1D SIMULATION-BASED DEVELOPMENT OF A SAFETY CONCEPT FOR THE INVESTIGATION OF A HIGH-PRESSURE GAS-DIESEL INJECTOR ON A SINGLE-CYLINDER RESEARCH ENGINE

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Abstract: 1D simulation has significantly supported the process of developing a diesel ignited high-pressure gas direct injection combustion concept, thus facilitating promising investigations at the SCE. It has been applied to a variety of tasks such as designing the media supply system, pre-optimizing engine operating parameters and developing the safety concept discussed in this paper. Application depends on two simulation models in particular: one validated MCE model and one SCE model enhanced in the course of the concept design phase. Since the MCE model can reliably reproduce the behavior of a full engine with single-stage turbocharging, it played a critical role in determining the boundary conditions for both the 3D-CFD simulation and the simulations with the SCE model. The SCE model, on the other hand, includes all components relevant for the test bed and thus permits both a reliable design of the gas path and the development of a safety concept, which is of remarkable importance for high-pressure gas applications. With regard to the safety concept, this paper presents and discusses the difficulties in detecting injector malfunction and different detection strategies.

Keywords: DIESEL AND GAS FUELED ENGINES, 1D SIMULATION

1. Introduction

The potential for savings in greenhouse gas (GHG) by substituting gases with high methane content (e.g., natural gas) for conventional liquid fossil fuels is considerable due to the comparatively low carbon dioxide emissions, cf. [1, 2]. Applications such as monovalent gas engines and diesel-gas engines that are based on the Otto cycle already exploit this GHG saving potential and are well known for their low emission of both particulates and NOx as well as for higher engine efficiencies, cf. [3, 4].

However, the feeding of a premixed gas-air mixture may result in knocking combustion when gases with low methane numbers are used as well as methane slip. Gas-diesel engines based on the diesel cycle directly inject the gaseous fuel into the combustion chamber during the high-pressure phase of the engine cycle. Ignition is triggered by the injection of a small amount of diesel pilot fuel. The resulting mixture-controlled combustion is not prone to knocking and as a consequence, low-quality gases can be used at high compression ratios and therefore high thermal efficiency. Furthermore, these engines have the potential to avoid engine-out methane emissions nearly entirely. Fully flexible gas-diesel engines [4] can be operated either in dual fuel (DF) mode with gaseous fuel as the main energy source or in diesel mode. This redundancy is important in marine applications in particular where fail-safe operation is critical. Application of these engines in liquefied natural gas (LNG) tankers is economically advantageous as the boil-off gas from the LNG storage system is effectively transformed into propulsion energy, thereby increasing overall efficiency, cf. [5, 6].

The development of a new dual fuel gas-diesel engine concept requires the definition and pre-optimization of many parameters in advance. Additionally, the system complexity resulting from having to provide two fuels simultaneously is higher than with monovalent engine concepts. Boundary conditions, knowledge of the thermodynamic states in the combustion chamber during the engine cycle as well as concept specific information on ignition and combustion are all required in the development process. Therefore, the 1D simulation that is part of LDM (LEC Development Methodology) [10] is a good tool that meets the demands of this type of investigation. This paper explains how 1D simulation is applied to a variety of different tasks in the development of a DF gas-diesel engine concept, focusing on a safety strategy for the single-cylinder engine (SCE) test bed.

2. Fuel injection system for gas-diesel engines

One challenge of injecting fuel into gas-diesel engines is that both diesel and gas must be provided at high pressure (HP) levels when they are injected into the combustion chamber at the end of the compression phase. For HP diesel generation, pressure control and media guidance, standard systems can be used. In contrast, HP gas applications for high-speed large engines are less common and the subject of current development activities, cf. [9]. Furthermore, it is particularly challenging to integrate more than one injection valve into the cylinder head. With respect to slow-speed and medium-speed large engines, systems with two or even more fuel injectors are feasible, cf. [5, 7]. In high-speed large engines that feature high power density, however, how the components are packaged within the cylinder head is critical because available space is limited.

From investigations of diesel-gas engines with premixed combustion, it is well-known that an off-center positioning of the pilot diesel injector in the cylinder head has disadvantages over the pilot diesel injector being situated in the center, cf. [4]. The off-center ignition of the lean gas-air mixture results in asymmetrical flame propagation, which in turn affects efficiency and combustion stability. Similar disadvantages can also be expected with the gas-diesel concept if the injectors are not arranged centrally.

