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# DYNAMIC AND STRUCTURAL ANALYSIS OF THE PISTON AND CONNECTING ROD OF AN ENGINE FUELED BY DIESEL OIL AND ETHANOL USING IN-CYLINDER PRESSURE DATA

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***Abstract.*** *This work studied the effects of the use of ethanol fumigation in a diesel power generator on the structural integrity of the engine piston and connecting rod. The study was performed using the multi-body and flexible bodies techniques, with finite elements models, to obtain the variation of stress magnitude at critical locations. The applied loads were obtained experimentally from a pressure transducer installed in one of the engine combustion chambers. The experimental results showed increase in the in-cylinder peak pressure with the ethanol addition and the numerical models showed, changing in the cycle stress distribution and increase in stress magnitude, which could reduce the components life cycle.*

***Keywords:*** *Dynamic structural analysis, Flexible Bodies, Diesel Engine, Ethanol*

# 1 INTRODUCTION

In recent years, it has been noticed an effort to modernize mechanical components, electronic fuel injection systems and emission control systems from internal combustion engines and an increase in the use of alternative fuels. The focus is the reduction of greenhouse gas emissions, responsible for an environmental threat as climate change and degradation of air quality (Hansdah et al., 2014).

Compression ignition engines exhaust gases contribute for the air pollution, including particulate matter, nitrogen oxides and carbon monoxide. The ethanol has potential to reduce oxides of nitrogen and particulate matter emissions from compression ignition engines (Brito et al., 2014), and many countries have adopted the use of ethanol as an additive to gasoline. Brazil is a major producer and there was an increase in domestic production of anhydrous and hydrated ethanol in the last decade (Franco et al., 2015).

The engine parts, mainly the cylinder, piston, connecting rod and crankshaft are submitted, under normal operating conditions, to thermal, mechanical and physical–chemical loadings (Gupta et al., 2014). Gupta et al. (2014) explain that there are different types of stresses induced in connecting rods, as the axial stress induced by cylinder gas pressure and inertial force generated by reciprocating of piston. The piston is responsible to conveying the expansion of the gases to the crankshaft, via the connecting rod (Hiremath et al, 2014) and requires specific geometry to improve performance and optimize the combustion process (Szmytka et al, 2015).

During the conversion of chemical energy into mechanical work process, for producing reciprocating motion of the piston during compression and expansion of in-cylinder gas, the pressure in the combustion chamber affects directly the power and engine performance (Zhao et al., 2001). The translational motion of the piston is governed by the combustion gas force and the induced inertial forces of piston, which are converted by the connecting rod to the rotation of the crank (Perera et al., 2010). Thus, the study of in-cylinder pressure in synchronous to the piston position or to the crank angle is important in structural analysis of engine parts.

Numerical calculations have been used during the connecting rod and piston development phase. This kind of study is important to understand the structural behavior of these pieces and reduce project lead time and prototypes cost (Tiwari et al., 2014). Abdul-Lateef (2012) performed a finite element analysis of an automotive connecting rod. The results showed the critical location of maximum stress and suitable materials for the connecting rod. Doshi et al. (2013) studied a connecting rod used in light commercial vehicle using a finite elements software for analysis. The results showed the stresses developed in connecting rod under static loading with different loading conditions of compression and tension.

Louvigny et al. (2009) analyzes the stress distribution in cylinder engines and explain that flexible multibody dynamic simulation solves the problem of static analysis, which is the difficulty to apply the correct loads and boundary conditions. For the dynamic analysis they used the in-cylinder pressure data to calculate more precisely the load applied. Hiremath et al. (2014) obtained in-cylinder pressure curves of an engine and applied in a multi-body dynamic analysis to obtain the higher stress concentration points in the engine piston. The study showed the stress distribution and the influence of the shape change in this distribution.

The objective of this work is to study the effects of the use of ethanol fumigation in a diesel power generator on the structural integrity of the engine piston and connecting rod. The study was performed using the multi-body and flexible bodies techniques, with finite elements models, to obtain the variation of stress magnitude at critical locations. The applied loads were obtained experimentally from a pressure transducer installed in one of the engine combustion chambers.

# 2 METODOLOGY

## 2.1 Experimental Methodology

The experiments were carried out in a production, naturally-aspirated, four-stroke, four-cylinder power generator diesel engine. Table 1 presents the diesel power generator main characteristics.

