GAS TURBINE AS RANGE EXTENDER FOR FUTURE ELECTRIC AUTOMOBILES

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Abstract. The propulsion of automobiles by motors, especially by hub motors, integrated into the wheels, offers remarkable advantages in terms of vehicle dynamics, stability and freedom of movement. But the most important benefit is the operation in conditions of local zero emission of pollutants and noise, which strongly recommend the utilization of such vehicles in urban areas. However, a major problem of the electric propulsion is the limited speed range caused by the poor energy density of every form of batteries. For the mentioned intelligent wheel robots, a supply of on board-electric energy is imperative. A solution with basic advantages is the use of thermal engines – such as piston, Wankel or Stirling – as on-board current generators. The paper presents a very promising alternative, which is the use of thermal turbomachines. A detailed comparison of the thermodynamic cycles of piston engines with gas turbines configured for current generation shows net advantages of the new solution in terms of efficiency and pollution limitation. For the continuous combustion at unchanged operation point a multitude of renewable fuels, alcohols, ethers or hydrogen, are applicable. Solutions with axial and radial gas turbine, which were successfully tested in automobiles with electric propulsion are described in base on characteristics and specific design aspects.

Key words: range extender, hub motors, gas turbines.

1. INTRODUCTION

The hub motors, integrated in wheels, are considered as the key of the long-term automobile propulsion. A motor offers remarkable advantage, from the zero local pollution and maximum torque at start to the degrees of freedom during wheel movement.

Figure 1 shows examples of typical torque and power curves for a car propulsion motor and for an internal combustion engine, in this case with spark ignition.

The maximum torque of an engine deploys not till then the engine speed notably increases, whereas the maximum torque of a motor is already available from standstill. On the other hand, the acceleration of a car with given mass, requires a force, which is generated by the momentum at the wheel. Thus, the torque from the propulsion unit, engine or motor, generates – considering a

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transmission ratio – the momentum, thereby the force at the wheel contact with the road. A similar torque is obtainable with an engine at a higher power in comparison with a motor, because of the necessary engine speed. Same torque at a relatively low speed – for example 345 Nm at 1 000 rpm, which means same power in this point – as deductible from Fig. 1, makes necessary a much higher maximum torque of the engine (600 Nm), in comparison with the motor (345 Nm), in order to obtain the required steep rise of the torque curve.

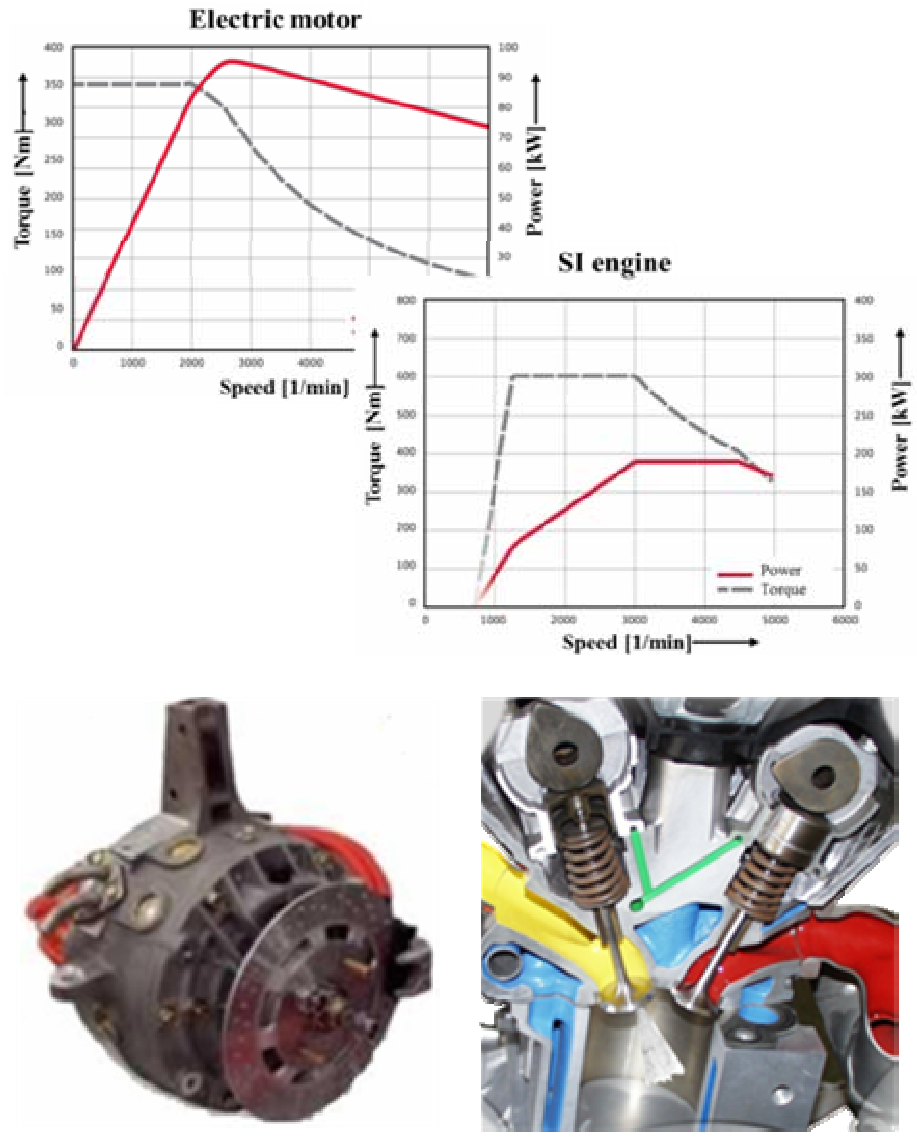


Fig. 1 – Typical torque/power curves for an electric motor
and for an internal combustion engine for automobile propulsion.

Because of the maximum torque from standstill, a same car with motor propulsion accelerates faster than with an engine, even though at higher engine torque. Considering the usual torque/speed range of a car in urban cycle, the power of a motor is considerably lower as the power of an engine, as deductible from Fig. 1. This means a considerably lower energy consumption per kilometer. Additionally, the propulsion by hub motors in all wheels has noticeable advantages in terms of vehicle dynamics, stability and freedom of movements. Four-wheel or two-wheel propulsion, front or rear, can be electrically activated. Electronic Stability Program (ESP), Antislip Regulation (ASR) or Anti-lock Braking System (ABS) are feasible in similar manner. Driving stability on curves is improvable by the orientation of front and rear wheel pairs.

