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COMPARISON OF RECIPROCATING ENGINE BOOSTING SYSTEMS

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ABSTRACT

The article reviews the boost systems of reciprocating internal combustion engines (ICE). It considers different variants of existing and prospective boost systems, including displacement and centrifugal compressors, turbocompressors, combined boost systems using mechanical and electric compressors. The work shows the positive effect of boosting on the performance of a powerplant and gives the comparative analysis of boost systems on the volume, efficiency of drive and compressor part, degree of pressure increase and other indicators. The positive and negative aspects of various aggregates, as well as their influence on the performance of ICEs are revealed. Based on the study there were made the conclusions and were chosen the most effective and promising directions for further research aimed at improving the performance of vehicles by the use of boost systems.

Keywords: internal combustion engine, boosting, turbocharging, combined powerplant, combined supercharging.

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1. INTRODUCTION

Boosting of an engine is one of the most effective ways to increase the performance of internal combustion engines. The installation of an additional unit - a compressor - allows significantly increase the liter capacity by a relatively small increase in the cost of a power plant. It should be noted that at the project stage a new engine is designed with an increased strength, so in most cases, the changes in ICE construction are not required. However, if a power unit was previously forced or the boost parameters might affect the performance reliability, it may be necessary to make some modifications like air cooler installation, cylinder-piston group strength increase, and the compression ratio reduction. Modern trends in engine building have a clear vector of development toward the so-called downsizing - reducing the working volume of the engine while maintaining or increasing the output power.

2. MAIN TYPES OF TRANSPORT ENGINES SUPERCHARGING

The main unit providing a boost is the compressor. The compressor supplies increased air pressure to the cylinders. But the compressor drive can be different both in energy source and in design. By the drive gear boost systems the compressors can be divided into three groups - mechanical, gas turbine and combined [1].

2.1. Mechanical charging

Mechanical boost is provided by a mechanical compressor (MC), which takes a portion of the useful power from the ICE crankshaft to compress and supply air under increased pressure to the cylinders. Mechanical charging includes the design of the charging systems provided by the mechanical drive of a pressurization unit. According to the principle of compressor pressure increase, they are divided into:

- displacement reciprocating compressors (extremely rarely used for pressurization);
- displacement rotary compressors (mostly bladed purging machines);
- centrifugal and axial (all turbocompressors);
- pressure wave superchargers (such as Comprex);

The use of mechanical compressors in ICE has a number of significant advantages:

- high boost pressure;
- almost instantaneous response to increased pressure;
- high torque at low rpm;
- Lack of turbo lags.

The use of MC allows significantly increase engine power by more than 50%, however, the mechanical drive compressor can take up to 30% of the engine power output.

A displacement compressor is a machine with the working process based on a change in the working volume. There are more than ten known constructions of displacement compressors, the main are reciprocating, rotary, lobe, vane, ring, etc. According to the working principle, there are displacement rotary compressors and reciprocating compressors.

2.2. Reciprocating compressors (RC)

Reciprocating compressors provide increased pressure due to the reciprocating motion of the piston. Usually, a crank mechanism is used that is connected by a compressor drive driven from the engine crankshaft. This type of compressors was rarely used as a supercharger and is currently used as pneumatic systems compressors and auxiliary units. The transient process of reciprocating compressors is short, therefore the reaction to the engine operating mode change occurs instantaneously. It should be noted that RCs are often used as purging pumps for purging and pressurizing large marine low-speed two-stroke diesel engines. Crankcase scavenging of two-stroke motorcycle engines should also be attributed to the RC. A significant RC's drawback is a large size, sometimes reaching the dimensions of the engine itself.

2.3. Displacement rotary compressors

There are several types of positive displacement compressors in which the working parts perform rotational motion [2]: vane; lobe; screw; ring.

The operation of the vane compressor is based on the rotor rotation with bias disposition in the cylindrical casing and the movement of the vanes located in the cavities in this rotor. The disadvantage of using this type of compressor is the complexity of vanes' lubrication since the air supplied to the cylinders must be free of oil impurities. In addition, there are problems with heating. The advantages are the possibility of rotating the rotor synchronously with the engine (proportional increase in the compressor's capacity with increasing demand for charge air), instant operation at the start of engine rotation and acceptable dimensions for a vehicle engine.

