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TECHNICAL PAPER

Structural analysis, survey and classification of kinematic chains for Atkinson cycle engines

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Abstract
This paper presents an Atkinson Cycle mechanisms classification. The proposed classification is based on mechanism theory, dividing the mechanisms into two main classes and eight subclasses. The reconfigurability of Atkinson Cycle mechanisms is discussed as well as the mechanism characteristics for each class. This classification was applied to the engines found in bibliography and patent survey. Both surveys were necessary to yield a complete state of the art, regarding not only academic but also technological advances. These surveys and the Atkinson Cycle engine classification expose the wide window of opportunities for engine development. The use of reconfigurable Atkinson Cycle engines can be a powerful tool to develop more efficient vehicles.

Keywords Atkinson Cycle · internal combustion engines · mechanism theory · patent survey · Atkinson Cycle engines classification · reconfigurability

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1 Introduction

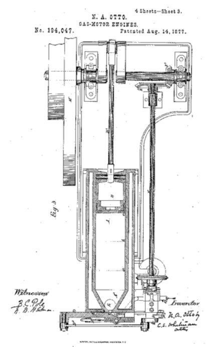
Over the last decades, environmental laws and regulations set lower CO_2 emission standards, requiring more efficient engines. Together with regulations, the fuel prices made efficiency a keypoint on regards to the internal combustion engine (ICE) development. Trends as downsizing, hybrids vehicles, electric vehicles, cylinder deactivation and variable compression engines indicate that higher efficiency ICE is the next challenge for vehicle manufacturers. Other approach for a higher efficiency is the use of different thermodynamic cycles than the traditional Otto Cycle.

The Atkinson Cycle engine was introduced in the 1880s by James Atkinson [1]. It uses an extended expansion stroke to improve thermal conversion efficiency (TCE). Recently, Toyota has implemented an Atkinson Cycle engine in association with an electric motor in their hybrid engines system: Hybrid Synergy Drive.[1] Honda has also released an Atkinson Cycle engine, called EXlink, which has a expansion stroke longer than the compression stroke.[2]

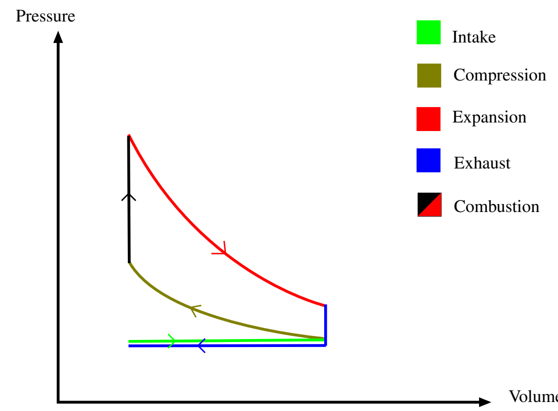
[1] Press release: All-New Third Generation Toyota Prius Raises the Bar for Hybrid Vehicles Again, Toyota USA Newsroom, 28 Sep. 2009.

[2] Press release: Performing more work with less fuel—EXlink (Extended Expansion Linkage Engine), Honda Worldwide, 2011.

Fig. 1 Otto Cycle engine



(a) Original Otto Cycle engine [9].



(b) Otto Cycle pV diagram.

The Atkinson Cycle engine can present up to 25% increase in the TCE when compared to the Otto Cycle [2]. However, there are different approaches for an Atkinson Cycle engine, such as using variable valve timing to simulated the Atkinson Cycle, using a specialized crankshaft mechanism to perform an extended expansion stroke or using rotatory engines. This paper focuses on reciprocating engine working with an extended expansion stroke.

2 Mechanisms for generating thermal cycles of internal combustion engines

The worldwide trend for tougher environmental laws has accelerated the race for more efficient vehicles. In Europe, passengers' vehicles must achieve an average of 95 g CO_2/km (c. 24,42 km/l) up to 2020.[3] In the USA, the Environmental Protection Agency set a goal of 54,5 mpg average (c. 23,17 km/l) up to 2025.[4] In Brazil, vehicle manufacturers that achieve 17,26 km/l average for gas and 11,96 km/l average for ethanol up to 2017 will receive tax discounts.[5] There are several approaches to reduce the vehicle CO_2 emission, from using a different engine thermodynamic cycle to hybrid or electric vehicles. Among these alternatives, there is the Atkinson Cycle engine.

Nowadays, with the technology evolution and the need for more efficient engines, different thermodynamic cycles have been devised. The main difference from Atkinson Cycle engines to Otto Cycle engines (the most common thermodynamic cycle for passenger vehicles) is the use of different stroke lengths to achieve a higher thermal conversion efficiency [3–8]. However, there are two different Atkinson Cycle implementations: using a non-usual crankshaft mechanism and using the classic slider-crank mechanism. There is also a variation in the second Atkinson Cycle implementation which uses a supercharger, originating a different thermodynamic cycle: the Miller cycle. The next sections briefly review the Otto, Atkinson and Miller Cycles.

2.1 Otto Cycle

The first Otto Cycle engine was developed by Nikolaus Otto in 1876 [9]. The Otto Cycle is a four-stroke cycle in which all strokes have the same length and it is generally realized with a slider-crank mechanism. Figure 1a, b shows the original Otto Cycle engine and the Otto pressure-volume (pV) diagram, respectively.

2.2 Atkinson Cycle

The Atkinson Cycle was created by James Atkinson in the 1880s [1]. The Atkinson Cycle is a four-stroke cycle with an extended expansion. Thus, the admission and compression strokes are smaller than the expansion and exhaustion strokes. The original Atkinson Cycle engine and the pV diagram are presented in Fig. 2a, b.

Recently, engines that use the Atkinson Cycle have been developed but with the classic slider-crank mechanism. These engines use valve timing control to reduce the compression stroke. This is achieved by delaying the intake valve closure and letting part of the mixture to return to the intake manifold. Thus, the compression stroke is effectively reduce, lasting from the intake valve closure to the top dead center. Figure 3 shows the pV diagram of this Atkinson Cycle approach. This implementation of Atkinson Cycle is used on Toyota hybrid system engines.[6]

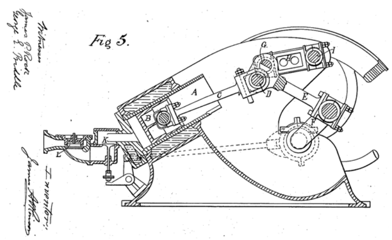
[3] European Parliament—Amending Regulation EC 443/2009.

