AIR/FUEL MIXTURE FORMATION IN TURBOCHARGED SPARK-IGNITION ENGINES: EFFORTS TOWARDS MITIGATION OF POLLUTANT EMISSIONS

Paulo de Tarso de Alexandria Cruz
Universidade de Brasília
Campus Universitário Darcy Ribeiro
Departamento de Engenharia Mecânica
Brasília – DF – Brazil
paulo.cruz@gmx.de

João Nildo de Souza Vianna
Universidade de Brasília
Campus Universitário Darcy Ribeiro
Departamento de Engenharia Mecânica
Brasília – DF – Brazil
vianna@unb.br

Cleverson Moreira e Silva
Universidade de Brasília
Campus Universitário Darcy Ribeiro
Departamento de Engenharia Mecânica
Brasília – DF – Brazil
cleversonsm@pop.com.br

Abstract. *The purpose of this work is to add to the understanding of the combustion process that takes place inside the combustion chamber of SI engines by means of simple but solid measurement principles. A normaly aspirated engine and its turbocharged counterpart were compared in terms of performance, consumption and emissions. The turbulence intensity inside the combustion chamber of both engines has been measured for a broad range of speeds. The results obtained show that due to increased turbulence intensity the turbocharged engine has an improved combustion process and emits lower quantities of CO,* CO_2 *and HC per unit of power.*

Keywords*: SI-engine, turbocharging, turbulence intensity, constant temperature anemometer, pollutant emissions*

1. Introduction

Despite the great advances in combustion technology, internal combustion engines are held greatly responsible for pollutant emissions, especially when employed for transportation purposes. Some of the technological alternatives to mitigate this effect are exhaust gas recirculation – EGR, catalysts, water induction, turbocharging etc.

Exhaust gas recirculation is the injection of flue gas back into the combustion chamber. It reduces pumping work, heat losses to the cylinder walls and also in the degree of dissociation of the high temperature burned gases. As a consequence, engine temperatures are reduced, which limits the degree of dissociation of high temperature burned gases. EGR systems are normally employed in parallel with turbochargers as a way to compensate for power losses. Vianna *et al* (2005) analyzed the association of an EGR system and compression increase by means of a turbocharger. Their work resulted in lower NO_X emissions for several recirculation levels.

The reduction of pollutant emissions after the combustion process has taken place can be performed by means of catalysts. They employ precious metal alloys with great affinity with pollutant components to reduce their concentration in flue gases. Catalysts are very sensitive to high temperatures and have the efficiency limited to a narrow air-fuel ratio operating range. Despite the proven efficiency of catalysts, they are no longer employed in Brazil as an attempt to lower automobile prices. To compensate for higher emissions and to comply with the pollutant laws, engines had their efficiency lowered.

Another way to reduce pollutant formation is to inject water into the combustion chamber at limited quantities. At the right amount, Brinion (1998) verified that water lowers the compression temperature, allowing for increased compression ratios while avoiding pre-ignitions. The results show that the water also reduced pumping work and flue gas temperatures, thus reducing the formation of nitrogen oxides - NO_X.

This work is the latest in a sequence of other works that have aimed at explaining the improved performance of a turbocharged engine with respect to its normally aspirated counterpart. In the first work, Vianna (1989) compared the two engines in terms of their overall performance, and measured the improvement brought about by the turbocharger. Vianna (1989) verified that the turbocharged engine consumes in average 8% less fuel per unit of output power. In the second work, Cruz “a” (2003) measured the mixture excitation inside the combustion chamber of both engines at a given speed and concluded that the improved performance is a consequence of increased pressure, temperature and mixture turbulence inside the combustion chamber. The first work provided an overall analysis of the system, while the second provided some microscopic explanations to the phenomena observed.

Comparatively, this work restates some of the results verified earlier, added the new experimental apparatus and measurement facilities. The overall analysis was added emission measurements, while the microscopic analysis was broadened to cover the engine's whole operating range. Based on in-cylinder measurements, the work provides some explanation to the improved performance verified.

