Faculty of Transportation Engineering and Vehicle Engineering
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INVESTIGATION OF THE FUEL INJECTION PROCESS IN COMPRESSION IGNITION ENGINES

Thesis book

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1 Introduction and Motivation

One of the most important system components in a given vehicle is the transmission system, which provides propulsion from a given energy source. Today, crude oil derivatives are still the most common energy sources. The Diesel engine - since Rudolf Diesel patented it more than one hundred and twenty years ago - has undergone significant development and has been among the drive units of different vehicles since the beginning.

Initially, the primary motivation in engine development was to increase the specific power and the effective power, which is why turbocharging has spread so much, that almost every vehicle diesel engine today is equipped with one. Subsequently, increasingly stringent regulations [1] [2] have prompted vehicle manufacturers to reduce emissions of internal combustion engines, leading to significant developments in two areas for diesel engines. The first is injection and intake air path systems, and the second is exhaust after-treatment systems. The former also provided one of the motivations for the present work, as the more in-depth understanding of diesel combustion processes leads through a deeper understanding of the injection processes [3].

The introduction of Common Rail (CR) injection systems has given a major boost to the spread of diesel vehicles [4]. With this step - and with the help of modern, high-efficiency turbochargers – diesel engines have become significantly more powerful, more flexible, and more economical at the same time. However, detailed descriptions of the operation of CR systems are rarely found in the literature. Although injector modeling has been addressed by several publications [5] [6] [7] [8] [9] [10], and the investigation of nozzle flow conditions and injection spray shape has long been in the focus of research [11] [12], compared to its practical importance this area has not yet been discussed in the required extent. At the beginning of the research work, my goal was to explore reaction kinetic processes in particular engine operating conditions. On the way there, I found that there were unexplored topics in both injection modeling and the measurement of injection processes. In my opinion, reducing raw emissions is a significant area for internal combustion engine development, which in the case of diesel engines, can be significantly affected by the injection process. For this reason, the relationship between injection, mixing, ignition, and combustion, i.e. the reaction kinetic processes of diesel engines, is an important research topic today and in the future.

In the focus of my research work, I thoroughly investigated the modeling of CR injectors for diesel engines, the processes and measurement of the individual injections, and the injection spray shape along with the factors influencing it. As a result of my work, a modeling and measurement toolkit has been developed that can be used to accurately predict the proceeding of an injection process under given boundary conditions.

Diesel injection has long been a research topic in Hungary as well [13]. Still, CR injection systems and high-pressure injection, as well as the effect of nozzle geometries, have not been studied and are not widely spread in the international literature. Based on the available information, I developed my own injector model, during the verification of which

I found shortcomings in the measurement procedure. After examining these, I developed a new method to validate the injector model, which can be used to produce a reliable input for combustion simulation.

Going closer to the combustion processes by one step, I studied the formation of the injection spray using 3D fluid dynamic simulations. During the modeling process, I found that the geometry of the nozzle hole has a crucial effect on the spray shape, so the question arose as to how the spray shape, and through it the droplet decomposition and mixing, could be influenced by different geometry changes. Accordingly, I systematically compared the effect of existing nozzles geometries and a new type developed by me on the spray shape. I drew conclusions about the effects of different geometric elements.

At the beginning of the research work, I had the following questions to answer:

- How is the diesel combustion process studied and modeled?
- What are the most critical elements of the diesel combustion process?

After a little research, it became clear that it is worthwhile to start describing the combustion processes through injection. After I turned my attention to this, my goal was to answer the following questions:

- What and how affects the injection process?
- How can an injection be described in advance?
- What processes take place in a CR injector during injection, and how do these affect the injection itself?
- How can be the injection process accurately measured?
- How is the spray developing, and what variables influence its shape and composition?

My new scientific results have been formed while trying to answer these questions, which I summarize in the following theses.

2 New scientific results

In the following, I have collected my theses formulated during the research work. The relevant chapter of the dissertation and related publications are indicated in parentheses.

1. THESIS 1

Using simulations and measurements, I found that the currently most widely used method for measuring the injection mass flow of diesel injectors, developed by W. Bosch, does not accurately reflect the dynamics of the injection mass flow rate. The parameters of the measuring device have a crucial influence on the measurement results. (Chapter 5), [P1, P8]

a. The diameters and lengths of the measuring and following tubes all affect the dynamics of the measured pressure traces (and hence the mass flow curves) through the change in the volume of the measuring liquid. The larger the measuring volume, the slower the pressure increasing phase takes place due to the compression modulus of the fluid.

b. The variable orifice, apart from the extremely small cross-sections, has no effect on the measured mass flow curves.

c. The system pressure has no effect on the measured values.

2. THESIS 2

I constructed a detailed, coupled electromagnetic, mechanical, and hydraulic model of a first-generation CR injector for medium-duty commercial vehicles, for the purpose of testing injection mass flow and needle lift. One of the novelties of the model is that it also contains the elements of the Bosch measuring device, so it is possible to study the relationship between the injector and the measuring device together, and the behavior of the measuring device itself. (Chapters 4 and 5.3.3), [P2, P5, P6, P7]

a. The novelty of the model is that it contains electromagnetic, mechanical, and hydraulic subsystems interconnection to describe the internal operation of the injector and measuring device.

b. The model inputs are injector control flow and manifold pressure. Its outputs are needle lift and injected mass flow run at the nozzles, as well as calculated mass flow traces from the measurement device. The latter has not been studied in simulation so far.

c. The geometrical parameters of the model and the mass of the moving parts were determined by measurement. Internal friction conditions and the contraction factors of the nozzles were estimated.

d. The model was validated for needle lifts in a wide operating point range (1.15..2.7 ms opening time, 450..890 bar rail pressure), the difference between the measured and simulated curves was within 1%, such accuracy has not been reported in the literature so far.

e. I validated the model from low partial load (1.15 ms opening time) to full load (2.55 ms opening time) for the injected dosage. The difference between the measured simulated values was less than 3%.

