Researcher Links UK-Russia Workshop

Scientific and Technical Grounds of Future Low-Carbon Propulsion

19th - 22nd November 2018, Northumbria University at Newcastle, UK

Experimental and numerical research of fuel injection system hydrodynamics effects in case of diesel and biofuel injection

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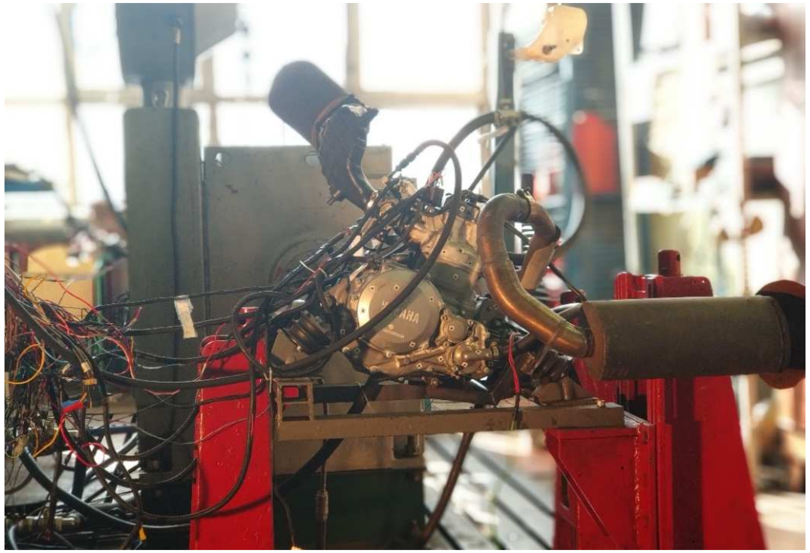
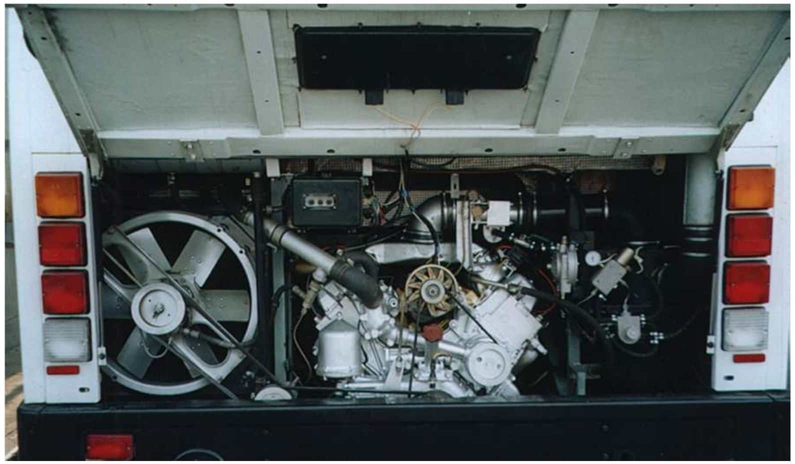
Department «Heat engineering and engines of internal combustion»

Internal combustion engines laboratory

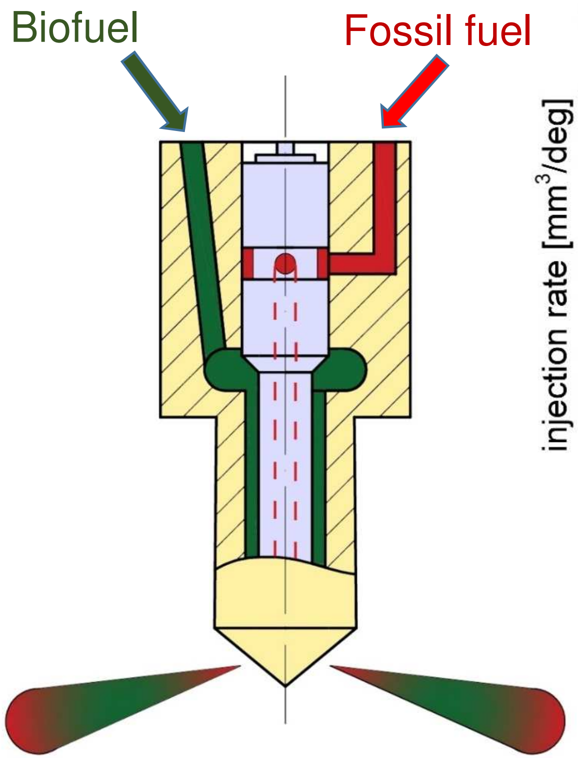


<u>Experimental tools</u>:
single-cylinder diesel;
diesel and petrol engines of different application;
test benches for injection systems .

<u>The laboratory develop and research</u>:
- diesel injection systems;
- mathematical modeling software;
- systems for injection of alternative fuels: natural gas, dimethyl ether (DME), ethanol, vegetable oils.