**Table 1. Diesel Power Generator Specification**

| Equipment | PARAMETER | VALUE |
|---|---|---|
| Engine | Number of cylinders | 4 |
| | Bore × Stroke | 0.102 m × 0.120 m |
| | Total displacement | $3.922 \times 10^{-3}$ $m^3$ |
| | Compression ratio | 17.0:1 |
| | Rated power @ 1800 rev/min | 44 kW |
| Electric generator | Number of poles | 4 |
| | Voltage | 220 V |
| | Number of phases | 3 |
| | Nominal power | 55 kW |
| | Frequency | 60 Hz |

The pressure was measured using a quartz piezoelectric sensor, model 6061B, manufactured by *Kistler Instrument Corporation*, with measuring range between 0 and 250 bar and sensitivity of -25.6 pC/bar. This sensor has a dynamic nature, providing an output signal only if stimulated, i.e., when there is a pressure variation. This feature affects how the sensor is calibrated, as its output signal is processed. The measurement apparatus must include a water cooling system. The cooling system confers stability to the sensor, enabling its use at high temperatures ambient, such as inside the engine cylinder. For the conversion of the sensor electric charge variation to voltage linear variation, it was used a charge amplifier, model 5037B. Figure 1 shows the Kistler pressure sensor and the charge amplifier.

The pressure sensor was positioned in the engine head to get the first cylinder pressure, as showed by Fig. 2. The data acquisition rate was set at 100,000 Hz, equivalent to an angular resolution of 0,108º CA, for an engine constant speed of 1800 rpm. Data from the pressure transducer were stored in worksheets for each load test. A trigger wheel with a magnetic sensor was used to synchronize the pressure data with the engine cycle and was acquired simultaneously with the pressure sensor.

**Figure 1. Kistler pressure sensor model 6061B and charge amplifier model 5037B**

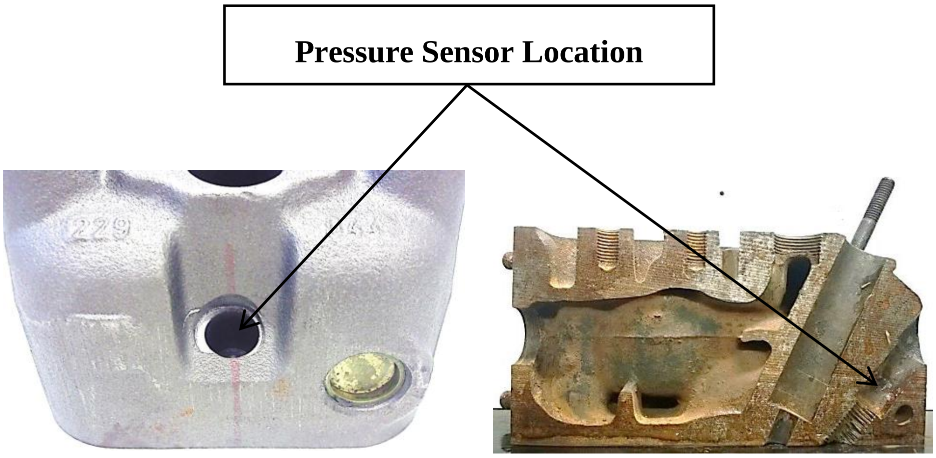


**Figure 2. Position of the pressure sensor in the engine head**

The tests were performed with diesel oil directly injected in the combustion chamber and ethanol fumigation in the inlet air manifold. The diesel oil used contains 7% of biodiesel (B7) and the hydrous ethanol concentrations were 0% (B7E0), 10% (B7E10), 20% (B7E20) and 30%. The pressure curves were positioned in function of the crank angle and was calculated the pressure average using 30 cycles.

## 2.2 Numerical Methodology

Multi-Body System Simulation (MBD) is defined as the study of the motion of mechanical systems caused by external forces, and is used to represent complex systems encountered in a wide variety of industries such as transportation. The system is represented by rigid and flexible bodies connected by various kinds of kinematic constraints and connectors (Goelke, 2015). Rigid body simulations do not capture deformations and to get these deformations, it may include flexible bodies in MBD simulations, to account the flexibility. Simulation of flexible bodies in an MBD system is able to calculate the body deformation, increases accuracy in load predictions, determines the stress distribution in a body and generate loads needed for fatigue analysis (Goelke, 2015).

In this work the numerical solver *MotionSolve*, by *Altair HyperWorks*, was used to simulate the piston and connecting rod motion and to study the bodies dynamic stress distribution, applying the experimental in-cylinder pressure as function of crank angle, for different diesel oil and ethanol concentrations. The piston and connecting rod CAD and finite elements models (FEM) were developed from the engine parts dimensions. This piston material is an aluminum-silicon alloy (young's modulus = 71 GPa) and the connecting rod material is a forged steel (young's modulus = 207 GPa). The FEM models were developed using tetrahedral elements with. Figure 3 shows the bodies, the CAD models, and the FEM models.

