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Energy and Exergy analysis of a light duty diesel engine operating at different altitudes

Análisis energético y exergético de un motor diesel de automoción operando en diferentes altitudes

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Abstract

Altitude above sea level produces a reduction in air density affecting the combustion process, pollutant emissions, and engine performance. In this work the combustion diagnosis of an automotive turbocharged diesel engine was carried out from in-cylinder pressure signal. Tests were performed at three altitudes above sea level, under steady state operating conditions, using conventional diesel fuel. As altitude above sea level increased, the fuel/air mixture became richer. The brake specific fuel consumption, combustion duration, premixed combustion phase, maximum temperature, heat rejected to the gases and exergy destruction were also increased; at the same time, brake thermal efficiency, maximum in-cylinder pressure and in-cylinder exergy decreased. Mechanical efficiency and injection timing remained approximately invariable. Exergy destruction differences were caused by the combustion process, without significant effects during compression and expansion. The greater irreversibility resulting from altitude increase was linked with the lower energy quality of the exhaust gases.

----- *Keywords:* Heat release, altitude effect, diesel engines, exergy analysis

Resumen

La densidad del aire disminuye con el aumento de la altitud sobre el nivel del mar, este aspecto afecta el proceso de combustión, la formación de emisiones contaminantes y por tanto el desempeño del motor. En este trabajo se presenta el diagnóstico del proceso de combustión de un motor diesel de automoción

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turbo-alimentado, mediante la medición de presión en cámara operando en tres alturas diferentes sobre el nivel del mar, bajo condiciones estacionarias, utilizando diesel convencional (acpm) como combustible. A medida que aumenta la altura sobre el nivel del mar se incrementa la relación combustible/aire (mezcla más rica) y con ello el consumo específico de combustible, la duración de la combustión, la combustión en fase premezclada, la temperatura máxima, el calor transferido a los gases y la exergía destruida, mientras que el rendimiento térmico efectivo del motor, la presión máxima y la exergía en el cilindro disminuyen. Sin embargo, la eficiencia mecánica y el tiempo de inyección se mantienen aproximadamente constantes. Las diferencias encontradas en la exergía destruida se deben a las variaciones del proceso de combustión, ya que no se encontraron efectos significativos en las carreras de compresión y expansión. La mayor irreversibilidad debida al aumento de la altura se debe a la baja calidad de la energía de los gases de escape.

----- *Palabras clave:* Tasa de calor liberado, altitud, motores diesel, análisis exergético

Introduction

The reduction of atmospheric pressure resulting from an increase of altitude reduces air density affecting engine power output and specific fuel consumption [1, 2]. Ambient temperature affects heat release rate, fuel-air mixture uniformity, engine volumetric efficiency and heat transfer rate through cylinder walls, but its effect on power output and consumption is lower than that of the atmospheric pressure [1-4]. Most of the reported works dealing with altitude effect have been focused on engine performance (power, torque, efficiency and specific fuel consumption) and emissions. A recent work presents a review of this topic from these two points of view [1]. To study the altitude effect on the processes of jet formation and air entrainment to the reaction zone, sophisticated experimental techniques complementing combustion diagnosis from in-cylinder pressure signal are required [5-8]. Nevertheless, combustion diagnosis by itself allows obtaining relevant information about the heat release process. From the literature review carried out, only one experimental work related with the thermodynamic diagnosis of combustion taking into account the altitude effect was found, and none using second law analysis. Lizhong et al. [9] used an atmosphere-simulating device which allowed to vary the intake and exhaust pressures in order to evaluate the performance of a 3.3 litres, four cylinder engine in two versions: naturally aspirated (NA) and turbocharged (TC); under two operating conditions: constant air-fuel ratio and constant amount of fuel injected. In the NA engine under constant air-fuel ratio conditions, it was found that as the atmospheric pressure decreased, the indicated thermal efficiency, mixing controlled combustion stage (diffusion) and combustion duration also decreased, while ignition delay, rapid combustion stage (premixed) and specific fuel consumption increased. With the TC engine, it was found that the altitude did not significantly affect ignition delay, but decreased the combustion premixed stage and increased combustion duration. The scarce information found in the literature, and the importance of this topic for Latin American countries, where there are important urban centres located higher than 1000 m above sea level, have motivated the authors to carry out an investigation based on the diagnosis of the combustion process, from the point of view of first and second laws of thermodynamics. The study carried out allowed determining the effect of altitude on the main parameters characterizing the combustion process (such as heat release rate, combustion duration and efficiency), and also on the specific fuel consumption and energy and exergy balances for the closed-valve period.