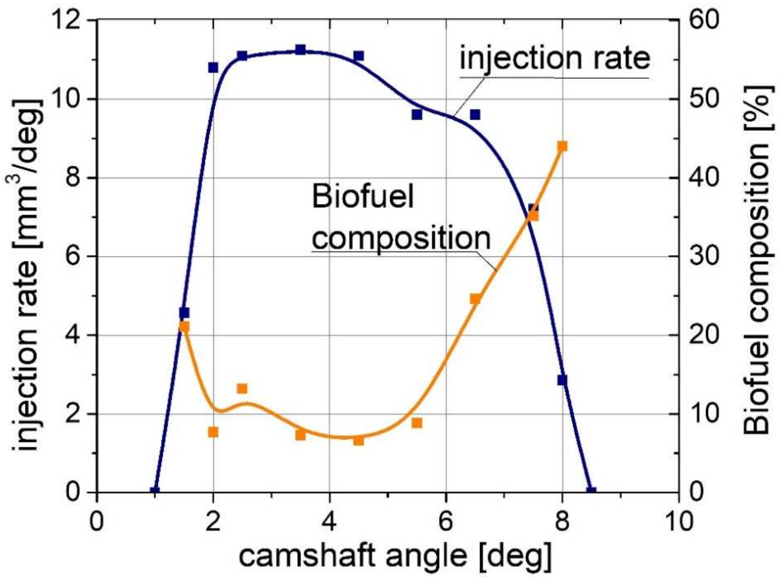
Mechanically injection system for alternative injection

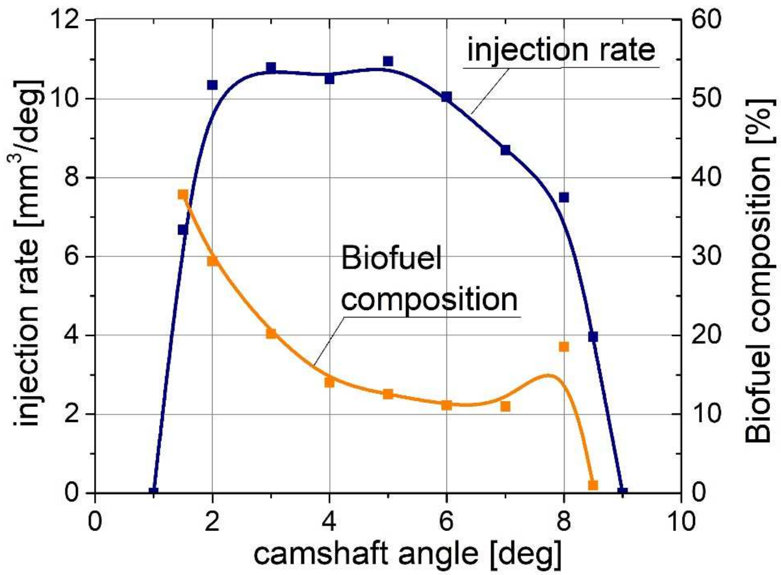


Nozzle of injector (designed by MADI)

$$B=\frac{Mass\_flo_{bio}}{Mass\_flo_{bio}+Mass\_flo_{fossil}}$$

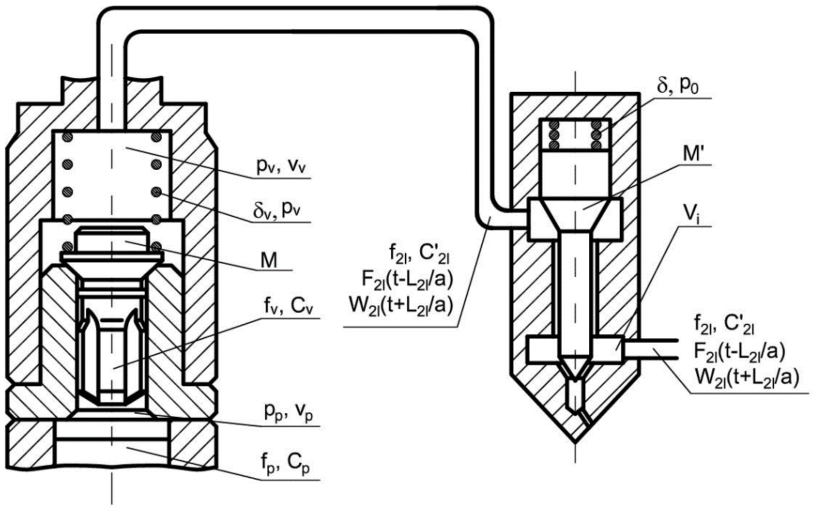
Biofuel composition (B) changes during the injection process.





