this paper, models of a traditional cam-driven plunger diesel injection system and a common rail injection system are presented. The models are developed using bond graphs, a modelling tool that for many years has shown its excellence in modelling systems consisting of sub-models from several energy domains in a unified approach.Through simulations, the performance of the common rail fuel injection system and the traditional injection system will be analysed and discussed. Of particular interest is the pressure differential over the nozzle bores.

2.INTRODUCTION

Traditional fuel injection systems for diesel engines are designed with the objective to secure acceptable fuel spray characteristics during the combustion process at all load conditions. Incorrect injection causes reduced efficiency andincreased emission of harmful species. In the later years, the common rail injection system with electronic controls hasbeen promoted as the future standard in fuel injection systems for diesel engines. Among the advantages claimed with
respect to the common rail concept are injection rate shaping, variable timing and duration of the injection, in addition tovariable injection pressure, enabling high injection pressure even at low engine loads. Medium speed diesel engines are different from the automotive diesel engines, especially in that the majority of them
operate at constant load and speed most of the time, and the advantages of the more complicated common rail system may not be justified. The common rail injection system is not capable of supplying all possible rate shapes, and rate shaping is mostly restricted to delivering a pre injection prior to the main injection. The major benefits from the common rail injection
system on medium speed diesel engines are thus the individual adjustment of the timing and duration of the injection for each cylinder. The rate of energy conversion in the cylinder, commonly called the rate of heat release, is closely related to the rate of injection. When the rate of injection is the key to an effective combustion process, it is vital to determine how the rate of
injection from the common rail system compares to the rate of injection from a traditional injection system. The characteristics of these injection systems will be discussed in this paper, using computer aided modelling and simulation. Today's fuel injection systems consist of components from several energy domains working together in a highly dynamic

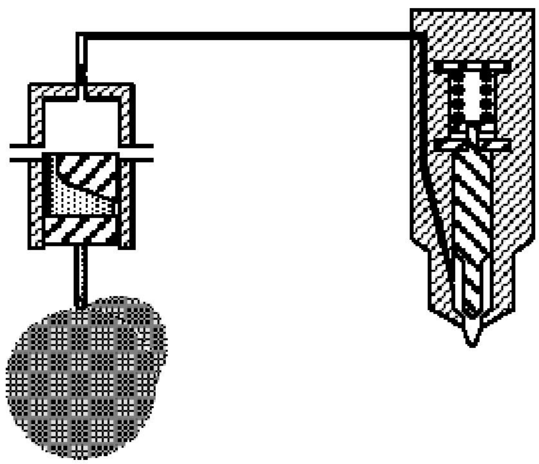

Figure 1 Traditional cam-driven fuel injection

system. The bond graph modelling approach 1has for many years shown its excellence in representing multi-domainsystems. By using bond graphs and matching software for modellingand simulation, it will be shown how this can be a powerful tool for engineers when evaluating the performance of physical systems. Converting a bond graph model into a set of first order differential equations is a straightforward systematic process that can easily be computerised. The models presented in this paper are developed in the modelling tool MS12, generating simulation code for ACSL3(Advanced Continuous Simulation Language).

3.OVERVIEW

The diesel fuel injection system consists of an injection pump, delivery pipes and fuel injector nozzles. Several different types of injection pumps and nozzles are used. In this paper only the traditional cam driven mechanical injection system
and the common rail system is discussed. The task of the fuel injection system is to meter the appropriate quantity of fuel for the given engine speed and load to each
cylinder, each cycle. Further, the injection system should inject that fuel at the appropriate time in the cycle at the desired rate with the spray configuration required for the particular combustion chamber employed. It is important that the injection begins and ends cleanly, avoiding any secondary injections. The fuel is introduced to into the cylinder of a diesel engine trough a nozzle with a large pressure differential across the nozzle orifice. This large pressure differential is required so that the injected liquid fuel jet will enter the chamber at sufficiently high velocity to atomise into small-sized droplets to enable rapid evaporation. The plume should traverse the combustion chamber in the time available and fully utilise the air charge.