Methodology

Model description

Combustion diagnosis was carried out using a two-species (air and combustion products), single-zone model, based on the approach proposed by Lapuerta et al. [10]. Atmospheric pressure was taken into account in the pressure signal processing. Heat transfer was calculated using the correlation of Woschni [11], adjusting its constants to the engine by means of energy balances [12]. The variation of air composition (molar fraction) with altitude was not taken into account for calculating the thermodynamic properties of species, since it was not significant in the altitude range evaluated [8]. In order to determine exergy, the dead state was defined by a pressure of 101.33 kPa, a temperature of 298.15 K, and the following composition (vol. %): 76.45 N_2, 20.56 O_2, 2.04 H_2O, 0.92 Ar and 0.03 CO_2. The same dead state was used for all altitudes since it has been shown that its variation with altitude has little effect on the results of exergy analysis [13, 14]. In diesel engines, where fuel's exergy only begins to contribute to exergy of the mixture of gases during the combustion process, the in-cylinder exergy balance is given by equation (1).

$$dE_{cyl} = \delta E_Q - \delta E_W - dE_{bb} + dE_f - \delta E_d \quad (1)$$

The terms of this equation, from left to right, account for the exergy related to heat transfer (δE_Q), work (δE_W), blow-by (dE_{bb}), fuel (dE_f) and exergy destruction (δE_d). Considering the blow-by as the only mass that can be exchanged, the variation of the mixture exergy is showed in equation (2).

$$dE_{cyl} = m_{cyl} de_{cyl} - e_{cyl} dm_{bb} \quad (2)$$

where e is the specific exergy and m the mass of the system. The subscripts are *cyl* for the system (in-cylinder mixture of gases) and *bb* for blow-by. The blow-by mass was obtained considering one-dimensional, compressible, isentropic flow [10], and its exergy was calculated assuming that this flow has the same exergy as the in-cylinder gases. The specific exergy of the in-cylinder gas mixture was obtained by means of the equation (3) [15-17].

$$e_{cyl} = \left(u_{cyl} - u_{cyl,0}\right) - T_0\left(s_{cyl} - s_{cyl,0}\right) + p_0\left(v_{cyl} - v_{cyl,0}\right) \quad (3)$$

where u, s and v are internal energy, entropy and specific volume, respectively. The subscript 0 refers to dead state conditions. Thermodynamic properties of the gas mixture were calculated assuming it was a mixture of ideal gases composed of two species: air and combustion products [18]. The internal energy of each species (denoted by subscript k) can be calculated acording to equation (4) [10]:

$$u_k = \Delta h^o_{f,k} - R_k T_0 + \int_{T_0}^{T} c_{v,k}\, dT \quad (4)$$

where Δh^o_f is the enthalpy of formation at standard conditions and R is the gas specific constant. The specific heat at constant volume (c_v) was estimated from the specific heat at constant pressure (c_p) using the ideal-gas hypothesis. c_p was calculated as a function of temperature using a fifth order polynomial, taking into account the instantaneous composition of the mixture. The entropy of the mixture was obtained assuming a mixture of ideal gases, and the individual species entropies were calculated with equation (5):

$$s_k = \Delta s^o_{f,k} + \int_{T_0}^{T} \left(c_{p,k}/T\right) dT - R_k \ln\left(X_k p/p_0\right) \quad (5)$$

Where Δs^o_f is the entropy of formation obtained from the data of enthalpy and Gibbs free energy of formation, and X_k is the molar fraction of species k in the mixture. The control volume only exchanges heat with the combustion chamber walls at the gas mean temperature. The exergy related to this process (Equation (6)) was calculated considering that heat is leaving the system [19, 20]:

$$\delta E_Q = -\left(1 - T_0/T\right)\delta Q_w \quad (6)$$

where δQ_w is the heat transfer to the walls. The exergy of work was obtained assuming that the compression-expansion processes are internally reversible [20, 21, 22] and taking into account the expansion work against the atmosphere, see equation (7).

$$\delta E_W = (p - p_0)dV \tag{7}$$

When a fraction of fuel is burned, its chemical exergy is released according to equation (8) [23-25]:

$$dE_f = e_f^{ch} dm_f^b \tag{8}$$

where the fuel-burning rate (dm_f^b) was calculated from fuel's lower heating value (*LHV*) and the heat release rate (δQ_R) obtained from the diagnosis model by means of the equation (9).

$$dm_f^b = \delta Q_R / LHV \tag{9}$$

The chemical exergy of the fuel, e_f^{ch}, was estimated from its composition and *LHV* [26, 27]. Carrying out the mass balance, replacing terms and solving equation (1) for the in-cylinder exergy destruction, equation (10) is obtained.

$$\begin{aligned} \delta E_d = -(1 - T_0/T)\delta Q_w - (p - p_0) \\ dV - m_{cyl} de_{cyl} + e_f^{ch} dm_f^b \end{aligned} \tag{10}$$

The exhaust gases chemical exergy was neglected because it is too low and difficult to use [16, 23, 28-31].