Injection rate

Fragment of mathematical model

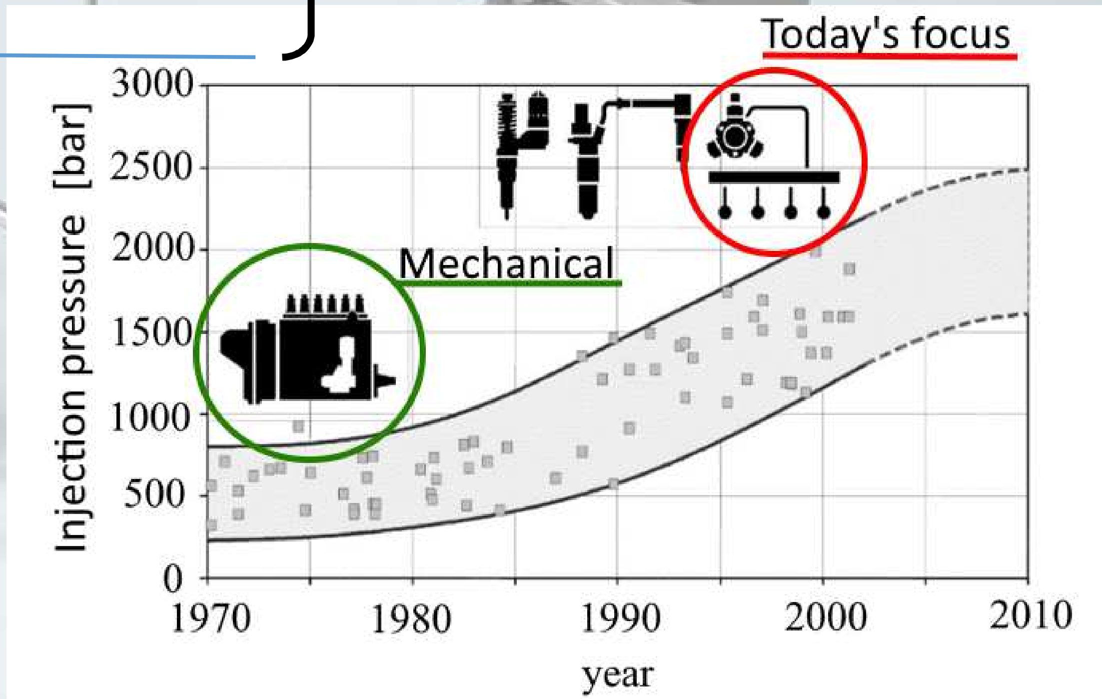


Injection systems development trends

Injection system development trends:

- Increase of maximum injection **pressure** (up to 3500 bar)
- **Multiple** injection
- Optimal for **electronic** control: start of injection, pressure, number of injections and etc.
- Different fuels:
    - Fossil fuel (diesel);
    - **Biodiesel;**
    - **Natural Gas.**

Common Rail* only



Development of injection pressure of HD engine [**]

* One of the first prototype (governed by an engine control unit) was made in MADI in 1984 under the direction of professor Khachiyan Aleksey Sergeevich

** – Data from: B. Mahr. Future and Potential of Diesel Injection Systems

The aim: development of new high-pressure common rail injection system for application on HD engines.

Stages:

- Development of test benches for Common Rail testing.
- Development of mathematical modeling software* for numerical analysis of injection systems.
  - Experimental research of existing Common Rail systems for analysis its and collect the data for models verification.
  - Programming of models and its verification.
- Make of new experimental models with help of software and experimental experience.

*With the financial support:
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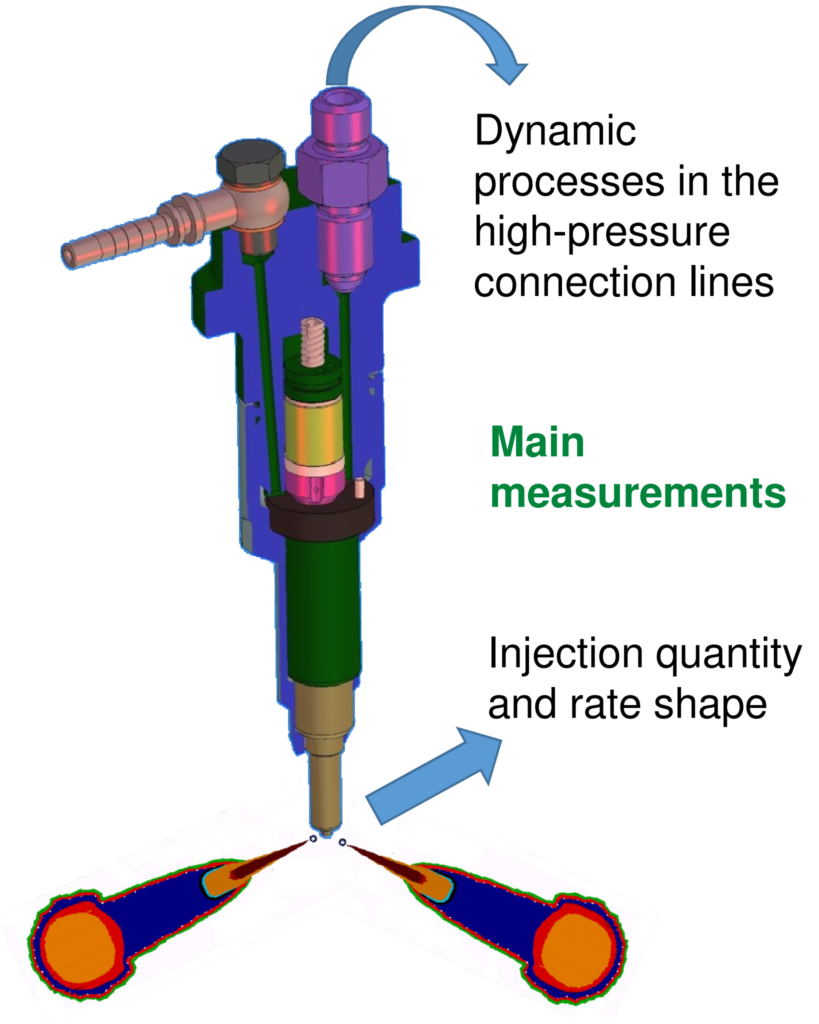
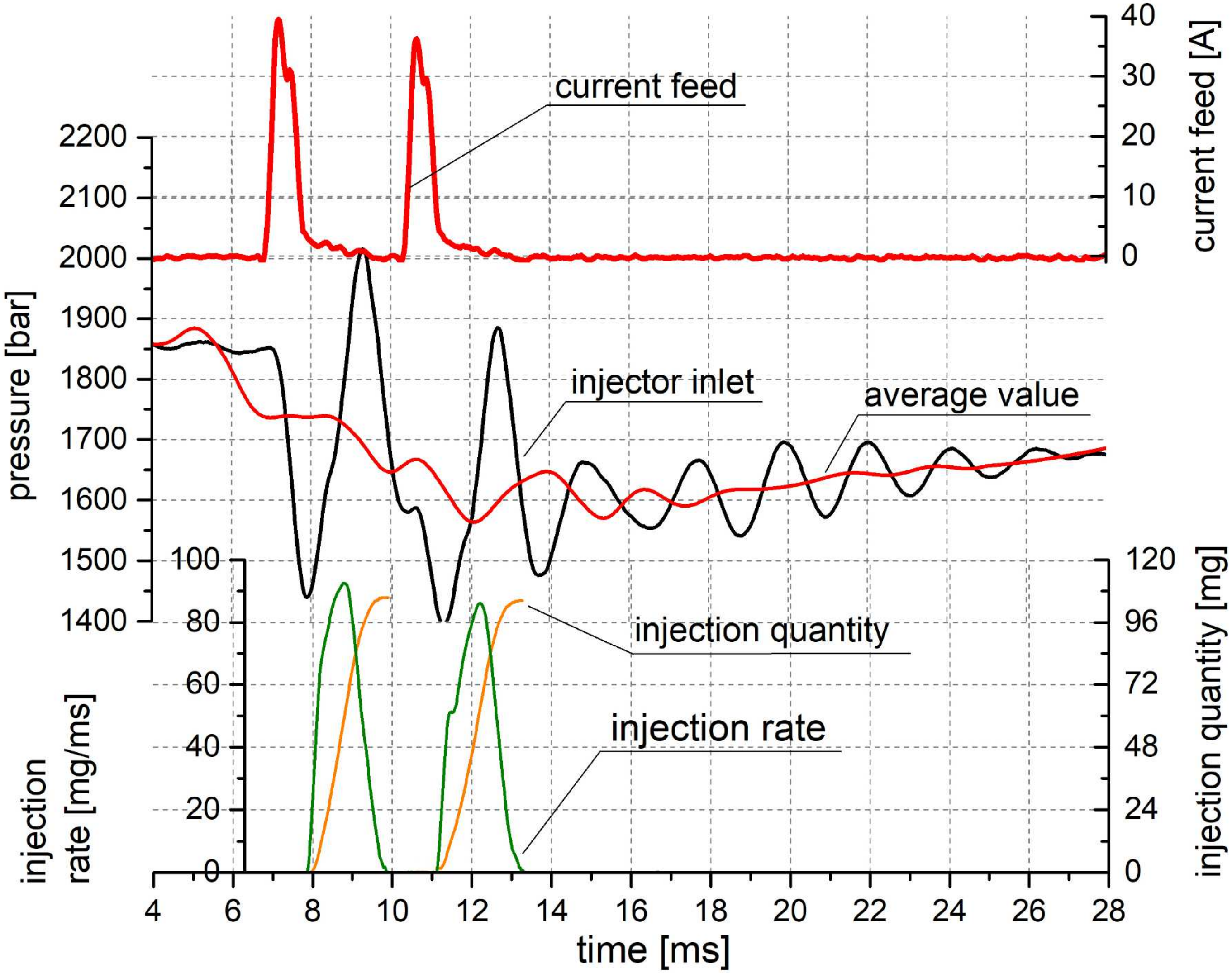
translation: «Фонд содействия развитию малых форм предприятий в научно-технической сфере» (Фонд содействия инновациям) (Dushkin Pavel, Договор № 13323 от 02 июня 2018 года)