[4] National Highway Traffic Safety Administration—USA Federal Register Vol 77 no. 199.

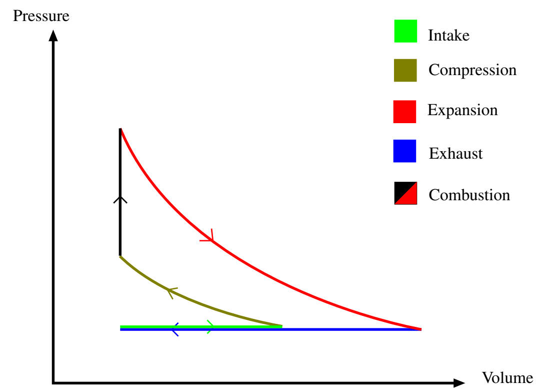
[5] Decree 7.819 / 2012.

[6] Press release: Our Point of View: Atkinson Meets Otto: Why the Prius is So Efficient, Toyota Open Road Blog, 2 Sep. 2008.

Fig. 2 Atkinson Cycle engine



(a) Original Atkinson Cycle engine [1].



(b) Atkinson Cycle pV diagram.

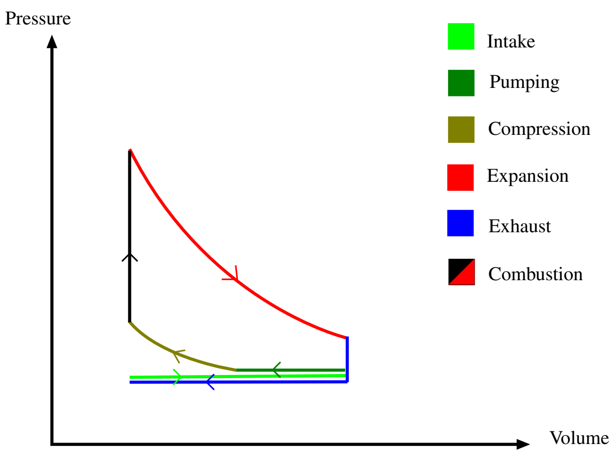


Fig. 3 Slider-crank Atkinson Cycle pV diagram

Besides the difference in the mechanisms, there are also differences in the pV diagram (as Figs. 2b and 3 show) and in the thermodynamic conversion efficiency [2].

2.3 Miller Cycle

The simulated Atkinson Cycle engine is frequently confused with the Miller Cycle engine, which was developed in 1957 by Ralph Miller [10], earlier than the simulated Atkison Cycle (1990s). Miller devised an engine capable of simulating a power stroke longer than the compression stroke with the classic slider-crank mechanism and a valve timing mechanism. However, the difference from the Atkinson Cycle to the Miller Cycle is that the second uses a supercharger to overcome the low power density of the first. Figure 4a, b shows Miller's engine valve timing mechanism and supercharged device, respectively. Figure 5 shows Miller Cycle pV diagram for a late intake valve closure (a different diagram is obtained from a early intake valve closure strategy). In Fig. 5, it can be seem the pumping phase, i.e., when the piston is moving upwards but the intake valve is still open, pumping the mixture back to the intake manifold.

2.4 Discussion about the terminology

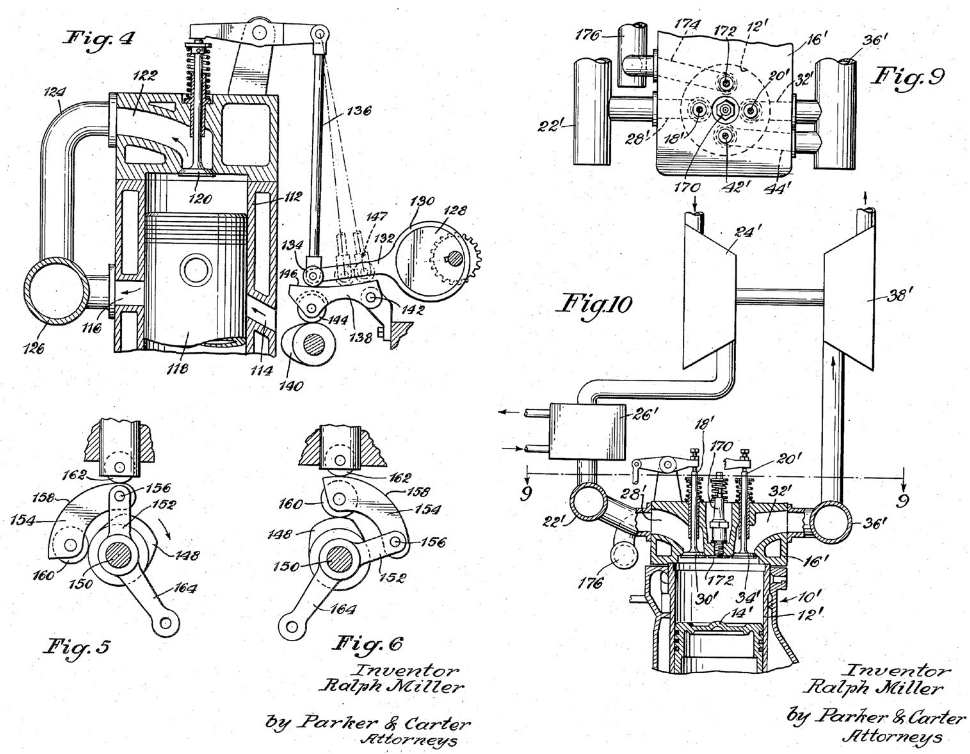
There are two basic implementations of an Atkinson Cycle engine. The first implementation was devised in the 1880s by James Atkinson [1]. This approach uses a non-standard engine mechanism to generate a power stroke longer than a compression stroke. The second implementation was developed in the 1990s and uses a standard crankshaft and a valve-timing device to simulate an Atkinson Cycle. Thus, by delaying the inlet valve closure, the compression stroke becomes smaller than the power stroke.

Several names are used to distinguish both implementations. The most commonly used term for the first implementation is real Atkinson Cycle engine [2, 11, 12]. It is sometimes explained or referred as strict Atkinson Cycle engine [2, 12] and Atkinson Cycle engine with asymmetrical crankshaft [12]. The expression "real Atkinson Cycle engine" is adopted in this paper.

