Analysis of the Engine Start-Up Process

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***Abstract*—The article describes, based on the author's own research, four different stages of a diesel engine start-up. In stage 1, the driving mechanisms of the engine are set in motion and there is a systematic increase in the angular velocity of the crankshaft as a result of driving it with a starter. Stage 2 is the rotation of the engine crankshaft with an almost constant angular speed using the starter itself. Stage 3 begins with the first ignition of the combustible mixture and the last stage (stage 4) only covers the occurrence of ignitions of the combustible mixture and results in starting the combustion engine. Then, the duration of the particular stages of the diesel engine start-up was analyzed.**

***Keywords*—engine, process, start-up**

I. Introduction

Successful start-up of a vehicle internal combustion engine is a necessary process in order to achieve its independent operation at idle speed [2,5]. During the independent operation, the engine internally generates mechanical energy by converting the chemical energy contained in the fuel via combustion. This energy enables to overcome all resistances during engine operation [9]. Each start-up process of a vehicle internal combustion engine is accompanied by numerous negative phenomena and processes that influence both the engine itself, as well as its environment. These negative phenomena and processes are particularly visible in the case of starting a diesel engine [3, 5, 11].

During engine start-up, the wear intensity of its tribological pairs increases as a result of insufficient lubrication due to the lubrication system inertia, high viscosity of the lubricating oil (especially at low ambient temperatures) and insufficient relative speed of the moving elements, [4, 10, 16]. Secondly, during the start-up of a diesel engine, insufficient atomization and evaporation of the first doses of fuel result in auto-ignition as well as incomplete combustion of the fuel-rich combustible mixture in engine cylinders [1, 3, 8]. Therefore, an increased emission of toxic components can be observed in the exhaust gases during the start-up [7, 14, 15]. When starting an internal combustion engine, the significant resistance to motion results in the high values of current consumed by the starter in a short time, thus causing sudden overloads in the vehicle electrical system. In addition, malfunctions in other electronic systems of the vehicle may occur due to the corresponding voltage drops at the battery terminals [12, 13].

Hence, special attention must be devoted to the start-up process of a diesel engine. This is shown in the research and published scientific articles on the topic [3,5,11,13]. This paper analyzes the duration of a four-stage transitional process, i.e. the start-up of a vehicle diesel engine. The considerations found in this article result from numerous years of research carried out by the author under the actual vehicle operation conditions [5,6].

II. Start-up stages of a diesel engine

The analysis of the angular velocity of the engine crankshaft and the amperage draw by the starter during the meshing phase of the starter with the flywheel of the crankshaft indicates that the start-up of a diesel engine should be considered as a multi-stage process. On the basis of the author's own research, four different stages of diesel engine start-up were distinguished [5]:

1. **Stage 1**, in which the moving mechanisms of an engine are put into motion and there is a systematic increase in the angular velocity of the crankshaft as a result of driving it with a starter.
2. **Stage 2** constitutes the engine crankshaft rotation at an almost constant angular speed with the help of the starter itself.
3. **Stage 3** is initiated with the first ignition of the combustible mixture. Intermittent operation of the starter as well as irregular combustion of the mixture in the engine cylinders occur in this stage.
4. **Stage 4**, involves only the occurrence of the combustible mixture ignitions and results in the start-up of the combustion engine.

