An overview on the Miller-Atkinson over-expansion thermodynamic cycle

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Abstract. The tightening of pollution and greenhouse gas regulations generated a change in the homologation procedure, i.e., a far more dynamic driving cycle and the testing of the vehicle in real driving conditions are now part of the type approval procedure. In order to cope with these new challenges, the car manufacturers must adopt new technologies such as Miller-Atkinson cycle, which lately started to grow in popularity. This being the context, our paper’s main purpose is to present the particularities of this over-expansion thermodynamic cycle, mainly underlining its effect on the internal aerodynamic of the spark ignition engine.

1. Context

Air pollution and greenhouse gas (GHG) emissions come largely from the burning of fossil fuels; whether we refer to industry, agriculture, households or road traffic, the resulting emissions have a high impact on the environment and air quality, [1]. If we relate only to the road transport sector, the associated pollutant emissions (or exhaust emissions) are presented in figure 1, [2].

Figure 1. Distribution of pollutant compounds related to road transport, [2].

The numbers presented in figure 1 cannot be overlooked any longer as they have an important impact on the human health. For instance, according to [1], in the European Union (EU), about half a million premature deaths were recorded in 2015 as a result of the exposure to fine particles (PM10, PM2.5 and less), unburnt hydrocarbons (UHC, NMVOC), nitrogen oxides (NOx) and carbon monoxide (CO). Apparently, fine particles are responsible for the highest number of deaths in the EU, 400,000 [1].
Concerning the GHG, transport itself is responsible for around a quarter of CO₂ emission in the EU, according to [3]. About 75% of this CO₂ is produced by road transportation, which is a significantly growing sector worldwide, as it is well known [4], [5].

As a result, more severe legislative packages have been introduced in EU to limit the impact of pollutant emissions and GHG on the environment and human health, [6]. Thus, the type approval procedure is now performed in lab conditions by using a far more dynamic driving cycle (WLTC – Worldwide harmonized Light-duty Test Cycle replaced the already old NEDC – New European Driving Cycle) and in real world conditions, as well (RDE - Real Driving Emissions) via a portable emissions measurement system (PEMS), [7], [8], [9].

The requirement to introduce the approval in real traffic conditions was imposed by the difference in pollutants levels obtained on the laboratory test bench and the actual traffic conditions. Table 1 shows the emission values obtained under laboratory conditions and in real traffic conditions, which reveals important differences, [10].

|                  | Euro 3 | Euro 4 | Euro 5 | Euro 6 |
|------------------|--------|--------|--------|--------|
| NOₓ Real         | 1000   | 800    | 800    | 600    |
| NOₓ Laboratory   | 500    | 250    | 180    | 80     |
| Difference [%]   | 100%   | 220%   | 340%   | 650%   |
| CO₂ Real         | 184    | 182    | 168    | 166    |
| CO₂ Laboratory   | 172    | 163    | 140    | 120    |
| Difference [%]   | 7%     | 12%    | 20%    | 38%    |

As seen in table 1, for a Euro6 diesel engine powered vehicle, the NOₓ emissions are almost seven times higher in real traffic conditions compared to the laboratory value. Thus, the objective is to minimize these differences, [10].

According to statistical data collected by [11], sales of diesel cars in the year 2017 decreased by 7.9% compared with the previous year, while car sales of petrol-powered engines increased by 10.9%. The decline in compression-ignition (CI) engines cars began in 2013 with the increase in taxes for owners of such vehicles, and the effect was amplified by the 2015 diesel-gate scandal [12].

This being the European current context, the question is how will the automotive industry respond to such concomitant constraints as reduction of pollution and GHG? Car manufacturers are currently facing one of the biggest challenges: real-traffic approval (RDE). As such, the internal combustion engines (ICE) have to face numerous transformations. As CI engines are finger pointed as being accountable for the aggravation of the air pollution (because of their NOx and ultrafine particles), the attention is now focused on the potential of the spark ignition (SI) engine. This one is known to be cheaper and less polluting than the CI engine, but its overall efficiency is lower, which justify the interest for adopting new technologies, relatively simple to implement in serial production such as the Miller-Atkinson over-expansion thermodynamic cycle, [13], [14].

After this brief introduction, which aimed to frame our study in the current automotive engineering context, the reminder of the paper comprises 2 main sections. Section 2 is about briefly presenting the over-expansion cycle and section 3 aims to focus on its effect upon the internal aerodynamic of the SI engine by making references to the existing literature. As it will be seen, it’s actually about a brief overview on this particular subject. Finally, the conclusions drawn from our overview are summarized.

2. The over-expansion thermodynamic cycles

2.1. Atkinson cycle
The Atkinson cycle was designed in 1882 by the British engineer James Atkinson. He built a four-stroke engine allowing all four strokes to run in a single crankshaft rotation, and with the use of...
additional mechanisms, the expansion and exhaust strokes are greater than intake and compression strokes, [30].

Figure 2. Diagram p-V of the Atkinson and usual Otto cycle.