A hub motor for such application can achieve 20 kW / 200 Nm.

A major disadvantage of the electric propulsion of automobiles derives from the restricted availability of electric energy on board: the energy storage in batteries only at low energy density implicates low operation range at high mass, volume and costs. Fuel cells based on hydrogen show akin disadvantages, despite of a more efficient energy conversion in comparison with such in batteries, similarly to the difference between heat convection and heat conduction. The main problems are, when using fuel cells, the storage of hydrogen on board, either at pressures between 30–90 MPa, or at a temperature of 20 K, and the complexity of the fuel cell itself, causing high costs.

2. GENERATION OF ELECTRICAL ENERGY ON BOARD OF A VEHICLE WITH MOTOR PROPULSION BY THERMAL ENGINE

The energy density during the conversion from a chemical source into electricity can be remarkable increased replacing the chemical reaction in a battery or the proton exchange in a fuel cell by combustion, which implicates high turbulence and high temperature of the chemical reaction. A base of comparison could be the reaction of hydrogen with oxygen in a fuel cell and in a combustion chamber, in both cases the final product being the same: water.

The combustion can be fitted only for generating electric energy in a fixed load/speed operating point of any kind of thermal engine: two- or a four-stroke piston engine with compression ignition or spark ignition, Wankel, Stirling or turbomachine (gas turbine). The respective thermal engine, which must only generate electric energy on board must not have contact with the propulsion line.

Figure 2 shows a prototype of General Motors, the Chevrolet E Flex Volt [1]. The propulsion motor has a maximum torque of 320 Nm, and a maximum power of 120 kW. The generation of electric energy on board is ensured by a turbocharged three-cylinder spark ignition engine which can develop up to 53 kW. The electric energy is stored intermediately in a Li-Ion battery with a capacity of 16 kWh.

The power of the propulsion motor, the power of the charging engine and the battery capacity can be considered as variables (x, y, z) in an equation including the provided driving cycle profile (a) and the intended operation range (b). The values of the variables (x, y, z) should be optimized in base on the adopted parameters cycle and range (a, b), with reference to the criteria costs, weight and dimensions.

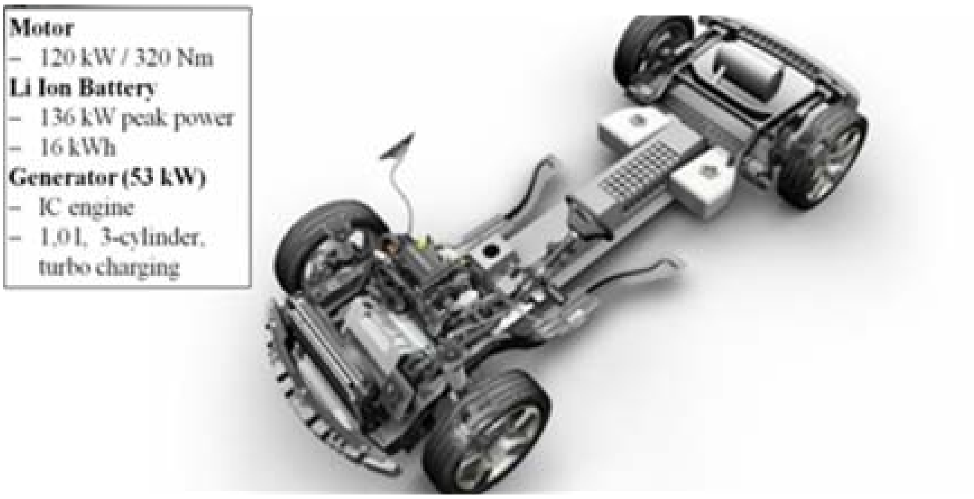


Fig. 2 – Four-stroke spark ignition engine as current generator for motor propulsion: Chevrolet E Flex Volt prototype *(source: General Motors)*.

The Chevrolet Volt solution is rather an attempt to join the elements in such propulsion system with motor propulsion, current generation by engine on board and temporary storage on energy in battery. The concept has demonstrated an excellent function, but it needs a next step of development and optimization. Therefore, the motor of the Chevrolet solution appears as oversized, whereas the engine is not only oversized but also to sophisticated for such simple task of generating current.

As shown in Fig. 3, during the operation on country roads, a middle-size car necessitates a torque of at most 100 Nm and a maximum power of 30 kW. In an urban area the speed is lower, thus, at comparable torque peaks the power remains under 20 kW. Surely, on a motorway both torque and power should be augmented, if the vehicle velocity becomes higher than 130 km/h. However, the aim of an electric vehicle is in principal to act in urban areas and their peripheries and not racing on motorways without speed limits.

A more simple solution is presented in Fig. 4, being developed by PSA Peugeot Citroen in cooperation with the author of this paper, at the West Saxon University of Zwickau [1].

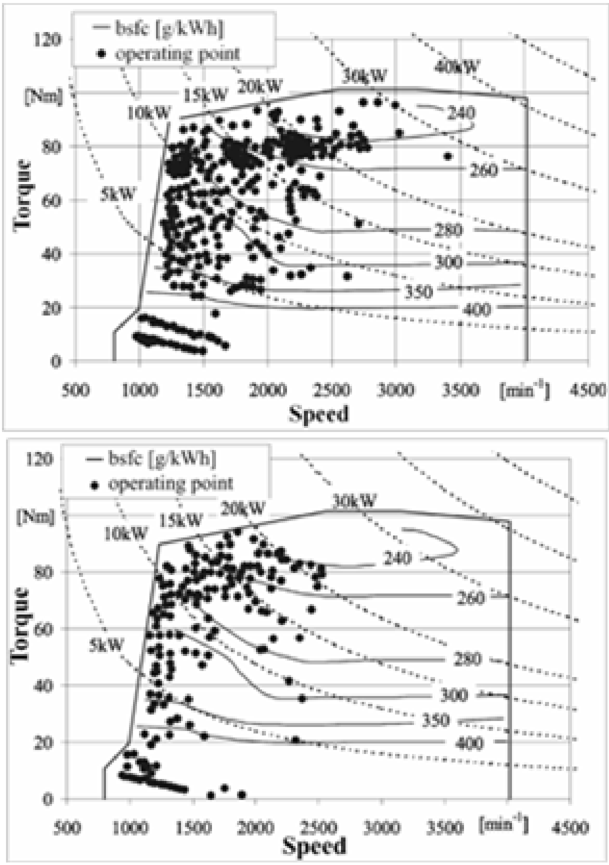


Fig. 3 – Operating domain of a middle-size car on country roads (left)
and in an urban area (right) statistically [1].

