EVOLUTION OF THE PRESSURE WAVE SUPERCHARGER CONCEPT

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Abstract. Born more than a century ago, the concept of exploiting the pressure wave phenomenon has evolved with rather small steps, experiencing an accelerated progress over the past decades. This paper aims an overview on the researchers’ results over time regarding the pressure wave technology and its applications, pointing out on the internal combustion engine’s supercharging application.

This review complements the past reports on the subject, presenting the evolution of the concept and technology, as well as the researcher’s efforts on solving the specific shortcomings of this pressure wave technology. Undoubtedly, the pressure wave rotors have been a research goal over the years. At first, most of the researches were experimental and the theoretical calculations required to improve the technology were too arduous. Recently, new computer software dedicated to accurate simulation of the processes governing the wave rotor operation, altogether with modern experimental measurement instruments and well-developed diagnostic techniques have opened wide possibilities to innovate the pressure wave supercharging technology.

This paper also highlights the challenges that specialists still have to overcome and aspects to become future preoccupations and research directions.

Keywords – Wave rotors, pressure wave supercharging, internal combustion engines, shock waves.

1. Introduction
The internal combustion engine (ICE) has a long history, evolving from its strange ancient “relatives”, such as the rudimentary internal combustion piston engine using the gunpowder as fuel, suggested by Jean de Hautefeuille in 1678 [1], to the contemporary highly-technologized engines. In more than three centuries, our society became dependent on the internal combustion engines, the thermal engines being used now for transport, trade and energy generation. Indeed, without the internal combustion engine, the world, as we know it today, would be quite a different place!

The first engines, as we know them today, developed in the mid-nineteenth century and were immediately used for transport. The development of the internal combustion engine helped initially to liberate manual labor, especially through physical force; later it made possible the developing of the aviation industry and other forms of transport and also helped to revolutionize the generation of electricity. From small, useful equipment near the house to large machines, from small sailing crafts to marine or aircraft engines, the internal combustion engine is indispensable in our activities and lives.

A constant concern for engineers and scientists was the improvement of the engine’s design, dimensions, performances, and, moreover, emissions in the latter days. The major research directions...
can be resumed as follows: improving the overall efficiency and performance, conservation of energy and heat recovery, reducing the fuel consumption and lowering the engine’s emissions.

A highly prevalent manner to increase the power output and the engine’s efficiency is supercharging, i.e. rising the intake manifold pressure by producing considerable boost for the inlet fresh mixture or combustion air. This is achieved by using superchargers or turbochargers, the equipment positioned within the intake manifold system.

The idea of supercharging is almost as old as that of the internal combustion engine itself. In 1885 Gottlieb Daimler received a patent describing the technique of using a gear-driven pump to force air into an internal combustion engine. In 1896, Rudolf Diesel tested the effectiveness of pre-compressed combustion air introduced into the admission of his engine. Around 1900, almost simultaneously, Sir Dugald Clark, Sulzer and Renault discovered that increasing artificially the volume of air charge entering an engine, substantially more power is produced. Right around the same time, Rateau developed the centrifugal compressor. In 1912-1915, Dr. Alfred Büchi developed the first exhaust gas-driven charger, and proposed the first turbocharged diesel engine, but his ideas were not well received at that moment. Only in 1925, Büchi achieved a power output increase of more than 40% and demonstrated the advantages of using the exhaust gas turbocharging [2]. This initiated the introduction of supercharging of internal combustion engines into the automotive industry.

In fact, turbocharging of automotive engines began in 1938 with truck engines, built by the company Swiss Machine Works Saurer. The World War II and the need for transportation power especially for the military purposes accelerated the development of the charging technology. The most striking application of turbocharging was to war planes engines [2].

Supercharging is about raising the engine’s charge density - air or fuel-air mixture - before filling the cylinders. In this way, higher mass of charge can be compressed in each cylinder, containing more oxygen available for combustion than conventional method of natural intake of fresh charge. As a result, combustion will be more effective, thereby raising the generated power.

Increasing the pressure intake air is performed usually in a compressor that can be driven directly from the crankshaft (supercharger) or by a turbine fixedly connected to the compressor shaft (turbocharger), turbine driven in turn by the engine’s exhaust gases.

A particular type of “compressor” is the pressure wave device - known as “wave rotor” or “pressure wave supercharger” (PWS) - that use also the energy of the combustion gases to induce forced air into the admission manifold, but rely on the pressure waves action inside narrow channels. The fast response on the engine performance for any of the engine speeds makes the PWS a good option for supercharging the IC engines for road vehicles.

2. PWS Operating Principles

PW superchargers transfer energy from the combustion gases to the air intake by means pressure waves. The PWS basically consists of a rotor, also called “cell wheel” in which are machined longitudinal narrow channels, positioned radially on one or two rows (Fig.1). The channels are filled with air at one end and with exhaust gases at the other end, putting the two fluids into direct contact and interaction. The rotation of the cell wheel, together with a certain positioning of the air and gases inlet and outlet ports generate boost. In short terms, the exhaust gases produce shockwaves that expands within the channels and compress the intake fresh air.