2. Methodology

The two engines were compared in terms of their overall performance and in-cylinder turbulence intensity. The first part of this work consisted of power, torque, fuel consumption and emissions measurements. The second part consisted of in-cylinder measurements.

2.1. Engine characterization

As the turbocharger was adapted to a normally aspirated engine, tests had to be made so as to provide a considerable pressure increase but still respect the material strength of the engine block and of the anemometer probe. The waste gate valve was then adjusted so as to limit the exhaust gas temperature to the highest value verified for the normally aspirated engine. This adjustment was made interactively until the desirable conditions were obtained.

Besides the waste gate valve adjustment, a supplementary fuel supply system was employed. The extra quantity of fuel was proportional to the intake manifold pressure increase. This auxiliary system is composed of an absolute pressure gauge, a fuel pump, an electrovalve placed on top of the fuel inlet, and the electronic circuitry. The electrovalve was synchronized with the sparkplugs so that it would pulse with every spark release.

Prior to any in-cylinder measurement, a few operating characteristics of the engines had to be tested, to make sure that the basic condition was met, namely, that the turbocharged engine has lower specific fuel consumption. These characteristics are fuel consumption, output power and carbon monoxide emissions.

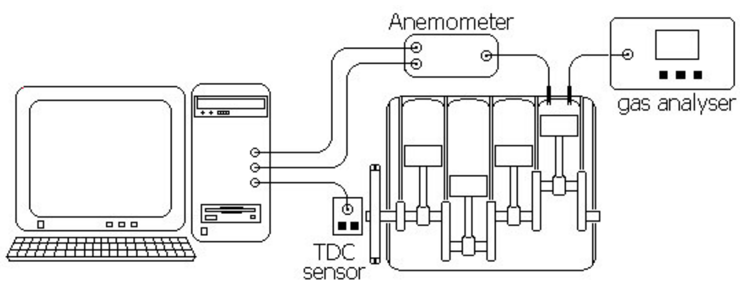

Figure 1. Experimental set-up for the engine characterization and in-cylinder measurements

2.2. In-cylinder measurements

These measurements were performed with a constant temperature anemometer. The film probe was adapted to fit the spark plug hole in the first cylinder, which operated in motoring condition. The remaining three cylinders operated in firing condition. This fact did not diminish the quality of the analysis as the mixture preparation occurs prior to the ignition timing, that is the induction and compression strokes. Besides, the behavior of the mixture in one cycle has very little effect on the next. These measurements required extreme care, as the film probe was not designed to operate in such harsh conditions. Tests had to be constantly performed so as to verify the integrity of the sensor without removing it from the sparkplug hole.

As the measurements were to be performed for the engine's whole operating range, it was necessary to determine how to achieve the same conditions for both engines. In a first attempt, the break power was kept constant, and the various speeds were obtained by opening the air inlet throttle. This alternative influenced the inlet flow in such a strong manner that was abandoned. In a second attempt, the break power was kept at its lowest, and the highest speed was achieved by opening the air inlet throttle. The air inlet throttle was then fixed, and the other speeds were achieved by increasing the break power. This second alternative made it possible to repeat the measurements in very similar conditions for both engines.

The sampling rate was changed for every speed so that measurement resolution could be kept at 1 point per crank angle. The number of samples was such that each measurement covered at least 300 cycles.

2.3 Data processing

All the in-cylinder measurement data was crank angle referenced by means of a TDC sensor. The TDC signal was calibrated against a compression signal provided by a piezoelectric pressure transducer. By means of the TDC determination, the beginning and the end of each cycle was then determined.