Test procedure and experimental equipment

Tests were carried out in an instrumented automotive diesel engine (Table 1) fuelled by commercial grade N.° 2 diesel fuel, whose elemental composition by weight was 87.2% carbon, 12.8% hydrogen and 0.023% sulphur, and an aromatic content of 29.3% (13% monoaromatics, 13.3% diaromatics and 3% polyaromatics). The utilization of the same fuel batch was guaranteed for all the tests.

Table 1 Engine characteristics

Reference	*ISUZU 4JA1*
Type	Turbocharged, direct injection, rotating pump
Swept volume	2499 cm^3
Configuration	4 in-line cylinders
Diameter x stroke	93 mm x 92 mm
Compression ratio	18.4
Rated power	59 kW (80 hp) at 4100 rpm
Maximum torque	170 Nm at 2300 rpm

Tests were carried out at three altitudes above sea level: 500, 1500 and 2400 m, whose corresponding atmospheric pressures are 96, 85 and 76 kPa. The engine was tested at 2000 rpm and 100 Nm at all three altitudes. This operation mode was chosen because it was the point of minimum air-fuel ratio and maximum smoke opacity. Measurements were duplicated in order to guarantee repeatability. No modifications on the engine or its fuel injection system (mass injected and injection timing) were done for the tests. Before each test exhaust temperature was stabilized to guarantee steady state conditions. Air consumption was measured with a hot-wire sensor (Magnetrol TA2), and fuel consumption with a Danfoss Masflo 6000 Coriolis-type mass flow sensor. For recording the instantaneous in-cylinder pressure a Kistler 6056A piezoelectric pressure transducer installed in the glow plug, and a Kistler 5011B charge amplifier were used. Injection pressure was recorded with an AVL 41DP 1200K piezoresistive pressure transducer, installed at the injection pump outlet. In order to guarantee confidence in the diagnosis results, 100 pressure curves were registered [32 - 34]. The piston instantaneous position was determined using an angular position encoder with a resolution of 1024 pulses/revolution (Heidennhain ROD 426) coupled to the crankshaft in the opposite extreme of the flywheel. The engine was coupled to a hydraulic dynamometer (GO-Power D512). The rotational speed of the crankshaft was measured with a sensor coupled to the injection pump. All data were acquired using Labview^{TM} software and National Instruments^{TM} data acquisition system (Model PCI-MIO-16E-4 board).

Results and discussion

Combustion diagnosis

The fuel-air equivalence ratio increased approximately by 9% for each 1000 m of altitude increase (Figure 1), due to the decrease in air mass concentration; thereby a higher quantity of fuel is injected in order to maintain the same brake power. The decrease in atmospheric pressure led to a reduction in the in-cylinder pressure during the complete thermodynamic cycle (Figure 2), being this effect more significant than that due to fuel-air mixture enrichment.

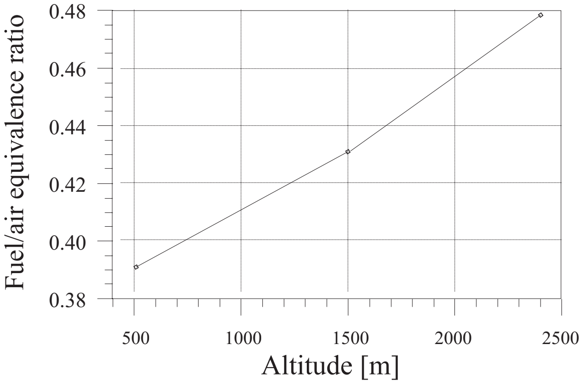

Figure 1 Fuel/air equivalence ratio

In figure 3, a slight delay in the start of combustion was registered with altitude increase as a consequence of oxygen impoverishment. Since the injection timing was approximately constant with altitude as shown in figure 4, a higher quantity of fuel was injected during the ignition delay period, and so a higher fraction of it was burned during the rapid combustion stage. The fraction of fuel burned during the diffusion stage tended to decrease with altitude, leading to an enlarged combustion process (Figure 5), and to a higher temperature during the expansion stroke.

