RETROFITTING AN EXPERIMENTAL SYSTEM FOR EXAMINING MECHANICAL DIESEL INJECTION SYSTEMS

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Abstract

An experimental rig along with a MATLAB script for examining mechanical diesel injection systems have been successfully developed in this work. The system is capable of extending further to include a high-speed camera for imaging spray breakup events occurring in the near-field of injector exit. The system developed in this study allows to record hydraulics characteristics of a number of consecutive injection shots. The MATLAB script allows to isolate fuel line pressure signal of single injection shot from those consecutive events (e.g. 400 shots used in this article), then to output the mean, coefficient of variation (CoV) in fuel line pressure and other interested parameters. The CoV values get a peak of 7% approximately and at the maximum pressure location. The high CoV peak might contribute to the engine cycle-to-cycle variation (CoV of indicated mean of effective pressure - IMEP) and this suggests an investigation to link this with CoV of IMEP in the future in an engine test-bed.

Keywords*: Mechanical injection system; diesel direct injection system; fuel line pressure; spray atomization.*

1. Introduction

Injection systems utilized in compression ignition (CI) engines have been extensively developed since Rudolf Diesel invented the CI engine in 1890s. From mechanically controlled systems developed in the early days, nowadays, electronically controlled fuel injection systems have been equipped widely in modern diesel engines. The significant development shifts most of the attentions towards the electronically controlled systems equipped in modern diesel engines [1]. However, mechanical injection systems are still very important for different applications thanks to their long lifetime, reliability, and capability of operating under different hash environment conditions. In military vehicles such as heavily armed and armoured combat vehicles, for example, mechanical injection systems are dominated until now [2]. Investigating the fuel injection characteristics for mechanical systems is therefore critically important

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as this can help not only to well exploit, diagnosis, and maintain but also to develop and extend the systems to utilize in different applications [3]. This work aims to develop an experimental system in laboratory to investigate injection profiles of diesel injection systems (including high pressure pump, high pressure line, and injectors) and a data processing code to output parameters interested. The achieved knowledge may be adopted for developing injection models, injector/pump diagnosing, and designing a new injection system. This system can also be extended to include a high-speed camera to simultaneously investigate the fuel fragment morphology and spray structure in the future and the injection profiles investigated in this current study.

Pressure signal in fuel line prior to the injectors of mechanically controlled fuel injection systems could be potentially used for different studying purposes: determining injection timing, examining the influence of fuel modulus and viscosity on injection timing [4], determining the fuel mass flow rate during the injection. Work done in [4] developed a novel method to evaluate the injection advance in diesel engines equipped with mechanically controlled fuel systems. The experimental data show that fuel's physical properties such as modulus and viscosity have significant effects on injection timing. This study has also demonstrated that the fuel properties of incompressible fuels like diesel and biodiesel, normally, do not affect the fuel line pressure.

In doctoral dissertations done by Nguyen Hoang Vu [5] and Pham Hong Son [6], fuel line pressure profiles of mechanical diesel injection systems were experimentally tested. Nguyen Hoang Vu [5] measured the pressure signal in a mechanically controlled fuel injection system in engine test-bed while Pham Hong Son [6] recorded the pressure profiles in a high-pressure pump diagnosis system. The aims of the measurements are to model the fuel injection flow rate based on Bernoulli correlations. Their achievements showed good correlations between the fuel line pressure signals and fuel flow rate and this provides an alternative approach to investigate engine cycle via the pressure signal. In these two theses, using the consecutive injections was not addressed. In other words, the results showed only single/separated pressure profile for each shot and this is inadequate to perform a statistic investigation or to examine the instability of spray atomization. This is quite important as the atomization is understood as a random process [7-9].

Accurately quantifying start of injection (SoI) or injection advance is very important for both theoretical/experimental studies on the engine performance, however, measuring this parameter is not always straight forwards and the fuel line pressure signal may be a solution for this. In mechanically controlled injection systems, the high-pressure pump creates high pressure in the fuel line and drives the fuel injection quantity control mechanisms through its camshaft. Theoretically, the injection timing or SoI could be determined from the cam profiles. However, there exist delay times in fuel supplying system (e.g. mechanical and hydraulic delays). To solve the issue, SoI could also be measured using the needle lift measurement, however, measuring needle lift profiles is critically complicated and expensive. Also, as mentioned earlier, fuel properties like modulus and viscosity play a significant role in timing of injection start [4] and this adds further difficulties to the measurement practices.