Therefore, advanced injection systems use instead of a multi-injector arrangement one combined gas-diesel injector installed in the center of the cylinder head in which the diesel nozzle is surrounded by the gas nozzle holes, cf. [8]. To obtain the best engine performance possible while complying with stringent emission legislation, the injector has to provide great flexibility in terms of injection timing, multiple injection and injection pressure with both diesel and gas injection. In order to ensure that the injector is always supplied with the required gas pressure and sufficient gas mass flow during the injection process as well, the gas path must be designed accordingly.

3. Advanced high-pressure gas-diesel injector

A recently developed advanced combined HP gas-diesel injector for large high-speed gas-diesel engines meets the demanding requirements described in the previous section. By applying common rail technology, the diesel fuel and the gaseous fuel can be injected flexibly and independently of each other. The
A prototype of a combined gas-diesel injector is available for a detailed investigation and evaluation of the injector concept. The maximum diesel rail pressure of this prototype is limited to 1600 bar in diesel operation mode. In dual fuel operation mode, the diesel rail pressure is limited to 1300 bar and the gas rail pressure is limited to 500 bar. Both gas injection and diesel injection are actuated by two independent valves that are electronically controlled by a modified engine control unit.

4. Media supply of the HP gas-diesel injector

Before the high-speed four-stroke single-cylinder research engine with the diesel-gas injector centrally mounted in the cylinder head is ready for tests, a media supply system has to be developed that is capable of achieving the required gas pressure and sufficient gas mass flow during the injection process in particular. The rough boundary conditions for the design of the media supply are largely specified by the engine application. The detailed engine specifications are given in Table 1.

Table 1: Technical specifications of the SCE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Rated speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Displacement</td>
<td>≈ 6 dm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16:1</td>
</tr>
<tr>
<td>Number of inlet/exhaust valves</td>
<td>2/2</td>
</tr>
<tr>
<td>Valve timing</td>
<td>Miller intake valve timing</td>
</tr>
<tr>
<td>Swirl/tumble</td>
<td>≈ 0/0</td>
</tr>
<tr>
<td>Charge air</td>
<td>Electrically driven air compressor with up to 10 bar boost pressure</td>
</tr>
<tr>
<td>Gas fuel supply</td>
<td>High-pressure ionic compressor with up to 600 bar gas pressure</td>
</tr>
<tr>
<td>Diesel fuel supply</td>
<td>Common rail system with up to 2200 bar diesel fuel pressure</td>
</tr>
</tbody>
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A well-known common rail technology was used for the diesel supply. In addition, the gas-diesel injector requires a high-pressure gas supply for operation in DF mode. In order to provide the required gas pressures and masses, a new high-pressure gas path in combination with an extended safety concept was developed and implemented on the test bed. An ion compressor boosts the gas pressure from the low public gas grid level up to 600 bar. The gas pressure in the gas path between the buffer volume and injector is adjusted precisely with finely resolved control valves located downstream of the compressor for fully flexible engine operation. In combination with the latest crank-angle and time-based measurement technology, a special high-pressure NG Coriolis mass flow device monitors all relevant parameters.

Compared to diesel applications with sophisticated flow limitation valves, however, the aggregate state of HP gas poses an increased risk to the engine in the event of injector malfunctions. To identify potential issues that arise during injector malfunction and to develop risk minimization strategies, the gas path shown in Figure 1 was the subject of extensive 1D simulation during the predesign process. In the direction of gas flow, this path consists of a HP buffer volume with a pressure sensor, a safety valve (SV) and another pressure sensor directly upstream of the injector. All these components are highly important for the test bed safety concept and will be discussed in more detail below.

5. Application of 1D simulation to develop a safety concept on the test bed

5.1. Development of 1D simulation models to support the design of a hardware configuration on the test bed

Different 1D simulation models were applied to support the predesign of the gas-diesel combustion concept. Boundary conditions for 3D CFD simulations as well as required engine performance data were calculated with a 1D simulation model of a multicylinder gas-diesel engine (MCE) with one-stage turbocharging. To depict the combustion process with this 1D model, heat release rates (ROHR) were taken from the 3D CFD simulations. To account for the increasing cylinder charge caused by fuel injection during the high-pressure phase of the combustion process, the gas-diesel injector was implemented into the 1D model by including one gas and one diesel injector element in each cylinder.

Since another 1D model of the gas injector alone was required to predict the gas injection rate, a simplified submodel was developed which consists of a spring chamber, needles and a needle chamber, cf. Figure 2 (left). The submodel calibration was based on simulation results provided by the manufacturer of the injector. Figure 2 (right) shows how well the simplified model predicts the target injection at the same boundary conditions.