The maximum motor torque is in this case 127 Nm and the maximum power 20 kW. The current generation can be accomplished with an internal combustion engine with only 10 kW, when considering the temporary energy storage in battery, which is allowed by the usual driving cycle. For such stationary function the engine can be as simple as possible. Thus, a spark ignition two-stroke engine has been developed. The engine is provided with gasoline direct injection, for avoiding the inherent scavenging losses of a two-stroke engine, which would lead to higher fuel consumption and pollutant emission in comparison with a four-stroke engine. Using direct injection such losses are entirely eliminated, consumption and pollutant emission being lower than from a four-stroke engine with similar power. But the most remarkable advantage of this two-stroke engine in comparison with a four-stroke concept is the incomparable weight of only 8 kg (dry) and the compact dimensions of $0.3 \times 0.3 \times 0.25$ m. With a gasoline reservoir with 15 l the operation range in an usual driving cycle is 420 km. The fuel consumption is 2.4 l/100 km and the carbon dioxide emission 60 g/km.

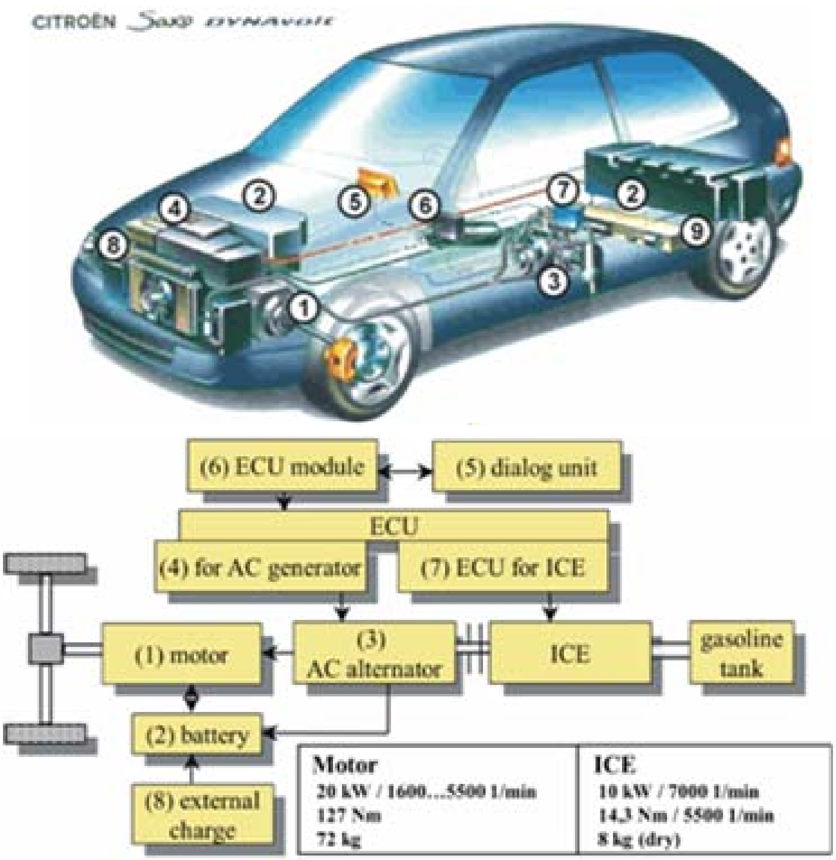


Fig. 4 – Two-stroke spark ignition engine as current generator for motor propulsion: Citroen Saxo Dynavolt [1].

Audi, using an engine with rotating instead an oscillating piston, has developed a similar non-sophisticated solution. This Wankel engine with compact volume generates current for a motor with 150 Nm / 45 kW. The buffering battery has a capacity of 12 kWh. The maximum range achieve 200 km, the fuel consumption is 1.9 l / 100 km and the carbon dioxide emission 46 g/km.

Obviously, the current generation on board of an automobile by means of a simple and compact engine – two-stroke or Wankel – for propulsion by motor in urban areas at a range between 200–400 km seem to be very competitive. In comparison, a Li-Ion battery only, for the same range, should have a capacity over 40 kWh, and subsequently a mass of more or less 500 kg, a large volume and a high price. On the other hand, a complex and expensive module like a fuel cell requires the energy from a hydrogen tank, which can store, for example, at 50–60 l no more than 5–6 kg hydrogen at 60 MPa. This corresponds to the energy of approximately 25 l gasoline.

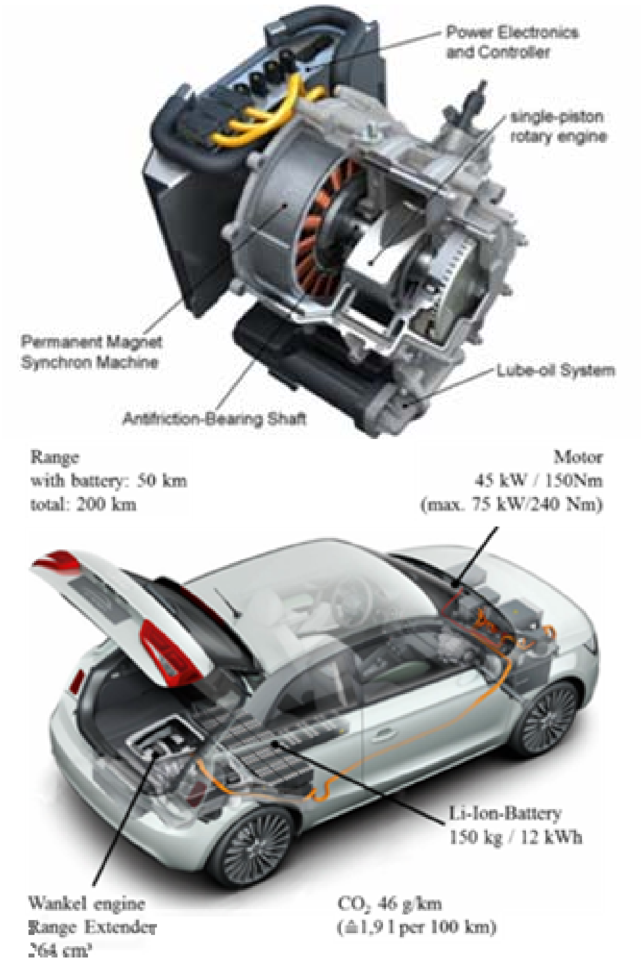


Fig. 5 – Wankel engine as current generator for motor propulsion:
Audi e-tron (source: Audi).