Experimental and numerical research of Common Rail fuel injection system

stand for testing of fuel systems



Common Rail experimental research



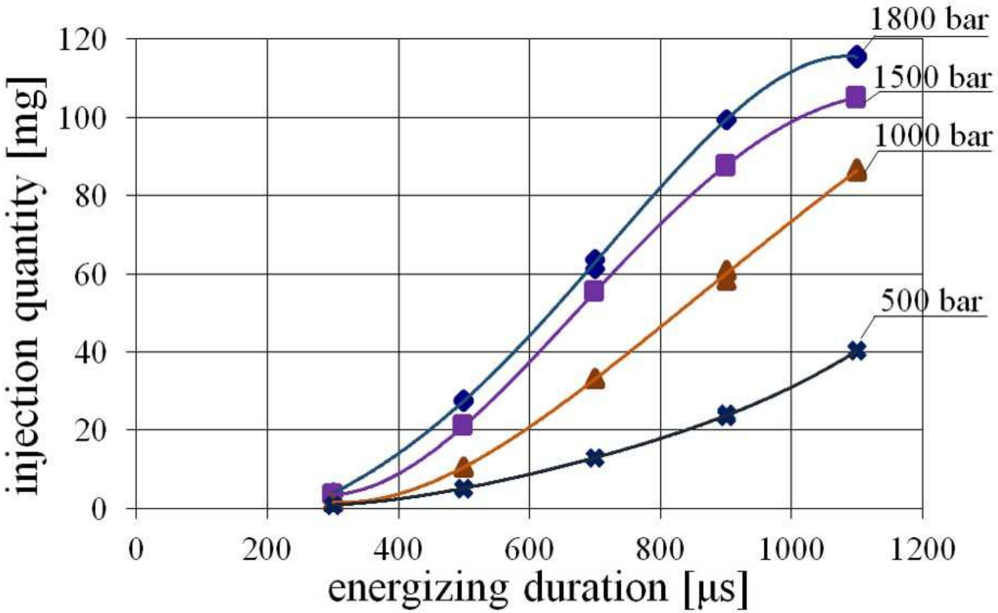
some results of the experiments on diesel fuel

Bosch injector (CRI2)
(rail pressure=1800 bar,
$\tau_{current\_1} = \tau_{current\_2}$=0,7 ms,
$\Delta\tau$=3 ms, diesel fuel)

Both impulses are the same.
Shapes of the first and the second injections are a bit different.