The calibrated 1D submodel of the gas injector was integrated into another model that focuses on the high-pressure gas path on the SCE test bed, cf. Figure 3. It includes all components of the gas supply path shown in Figure 1: HP gas buffer, safety valve, pressure sensors, HP gas injector, gas hose and pipes. The diesel injector is modeled separately. The conditions at intake and exhaust boundaries were taken from the 1D MCE simulation.
5.2. Development of a safety concept of a high-pressure gas-diesel injector using 1D simulation

In the development of the reliable safety concept, the pressure conditions within the gas supply path during standard operation from engine start to stop were investigated with this 1D SCE model. All 1D investigations of the gas path used the measurement positions directly upstream of the injector and in the buffer volume. Building on these results, the same model was used to simulate the scenario of a stuck gas needle and its effect on the gas path respectively on the engine at different engine loads while taking the safety valve closing time into account. Finally, successful action strategies were derived. These strategies will be discussed in more detail below in the context of selected scenarios.

5.2.1. Malfunction due to the gas needle sticking during standard engine operation

Figure 4 shows the pressure curves directly upstream of the injector and in the buffer volume of two consecutive working cycles in the event of an injector malfunction during standard engine operation at part load (30%) and full load (100%). Irrespective of the load and position, almost identical pressure curves can be determined in the first working cycle (standard case) with a characteristic pressure fluctuation for the gas injection close to the specified pressure level. Compared to the second working cycle, which represents the scenario of injector malfunction due to the gas needle sticking, the gas pressure drops below the characteristic pressure fluctuation; this is seen most clearly with regard to the position upstream of the injector. In this case, a malfunction can be detected with a threshold value, i.e. if the pressure upstream of the injector falls below this threshold value, the closing process (∼0.1 s) of the safety valve is triggered immediately and the diesel injection is also switched off in parallel.

5.3. Malfunction due to the gas needle sticking at engine start

Even if an injector malfunction can be detected during standard engine operation, the same approach does not work during engine start. The following section reveals the difficulties in detection by comparing a case in which injector malfunction occurs with a case in which the injector works properly. In this case, the DF engine starting procedure corresponds the one shown in Figure 6. First, the engine is motored up to reference speed (not shown) and the pressure in the gas buffer is raised to the target value of 400 bar before pilot diesel injection occurs (1). In the next cycle, the safety valve is opened (2) and the gas stored in the buffer volume is then able to reach the injector. During this process, the pressure level upstream of the injector increases and finally reaches the same pressure rating as the buffer volume while the gas compressor supplies additional HP gas until the target value of 400 bar is restored throughout the entire gas path (3). Afterwards, the system is ready for the additional gas injection to start the DF mode (4).

Even if the safety valve closed immediately after the malfunction was detected, it would not be possible to hinder the gas remaining between the safety valve and the injector from expanding into the combustion chamber. Figure 5 shows the impact of the gas needle sticking on three subsequent combustion cycles considering the valve closing time at 400 bar gas rail pressure. Combustion is represented by one ROHR, which is calculated using 3D CFD simulation for standard operation with the corresponding excess air ratio (EAR), cf. working cycles 1 and 2 in Figure 5. The same ROHR were used to simulate working cycles with injector malfunction, cf. working cycles 3, 4 and 5 in Figure 5. The results show that the gas remaining downstream of the safety valve influences at least three further cycles and produces very rich air-gas mixtures in the combustion chamber as well as an increased risk of engine damage.

Compared to the starting procedure discussed in Figure 6, the difference in the case of injector malfunction (cf. Figure 7) becomes clear after step (2).
Immediately after the safety valve malfunction is opened, the gas pressure directly upstream of the injector rises quickly but cannot meet the level of the buffer volume due to the stuck gas needle. Subsequently, the high pressure gradient between the HP gas path and comparatively low-pressure combustion chamber initiates an unlimited gas flow directly into the combustion chamber, which ultimately includes the previously mentioned dangers for the engine.

Since error detection in the gas path via a threshold value worked insufficiently in accordance to the simulation results, further simulations were carried out to identify additional helpful strategies. The indicated cylinder pressure signal was identified as a promising parameter for much faster detection of injector malfunction during both engine start and standard operation. In this gas-diesel concept, air alone is compressed between inlet valve closing (IVC) and start of injection (SOI) in standard operation independent of gas pressure or engine load. As a result, the pressure curve signal can be calculated by a polytropic state change in this time window and used in a real-time comparison with the measured signal of the indicated pressure sensor, cf. Figure 8. If the gas needle stuck, additional gas would flow into the combustion chamber during this time window and the value of the measured indicated pressure would deviate from the predicted curve without delay. Thanks to this finely resolved monitoring, injector malfunction is detected very quickly and has been successfully used on the test bed in combination with error detection in the gas path via a threshold, which facilitates additional monitoring of malfunctions within the gas supply system.

7. References


8. Acknowledgments

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