Work done in [10] has examined the pressure signals in a diesel fuel injection system equipped with a traditional mechanically controlled fuel injection pump. Two different pressure sensors were mounted in the fuel line at the injector inlet and at the high-pressure pump outlet, respectively. Different fuels including biodiesel and diesel #2 under different temperatures were tested in this work. Testing different fuels at different heating conditions aims to investigate the influence of fuel modulus, viscosity and density on the injection timing and ignition delay as well as the maximum of the fuel line pressure. It revealed that the decreasing fuel temperature advances the fuel pressure rise, but the rise is partially compensated by increased ignition delay at some engine working conditions (e.g. low load). The advance in pressure rise was also observed in the both injector inlet and pump outlet and this suggests that the fuel pressure propagation is mainly attributed to the injection advance.

Pressure in the fuel line prior to the injectors could be a good indicator for quantifying SoI. Also, as mentioned earlier, the pressure is also a good reference for fuel mass flow rate supplying to the engine [5, 6]. Exactly, quantifying the SoI is very difficult and requires careful calibrations. Using the fuel line pressure for SoI is quite common in literature, but details of the quantifying SoI are scarce. Today, with the development of high-speed cameras, linking signals like the pressure profile and start of injection is possible but this is quite costly. Using a camera is impossible in practical engines, but this can be suitable for optically accessible engines or in separated fuel supply systems (like the one developed in this study).

In this article, an experimental system was developed to investigate the injection characteristics. For the long term, this aims to develop a tool to study entire spray atomization process from fuel supplying to injector performance and finally the primary and secondary atomization process. In this work, we limit to measuring pressure signals in fuel line prior to the injector inlet using a super-high frequency pressure transducer, a number of injection shots will be recorded for each injection condition and a MATLAB code will be developed for data processing. The code is capable of outputting the mean and coefficient of variation of line pressure and other interested parameters.

2. Experimental setup

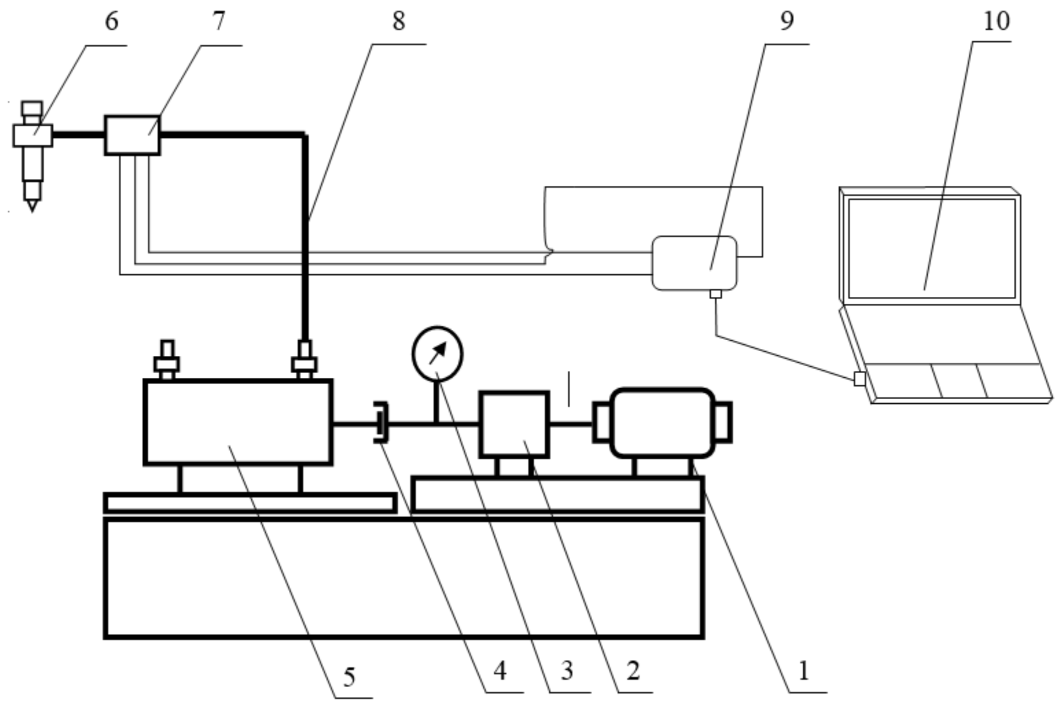


Fig. 1. Schematic of experimental setup

1- Electrical engine; 2- Speed exchanger; 3- Speed indicator; 4- Coupling; 5- High-pressure pump; 6- Injector; 7- Pressure transducer; 8- High-pressure line; 9- Data Acquisition (DAQ); 10- LabVIEW in-house program.