The rotor is mounted inside a cylindrical casing, in between two static end plates provided with the inlet and outlet passages (ports) of air and gases, respectively.
The PWS inlet working fluids are: the high pressure gases coming from the exhaust manifold of the engine (HPG) and the low pressure fresh air (LPA), while the outlet fluids are: the low pressure gases (LPG) evacuated through the engine exhaust system and the high pressure air (HPA) delivered into the admission manifold towards the cylinders (Fig. 2).

The number and location of the ports, as well as the thermal energy source have made the distinction between various applications of these devices, serving different purposes. For instance, the four ports configuration was used for supercharging the internal combustion engines, three ports design was applied to pressure separators or pressure equalizers, while rotors with two, four, five or nine ports were integrated into gas turbines applications [5].

**Figure 1 – PWS construction elements [4]**

**Figure 2 – Four port PWS working fluids and assembly elements**
3. Pressure wave machines’ history.

The concept of supercharging, i.e. supplying an internal combustion engine with pressurized air, dates back to early last century. The oscillatory and thermodynamic phenomena last since forever on Earth, but scientists have deciphered these processes in relatively recent years and continue to study them. The turbulent movement of particles, the steady or non-steady fluids flow, as well as the oscillatory phenomena has shown their potential more since the beginning of the 20th century. However, the laborious and detailed calculations necessary to study the non-steady phenomenon inside fluids have hindered progress to be made in this direction.

The beneficiaries of these complex and interconnected processes are the internal combustion engines and other machines that can record improved performances whether these phenomena are known and accurately described.

Basically, the concept that describes the operating principles of machines using the non-steady flow is the transfer of energy by means of pressure waves. The wave pressure devices have some common characteristic elements: a rotor with longitudinally shaped narrow channels within. The ports machined into the end fixed plates control the working fluids flow from the manifold pipes towards the pressure wave channels and vice-versa. The energy transfer is achieved through the direct interaction between fluids by using the non-steady pressure waves.

Unlike the steady-flow turbomachines that compress or expand the working fluids, the wave rotor performs both compression and expansion in the same component [5]. Despite the advantages of the rotor wave machines comparing to turbomachines, such as the rapid response, the low speed, the simple geometry translated into low fabrication costs, the reduced erosion of the channels and the possibility of good self-cooling of the rotor, the pressure wave machines raised some challenges that limited the large commercial implementation of these devices.

These difficulties were of mechanical nature - like sealing and thermal - and of theoretical nature - understanding and defining the complex non-steady flow phenomenon was the main factor that hampered the pressure wave machines development. During the last century, the efforts to improve the geometry and functioning features of the rotor wave, accordingly to a certain application, were sustained by the continuous progress made in solving the equations describing the inner nonlinear phenomena and in implementing the new techniques and technologies. Also, a continuous impetus for achieving energy efficiency, for withdrawing the oldest technology and for finding new, innovative and economic technical solutions, have stimulated researchers’ interest in the pressure wave technology.

Shock wave engines with internal combustion, rotary thermal separators, such as wave rotor refrigerators, the shock tunnels, pulse detonation engines, wave rotors and its best known device, the Comprex, which was developed as a replacement for conventional turbochargers, etc., are some applications using the pressure wave compression and unsteady-flow phenomena.

The first pressure exchanger presentation dates from 1906 [8] when Knauff patented a cell drum called ‘semi-static pressure exchanger” (SSPE) because its pressure characteristics are almost entirely independent of its speed [9]. This device was initially described as a rotor with curved rotor blades and inclined stator nozzles that provided output shaft power, therefore showing a pressure exchange engine, using a steady-flow energy transfer by mixing compressible or incompressible fluids [9]. In 1913 a German engineer, Burghard patented a device resembling with the actual cell wheel. His device was a rotating drum with axial channels shaped on the periphery, as a continuous source of pressurized air [7]. As the knowledge on the unsteady flow domain was insufficient, his device was never developed. In 1928 another SSPE was proposed by Lebre [10] for a refrigerating unit, both with a geometry implying long narrow channels.

Also, around 1928, Burghard recognized the process of unsteady-flow transfer in compressible fluids using the pressure wave process, and patented a more simpler device [11 in 9] known as ‘dynamic’ pressure exchangers (DPE) to distinguish it from previous "static pressure exchangers". Inside DPE the pressure waves are used in both compression and expansion processes eventuating within the rotor channels. This gave the designation of these devices as “wave rotors”.
Inspired by Burghard patent, researchers have sought for decades solutions for the development of the wave rotors concept, being limited by the difficulties mainly related to poor understanding of unsteady-flow processes.