Atkinson: 1-2 Intake; 2-3 Compression; 3-4 Combustion; 4-5 Expansion 5-1 Exhaust
Otto: 1”-2” Intake; 2”-3” Compression, 3”-4” Combustion 4”-5” Expansion 5”-1” Exhaust

Figure 2 shows that in the case of the Atkinson cycle due to the inequality of the expansion-exhaust strokes, a greater amount of mechanical work is obtained compared to the Otto cycle. The Atkinson’s engine had advantages in terms of heat efficiency and pumping, but also has a number of drawbacks, such as, lower power and increased complexity of the mechanical parts used to obtain a different length of the compression stroke compared to the expansion stroke, [15].

2.2. Miller cycle

The Miller cycle was patented by the American engineer Ralph Miller and represents another alternative to the classic Otto cycle. In the case of the Miller cycle, the compression stroke has the same length as the expansion stroke, but instead, the volumetric effective compression ratio ($\varepsilon_{ec}$) is lower than the volumetric expansion ratio ($\varepsilon_e$), [16]; thus, it can be defined as an engine cycle that dissociates the volumetric compression ratio and the volumetric expansion ratio by using different strategies for the intake valve(s) closing moments (IVC), [17], [18].

The dissociation of the above mentioned volumetric ratios in the Miller cycle is most frequently done with the following two methods, [16]:
- Still keeping the intake valve open during the first part of the compression stroke, a strategy known as LIVC (late intake valve closing),
- Closing the intake valve during the intake stroke, so before the piston reaches the BDC, a strategy known as EIVC (early intake valve closing).

2.2.1. Late intake valve closing (LIVC). This method involves maintaining the intake valve(s) open for a longer period of time compared to an Otto cycle. In case of the Miller-LIVC cycle (figure 3, a), the intake valve is kept open all the way during the intake stroke and on a part of the compression stroke, as well. So, the air is admitted into the cylinder in the first phase (1-1’) and subsequently discharged into the intake manifold in the second phase (1’-2). Thus, the compression stroke is divided into two distinct cycles: phase I (1’-2), in which the intake valve is opened while the piston moves to the TDC position and phase II (2-3), in which the intake valve is closed and the actual compression starts, [16].

By using this LIVC concept, not only that the over-expansion is achieved (with respect to the actual compression) but the engine’s power control may be performed without the need for a throttle.
(i.e., throttle-less) if the actual IVC moment varies according to the engine’s load as follows: the smaller the engine’s load the later the IVC moment; thus, the un-needed part of the absorbed air mass will return to the intake manifold, [19].

2.2.2. Early intake valve closing (EIVC). This method involves closing the intake valve before the piston reaches the TDC (figure 3, b). Consequently, a smaller amount of air for combustion is retained in the cylinder. After the point of IVC, the air trapped inside the cylinder is submitted to a kind of expansion (see the phase IVC-2 in figure 3, b), generating not only a cooling effect for the air charge but a calmer internal aerodynamic. Obviously, it’s about a phenomenon featuring a mechanical work consumption, which, in theory, is fully recovered in the first part of the compression (see the phase 2-3 in figure 3, b) as in the phases IVC-2-3, the air is acting like an actual spring, reducing the effort for compressing the mixture in the beginning of the compression stroke, [16], [20].

As in the case of LIVC, here, as well, it can easily be noticed the fact that the actual compression (3-4) is reduced in respect to the expansion stroke (5-6); moreover, the throttle-less engine load control may be used for this case, too: the lower the engine load, the earlier the IVC, i.e., the intake valve should close when the needed air for the demanded torques was captured inside the cylinder.

3. Literature review

As mentioned in the introduction, nowadays, the main challenge is to improve the SI engine’s efficiency, in order to meet the future CO₂ limits. Simultaneously, the associated pollution should be at a level usually called “near-zero impact” [21]. According to [13], the planned target of 95 g CO₂/Km for an average vehicle mass of 1372 Kg requires a significant increase in the engine’s efficiency.

Miller-Atkinson strategies improve the efficiency of the SI engine thanks to the over-expansion (see relation 1). This may be obtained either by an adapted but fixed valve timing diagram or by a variable valve timing/actuation (VVT/VVA) system allowing IVC moments specific to Miller-Atkinson cycle whenever this is desired. Another reason for which Miller-Atkinson cycle is growing in popularity lately is because thanks to the over-expansion, it generates lower exhaust temperatures which are needed ever since the introduction of the RDE in the type approval procedure that requires a stoichiometric mixture over the entire operating area of the engine for reasons of having maximum TWC (three-way catalyst) efficiency. Thus, the usual enrichment performed in the high speed and load conditions to cool down the exhaust gas cannot be applied any longer. Furthermore, the resulting lower exhaust temperature allows using a variable geometry turbine (VGT) with additional benefits
However, there are also drawbacks. For instance, employing EIVC strategy (this is the one usually chosen to obtain the over-expansion cycle) comes with a negative influence on the engine’s internal aerodynamic (i.e., air flowing inside the cylinder) due to the expansion process occurring after IVC till the TDC position.