As for the second implementation, several words are used, such as modified Atkinson Cycle engine [2, 13], quasi-Atkinson Cycle engine [11], modern Atkinson Cycle engine [14], aspirated Miller engine [15]. Sometimes, it is described as an engine with Late Intake Valve Closure strategy [16] or Atkinson Cycle engine with classic or normal crankshaft [12]. The expression "simulated Atkinson Cycle engine" is adopted in this paper.

This paper focuses only on real Atkinson Cycle engines; thus, bibliography review and classification do not include simulated Atkinson Cycle engines.

Fig. 4 Miller Cycle engine



(a) Valve timing mechanism [10]. **(b)** Supercharger device [10].

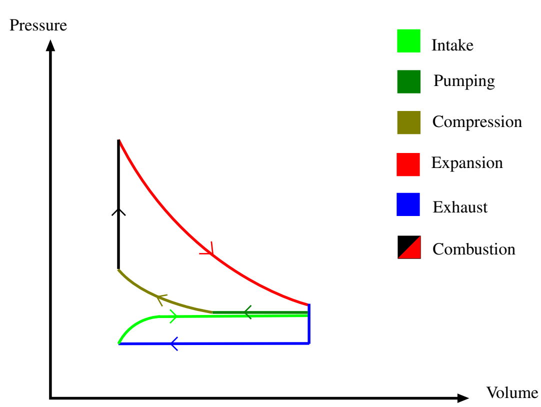


Fig. 5 Miller Cycle pV diagram

3 Bibliography review

Section 2 exposed two different approaches for Atkinson Cycle engines: the real Atkinson Cycle engine and the simulated Atkinson Cycle engine. As this paper focuses on real Atkinson Cycle engines, the state of the art survey and further works regard only this type of Atkinson Cycle engine.

Three approaches were used for bibliographical survey: patent survey, market survey and academic survey.

The market survey revealed that simulated Atkinson cycle engines are more common to be found in production vehicles. Toyota, Lexus and Mazda[7] are among the vehicle manufacturers that use a simulated Atkinson cycle engine in hybrid vehicles. Honda has developed a real Atkinson Cycle engine, called Honda EXlink (extended expansion linkage engine) [15]. However, currently no production vehicle uses a real Atkinson cycle engine.

There are several studies regarding the thermodynamic efficiency of Atkinson cycle engines [2, 11–13, 15, 17–20]. However, there are few studies regarding Atkinson Cycle engines from a mechanisms synthesis point of view [21, 22].

Hou [20] states that an Atkinson Cycle engine can be up to 10% more efficient than a conventional four-stroke Otto Cycle engine. The mechanical efficiency of a real Atkinson Cycle engine is estimated to be about 96% [2]. Gheorghiu simulations [2] show a real Atkinson Cycle engine presents a higher indicated fuel conversion energy (IFCE) than a simulated Atkinson Cycle engine and an Otto Cycle[8] engine (all engines in this simulation used supercharger). An aspirated Atkinson Cycle engine has up to 15% more IFCE than an aspirated Otto Cycle engine. When combined

[7] Press release: Mazda Develops New Naturally-Aspirated MZR 1.3L Miller-cycle Engine, Mazda News Releases, 31 May 2007.

[8] Gheorghiu uses a Seiliger Cycle engine as the comparison reference since it represents more accurately the Otto Cycle engine real behavior; however, for didactical purpose, we call it Otto Cycle in this paper.

with a supercharger, a real Atkinson Cycle engine presents 25% increase in the thermal conversion efficiency in relation to a supercharged Otto Cycle.

A comparison between real and simulated Atkinson Cycle engines is done by [13] and [2]. For aspirated engines, simulated Atkinson Cycle engines presents minor improvement in thermal conversion efficiency in relation to Otto Cycle engines. However, real Atkinson Cycle engines presents a greater improvement in thermal conversion efficiency in relation to Otto Cycle engines [13]. For supercharged engines, Gheorghiu shows that a real Atkinson Cycle engine presents a better IFCE in relation to an Otto Cycle engine than a simulated one [2].

Banowetz presents a structured approach to synthesize new innovative mechanisms for variable non-uniform stroke engines [21]. Although in general the identification and heuristic rules of Banowetz are reasonable, some options could be deeper explored. For instance, a prismatic actuated joint could be physically realized by a screw and nut with a self-locking gear-box. This prismatic joint realization could avoid any unintended sliding at high velocities. Also, non-binary crankshafts or connecting rods could be investigated.

Six new topologies for variable non-uniform stroke engine mechanisms are presented by Banowetz. The benefits and drawbacks of each mechanism are discussed, focusing on practical aspects. Finally, Banowetz lists a series of challenges to overcome in the variable non-uniform stroke engine mechanisms synthesis. Among those challenges are the mechanism size, complexity, balancing, lubrication and uneven cylinder wear, which can reduce its feasibility.

Good [22] presented an optimum piston displacement curve for TCE. However, his focus is on the dimensional synthesis to achieve such displacement curve rather than on topological synthesis. Good investigated two topologies: the Atkinson Cycle original mechanism and geared five-bar mechanisms with non-circular gears.

To propose a classification of Atkinson Cycle engines based on mechanism theory, a state of the art survey is necessary that retrieves all representative mechanisms. Thus, the market and academic surveys were completed by a patent survey to obtain a more representative technology map. The patent survey results are exposed in Sect. 4.

4 Technology review

The bibliography review gave a broad idea about the state of the art on Atkinson Cycle engines. However, most researches deal with thermodynamic cycles and only a few of them address the Atkinson Cycle engine mechanisms. So, to understand the state of the art and the technology advances regarding Atkinson Cycle engine mechanisms, it was necessary to do a patent survey, which also indicates technology and innovation trends on the field.[9]

In this sense, an extent patent survey was done. Initially, a preliminary search was performed testing different search parameters in a wide-focused approach. Then, the results were analyzed matching the search parameters with the result quality and quantity. A detailed search was done with the best search parameters from the preliminary search in a depth-focused approach. Analyzing the detailed search results, an increase was noted in quality and quantity of relevant patents in relation to the preliminary search results. The patents were individually analyzed and a new classification was devised.

4.1 Preliminary search

These searches were done using several different keywords in both patent title and abstract, such as “Atkinson”, “variable intake power strokes”, “unsymmetrical cycle”, “variable expansion compression ratio” and “variable displacement”. The search engines used were European Patent Offices Espacenet, World Intellectual Property Organizations Patentscope, Thomsom Reuters Derwent Innovation Index, Google Patents and Free Patents Online. The patent database used were the ones available in the mentioned search engines.