Some inventions related to the wave phenomenon were patented in the same period in different countries. In 1933 Michael Kadenacy (UK) tuned the engine exhaust pipes using the pressure wave effect, later called “Kadenacy effect”, obtaining considerable power output, but in a narrow range of speeds. Around 1938, Johann Wydler (USA) designed a rotating device that used the exhaust gases energy for supercharging a reciprocating engine. Prof. Arthur R. Kantrowitz at Cornell University designed a device working with high pressure ratio compression and expansion waves. His efforts were thwarted by the mechanical difficulties occurred [13]. However, at Cornell Aeronautical Laboratory CAL the non-steady flow concept was developed over the years, having an important contribution in developing of energy exchangers for gas turbine and various stationary power applications [12 in 5].

During the World War II, in 1940, Claude Seippel of the Brown Boveri Co., trying to apply the Lebre principle to a heat pump, acknowledged that the pressure waves can efficiently transmit energy, i.e. the expansion of a gas towards another gas to be compressed [13], both gases being in direct contact. The first machine using the wave rotor concept was implemented in Switzerland by Seippel as a high-pressure stage for a gas-turbine locomotive engine.

Seippel coined the term “COMPREX” due to COMPression - EXpansion processes that take place within the rotor channels.

The rotor had 30 channels shaped within, rotating with 6000rpm. Two ports on each side of the rotor allowed the passing of gas and air. The pressure ratio was initially 3:1 with a global efficiency of 69%, as reported in the tests performed in 1941-1943 [5]. According to Seippel’s patents [14-17], a power boost of 80% and a 25% increase in performance were expected. Even though the first rotor worked satisfactorily, proving the potential of pressure waves in transferring energy, when installed on an engine, it showed that improvement in designing and matching need to be done. The device was replaced by a heat exchanger which yielded a somewhat higher overall thermal efficiency. No further development work is known to have been made [9].

However, the work of these researchers outlined the idea of using the pressure wave rotor for turbocharging diesel engines. First attempt in implementing this new concept and to gather enough data to establish a correlation between measured performance and theory was made by ITE Circuit Breaker Co., Philadelphia, USA, under the supervision of Prof. Arthur R. Kantrowitz and support of the Bureau of Aeronautics. The first units were designed and built starting with 1949. In 1951 came the first encouraging results. In 1954 were run the first tests that proved that pressure wave superchargers can be used for supercharging the diesel engines. In 1955 a cooperative program between ITE Circuit Breaker Co. and Caterpillar Tractor Co. started, the result being a small PWS prototype that incorporated all the experience gained. ITE continued to perform tests until 1957 when the tests on vehicle [13], using the so-called device COMPREX as a diesel-engine supercharger. The early version of the supercharger did not yield sufficient manifold pressure at very low engine speed, at which the clutch is engaged [9]. However, the tests proved that the wave rotor is a simple device, it can deliver high air density over a wide speed range and it allows rapid load changes with no lag or smoke [13].

A cooperative program between ITE and BBC Brown Boveri & Co. started in 1955 as a result of the promising results obtained. BBC, as a turbochargers producer, continued to develop pressure-wave superchargers for diesel engines, in a partnership with the Swiss Federal Institute of Technology (ETH, Zurich). They succeeded to make cycle modifications to overcome the deficiency of the early version of superchargers [9].

Around the same time, the British company Power Jets Ltd. started to work on multiple wave rotor applications, initially on IC supercharging but later on gas turbines, pressure equalizers, air cycle
refrigeration devices. For instance, the Hungarian engineer Jendrassik worked at Power Jets Ltd. to develop the rotor wave as a high pressure topping stage for aircraft engines applications [5].

Also, in the mid 50’s, a new rotor geometry was designed by Pearson at Ruston-Hornsby Turbine Company in UK, producer of diesel engines and gas turbines. The device called the Pearson Rotor used its helical channels to change the path of waves and to produce shaft work the same way a conventional gas turbine would. The rotor was 23 cm diameter and 7.6 cm length, and, despite its reduced dimensions, it realized a single cycle per each rotation [19 in 5]. The Pearson Rotor was known as the wave turbine engine and worked successfully in a wide range of operating speeds (3000–18,000 rpm), producing up to 26 kW at its design-point [5]. The Pearson Rotor encountered a series of difficulties, such as sealing against leakage and incomplete scavenging. Unfortunately, the motor was destroyed due to excessive speed and its further development ended abruptly. The Pearson rotor represented a notable design of a device made for producing significant power output, being in the same time a successful pressure exchanger.