3. GENERATION OF ELECTRICAL ENERGY ON BOARD OF A VEHICLE WITH MOTOR PROPULSION BY GAS TURBINE

Despite the advantages of compact engines with oscillating or rotating pistons for current generation it appears as more efficient to replace the successive stages of the thermodynamic process in the same space – as in such machines – by simultaneous stages in different modules of the machine. A continuous flow of air and fuel can be better optimized in every stage of the process, namely during compression, combustion, expansion.

A continuous flow for a continuous process stage, for example for compression, is simpler when using a rotating machine such as a radial or axial compressor. Similarly, for expansion is simpler to utilize a radial or an axial turbine. However, a compressor with oscillating piston or pistons can accomplish the same task of generating a compressed, steady air flow at a sufficient swept volume and by coupling a pressure accumulator.

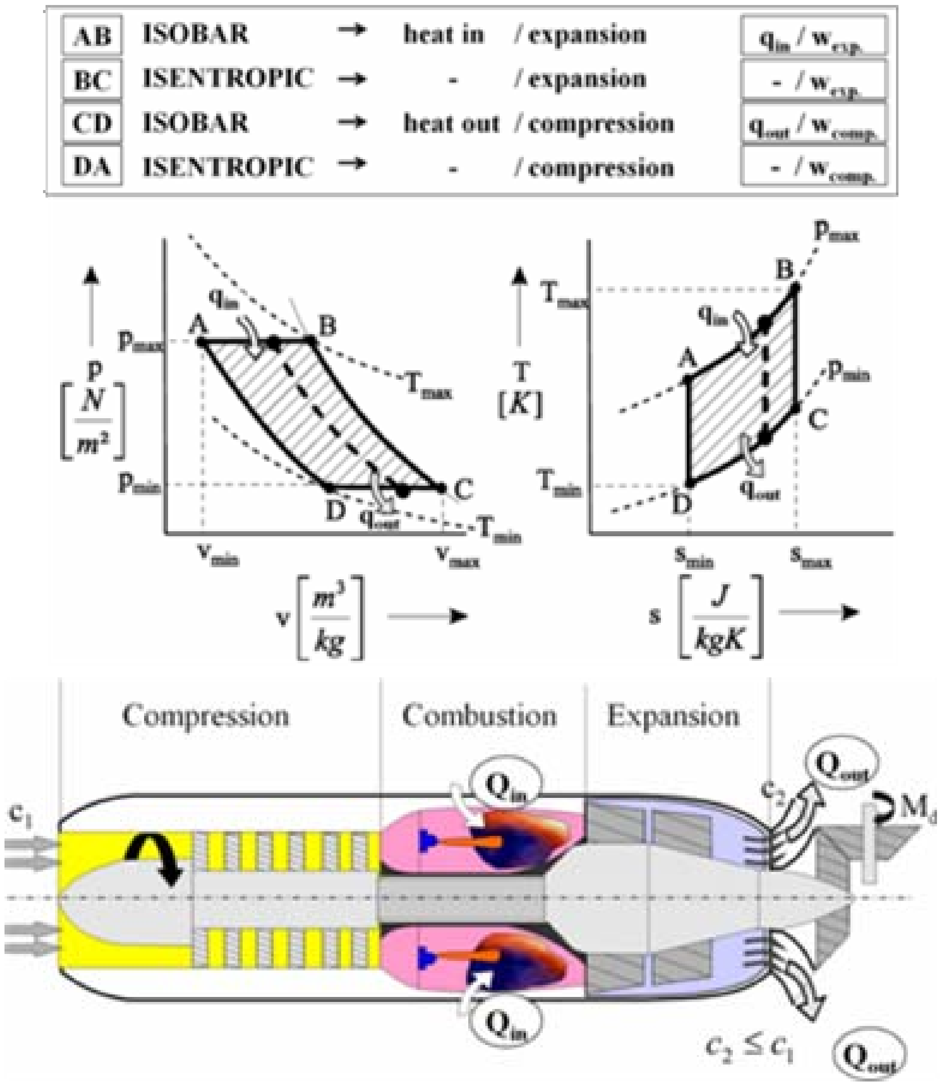


Fig. 6 – Ideal thermodynamic cycle (Joule process) and schematic of a turbomachine (gas turbine) with axial compressor and turbine [1].

In comparison with the process in compression ignition or spark ignition engines with oscillating pistons, the expansion in a gas turbine is extendible down to the atmospheric pressure. Consequently, the specific work and the thermal efficiency increase, as presented in the following section.

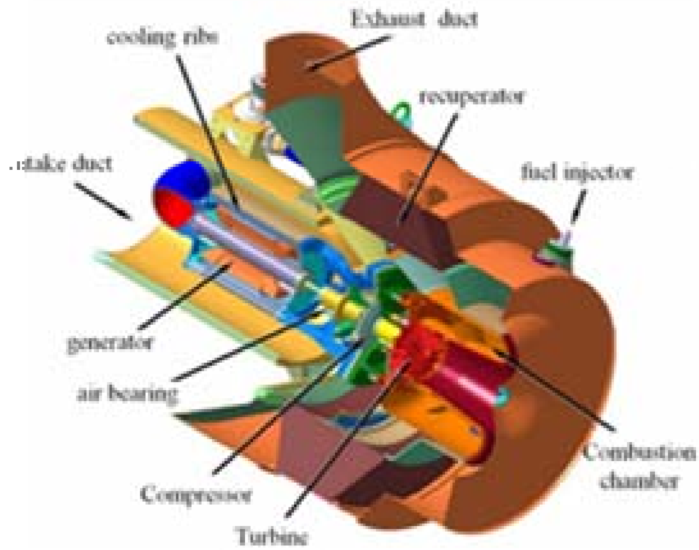


Fig. 7 – Schematic of a gas turbine with radial compressor and radial turbine (source: Capstone).