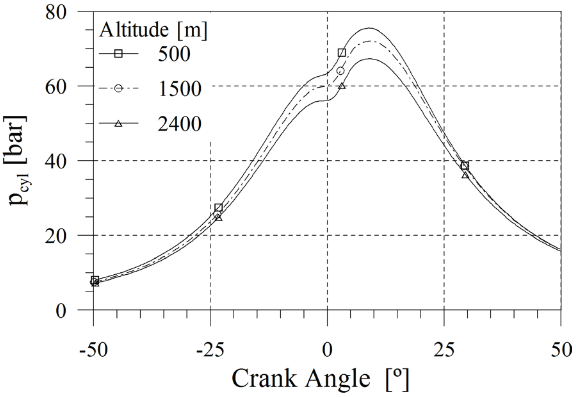

Figure 2 In-cylinder pressure

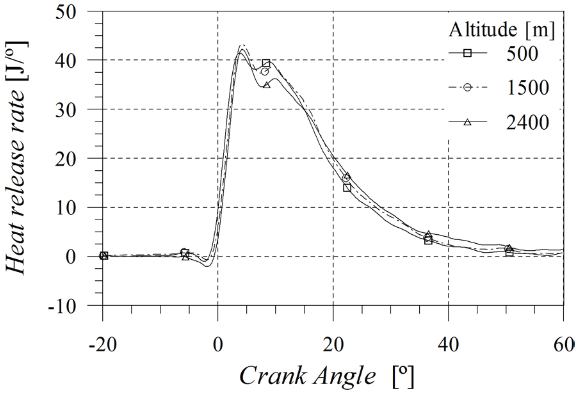

Figure 3 Heat release rate

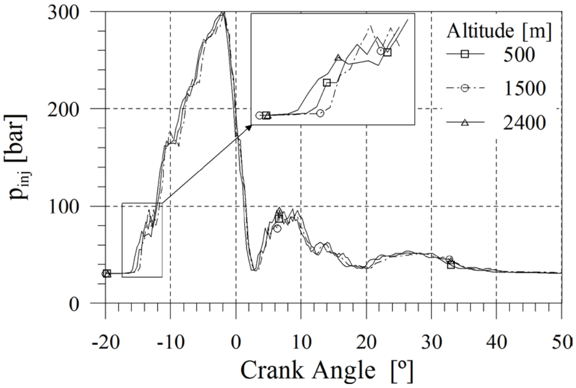

Figure 4 Injection-line pressure

As a consequence of this, also the duration of the combustion process was higher, showing an increase of about 2 CA going from 500 to 1500 m and about 5 CA from 1500 to 2400 m as shown in figure 5. Combustion duration was defined as the angular interval occurring between the 10 and 90% of cumulative heat release [35]. This behaviour was a affected also by the decrease in air mass concentration as altitude increased, which reduces the rate of combustion [8].

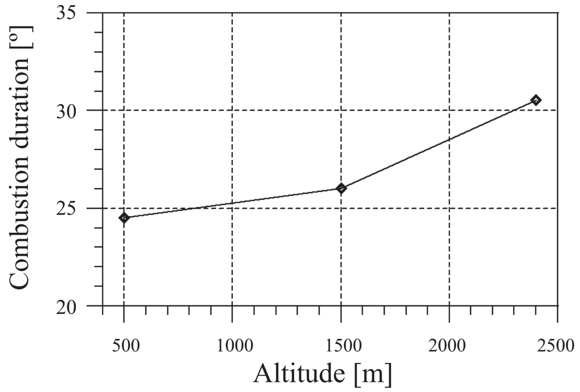

Figure 5 Combustion duration

As can be seen in figure 6, the angle corresponding to the maximum mean temperature tended to move slightly to the right. There was not variation of temperature with altitude during the compression stroke, however from the peak value there was an increasing tendency, due to greater premixed combustion stage (Figure 3) and longer combustion duration (Figure 5).

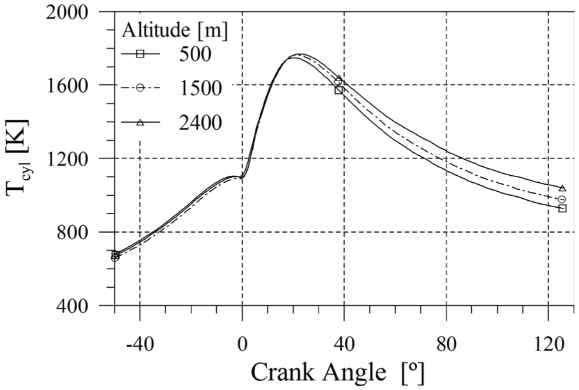

Figure 6 Mean in-cylinder temperature

The maximum mean temperature increased about 20 ºC for each 1000 m of altitude increase. This trend together with the measured higher fuel consumption, allows to explain the higher mean temperature at exhaust valve closure (EVC), which tended to increase around 30 ºC for each 1000 m of altitude increase. Brake thermal efficiency was reduced at high altitudes as a consequence of a decrease in the in-cylinder pressure and an increase of the fuel/air equivalence ratio. This decrease was around 4.6% going from 500 to 1500 m, and close to 7.7% going from 500 to 2400 m (Figure 7), in agreement with results reported by Lizhong et al. [9] and Xiaoping et al [36]. As a consequence of brake thermal efficiency reduction, the brake specific fuel consumption (bsfc) increased about 8% for each 1000 m of altitude increase (Figure 8).