Experimental system designed in this study is schematically described in Fig. 1. Originally, this is a high-pressure pump diagnosis rig (STAR-12). This is a pure mechanical system, however, our initial efforts in this study are retrofitting it to be capable of measuring high-pressure line pressure profiles under different operating conditions. In the long term, we aim to extend the system to investigate the spray atomization characteristics for different types of fuels (e.g. diesel, biodiesel, diesel with additives) and injectors. It is expected to include high speed cameras and light sources so that shadowgraph, particle velocimetry (PIV), and particle tracking velocimetry (PTV) approaches [7] could be adopted.

Original items including electrical engine, speed exchanger, speed indicator, coupling, low and medium pressure pumps are remained in this update. The electrical engine driving the high-pressure pump is a 50 kHz – 380 V – 3 phases – 2.8 kW engine (#1). The engine can work either clock- or anti-clockwise and the speed of the exchanger (#2) varies between 65 and 2500 rpm. Fuel system includes low-pressure pump, medium-pressure pump and is driven by a 0.35 kW electrical engine. The high-pressure pump used in this study is a 12-injector Bosch type having a piston with a diameter of 10 mm and a whole stroke of 10 mm. The fuel from high pressure pump (#5) is supplied for a 7-hole injector with a diameter of 250 µm. The angles between the hole and the injector-body center-line are 140°. It is important to note that the injector used here is an old item, so values obtained here like maximum pressure and the pressure profiles may not necessarily represent as references for other purposes like validating simulation models. This study aims to develop an experimental system and as such a new injector is not necessary to this end. In the future, the system will be extended to examine injection characteristics, then different injectors (both new and old) will be used.

A high-frequency pressure transducer (#7) is located in the high-pressure fuel line just right before the injector to measure the fuel line pressure. The transducer is capable of measuring hydraulic pressure up to 1600 bar which is equivalent to that in modern common-rail injection systems. The transducer signal is passed to the data acquisition - DAQ (#9) and recorded by an in-house LabVIEW program coded in this study. The DAQ is manufactured by NI with a working frequency of 8 MHz. The system is calibrated carefully to accurately measure fuel flow rate and fuel line pressure for consecutive injection shots. The pressure raw data of 500 consecutive injection shots is processed using a MATLAB code developed in this study which is presented in the following section.

3. Developing a script for data processing and preliminary results

3.1. MATLAB script

A MATLAB script has been successfully developed in this study to process the data and the algorithm is shown in Fig. 2.