A total of 187 patents related to real Atkinson Cycle engine mechanism were found in this search. Then, the parameters that yielded the best results were used to perform a detailed search in a depth-focused approach. Among these parameters were selected keywords, selected international patent classification (IPC) and selected companies as assignees (manufacturers and engine developers).

4.2 Preliminary search analysis

The results from this preliminary search were analyzed and the search parameters were ranked according to the quality and quantity of the results. Some patents which the focus were not on the Atkinson Cycle engine mechanism but on a marginal addition, such as use of belt instead of chain, were eliminated to avoid misguided data-analysis. To submit a new patent for minor changes or improvements is a common practice in the patent field, creating a so-called patent wall [23]. Also, several equivalent patents were found, i.e., the same patent submitted to different patent offices. In these cases, only one patent was considered. The remaining patents were analyzed. Table 1 shows the IPCs found in the survey, number of times each IPC was used and its

[9] Press release: Toyota And Hybrids Drive Automotive Patents, Toyota Australia, 20 Aug. 2015.

Table 1 Related IPCs during the patent survey

IPC	Number of patents	IPC description
F02B75/04	15	Engines with variable distances between pistons at top dead-center positions and cylinder heads
F02B41/04	9	Engines characterized by special means for improving conversion of heat or pressure energy into mechanical power...with prolonged expansion...in main cylinders
F02B75/02	6	Engines characterized by their cycles, e.g., six-stroke
F02B75/32	6	Engines characterized by connections between pistons and main shafts and not specific to preceding main groups
F02D15/02	5	Varying compression ratio...by alteration or displacement of piston stroke
F01B9/02	3	Reciprocating-piston machines or engines characterized by connections between pistons and main shafts... with crankshaft
F02B41/00	3	Engines characterized by special means for improving conversion of heat or pressure energy into mechanical power
F01B31/14	2	Component parts, details, or accessories...changing of compression ratio
F01B7/12	2	Machines or engines with two or more pistons reciprocating within same cylinder or within essentially coaxial cylinders... with oppositely reciprocating pistons...acting on same main shaft...using rockers and connecting-rods
F02B75/16	2	Engines characterized by number of cylinders, *e.g.*, single-cylinder engines
F16C3/28	2	Adjustable cranks or eccentrics
F01B9/04	1	Reciprocating-piston machines or engines characterized by connections between pistons and main shafts...with rotary main shaft other than crankshaft
F01L1/02	1	Valve drive
F01L1/04	1	Valve drive...by means of cams, camshafts, cam discs, eccentrics, or the like
F01L1/10	1	Valve drive...by means of crank- or eccentric-driven rods
F01L1/44	1	Multiple-valve gear or arrangements
F02B1/00	1	Engines characterized by fuel-air mixture compression
F02B1/04	1	Engines characterized by fuel-air mixture compression...with positive ignition...with fuel-air mixture admission into cylinder
F02B29/08	1	Engines characterized by provision for charging or scavenging...by modifying distribution valve timing for charging purposes
F02B3/06	1	Engines characterized by air compression and subsequent fuel addition...with compression ignition
F02B33/02	1	Engines characterized by provision of pumps for charging or scavenging...with reciprocating-piston pumps
F02B33/20	1	Engines characterized by provision of pumps for charging or scavenging...with reciprocating-piston pumps ...with reciprocating-piston pumps other than simple crankcase pumps...with pumping-cylinder axis arranged at an angle to working-cylinder axis, e.g., at an angle of 90°
F02B75/00	1	Other engines, e.g., single-cylinder engines
F02B75/22	1	Other engines, e.g., single-cylinder engines...characterized by number of cylinders, e.g., single-cylinder engines...multi-cylinder engines...with cylinders in V-, fan-, or star-arrangement
F02B75/048	1	Other engines, e.g., single-cylinder engines...with variable distances between pistons at top dead-center positions and cylinder heads...by means of a variable crank stroke length
F02D15/00	1	Varying compression ratio
F02F3/00	1	Pistons
F16C3/24	1	Shafts...with return cranks, i.e., a second crank carried by the crank-pin
F16H21/20	1	Crank gearings...with adjustment of throw

Table 2 Companies without patents on the searched IPCs

Acura	Alfa Romeo	Briggs and Stratton
Chery	Chevrolet	Cummings
Detroit Motors	Dodge	FIAT
FPT	Gomecsys	Infiniti
Jaguar	Jeep	KIA
Lancia	Land Rover	Lexus
Lotus	Mahindra	Meta Motoren und Energie
MWM	Perkins	Rolls Royce
Subaru	Volkswagen	Volvo

description. Besides the IPCs found in the survey, other relevant IPCs were searched.

The first five IPC description match with real Atkinson Cycle engine mechanisms, avoiding simulated Atkinson Cycle engines. In addition, those are the IPC with more occurrences; thus, the first five IPCs in Table 1 are the most relevant. Part of the remaining IPC appeared as secondary IPC, adding further details about the device, such as number of cylinders, cylinder disposition (opposite, inline, V-block) and adjustments on compression ratio.

Regarding the keywords, several patents do not use the word Atkinson explicitly. In general, an Atkinson Cycle engine is described as "variable displacement", "variable stroke", "variable ratio" or "asymmetrical stroke". This choice of words is done since it broadens the patent application field, being an advantage for the assignee. In addition, the use of descriptive words instead of the word "Atkinson" makes the patent survey more challenging. As these keywords describe an Atkinson Cycle engine as well as a variable compression ration engine, several VCRs were found and eliminated from the survey. Sometimes, these choice of keywords is intentionally done to hide the patent.

Also, several simulated Atkinson Cycle engine patents were found, commonly under the IPC F01L or F02B. It was noted that the use of "variable displacement" as keyword reduces the occurrence of simulated Atkinson Cycle engine patents. Simulated Atkinson Cycle engine patents were discarded.

4.3 Detailed search

The detailed search was done using the parameters that yielded the best results in the preliminary search. The first five IPCs from Table 1 were used as search parameters. The keywords used focused on avoiding simulated Atkinson Cycle engine patents, such as "unsymmetrical", "asymmetrical", "intake power stroke", "crankshaft mechanism stroke ratio" and "stroke ratio mechanism". "Atkinson" was also used as keyword for its few but centered results. The search for "crankshaft mechanism" was devised to avoid simulated Atkinson Cycle engine patents. Patents related to variable compression ratio engines were avoided by searching for unsymmetrical strokes. These keywords were looked for in the patents title or abstract.

