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EXPERIMENTAL AND NUMERICAL STUDY ON ENERGY ABSORPTION CHARACTERISTICS OF MILD STEEL AND ALUMINIUM SQUARE TUBES UNDER AXIAL LOADING

Nakka Venkata Swamy KALYAN, Bedadhala Bharadwaja REDDY,
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Abstract: *Energy absorbing tubes are highly used in automobile crash applications, for absorbing the energy produced during a frontal collision between automobile vehicles. These energy absorbing tubes are studied for various cross-sections, materials and operational conditions. These tubes by deforming themselves absorb the energy produced during the collision. In the present study, energy absorption characteristics of square tubes is studied for two different materials, namely Mild steel and Aluminium, under uniaxial compressive loading.*
The results of the compression test are used for simulating the test in ABAQUS 6.13 for understanding the deformation characteristics and validating the experimental results.

Key-Words: *Mild steel tubes, Aluminium tubes, Energy Absorption, Axial load, Numerical analysis.*

1. INTRODUCTION

Light weight design of automobile vehicle has become a priority now-a-days, for increasing the environment friendly nature, fuel efficiency and other modern vehicular requirements and also for achieving impact or collision safety requirements so as to reduce the damage during accidents involved with automobile vehicles. Most accidents are due to head-on collisions of vehicles and which forces for design of light weight, high energy absorbing and efficient crash boxes/energy absorbers, for absorbing full or part of impact energy, produced during the collision, by their deformation. Generally, Crash box is located in between the bumper and the side rails, protecting the automobile vehicle components and people, by absorbing the impact energy and reducing the plastic flow of stress levels to the automobile vehicle frame [1]. Many cross-sections like rectangular, hexagonal and octahedral cross-sections are used for tubes for crash box applications [2] and the performance of the crash box for crashworthiness is generally carried out on the basis of Research Council for Automobile Repairs (RCAR) regulations [3].
Many researches, experimental and numerical investigations, were conducted on different cross-sections of tubes, materials of tubes, dimensions of tubes and testing at different strain rates, namely quasi-static and dynamic strain rates [4-12]. El-Hage at al. [13] from his research work suggested a taper at the end of the square tubes for controlling the fold initiation load and maintaining the stability of crushing mechanism, by without altering the mean crushing force.
Zarei and Kroger [14] determined that if the length of the tube is more than a critical length, the deformation that takes place is a global Euler buckling and it is a poor energy absorber characteristic and also should be avoided and necessary optimal design of energy absorbers should be maintained. Gupta [15] performed numerical and experimental investigations on crashworthiness of circular tubes of varying geometrical dimensions, under dynamic and quasi-static loadings and inferred that the energy absorption during dynamic loading is almost 1.56- 12.3% times that of quasi-static loading results and also stated that the energy absorption characteristics are enhanced by increasing the thickness and diameter of the tubes. Gameiro and Cirne [16] inferred that the circular tubes under uniaxial loading provide almost a uniform operating load and are most common in crash box applications. Zarei and Kroger [1] inferred that the circular tubes are commonly used and better energy absorbing elements due to their efficiency and light weight attribute under axial loading.

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Yuen et al. [17] studied the energy absorption characteristics of both circular and square tubes and inferred that the circular tubes are a showing better crashworthiness than square tubes and are most the efficient ones. Hosseini et al. [18] developed a mathematical model for studying the axisymmetric crushing of frusta under axial loading and from the results, it was inferred that the experimental and numerical results are in better agreement and is due to the consideration of compressive strength more than the tensile strength of the material. Nia and Hamedani [19] performed experimental and numerical investigations on energy absorption characteristics of various cross-sectioned tubes and inferred that the energy absorption characteristics were less for the low edged polygon i.e. triangular cross-section and the circular cross-section tubes have high specific energy absorption. Ahmad et al. [20] examined both experimentally and numerically, the crushing behavior and energy absorption characteristics of empty and foam filled conical tubes under impact loading and found that the thickness and semi-apical angle of the tube have great influence on the mean load and energy absorption characteristics of both empty and foam filled tubes and the mean load and energy absorption characteristics decrease as the impact angle is increased. Ghamarian et al. [21] investigated on the compression characteristics of end capped conical tubes under quasi-static loading, both experimentally and numerically and reported that the specific energy absorption of empty circular tubes is 18.4% lesser than that of the empty conical tubes. Li et al. [22] studied the compression behaviour of empty, foam-filled single and foam-filled double circular tubes under uniaxial and oblique loading and determined that the few new deformation mechanisms namely, spiral fold, irregular extension fold and diamond deformation mechanisms, and found that the specific energy absorption of foam-filled double circular tubes is higher than that of empty tubes and the specific energy absorption of foam-filled single circular tubes is lesser than that of the empty tubes for the current loading conditions. Mirzaei et al. [23] studied experimentally and analytically regarding the crushing behaviour of circular hybrid tubes under axial loading, both static and dynamic conditions and developed a mathematical model for determining the mean crushing force and fold length of the tubes and found that the energy absorption of the hybrid tubes is higher for dynamic loading and the results were in good agreement with each other. Kim et al. [24] prepared an Al SHS beam, reinforced with CFRP composites for enhancing its stiffness and crashworthiness and under axial impact loading, it was inferred that the crashworthiness is enhanced by increment in the thickness of the CFRP composites. Goel M. D. [25] performed numerical simulations for determining the energy absorption and crushing characteristics of bi-tubular and tri-tubular circular and square empty and foam filled tubes and compared these results with single empty and foam filled circular and square tubes. The results indicated that the bi-tubular and tri-tubular circular and square empty tubes have enhanced energy absorption characteristics and these characteristics are more enhanced when they are foam filled. The comparison of results of circular and square tubes, for same configurations, showed that the energy absorption characteristics are higher for circular tubes. Mohsenizadeh et al. [26] performed experimental and numerical study on comparison of crash response and energy absorption characteristics for empty, conventional foam filled and auxetic foam filled square tubes, under quasi-static axial loading. He inferred that according to the obtained results auxetic foam filled tubes have higher energy absorption, greater mean crushing force and crush force efficiency when compared to empty and conventional foam filled square tubes. Kılıçaslan [27] prepared numerical models for studying the dynamic crush behaviour of empty corrugated and aluminium foam-filled corrugated single and bi-tubular tubes. The results inferred that the foam-filled corrugated tubes have progressive and controlled deformation mode and decreased peak force. It was found that the specific energy absorption was decreased as the corrugated surfaces were introduced and highest specific energy values are found for foam-filled bi-tubular corrugated tubes of higher lengths and also it increases increasing inner radius and wall thickness. And also the crush force efficiency was increased for foam-filled single corrugated tubes and is decreased for foam-filled bi-tubular corrugated tubes. Rajak et al. [28] performed experimental comparative investigations on empty and foam filled aluminium tubes and inferred that foams a good energy absorption enhancing agents and the energy absorption of foam filled tubes is higher than that of the empty tubes. Rajak et al. [29] studied the energy absorption characteristics of various foam filled mild steel tubes under compressive loading and inferred that the foam filling enhanced the energy absorption capacity of the tubes by many folds and low density foam has maximum energy absorption capacity. Gao et al. [30] simulated and studied the energy absorption properties at oblique loading of a novel foam filled ellipse tube (FET) and compared the results with other different cross-sectioned empty and foam filled tubes and also performed experimental investigation and compared the results with the results of numerical simulation.

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The results inferred that the energy absorption capacity and specific energy absorption of FET is higher than other different cross-sectioned empty and foam filled tubes. A multi objective design (MOD) is conducted on the FET for maximising specific energy absorption at oblique angle and minimising peak crushing force in axial direction simultaneously, varying wall thickness, density of foam and radial rate at different impact angles and on comparing the results with the experimental results, it was found that the specific energy absorption at oblique angle is increasing and with simultaneous decrease in peak crushing force in axial direction.
The work included in this paper, is a comparative study of energy absorption characteristics of mild steel and aluminium square cross-sectioned tubes under uniaxial compressive loading and also validated the results of the compression test with numerical analysis in ABAQUS 6.13.

2. MATERIAL SELECTION

2.1. Mild steel for tubes

Commercially available steels are generally low and high alloy steels, of which mild steel is basically a term used to indicate low-carbon steel of low alloy steel, which consists carbon by <0.25 wt% [31]. Mild steel is generally produced in high quantities according to its usage and is cheaper of all the steels. These are basically a good weldable and machinable materials and require cold working for enhancing strength. The mild steel used as the compression test specimen is an AISI 1010 plain low carbon steel (UNS G10100).

2.2. Al alloy for tubes

Commercially available Al alloys are classified into many series like 1xxx, 2xxx, 3xxx, 5xxx, 6xxx, 7xxx & 8xxx series, by the Aluminium Association [32]. 1xxx series alloys contains >99.8% Al as constituent and are mostly confined to high corrosion resistant or ductile applications and sometimes are used for cladding applications also. 2xxx series alloys are generally Al-Cu systems with high solubility and strength and are used in applications where strength is beyond 500MPa. 3xxx series alloys are high formable which are available as thin sheets and used as common commodity. 5xxx series alloys are Al-Mg systems containing Mg <6% and are usually used in corrosion and structural applications of marine. 6xxx series alloys are predominantly Al-Mg-Si systems which are used as structural materials, corrosion resistances and automobile applications and are basically weldable materials. 7xxx and 8xxx series alloys are generally Al-Zn-Mg and Al-Cu-Li systems respectively which are used in high strength and light weight aerospace and aeronautical applications [33]. The alloy material used for the square Al tubes as compression test specimens is Al 6061 alloy.

2.3. Sample preparation

Square tubes of outer side 22 mm, thickness 0.5 mm and height 50 mm of both mild steel and aluminium are prepared for the compression test. The materials used for the test are mentioned above and the tubes are seamless tubes i.e. they are not welded, and are manufactured by extrusion process. These test specimens for the compression test, both mild steel and aluminium, are supplied by the Sadhana-Parwati Metal Pvt. Ltd. Dhanbad. The geometry and the compression test specimens i.e. square mild steel and aluminium tubes are shown in the Figure 1.

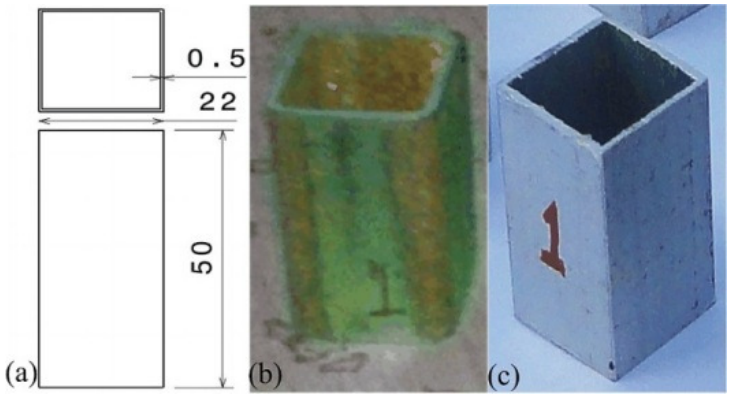

Figure 1. (a) Dimensions of both tubes (b) Mild steel tube (c) Aluminium tube

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3. EXPERIMENTAL SETUP

3.1. Compression test

The square tubes of mild steel and aluminium are subjected to compression loading in Universal Test Machine (Instron-8801) at strain rates of 0.01 and 0.1 s^{-1}. The specimen is placed between the cross heads of the loading unit and compressive load is applied on the specimens, for both mild steel and aluminium. The compression test is performed on three samples per each strain rate, for both mild steel and aluminium tubes. The compressive behaviour and energy absorption characteristics of the square tubes of mild steel and aluminium are determined at IIT (ISM) laboratory. Using experimental compression data, numerical simulation is performed in for validating the results in ABAQUS 6.13 at Advanced Research Laboratory, IIT (ISM).