3. THESIS 3

Based on Thesis 2, I developed a new method to measure the injection mass flow rate of diesel injectors, which combines simulation and measurement results. The simulation model includes a detailed model of both the injector and the measuring device, so it is not necessary to compare the measurement results with the output of the injection model, but with the output of the measuring device included in the simulation. (Chapter 5.3), [P1, P8, P9]

a. I have shown that the injection rate of the injector does not match the curves indicated by the measuring device.

b. When comparing the simulation and measurement results, the difference between the simulated measurement device and the measured data at different working points was below 10%.
c. The model described in Thesis 2 was also validated for the injection mass flow rate.

4. THESIS 4

I developed a new type of nozzle geometry, which has not been studied in the literature so far and examined its effect on the evolution of the injected spray shape compared to the spray of two other nozzle types. The compared geometries were cylindrical, conical with a large inlet radius, and a double-conical with large inlet radius nozzle that was developed by me. (Chapter 6.), [P3, P4, P10, P11]

a. The cylindrical nozzle had a diameter of 0.154 mm and significant cavitation within the nozzle hole.
b. For the conical nozzle, I used an inlet rounding radius of 0.04 mm and a 1.3 k-factor confuser design to avoid cavitation. As a result, cavitation was eliminated, the spray cone angle was significantly reduced by 50%, and the mass flow approximately increased by 20%.
c. I designed the double conical nozzle geometry to combine the advantages of the previous two. It has an inlet and outlet diameter of 0.165 mm, inlet radius equal to that of the Ks nozzle, and a minimum diameter equal to that of the Ks nozzle (0.154 mm). The simulation results showed minimal cavitation, a radius cone angle only 14% smaller than the cylindrical nozzle, but a mass flow 19% higher.

I presented the results of the dissertation at the following conferences and journals (the relevant theses are in parentheses):

[P1] Vass Sándor, Németh Huba: „Sensitivity analysis of instantaneous fuel injection rate determination for detailed Diesel combustion models”, PERIODICA POLYTECHNICA-TRANSPORTATION ENGINEERING 41 : 1, pp. 77-85., 2013. **(T1, T2, T3)**

[P2] Bárdos Ádám, Vass Sándor, Németh Huba: „Validation of a detailed commercial vehicle turbocharged diesel engine model”, A JÖVŐ JÁRMŰVE: JÁRMŰIPARI INNOVÁCIÓ 2014 : 1-2 pp. 25-31., 2014. **(T2)**

[P3] Vass Sándor, Németh Huba: „CFD Modelling of a Common Rail Injector Nozzle, Flow and Spray Characteristics, Validation Using High Speed CCD Camera”,

Proceedings of the 14th mini conference on vehicle system dynamics, identification and anomalies : VSDIA 2014, Budapest, Magyarország, pp. 453-463., 2015. **(T4)**

[P4] Vass Sándor, Németh Huba: „Diesel porlasztó fúvókák geometriai kialakításának hatása az áramlásra, összehasonlítás numerikus szimulációk segítségével", GÉP LXVIII. : 2, pp. 23-33., 2017. **(T4)**

[P5] Vass Sándor, Németh Huba: „Detailed electromagnetic model of a common rail injector", 34th International Colloquium on Advanced Manufacturing and Repairing Technologies in Vehicle Industry, Budapest, pp. 165-168., 2017. **(T2)**

[P6] Zöldy Máté, Vass Sándor: „DETAILED MODELLING OF THE INTERNAL PROCESSES OF AN INJECTOR FOR COMMON RAIL SYSTEMS", JOURNAL OF KONES: POWERTRAIN AND TRANSPORT 25 : 2, pp. 415-426., 2018. **(T2)**

[P7] Vass Sándor, Zöldy Máté: „Detailed Model of a Common Rail Injector", ACTA UNIVERSITATIS SAPIENTIAE ELECTRICAL AND MECHANICAL ENGINEERING : 11, 2019. **(T2)**

[P8] Vass Sándor, Zöldy Máté: „EFFECTS OF BOUNDARY CONDITIONS ON A BOSCH-TYPE INJECTION RATE METER", Transport **(T1, T3)**
IF = 1,701

[P9] Vass Sándor, Zöldy Máté: „A MODEL BASED NEW METHOD FOR INJECTION RATE DETERMINATION", Thermal Science **(T3)**
IF = 1,557

[P10] Vass Sándor, Zöldy Máté: „FÚVÓKAGEOMETRIA HATÁSA A PORLASZTÁSI SUGÁRKÉPRE, DÍZEL PORLASZTÓK FÚVÓKÁINAK CFD SZIMULÁCIÓJA", OGÉT 2020 **(T4)**

[P11] Vass Sándor, Zöldy Máté: „DÍZEL ÉGÉSFOLYAMATOK VIZSGÁLATA 3D SZIMULÁCIÓ SEGÍTSÉGÉVEL", Műszaki szemle **(T4)**

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[13] D. Brodszki, Feltöltött Dieselmotorok, Budapest: Műszaki Könyvkiadó, 1966.