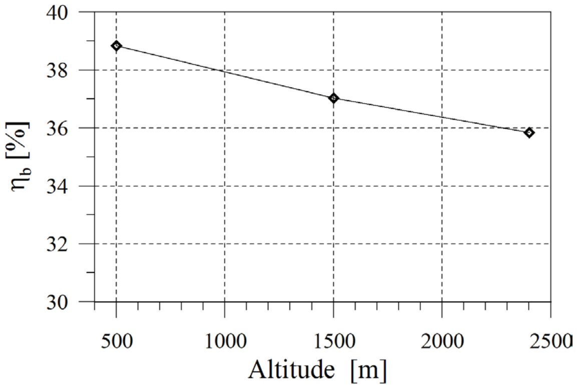

Figure 7 Brake thermal efficiency

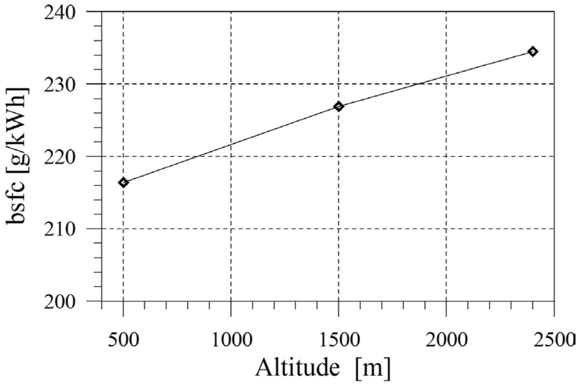

Figure 8 Brake specific fuel consumption

The energy balance calculated for the closed valves period is presented in Figure 9. Since tests were carried out at equal power, the work fraction decreased slightly with altitude because fuel consumption increased while indicated work was practically constant. The fraction of losses associated with heat transfer was not affected by altitude, while the fraction of energy stored in the gases at the moment of the exhaust valve opening (EVO) increased about 5% for each 1000 m of altitude increase. This was a consequence of the fuel-air equivalence ratio increase, which was also reflected on the rise in specific fuel consumption and exhaust gas temperature. The energy fraction corresponding to blow-by, in addition to be very small (less than 1%), was not affected by altitude.

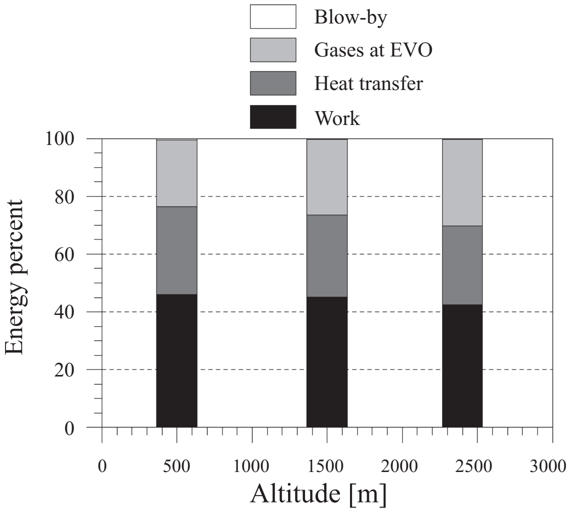

Figure 9 Energy balance

Exergy analysis

As observed in figure 10, the exergy of the in-cylinder gas mixture decreased with altitude. This effect was evident from the compression stroke, due to the lower pressure within the cylinder, and this trend was maintained during the combustion process, according to the higher in-cylinder pressure during this period. The pressure gradient during expansion decreases with altitude reducing the work transfer rate, which causes the in-cylinder exergy to drop slower for higher altitude. As can be seen in figure 11 exergy destruction mainly occurred during the combustion process, confirming that combustion is the main source of irreversibilities in the cylinder, and coinciding with the results of other investigations [23, 25, 28, 37, 38]. Like heat release, exergy destruction exhibits two peaks corresponding to premixed and diffusion-controlled combustion phases, respectively. Premixed-combustion phase is significantly more irreversible than the diffusion phase because of the rapid reactions that take place in the former. As altitude increases the maximum exergy destruction rate becomes higher because the rapid-combustion peak becomes more important (figure 3) and a greater amount of fuel is burned during this period. In contrast to heat release behaviour, the difference between premixed and diffusion peaks remains practically unchanged for exergy destruction rate. This means that the variation of the total irreversibility with altitude is mainly determined by the rapid-combustion phase. Figure 12 shows the cumulative exergy destruction for the closed-valve period, expressed as a fraction of the exergy supplied by the fuel. During compression, there was small exergy destruction at all altitudes, mainly, as a consequence of the heat transfer to the walls. On the other hand, at the beginning of the combustion process, exergy destruction rose sharply and then became stable, being higher as altitude increased, as a consequence of the behaviour of the exergy destruction rate.