3.2. Density measurement

The densities of AISI 1010 carbon steel and Al 6061 alloy are determined using the data obtained by the measurements of weight and volume. The calculations of density show that the density of AISI 1010 carbon steel lies between 0.010745 and 0.011408 gmm^{-3} and density of Al 6061 alloy lies between 0.003714 and 0.003966 gmm^{-3}. The density calculations if the AISI 1010 carbon steel and Al 6061 alloy are tabulated in table 1.

Table 1
Densities of the test specimen materials

Material	*Strain rate (s^1)*	*Weight (g)*	*Volume (mm^3)*	*Column density (gmm^{-3})*
Mild steel	0.01	23.5285	2150	0.010943
		22.5261		0.010477
		23.1010		0.010745
	0.1	23.2078		0.010794
		23.7880		0.011064
		24.5262		0.011408
Aluminium	0.01	8.1920		0.003810
		8.5263		0.003966
		8.2328		0.003829
	0.1	7.9857		0.003714
		8.2054		0.003816
		8.4112		0.003912

3.3. Energy Dispersive X-Ray (EDX) test

The test specimens of both mild steel and aluminium are characterized for determining their chemical composition and the Energy Dispersive X-Ray (EDX) test is performed on the test specimens at Center for Research, IIT (ISM). The results of EDX tests infer that the composition of Mild steel is 99.36 wt% Fe, 0.11 wt% C, 0.47 wt% Mn, 0.031wt% P and 0.029 wt% S and figure 2 (a) shows the EDX report of AISI 1010 carbon steel and the composition of Al 6061 alloy is 92.03 wt% Al, 0.52 wt % Mg, 1.6 wt% O and 5.84 wt% Cu and figure 2(b) shows the EDX report of Al 6061 alloy.

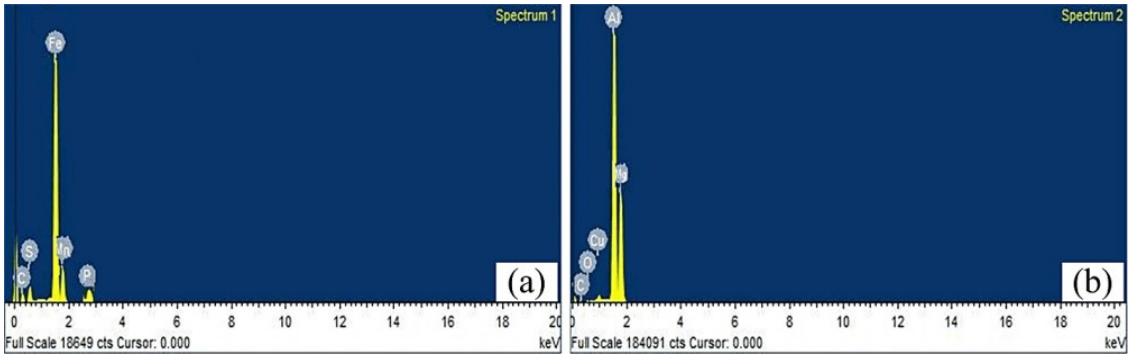

Figure 2. (a)EDX analysis of AISI 1010 carbon steel (b) EDX analysis of Al 6061 alloy

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3.4. Micro-structure characterisation

The micro-structure of the test specimens of both mild steel and aluminium are studied, under Field Emission Scanning Electron Microscope (FESEM), for understanding the structure of surface and voids on the surface. The test specimens are polished with Keller's reagent by means of the standard metallography. The micro-structure characterization is performed using SEM (Model: ZEISS, SPURA 55, Germany) at Center for Research, IIT (ISM), using Mean Intercept Length Method (MILM). The micrographs of mild steel and aluminium alloy, produced after the micro-structure analysis by SEM are shown in figure 3 (a) and figure 3 (b) respectively.

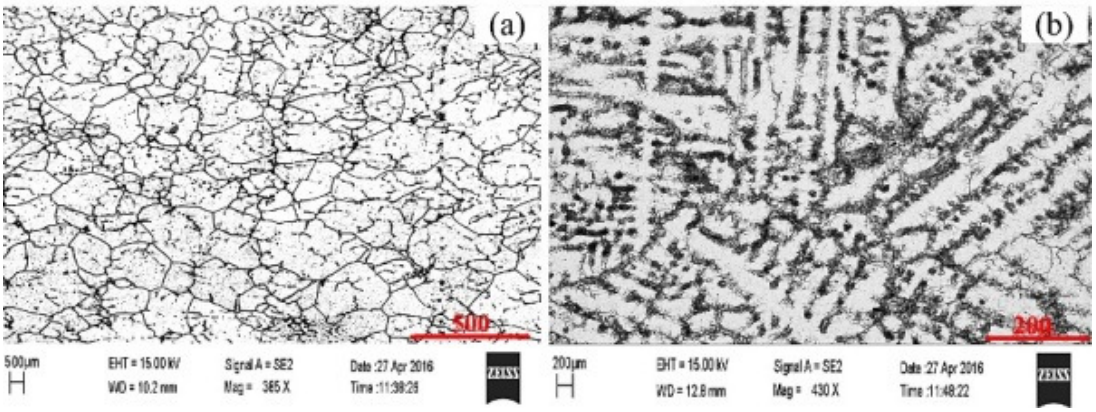

Figure 3. Micrograph of (a) AISI 1010 carbon steel and (b) Al 6061 alloy

3.5. Numerical analysis

Using the data of the compression test of the mild steel and aluminium specimens, numerical analysis of the compression test is simulated in ABAQUS 6.13, for both mild steel and aluminium specimens, by applying the loads and constraints [34].

4. RESULTS AND DISCUSSION

4.1. Compression and energy absorption characteristics

The compressive and energy absorption characteristics of the tubes are highly dependent on the deformation mechanism, strain rate and effects of inertia. The strain rate of the loading conditions is highly influential on the performance of the tubes as they alter the performance and deformation characteristics of the tubes. Depending on the strain rate, the loading conditions are only two kinds, namely quasi-static and dynamic loads. In quasi-static loading, force applied on the samples is almost constant and the effects of inertia are also very low and in dynamic loading, the deformation mechanism is different from that of the quasi-static one because of the effects of inertia. The deformation of tubes subjected to quasi-static loading happens with the formation of folds which propagates into crushing or buckling of the tubes and this is observed in both the mild steel and aluminium tubes, both experimentally and in simulation. The compression characteristics of the tubes also depend on the effects of strain rate on the particular tube material and it is clear between the mild steel and aluminium tubes, as the plastic flow of mild steel and aluminium are highly influenced by the strain rate and show their difference in operation at different strain rates. The energy absorption characteristics are mainly characterised by specific energy absorption and total energy absorption of the tubes. The specific energy absorption capacity, SE per volume of the tubes for a plateau stress σ_P (dependent on strain) and strain ε is determined by,

$$SE = \int_{\varepsilon_1}^{\varepsilon_2} \sigma_p . d\varepsilon \tag{1}$$

and total energy absorption capacity, E_T of tube of volume V, constituted by many small volumes dV is determined by,

$$E_T = \int \left[\int_{\varepsilon_1}^{\varepsilon_2} \sigma_p . d\varepsilon \right] . dV \tag{2}$$

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The energy absorption characteristics, i.e. specific energy absorption and total energy absorption, deformation mechanism and compression behavior of both mild steel and aluminium tubes at both strain rates are determined and performance issues of both mild steel and aluminium tubes due to strain rate sensitivity of tube materials is explained in the following sections.

4.2. Compression test

The stress-strain data of three samples per each strain rate for both mild steel and aluminium are obtained from the compression test performed on the test specimens. Among these data collected, for each strain rate of both mild steel and aluminium, maximum performance data is opted for studying the compressive and energy absorption properties of mild steel and aluminium tubes.

4.2.1. Mild steel tubes

As mentioned above, three samples were tested for each strain rate of loading and the stress-strain data of the three samples for each strain rate is collected. Among the three stress-strain data collected for each strain rate, the maximum is opted and the stress-strain curve for that data at that particular strain rate is plotted. The densification strain for the stress-strain curve is taken as 0.8 and the stress-strain curves of maximum data of the mild steel tubes is shown in figure 4. The energy absorption characteristics of the mild steel tubes at both the strain rates is tabulated in the table 2. It is observed that the stress-strain curve of 0.01 s^{-1} strain rate is completely a skew with uneven plateau stress and the stress-strain curve of 0.1 s^{-1} strain rate is better than the 0.01 s^{-1} curve with almost constant plateau stress. The plateau stress of the tubes at strain rate 0.01 and 0.1 s^{-1} is 2.4 and 3.2 MPa respectively. The specific energy absorption and total energy absorption at strain rates 0.01 and 0.1 s^{-1} are 1.92 and 2.56 $MJmm^{-3}$ and 4.128 and 5.504 J respectively. It is clear that the specific energy absorption and total energy absorption is maximum at the strain rate 0.1 s^{-1} and it can be stated that the mild steel tubes show better performance at 0.1 s^{-1} strain rate.

Table 2
Energy absorption data of mild steel tubes

Strain rate	***Plateau Stress (MPa)***	***Densification strain***	***Specific Energy (MJm^{-3})***	***Volume (mm^3)***	***Total Energy (J)***
0.01	2.4	0.8	1.92	2150	4.128
0.1	3.2		2.56		5.504

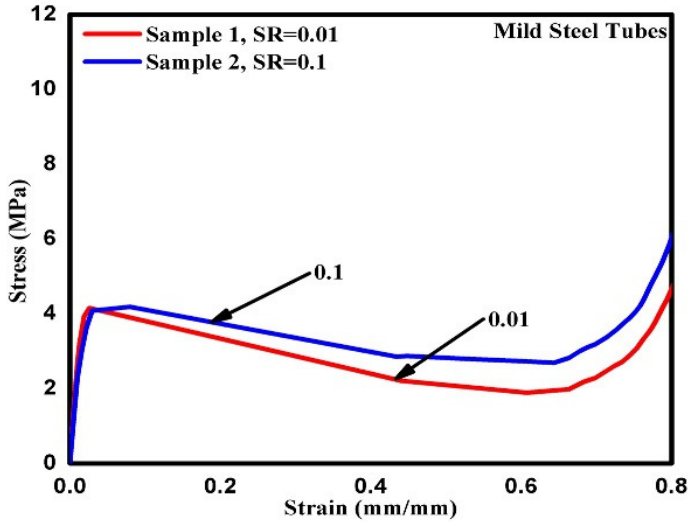

Figure 4. Experimental stress-strain curves of mild steel tubes

4.2.2. Aluminium alloy tubes

The stress-strain data of three samples at each strain rate is collected, similar to mild steel tubes, for the aluminium alloy tubes and the maximum data among the three for each strain rate is opted and stress-strain curve and energy absorption characteristics were determined for both the strain rates.