When working with internal combustion engines, there are three main alternatives for determining mean flow velocities. The problem is rather complex due to the alternating nature of the flow. The first alternative, and simplest, is the crank angle ensemble average. The cycles are superimposed, and a mean value is calculated for each crank angle. The fluctuations are then calculated about this mean for each angle. The second alternative consists of filtering the signal with a variable filter. This frequency variation aims at considering an adequate length scale for each crank angle. The third alternative consists of applying a filter to the wavelet transform of the signal. Wavelet transforms are space-time correlations of a mother function and the signal. This mother function is dilated and translated along the signal, and the result is a scalogram, similar to a spectrogram. Due to its simplicity and accuracy the first alternative, crank angle ensemble average, was used in this work.

For this work, the turbulence intensity was considered as the root mean square of the velocity signal fluctuations with respect to the ensemble average of the signal, rather than the actual velocity. As the anemometer is a thermal sensor, this so-called turbulence intensity incorporates the influences of velocity, temperature and pressure in one single variable. The signal decomposition is as follows:

$$E(\theta,n)=\overline{E}(\theta)+e(\theta,n) \tag{1}$$

$$IT=\frac{rms(e(\theta,n))}{\overline{E}(\theta)}\%\ , \tag{2}$$

where $E(\theta,n)$ is the velocity signal at crank angle θ of cycle n, $\overline{E}(\theta)$ is the signal ensemble average at crank angle θ, and $e(\theta,n)$ is the velocity fluctuation about the mean at θ of cycle n.

3. Results and Discussion

3.1. Engine Characterization

As mentioned before, both engines had to be analyzed in terms of their overall characteristics so that the in-cylinder measurements could be made. These measurements were carried out for the speeds of 1750, 2000, 2500, 3000 and 3500. Due to the unstable operating conditions at 4000 rpm this speed was left out of the analysis. The most important characteristics are temperature exhaust, specific fuel consumption and specific pollutant emissions. Exhaust manifold temperature, specific fuel consumption, specific CO, CO_2 and HC specific emissions are illustrated in Figures 2 through 6 respectively. Turbulence intensity results are illustrated in Fig. 7

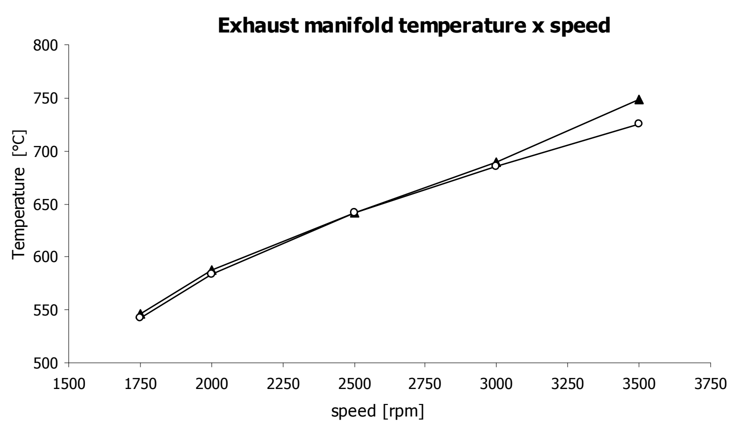

Figure 2. exhaust manifold temperature. ○ - normally aspirated; ▲ - turbocharged

As mentioned before, the exhaust temperature of the turbocharged engine was limited to the values observed for the normally aspirated engine. This control is critical to the integrity of the system, once the engine could undergo severe damage due to overheating. Figure 2 illustrates that this control was effective.