Lobe compressors are widely used (in comparison with other displacement compressors) in ICE for pressurization. The operation process is similar to the operation of a gear pump. The air enters the compressor through port and, with the rotation of the rotors, through the discharge cavity, withdraws via port. Later the design of compressors was improved by the American scientist Eaton. The spur rotors were replaced by helical rotors; the air began to move along the compressor, the number of toothed lobes was increased.

The essential advantage of Roots-Eaton-type compressors is their simplicity. In addition, due to the lack of contact between the rotors and between the rotors and the casing, the compressor can reach high speeds, which reduces the size and weight. Due to the mechanical drive with a crankshaft, the timely charged air input is provided. The obvious disadvantages are engine power consumption for compressor drive, relatively low speed of rotation compared to turbochargers, and, consequently, large dimensions, uneven pulsating air supply, heating of charged air due to a turbulent regime.

Another type of displacement compressors is screw compressors (Lysholm type compressors). They are similar in design to lobe ones, however, the bias angle of the rotor axes relative to the shaft axis is greater, and the pitch of the screw is more significant. The air filling the screw cavities of the female rotor is pushed by the teeth of the male rotor from the suction side. Compared to Roots-type compressors, the screw compressors have higher efficiency, allow higher pressures. The advantage is that pressure ratio increase over a wide range does not depend on the rotational speed; h.e. a high-pressure ratio increase can be achieved with low productivity. In addition, there is no area of unstable operation; the compressor is stable over the entire performance range.

2.4. Centrifugal compressors (CC)

Centrifugal compressors are most widely spread, both as a separate compressor and as a part of turbochargers [3]. The main part of the CC is the impeller of a complex cone-shaped form, equipped with special blades. The efficiency of the compressor depends on how correctly designed and precisely manufactured the blades are. A significant disadvantage of a CC is the demand for high rotational speeds (up to 200000 rpm). This entails the need for the use of special materials of the impeller and bearings construction and the development of a drive with a large transmission ratio. As well noise problems and operational life problems appear. However, due to the small dimensions and low weight, the CC is the most widely used type of blade machines.

2.5. “Comprex” system

A special feature of the ICE is the presence of pulsations of gases at the outlet from the combustion chamber, which form pressure waves. Based on this feature [4] the company BROWN-BOWERI developed the "Comprex" system. The operation principle is that the pressure wave passing through the pipeline channel is reflected negatively at the free end, h.e. as a discharging wave. And at the closed end - like a pressure wave. The wave of discharge is the other way around. The main advantage of the system is the possibility of obtaining a favorable flow of the full-load curve of the engine by driving torque. After reaching the maximum of the full-load curve, there is a slight decrease in torque, in contrast to a sharp decline when using turbocharger systems. In addition, it is possible to increase the maximum by up to 70% compared to the engine without a boost and reach it at a speed of 0.5, which ensures high adaptability ("elasticity"). Additional advantages - higher environmental performance, consumption of a small amount of energy, no need for a cooling system. The disadvantages are large dimensions, the need for communication with the motor shaft and a higher cost compared to the turbocharging.

2.6. Gas turbine charging (turbocharging)

The most modifications of the forced production petrol engines are performed with a turbocharger. Whereas usually it is not required to change the design of the basic engine for the charger drive. The use of energy of exhaust gases does not cause an increase in internal losses to the charger drive.

The gas turbine charging is carried out by a centrifugal compressor driven by a gas turbine using the energy of the engine exhaust gases. The unit consisting of a turbine and a compressor, connected by a shaft, is called a turbocompressor (TC). The construction of the impellers may vary. The most commonly used construction in the compressors is radial wheels, due to their small dimensions and relatively low cost. Turbine wheels use axial and radial designs. While for the wheel with a diameter less than 160 mm only radial constructions is used, for those with a diameter more than 300 mm - axial ones, and in the diameter range in between the two types is used.