The compression is realizable, for example, with an axial compressor, as shown in Fig. 6 in serial disposed compressor units which consists on rotor and stator. Basically, this compression can be considered as isentropic [2]. The combustion of continuously streaming masses of fuel and air is isobaric. The advantages regarding the fuel/air mixture formation and combustion in comparison with such processes in piston engines are evident: the injector is open, this means without opening and closing needle; the inner form of the injector allows a controllable fuel flow swirl, leading to a sufficient atomization. The spray penetration length has practically no importance in an open chamber without length restriction. The contact of the fuel spray with the enveloping air can be optimized following different conditions. For example, the mostly cylindrical shell of the combustion chamber, which comprises the fuel/air mixture, is enveloped by a secondary air flow, coming from the same compressor as the main air flow. This air envelope diminishes the thermal stress and radial heat losses. Moreover, the shell contains holes for a suction of secondary air just in the zones where the local maximum temperature within the burning mixture are very high, at the limit of dissociation and therefore of NO_x formation. The expansion is realized in turbines with more stages: in a first stage or in a first group of stages is generated the work for the compressor, which is transmitted to those by an axial shaft. The second stage or group of stages transforms the remaining enthalpy of burned gas into the effective work – corresponding to the effective cycle work in a Joule process. This effective work can be used by means of a gear for the direct propulsion of an automobile or for the current generation on board [1]. Such an application as a generator is illustrated in Fig. 7, when using a very compact machine with radial compressor and radial turbine.

Basic Specifications

Vehicle:	2007 MINI Cooper S
Base Price:	$27,400
Price as Tested:	$175,000 (est.)
Engine(s):	
MINI Cooper	1.6L 4-cyl (front)
Rolls Royce	Allison C18 Jet Turbine (rear)
Combined Horsepower:	528
Combined torque:	600 lb/ft
Transmission:	
6-speed automatic (front)	
Direct belt-drive (rear)	
Rear axle:	'06 Corvette C-5 (3.31:1)
0-60mph:	4.3 seconds
¼-mile:	12.1 sec @ 119.6 mph
Top Speed:	138 mph (limited)
Builder: Marine Turbine Technologies, LLC (Franklin, LA)	

Fig. 8 – MINI Cooper S with propulsion by gas turbine (rear) and piston engine (front).

However, there were also applications for direct propulsion with gas turbines in automobiles, as developed by Jaguar (axial gas turbine), Capstone or Velozzi, (radial gas turbine). The main problem for direct propulsion is that the flows through compressor, combustion chamber and gas turbine can be optimized only in restricted areas of load and speed. A very suggestive example of such application is presented in Fig. 8.

4. THERMODYNAMIC CYCLE OF A GAS TURBINE WITH HEAT RECUPERATION FOR GENERATION OF ELECTRICAL ENERGY ON BOARD OF A VEHICLE WITH MOTOR PROPULSION

In the presented forms of gas turbines for current generation on board, as shown in Fig. 6 and Fig. 7, the burned gas expands down to the surroundings pressure, but – corresponding to the Joule cycle in Fig. 6 – at a higher temperature as those of the atmospheric air. From this temperature difference results the heat exhaust at constant pressure in the Joule cycle, as marked in Fig. 6. It could be efficient to recuperate as much as possible of this heat in a heat exchanger, using it, in an effective manner, in the next cycle.

In a first stage of thermodynamic analysis a comparison of the ideal thermodynamic cycle of a gas turbine with a Diesel process, with same kind of heat input at constant pressure, appears as representative. For an evaluation of the results not only as specific, but also as absolute values, the aspirated airflow corresponds to a Diesel with a swept volume of 1 800 ccm at 3 000 rpm–58.25 g/s[2].

The ideal cycle is considered for ideal gas (air), starting at 0.1 MPa and (273.15 + 10) K. The maximum temperature of both processes, Diesel and Joule was fixed at (273.15 + 1 900) K. The compression ratio of the Diesel cycle is 22, resulting in a maximum pressure of 7.57 MPa. In a gas turbine, the pressure cannot achieve such values if using radial or axial compressors instead of a piston-cylinder unit. Therefore, the maximum pressure for the gas turbine was fixed at 0.7 MPa, as a realistic value. Figure 9 shows the differences between both cycles in p, v – and T, s – diagram.

Obviously, in order to achieve the same maximum temperature with a lower pressure level, the heat input into the gas turbine increases. But the heat exhaust increases as well. However, the specific work as deductible from the surfaces in the p, v – or T, s – diagrams is quite similar – 719.9 kJ/kg for the gas turbine and 783.3 kJ/kg for the Diesel. This fact is explainable by the additional expansion in the case of the gas turbine, despite a lower maximum pressure. The gas turbine reaches at these values, with the air mass flow corresponding to the Diesel a power of 41.94 kW, in the range of a current generator on board of an automobile.

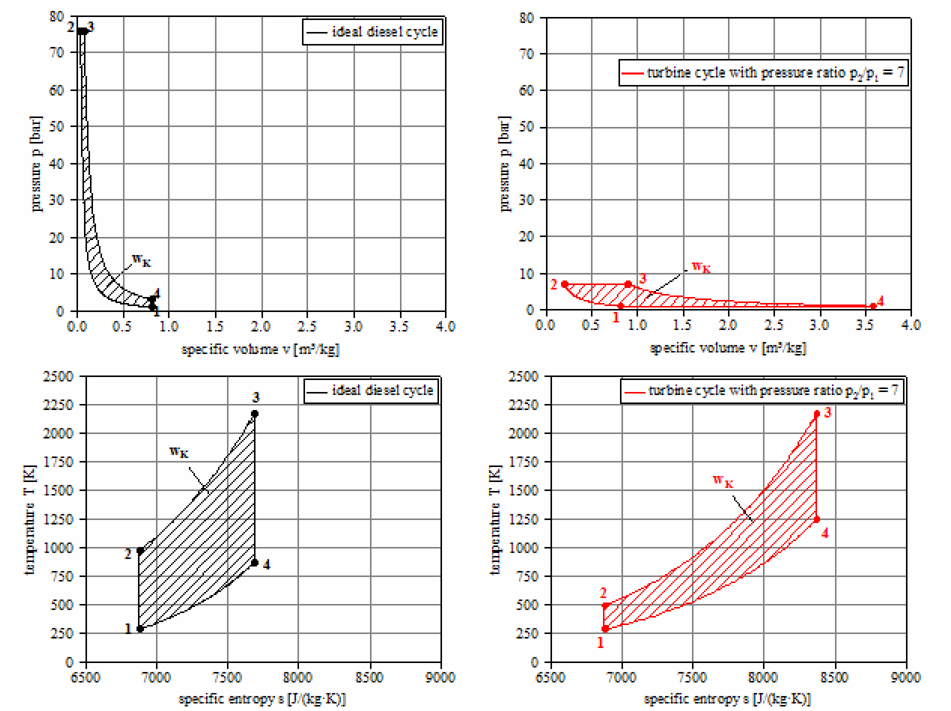


Fig. 9 – Comparison of the ideal Diesel and Joule cycles at same maximum temperature but with different maximum pressures.