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Similar to mild steel tubes, the densification strain is taken as 0.8 and stress-strain curves for the aluminium alloy tubes are as shown in figure 5 and the energy absorption characteristics of the aluminium alloy tubes is tabulated in table 3. The stress-strain curves of aluminium tubes at both the strain rates is skew and distorted with uneven plateau stress and the pattern of the curve is almost similar with a small distance between each other. The plateau stress obtained from the stress-strain curves for strain rates 0.01 and 0.1 s^{-1} are 6.6 and 6.0 MPa respectively. The specific energy absorption and total energy absorption of the aluminium tubes at the strain rates 0.01 and 0.1 s^{-1} are 5.28 and 4.8 $MJmm^{-3}$ and 11.352 and10.320 J respectively. The maximum energy absorption capacity for aluminium tubes is found at 0.01 s^{-1} strain rate and can be stated that the performance of aluminium alloy tubes is better at 0.01 s^{-1}.

Table 3
Energy absorption data of aluminium tubes

Strain rate	***Plateau Stress (MPa)***	***Densification strain***	***Specific Energy (MJm^{-3})***	***Volume (mm^3)***	***Total Energy (J)***
0.01	6.6	0.8	5.28	2150	11.352
0.1	6.0		4.8		10.320

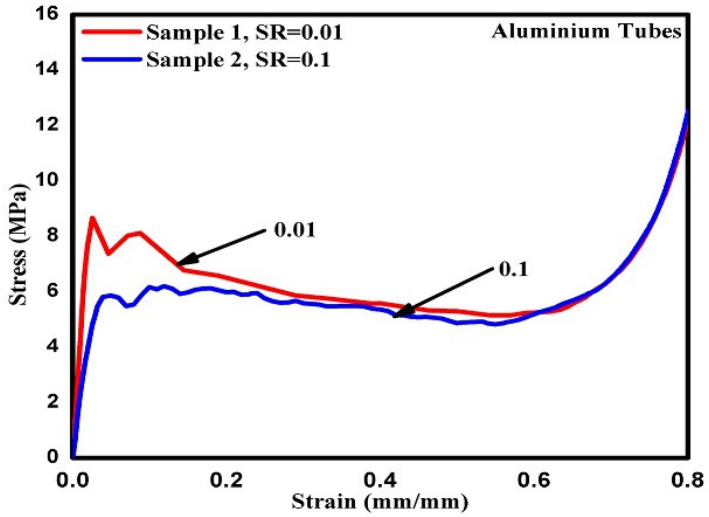

Figure 5. Experimental stress-strain curves of aluminium alloy tubes

4.3. Simulation results

The numerical analysis of the compression test in ABAQUS 6.13 is adopted for both mild steel and aluminium tubes, for studying their compression behaviour and deformation characteristics. The results of the simulation helped in better understanding the mechanism of deformation of both the mild steel and aluminium tubes. The simulation is performed for the maximum data that is opted for studying the energy absorption characteristics of mild steel and aluminium tubes. The results clearly show the stress transfer in both tubes during the compression process taking place.

4.3.1. Mild steel tubes

The maximum stress during initial stages of the compression is observed, as usually at the top of the tube, where the force is applied by the machine. The maximum stress then, after slight deformation, is transferred to the lower region of the force applied area and again shifts to the top where force is applied. After this, the maximum stress remains at the top of the tube and the folding of the tube faces takes place till the compression is performed with maximum stress at the top (force applied area). The stress-strain data obtained by the simulation results is near to the experimental results and the curve is almost similar to the experimental one. The stages of deformation of the mild steel tube in the experiment and in the simulation are clearly shown in the figure 6. The folding of the tube faces in the simulation is similar to that of the compression test specimen ones.

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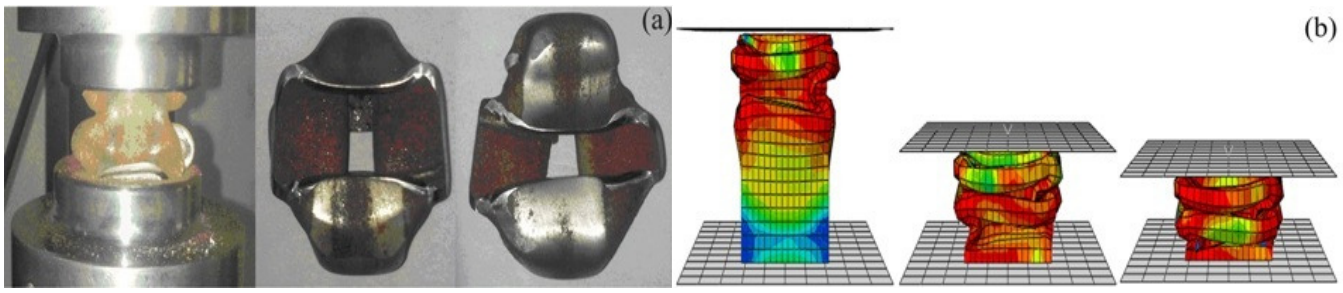

Figure 6. Stages of deformation of mild steel tube (a) experiment and (b) simulation

4.3.2. Aluminium tubes

The maximum stress at the initial stages of compression is observed at the top of the tube, where force is applied, similar to the above case and unlike in the case of mild steel tubes, the maximum stress is always at the top of the tube and does not shift to the lower regions of the force applied area. This phenomenon is continued, similarly as above, till the compression test is performed. The results of the simulation and the compression test are in good agreement with each other and folding mechanism are also similar in both simulation and compression test. The stages of deformation in both simulation and compression test are shown in the figure 7.

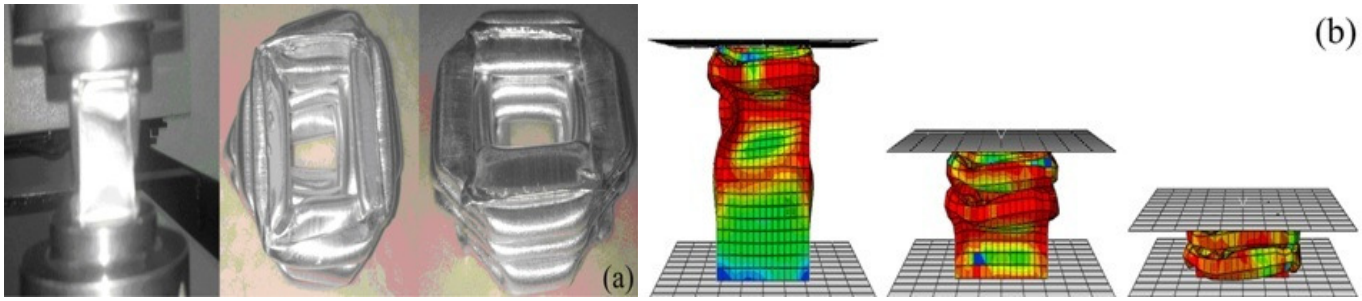

Figure 7. Stages of deformation of aluminium tube (a) experiment and (b) simulation

5. CONCLUSION

A comparative study on energy absorption characteristics of square cross-sectioned mild steel and aluminium tubes is performed and the deformation mechanism is studied and validated with the results of numerical analysis performed in ABAQUS 6.13.

The following are the conclusions made from the current study:

- The density of the AISI 1010 carbon steel used for test lies between 0.010745 and 0.011408 gmm^{-3} and Al 6061 alloys lies between 0.003714 and 0.003966 gmm^{-3}.
- The EDX tests on the AISI 1010 carbon steel shows that the Fe content is 99.36 wt% and C content is 0.11 wt% and for Al 6061 alloy shows that the Al content is 92.03 wt%.
- The micro-structure of both AISI 1010 carbon steel and Al 6061 alloy are studied and observed that they are ductile in nature, known fact and the mild steel has many cracks at the surface, may be due to the heat treatment and manufacturing processes and aluminium has many tiny voids on the surface.
- The maximum specific energy absorption of mild steel tube is 2.56 $MJmm^{-3}$ at a strain rate of 0.1 s^{-1} and can be concluded that mild steel tubes perform well at 0.1 s^{-1} strain rate. The maximum specific energy absorption of aluminium tube is 5.28 $MJmm^{-3}$ at a strain rate of 0.01 s^{-1} and can be concluded that aluminium tubes show good performance at 0.01 s^{-1} strain rate.
- The maximum specific energy capacity is higher for aluminium tube than the mild steel tube and higher specific energy capacity than mild steel is observed for aluminium at both strain rates. It can be concluded that aluminium is better energy absorbing material than mild steel for square cross-section tubes.
- Simulation results clearly show the stress transfer in the entire tube during the compression process and also show similar folding mechanism like in the case of experiment, for both mild steel and aluminium tubes. The results also show a similar stress-strain characteristic as the experimental ones, for both the tube materials.