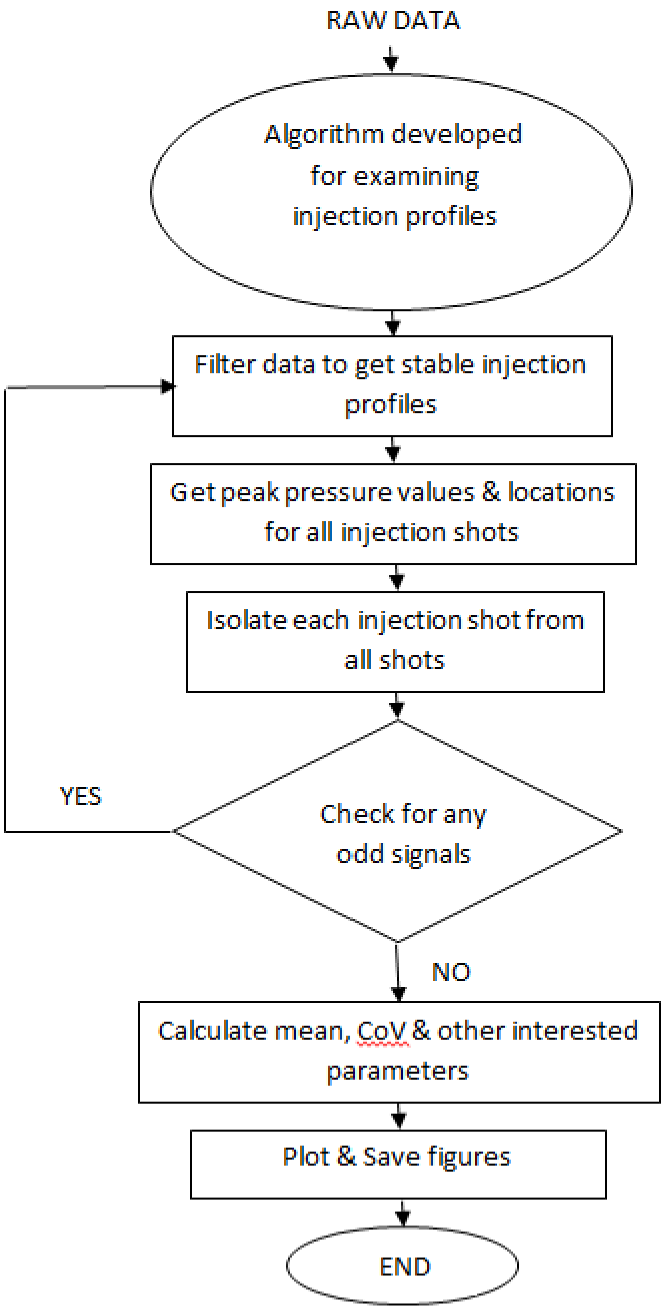
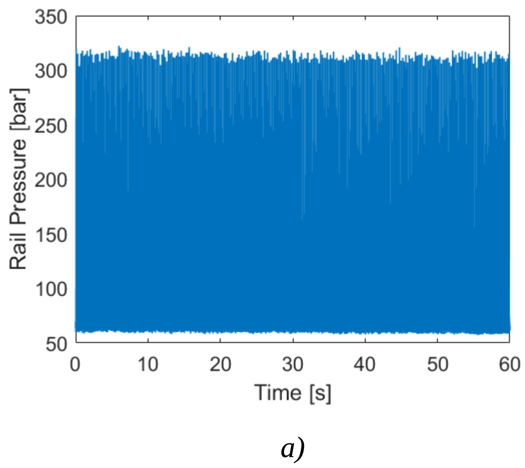


Fig. 2. Script flow diagram developed in this study for injection profile processing

As mentioned earlier, line pressure profiles of consecutive injection shots are recorded aiming to investigate the injection characteristics. Spray atomization is a random process in which liquid break-up is occurred under a number of instability phenomena like Rayleigh-Taylor and Kelvin-Helmholtz [8] and as such it is critically important to adopt statistic approaches to investigate spray injection characteristics [9]. Measuring and processing consecutive injection shots are therefore necessary to examine the random process - atomization. In this study, a number of consecutive injection shots are recorded and the MATLAB code developed here is firstly to get rid of unstable shots in the beginning and at the end (if any), then to choose approximately 400 consecutive shots to process. It is noted in an earlier study [7, 9] that consecutive 300 cycle data is adequate to statistics important spray primary-atomization events.

The processing starts by finding out the peak injection pressure locations and values. The peak values and locations are the base for isolating single injection shots in the next step. Final checks are then performed for any odd cycles. Interested parameters like the mean, coefficient of variation are calculated from the good data set. The preliminary results output using the code will be presented in the following section.

3.2. Preliminary results



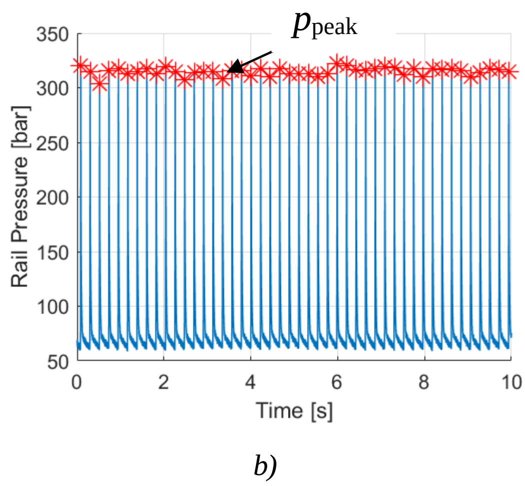


Fig. 3. An example of (a) data recorded for 400 injection shots (cycles) and (b) maximum pressure values noted by MATLAB code developed in this study (output only some cycles from 400 cycles recorded to clearer show the injection profiles)