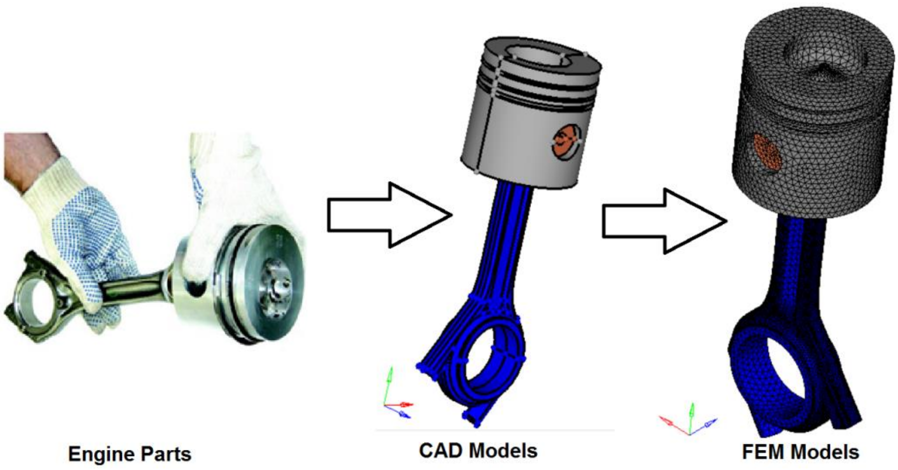


**Figure 3. Model development**

The piston and the connecting rod motion was simulated during a complete engine cycle, or 720º CA (crank angle), with a speed of 1800 rpm, which was the engine speed during the experimental tests. The in-cylinder pressure curve was used as input load to the numerical model, using the pressure sensor data synchronized to the engine cycle (crank angle) during 720º CA. A simulation for each ethanol concentration was developed and the pieces stress distribution during the engine cycle was obtained. Figure 4 shows the methodology scheme.

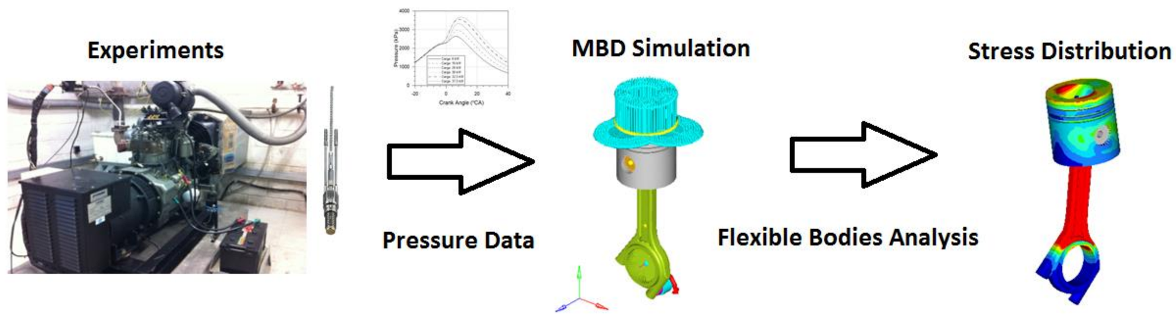


**Figure 4. Methodology Scheme**

# 3 RESULTS

The averaged in-cylinder pressure for different ethanol concentrations are shown in Fig. 5 for the complete cycle, for the engine load of 37,5 kW. Figure 6 shows the pressure during the combustion phase, where the maximum in-cylinder pressure increased as the ethanol concentration increases, being 4012 kPa, 3965 kPa, 3805kPa and 3667 kPa for B7E30, B7E20, B7E10 and B7E0, respectively. The fuel ignition delay is the time interval between the start of fuel injection and the start of combustion (Heywood, 1988). It can be noted that the ethanol addition shift the curve peak pressure due the increase in ignition delay with increase in ethanol concentration. The ignition delay for each case was: 22,0ºCA (B7E0), 24,3ºC (B7E10), 25,1ºCA (B7E20) and 26,2ºCA (B7E30). Theses parameters, peak pressure and ignition delay, changed the load configuration in the engine parts and, consequently, the stress distribution during the engine cycle.