Other searches combined the first five IPCs from Table 1 with vehicle manufacturers or engine developers as assignee.

Table 3 Number of companies' patent per IPC

Company	F02B75/			F02B41/04	F02D15/02	Total
	02	04	32			
Audi	0	14	3	2	4	23
BMW	0	2	1	0	2	5
Chrysler	0	6	0	0	0	6
Citroën	0	2	0	0	0	2
FEV	0	0	1	0	0	1
Ford	0	2	0	0	3	5
General Motors	0	2	0	0	0	2
Honda	0	65	1	8	9	83
Hyundai	0	11	0	0	7	18
MCE-5	0	0	1	0	0	1
Mercedes-Benz	0	6[a]	1	0	4	11
Mitsubishi	0	1	0	0	3	4
Nissan	0	12	3	1	8	24
Opel	0	0	2	0	0	2
Peugeot	0	2[b]	0	0	1	3
Porsche	0	1	0	0	0	1
Renault	0	1	0	0	2	3
Saab	0	1	0	0	0	1
Tata	0	0	1	0	0	1
Toyota	0	3	2	0	5	10

[a]Same patents from Chrysler

[b]Same patents from Citroën

4.4 Detailed search analysis

Analyzing the detailed search results, it was noted the total number of patents has decreased while the number of related patents as well as their quality increased. Thus, this detailed search yielded more focused results. Vehicle manufacturers are often sold and acquired by groups; thus, the patents owned by companies are exposed by vehicle manufacturer and not groups. Table 3 shows the number of patents each company owns within each main IPC. Table 2 shows searched companies that do not own any patent in the main IPC.

The 206 patents in Table 3 are not necessarily about real Atkinson Cycle engines. Patents non-related to the topic

Table 4 Companies that own more patents on the searched IPCs

Company	Patents	Company	Patents
Honda	83	Hyundai	18
Nissan	24	Mercedes-Benz	11
Audi	23	Toyota	10

were found since in the company search only the IPC and the company as assignee were used as filters. The exception was the searches done with IPC F02B75/04 and the companies Honda, Nissan, Mitsubishi, Mercedes-Benz, Toyota and FEV. In this case the search yielded too many non-related results; thus, keywords such as "crankshaft" and "mechanism" were used to narrow the results.

Based on the patent assignee, the six companies that own more patents are exposed in Table 4.

Eastern Asian-based companies are among the top owners of patents in these IPCs. An analysis has shown that the high number of patents for Eastern Asian-based companies can be attributed to the patent-wall culture, since most patents regard minor improvements or modifications of prior patents. Besides Japanese and Korean vehicle manufacturers, German companies are among the top owners of patents in these IPCs. Within those IPCs, Audi and Mercedes-Benz own real Atkinson Cycle engine patents. Figure 6 shows the distribution of patents per manufacturer country.

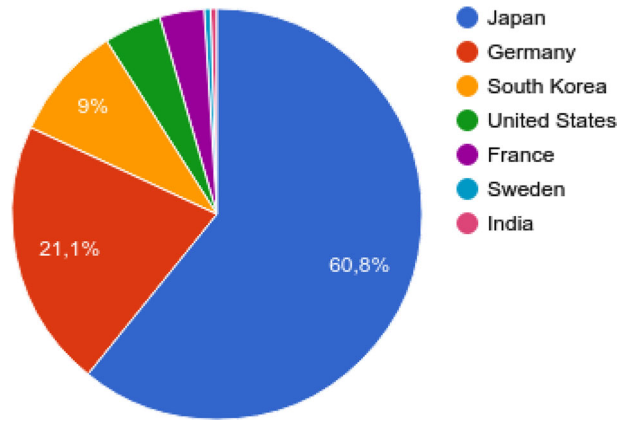


Fig. 6 Distribution of patents of the companies per manufacturer country

5 The classification of Atkinson Cycle engines

As presented in Sect. 3, most works regarding Atkinson Cycle engines are related to thermodynamic models and TCE. As for the patents, a significant amount uses the Simulated Atkinson Cycle, in which case the patent scope relies on control or devices for variable valve timing. Mechanism design is the keypoint to perform the real Atkinson Cycle; however, just a few works address on real Atkinson Cycle mechanisms design.

In view of this, there is a great innovation potential for real Atkinson Cycle engines. This statement is supported by the last advances in the mechanisms and machine field with the recent concept of mechanism reconfigurability and mechanism adaptability [24–26]. This paper presents a classification of mechanisms for real Atkinson Cycle engines and it discusses a representative mechanism of each class, highlighting the each class reconfigurability.

Section 4 presented the patent survey results. Several results were found, including repeated patents submitted in different patent offices and patents presenting minor or peripheral improvement. Also, in the company search, there were results which do not concern real Atkinson Cycle engines. Thus, to achieve a small quantity of patents but still maintain an accurate representative sample, the following considerations were made:

- Different concepts of engine design (such as axial piston, linear engines, wobble plate engines) were considered out of scope and discarded of further analysis;
- When a patent was filed in several countries, just one result (normally the first application) was taken into account for further analysis;
- Same companies (specially Asians) have the culture to fill different patents for every minor improvements in their concepts (patent wall). All these patents were also considered as one for the further analysis;
- It is also common for the companies dividing the patents according to the field of invention. So, for a given concept, it is possible to find patents explaining the mechanisms, detailing the hydraulics, presenting the control system and so on. In this case, all patents were considered as one for the further analysis.

Once the stated requirements were applied to reduce the quantity of patents, 24 representative patents remained. The representative patents and their details are exposed in Table 5. The top five manufacturers in real Atkinson Cycle engines are: Honda, Nissan, Hyundai, GM and Audi.

Each patent was analyzed through mechanism theory, listing its structural and functional characteristics. Then, the patents are classified according to the mechanism characteristics. This classification not only divides the devices in distinct non-overlapping classes but also can be used to trace technology development, showing the most explored areas as well as the most promising areas. Thus, patent data are used to generate useful information that aids

Table 5 Final results of patent survey regarding real Atkinson

Patent	Year	Assignee
[27] EP 0570627 A1	1992	Individual
[28] GB 346592	1930	Individual
[29] JP 2002349303	2001	Honda
[30] JPS 588233 A	1981	Individual
[31] US 20110226199 A1	2010	Individual
[32] US 8826800 B2	2011	Individual
[33] US 8839687 B2	2012	Individual
[34] DE 102010027351 B4	2010	Audi
[35] JP 2008111397	2006	Nissan
[36] US 7661395 B2	2005	Honda
[37] US 4 517 931 A	1983	Individual
[38] US 6230671 B1	1998	Individual
[39] US 7185615 B2	2002	Honda
[40] US 7305938 B2	2005	Honda
[41] CN 102536455	2010	Individual
[42] US 4380972	1979	Individual
[18] DE 102013003682	2013	Individual
[43] US 4917066	1986	Columbia University
[44] US 5927236 A	1997	Individual
[45] EP 0084542 A1	1981	Individual
[46] WO 2010086130 A1	2009	AUDI
[47] US 8794200 B2	2012	GM
[48] US 8074612 B2	2008	Hyundai
[49] US7228838	2004	Nissan

the designer to identify unexplored areas and promising functional and structural requirements.