The main disadvantage of turbocharging is the inertia of its rotor. This negatively affects the dynamics of acceleration, especially in gasoline engines operating at a minimum idle speed, when the supercharger rotor should be accelerated from a minimum speed of 120 000-150 000 rpm in a split second. This phenomenon is called «turbo lag». The TC has another disadvantage. When the throttle valve is suddenly closed the pressure drop increases, which leads to an increase in the rotor speed and the compressor can switch to the surge operation mode. That leads to deteriorating of its operation, growing of losses.

When using Twin Turbo system with a parallel connection, two identical TCs work simultaneously and in parallel to each other. Parallel work is provided by the even division of the flow of exhaust gases between the turbochargers. The compressed air comes out from each compressor and enters the common intake manifold, and then is distributed along the cylinders. Parallel Twin Turbo system is used usually on diesel V-engines. The efficiency of operation is provided by a replacement of one big turbocharger by two of smaller size, and consequently, with a smaller moment of inertia. This allows reducing the turbo lag effect.

In the system of a consistent Twin Turbo, the first TC always operates, and the second starts to work under certain operation conditions (increased speed, load). It is possible to connect consistently two identical in the characteristics TCs, and the electronic control system provides a transition between modes and regulates the flow of burned gases to the second turbocharger by a special valve. When the burner control valve is fully opened, both turbochargers operate in parallel. Compressed air enters the common intake manifold from two turbochargers and is distributed along the cylinders. It is used both for diesel and gasoline engines.

One of the directions for the development of TCs is the TC with variable geometry [5]. Variable geometry TC differs from the classic turbochargers by the presence of a ring of special blades. The blades have a special aerodynamic shape, which increases the efficiency of the boost. The motion of the blades is driven by a membrane vacuum drive, servo mechanism, hydraulic or pneumatic drive. In high-power engines, the blades do not rotate but are covered with a special casing or move along the axis of the chamber (variable geometry TC with sliding blades).

2.7. Combined supercharging

Combined supercharging provides simultaneous use of mechanical and gas turbine supercharging. Due to the drawbacks of the first one (high power take-off, low efficiency), and of the second one (turbo lag, high temperatures), it is logical to use the units during their best performance. There are several combinations developed that allow significantly improving the engine performance.

2.8. Use of mechanical compressor and turbocharger (TSI system)

A combined application of these devices allows implementing the nominal torque in a wide range of engine speed. In the engine design, a mechanical supercharger of the Roots-type, considered earlier, is used. The mechanical supercharger has a belt gear from the crankshaft. The gear is activated by a magnetic transmission. To adjust the boost, an adjusting flap is installed pressure parallel to the compressor. A standard turbocharger is also installed.

The efficient operation of a dual charging is provided by the engine control system which, in addition to the electronic unit, combines the input sensors and actuators. The magnetic transmission is activated by the signals from the engine control unit when a voltage is applied to the magnetic coil. The magnetic field attracts the friction disk and closes it with the pulley. The mechanical compressor starts to rotate. The compressor operates until the voltage is applied to the magnetic coil. The servo drive turns the regulating valve. With the valve closed, all the suction air passes through the compressor. The pressure control of the mechanical compressor is controlled by opening the damper valve. At the same time, part of the compressed air is fed back into the compressor, and the boost pressure is reduced. With the compressor turned off, the damper is fully open. The turbocharging pressure control valve is activated when the exhaust gas energy generates an overpressure pressure. The valve operates the vacuum drive, which in turn opens the bypass valve. A portion of the exhaust gases passes by the turbine. Depending on the engine speed (load), the following modes of operation of the dual-boost system are distinguished:

- Naturally aspirated (up to 1000 rpm).
- Mechanical charger operation (1000-2400 rpm).
- Co-operation of a supercharger and a turbocharger (2400-3500 rpm).
- Turbocharger operation (over 3500 rpm).

The application of this system entails a complication in the design of engine systems. Like most other engines of this design, modern VW turbocharging engines demand the high quality of fuel and oil, and also require following the elementary rules for the operation of turbo-motors, for example, a short work at idle speed after a trip. When using low-quality gasoline, the engine's life is reduced to 120 000 km, and its repair requires serious expenses.