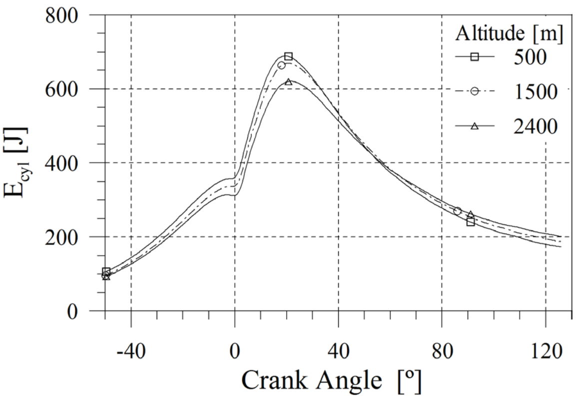

Figure 10 In-cylinder exergy

The exergy balance for the closed-valve interval is shown in figure 13. Similar to the energy balance, the exergy associated with blow-by was practically negligible and did not change with altitude. There was a small variation with altitude in the exergy terms of heat transfer and gases at EVO, being these considerably lower than the corresponding energy balance terms (Figure 9).

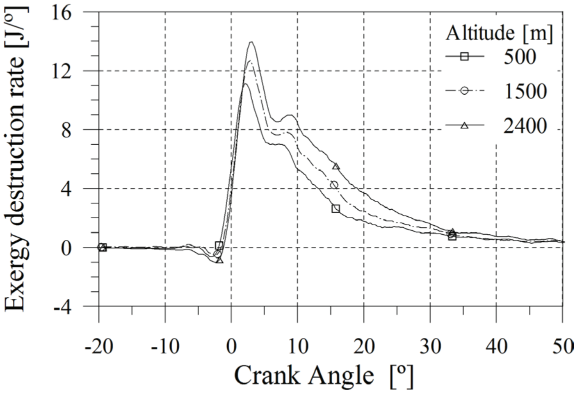

Figure 11 Exergy destruction rate

By using exergy analysis it is possible to evaluate the true energy potential of engine flows which is essential in developing integrated energy systems such as cogeneration or bottoming cycles. This is demonstrated by the differences observed in the first and second law results for the heat transfer to cooling water and exhaust gases terms.

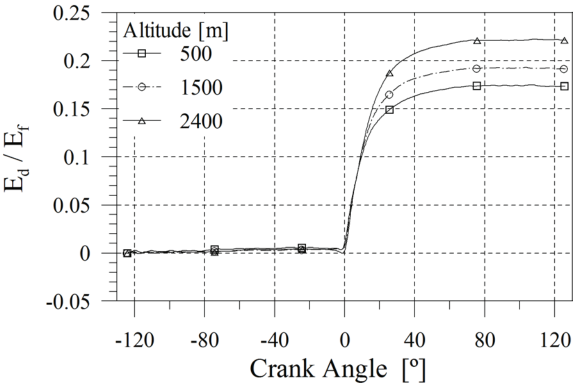

Figure 12 Cumulative exergy destruction

Comparing both balances, it can be observed that the increase in exergy destruction with altitude is related with the quality loss of the energy stored in the exhaust gases at EVO (Figure 16). This is illustrated by the efficiency of the exhaust gases, defined as their exergy/energy ratio [39], shown in figure 14. This figure shows how the energy quality of the gases at EVO decreases with altitude, which means that the greater irreversibility observed resulted in a reduction of the ability for producing useful work and of the potential for using exhaust gases.