REFERENCES

[1] Zarei, H. R., & Kroger, M., *Optimization of the foam-filled aluminum tubes for crush box application*, Thin-Walled Structures, vol. 46(2), pag. 214-221, 2008.
[2] Kim, S. B., Huh, H., Lee, G. H., Yoo, J. S., & Lee, M. Y., *Design of the cross section shape of an aluminum crash box for crashworthiness enhancement of a car*, International Journal of Modern Physics B, vol. 22(31n32), pag. 5578-5583, 2008.
[3] RCAR. Research Council for Automobile Repairs, *www.RCAR.org*, 1999.
[4] Jones, N., & Abramowicz, W., *Static and dynamic axial crushing of circular and square tubes*, Metal forming and impact mechanics, 10th edition, pag. 225-247, 1985.
[5] Abramowicz, W., & Jones, N., *Dynamic progressive buckling of circular and square tubes*, International Journal of Impact Engineering, vol. 4(4), pag. 243-270, 1986.
[6] Grzebieta, R. H., *An alternative method for determining the behaviour of round stocky tubes subjected to an axial crush load*, Thin-walled structures, vol. 9(1), pag. 61-89, 1990.
[7] Wang, X. G., Bloch, J. A., & Cesari, D., *Axial crushing of tubes made of multi-materials*, In Proceedings of the 4th international MECAMAT seminar on mechanics and mechanisms of damage in composites and multi-materials. St. Etienne (France, London): Mechanical Engineering Publications Ltd, pag. 351-60, 1991.
[8] Gupta, N. K., & Velmurugan, R., *Consideration of internal folding and non-symmetric fold formation in axisymmetric axial collapse of round tubes*, International Journal of Solids and Structures, vol. 34(20), pag. 2611-2630, 1997.
[9] Gupta, N. K., *Some aspects of axial collapse of cylindrical thin-walled tubes*, Thin-Walled Structures, vol. 32(1), pag. 111-126, 1998.
[10] Song, H. W., Wan, Z. M., Xie, Z. M., & Du, X. W., *Axial impact behavior and energy absorption efficiency of composite wrapped metal tubes*, International Journal of Impact Engineering, vol. *24*(4), pag. 385-401, 2000.
[11] Guillow, S. R., Lu, G., & Grzebieta, R. H., *Quasi-static axial compression of thin-walled circular aluminium tubes*, International Journal of Mechanical Sciences, vol. 43(9), pag. 2103-2123, 2001.
[12] Al Galib, D., & Limam, A., *Experimental and numerical investigation of static and dynamic axial crushing of circular aluminum tubes*, Thin-Walled Structures, vol. 42(8), pag. 1103-1137, 2004.
[13] El-Hage, H., Mallick, P. K., & Zamani, N., *A numerical study on the quasi-static axial crush characteristics of square aluminum tubes with chamfering and other triggering mechanisms*, International Journal of Crashworthiness, vol. 10(2), pag. 183-196, 2005.
[14] Zarei, H. R., & Kröger, M., *Multiobjective crashworthiness optimization of circular aluminum tubes*, Thin-walled structures, vol. 44(3), pag. 301-308, 2006.
[15] Gupta. N. K., *A study of the influence of diameter and wall thickness of cylindrical tubes on their axial collapse*, Thin-walled structures, vol. 44(3), pag. 290-300, 2006.
[16] Gameiro, C. P., & Cirne, J, *Dynamic axial crushing of short to long circular aluminium tubes with agglomerate cork filler*, International Journal of Mechanical Sciences, vol. 49(9), pag. 1029-1037, 2007.
[17] Chung Kim Yuen, S., Nurick, G. N., & Starke, R. A., *The energy absorption characteristics of double-cell tubular profiles*, Latin American Journal of Solids & Structures, vol. 5(4), 2008.
[18] Hosseini, M., Abbas, H., & Gupta, N. K., *Change in thickness in straight fold models for axial crushing of thin-walled frusta and tubes*, Thin-Walled Structures, vol. 47(1), pag. 98-108, 2009.
[19] Nia, A. A., & Hamedani, J. H., *Comparative analysis of energy absorption and deformations of thin walled tubes with various section geometries*, Thin-Walled Structures, vol. 48(12), pag. 946-954, 2010.
[20] Ahmad, Z., Thambiratnam, D. P., & Tan, A. C. C., *Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading*, International Journal of Impact Engineering, vol. 37(5), pag. 475-488, 2010.
[21] Ghamarian, A., Zarei, H. R., & Abadi, M. T., *Experimental and numerical crashworthiness investigation of empty and foam-filled end-capped conical tubes*, Thin-Walled Structures, vol. 49(10), pag. 1312-1319, 2011.
[22] Li, Z., Yu, J., & Guo, L., *Deformation and energy absorption of aluminum foam-filled tubes subjected to oblique loading*, International Journal of Mechanical Sciences, vol. 54(1), pag. 48-56, 2012.

ISSN 2457 – 5275 (Online, English)
ISSN 1842 – 4074 (Print, Online, Romanian)

[23] Mirzaei, M., Shakeri, M., Sadighi, M., & Akbarshahi, H., *Experimental and analytical assessment of axial crushing of circular hybrid tubes under quasi-static load*, Composite Structures, vol. 94(6), pag. 1959-1966, 2012.
[24] Kim, H. C., Shin, D. K., Lee, J. J., & Kwon, J. B., *Crashworthiness of aluminum/CFRP square hollow section beam under axial impact loading for crash box application*, Composite Structures, 112th edition, pag. 1-10, 2014.
[25] Goel, M. D., *Deformation, energy absorption and crushing behavior of single-, double-and multi-wall foam filled square and circular tubes*, Thin-Walled Structures, 90th edition, pag. 1-11, 2015.
[26] Mohsenizadeh, S., Alipour, R., Rad, M. S., Nejad, A. F., & Ahmad, Z., *Crashworthiness assessment of auxetic foam-filled tube under quasi-static axial loading*, Materials & Design, 88th edition, pag. 258-268, 2015.
[27] Kılıçaslan, C., *Numerical crushing analysis of aluminum foam-filled corrugated single-and double-circular tubes subjected to axial impact loading*, Thin-Walled Structures, 96th edition, 82-94, 2015.
[28] Rajak, D. K., Kumaraswamidhas, L. A., & Das, S., *Energy absorption capabilities of aluminium foam-filled square tube*, Adv. Mater. Lett, vol. 6(1), pag. 80-85, 2015.
[29] Rajak, D. K., Kumaraswamidhas, L. A., & Das, S., *Energy absorption capacity of empty and foam filled mild steel tube under low strain rate at room temperature*, Adv. Mater. Lett, vol. 6(6), pag. 548-553, 2015.
[30] Gao, Q., Wang, L., Wang, Y., & Wang, C., *Crushing analysis and multiobjective crashworthiness optimization of foam-filled ellipse tubes under oblique impact loading*, Thin-Walled Structures, 100th edition, pag. 105-112, 2016.
[31] Gandy, D., Carbon steel handbook, Electric Power Research Institute, Inc., California, USA, 2007.
[32] Hatch, J. E., *Aluminum: properties and physical metallurgy*, Aluminum Association, ASM International, 1984.
[33] Sukiman, N. L., Hughes, A. E., Thompson, G. E., Mol, J. M. C., Birbilis, N., Garcia, S. J., & Zhou, X., *Durability and corrosion of aluminium and its alloys: overview, property space, techniques and developments*, INTECH Open Access Publisher, 2012.
[34] Systemes, D., *Abaqus analysis user's manual*. Simulia Corp. Providence, RI, USA, 2007.

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ISSN 1842 – 4074 (Print, Online, Romanian)

ABOUT THE CONSTRUCTIVE AND FUNCTIONAL PARTICULARITIES OF SPARK IGNITION ENGINES WITH GASOLINE DIRECT INJECTION

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Abstract: *The paper aims to analyze and explain the mechanism for the formation of stratified mixtures in a correlated manner with constructive and functional particularities of the gasoline direct injection engines. There are analyzed the stages of formation mechanism of this type of mixture, by using organized movements with the control of fuel jet. It points out that burning stratified mixtures represent a serious reserve regarding dynamic, economic and environmental performances of spark ignition engines. Reason why, we believe the widespread implementation of this technology is today an immediate need.*

Key-Words: *Stratified mixtures, Organized movements, Gasoline direct injection, Lean mixtures*

1. ANALYSIS OF MIXTURE FORMATION FEATURED IN GDI ENGINES

The actual trend in terms of internal combustion engines is to obtain higher dynamic performances with a low fuel consumption, respecting at the same time the current legislation. In order to compliance with these requirements that become more and more exigent, automotive manufacturers chose to implement on their engines gasoline direct injection and downsizing techniques. Gasoline direct injection known as GDI, although is not a new technique, it was used for the first time by Mercedes for the mechanical variant and by Mitsubishi in 1996 for the electronic version, its applicability it's increasing fast [7]. Direct injection system for gasoline engines is similar with the one used for diesel engines, with except of few particularities. Therefore, gasoline direct injection system consist of: low pressure fuel pump, high pressure fuel pump, common rail, piezoelectric injectors, fuel rails [6]. Gasoline direct injection necessarily requires obtaining stratified air-fuel mixtures.
Combustion in lean mixture area is especially possible due organized movements of air such as swirl, tumble, squish and control of the fuel jet (Figure 1).

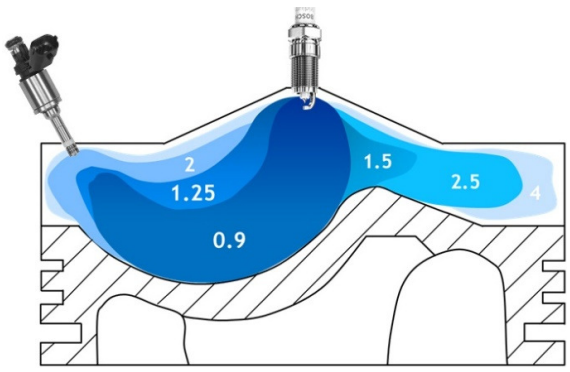

Figure 1. The distribution of air excess coefficient in the cylinder [1]

By using these types of movements, the air-fuel mixture becomes heterogeneous, mixture layering involves excess of fuel around the spark plug for a proper ignition and lean mixture in the other areas. Lean mixture in exterior areas acts like a thermic isolation layer (Figure 2).

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a) Swirl b) Tumble c) Squish

Figure 2. Types of organized mixtures [1]

Overall the mixture in combustion chamber is lean or very lean, without affecting the flame velocity. Swirl motion (Figure 2a) assume air mass rotation around the cylinder axis. This type of movement confers a various number of advantages such as: rapid homogenization of the mixture, high flame velocity, ignition stability by orientating the fuel mass towards the spark plug and fast evaporation of the fuel. It can be generated by the helical path of the intake manifold, valves and piston. Intake manifold and the valves serve to generate the swirl motion, while the form of the piston head is designed to increase the effect. The disadvantage of this type of flow is given by the fact that oil film that lies on the cylinder wall can be driven by the mixture in case of an intensive swirl flow. Tumble motion (Figure 2b) assume tangential rotation of the air mass or mixture in a perpendicular plan on piston head surface. Tumble motion is generated by the circular axis of the intake manifold and maintained by piston head profile. Thus, during the compression stroke the tumble effect can be amplified by piston head profile. Squish motion (Figure 2c) is a radial movement that is obtained at the end of the compression stroke, by step effect when the mixture reaches the piston and cylinder head cavities. Working principle of the gas direct injection engines is mostly similar with the diesel engine. The major difference is given by the fact that this engine can run with both type of mixtures, stratified and homogenous and the combustion is initiated by using a spark plug. The area where the engine is working with stratified mixtures is common for constant acceleration phases while the area in which the engine is working with homogenous mixtures is specific for transitional phases with fast accelerations and during start phase. In case of the stratified combustion, the fuel is injected at the end of the compression stroke, while for homogenous combustion the fuel is injected at the beginning of the intake stroke [1]. When the engine is running in stratified mode, air excess coefficient has values between 0.9-4.0.

2. FUEL JET CONTROL

Gasoline direct injection assume guiding the fuel jet that is delivered in the cylinder, in such way as the mixture to be found near the spark plug in order to have a proper ignition. Fuel jet control it can be realized using three methods: wall guiding, direct guiding and air guiding of the fuel jet. Wall guiding of the fuel jet (Figure 2a) assume orientating the fuel mass toward the spark plug using the profiled surface of the piston head. The fuel mass is injected in the piston surface and due the piston movement during the compression stroke to the top dead center, the fuel is redirected to the spark plug. The disadvantage of this method is given by the impact on the fuel consumption, hydrocarbons and carbon monoxide emissions. These pollutants appear because the fuel mass does not evaporate and make deposits on piston surface. Air guiding (Figure 2b) of the fuel jet assume installing air flaps for every cylinder in the intake manifold. The air flaps serve to control the air flow and amplifying the tumble effect of the mixture. The air flux transfers the fuel mass to the spark plug. The advantage is given by the fact that the fuel mass is isolated from the walls by the air, thus the risk of fuel deposits on piston and cylinder surface is considerably lowered. Direct guiding (Figure 2c) of the fuel mass assume placing the injector near the spark plug. The fuel mass being ignited at short time after the injection.