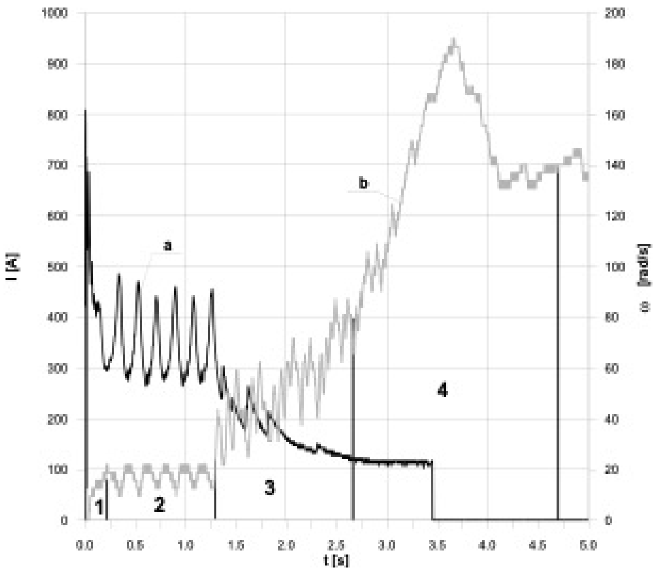

Fig. 1. The course of the angular velocity of the crankshaft and the amperage draw by the starter during the "model" start-up of a vehicle diesel engine with four distinguished stages; a – current intensity, b – angular speed of the crankshaft, 1 – starting stage 1, 2 – starting stage 2, 3 – starting stage 3, 4 – starting stage 4 [5].

In Figure 1, attention should be drawn to a clear increase in the amperage value and a decrease in the angular velocity of the crankshaft when individual cylinders enter the compression stroke. This is due to the moment of resistance to compression of the fuel-air mixture.

It should be noted that under the actual conditions of vehicle use, the situation where a diesel engine is started, e.g. without stage 2, or where a return to stage 2 occurs following stage 3, is possible. Other transitions between the afore-mentioned stages can occur as well. This is discussed in greater detail in [5]. The duration of each of the four distinguished stages of starting a vehicle diesel engine, based on the author's own research, will be analyzed in the further part of this paper [5, 6].

III. Analysis of the Duration of Individual Stages of the Diesel Engine Start-up

During the stage 1 of diesel engine start-up, the moving mechanisms of the engine are put into motion and a systematic increase (see Fig. 1) in the angular velocity values of the crankshaft occurs under the influence of driving it with a starter. The course of changes in the angular velocity during stage 1 depends mainly on the crank mechanism inertia [5].

In line with the author's own research carried out under the actual vehicle operation conditions, it is stated that the average duration of stage 1 of diesel engine start-up is 0.115 s [6]. Figure 2 shows a histogram of the statistical distribution for the duration of stage 1 of engine start-up.

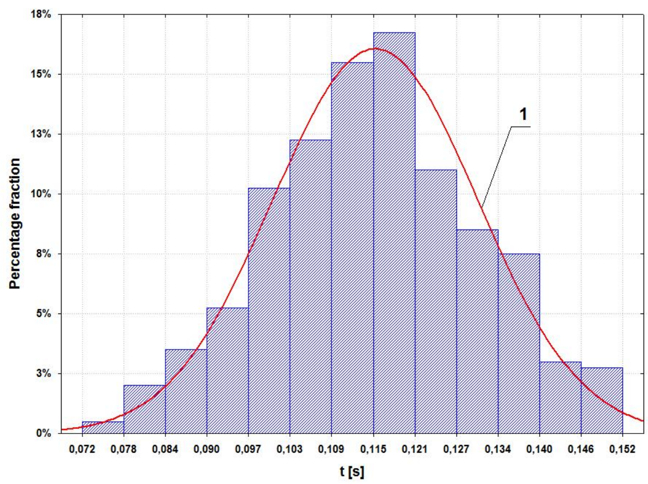

Fig. 2. Histogram reflecting the duration distribution of stage 1 of the 4CT90 diesel engine start-up; normal distribution fit; 1 – normal distribution density function fitted to empirical data [6].

Figure 2 indicates that stage 1 of diesel engine start-up lasts from 0.108 s to 0.121 s in 32.7% of the registered cases. Out of the observed cases, only 5.8% were longer than 0.14 s [6].

In stage 2 of the internal combustion engine start-up, its crankshaft is rotated only with an electric starter at "almost constant" angular speed. This speed depends solely on the state of charge of the batteries [5]. Stage 2 occurs until the first self-ignitions of the air-fuel mixture in the combustion chambers of the diesel engine. This is shown in Figure 1.

The author's own research showed that stage 2 is very short (more than 72% of cases were shorter than 0.2 sec.) or that it did not occur at all (4% of cases) [6]. This is reflected in the histogram shown in Figure 3.