Among the characteristics studied in each mechanism are:

- type and quantity of actuators,
- type of synchronization device,
- mobility[10] (M),
- number of independent loops (v),
- number of joints (j) and
- number of links (n).

Initially, the mechanism mobility was used to divide the patents into two major groups:

- *M1—Pure Atkinson*: this class presents engines with one degree of freedom. Similar to a conventional engine, this degree of freedom is used to transform the piston translation in the crankshaft rotation. However, being a real Atkinson Cycle engine, a specialized mechanism is necessary to execute the power and compression strokes with different lengths.
- *M2—Reconfigurable Atkinson*: this class presents engines with two degrees of freedom, which are able to adjust their compression ratio during operation. Therefore, this adjustment makes them reconfigurable engines. The engines in this class present a more complex mechanism to achieve this reconfigurability in the compression ratio. Thus, the two mobilities are: the main mobility, which is used to run the engine; and the adjustment mobility, which is used to change the compression ratio.

[10] The mobility M of a mechanism is the number of independent coordinates needed to define the own configuration, and it is usually associated to degree of freedom concept. It is generally given by $M = \lambda(n - j - 1) + j$, where n is the number of links, j is the number of 1-DOF joints and λ is the order of screw system [50].

Table 6 The classification for the Atkinson Engines

Main class	Sub-class	Description
Pure Atkinson	M1C1	M = 1 and $v = 1$
	M1C2	M = 1 and $v = 2$
	M1C3	M = 1 and $v = 3$
	M1C4	M = 1 and $v = 4$
Reconfigurable Atkinson	M2C1	M = 2 and $v = 1$
	M2C2	M = 2 and $v = 2$
	M2C3	M = 2 and $v = 3$
	M2C4	M = 2 and $v = 4$

Several authors recognize the mechanism complexity and the number of parts as a challenge in Atkinson Cycle engines [3, 7, 51]. Thus, a further division regarding the mechanism complexity is done inside these two classes. The number of independent loops was used as a mechanism complexity parameter. Table 6 presents the real Atkinson Cycle engine classification. More details and a case study of each class are exposed in the next sections.

Finally, as the next sections expose, it were found engines only in classes M1C2, M1C3, M1C4, M2C2, M2C3 and M2C4. However, different engine concepts can be included in this mechanism-based classification by expanding the classes. Therefore, differently from a working principle-based classification, a mechanism-based classification inherently comprises future developments. Also, the mechanism-based classification can expose which areas are well explored and which is still unexplored. Hence, this classification aids in the search for innovative designs.

5.1 M1—Pure Atkinson engines

The Pure Atkinson Cycle engine presents only one degree of freedom. However, differently from the conventional slider-crank engine, it needs a specialized mechanism to perform the real Atkinson Cycle. The 16 representative

Table 7 Results for pure Atkinson

Classification	Patent	Year	Assignee
M1C2	[28] GB 346592	1930	Individual
M1C2	[30] JPS 588233 (A)	1981	Individual
M1C2	[27] EP 0570627	1992	Individual
M1C2	[29] JP 2002349303	2001	Honda
M1C2	[31] US 20110226199 A1	2010	Individual
M1C2	[32] US 8826800 B2	2011	Individual
M1C2	[33] US 8839687 B2	2012	Individual
M1C3	[37] US 4517931 A	1983	Individual
M1C3	[38] US 6230671 B1	1998	Individual
M1C3	[39] US 7185615 B2	2002	Honda
M1C3	[36] US 7661395 B2	2005	Honda
M1C3	[40] US 7305938 B2	2005	Honda
M1C3	[35] JP 2008111397	2006	Nissan
M1C3	[34] DE102010027351 (B4)	2010	Audi
M1C4	[42] US 4380972	1979	Individual
M1C4	[41] CN102536455	2010	Individual

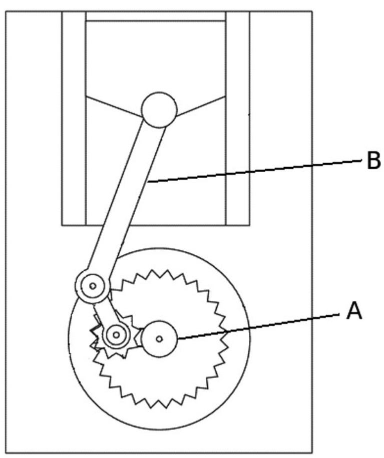


Fig. 7 Class M1C2 example: Patent US 20110226199 A1 [31] with planetary gear set

patents in this class are exposed in Table 7, the first column shows the patent classification according to Table 6.

5.1.1 Class M1C1

The first class inside class M1 presents a kinematic chain with only one closed loop. In this configuration only a slider-crank mechanism is possible for a reciprocating engine. Although the slider-crank mechanism is used in simulated Atkinson Cycle engines, such mechanism cannot be used in real Atkinson Cycle engines. Thus, no further analysis in done in this class.

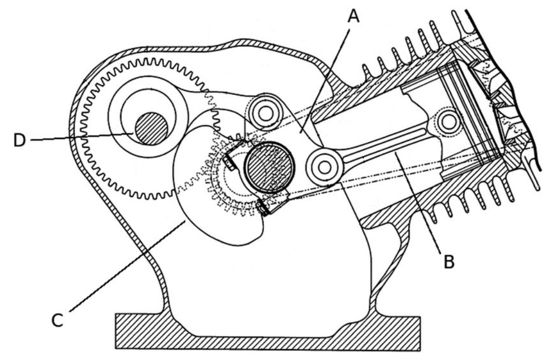


Fig. 8 Class M1C3 example: Patent US 7661395 B2 [36]—Honda

5.1.2 Class M1C2

Mechanisms in class M1C2 have $M = 1$ and two independent loops. Typically, the patents in this class use planetary gear set to achieve a real Atkinson Cycle. Figure 7 depicts the representative example of mechanisms in this class. Notice the engine uses a planetary gear set between the crankshaft (A) and the connecting rod (B). Five out of seven patent use this planetary gear set and all the seven patents are generated from the Stephenson kinematic chain.