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The advantage of this method is given by the fact that the risk of fuel deposits on the cylinder walls or piston surface is eliminated and by the fact that the fuel ignition is more sensitive to the air fluctuations. The main disadvantage is given by the quantity of the fuel deposits on the spark plug electrodes, leading to a low reliability [7].

a) Wall guiding b) Air guiding c) Direct guiding

Figure 3. Fuel jet control [4]

In order to achieve a high penetration in the cylinder of the fuel jet, in order to have a good spray angle and a fast evaporation of the fuel, the injection pressure is raised to 40-130 bar.
The injection pressure can't pass this threshold of pressure in order to eliminate the risk of the fuel reaching the cylinder wall [7].

3. FUNCTIONAL PARTICULARITIES OF GASOLINE DIRECT INJECTION ENGINES

As it was already mentioned, gasoline direct injection engines can work with both, stratified and homogenous mixtures.

3.1 Intake (stratified)

While the engine is working in stratified mode, since the control is done qualitatively, the butterfly is maintained fully open in order to achieve highest engine air load efficiency. The air flaps are positioned in such way that the air flow be generated largely through the upper zone of the valve in order to generate a tumble or swirl motion. As the piston descends to bottom dead center during the intake stroke, tumble impregnated air movement tends to be damped by the movement of the piston.
However, due to the piston profile, movement intensity of the air it is preserved and even easily enhanced during the process of compression (Figure 4) [5].

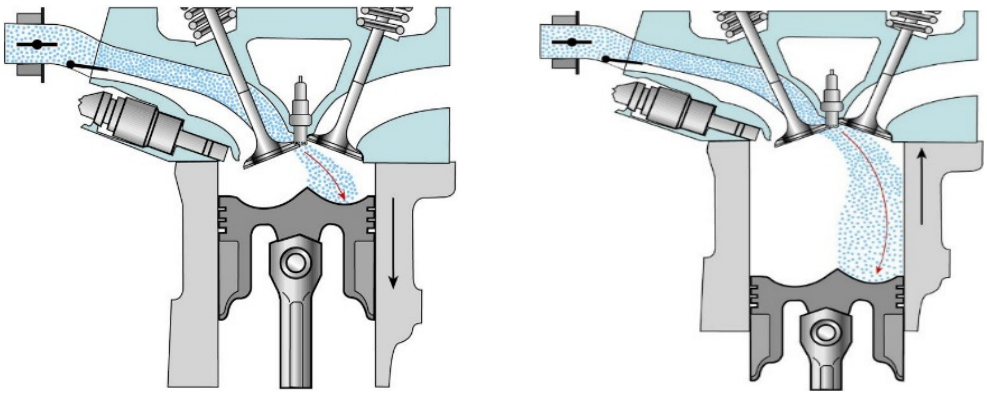

Figure 4. Intake stroke (stratified) [5]

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3.2 Compression (stratified)

At the end of compression stroke fuel injection takes place in the piston cavity which lends to a reverse tumble of the fuel against the air movement. In this way the fuel is redirected to the spark plug, improving ignition (Figure 5) [5].

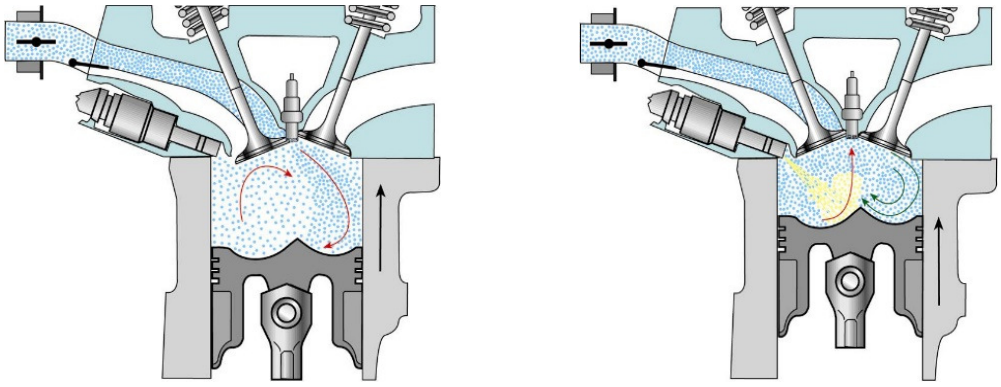

Figure 5. Compression stroke (stratified) [5]

Since the adjustment is done qualitatively, the engine load is managed by controlling the quantity of fuel. When the operation mode is changing from the stratified mode to the homogeneous one the first step is to reposition the butterfly to the pedal request. At the same time the air flaps are closing in this way flows between both intake sections [5].

3.3 Intake (homogenous)

In this case, the moment of fuel injection is the same as in multi-point injection engines. Because the injection takes place at the beginning of the intake stroke, the fuel has enough time to mix with the air (Figure 6) [6].

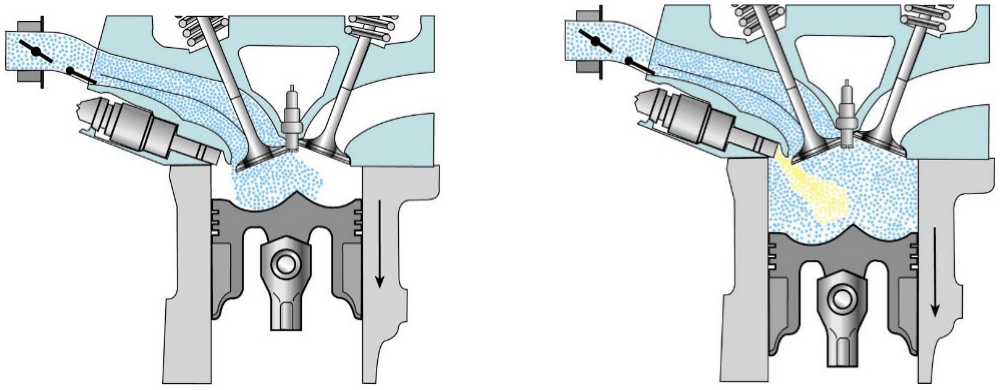

Figure 6. Intake stroke (homogenous) [5]

3.4 Compression (homogenous)

Follows normally, the air-fuel mixture is compressed, and when the piston is near the top dead center, the ignition takes place with advance and the combustion is initiated [6].

The decision regarding the operation mode of the engine belongs entirely to the electronic control unit depending on driving conditions and the operating modes changes occur without distorting the stability of the engine [5].

The gasoline direct injection engines allows bigger compression ratios without increasing the risk of knocking. Thus the economic and dynamic performances are increased compared to the multi-point injection engine. In addition, intense movements of the mixture amplify the evaporation process which involves reducing the gas temperature in the cylinder, therefore there is no risk of NOx emissions increase. By using stratified mixtures, the amount of fuel injected at every cycle is lowered, having benefits over the fuel consumption and CO_2 [3].

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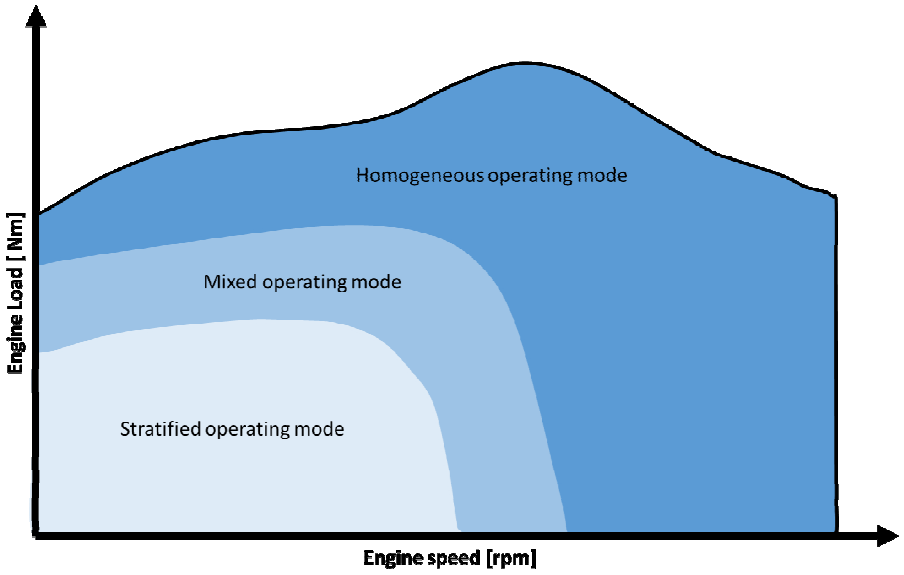

Figure 7. Operating modes repartition [5]

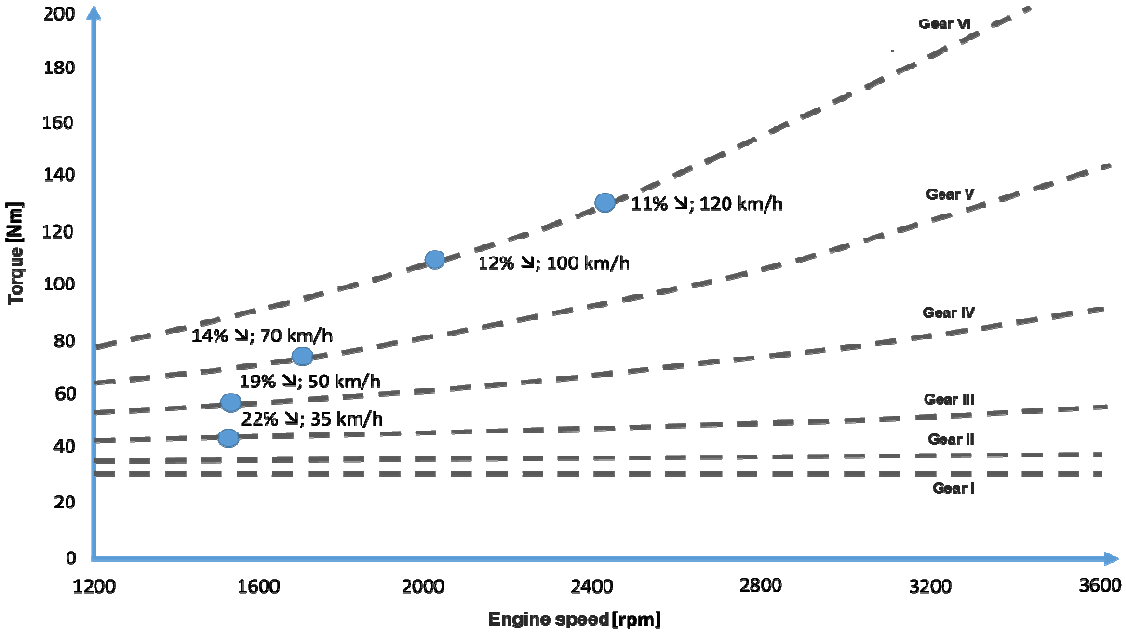

Figure 8. The influence of gasoline direct injection over the fuel consumption [3]

Figure 8 is showing the influence of gasoline direct injections over the fuel consumption for a middle class car ([3]Fuel Efficiency Improvements from Lean, Stratified Combustion with a Solenoid Injector) equipped with a 6-gear gearbox; it is found that by using lean mixtures for spark ignition engines the fuel consumption is reduced by 11-22% in comparison with the multi-point injection engine. At low loads, in stratification operation mode, this type of engine running with the butterfly fully open, thus the pumping losses are reduced.