Thus, the fuel injection process controls only four basic functions:
1. *Timing and duration of injection*
2. *Injection rate shape*
3 *Injection quantity*
4. *Spray quality*

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An auxiliary cam on the engine camshaft drives a single-cylinder injection pump. Early in the stroke of the plunger, the inlet port is closed and the fuel trapped above the plunger is forced through a check valve into the injection line. The injection nozzle has several holes through which the fuel sprays into the cylinder. A spring-loaded injection needle keeps the injection valve closed until the pressure in the injector volume, acting on parts of the
needle surface, overcomes the spring force and opens the valve. Thus, the phase of the pump camshaft relative to the engine crankshaft controls the start of injection, while the force given by the initial displacement of the spring gives the opening pressure. Injection is stopped when the inlet port of the pump is uncovered by a helical groove in the pump plunger, and the high pressure above the plunger and in the injector volume is released. The injection pump cam design and the position of the helical groove determinethe amount of fuel injected into the cylinder. Thus for a given cam design,the rotating plunger and its helical groove controls the load.

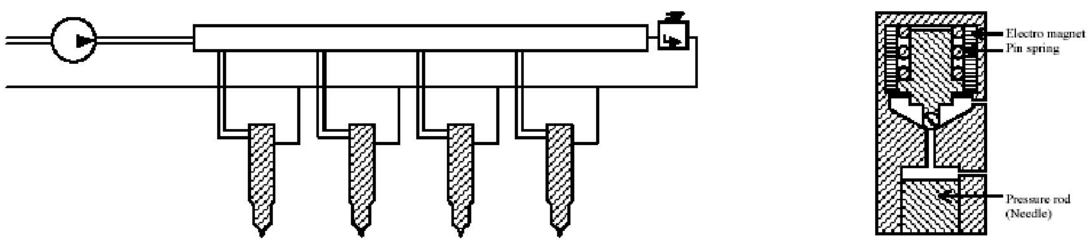

Figure 2 Common rail fuel injection sistem

Contrary to the traditional injection system, pressure generation and injection are decoupled in the common rail system. The injection pressure can even be generated independently of engine revs and the injected fuel quantity can be freely
selected within limits. A prerequisite for this decoupling of pressure generation and injection in common rail systems is the high-pressure accumulator, which consists of the rail and the high pressure fuel lines to the nozzles. The key component of
the system is the solenoid valve controlled injector. In order to control the opening and closing time of the needle, a small chamber of pressurised fuel is present at the top of the needle. This volume is connected to the rail through a small orifice that assures that same pressure between the nozzle and the chamber when the valve is closed. At the same time, a small
solenoid balance valve is in operation in this area that can open at an accurately specified time, thus creating a pressure drop. This will result in a negative net force on the valve needle, and the injection is initiated. As soon as the solenoidcloses, the pressure in this chamber will increase again resulting in the closure of the needle. Shaping the injection rate, obtaining pilot injection and multiple injections are done by controlling the nozzle needle movement
Fuel injection and combustion

The direct ignition combustion process can be divided into four phases:
1. Ignition delay: The time between start of injection *and start of combustion*
2. Premixed combustion phase: Combustion of the fuel that has mixed with air within the flammability limits during the ignition delay
3. Mixing controlled combustion phase: Combustion of fuel at a rate which mixture becomes available for burning
4. The late combustion phase: Combustion of the final amounts of fuel, soot and other fuel rich areas

It is desirable to have the shortest possible ignition delay and to minimise the amount of fuel injected during this time, and thereby limit the rapid energy release in the premixed combustion phase. Obviously, it is also important to limit the energy release in the late combustion phase, meaning that as much as possible of the energy release should be mixing controlled. Several processes controls the mixing controlled combustion phase:

- *Liquid fuel atomisation*
- *Vaporisation*
- *Mixing of fuel vapour and air*
- *Pre-flame chemical reactions*

The vapour-air mixing process is primarily controlling combustion in this phase. The authors believe that in a more "ideal process", the pressure in the sac volume should rise very distinct to a sufficient high level during start of injection to secure good atomisation and rapid mixing between fuel and air. This results in a short ignition delay and equally short premixed combustion phase. The initial pressure should be limited in order to reduce the premixed heatrelease and thereby avoiding unnecessary large pressure gradients and local temperature peaks. During the mixing controlled combustion phase, the rate of injection should be progressive in order to maintain the cylinder pressure as the cylinder volume is increasing and less oxygen is available for combustion. The closing of the injection valve should also be distinct to minimise the period with decreasing pressure, thereby reducing the amount of fuel injected with reduced penetration.

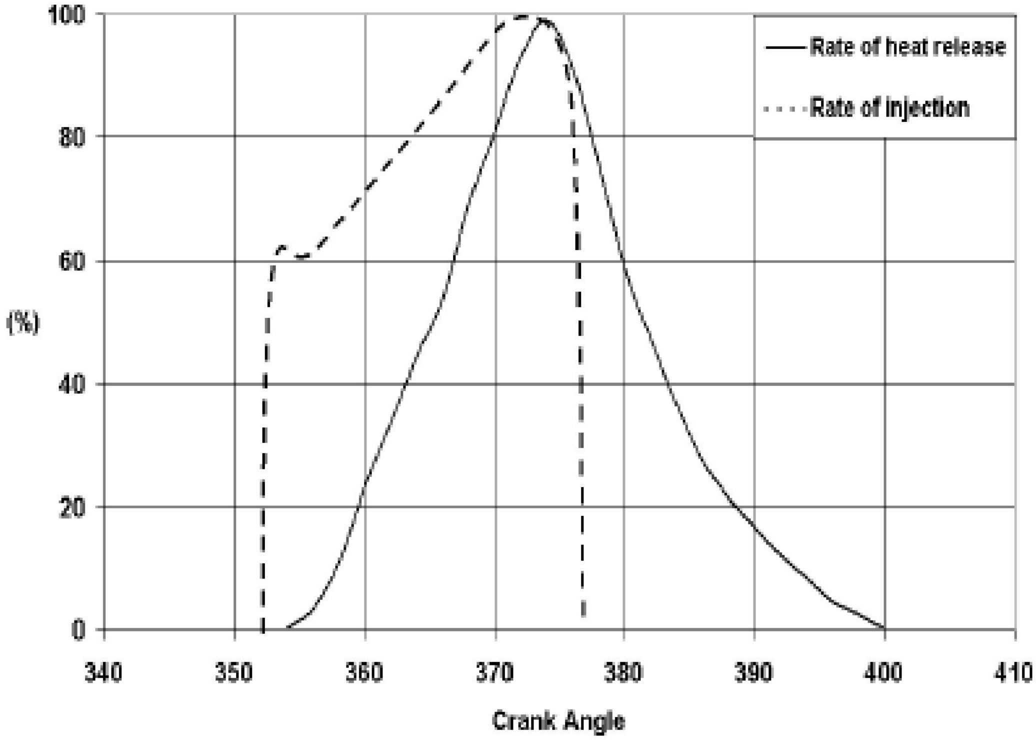

Figure 3 Ideal injection rate and rate of heat release

4.MODELLING

From a modellers point of view, fuel injection systems consist of more or less the same components, enabling the modeller to use and re-use basic sub models. This re-usability of models is crucial in an effective modelling environment. We will now present the sub-models required for assembling overall models for both the traditional injection system 4
and thecommon rail injection system. Nozzles Hydraulic nozzle flow is modelled using the general equation:The nozzle is modelled as a resistor (R-element). Input to this model is upstream and downstream pressure, while the output is flow rate.