However, it is also interesting to compare both cycles at same maximum pressure and at same maximum temperature. The use of piston compressors coupled with accumulators for a Joule cycle appears as well feasible. The p, v – and T, s – diagrams of both cycles are shown in Fig. 10. The difference to the precedent case is obvious. For a direct comparison the p, v – and the T, s – diagrams of both gas turbine variants and of the Diesel are superposed, as illustrated in Fig. 11.

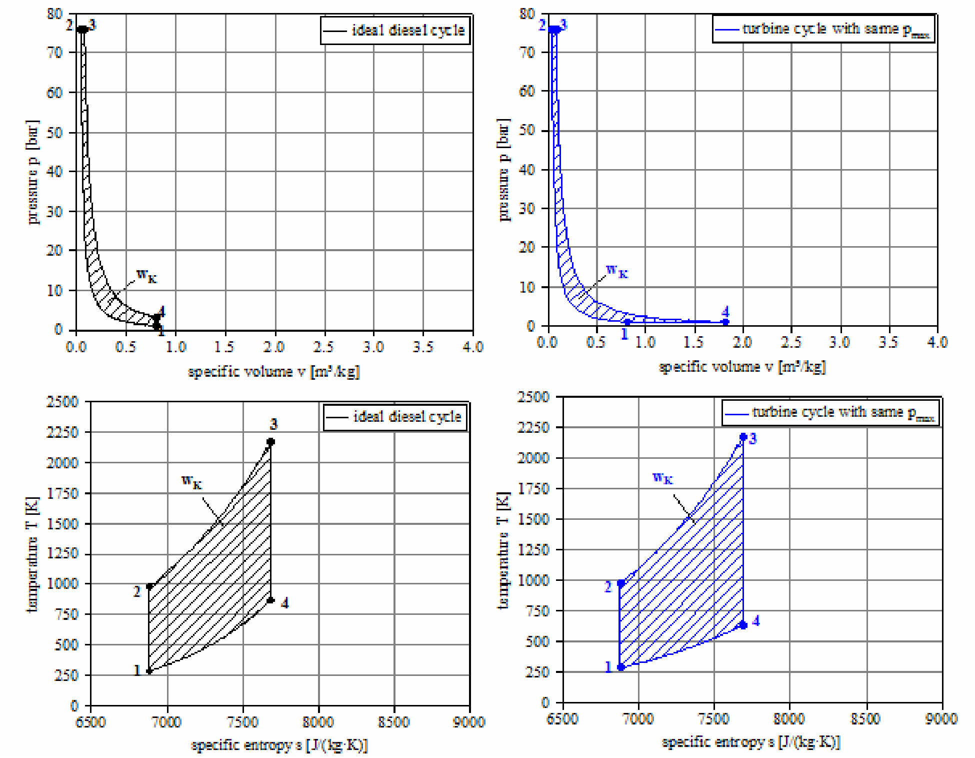
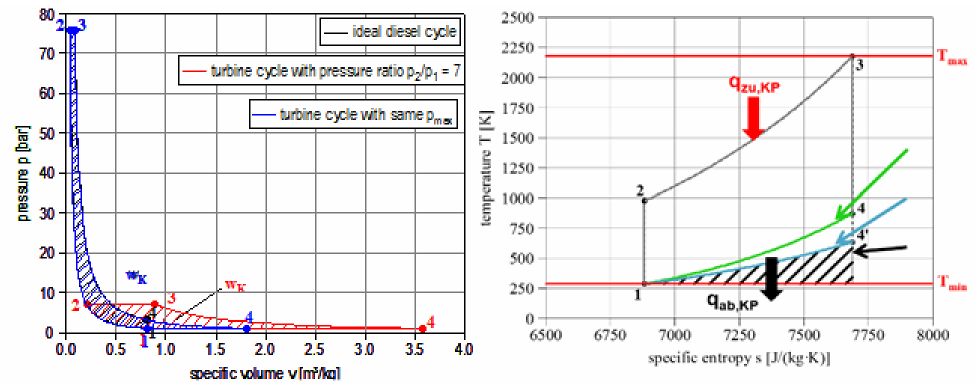
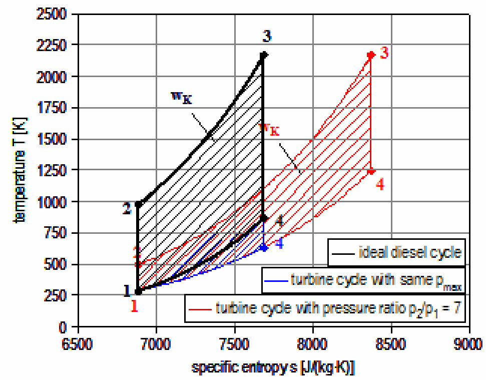


Fig. 10 – Comparison of the ideal Diesel and Joule cycles
at same maximum temperature and the same maximum pressure.

As deductible from the *T*, *s* – diagram and shown in the table, the thermal efficiency of the gas turbine with same maximum temperature and pressure as in the Diesel cycle is much higher – 70.94% instead 51.02 %, fact which is explainable by the extended expansion, causing a less heat exhaust at same heat input. For same reason, the specific work of this gas turbine cycle is higher than in the Diesel cycle, as also deductible from the difference of areas in the *T*, *s* – diagram. The gas turbine cycle with a maximum pressure of 0.7 MPa achieve, however, a thermal efficiency of 42.64%. This maximum pressure should be object of future optimization.