2.9. Use of a power turbine (Turbocompound system)

The purpose of creating a turbo-compound system is to increase the power and performance characteristics of diesel engines by using the energy of the exhaust gases of an additional turbine. The turbocompound turbine rotates at a speed of 55000 rpm. This motion is transmitted through the turbine gears and the hydraulic transmission, and then through the gears of the gas distribution mechanism to the crankshaft. Transmission of rotation on them creates a useful increase in torque, which is reflected in the change in torque on the flywheel. This additional thrust arises without an increase in fuel consumption [6]. An essential disadvantage of the turbocompound system is the complication of the design, which entails a complication of engine maintenance and cost increase.

2.10. Application of electric machine with TC (Hybrid turbo)

Electric compressors (EC) can be conditionally attributed to a mechanical charger. The scheme of operation is based on the CC, the impeller is also used, but the system is driven by the electric motor powered by the electric vehicle onboard network. Usually, these compressors are used for combined supercharging, ensuring operation at low rpm and turning off at high speeds. EC, as is, has not yet found application in ICE systems.

The use of electric compressors is most rational together with the traditional TC. The scheme of operation is similar to the TSI system, but instead of a mechanical compressor, EC is used. Under the shortage of power at low speeds during acceleration of the engine, the EC, in contrast to the TC, has the almost instantaneous acceleration to the maximum performance, providing the necessary inflatable air. With further speedup, when the TC has already acquired the required power, the EC is switched off.

Usually, the combined installation of a conventional compressor and a turbocharger is quite bulky, since a reducer or belt drive is required to connect the supercharger to the crankshaft and an electromagnetic transmission to disable the drive at high speeds. If the supercharger has an electric drive, it can be installed anywhere, while retaining the freedom of assembly. The absence of a mechanical connection also significantly reduces vibration and noise, which is probably the most important drawback of the superchargers. In 2016 Audi SQ7 4.0TDI SUV became the first car with the electric supercharger [7].

However, the electronic compressor requires about 7 kW (or 9.5 hp) for its operation. In addition, the onboard 12-volt electrical system is unable to provide its power. As a result, an additional 48-volt system is required, including an additional lithium-ion battery, a 48/12V converter, and an AC alternator, that increases both the weight of the unit and the price.

One of the ways of development is the use of an electro machine located directly in the case of a TC. This system helps to "unwind" the turbine faster in the electric motor mode, and at high rotational speeds, to process excess power into electric energy.

3. METHODS

The above-considered systems allow increasing various ICE parameters. However, the efficiency of each of them is different, which causes a variety of applied methods of pressurization. Comparison of systems can be carried out according to various indicators. This article suggests the following indicators: average volume, the presence of a turbo lag, efficiency (of a drive and a compressor parts), pressure increase ratio and the proportion of engine power consumed. It allows evaluating the feasibility of using boost units in vehicles.

The sequence of the comparison is as follows: the characteristics of the most common representatives of the supercharger class are preliminarily determined. If there is a spread of values, their range is extracted. Further, the ranking is performed according to the principle «more points - better characteristics». The results of the comparison are recorded in a rating table in which aggregates with the same characteristics have the same number of points, equal to the average of the positions occupied. The indicator of relative effectiveness has a weighting factor of two since it takes into account the other two indicators.

4. RESULTS

The data discussed earlier in the article [8] made it possible to reveal that the most effective in terms of operational and specific indicators of ICE for gasoline engines is the use of combined supercharging or parallel with a twin-screw turbine, while the highest efficiency and environmental performance are achieved by parallel systems. For diesel engines, the best effect is provided by the use of a two-stage sequential boost with auxiliary electrical devices.

This also contributes to a reduction in specific fuel consumption and CO_2 emissions. The subject of this study is not only the efficiency of turbo-units but also mechanical compressors.

It should be noted that the indicator of the average volume occupied, currently, can come to the fore. Reducing the size of power and transmission units in order to increase the space for passengers leads to the need for the development of compact and efficient devices. A comparison of the boost systems is shown in Table 1.