Due to increased compression ratio the engine has a higher degree of compression and expansion. Loss of heat through the cylinder walls is limited because the combustion is insulated by a layer of air. All of the above has the effect of increasing the efficiency of the engine, getting close to the compression ignition engine efficiency [3].

Lean mixtures, significantly decrease the HC and CO emissions and the increase of NOx concentrations is not significantly mostly because the temperatures of NEDC cycle are relatively low. The NOx increase due to the air excess are countered by conventional post-treatment devices.

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A specific problem that occurs at this type of engines is given by the amount of PM emissions.
This disadvantage can be overcome by using the gasoline particulate filter [4].

4. CONCLUSION

At the current stage, direct injection is an indispensable solution in order to achieve spark ignition engine taht ensure compliance with the legislative requirements regarding dynamic, economic and environmental performances.

REFERENCES

[1] F. Zhao, M.-C. Lai, D.L. Harrington, *Automotive spark-ignited direct-injection gasoline engines*, PERGAMON, USA 1999
[2] Walter F. Piock, Peter Weyand, Edgard Wolf, Volker Heise, *Ignition Systems for Spray-Guided Stratified Combustion*
[3] Harry L. Husted, Walter Piock and George Ramsay, *Fuel Efficiency Improvements from Lean, Stratified Combustion with a Solenoid Injector*, Delphi Corporation
[4] Mustafa Bahattin Çelik, Bülent Özdalyan, *Gasoline direct injection*, InTech 2010, Turkey
[5] *** *Direct Petrol Injection System with Bosch Motronic MED 7*; Self-Study Programme 253 Volkswagen
[6] Florian Ivan, *Note de curs*, Universitatea din Pitesti, 2012
[7] www.e-automobile.ro, *Motoare pe benzină cu injecție directă*

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EXPERIMENTAL INVESTIGATIONS OF THE HYDROGEN USE AT THE AUTOMOTIVE DIESEL ENGINE

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Abstract: *The hydrogen has a great potential for the improving energetically and pollution performance of compression ignition engines due to its good combustion properties. The paper presents comparative results of the experimental researches carried on a truck compression ignition engine of 10.34 L displacement fuelled with diesel fuel or with hydrogen and diesel fuel by diesel-gas method at the operating regimen of 40% load, engine speed of 1400 rpm and for two injection timing values. The obtained results of the experimental investigations highlight the engine performance improving at its fuelling with hydrogen addition.*

Key-Words: *Hydrogen, Diesel engine, Pollution, Fuel, Combustion*

1. INTRODUCTION

In the last time, a special attention is given to reducing main pollutant emissions of the automotive internal combustion engines which appear because of fuels combustion imperfection. The main pollutants of diesel engine are: carbon monoxide, CO, unburned hydrocarbons, HC, nitrogen oxides, NO_x, particles, PM, smoke and carbon dioxide CO_2 which has greenhouse effect. Today, a severe legislation is promoted to limit the pollutants emissions level by applying of new control methods. The strategies used for reducing environmental pollution led to straitening the researcher's attention to alternative fuels use [1][2][3], like hydrogen. Hydrogen is a privileged alternative fuel for the internal combustion engines due to its properties, table 1, which makes it the cleanest fuel and due to its unlimited producing resources [4][5][6].
Due to its proprieties it seems very possible to reach homogenous air-fuel mixtures during the pre-formed phase of the air-fuel mixture combustion.
So, is possible to decrease the soot, CO and HC emissions level by using hydrogen in diesel engine at the same energetic level achieved when only diesel fuel is used. The hydrogen does not contain sulphur and carbon in its composition, this lowering the pollutants emission considerably, in special at small and medium engine loads. Hydrogen has high resistance to auto ignition, which prevents its use as fuel unique in diesel engine, an ignition source being required [7][8][9][10].
One of the methods of hydrogen use recommended for diesel engines is the diesel-gas method due to its advantages: can be easy implemented on the diesel engine; the air-hydrogen mixture has a higher homogeneity, being assured all conditions for a reliable diesel engine operate. The hydrogen is injected into the intake manifold, the hydrogen-air mixture with a great homogeneity being ignited by the flame initiated by auto ignition of diesel fuel injected into the engine cylinder. The experimental investigations conducted in different laboratories on diesel engines fuelled with hydrogen and diesel oil highlighted some specific aspects comparative to diesel oil engines fuelled: the engine specific power increases with 10-15% comparative to using only diesel fuel [11]; the engine thermal efficiency increases at partial engine loads with about 5% to using only diesel fuel [11]; pollutants emissions decrease. At the increase of amount of hydrogen that replaces the diesel fuel, due to higher homogenization of air-fuel mixture, the maximum pressure during combustion increases [12]. At the hydrogen-gas oil fuelled engine operate CO, HC and smoke emissions level has a lower level than the standard diesel engine due to a better combustion, the lower carbon content in air-fuel mixture and higher homogeneity of air-hydrogen mixture [11]; the emissions level of CO_2 has a slight increase [2][13].

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Table 1
Properties of hydrogen and diesel fuel

Property		Diesel fuel	Hydrogen
Molecular mass, [kg/kmol]		226	2.016
Theoretical air-fuel ratio, [kg air/kg fuel]		14.7	34.32
Density, at 0°C and 760 mmHg, [kg/m^3]		820-860	0.0899
Flammability limits in air, at 20 °C and 760 mm Hg	% vol.		4.1-75.6
	λ_i....λ_s	0,34…1,68	0.136…10.12
Flame velocity in air (λ=1), at 20 °C and 760 mm Hg [m/s]			2.37
Cetane Number		45-55	
Min. ignition energy in air [mJ]		0.2-0.3	0.15
Heat of Vaporization [kJ/mol]		250-314	458.1
Boiling temperature, ^{0}C, la 101300 Pa		180-359	-253
Autoignition temperature, [K]		628	845
Lower Heating Value (gas at 0°C and 760mmHg)	stoichiometric fuel-air mixture [kJ/m^3]	3344	3279
	[kJ/kg]	41800	119 600

Naber explains the increasing concentration of CO_2, through the condensation of water vapour which results from the hydrogen burning in greater quantities, on the exhaust way decreasing the total flow of exhaust gas assessed. NO_x emissions level grows at the increase hydrogen addition in particular at high loads because the temperature in the engine cylinder is bigger [14].
N. Saravanan [12] and M. Younkins [15] have found that NO_x emissions level decreases with about 14% at the engine fuelling with hydrogen in small quantities (up to 15% energetic of replace of diesel fuel) at small engine loads, because of the shorter duration of the high temperatures developed in the engine cylinder, avoiding the formation of NO_x emissions.
At bigger amounts of hydrogen use, the NO_x emissions level increases compared to the level of emissions of a standard diesel engine because of the maintenance in time of high temperatures in the cylinder. In this paper are presented some results of experimental researches done on a diesel engine truck, powered by adding hydrogen at engine load of 40% and speed of 1400 rpm for two injection timing values. The general objective of the research is the use of hydrogen at the diesel engine for improving energetically engine performance and for decrease of the pollutants emissions level.
By achieving these specific objectives the paper brings an important contribution to alternative fuels use at diesel engines and to solving pollution problems in large urban and agriculture areas, the solution can being easily implemented on diesel engines in running, even on the old design which can be converted to fit the current rules of pollution.

2. EXPERIMENTAL RESEARCH

The experimental research has been followed on the D2156 MTN8 engine at the operating regimen of 40% load, engine speed of 1400 ±2% rpm and normal thermal regimen (80°C cooling agent temperature) for two injection timing values.
The engine was mounted on a test bench equipped with an eddy-current dynamometer and adequate instrumented with: data acquisition system, thermometers, thermocouples, thermo resistances and manometers monitoring the engine functional parameters, air flow meter, hydrogen flow meter, gas-oil consumption device and gas analyzer.
In the figure 1 is presented the scheme of the experimental bench.

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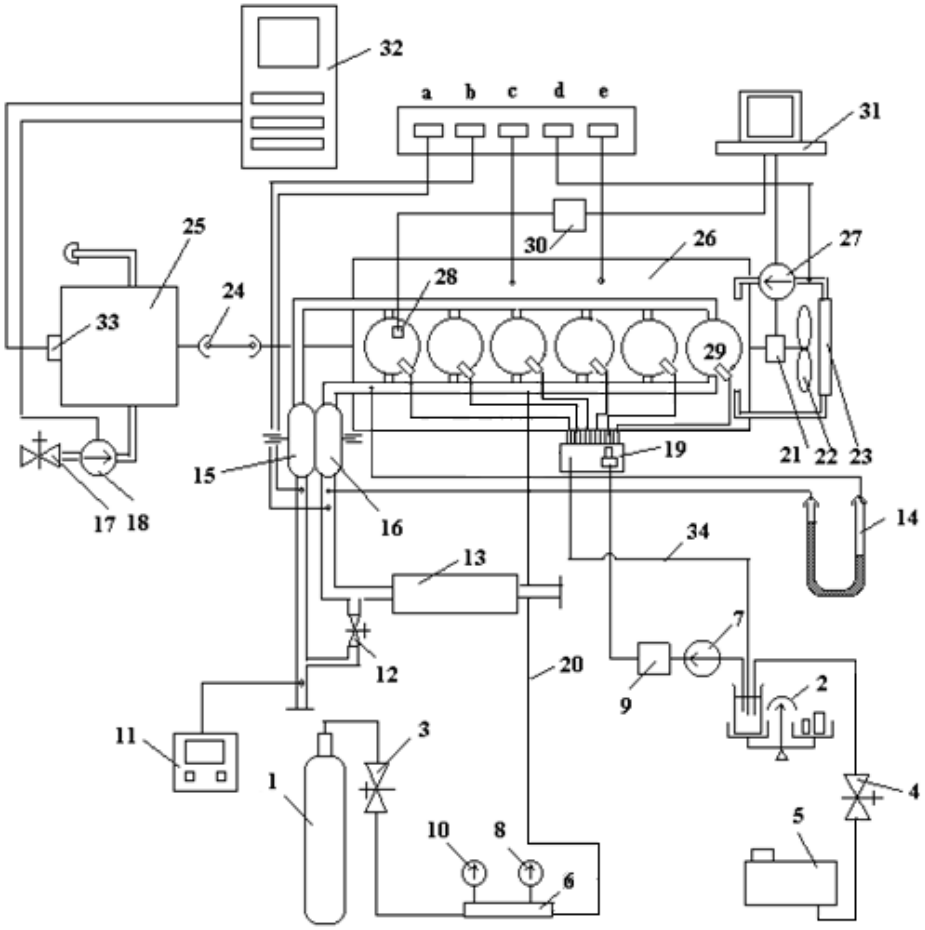

Figure 1. The scheme of the experimental bench

1.Hydrogen bottle 2.Weight balance; 3. Hydrogen valve; 4. Diesel fuel valve; 5. Diesel fuel tank; 6. Pressure regulator; 7. Diesel fuel supplying pump; 8. Manometer high pressure; 9. Diesel fuel filter; 10. Low pressure manometer; 11. AVL DiCom 4000 gas analyzer; 12. Gas recirculation valve; 13. Meriam air flowmeter; 14. Differential manometer for turbocharging pressure measuring; 15-16. Turbo-compressor group; 17. Dynamometer water cooling valve; 18. Water circulation pump for dynamometer cooling; 19. Diesel fuel injection pump; 20. Hydrogen pipe; 21. Incremental speed transducer; 22. Ventilator 23. Cooling liquid radiator; 24. Couple; 25. Hoffman eddy-current dynamometer; 26. D2156 MTN8 diesel engine; 27. Water circulation pump for the engine cooling; 28. Kistler piezoelectric pressure transducer; 29. Injector; 30. Kistler charge amplifier; 31. PC with Keithley acquisition board; 32. Dynamometer controller; 33. Dynamometer power cell; 34. Diesel fuel pipe; a) Inlet air temperature indicator; b) Exhaust gas temperature indicator; c) Oil temperature indicator; d) Oil pressure indicator; e) Water cooling temperature indicator.