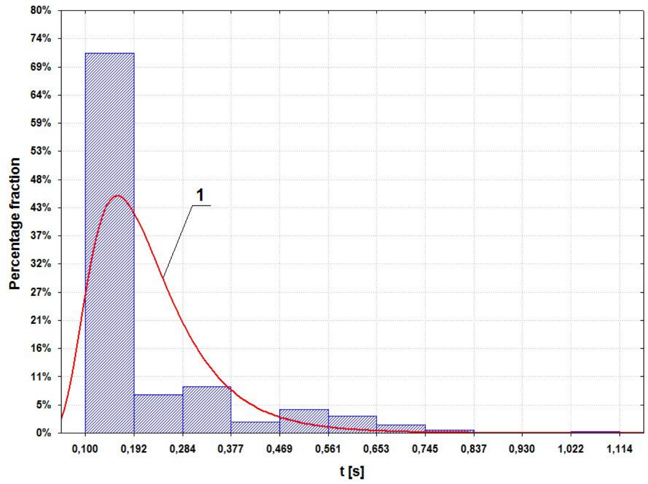

Fig. 3. Histogram reflecting the duration distribution of stage 2 the 4CT90 diesel engine start-up; 1 - log-normal distribution density function fitted to empirical data with threshold: 0.000, scale parameter: -1.6180, and shape parameter: 0.4601 [6].

Figure 3 shows that the average duration of the start-up stage 2 during which the crankshaft is driven by the starter only, amounted to 0.225 s. Stage 2 was shorter than 0.178 s in 67.3% of registered cases. In most cases (99.7%), stage 2 took up to 1 s [6].

Stage 3 of the diesel engine start-up is initiated with the first self-ignition of the combustible mixture in the combustion chamber of an engine. This stage is characterized by the intermittent starter operation as well as irregular combustion of the fuel-air mixture in the engine cylinders (see fig. 1).

It should be mentioned that in the course the actual vehicle internal combustion engine usage, in the vast majority of starts (almost 84%) there is no stage 3. However, there are also start-ups in which the engine crankshaft is driven again with the starter itself following the occurrence of stage 3, that is, there is a return to stage 2. In the tested engine, such starts accounted for about 1% [6].

In the research conducted by the author, the average duration of stage 3 amounted to 0.137 s, which is shown by the histogram of the statistical distribution of stage 3 duration (see Figure 4). It can be seen that the duration of stage 3 of the start-up was within the range of 0.095 s up to 0.13 s in 58.2% of registered cases [4].

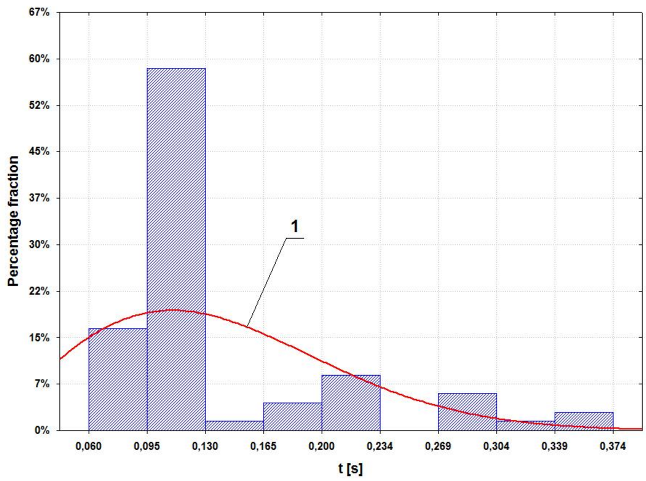

Fig. 4. Histogram reflecting the duration distribution of stage 3 of the 4CT90 diesel engine start-up; 1 – Rayleigh distribution density function fitted to empirical data with threshold parameter: 0.000, and scale parameter: 0.1097 [6].

Finally, in stage 4 (see fig. 1) there is only self-ignition of the fuel-air mixture and the start-up process is about to finish. Figure 5 shows a histogram of the statistical distribution of the stage 4 duration. Figure 5 shows that the stage 4 of the diesel engine start-up lasted from 0.683 s to 0.886 s in 29.3% of registered cases. The start-ups of the internal combustion engine in which the stage 4 lasted up to 1 s in 65.1% of cases. The mean duration of stage 4 of the start-up equaled 0.958 s [6].