Table 1 Comparison of the main properties of charging systems

Type	**Average volume, dm^3**	**Turbolag presence**	**Efficiency (drive/compressor)**	**Compression ratio**	**Engine supplied power, %**
Reciprocating	Consistent with the engine size	-	(0.9…0.95)/(0.80…0.92)	5.0…9.0	30…40
Vane	5…8	-	(0.9…0.95)/(0.60…0.70)	1.5…4.0	20…30
Roots-type	12…15	-	(0.9…0.95)/(0.80…0.90)	1.2…1.8	10…20
Screw	12…15	-	(0.9…0.95)/(0.75…0.82)	1.5…3.0	10…20
Centrifugal	2…5	-	(0.94…0.98)/(0.60..0.70) [9]	1.1…3.0	5…15
Axial	2…5	-	(0.94…0.98)/(0.65…0.75)	1.2…1.6	5…15
“Comprex”	6…8	-	n/a	1.5…3.0	0…2
Turbocharger	4…7	+	(0.70…0.80)/(0.60..0.70)	1.1…3.0	0…2
Twinturbo	7…10	+	(0.72…0.82)/(0.62..0.72)	1.1…3.0	0…2
Variable geometry TC	4…7	+	(0.75…0.85)/(0.60..0.70)	1.1…3.0	0…2
MC + TC	16…20	-	(0.70…0.95)/(0.60…0.75)	1.2…3.0	0…15
Turbocompound	n/a	-	n/a	n/a	n/a
Hybrid turbo	7…10	-	(0.90…0.98)[10]/(0.6…0.7)	1.1…3.0	3…5

It is obvious that the same supercharge unit can have an advantage by one indicator and be ineffective by another criterion. For example, having the smallest dimensions, a centrifugal mechanical compressor can consume up to 15% of the engine's power to the drive. So an integrated approach is required to assess the efficiency of the application of units in a vehicle power plant.

5. DISCUSSION

The Figure 1 shows that the supercharging devices with the smallest dimensions are driven radial and axial compressors. Despite the availability of drive parts (usually made in the form of pulleys with a belt), they are smaller than most turbochargers. The next in line are regular turbochargers and TC with variable geometry, despite their large dimensions, they have a more compact configuration. Screw compressors and compressors of a Roots-type are much larger than those listed above. As a result, the combined supercharging from the TC and a mechanical compressor can have the largest dimensions. We do not consider reciprocating compressors and a turbocompound system, the first being too large, and the second lacking data. Twin-turbo and Hybrid turbo systems take an intermediate position between mechanical and turbochargers.

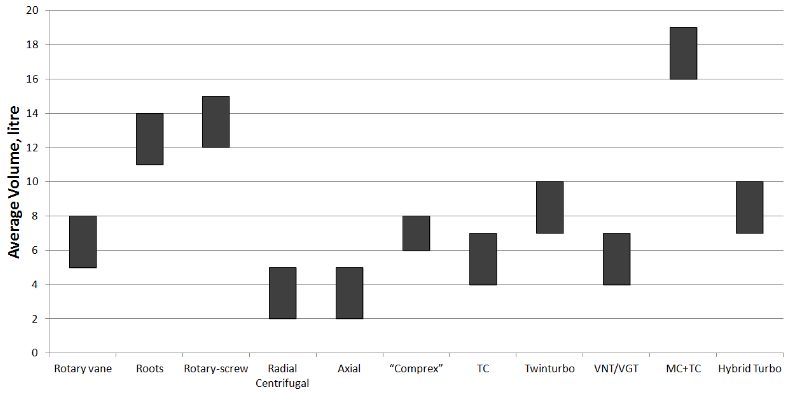

Figure 1 Comparison of supercharging systems in terms of overall dimensions

Comparison of boosters by efficiency shows how much spent energy a device converts into useful work. It is worth noting that there is a power circuit drive-compressor, each element of which has its efficiency. It does not matter whether the type of a drive is mechanical or gas-dynamic, losses always occur. For example, when using a screw mechanical blower, the losses occur: when the drive belt slips, in the gears of the drive and synchronizing gears, in the rolling bearings. At the same time, when the turbocharger operates, the efficiency of the turbine usually does not exceed 75%. In the end, it leads to the fact that the overall effectiveness depends on both parts. Figure 2 shows that a piston compressor has the highest efficiency (80%). It is followed by a Roots-type compressor (79%) and a screw compressor (73%). The efficiency of turbochargers in different variations is in the range of 48-52%.