In late 1955 at Cornell Aeronautical Laboratory, Inc., Buffalo, New York was initiated a study of a high-stagnation-temperature testing unit, that put the premises of developing a device based on shock-tubes principles, which could produce a continuous stream of high-temperature, high-velocity air, device called the CAL Wave Superheater [20]. The validated results of the small scale Wave Superheater led to the development of the 9000°R Wave Superheater, including an operational Wave Superheater Hypersonic Tunnel. The working principle involves the use of a group of shock tubes mounted on the periphery of a rotating drum, to generate high temperature, high density and high velocity air. It requires a controlled flow of pre-heated helium driver gas for the hypersonic wind tunnel and a controlled flow of pre-heated charge air (which has to be superheated prior to expansion to more than 4000 K and at a pressure of 120 atm), a controlled flow of pre-heated prime helium gas and a controlled flow of coolant helium gas [20]. The CAL Wave Superheater remained as a remarkable proof of the capabilities of wave rotor devices.

Klapproth (General Electric Company) and Goldstein (NASA), in the late 1950s, initiated conceptual and feasibility studies of combustion within rotating devices [22-24 in 21], with application on turbojets, gas turbines and ramjets. Between 1956 and 1963 General Electric Co. (GE) conducted investigations on pressure-exchangers and shock wave combustors. In Ohio, Klapproth & co. focused on designing and testing experimental four-port pressure-exchange wave engines, one with straight and one with curved channels [21], a wave engine using air-gap seals. Some difficulties, such as inaccurate flow calculations and a lack of attention given to the inner reflected waves resulted in a lower power output as was predicted [36 in 5]. However, the Klapproth rotor clearly proved the possibility of complete energy transfer within a wave rotor.

Therewith, in California, GE focused on designing a prototype of a shock wave engine having curved channels and the combustion process inside the rotor [21]. This configuration eliminates the external combustion chamber, resulting a lower weight and a compact size. Between 1956 and 1958 the experience gained was applied in fabrication of the first internal combustion wave rotor. As described by Weber [25], the only test performed on the prototype lasted about 20 seconds because the thermal expansion of the rotor exceeded the gap between the rotor and the end plates, thus, the rotor seized between the end casings. The test pointed on the difficulty in controlling the clearance between the end plates and the rotor because the thermal expansion phenomena. Despite the leaks, an overall pressure ratio of the wave rotor was achieved of 1.2 to 1.3, corresponding to global temperature ratios of 1.9 - 2.6 measured between inlet and outlet ports of low pressure [5]. In 1963 the GE company interrupted the studies of the wave rotor, reportedly due to changes in business strategy [26].

D. B. Spalding of Imperial College London continued the theoretical and experimental work of Jendrassik from Power Jets Ltd., elaborating the first wave rotor calculation methods that took into
account the heat and friction losses and their effect. The numerical model provided solutions free from instabilities and improbabilities [28].

An interest in researching the wave rotor have shown, also in the mid-60s’, Rolls-Royce company in the UK, by cooperating with Brown Boveri & Co. and with Berchtold of ETH Zurich și Spalding of Imperial College London as consultants [30 in 5]. Their efforts were focused on developing a wave rotor as a topping stage for a small helicopter engine, based on a reverse-flow configuration rotor incorporated into a single turbine engine. The difficulties in designing and quickly performing changes, as well as other challenges, like leakage, start-up, bearing durability, fuel control, affected the device performance. The program was canceled in 1972 against the background of financial difficulties [31].

In 1971 the first COMPREX prototype was installed on a truck engine by the company Valmet Tractors from Finland, while around the same year Mercedes-Benz started testing the COMPREX for their passenger diesel cars. Diesel engines’ supercharging using pressure wave rotors became of big interest starting with 1974 when car manufacturers like Opel, Ford, Mercedes-Benz, Volvo, Peugeot and Ferrari focused their attention on COMPREX supercharging. The first success that became a limited edition was the 2.3 liter supercharged engine on the Opel Senator model.

The first extended application of Comprex® on vehicles was in 1987, when ABB (the new company formed by merging ASEA with Brown Boverly, Co.) sold the Comprex activity to Mazda. The new Mazda 626 Capella model [32] (Fig.3) was equipped with a 2.0 liter engine supercharged with Comprex. Mazda sold more than 150,000 units and is considered one of the most successful commercial applications of PW technology. ABB continued to use the pressure wave technology for gas turbine applications [5].

In 1994, when Mazda was taken over by Ford, the PWS series production was cancelled. Later, all the rights were sold to Caterpillar that, in collaboration with the new founded company Comprex AG (started by former BBC’s employees) used the PWS technology to charge diesel engines in order to decrease the NOx emissions [53]. In 1998 Comprex AG was taken-over by the swiss company Swissauto WENKO AG.