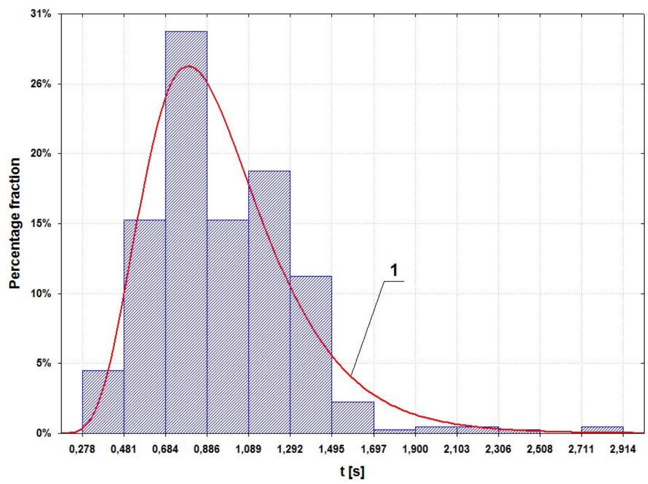

Fig. 5. Histogram reflecting the duration distribution of stage 4 of the 4CT90 diesel engine start-up; 1 – log-normal distribution density function fitted to empirical data with threshold parameter: 0.000, scale parameter: -0.1053, and shape parameter: 0.3574 [5].

It should be mentioned that the start-up time of a vehicle diesel engine is the total duration of each of its four stages combined. In the conducted tests, the average value of the combustion engine start-up time amounted to 1.139 s. Nearly 29% of the registered diesel engine start-up times did not exceed 1 s, and 73.8% lasted up to 1.5 s (see Figure 6) [6].

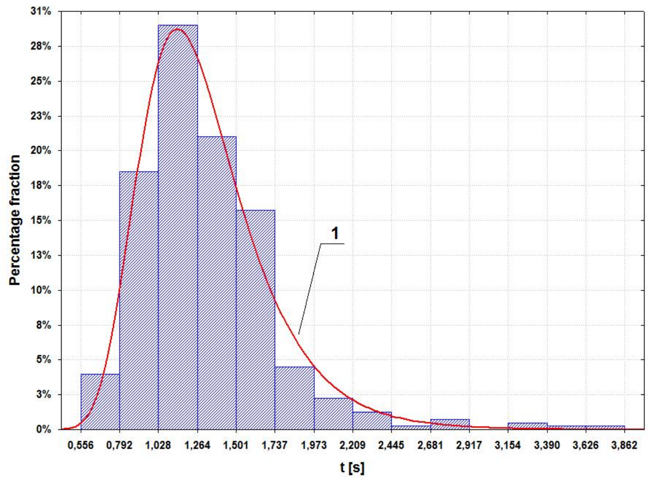

Fig. 6. Histogram reflecting the 4CT90 diesel engine start-up time; 1 – extreme value distribution density function adjusted to empirical data with position parameter: 1.1391 and scale parameter: 0.2971 [6].

When comparing the duration of individual stages of the diesel engine start-up, it can be stated that the main factor that determines the starting time is the stage 4 duration. This is shown in Figure 7, where the scatter plot between the duration of stage 4 and the internal combustion engine start-up time is presented, with the confidence intervals for the forecasted mean observation and prediction calculated with the assumption of compliance with the normal distribution at the confidence level of 95%.

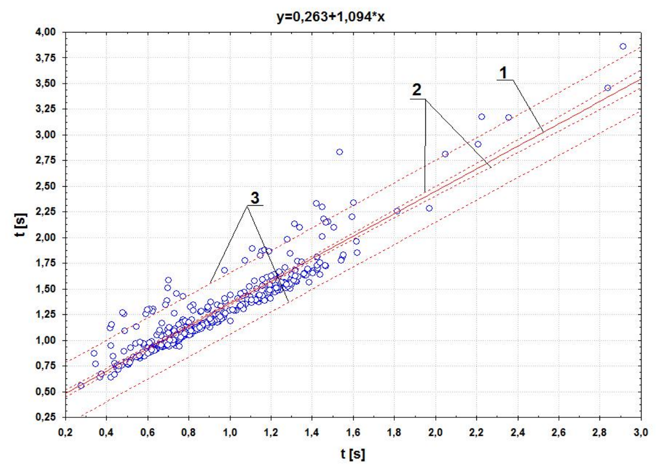

Fig. 7. The scatter plot for the duration of the stage 4 and the 4CT90 diesel engine start-up (y axis); 1 – regression line, 2 – confidence interval for the predicted mean observation, 3 – confidence interval for the predicted observation (prediction interval).