The pressure increase ratio is an important characteristic of the compressor. Most of the boosters have a wide range of operation. However, the area of maximum efficiency is usually limited to a narrow framework. Often in vehicle power plants, a pressure increase in the range of 1.2 ... 1.8 is required. Therefore, as seen in Figure 3, the reciprocating compressor does not meet the requirements for this feature. The axial compressor is located at the edge of effective utilization, and the compressor of the Roots-type at a pressure increase of 1.8 reaches its minimum efficiency of 80%.

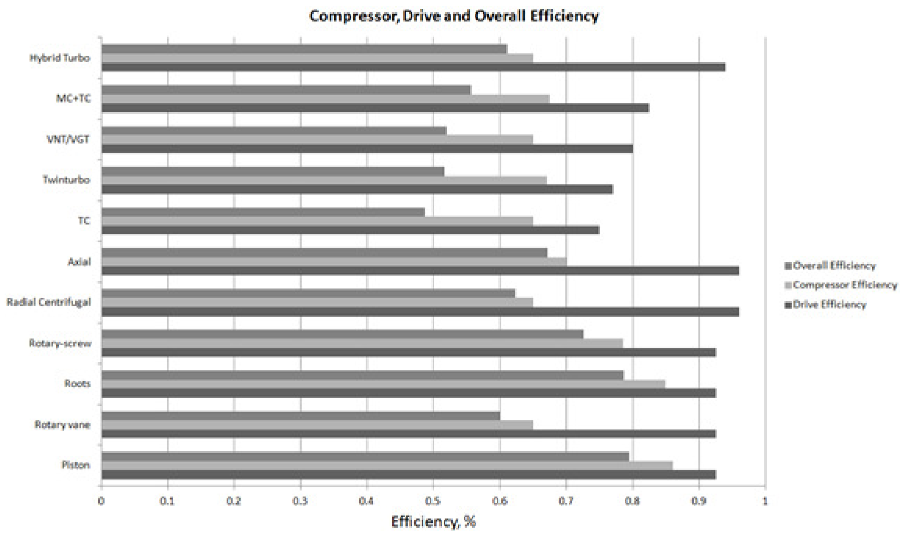

Figure 2. Comparison of boost systems by efficiency

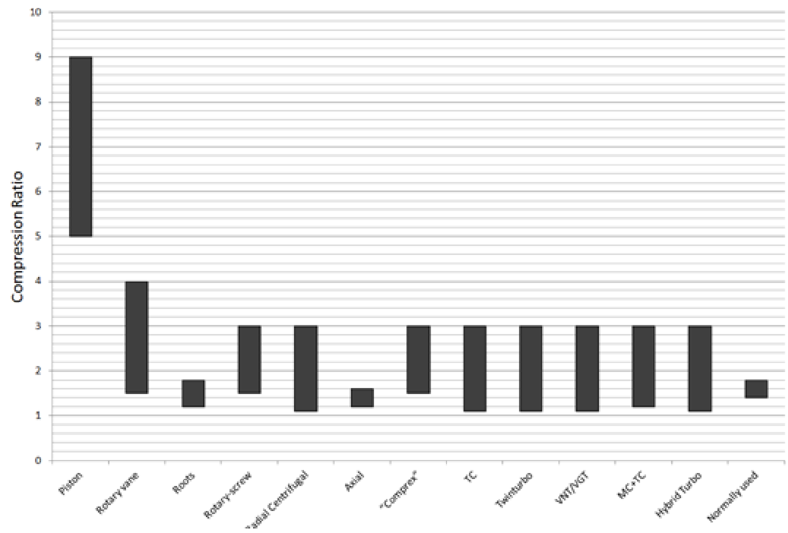

Figure 3 Comparison of supercharging systems by a compression ratio

The value of the engine's power output can be combined with the index of the overall efficiency of the boost unit. This will allow a more comprehensive assessment, taking into account not only the capabilities of the unit itself but also the power plant's power consumption. The indicator of relative efficiency is the ratio of total efficiency to the share of the engine's power. Please note that for gas-dynamic boost, the engine's power output is expressed in the created resistance at the output of exhaust gases. As a rule, it does not exceed 2%. The diagram in Figure 4 shows the obvious advantage of a gas-dynamic boost over the mechanical one. This is due to the high power consumption of the engine on the drive during mechanical supercharging. Also, the hybrid turbo system follows a gas-dynamic supercharging in terms of relative efficiency ratio.

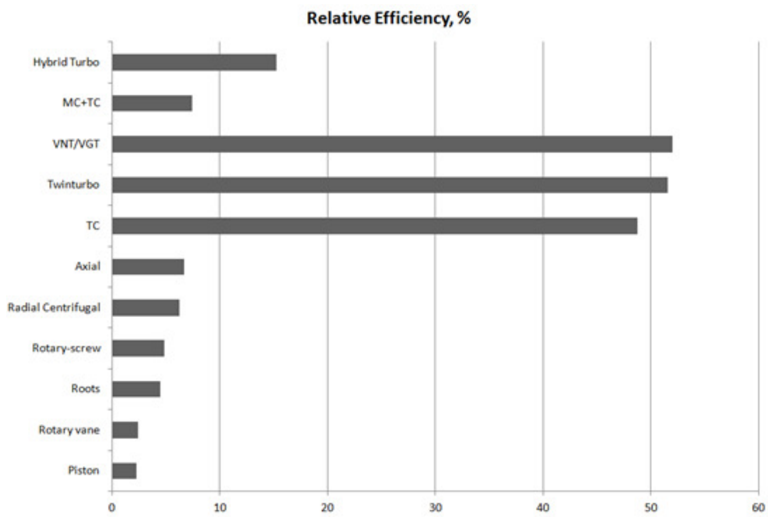

Figure 4 Comparison of boost systems by relative efficiency