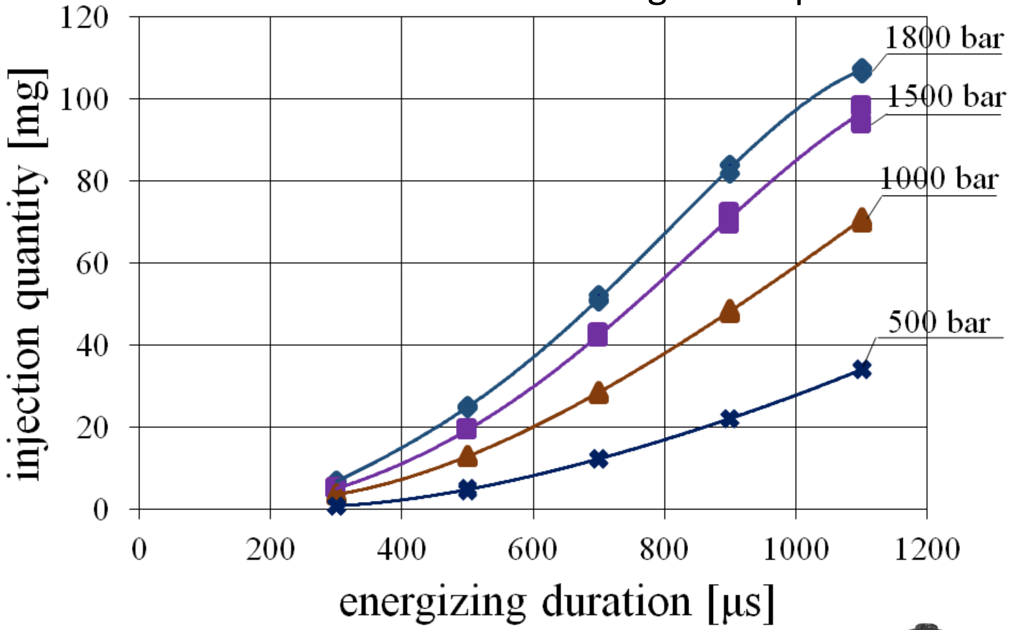
Characteristics on diesel and sunflower oil (experiment)

Fossil fuel



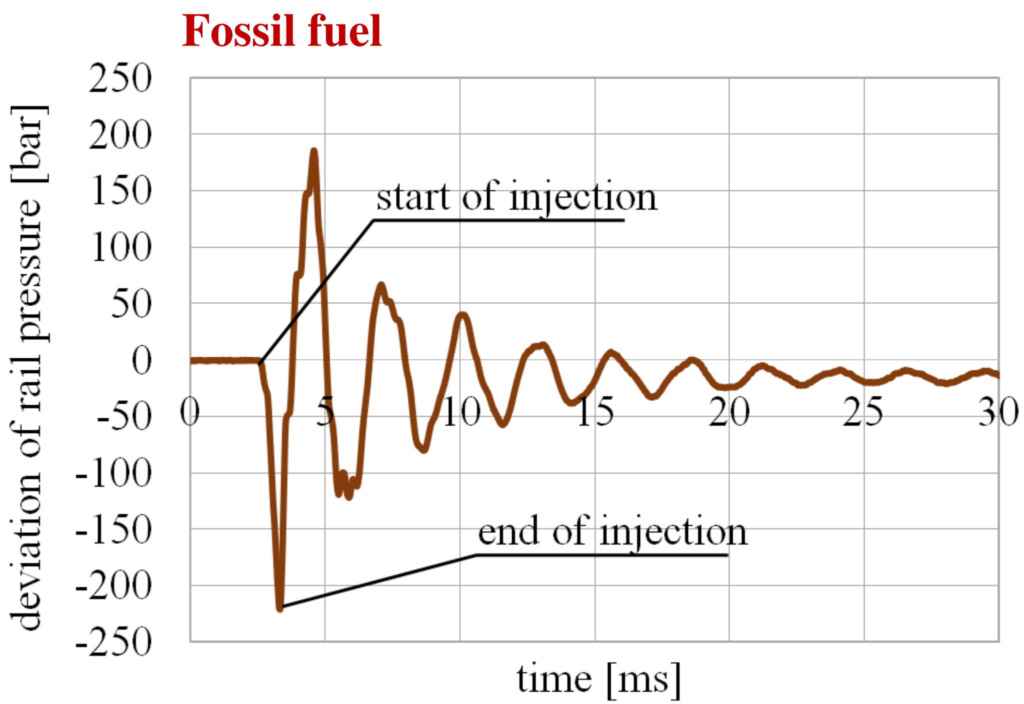
Biofuel
(high-viscosity)