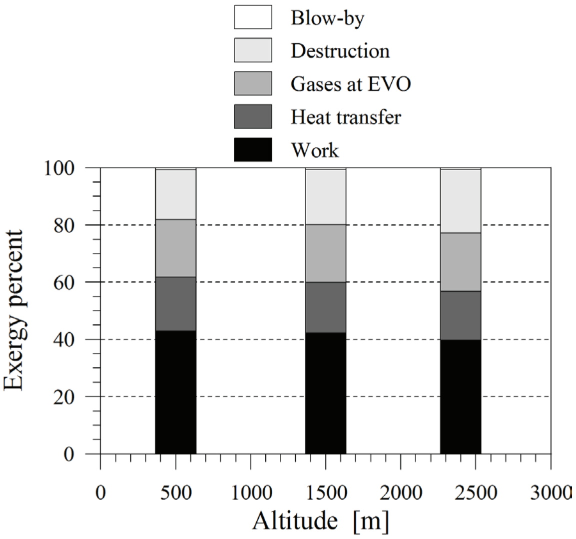

Figure 13 Exergy balance

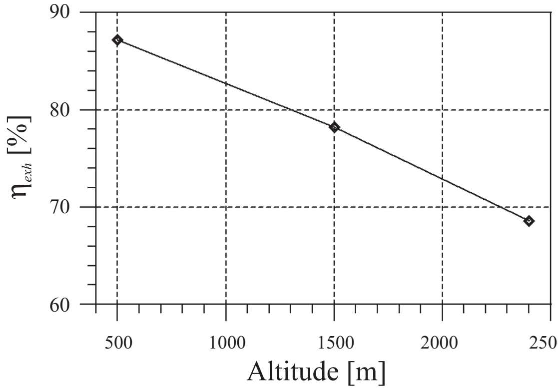

Figure 14 Exhaust efficiency

Conclusions

The objective of this work was to investigate the heat release process in an automotive diesel engine operating at different altitudes above sea level (500, 1500 and 2400 m). Measurements were carried out at equal power without performing any modification in the injection system. Based on the experimental results, the following conclusions can be drawn:

1. The altitude affects in an important way the engine performance, despite the turbocharger
2. The combustion process was affected with altitude due to the lower in-cylinder pressure and mass air concentration.
3. Exergy destruction increased with altitude due to the worse use of the chemical fuel exergy.

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References

1. M. Lapuerta, O. Armas, J. R. Agudelo, C. A. Sánchez. “Estudio del efecto de la altitud sobre el comportamiento de motores de combustión interna. Parte 1: Funcionamiento”. *Información Tecnológica*. Vol. 17. 2006. pp. 21-30.
2. J. R. Sodré, S. M. C. Soares. “Comparison of engine power correction factors for varying atmospheric conditions”. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. Vol. 25. 2003. pp. 295-305.
3. S. M. C. Soares, J. R. Sodré. “Effects of atmospheric temperature and pressure on the performance of a vehicle”. *Proc. Instn. Mech. Engrs. Part D*. Vol. 216. 2002. pp. 473-477.
4. J. B. Heywood. *Internal combustion engine fundamentals*. Ed. McGraw-Hill. New York. 1988. pp. 980.
5. J. Arrègle, J. J. López, J. M. García, C. Fenollosa. “Development of a zero-dimensional diesel combustion model. Part 1: Analysis of the quasi-steady difussion combustion phase”. *Applied Thermal Engineering*. Vol. 23. 2003. pp. 1301-1317.
6. H. Hiroyasu, M. Arai, M. Tabata. “Empirical equations for the Sauter mean diameter of a Diesel spray”. *SAE 890464*. 1989. pp. 1-12.
7. J. E. Dec. Conceptual model of DI Diesel combustion based on laser-sheet imaging. *SAE 970873*. 1997. pp. 1-15.
8. M. Lapuerta, O. Armas, J. R. Agudelo, A. F. Agudelo. “Estudio del efecto de la altitud sobre el comportamiento de motores de combustión interna. Parte 2: Motores diesel”, *Información Tecnológica*. Vol. 17. 2006. pp. 31-41.
9. S. Lizhong, S. Yungang, Y. Wensheng, X. Junding. “Combustion Process of Diesel Engines at Regions with Different Altitude”. *SAE 950857*. 1995. pp. 1-10.
10. M. Lapuerta, O. Armas, J. J. Hernández. “Diagnosis of DI Diesel combustion from in-cylinder pressure signal by estimation of mean thermodynamic properties of the gas”. *Applied Thermal Engineering*. Vol. 19. 1999. pp. 513-529.
11. G. Woschni. “A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine”. *SAE 670931*. 1967. pp. 1-15.
12. B. D. Hsu, *Practical diesel-engine combustion analysis*. Society of Automotive Engineers – SAE. Warrendale. 2002. pp. 1-10.
13. M. A. Rosen, I. Dincer. “Effect of varying dead-state properties on energy and exergy analyses of thermal systems”. *International Journal of Thermal Sciences*. Vol. 43. 2004. pp. 121–133.
14. J. Etele, M. A. Rosen, “Sensitivity of exergy efficiencies of aerospace engines to reference environment selection”. *Exergy Int. J*. Vol. 1. 2001. pp. 91-99.
15. D. E. Foster. “An overview of zero-dimensional thermodynamic models for IC engine data analysis”. *SAE 852070*. 1985. pp. 1-15.
16. J. A. Caton. “Results from the second-law of thermodynamics for a spark-ignition engine using an engine cycle simulation”. *Fall Technical Conference, ASME-ICED*. 1999. pp. 35-49.
17. H. N. Shapiro, J. H. Van Gerpen. “Two zone combustion models for second law analysis of internal combustion engines”. *SAE 890823*. 1989. pp. 1-12.
18. M. Lapuerta, R. Ballesteros, J. R. Agudelo. “Effect of the gas state equation on the thermodynamic diagnostic of diesel combustion”. *Applied Thermal Engineering*. Vol. 26. 2006. pp. 1492-1499.
19. A. Valero, M. Lozano. “Energy, entropy, exergy and free energy balances. Methods for the diagnosis of industrial facilities”. *Ingeniería Química*. Mayo. 1987. pp. 143-153.