Figure 3 - Mazda 626 2.0L Diesel (under-hood view)

At the end of 70s’, Mathematical Science Northwest Inc. with the support of DOE and DARPA, investigated the application of wave machines as a top stage for a gas turbine coal-derived fuels; as a high temperature air compressor for a power plant based on burning coal; and as a "dirty" gas expander or air compressor for coal burning on pressurized, fluidized bed power plants. The work implied the developing of an experimental wave rotor, with 100 channels, 45 cm diameter and 40 cm length, four ports and two additional small ports (provided for more uniform flow through ports). The calculations of energy exchanger performance were made using a computer program, FLOW, which was developed for modelling the one-dimensional unsteady flows. FLOW included also the modelling of wall friction and heat transfer processes [33]. The experimental results were very well correlated to the numerical computational ones, for a large range of operating conditions. The FLOW software used algorithms that took into account the real conditions and configurations: heat transfer, viscosity, influence of speed, port configuration and channel geometry, flow leakage [5]. Their influence on the wave rotor performance was analyzed for on-design, as well as off-design conditions. Configuration
changes during the tests included variation of the clearance between rotor and end walls, configuration of the inlet and outlet ports, and increasing the area of the main driven stream outlet port. Operating parameters that were varied were: the driver and driven gas inlet pressures, driven gas outlet pressure, rotor speed, and flow rates through the port [33].

The first test conclusion, reported by Thayer, was that decreasing the clearance between the rotor and stationary port faces reduced the leakage and substantially improved the efficiency. Therefore, the leakage was proven to be a key problem for efficient operation of a pressure wave rotor. Also, the experiments showed that efficiency was relatively constant at pressure ratios less than approximately 0.8 and it dropped quite rapidly at higher pressure ratios, due to a decrease in mass flow rate through the compressed air outlet port. Another conclusion validated by tests was that a significant increase in efficiency can be achieved if the width of the exhaust gas outlet manifold was increased. The data obtained from tests on MSNW wave rotor and the computed analysis led to a much thorough understanding of the operation of real energy exchangers and the wave mechanisms [33].

The flow modelling was probably the most critical step in developing an accurate fluid dynamic representation of the dominant unsteady flow processes and the principal losses, many of which are two- or three-dimensional in nature. Efforts on numerical simulation were reported also during the conference hosted by the Naval Postgraduate School, Monterey, California in March, 1985, the ONR/NAVAIR Wave Rotor Research and Technology Workshop. According to Atul Mathur [34], an interest in developing and understanding of the basic flow processes and potential applications of pressure exchangers or wave engines prompted the initiation of a research effort at the Turbopropulsion Laboratory of the Naval Postgraduate School. The research directions were: development of an unsteady flow code, together with numerical studies and experimental work.

Mathur introduced a numerical one-dimensional code, using the Random Choice Method, based on the solution of Riemann problems. The method solves the governing Euler equations in one-dimension by solving a sequence of adjacent Riemann problems, specified as the initial conditions for each succeeding time step [34]. The code proved to be useful for more rapid computational calculations of the unsteady flow process inside the wave rotor and of some preliminary design features. However, it was not recommended for describing the real flow processes that involve friction and heat losses, or for multi-dimensional flows [35]. The results of the uni-dimensional code were used in developing of new software, called ENGINE, for performance calculations of jet engines [5].

A bi-dimensional code, based on Godunov method, was developed by S. Eidelman, showing that it is essential to take into account the gradual opening of the passages when designing a wave machine, for a proper timing, number and geometry of passages, and also because of the losses occurring due to mixing and wave reflections [5, 37].

Also, around 1985, at Cornell University, researches on wave rotor were resumed; the direction approached being mainly on new analytical methods and concepts of three-ports rotor wave, five-ports rotors, double-wave rotors, etc. [5]. The idea of increasing the pressure ratio and thus the efficiency by using a compound unit, including of two or more wave rotors, one being the supercharger for the other, was suggested first by Muller in 1954 [38 in 9].

As synthesized in [5], during the 90’s other researchers became interested in investigating and developing numerical methods to describe processes inside pressure wave machines: Eldin et al. of University Wuppertal, Germany (numerical method based on characteristics theory), Piechna et al. of Warsaw University of Technology (one- and two-dimensional numerical models), Oguri et al. of Sophia University Japan, Guzzella et al. at ETH Switzerland (a control-oriented model for pressure wave devices used for engine supercharging, with accent on transient exhaust gas recirculation modeling), as well as a diesel NOx emissions investigation under Comprex® supercharging performed in Turkey.
Since the 90’s, significant progress was made in computer and automation fields, therefore, analytical as well as experimental researches got a tremendous help, becoming easier to perform, to model, simulate and to process the data results. A significant number of studies revealed a real potential of pressure wave devices together with the improvements that need to be done in order to obtain higher efficiency or overall performance.

The National Aeronautics and Spatial Administration, NASA, was interested in studying the wave rotor combustors for improvements of aircraft propulsion systems performance. Daniel E. Paxson at NASA Glenn Research Center developed a wave rotor simulation cod, i.e. a quasi-one-dimensional, time-accurate, reactive, CFD Euler solver. The model was experimentally validated and was able to picture the cycle complex dynamic gas processes, to calculate the wave rotor geometry and to allow many cycle modifications in order to study their effect on the on-design and off-design performance [39, 40 in 21]. The code is recognized as a general analysis tool for wave rotors [21].