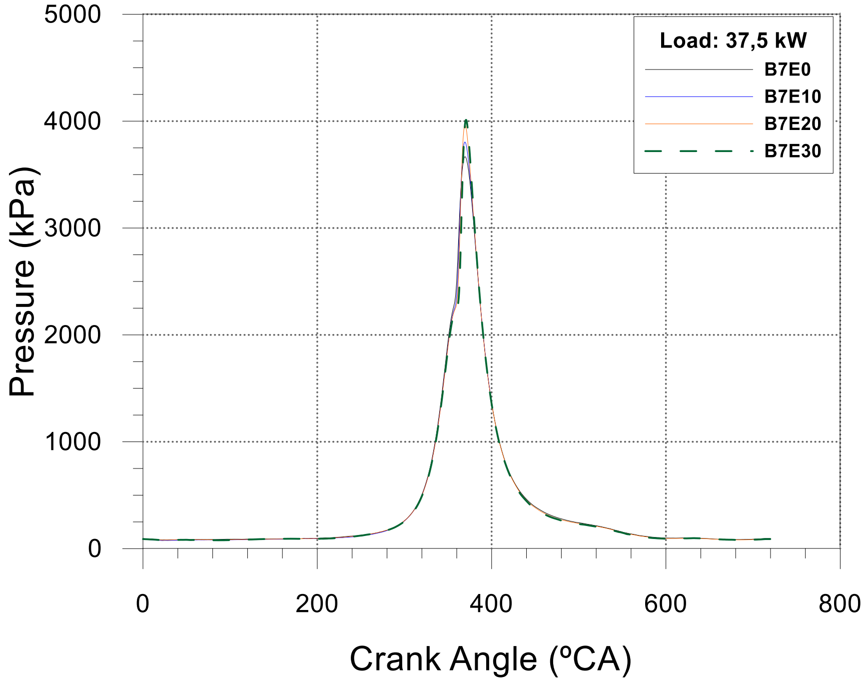


**Figure 5. In-cylinder pressure for different ethanol concentrations**

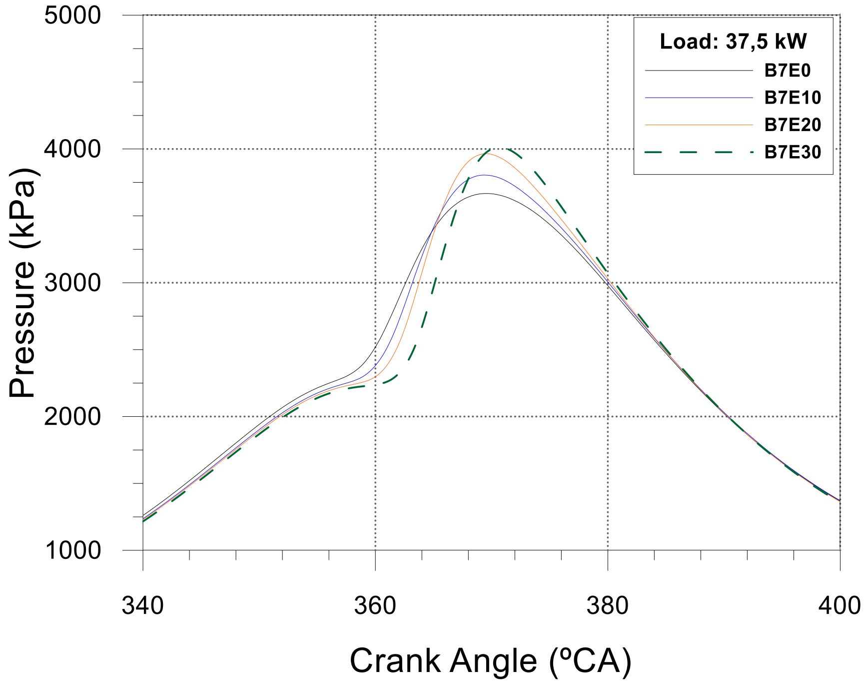


**Figure 6. In-cylinder pressure during combustion for different ethanol concentrations**

The dynamic flexible bodies analyses provided the stress distribution in the piston and connecting rod during the complete engine cycle. Figure 7 shows the moment of maximum von Mises stress in the connecting rod, for the different ethanol concentrations, that occurred in the peak pressure moment. The color scale maximum value was fixed in 70 MPa for better visualization and comparison. It can be noted that the increase in ethanol concentration increase the stress level in the connecting rod, mainly in the connecting rod beam. Figure 8 shows the evolution of von Mises stress during the cycle, in the region where the maximum values were found, located in the connecting rod and pin union. It can be noted differences between the experimental applied force and the stress response, due the induced inertial forces of piston. Figure 9 shows the evolution during the combustions, with maximum values of 62.4 MPa (B7E0), 65.0 MPa (B7E10), 71.2 MPa (B7E20) and 73.5 (B7E30).

The same behavior was found in the piston von Mises stress distribution, with maximum value in the peak pressure moment, with stress distribution showed by Fig. 10. The maximum values were 14.5 MPa (B7E0), 14,9 MPa (B7E10), 15.9 MPa (B7E20) and 16.1 (B7E30).