5.1.3 Class M1C3

Class M1C3 is composed of mechanisms with $M = 1$ and three independent loops. This class representative mechanism is shown in Figure 8. The trigonal link[11] (A) connects the main connecting rod (B) with the main crankshaft (C) and the auxiliary crankshaft (D). The main crankshaft rotational speed must be twice as the auxiliary crankshaft rotational speed to achieve the Atkinson Cycle. Similar mechanisms were found in six of the seven patents in this class. The difference among those mechanism relies on the crankshafts synchronization method, such as gears, pulleys or chains.

5.1.4 Class M1C4

Class M1C4 is defined by having mechanisms with $M = 1$ and four independent loops. The representative mechanism in this class is exposed in Fig. 9. The piston (A) is connected by a connecting rod (B) to an intermediate point of a floating link (C) which is constrained by a tracking arm (D). The floating link (C) is also connected to a pair connecting rods (E and F) which connects the primary and secondary crankshafts (G and H , respectively). Similar to M1C3 representative mechanism, the main crankshaft

[11] Honda uses the expression “trigonal link” to refer to a specific ternary link in their Atkinson Cycle engine [15].

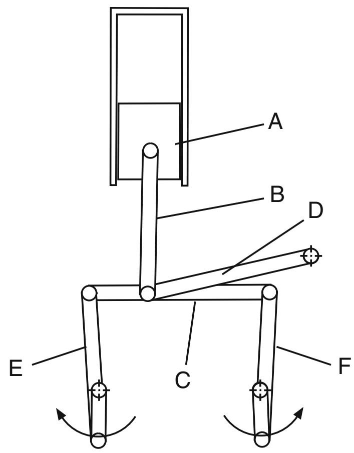


Fig. 9 Class M1C4 example: Patent US 4380972 A [42]—four closed loops in the kinematic chain

Table 8 Results rearranged to shown the number of patents by company in each class

Classification	Results	Main assignees	Number of patents
M1C2	7	Honda	1
		Individuals	6
M1C3	7	Nissan	1
		Audi	1
		Honda	3
		Individuals	2
M1C4	2	Individuals	2

rotates with twice the speed of the secondary crankshaft. Finally, only two patents in this class were found, which can be explained by the complexity of this mechanism class.

The assignees distribution for each class of Pure Atkinson Cycle engines are shown in Table 8. While only one company has a class M1C2 patent, three companies have five class M1C3 patents. This might indicate that class M1C3 have more potential to become final products. Comparing the representative patents of these three classes, it can be noticed that class M1C2 makes use of planetary gear sets. The use of one planetary gear sets per cylinder associated with high velocities and forces can lead to manufacture, maintenance and balancing challenges. Thus, although the number of components per cylinder is low, the type of pairs can generate more noise and friction, reducing the feasibility. On the other hand, the representative patents of class M1C4 presents high complexity and number of links, which can result in balancing challenges. Therefore, it seems that class M1C3 presents a balance between number of links and type of pairs complexity.

Table 8 shows that Honda owns 25% of this class patents. Nissan and Audi own one patent each. The other

Table 9 Results for reconfigurable Atkinson

Classification	Patent	Year	Assignee
M2C2	[43] US 4917066 A	1986	Columbia Univ.
M2C2	[44] US 5927236 A	1997	Individual
M2C2	[18] DE 102013003682 A1	2013	Individual
M2C3	[45] EP 0084542 A1	1981	Individual
M2C3	[48] US 8074612 B2	2008	Hyundai
M2C3	[46] WO2010086130 A1	2009	Audi
M2C4	[49] US 7228838 B2	2004	Nissan
M2C4	[47] US 8794200 B2	2012	GM

patents assignees are individuals non-related to vehicle manufacturers.

5.2 M2—Reconfigurable Atkinson engines

In the Reconfigurable Atkinson Cycle engine, one degree of freedom is added to change the compression ratio. This can be used to make the engine more efficient or increase power output when necessary. As exposed in Sect. 2, there is a need to develop more efficient engines, which led companies to research reconfigurable engines, such as variable compression ratio (VCR) engines [52, 53].

The eight representative patents of Reconfigurable Atkinson Cycle engines are shown in Table 9. The Sects. 5.2.1–5.2.4 present a case study for each class in Table 9.

5.2.1 Class M2C1

Class M2C1 comprises the mechanisms which have $M = 2$ and one loop. The only possible mechanism in this class is a five-link closed loop [50]. This mechanism is commonly used for some VCR engines, as Fig. 10 depicts. It can perform the real Atkinson Cycle when the internal volume is adjusted synchronously with the engines strokes. However, it would require precision and would generate balancing issues given the adjustment link mass. Thus, it is not feasible.

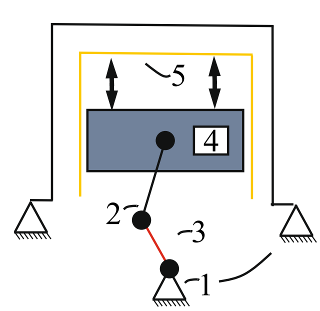


Fig. 10 Class M2C1 example: a five-link closed loop mechanism

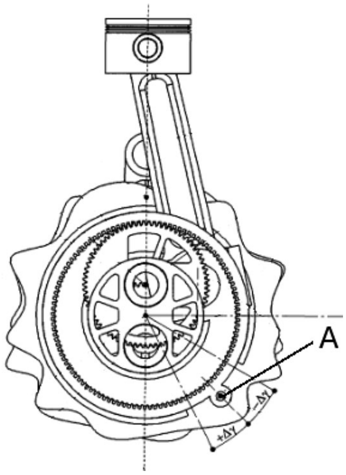


Fig. 11 Class M2C2 example. Patent DE 102013003682 A1 [18]

5.2.2 Class M2C2

Class M2C2 stands for mechanisms with $M = 2$ and two independent loops. Patents in this class are similar to the ones in class M1C2, making use of planetary gear sets. However, one additional link is responsible to adjust the compression ratio. A representative example is shown in Fig. 11. In such figure, the compression ratio is adjusted by changing the position of link (A), rotating the planetary gear set ring.