Comprex® developed by BBC in mass production implied also solving the shortcomings resulted, such as leakage, noise and rotor unequal heating: the rotor was mounted within a pressurized casing to limit the leakage and was produced by materials with low thermal expansion coefficient [36 in 5]. The performance was also improved by covering a wide engine speed range through pockets shaped within the end plates in order to control the reflected waves. The result was a reliable product for its purpose: ICE supercharging. There were produced 8 models with different geometrical dimensions, from CX-65 to CX-125, the numbers in the model’s name representing the diameter (in mm) of the wave rotor. In Table 1 are presented the main features of the production Comprex models (except CX-65 and CX-125) [61], according to the dimensions represented in Fig. 4:

| Comprex model | Comprex length L [mm] | External diameter D5 [mm] | LPA D1 [mm] | HPA D2 [mm] | HPG D3 [mm] | LPG D4 [mm] | G [kg] | Effective pressure of ICE [kW] | Maximum Comprex speed [rpm] |
|---------------|------------------------|---------------------------|------------|------------|------------|------------|-------|-----------------------------|-----------------------------|
| CX – 71       | 274                    | 113                       | 49         | 36         | 39         | 50         | 4.9   | 25…40                       | 23900                       |
| CX – 78       | 303                    | 118                       | 55         | 36         | 43         | 56         | 5.4   | 30…48                       | 21800                       |
| CX – 85       | 310                    | 126                       | 62         | 36         | 47         | 61         | 6.2   | 35…57                       | 20000                       |
| CX – 93       | 335                    | 129                       | 64         | 46         | 52         | 67         | 7.2   | 40…70                       | 18300                       |
| CX-102        | 364                    | 143                       | 72         | 46         | 57         | 73         | 8.4   | 50…83                       | 16700                       |
| CX-112        | 396                    | 150                       | 80         | 46         | 62         | 80         | 11.6  | 60…100                      | 15200                       |

Table 1 – Main features of Comprex models (see Fig. 4)

![Figure 4 – Geometrical dimensions of Comprex models](image-url)
Even though the Comprex® had shown a huge potential, it could not overpower the conventional turbocharger. In the early 90’s, Swissauto WENKO AG in cooperation with two Swiss companies: BRM Design and Esoro developed for Greenpeace a novelty project, SmiLE (Small, Intelligent, Light and Efficient), which had the targets to double the fuel mileage of a production car (Renault Twingo), keeping the same main features: performance, capacity of transport, safety and comfort. SmiLE was the first street legal car that attained consumption values of 2.3 - 2.5 Liters per 100km during test drives in real traffic conditions (3.4 l/100 km for NEDC), confirmed by the German TüV [45]. With the new designed engine, 360cc, the SAVE concept engine, supercharged with a PWS, emissions were lower than the standards for Euro III, while the overall weight of the car was reduced by 150 kg.

The three-cylinder engine was optimized according to the SAVE approach, being provided with a regular throttle valve to control the load for low torques, variable gas pockets to control high loads and an additional valve to control the scavange air flow mass leaving the PWS. The pressure ratio of the PWS was controlled by a waste-gate valve. In the SAVE concept, an unusual element is boosting pressure with a PWS, while this was only used for diesel engines. Initially, the SAVE engine was supposed to work with a TC or a MC, but after six years of unsuccessful attempts (noise and comfort problems with the MC, unsatisfactory pressure ratios, high temperature, efficiency and high shaft speeds when using the TC, mainly because of unusual behavior on small displacement engines, under 1 liter), a PWS was chosen to increase the intake air pressure. Wenko improved over three years the PWS for the SmiLE project, increasing the pressure ratios at low speeds (from 1.2 bar to 2.4 at 2000rpm), lowering the noise level over the entire operation range by 8-15dB(A), as well as improving the compression efficiency at medium and high engine speeds [52].

SmiLE was the first success of downsizing/supercharging applied technology, proving the advantages of the PWS:
- high boost pressures at low speeds (an average value of 2 bar attained at engine speed of 1700 rpm);
- extremely fast response times (under 10ms);
- no significant problems when over-speeding, or due to mechanical or thermal stresses at high pressure levels;
- good noise reduction with the asymmetrical multi-cell version (the SmiLE vehicle was provided with a single absorption muffler that kept the noise under the Swiss regulations value of 69.5dB).

From 1998 to 2008, Swissauto WENKO AG improved the concept, presenting in 2008 the VW Golf 5 demonstrator car, equipped with 1.0 liter engine supercharged with the new Hyprex®, with no other changes made to the vehicle. The original Golf 5, with a NA double displacement engine of 2.0 liter, was compared with the highly supercharged demonstrator car, showing that downsizing with factor 2 and using the Hyprex® PWS bring significant improvement in the overall vehicle performance. Values of 210 Nm torque were obtained at 1400 rpm and an output power of 110 kW at 5000 rpm. More, acceleration and march-through were improved, the fuel consumption was reduced [45].