Thus, it is possible to make a rating table with the supercharging units ranking by the considered characteristics. Table 2 shows the units with open data. Comprex and turbocompound systems are excluded.

Table 2 Ranking of boost units

Type	Average volume	Turbo lag presence	Compression ratio	Relative efficiency	Total score
Reciprocating	1.0	7.5	1.0	2.0	11.5
Vane	7.0	7.5	7.5	4.0	26.0
Roots type	4.0	7.5	3.0	8.0	22.5
Screw	3.0	7.5	7.5	6.0	24.0
Centrifugal	10.5	7.5	7.5	10.0	35.5
Axial	10.5	7.5	2.0	12.0	32.0
TC	8.5	2.0	7.5	18.0	36.0
Twin-turbo	5.5	2.0	7.5	20.0	35.0
Variable geometry TC	8.5	2.0	7.5	22.0	40.0
MC + TC	2.0	7.5	7.5	14.0	31.0
Hybrid turbo	5.5	7.5	7.5	16.0	36.5

The Table 2 reveals that the most efficient charging system unit is a turbo compressor with variable geometry (40 points). The next is the hybrid turbo system (36.5 points). The third is a regular turbocharger (36 points). This analysis correlates with modern trends in the field of combined supercharging - the transition to turbochargers with a complex structure and the use of electric machines.

6. CONCLUSION

The analysis shows, that the most efficient for vehicle power plants is the use of a combined supercharging. Despite the fact that the leader of the rating is a turbocharger with variable geometry, its development potential is descending gradually. While electric machines in the power unit are getting more popular. Obvious advantages - the configuration freedom, the possibility of separating the hot and cold parts, smaller sizes - help effectively use electric compressors and turbines. However, do not forget about the need to organize a high-voltage onboard network, which imposes significant restrictions on practical use.

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