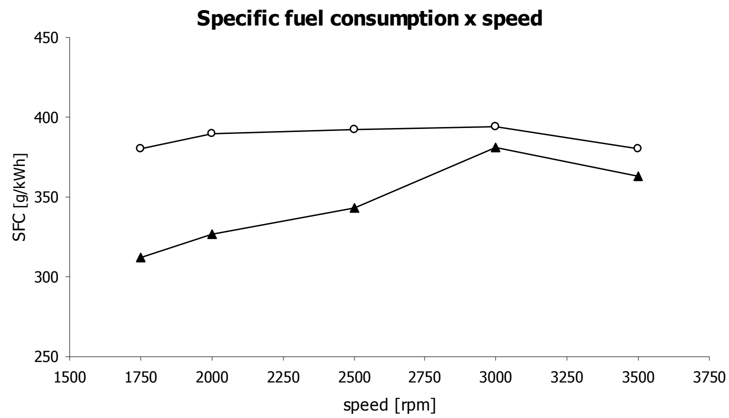

Figure 3. specific fuel consumption. ○ - normally aspirated; ▲ - turbocharged

It was imperative to adjust the operating parameters of the turbocharged engine, specially the compressor pressure ratio, so that it would provide lower specific fuel consumption, that is, more output power per unit of fuel. Figure 3 confirms the results obtained by Vianna (1989), when the turbocharged engine provided an average 8% lower SFC.

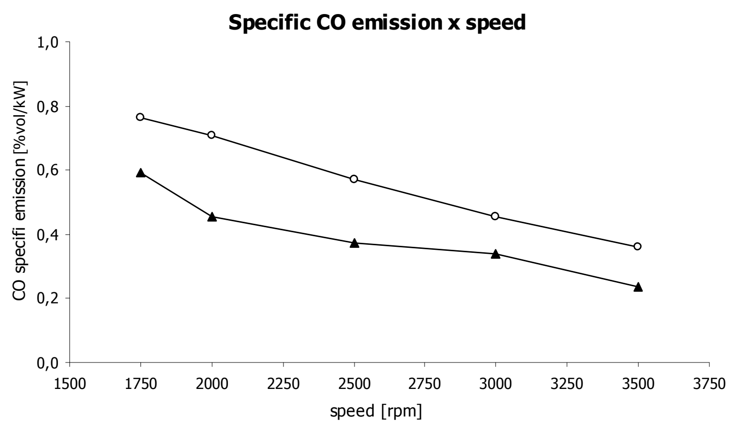

Figure 4. Specific CO emission. ○ - normally aspirated; ▲ - turbocharged

One of the variables that indicate the efficiency of the combustion process of a hydrocarbon is the emission of carbon monoxide. The lower the emission, the better is the process. Figure 4 illustrates the emission of CO normalized by the output power.

The results illustrated in Fig. 3 and Fig. 4 together provide the exact information expected from the engine characterization: that turbocharging the engine leads to an improved combustion process which results in lower fuel consumption per unit of output power. This improved combustion process is a result of greater quantity of air per unit of fuel, or lower equivalence ratio, and as brought in the next section, higher in-cylinder turbulence intensity. In addition to the technical benefits of an improved combustion, the reduced emissions of CO are of greatest importance, due to its toxicity. Besides being colorless, tasteless and odorless, the affinity between CO and hemoglobin is some 210 times greater than that of O_2, which makes it even more poisonous.

Considering the regular operating speed range, which goes from 2500 to 3500 rpm, the specific CO_2 emissions are also lower for the turbocharged engine. The most predominant effect of CO_2 emissions is the green house effect, with all its global warming consequences.