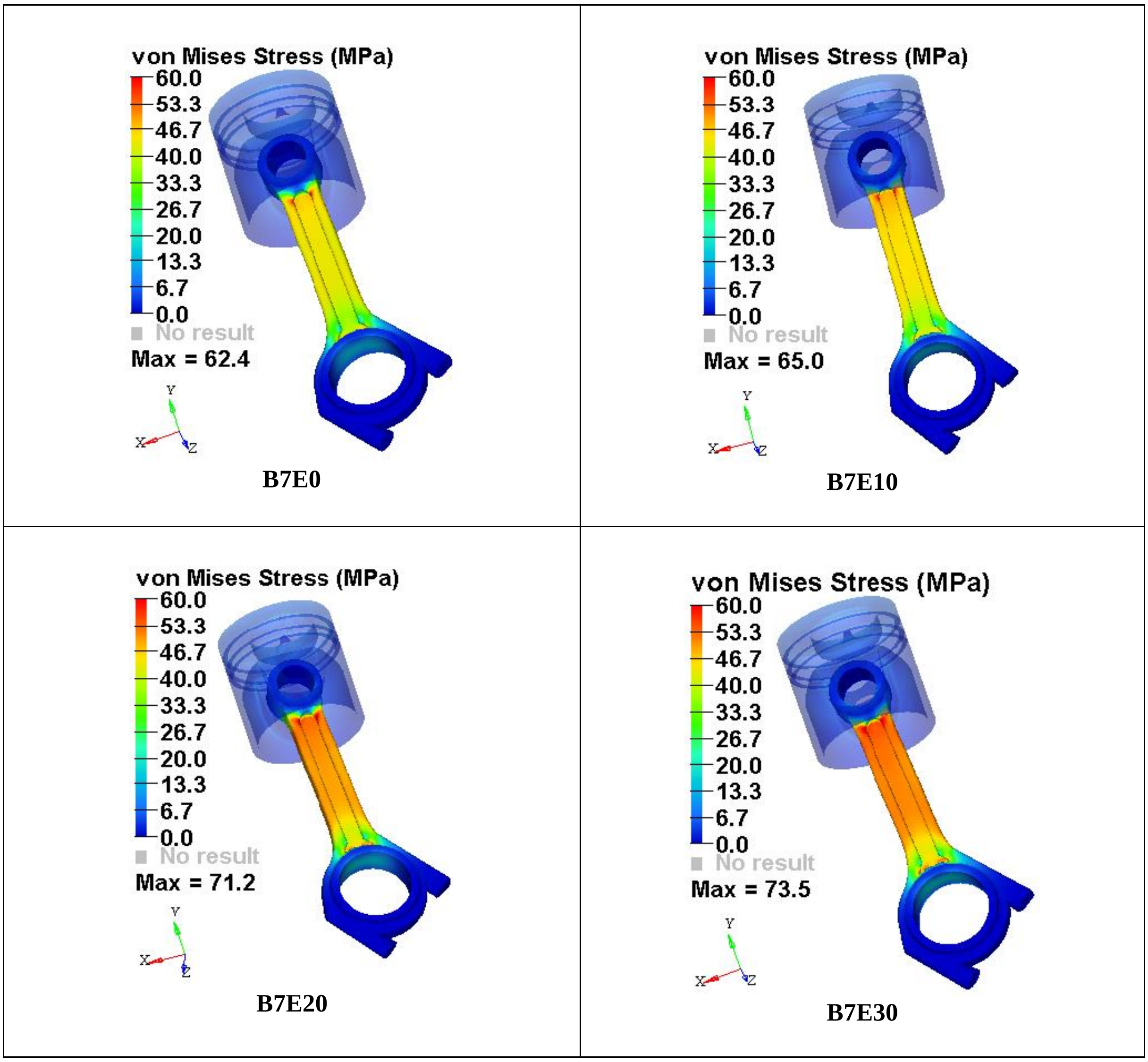


**Figure 7. Connecting rod von Mises stress distribution**

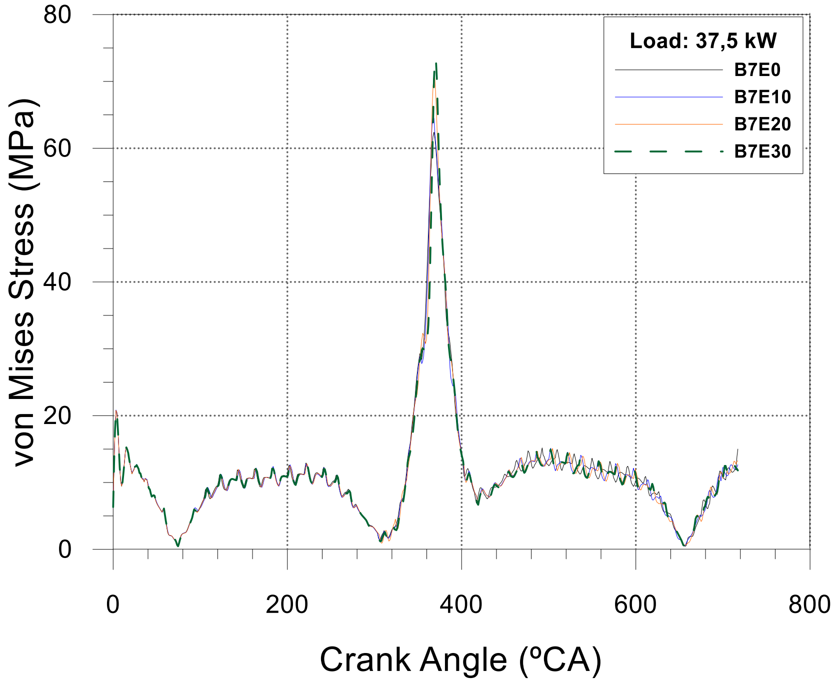


**Figure 8. Connecting rod von Mises stress evolution**

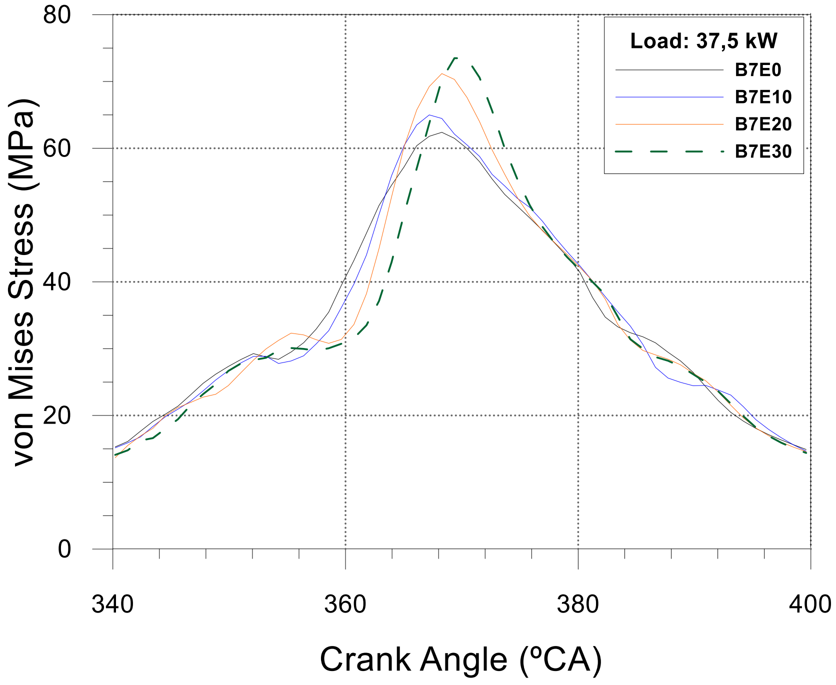


**Figure 9. Connecting rod von Mises stress evolution during the combustion**

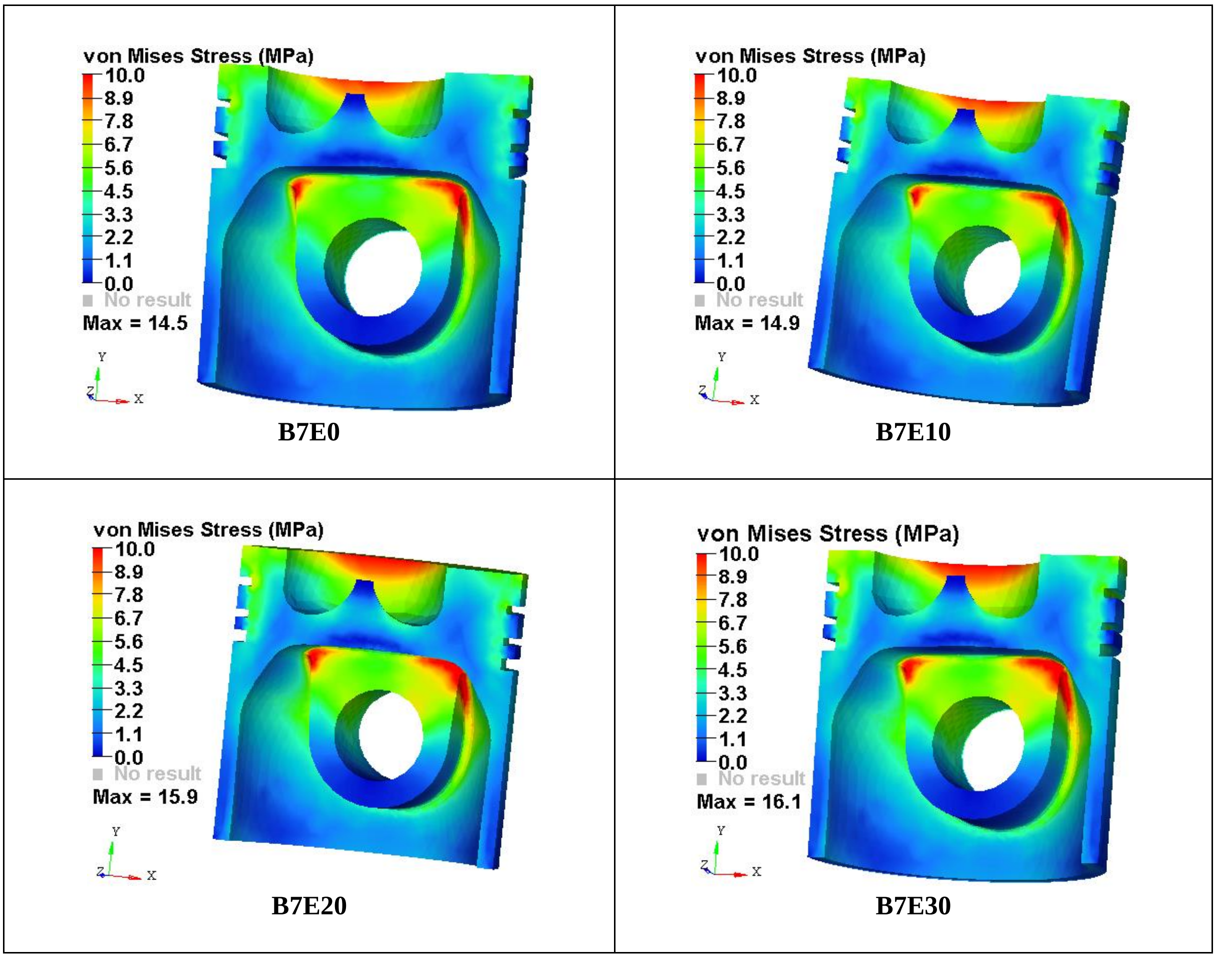


**Figure 10. Piston von Mises stress distribution**

Figure 11 shows the signed von Mises stress distribution for the parts during the peak pressure. The signed von Mises is the von Mises stress with the sign of the maximum absolute principal stress value (Papuga, 2012). It can be noted that the parts are submitted mainly to compressive stress. The connecting rod beam compressive stress increase with the ethanol concentration increase. Figure 12 shows the signed von Mises stress evolution in the beam center. The maximum values were -43.4 MPa (B7E0), -44.90 MPa (B7E10), -49.3 MPa (B7E20) and -51.3 (B7E30). This compressive load increase is important for a buckling analysis. Furthermore, the increase in the signed von Mises alternating stress during the cycle was noted, and could decrease the parts cycle life.