5.2.3 Class M2C3

The mechanisms in this class present $M = 2$ and three independent loops. Fig. 12 shows the Audi concept in this class. The mechanism is similar to the one presented in class M1C3, except that it uses a device similar to a VVT (Variable Valve Timing) in crankshaft (A) to achieve a variable compression ratio. The two crankshafts have a speed relation of 2:1 and rotate in opposite direction.

5.2.4 Class M2C4

The class M2C4 is defined by having mechanisms with $M = 2$ and four independent loops. These mechanisms are similar to the ones in class M2C3. However, one element is added, see gear (A) in Figure 13. Notice that crankshafts in class M2C3 have opposite rotation direction since they are connected by gears. In class M2C4, pulleys are used to make the two crankshafts rotate at speed relation of 2:1; however, one additional gear is needed to change the rotation direction. The compression ratio adjustment is achieved in a similar manner as in class M2C3.

The representative patent assignees for Reconfigurable Atkinson Cycle engines are shown in Table 10. Four vehicle manufacturer have Reconfigurable Atkinson Cycle engine patents: Audi, Hyundai, General Motors and Nissan.

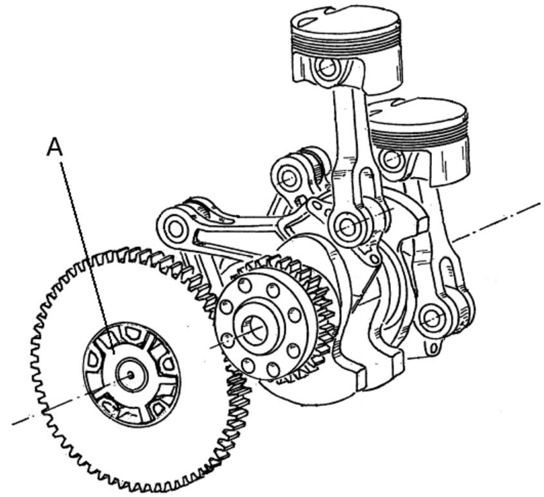


Fig. 12 Class M2C3 example. Patent WO 2010086130 A1 [46]

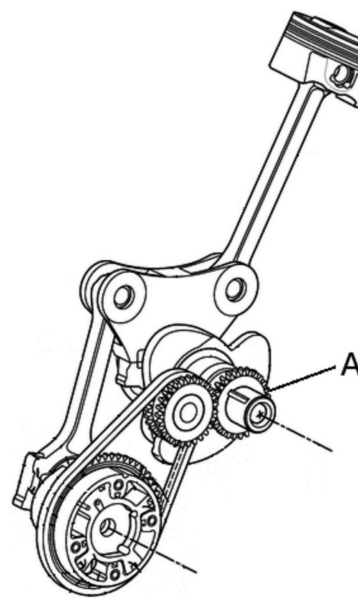


Fig. 13 Class M2C4 example. Patent US 8794200 B2 [47]

6 Discussion of the reconfigurability

The reconfigurability of mechanisms has received special attention from the international scientific community for its advantages when compared to the traditional ones [24–26]. The advances regarding reconfigurability are present in many areas such as reconfigurable mechanisms and robots, variable topology modeling, metamorphic mechanisms and robots, origami-inspired mechanisms and modular devices [24–26]. Engines is a recent area of application of the

Table 10 Results rearranged to shown the number of patents by company in each class

Classification	Results	Main assignees	Number of patents
M2C2	3	Univ. Columbia	1
		Individuals	2
M2C3	3	Audi	1
		Hyundai	1
		Individuals	1
M2C4	2	GM	1
		Nissan	1

reconfigurability in mechanisms, Hoeltgebaum *et al.* [52–54] studied the reconfigurability of VCR engines and they discuss the potential for innovation in VCR engines regarding the reconfigurability.

Atkinson cycle engines mechanisms were classified in Sect. 5 by mobility and number of loops into two main classes and eight subclasses.

- **M1—pure Atkinson**
  - Class M1C1
  - Class M1C2
  - Class M1C3
  - Class M1C4
- **M2—reconfigurable Atkinson**
  - Class M2C1
  - Class M2C2
  - Class M2C3
  - Class M2C4

As indicated in Sect. 5, mechanisms from class M1 have just one degree of freedom like a "conventional" engine, just the spark and the power stroke are necessary to make the engine run. On the other hand, mechanisms from class M2 have two degrees of freedom and they are able to adjust their compression ratio during operation using a second degree of freedom. So, 1-DOF is used to run the engine and perform the Atkinson Cycle and 1-DOF is used to adjust the compression ratio. Therefore, according to Kuo *et al.* [55], the engines from classes M2 which we called M2—Reconfigurable Atkinson are in fact reconfigurable mechanisms and for these engines we have:

1. The core DOF—conversion of the reciprocating piston motion into crankshaft rotary motion;
2. The reconfigurability DOF—variable compression ratio control.

It is important to state that the reconfigurability DOF is the DOF that allows the variation of the engine configuration to change the compression ratio during operation. The characteristic of a short admission and compression stroke and a long expansion and exhaustion stroke is inherent of an Atkinson Cycle engine and it is performed by the core DOF of the engine mechanism.

7 Conclusions

The Atkinson Cycle is an option to increase ICE thermal conversion efficiency. There are different Atkinson Cycle implementations, such as rotatory engines and reciprocating engines performing the real Atkinson Cycle or the simulated Atkinson Cycle. The simulated Atkinson Cycle engine mechanism is similar to the widely known Otto Cycle engine mechanism; thus, its development presents shortcuts. However, the real Atkinson Cycle engine presents a higher indicated fuel conversion energy.

A bibliography review was done, but only a patent survey can yield the Atkinson Cycle engine technology stage. Several different mechanisms for real Atkinson Cycle engine were found in the patent survey. To clearly expose the current state of the art, a classification of real Atkinson Cycle engines was presented based on the mechanism theory.

The proposed classification divides real Atkinson Cycle engines according to the reconfigurability presence. Also, a subdivision regarding the mechanism complexity is done. This classification can easily be used to label mechanisms as it depends on the mechanism structural characteristics. Also, differently from a working principle-based classification, a mechanism-based classification supports future concepts without redefining a new class. Together with a mechanism atlas, this classification shows mechanism that were used and unexplored mechanisms, which result in innovative and possibly promising solutions.

This initial study and the proposed classification provide a broad material for kinematicians and mechanisms and machine specialists to synthesize new mechanisms for real Atkinson Cycle engines.

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