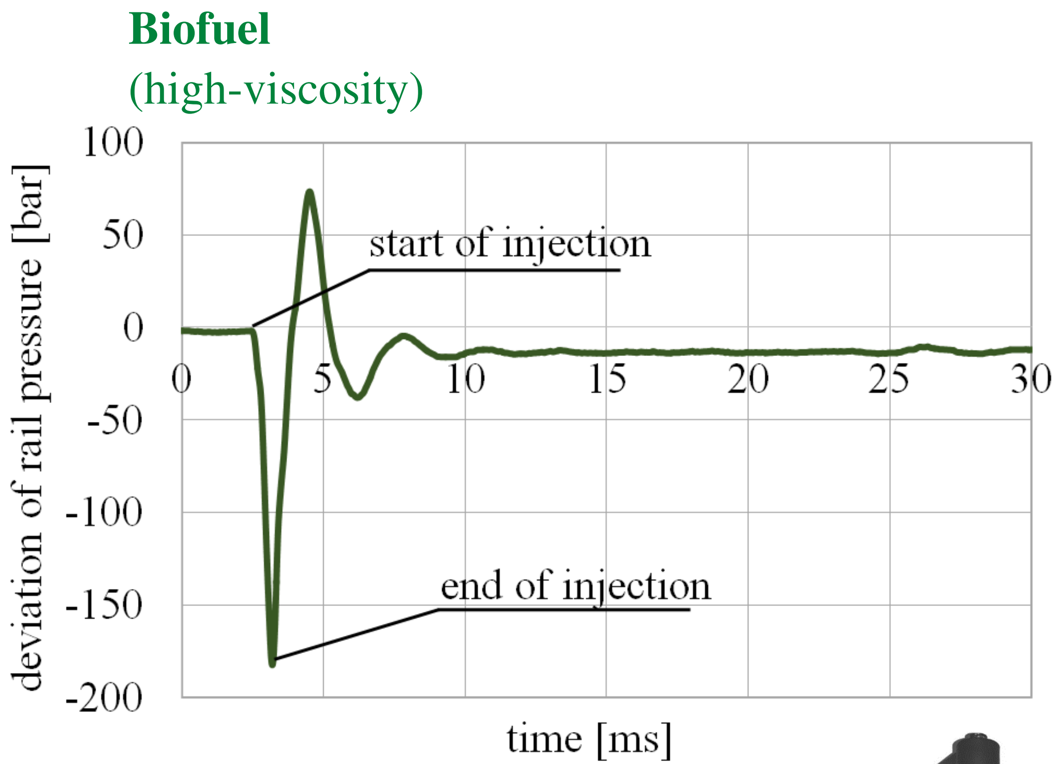
Injection quantity reduce by an average of 15 percent



Characteristics of Bosch CRI2 injector working on diesel fuel and sunflower oil
(rail pressure 300…1800 bar, $\tau_{current}$=300…1100 µs,
diesel fuel and sunflower oil)

Pressure oscillations on diesel and sunflower oil (experiment)





Pressure oscillations in the injector inlet
Bosch injector (CRI2)
high pressure connector line: length 1000 mm; diameter 2,2 mm

Pressure oscillations in the injectors inlet decrease because oil has more viscosity and hydraulic friction is higher for high-viscosity fuels

Mathematical modeling of CR injector

✓ Processes in fuel connection lines: equation of continuity and equation of motion

$$\begin{cases} \dfrac{\partial p}{\partial x} + \rho_T \dfrac{\partial s}{\partial t} + 2\rho_T k s = 0 \\ \dfrac{\partial s}{\partial x} + \dfrac{1}{a^2 \rho_f} \dfrac{\partial p}{\partial t} = 0 \end{cases}$$

Solving by method of d'Aleambert-Gukovskiy

pressure at the "x"

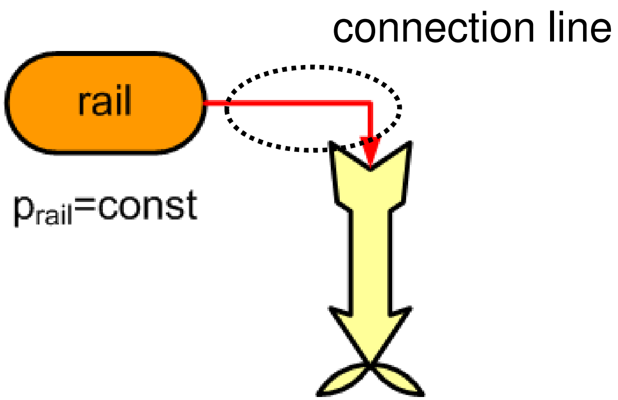
rail pressure

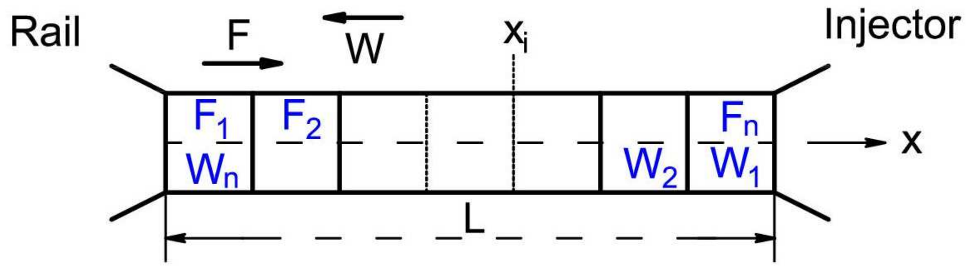
friction (empirical model)

$$\begin{cases} p = p_{rail} + F\left(t - \dfrac{x}{a}\right) \cdot e^{-kt_1} - W\left(t + \dfrac{x}{a}\right) \cdot e^{-kt_2} \\ S = \dfrac{f_{\text{line}}}{a\rho_{\text{fuel}}} \left(F\left(t - \dfrac{x}{a}\right) \cdot e^{-kt_1} + W\left(t + \dfrac{x}{a}\right) \cdot e^{-kt_2} \right) \end{cases}$$

waves

fuel flow rate

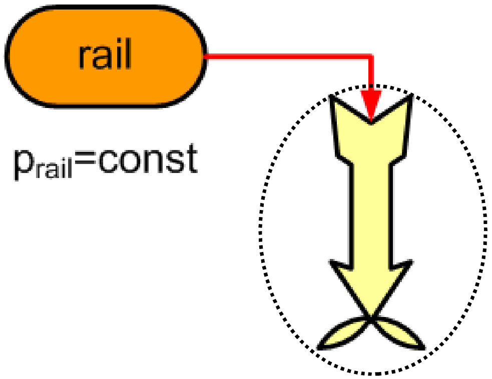




Connection line

Fuel flow is calculated with help of the F and W pressure waves. These waves move across the line with the speed of sound.