Figure 3 shows an example of data recorded for consecutive injection shots (a) and maximum pressure values (b) noted by MATLAB code developed in this study (output only some cycles in this figure to clearly show the pressure signal). Fluctuations are noted for peak pressure values shown in Fig. 3 and this is expected as the spray atomization is a random and instable process as mentioned earlier. In this measurement, the mean, standard of deviation (Std) of peak pressure (p_{peak}) through 400 cycles is 218 bar and 3.75 bar, respectively. The coefficient of variation (CoV) in p_{peak} is 7%. Approach used to calculate CoV in (p_{peak}) is similar to that used in CoV of indicated mean in effective pressure (IMEP) [11] and the CoV in p_{peak} calculation is shown in Equation (1) below:

$$\text{CoV} = \frac{Std(p_{peak})}{Mean(p_{peak})}.100\% \quad (1)$$

More information about CoV in p_{peak} will be shown in Fig. 6 and related discussion.

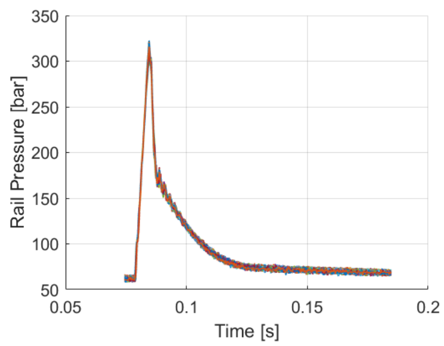


Fig. 4. All injection profiles placed in one cycle

As mentioned in previous section, injection shots are isolated from the consecutive injection shots using the MATLAB code and Fig. 4 shows all shots in one place and the figure illustrates that the recorded data is good and the code works well to isolate the shots. From pressure profiles of 400 injection shots, the mean of all shots can be computed and the mean curve of injection pressure is plotted in Fig. 5. Useful information could be output from the figure (e.g. the fluctuation in line pressure between 0.07s to the end), however, this is beyond the scope of this current work.

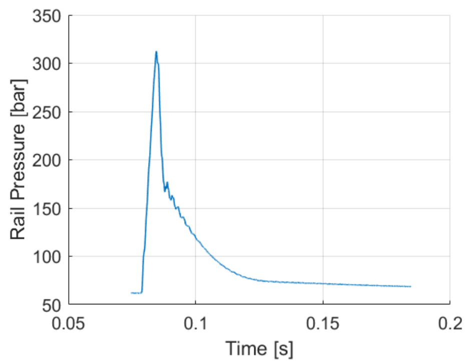


Fig. 5. Mean of all injection profiles

Figure 6 shows the coefficient of variation (CoV) in cycle injection pressure. The CoV values are calculated for each pressure value in the cycles using similar approach shown in Equation (1). It is quite interesting to note here that the CoV trend observed here is almost identical to that of the fuel line pressure. CoV in pressure gets peak at the location of peak pressure. The maximum CoV in pressure is 7% and this is expected to a diesel injector. Except for the maximum value of CoV observed at p_{peak} location as discussed, CoV values fluctuate around 1-2% during the injection process. It is found earlier that the stability limit for diesel engines reaches when CoV of IMEP is 2% approximately while that for spark ignition engines reaches when the CoV of IMEP value exceeds 10%. Observations in this study may suggest for future studies on variation of injection pressure along with combustion cycle-to-cycle variations in engines. Engine stability limits are difficult to quantify, but it may be evaluated through a limit value for CoV of IMEP and CoV in fuel line pressure in the engine test-bed.