20. M. J. Moran, H. N. Shapiro. Fundamentals of Engineering Thermodynamics. 5th ed. Ed. John Wiley & Sons. The Atrium. 2006. pp. 855.

21. I. Dincer, Y. A. Cengel. "Energy, entropy and exergy concepts and their roles in thermal engineering". *Entropy*. Vol. 3. 2001. pp. 116-149.

22. C. D. Rakopoulos. "Evaluation of a spark ignition engine cycle using first and second law analysis techniques". *Energy Conversion and Management*. Vol. 34. 1993. pp. 1299-1314.

23. F. Bozza, R. Nocera, A. Senatore, R. Tuccillo. "Second law analysis of turbocharged engine operation". *SAE 910418*. 1991. pp. 1-10.

24. J. Li, L. Zhou, K. Pan, D. Jiang, J. Chae. "Evaluation of the thermodynamic process of indirect injection diesel engines by the first and second law". *SAE 952055*. 1995. pp. 1-12.

25. C. D. Rakopoulos, E. G. Giakoumis. "Second-law analyses applied to internal combustion engines operation". *Progress in Energy and Combustion Science*. Vol. 32. 2006. pp. 2-47.

26. J. Szargut, D. R. Morris, F. R. Steward. *Exergy analysis of thermal, chemical, and metallurgical processes*. Ed. Hemisphere Publishing Corporation. New York. 1988. pp. 345.

27. T. J. Kotas. The exergy method of thermal plant analysis. Ed. Krieger Publishing Company. Malabar. Florida. 1995. pp. 350.

28. D. C. Kyritsis, C. D. Rakopoulos. «Parametric study of the availability balance in an internal combustion engine cylinder». *SAE 2001-01-1263*. 2001. pp. 1-13.

29. C. D. Rakopoulos, D. C. Kyritsis. "Comparative second-law analysis of internal combustion engine operation for methane, methanol, and dodecane fuels". *Energy*. Vol. 26. 2001. pp. 705-22.

30. C. D. Rakopoulos, E. G. Giakoumis. "Development of cumulative and availability rate balances in a multi-cylinder turbocharged indirect injection diesel engine". *Energy Conversion and Management*. Vol. 38. 1997. pp. 347-369.

31. C. D. Rakopoulos, E. G. Giakoumis. "Availability analysis of a turbocharged diesel engine operating under transient load conditions". *Energy*. Vol. 29. 2004. pp. 1085-1104.

32. M. Brunt, A. Emtage. "Evaluation of IMEP routines and analysis errors". *SAE 960609*. 1996. pp. 1-17.

33. A. Agudelo, J. R. Agudelo, P. Benjumea *Diagnóstico de la combustión de biocombustibles en motores*. Ed. Universidad de Antioquia. Medellín. Marzo 2007. pp 147.

34. Ilba Cuadrado. J. R. Agudelo, C. Sánchez. *Flujo compresible en múltiples de motores*. Ed. Universidad de Antioquia. Medellín. Septiembre 2008. pp 123.

35. Y. Zhang, J. H. Van Gerpen. "Combustion analysis of esters of soybean oil in a diesel engine". *SAE 960765*. 1996. pp. 1-12 .

36. B. Xiaoping, Z. Gengyun, Z. Xiaojing. "Predicting Vehicle Turbocharged Diesel Engine Performance at Altitude". *SAE 961826*. 1996. pp. 1-9.

37. M. K. Anderson, D. N. Assanis, Z. S. Filipi. "First and second law analyses of a naturally-aspirated, Miller cycle, SI engine with late intake valve closure". *SAE 980889*. 1998. pp. 1-12.

38. J. A. Velásquez, L. F. Milanez. "Analysis of the irreversibilities in diesel engines". *SAE 940673*. 1994. pp.1-12.

39. A. Parlak, H. Yasar, O. Eldogan. "The effect of thermal barrier coating on a turbo-charged Diesel engine performance and exergy potential of the exhaust gas". *Energy Conversion and Management*. Vol. 46. 2005. pp. 489-499.