There is a very high correlation between the stage 4 duration and the start-up time of the internal combustion engine. The linear correlation coefficient between these variables is equal to r = 0.9313, proving a very strong relationship between the analyzed times.

IV. Conclusions

The paper, which summarizes the multiannual research conducted by the author under the actual operating conditions of a diesel vehicle engine describes four consecutive stages of its start-up. The presence of these stages results from the occurrence of complex phenomena and processes during the start-up. The analysis of the obtained and presented test results clearly indicates that the duration of the combustion engine start-up is determined by the duration of stage 4.

References

[1] K. F. Abramek, "Ocena wpływ paliwa w początkowej fazie rozruchu silnika na intensywność przedmuchów gazów do skrzyni korbowej," Zeszyty Naukowe WSOWL. Nr 4(174), 2014, pp. 98–103. [in Polish].

[2] P. Bera, "Development of Engine Efficiency Characteristic in Dynamic Working States. Energies, vol. 12(15), pp. 2906, 2019.

[3] J. Caban, "Wpływ parametrów wtrysku paliwa na przebieg procesu rozruchu silnika o zapłonie samoczynnym," Doctoral thesis, Politechnika Lubelska. Lublin, 2018. [in Polish].

[4] A.Datoo, M. F. Fox, "An initial investigation of the lubricant condition in the automotive ring zone under cold start conditions," Editors Dowson D. and others. Tribological research and design for engineering systems. Tribology series 41, Elsevier, 2003. pp. 517-523.

[5] P. Droździel, "Widmo rozruchu silnika o zapłonie samoczynnym jako kryterium oceny warunków użytkowania samochodu," PNTTE. Warszawa, 2009. [in Polish].

[6] P. Droździel, L. Krzywonos, Š. Liščák, "Selected aspects of diesel engines start-ups," Wydawnictwo-Drukarnia Liber Duo. Lublin, 2013.

[7] J. Gao, G.Tian, A. Sorniotti, A. E. Karci, R. Di Palo, "Review of Thermal Management of Catalytic Converters to Decrease Engine Emissions during Cold Start and Warm Up," Applied Thermal Engineering, vol. 147, 2019, pp. 177–187.

[8] B. Giechaskiel, A. Alessandro, A.A. Zardini, M. Clairotte, "Exhaust Gas Condensation during Engine Cold Start and Application of the Dry-Wet Correction Factor, " Applied Sciences. Vol. 9, no. 11, 2019, pp. 1-15.

[9] J. B. Heywood, "Internal combustion engine fundamentals 2E," McGraw-Hill Education, 2018.

[10] M. F. Jensen, J. Bottiger, H. H. Reitz, M. E. Benzon, "Simulation of wear characteristics of engine cylinder," WEAR. No. 253, 2002, pp. 1044-1056.

[11] J. Mysłowski, "Rozruch silników samochodowych z zapłonem samoczynnym," WNT. Warszawa, 1996. [in Polish].

[12] J. Pszczółkowski, "Analiza i modelowanie procesu rozruchu silników o zapłonie samoczynnym," Redakcja Wydawnictw WAT. Warszawa, 2009. [in Polish].

[13] J. Pszczółkowski, "Badanie charakterystyk rozrusznika elektrycznego," Autobusy, vol. 6/2019, pp. 240-247. [in Polish].

[14] A. S. Ramadhas, H. Xu, D. Liu, J. Tian, "Reducing Cold Start Emissions from Automotive Diesel Engine at Cold Ambient Temperatures," Aerosol and Air Quality Research. No. 16, 2016, pp. 3330–3337.

[15] R. Suarez-Bertoa, C. Astorga C, "Impact of Cold Temperature on Euro 6 Passenger Car Emissions," Environmental Pollutio, vol. 234, 2018, p. 318–329.

[16] T. A. Tran, "Some methods to prevent the wear of piston-cylinder when using low sulphur fuel oil (LSFO) for all ships sailing on emission control areas (ECAs),"Diesel and Gasoline Engines, 2020.