Nevertheless, as mentioned in the introduction of this section, it could be efficient to minimize the heat exhaust. A continued expansion in the turbine down to the ambient temperature, as it could be suggested in the lower *T*, *s* – diagram in Fig. 11 is not possible, because of the limit imposed by the ambient pressure. But this heat can be captured in a heat exchanger, being then introduced in the next Joule cycle, as first part of heat induction, before combustion. This strategy is illustrated in Fig. 12, in base of a *T*, *s* – diagram. The surface of the captured heat is the same as the surface of the induced heat (*q* vs WT).





		diesel	turbine (red)	turbine (blue)
q_{12}	[kJ/kg]	0	0	0
w_{12}		-496.256	-151.104	-496.256
q_{23}		1204.791	1687.935	1204.791
w_{23}		344.1026	482.0943	344.1026
q_{34}		0	0	0
w_{34}		935.3937	665.2413	1106.826
q_{41}		-590.086	-968.246	-350.116
w_{41}		0	268.7063	173.033
η_{th}		51.02%	42.64%	70.94%

Fig. 11 – Comparison of the ideal Diesel and Joule cycles
at same maximum temperature and the same maximum pressure / different maximum pressure.

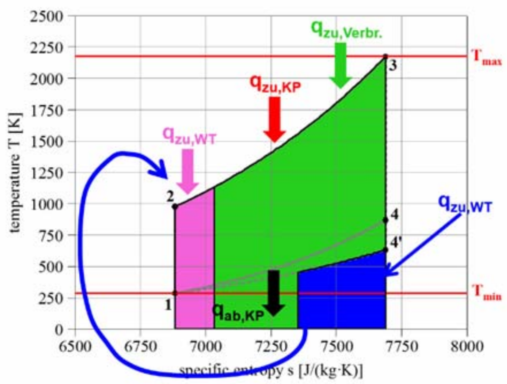
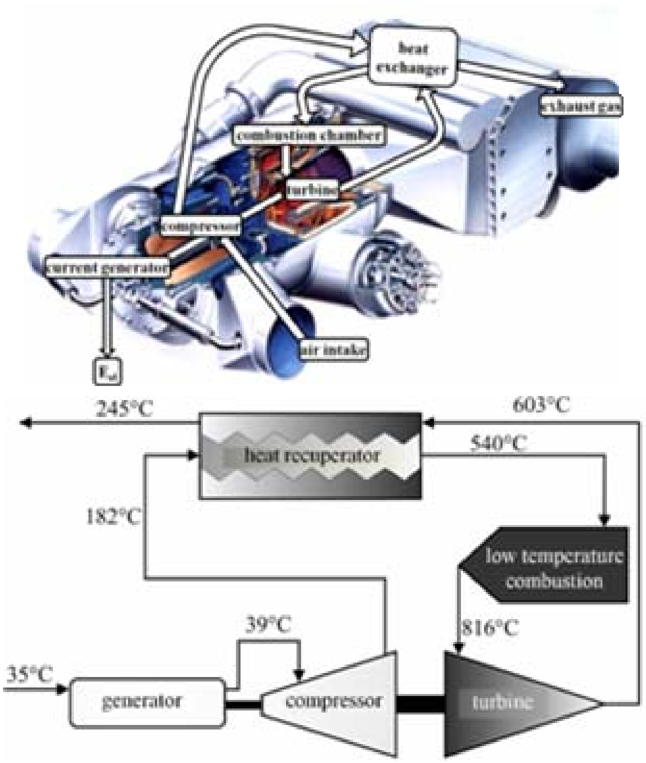


Fig. 12 – Joule cycle with recuperation of a part of heat at exhaust using a heat exchanger; this heat is induced in the next cycle before combustion.

Although the fact that a complete capture of this heat is not achievable because of the dimensions of the heat exchanger, this measure is very effective.

A solution of this type shows Fig. 13. In the compressor with a pressure ratio of 3:1; the temperature increase – in the example in Fig. 8 from 39°C to 182°C.

After compressor, in a heat exchanger, the gas becomes a first heat input – in this example from 182°C to 540°C. A second heat input is generated by a catalytic combustion in a burner – up to 816 °C. The thermal efficiency is not at the best level at such temperature, but a NO_x emission is not expectable, and the technical complexity is very moderate.



Power:	24 kW	fuels:	
Speed:	96000 min^{-1}	- nat. gas, propane, butane	
Compression ratio:	3:1	- gasoline, methanol, ethanol	
efficiency:	- compressor	79,6%	dimensions:
	- turbine	85,0%	- length: 91 cm
	- generator	96,0%	- diameter : 41 cm
	- recuperator	85,0%	- mass: 41 kg

Fig. 13 – Schematic and function principle of a NoMac gas turbine.

The burned gas expands in the turbine down to 603°C the flow being directed at this temperature to the heat exchanger, which gives, as explained, a first heat input to the gas after compressor. At the exit, the burned gas has in this example 245°C. This machine achieves a power of 24 kW at 96 000 min^{-1} and works with any kind of fuel, from natural gas or propane to gasoline or methanol. Their dimensions are very compact, the mass is only 41 kg recommending such a solution as an efficient current generator on board of automobiles [1].

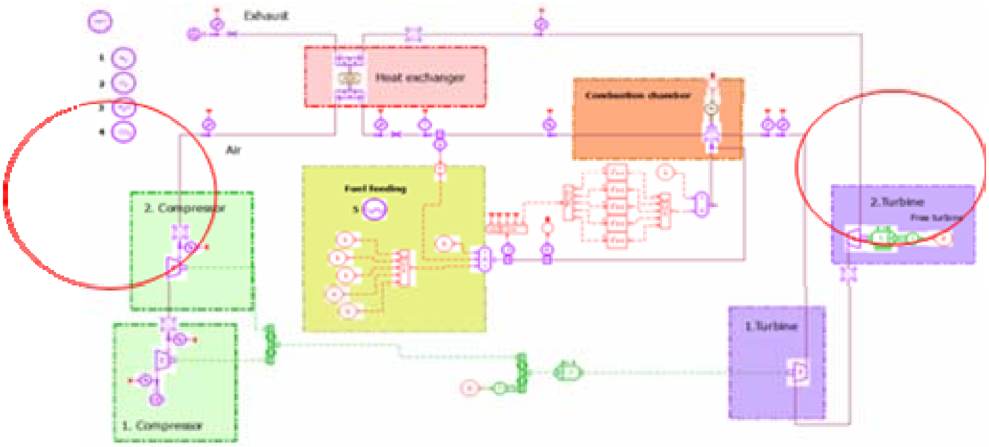


Fig. 14 – Configuration of the elements for the calculation of a gas turbine variant with heat recuperation using the Code AmeSim.