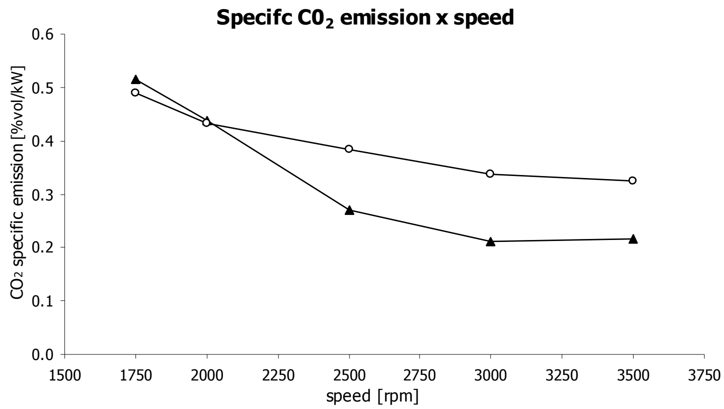

Figure 5. Specific CO_2 emission. ○ - normally aspirated; ▲ - turbocharged

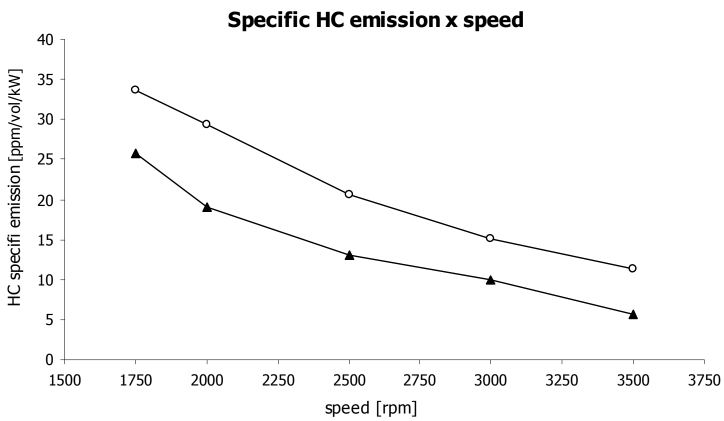

Figure 6. Specific HC emission. ○ - normally aspirated; ▲ - turbocharged

Similarly to the others pollutants considered, specific HC emissions were lower for the turbocharged engine along the whole operating range. Unburned hydrocarbons cause headaches, dizziness and lethargy, besides eye irritation and choking sensations. It is also computed as a CO_2 equivalent greenhouse gas.

Another significant pollutant, which was not included in this analysis due to due to apparatus limitations, is NO_X. Its emissions do not form until flame temperatures reach about 1300 °C. The most relevant factors that affect NO_X formation are high flame temperature, long residence time at high temperatures, the degree of fuel/air mixing, and high O_2 concentration in the flame. As both high flame temperatures and high air/fuel ratios occur in turbocharged engines, they normally require accessories such as ERG valves or water injection systems. Associated to hemoglobin, NO_X forms metahemoglobin, which has a 200.000 times greater affinity to O_2. Other relevant impacts of nitrous oxides emissions are acid rain, smog (ground level ozone) and the green house effect.

Together, these results confirm the technical and environmental benefits of turbocharging the internal combustion engines. Emissions per unit of output power of these pollutants were proven lower for the turbocharged engine along the regular operating range.

For trading purposes, the Intergovernamental Panel on Climate Change – IPCC has established the equivalence between the emission of green house gases and carbon monoxide. Therefore, the equivalent CO_2 concentration is the concentration of CO_2 that would cause the same amount of global mean radiative forcing as the given mixture of CO2, other greenhouse gases, and aerosols.

3.2 In-cylinder measurements

A whole series of relevant processes take place inside the combustion chamber of SI engines. The geometry of the intake manifold, valves and piston head, duration of valve overlap if any, number of valves per cylinder etc., all play an important role in determining the quality of the mixing process. For example, the higher the turbulence intensity inside the combustion chamber, the better will be the mixture formation, the thicker will be the flame front and the faster it will propagate.

The engine used for this work is carbureted, with a tangential intake manifold and 2 valves per cylinder. Such configuration leads to higher fuel consumption, low tumble intensity and higher swirl ratio.