The Hyprex®, is driven by an electrical motor controlled by the engine’s Electronic Control Unit (ECU). This new supercharger is not provided with pockets in its stator, it regulates the boost pressure and the scavenging process by means of a Gas Pocket Valve (GPV). This valve is also controlled by the ECU. As the Hyprex® is designed to work on small gasoline engines, for which the boost pressure as well as the EGR rate have a significant influence upon the engine’s performance and emissions, the GPV together with the ECU have an important role [6]. Swissauto WENKO AG drew up all the patent applications regarding the relation of pressure wave charging for spark-ignition engine use [45]. The difficulties occurred in developing the pressure wave charger for gasoline engines were related to the appropriate adjustment of the charger to the wide operation map of these engines. Hyprex was further developed to our days because of its thermodynamic advantages, reliability and its direct responding speed, making it ideal for charging small displacement gasoline engines. The benefits of Hyprex imply boost response time and increased pressure ratios, lower specific fuel consumption and reduced noise and emissions [45].
In 2010, Swissauto Engineering SA renewed the Hyprex patent for the next 10 years, being known at the moment as the only company currently producing PWSs for small gasoline engines. Unfortunately, in 2015 the company was translated to Swissauto Technology AG that, in January 2017, was in full process of liquidation.

Since the beginning of the 90s’, as reported by [5], a number of universities oriented their researches towards the wave rotor technology and its applications. University of Florida proposed numerical and analytical methods to investigate certain wave rotor geometry variations and its design. After 2000, at University of Tokyo, Nagashima and co. developed 1-D and 2-D numerical models that can simulate the flow behavior inside the rotor channels; also, the group investigated the rotor wave application in ultra-micro gas turbines [46, 47 in 5]. Since 2002, Michigan State University has been preoccupied by pressure wave technology application, such as wave rotor micro-turbines, refrigeration cycles using R718, ultra-micro-gas-turbines, wave rotors with radial flux (in collaboration with Warsaw University of Technology, Poland). Also, Michigan State University together with Warsaw University of Technology developed the FLUENT software [48-51] used for the investigation of the gaso-dynamic phenomena inside the rotors with axial and radial fluxes.

From 2014 to 2017 an interest on developing small scaled wave-rotors as study model, in order to improve power output values for aircraft propulsion, have shown Mataczynski et al. from Air Force Laboratory, D. Paxson from NASA, Hoke et al. from Innovative Scientific Solutions Co. In 2014, tests and flow calculations were performed on 16 inch length wave rotors working with a two-stroke internal combustion engine, proving that the PWS is capable of providing up to 50% increase in the intake mass flow, thus boosting the inlet pressure by up to 135%. With these values, the aircraft engine should work as it is close to the ground level, producing the designed power output [41]. In 2015, the same team validated the small scaled wave rotor results [42]. In 2016, representatives of the three institutions made improvements in design and performances of the small PWS and tests over a large range of operation conditions were performed. The changes and experiments provided valuable data for validation of the design and improvement of the simulation codes [43]. The study on small scaled superchargers described their performances, while the experimental results have shown the capability of the wave rotors, aiming the use of PWS in small aircraft propulsion [44].

4. PWS Performance Features. Comparison TC - PWS – MC - NA.

As depicted in [53], in terms of efficiency, PWSs showed a better downscaling behavior than turbochargers (TC) and mechanical superchargers (MC). In a PWS the energy is transmitted instantaneously and directly from one fluid to the other, therefore, no “turbo lag” can occur, as it does in a TC, caused by inertia, leakage, and local losses. This results in a good driveability for the PW supercharged engine, i.e. a fast dynamic torque response (fast, steady, and smooth rising of engine’s torque) to the driver’s request. Exhaust gas recirculation (EGR) can also occur within a PWS because of direct contact of fresh air and exhaust gas. In spark ignition engines, EGR has to be reduced, while in compression ignition engines EGR has to be enabled. EGR may be an advantage if it is controllable. Modern versions of PWS are provided with a controlled valve to solve the EGR problem. Regarding the noise, caused by the pressure waves in the exhaust manifold, tests have demonstrated a low noise level for PWS, triggering a smaller muffler built into the exhaust manifold. In opposition, the space for PWS installation is approximately twice as that of a turbocharger. Also, larger exhaust pipes are necessary to reduce the oscillatory pulses caused by the valves [54, 55 in 53]; this induces increased heat transfer and thus a longer time for the torque to be build-up. In order to reduce pulsations, a three-way catalytic converter can be installed between the engine’s exhaust valves and the PWS. This solution is difficult to implement because of the small available space, especially for the earlier models of PWS which were belt-driven. The modern PWS are either driven by an electric motor or simply free-running [53].
In the 1980s, the cost for manufacturing a PWS was approximatively twice as that of a TC, mainly because the rotor was made by expensive materials and because the TC was already in serial production. Also, considering the system complexity due to back-pressure effect, as well as EGR control, the effort for producing engines functioning with PWS might be higher than for the turbocharged ones.