$$Q = C_f \cdot A \cdot \sqrt{\frac{2}{\rho} \cdot (p_u - p_d)}$$

Hydraulic flexibility of volumes Hydraulic flexibility must be included in a model where high frequency dynamic behaviour is to be studied. The hydraulic flexibility is given by the bulk modulus of the fluid at constant temperature, defined as

$$\beta = \rho \cdot \left(\frac{\partial p}{\partial \rho}\right)_T$$

for a constant volume element, the constitutive relation becomes

$$p = p_0 + \frac{\beta}{V} \cdot \int (Q_u - Q_d) dt$$

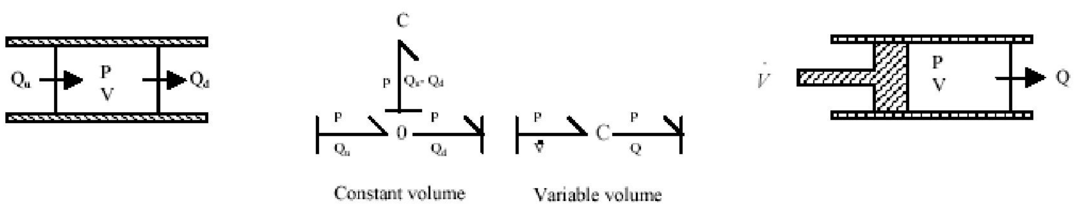

Figure 4 Flexibility elements

In addition to the hydraulic force (Through the transformer), forces from the return spring (C-element) and friction (R-element) are acting on the valve needle (I-element). When the valve is in closed position, the needle rests at the valve seatand when the valve is fully open, the needle hits a restriction. These contact forces are shown as “bumpers”, a spring anddamper system (C- and R-element). Fig. 5 Bond graph model of mechanical parts of the injectors (Common rail injector bottom)The common rail injector is modelled much in the same manner as the traditional injector. The only difference is the additional force originating from the pressure in the volume above the pressure rod. In order to determine the motion of the valve needle, the pressure distribution along the needle must be determined accurately since it varies due to the acceleration of the fluid as it enters the sac volume. The flow is considered as steady state without friction with known pressure in the injector volume. The local pressure can then be found by using Bernoulli’s lawThe mechanical part of the injector model will now be connected to the hydraulic part. The fuel flows trough the bores (Pipe) and into the variable volume surrounding the valve needle (C-field). The pressure in this volume acts on the injector needle. The fuel then flows through the flow area given by the position of the needle (R- element) and in to the sac volume (C-element). The pressure differential between the sac volume and the engine cylinder (Se-element) determines the flow into the cylinder through the nozzle bores (R-element). Bond graph model of conventional injector As we can see to the right, the bond graph model of the common rail injector is a bit more comprehensive than the model of the traditional injector. The model of the mechanical part of the solenoid valve is quite similar to the

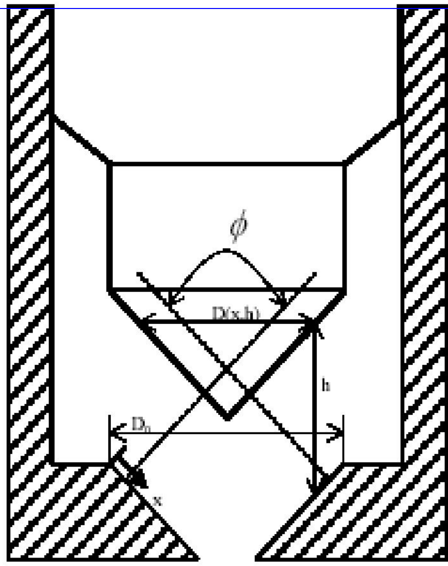

Fig 5 Injector needle

model of the mechanical part of the valve needle. The major difference is the force from the electromagnet (Se-element). At the top of the internal bores (Pipe), the fuel flows through a small orifice (R-element) into a variable volume on top of the pressure rod (C-field). The pressure in this volume acts on both the valve need leand the valve shutter. From this volume, the fuel flows through a valve (R-element) where the flow area is determined by the position of the valve shutter (Solenoid controlled) and into an another variable volume (C-field). This volume is connected through an orifice (R-element) to the low-pressure fuel system (Se-element). Input to the injection valve models is the upstream pressure.