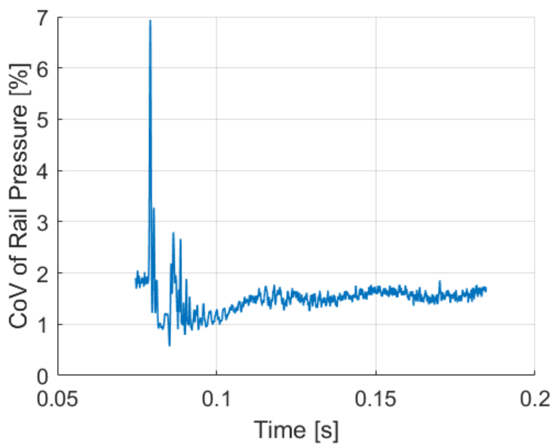


Fig. 6. Coefficient of variation (CoV) of line pressure

Figure 7 shows an example of injection profiles plotted for different working conditions (speed and load). This is only to demonstrate that the system and MATLAB code developed here are capable of examining fuel line pressure profiles under different operating conditions and this will be subject to our future work. This achievement may suggest an interesting work to link the information obtained here with atomization characteristics where a high-speed camera system is used to image the liquid fragments derived in the near-field of injector exit. This may contribute to the understanding of spray structure and liquid fragment dynamics and this in turn may help to control the injection process more efficiently and to improve atomization quality.

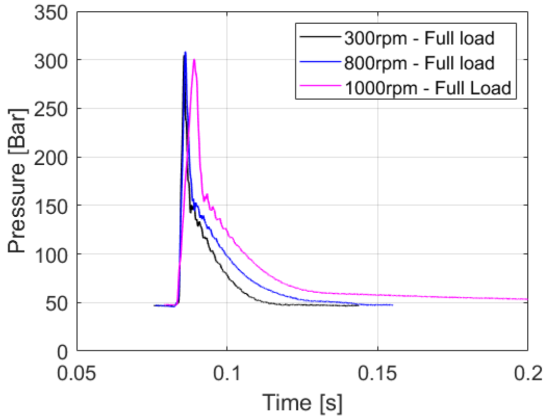


Fig. 7. Mean of pressure at different working conditions

4. Conclusion

An experimental system and a processing MATLAB code have been successfully developed to investigate the injection profiles for mechanical diesel injection system. This initial effort can operate under a wide range of camshaft speed and load conditions. Using a high frequency pressure transducer and data acquisition system, fuel line pressure signal of a number of consecutive injection shots can be recorded. The in-house MATLAB code allows outputting the mean injection profile for all injection shots and also coefficient of variation in the line pressure. Although some interesting results are shown, the system needs to be further advanced to evaluate measuring uncertainties. The outcome also suggests future studies on the spray macro parameters (spray angle, penetration, and revolution) and micro information (spray structure, fragment morphology, fragment density, volume and velocity) using high speed cameras and shadowgraph technique. Links between line pressure profiles and macro/micro information may be established and this may provide a useful knowledge for diesel breakup phenomenon which is normally described by Rayleigh-Taylor and Kelvin-Helmholtz instability.

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CẢI TIẾN HỆ THỐNG THỰC NGHIỆM NGHIÊN CỨU ĐẶC TRƯNG PHUN CHO HỆ THỐNG PHUN CƠ KHÍ

Tóm tắt: *Một hệ thống thực nghiệm nghiên cứu đặc trưng phun của hệ thống phun nhiên liệu diesel kiểu cơ khí và bộ xử lý MATLAB đã được xây dựng trong bài báo này. Hệ thống này cho phép phát triển trong tương lai để nghiên cứu chuyên sâu quá trình phân rã tia phun trong vùng cận vòi phun khi sử dụng camera tốc độ cao. Hệ thống cho phép đo đặc trưng dòng thủy lực trong đường ống theo thời gian cho nhiều lần phun liên tục. MATLAB code cho phép tách tín hiệu từng lần phun từ tín hiệu của nhiều lần phun (ví dụ: 400 lần trong nghiên cứu này). Các tín hiệu tách ra được MATLAB code xử lý trích xuất các thông số quan trọng như đường trung bình, hệ số thay đổi áp suất (coefficient of variation - CoV). Kết quả sơ bộ cho thấy hệ số thay đổi áp suất trên đường ống - CoV đạt giá trị cực đại (khoảng 7%) tại vị trí áp suất phun lớn nhất. Giá trị cao của CoV ghi nhận trong bài báo này có thể là một trong các nguyên nhân chính ảnh hưởng đến hệ số thay đổi áp suất chỉ thị trung bình của động cơ (CoV of indicated mean of effective pressure - IMEP) và đây là một ý tưởng để có thể triển khai nghiên cứu trong tương lai trên bệ thử động cơ.*

Từ khóa: Hệ thống phun cơ khí; phun trực tiếp nhiên liệu diesel; áp suất nhiên liệu trên đường ống; phân rã tia phun.

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