Mathematical modeling of CR injector
(processes in the injector volumes)



✓ Processes in volumes (V_i):
equation of mass balance

Solving by method of Euler

$$\frac{d\rho_i}{dt} = \frac{1}{V_i} \cdot \left[\sum G_{i-j} + \rho_i \sum S_{i-j} + \rho_i \sum \frac{dV_{i-n}}{dt} \right]$$

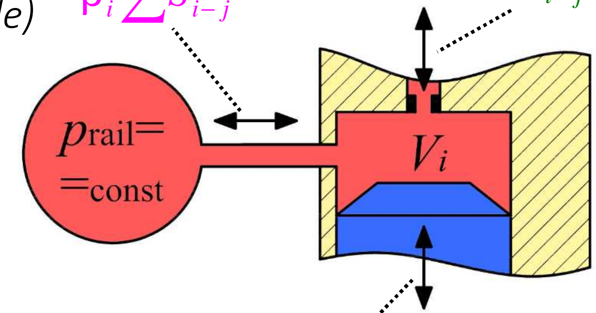
density of fuel in the volume

discharge coefficient (empirical) μ

$$G_{i-j} = (\mu f)\sqrt{2\rho_i \left| p_i - p_j \right|}$$

flow between the volumes

flow by the connector line (previous slide) $\rho_i \sum S_{i-j}$



change of volume $\rho_i \sum \frac{dV_{i-n}}{dt}$

compressibility (empirical)

Mathematical dependence of pressure and density

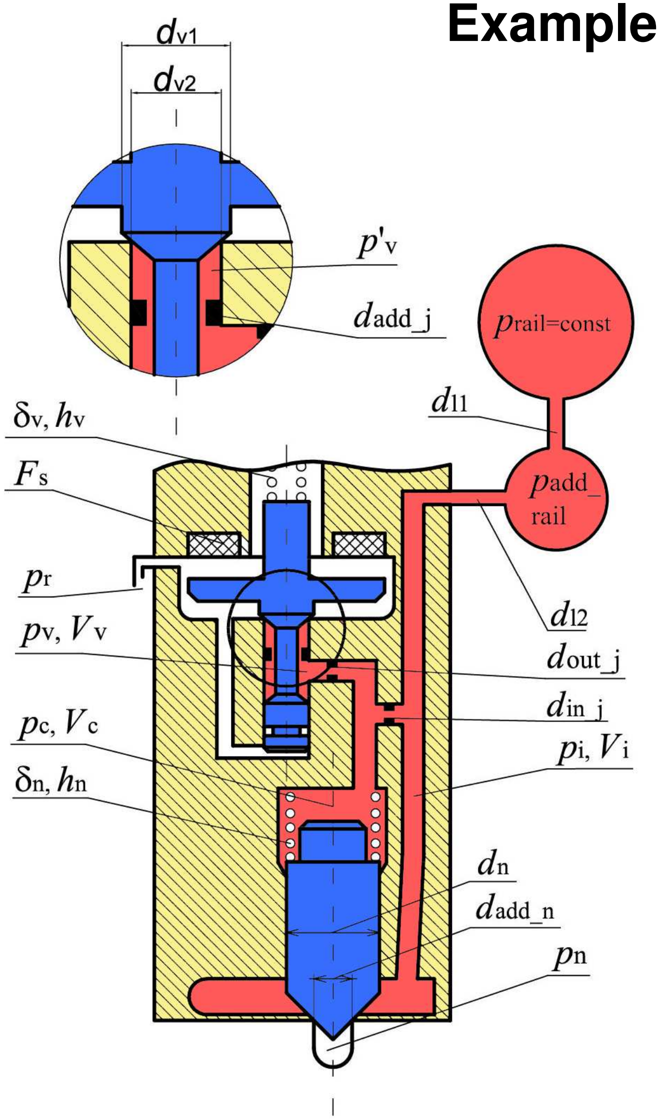
$$p_i = \frac{\rho_i - \rho_t}{\rho_t \cdot \alpha_j}$$

Mechanical motion: dynamic equation

$$\frac{dS_i}{dt} = \frac{1}{M_i} \cdot \sum F_i$$

The injector is splitted for different volumes and we calculate how much fuel gets into and out of each volume