A benchmarking between the operational behavior of engine chargers, i.e. pressure wave superchargers (PWS), turbochargers (TC), mechanical compressors (MC) or naturally aspirated engines (NA) reveal significant differences in terms of efficiency, power, torque, specific fuel consumption. According to the results presented by Wiedemann and Rhode in [57], Tatsutomi et al. in [58], Wunsch in [59] and Hiereth in [60], collated in Fig.5, Fig.6 and Fig.7, the Comprex supercharger register a higher adiabatic efficiency than other conventional chargers in normal operating conditions. The high efficiency of PWS comes from the internal cooling effect of fresh air sweeping the channels, while in the TC or MC the rise in heat lowers the efficiency. Comprex is also experiencing losses caused by the bearings friction and windage, but they are negligible. Also, the power lost by driving the rotor is very low, about 0.5% of total load [56], and no work is lost for air compression.

**Figure 5 – Comparative power output for passenger car engines (LKW) and truck engines (PKW).**

Figure 6 – Torque variation for passenger car engine

Figure 7 – Specific fuel consumption for PWS, TC, MC and NA engines

The mechanical supercharger gives an approximately equal torque curve over the entire rotational speed range as in the case of a large aspirated motor [57], similar with the NA engine. When
comparing the TC with the PWS for passenger car engines, it is obvious that a very high torque was achieved at about 2000 rpm, whilst the maximum power is achieved over 3000 rpm, but for the TC the curve has a smoother slope, which keeps the peak value of the power closer to the peak torque value at the optimum engine speed, than for the PWS.

In the matter of fuel specific consumption for passenger cars (PKW), the NA engine is more effective at low loads in comparison to PWS system, while for the truck (LKW) engines the pressure wave supercharging is better than turbocharging. Therefore, the engine should be operated in bypass or combined mode according to the optimum speed range, in order to remain in the lower consumption zone. However, at high loads and real traffic conditions, the PWS has real consumption advantages.

5. Future research targets.

PWS has proved to be a solution with high potential to ensure efficient engine charging, being able to fulfill all main functions in the simplest way and with the shortest time delay. It has the capability to be tuned with the internal combustion engine over its full range of operating speeds. The solution of driving the rotor with an additional electric motor, operating at speeds that can be adjusted in a dynamic mode, accordingly to the waves’ behavior inside the rotor channels, is an interesting and rewarding one. Researches in this field showed promising results.

In order to increase the efficiency of the load exchange and to reduce the intensity of the noise produced during operation, a future solution is that of introducing a device to ensure the adjustment of the angular positions of the windows (pockets) in the front covers. Their rotation can be achieved with a step-by-step motor and the command by a specialized electronic unit. Decreasing the rotor noise can be realized, e.g. by shielding the supercharger housing.

The connection of the pressure wave supercharger to the engine intake and exhaust manifolds with shorter piping and its positioning in the car body compartment are specific study subjects for each engine.

Also, providing pressure transducers (e.g. piezoelectric) on the PWS equipment, capable of ensuring the assessment of the air and flue gas pressures in dynamic mode, should ensure the necessary information for the rotor speed controlling and the front cap position settings.

Finally, the cost of PWS manufacturing is a permanent problem, but the new and modern technologies and materials will reduce the total costs of the PWS, increasing, in consequence, the PWS position within the automotive industry.

6. Conclusions.

The pressure wave supercharging concept, as well as the general wave technology, as shown in the section above, has sparked since 1906 the interest of researchers and manufacturers. In more than a century, thanks to the development and implementation of new technologies, new reliable high-strength and high-temperature resistant materials and nevertheless of the computational performances, workable wave machineries could be realized and improved. Comparing to other engineering and production fields, the wave technology registered relatively slow progress, though considerable results were achieved especially on steady-flow turbo-machineries, despite the well-recognized better efficiency of non-steady flow machines using the shock compression, process more efficient than the isentropic one.

Pressure wave superchargers offer advantages that cannot be overpassed, but still have some disadvantages that have to be overcome. Therefore, researchers have a wide range of possibilities to improve the technology, by theoretical studies, as well as by testing, observing, measuring and implementing innovative ideas. The complex phenomena occurring inside the wave rotor cells challenged the researchers more than a century - and still does – to find solutions for the theoretical equations that describe the fluid behavior, as well as geometrical adjustments, new configurations or
new and reliable materials for the pressure wave supercharger elements. The results will thus highlight the main advantages, pointing on the most appropriate applications. Further theoretical and experimental studies will open the path for new large-scale industry-wide applications of the pressure wave technology and, undoubtedly, for promoting pressure wave superchargers for road vehicles applications.

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