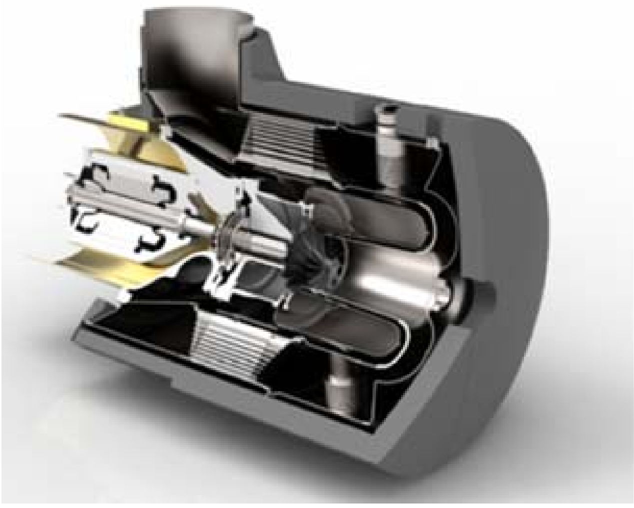


Fig. 15 – Advanced concept of compact gas turbine with heat recuperation, utilizable as current generator in automobiles with electric propulsion (source: Capstone).

The process in such turbomachine can be calculated and optimized using CFD codes. In the present study, different configurations, with one or two compressors and turbines, with different shapes of the combustion chamber, various types of heat exchanger and a multitude of utilizable fuels – from Diesel and gasoline to natural gas have been calculated using the Code AmeSim. This Code offers a very large library with a good assortment of mechanical, fluid mechanic, hydraulically elements and electrically controlled actuators. Figure 14 shows the configuration of the elements for the calculation of a gas turbine variant with heat recuperation.

Figure 15 presents an advanced concept of compact gas turbine with heat recuperation, utilizable as current generator in automobiles with electric propulsion. Figure 16 shows a cross-section through this machine.

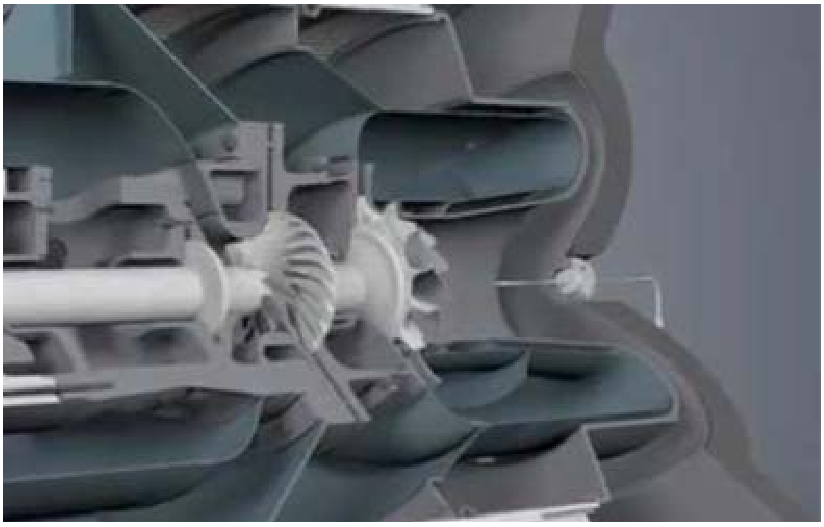


Fig. 16 – Cross-section through a gas turbine with radial compressor and radial turbine (source: Capstone).

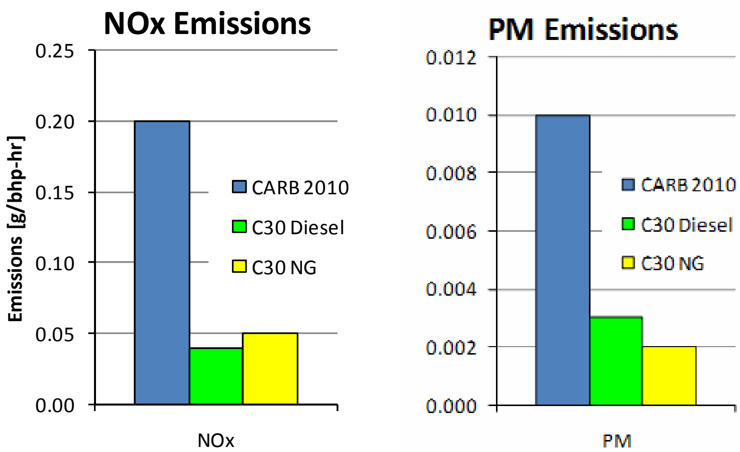


Fig. 17 – NO_x and the particulate emissions using Diesel fuel and natural gas in a compact gas turbine with heat recuperation.

The results of this technique in terms of emissions are very encouraging, as shown by the experimental results with the gas turbine in Fig. 16. The NO_x and the particulate emissions using Diesel fuel and natural gas remain under the limits provided by the US norm CARB 2010, as shown in Fig. 17 without use of any catalyst.

5. CONCLUSIONS

The worldwide dynamically expanding large urban areas are confronted with an intolerable level of noise and pollutant emissions, which will be drastically reduced by lows in the next future. Mobility by car in urban areas, in conjunction with public transportation, will be only allowed without local emission of pollutants. The automobile with electric propulsion is the only solution for this imperative, offering as well maximum torque from standstill and many degrees of movement freedom when equipped with hub motors in wheels. The generation of electric energy on board by combustion is more advantageous as the storage in batteries or conversion by fuel cells. A thermal machine as current generator can be operated out of urban center, charging the battery on board for the zero emission traffic zones. The thermal machine operating in a fixed point of load and speed can be conceived as simple as possible. In a turbomachinery (gas turbine), the thermodynamic process stages are better fittable than in piston engines. The thermal efficiency of a gas turbine depends on the achievable maximum pressure. The utilization of a part of exhaust heat as heat input in the next cycle, using a heat exchanger, is an additional way to improve the efficiency. Compact gas turbines for use as current generators on board of automobiles are feasible at reasonable complexity and price.

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