3. RESULTS AND DISCUSSIONS

The engine was fuelled firstly only with fuel diesel then with diesel fuel and hydrogen in addition at different rate between 9.12 L/min and 39.6 L/min corresponding some percents of substitute energetic ratios of diesel fuel by hydrogen of 1.14%, 2.62%, 3.73% and 4.81% for injection timing of 24 CAD and between 9.6 L/min and 40.15 L/min corresponding some percents of substitute energetic ratios of diesel fuel by hydrogen of 2.4%, 2.68%, 4.00% and 5.4% for injection timing of 28 CAD. Because the percents of diesel fuel substitute ratios with hydrogen are small, the maximum pressure and maximum rise pressure rate slightly increase, (Figure 2), due to small increase of the amount of fuel which burns in the pre mixed combustion faze and of the auto ignition delay decrease comparison to diesel fuel engine. The brake specific fuel consumption evaluated in paper through minimum brake specific energetic consumption, BSEC, is smaller than one of diesel fuel engine with 8% for 24 CAD injection timing and with 5.6% for 28 CAD injection timing, (Figure 3), due to combustion improvement.
In figure 4 the variation of carbon monoxide emissions level with different substitute ratios is shown, emission level being constant for both values of the injection timing.
The variation of HC and smoke emissions level is shown in figure 5 and 6.

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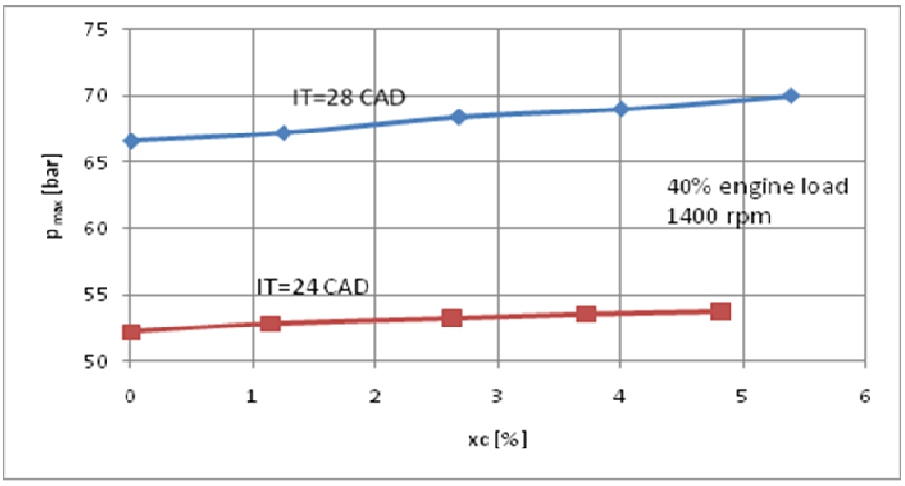

Figure 2a. Maximum pressure vs. different substitute ratios x_c, at the engine regime of 40% load and 1400 min^{-1} speed

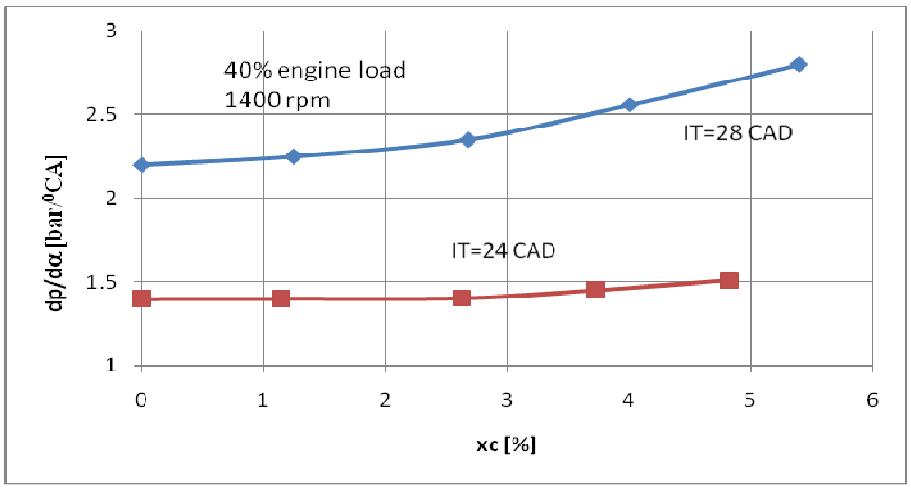

Figure 2b. Maximum pressure rise rate vs. different substitute ratios x_c, at the engine regime of 40% load and 1400 min^{-1} speed

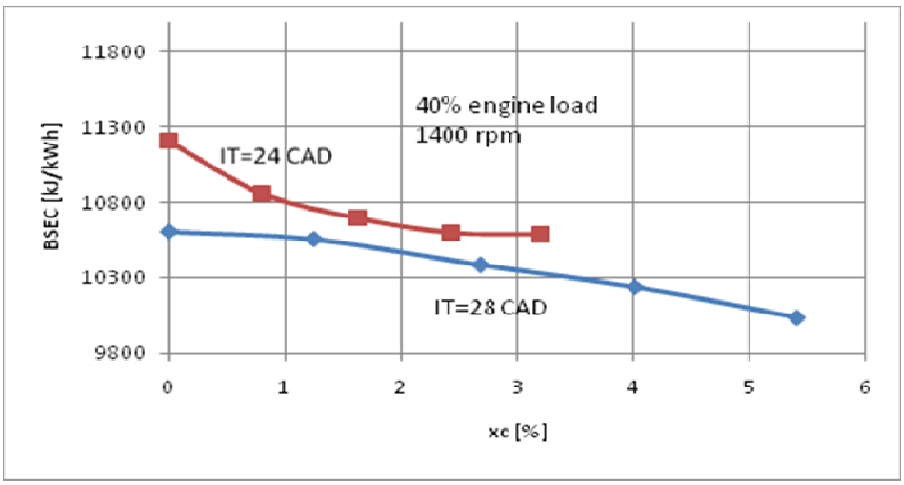

Figure 3. Break Specific Energetic Consumption vs. different substitute ratios x_c, at the engine regime of 40% load and 1400 min^{-1} speed

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The HC and smoke emissions level slowly decreases comparative to diesel fuelled engine due to combustion improvement and better homogeneous fuel-air mixture.

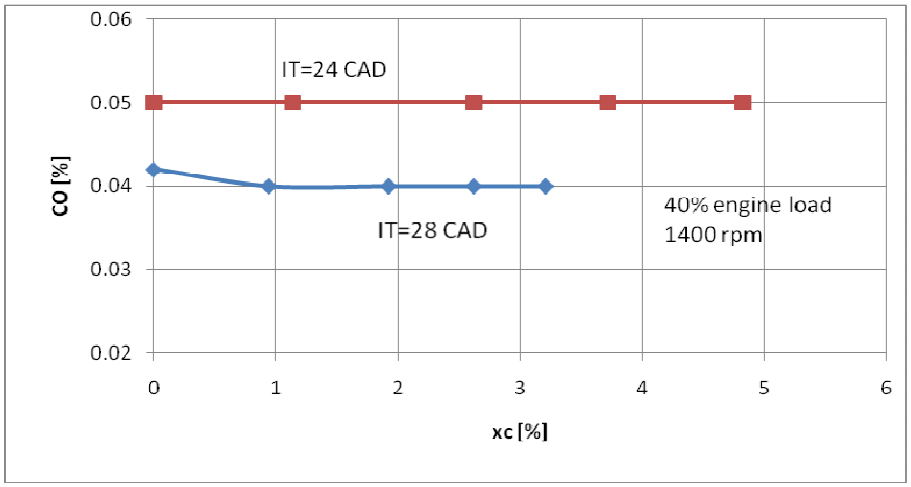

Figure 4. CO emission level vs. different substitute ratios x_c, at the engine regime of 40% engine load and 1400 min^{-1} speed

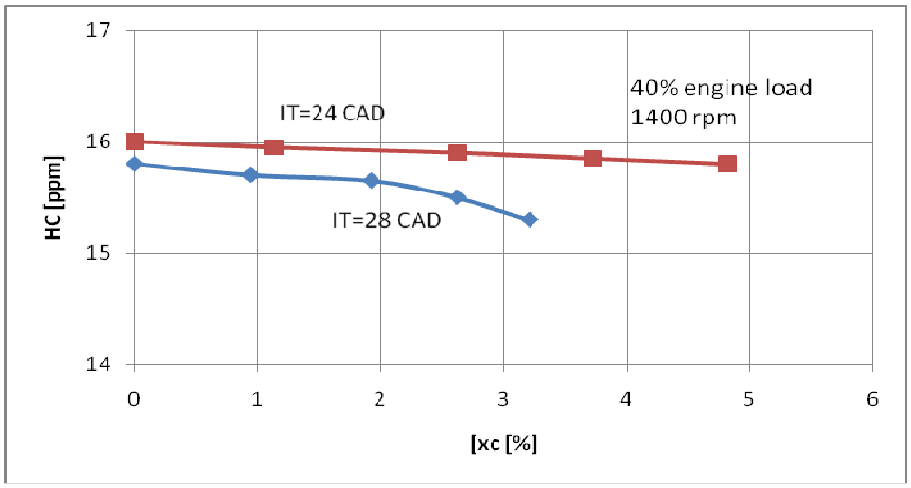

Figure 5. HC emission level vs. different substitute ratios x_c, at the engine regime of 40% engine load and 1400 min^{-1} speed