Example of main equations for CR injector

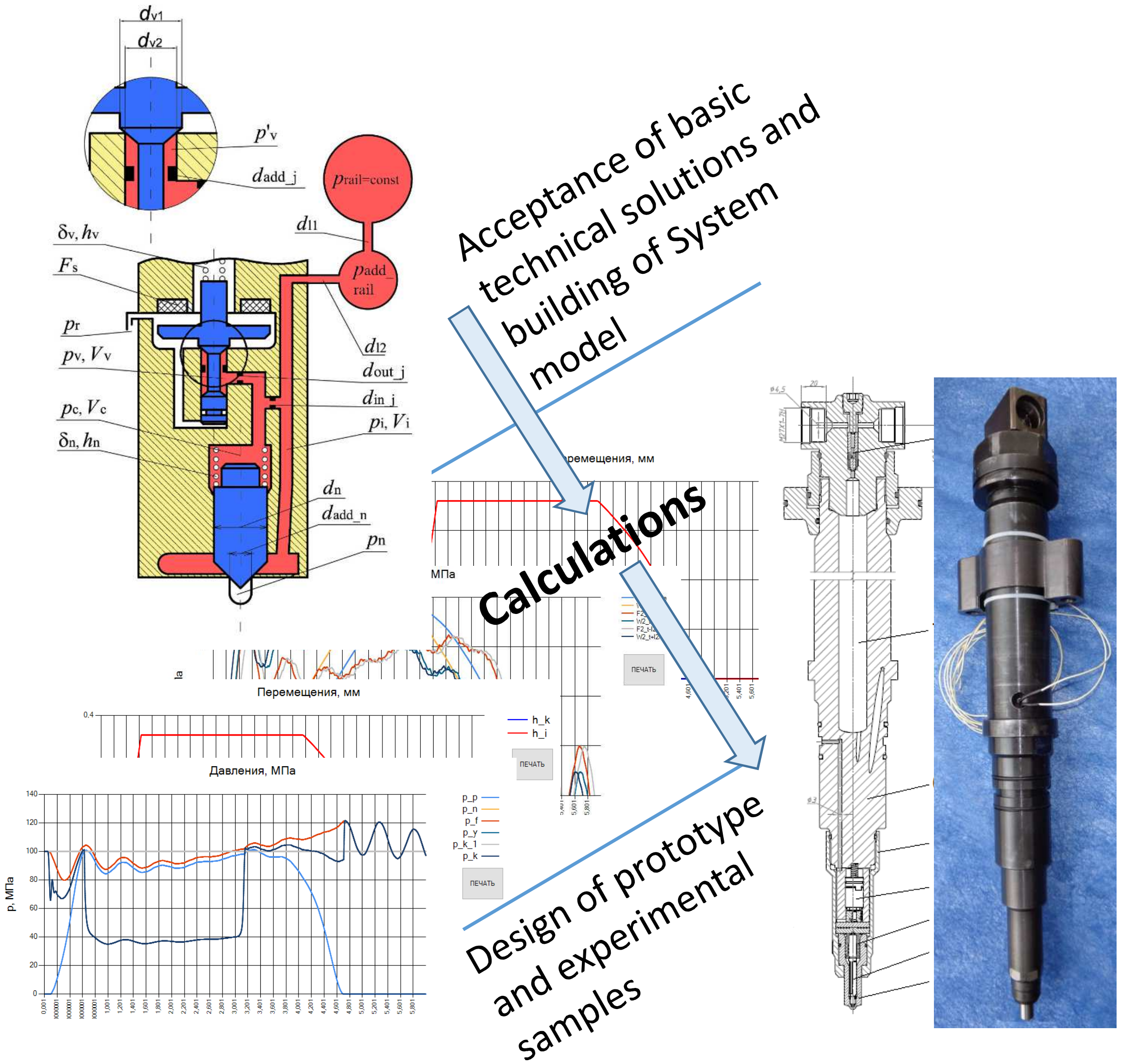


System model

$$
\begin{cases}
\dfrac{d\rho_{add\_rail}}{dt} = \dfrac{1}{V_{add\_rail}}\left[\rho_{addrail}\cdot S_{l1} - \rho_{line2}\cdot S_{rail2}\right]; \\
\dfrac{d\rho_i}{dt} = \dfrac{1}{V_{inj}}\left[f_{l2}\cdot\rho_{add\_rail}\cdot S_{l2} - q_{in\_j} - q_{nozzle} - S_n f_n \rho_i - Z_n\right]; \\
\dfrac{d\rho_c}{dt} = \dfrac{1}{V_c}\left[q_{in\_j} - q_{out\_j} + S_v f_v \rho_c + Z_v\right]; \\
\dfrac{d\rho_v}{dt} = \dfrac{1}{V_{valve}}\left[q_{out\_j} - q_{summ}\right]; \\
\dfrac{dS_n}{dt} = \dfrac{1}{M_n}\left[\left(f_n - f_{add\_n}\right)\left(p_i - p_{i\_0}\right) + f_{add\_n}\cdot p_n - \delta_n h_n - f_n\cdot p_c\right]; \\
\dfrac{dh_n}{dt} = S_n; \\
\dfrac{dS_v}{dt} = \dfrac{1}{M_v}\left[F_s - F_{s\_0} - \delta_v\cdot h_v + \sigma_v\left(f_{v1} - f_{v2}\right)\left(\dfrac{p'_v + p_r}{2}\right)\cdot K\right]; \\
\dfrac{dh_v}{dt} = S_v
\end{cases}
$$

Main equations

Advantages and disadvantages of MADI software



+ System model contains hydraulic and mechanical elements based on real objects – parts of Common Rail system.
+ Calculation accuracy is checked by experiments.
+ *We can make a new additional mathematical model by technical project.*
+ Software is easy to use for different specialists.
+ The first version of the software has been used for designing new experimental models of Common Rail Injector..`

• At this stage the number of functions is limited, for example multi-factors optimization.

- Small variability of the model.

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Thank you for your attention
Ready to answer your questions

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