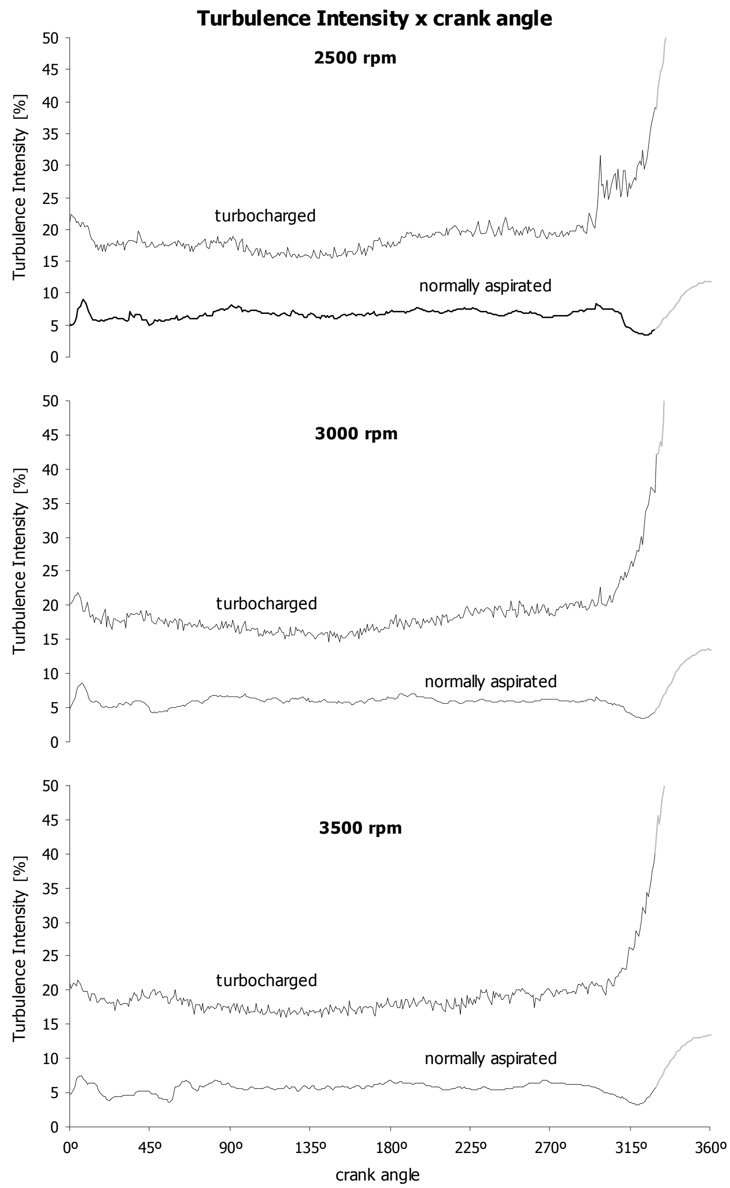

Figure 7. Turbulence Intensity at 2500, 3000 and 3500 rpm.

The behavior of the turbulence intensity illustrated in Fig. 7 is similar for all speeds considered. Along the intake stroke and most of the compression, the turbulence intensity of the turbocharged engine is at least two times higher. As the piston approaches TDC, the turbulence intensity increases just before the ignition timing, which is around 30º BTDC. Other in-cylinder investigations have shown that the greatest turbulence takes place during the induction stroke. The position of the anemometer probe did not allow for the verification of this information, which can only be confirmed by means of optical measurement techniques. Despite the fact that the measuring point did not allow for the analysis of some important features of the flow, the anemometer sensor was still capable of producing valuable data. As suggested earlier, the turbocharger brings about higher turbulence intensities, which lead to an improved mixing process and then, to a better combustion process as well.

4. Conclusions

The exhaust manifold temperature was adequately controlled by adjusting the compression ratio of the turbocharger and also the auxiliary fuel injection system.

Lower CO emissions, along with lower specific fuel consumption confirm the hypothesis that the combustion process in the turbocharged engine is more efficient than that of its normally aspirated counterpart.

Besides the technical benefits of turbocharging, emission measurements have also shown the benefits obtained in terms of pollutant emissions.

The turbulence intensity, defined as the root mean square of the velocity signal expressed in percentage, presented higher values for the turbocharged engine than those of its normally aspirated counterpart.

Despite the sequence the results were presented, the turbocharger brought about higher in-cylinder turbulence along the intake and compression strokes, which lead to an improved combustion process, verified in terms of output power and pollutant emissions.

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