The sub models presented above are modelled using the modelling tool MS1. The sub-models are used to assemble total models of a traditional injection system and a common rail injection system much in the same manner as building the physical system. Using bond graphs in combination with matching software enables the engineer to make changes andmodifications to a model in a straightforward manner without reformulation of equations. The figure below shows the twomodels as they appear in MS1. The fuel injection system models as they appear in MS1 MS1 is a modelling environment aimed at the study of dynamic systems that can be represented by ordinary differential-algebraic equations. Its multi input/output possibilities provide a consistent handling of several model representations in addition to bond graphs. MS1 generates source code used for simulation in the designated solver, in our case ACSL.

The plot shows the pressure in the sac volume for both the traditional injection system and the common rail injection system. The pressure in the rail is 1000 bar. Characteristically, the common rail system gives a distinct opening and closing of the injection valve. This secures rapid
atomisation and mixing between fuel and air in the initial phase, and minimises the end-phase of the injection period with rapidly dropping pressure. The pressure in the sac volume is fairly constant throughout the injection. For the traditional injection system, the pressure in the sac volume rises more slowly in the early stages of injection. However, throughout the injection the pressure in the sac volume continues to increase due to the cam profile and is exceeding the pressure obtained by the common rail system. But in the final stage, the pressure in the sac volume decreases slower as the pressure is relieved at the pump side of the system. Now, what does this mean? A constant or slightly decreasing pressure in the sac volume gives a too intensive rate of injection at the start causing a steep combustion pressure rate, limited by the maximum firing pressure. The next phase of combustion, the rate of energy conversion is mixing

controlled meaning that the injection pressure should be as high as possible. The injection pressure supplied by the common rail system is at it's highest during the initial stages of the
combustion, and may even decrease throughout the injection. All together this means that the rate of injection is not optimal for a medium speed combustion process. For the traditional cam driven system the rate of injection is progressive which is beneficial for the diesel process. The start of the injection is depending upon the spring force of the injector and the injection process is load dependent. The end of the injection is also a weak part of a mechanical system. Thus, the ideal system should be a combination of the two.

5.SUMMARY AND CONCLUSIONS

Bond graph models are developed for the most common components found in injection systems. These sub-models areused to assemble models of a traditional injection system and a common rail injection system much in the same manner as assembling the physical system. Earlier, the most time consuming part of modelling and simulation was the formulation of proper source code for simulation. Less time was left to the actual modelling of the system, and perhaps most important of all, analysis of simulation results. By using bond graphs in combination with matching software like MS1, this is no longer the case. The generation of computer code is done by merely pressing a button. This allows for the modeller to get source code from the updated model in just a matter of seconds. Simulations are performed in ACSL allowing for fast and accurate results.
The rate of energy conversion in the cylinder, commonly called rate of heat release, is closely related to the rate of injection, implying that the rate of injection is the key to an effective combustion process in the diesel engine. For common rail systems, the pressure differential over the nozzle bores is constant or declining throughout the injection. In the authors' opinion, the rate of heat injection should be progressive throughout the injection in order to maintain high cylinder pressure in the expanding cylinder volume where the concentration and availability of oxygen is declining. The traditional injection system will provide an inclining pressure pattern in the cylinder, but is not able to provide high injection pressure at all load conditions. The end of the injection is also a weak part of a mechanical system and variable timing and duration of the fuel injection is not easy to obtain. A more ideal injection system should be a combination of the two and MARINTEK is currently conducting internal activities based upon traditional injection system where a progressive pressure differential throughout the injection is obtainable along with a more distinct opening and closing of the injector.

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