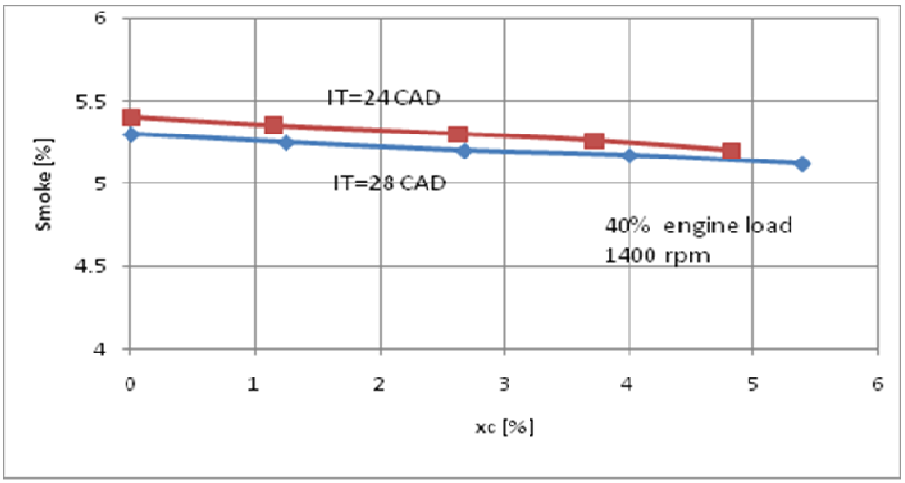

Figure 6. Smoke emission level vs. different substitute ratios x_c, at the engine regime of 40% engine load and 1400 min^{-1} speed

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In the figure 7 is presented the variation of NO_x emissions level with different substitute ratios.
With hydrogen-diesel oil dual fuelling operation mode NO_x emissions level decreases with 12% comparative to diesel engine for a 2.62% percent of substitute ratio of diesel fuel by hydrogen at 24 CAD injection timing and with 7% comparative to diesel engine for a 0.96% percent of substitute ratio of diesel fuel by hydrogen at 28 CAD (at this value of injection timing the NO_x decrease is smaller due to higher temperature level).
Similar results were obtained and by other researchers.
Thus, Lambe and Watson [1] and Tomita et al [2] have reported considerable reductions in NOx emissions level at the engine operate with hydrogen addition.
The high effect of the temperature on the NO_x emissions formation is known.
At the engine small loads the diesel-fuel cycle dose is reduced.
At the hydrogen adding, at the same engine load, the cycle dose of diesel fuel and the combustion duration decrease.
For the investigated engine operating regimen (small engine load and hydrogen additions) the combustion duration for which the heat release rate is greater than at the engine operate with diesel fuel is shorter.

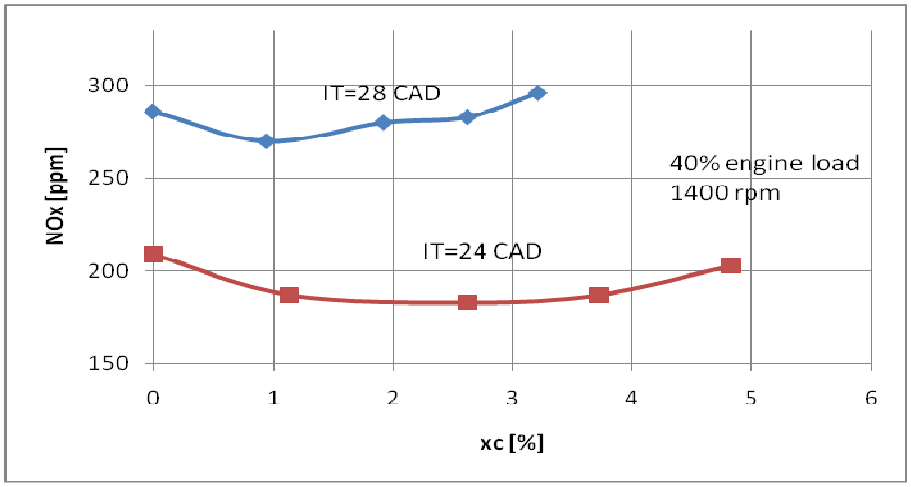

Figure 7. NO_x emission level vs. different substitute ratios x_c, at the engine regime of 40% engine load and 1400 min^{-1} speed

The authors explication regarding the NO_x emissions level decrease at the engine operate with small hydrogen quantities in addition is the fact that though the hydrogen fast burns and the temperature increases is avoided NO_x emissions formation due to a shorter duration of the combustion and high temperatures are registered only for short time ~1.8 ms.
Same explication is given by Georgios Pechlivanoglou: “the combustion is so rapid that the high temperatures exist only for approx. 2ms” [16].
Whatson [1] and Thalibi et al. [3] explains NO_x decrease at the hydrogen adding through the increase of the mole fraction of water vapours in the combustion products produced at the hydrogen combustion which absorb energy released from combustion and thus the peak combustion temperatures decrease [3]. At the hydrogen addition increase the temperature effect regard the NO_x formation is high because the heat release is greater and high temperatures time duration increases.
Thus, is explained the NO_x emissions level increase at percents of substitute ratio of diesel fuel by hydrogen greater of 3%.
The variation of carbon dioxide emission level with different substitute ratios is shown in figure 8, emission level being near constant.

4. CONCLUSION

The use of hydrogen at the diesel engine is a good opportunity because improves the combustion process due to its better combustion characteristics in comparison to gas-oil.
The engine performances are improved. The NO_x emissions level decreases for small hydrogen addition.

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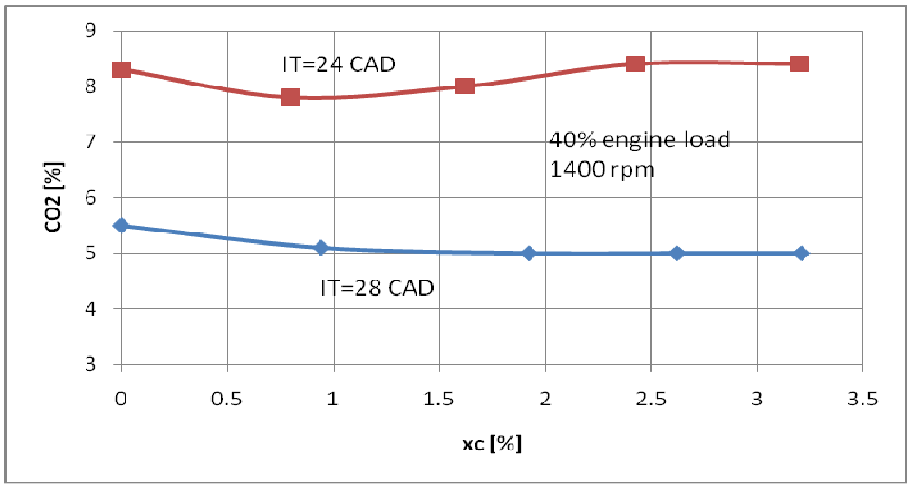

Figure 8. CO_2 emission level vs. different substitute ratios x_c, at the engine regime of 40% engine load and 1400 min^{-1} speed

The smoke and HC emissions level decreases.
The small hydrogen additions use is another advantage due to the fact that it can be produced at the vehicle board and doesn't required major engine design modifications. Hydrogen can be considered a good alternative fuel for diesel engine, assuring the partial replace of the fossil.

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REFERENCES

[1] S. Lambe, H. Watson, *Optimizing the design of a hydrogen engine with pilot diesel fuel ignition, international journal vehicles design*, 1993, 14:370E89
[2] Tomita E, Kawahara N, Piao Z, Fujita S, Hamamoto Y., *Hydrogen combustion and exhaust emissions ignited with diesel oil in a dual fuel engine*. SAE Pap 2001:2001e01e3503
[3] M. Talibi, P. Hellier, R. Balachandran,N. Nicos Ladommatos, *Effect of hydrogen-diesel fuel co-combustion on exhaust emissions with verification using an in-cylinder gas sampling technique*, International Journal of Hydrogen Energy, 39 (2014) 15088 el. 5102
[4] H. Rottengruber, M. Berckmuller, S. Eelsasser, N. Brehm, C. Schwarz, *High-Efficient Comustion Concept for Direct Injection Hydrogen Internal Combustion Engine*, *15th World Hydrogen Energy Conference, Paper Nr. 28 J-01, Yokohama*, Japan , 2004.
[5] V. Subramanian, J. Mallikarjuna, A. Ramesh, Improvement of Combustion Stability and Thermal Efficiency of a Hydrogen Fuelled SI Engine at Low Loads by Throttling, Advances in Energy Research, 2006, www.ese.iitb.ac.in/~aer2006/papers/ar_168.doc
[6] *M.G. Popa, N. Negurescu, C. Pană*, Motoare Diesel. Procese (Diesel Engines. Processes), Vol. I, II, Editura MATRIX ROM, Bucuresti, 2003.
[7] Nagaki H., Hitohidde F. and Takahashi S., *Acceptability of Premixed Hydrogen in Hydrogen Diesel Engine*, SAE Paper 1999-01-2521, 1999.
[8] Tsujimura T., Mikami S., Achiha N., Tokunaga Y., Senda J. and Fujimoto H., *A study of direct injection diesel engine fueled with hydrogen*, Proc. 2003 SAE World Congress, Detroit, Michigan, USA, 2003.

ISSN 2457 – 5275 (Online, English)
ISSN 1842 – 4074 (Print, Online, Romanian)

[9] Van Blarigan P., *Advanced internal combustion engine research,* Proc. of 2000 DOE Hydrogen Program Review, San Ramon, California, USA, 2000.
[10] Shudo T., Suzuki H., *New heat transfer equation applicable to hydrogen-fuelled engines*, Proc. of ICEF2002, New Orleans, Louisiana, USA, 2002.
[11] Van Blarigan, P. and Green R., *NOx Emission Data Verified in a Hydrogen Fueled Engine,* Combustion Research Facility News, vol.17, no.4, January/February, 1995.
[12] Stenlaas O, Egnell R, Johansson B, Mauss F., *Hydrogen as homogeneous charge compression ignition engine fuel*, Paper 2004-01-1976, SAE Fuels & Lubricants Meeteng, 2004.
[13] Naber J., *Hydrogen combustion under diesel engine conditions*, Int. J Hydrogen Energy, 1998; 23:363e71.
[14] N.Saravanan and G.Nagarajan, *Experimental investigation in optimizing the hydrogen fuel on a hydrogen diesel dual-fuel engine*, International Journal of Energy and Fuels, Volume 23, pp. 2646-2657, 2009.
[15] Younkins, M., Boyer, B., and Wooldridge, M., *Hydrogen DI Dual Zone Combustion System*, Paper 2013-01-0230, SAE 2013 World Congress , Detroit, USA
[16] Georgios Pechlivanoglou, *Hydrogen Enhanced Combustion History, Applications and Hydrogen Supply by Plasma Reforming*, University of Oldenburg PPRE 2005-2007.

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Total number of issues: 30 — Type: Open Access
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2. Ingineria automobilului (in English: ***Automotive Engineering***)
ISSN 1842 – 4074
Period of publication: as of 2006 — Format: print and online, Romanian
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3. Ingineria automobilului (in English: ***Automotive Engineering***)
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4. *Romanian Journal of Automotive Engineering*
ISSN 2457 – 5275
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Frequency: Quarterly — Electronic publication on: www.ro-jae.ro
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Summary – on September 30, 2016

Total of series:	*4*
Total years of publication:	*22 (11=1990 – 2000; 11=2006-2016)*
Publication frequency:	*Quarterly*
Total issues published:	*71 (Romanian), out of which, the last 24 were also published in English*