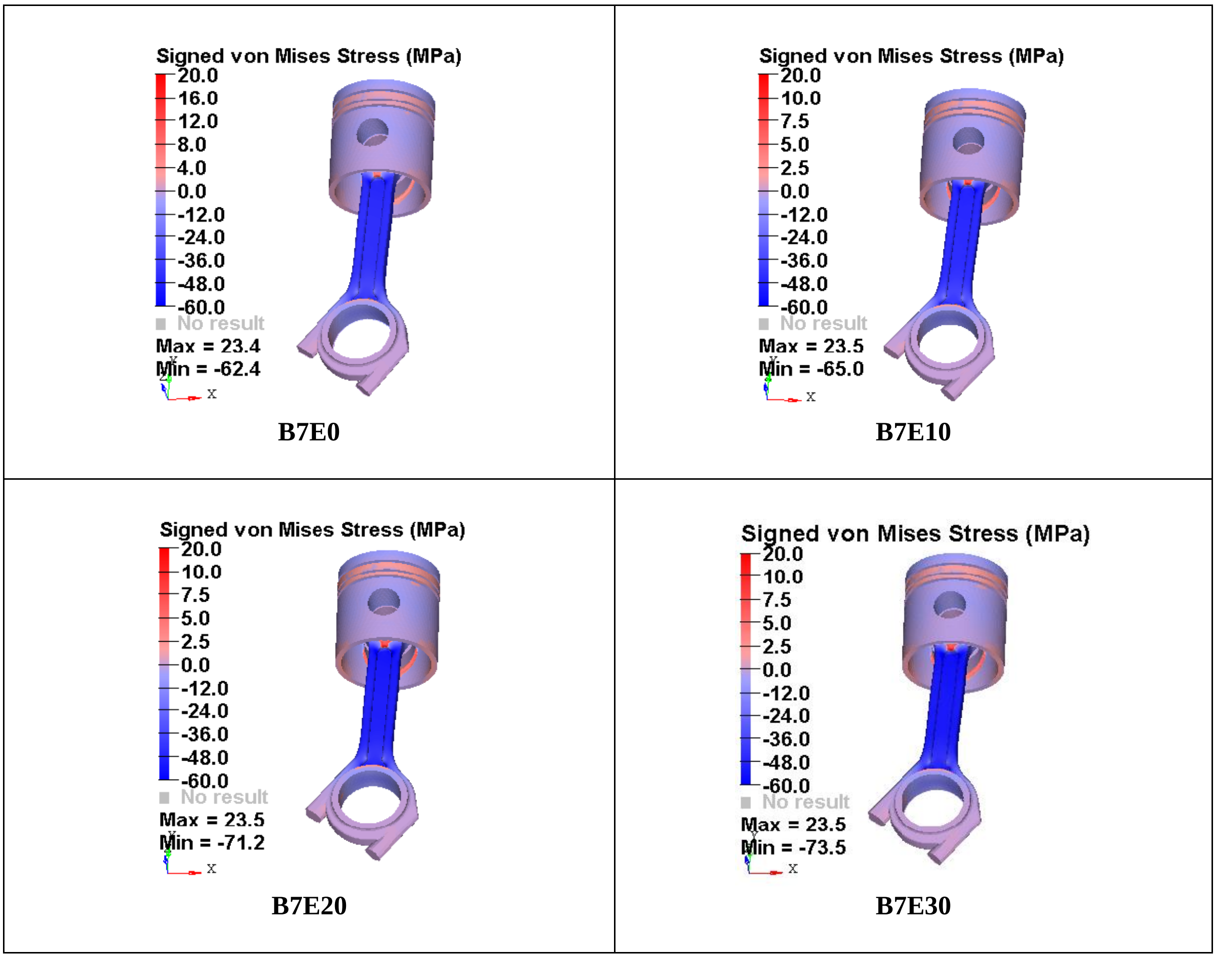


**Figure 11. Signed von Mises stress distribution**

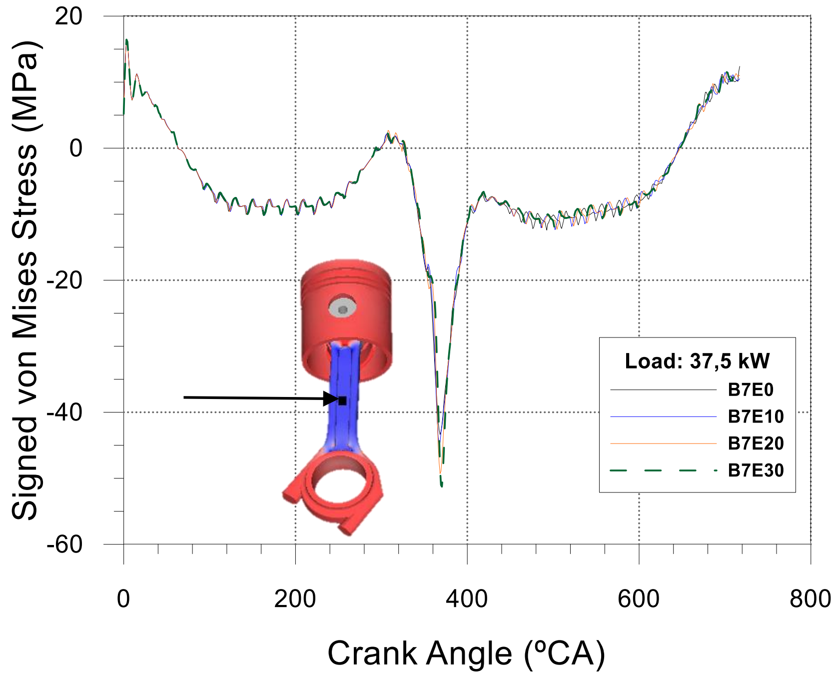


**Figure 12. Connecting rod von Mises stress evolution during the combustion**

# 4 CONCLUSIONS

This study showed the use of the multi-body and flexible body analysis of an engine connecting rod and piston, using pressure experimental data as input load. The engine was fueled with diesel oil directly injected in the combustion chamber and ethanol fumigated in the air inlet manifold. The experiments results showed increase in in-cylinder pressure and the ignition delay with the ethanol addition. These changes effect in the stress distribution of the engine parts were studied, and showed increase in the stress level in the connecting rod, up to 18% with 30% of ethanol, and in the piston, up to 11% with 30% of ethanol. The critical areas are also observed. For the connecting rod, the critical area is located in the union of the rod smaller end, and the beam and for the piston, is located in the pin connecting area. The connecting rod beam is submitted to compressive loads, which increase with the addition of ethanol, suggesting a buckling analysis. The signed von Mises analysis showed increase in the alternating stress during the engine cycle, which could decreases the structure cycle life.

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