Martin et al. [13] studied the evolution of turbulent kinetic energy (TKE) inside the cylinder for three cases: standard one, LIVC and EIVC. In figure 4, it can be observed that in the opening phase of the intake valve, the evolution of the TKE is similar in all three cases. By proceeding further with the analysis of TKE’s evolution, in the case of EIVC, during the valve closing phase, the turbulent motion is intensified due to the reduction of the valve area generating an amplification of the flow velocity, but it is subsequently dissipated to a lower value than in the other two cases. In the case of LIVC strategy, the turbulent motion towards the end of the compression stroke is slightly more intense than in the EIVC case.

![Figure 4. Evolution of kinetic energy, [13].](image)

The level of turbulence during the intake process has a decisive influence not only on the potential of fuel consumption reduction in the part loads area but also on the reduction of pollution. Therefore, it is paramount to have an important level of turbulence prior to spark producing so that combustion evolves in a fast and clean way. To further capitalize on this gain, a first step is to determine the most appropriate method that leads to the maintenance and amplification of turbulent movements. Three types of changes have been applied by Martin et al. [13] to reach this goal: applying a masking procedure at the level of the intake valve, applying a tumble port and applying a low-level turbulence port. As reported by the same authors, the EIVC strategy can be applied to achieve a maximum fuel reduction potential of up to 5.6%, and depending on the engine’s operating point, it is necessary to optimize lift laws to provide a balance between pumping losses and turbulence losses. In the case of LIVC, a maximum fuel reduction potential of up to 8.8% was achieved in the low load area, [13].

To change the type of strategy used, a VVA system is needed: for example, as presented in [23], at speeds below 3000 rpm, the Miller EIVC cycle is applied, while the Miller LIVC cycle is applied at speeds above 3000 rpm. As explained by Mayer et al. [23], the differential use of the Miller cycle results from the constraint between overcharging pressure and valve lifting pattern. At high speeds, to run in this operating mode, the Miller EIVC would require too much overcharging pressure compared to LIVC. In addition, at high speeds, the Miller strategy is time limited due to the valve minimum lifting distance. Conversely, in the LIVC low speed range, there are more phenomena that have a negative effect on engine performance. In the scavenging area, to reduce the detonation phenomenon, a portion of the unburned air-fuel mixture reaches the exhaust manifold, resulting in more pollutant emissions and exothermic reactions at the catalyst level. In addition, the risk of detonation is increased in the Miller LIVC because the air-fuel mixture is discharged into the intake manifold at the beginning of compression stroke where it starts heating [23].
Organized air movements (the macro-scale movements) are one of the key elements for combustion optimization. As already presented before, a negative feature of the EIVC method is that when the valve closes early, the level of turbulence is diminished; furthermore, the reduced valve opening duration limits the development of an intense tumble motion at the end of the intake process. To combat these deficiencies, Budack et al [24] present a study showing the degree of turbulence for several engine versions: the previous generation, standard Otto (grey colour in figure 5), the current generation, Miller EIVC, not optimized from tumble air motion standpoint (red colour in figure 5), and optimized (green colour in figure 5). The colour spectrum in the figures below showing the air motion inside the cylinder symbolizes the turbulence level in the cylinder (red – high level, blue – low level) while the shape of the lines suggests the type of motion, [24].

![Image](image_url)

**Figure 5.** Optimization of turbulent movements, [24]

Therefore, as presented in [24], only by applying the EIVC strategy, without making any optimization from tumble standpoint, the turbulent movements are reduced to 25% of the intensity of the initial value; in order to recover from this decrease, first, it was necessary to develop a new intake port proper to turbulent movement. Another essential change occurred at the valve level by introducing a masking procedure allowing the air to enter the cylinder through the upper side of the intake valve at low lifts. As argued by Budack et al [24], the effect of this change was especially noted in the valve closing phase where turbulent motion receives a pulse. The last step was to optimize the shape of the piston so that the turbulent motion is maintained and amplified, [24]. Applying all these optimizations, the turbulence level has reached similar values to the previous generation, while preserving the benefits of the Miller cycle, [24].

4. Conclusions and future work
Currently, the interest in the Miller-Atkinson cycle among car makers is becoming more and more visible. One of the main reasons we are witnessing this increase in popularity of over-expansion thermodynamic cycles is linked to the modification of global pollution and GHG rules.

A very important element with a high degree of influence on the Miller-Atkinson cycle efficiency is the turbulence level in the cylinder. Depending on the manufacturer, different methods are applied by which this less conventional cycle can be achieved, for example some of them chose a full EIVC operation, while others rely on the combination of EIVC / LIVC strategies or a series of intermediate valve laws between EIVC and LIVC.
An important issue of Miller-Atkinson cycle is related to the turbulent flow during the intake and compression stroke. This overview showed some solutions used to recover the inherent loss of turbulence which are to be used in our next stage: building a CFD simulation to explore them.

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