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A STUDY ON IMPROVEMENT IN COMPUTATIONAL EFFICIENCY FOR HCCI ENGINE USING TURBOCHARGERS AND SUPERCHARGERS

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ABSTRACT

This research deals the oxidation mechanism behind auto ignition combustion and HCCI is analyzed, while in the third section, a historical review on the early research on auto ignition is presented. HCCI combustion is presented in more detail, including aspects such as the effect of fuels, and fuel additives, engine design, etc, as well as the HCCI engines in production. Experimentally has to investigate on controlling HCCI is to be presented, with emphasis on fuel injection strategies, Exhaust Gas Recirculation (EGR) and temperature in homogeneities.

KEYWORDS: Homogenous Charge Compression Ignition (HCCI),Variable Compression Ratio (VCR), Exhaust Gas Recirculation (EGR), Super chargers and Turbo chargers.

INTRODUCTION

HCCI has characteristics of the two most popular forms of combustion used in SI (spark ignition) engines- homogeneous charge spark ignition (gasoline engines) and CI engines: stratified charge compression ignition (diesel engines). As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion.

The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve gasoline-like emissions along with diesel engine-like efficiency. In fact, HCCI engines have been shown to achieve extremely low levels of Nitrogen oxide emissions (NOx) without an after treatment catalytic converter. The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet automotive emission regulations.

Recent research has shown that the use of two fuels with different reactivates (such as gasoline and diesel) can help solve some of the difficulties of controlling HCCI ignition and burn rates. RCCI or Reactivity Controlled

Compression Ignition has been demonstrated to provide highly efficient, low emissions operation over wide load and speed ranges.

LITERATURE REVIEW

The autoignition combustion process has been studied and analyzed since the beginning of the 20th century. However, it has been studied in an attempt to understand fuel properties and how easily fuels can auto ignite and not as the process itself. Only more recently [1], the auto ignition combustion has been used to produce positive work in an engine.

As early as 1922 [2], experiments were conducted on the autoignition of n-heptane, ether and carbon bisulphide by sudden compression. An apparatus designed by Messrs. Ricard & Co. that would allow researchers to simulate the conditions obtained in an engine cylinder was used. A heavy flywheel was kept spinning by an electric motor at about 360 Revolutions Per Minute (RPM) and the Compression Ratio (CR) was varied by altering the cylinder position. The two-stage combustion of n-heptane was observed by recording the pressure traces. It was also observed that the ignition temperature (above which an explosion took place), depended both on the properties of the combustible substances (i.e. octane number), on the conditions of the experiments (i.e. CR, initial temperature and pressure) and on the rate of heat losses from the gas. Furthermore, an equation was derived for the time for complete combustion of the explosive mixtures of gases when suddenly compressed to a temperature above its ignition temperature.

A rapid-compression machine capable of producing CRs up to 15:1 was used in the 1950s [3], [4], [5] to investigate the effect of fuel composition, compression ratio and fuel-air ratio on the autoignition characteristics and especially the ignition delay (i.e. the time from when the mixture was suddenly compressed until autoignition) of several fuels that included heptanes, iso-octane, benzene, butane and triptane. An air-fuel mixing tank was used to ensure the correct ratio, the pressure records were taken with a catenary-type strain-gage indicator and a Fastax camera (operated at a rate of 10,000 frames per second) was used in taking flame and Schlieren photographs. It was concluded that all fuels had a minimum value of ignition delay at their chemically correct air-fuel ratio that increased with decreasing compression ratio.

HCCI ENGINE DESIGN

Variable Compression Ratio (VCR)

The effect of CRs ranging from 10:1 to 28:1 on various fuels was extensively studied [6],[7]. VCR can be achieved using a modified cylinder head that its position can be altered during operation using a hydraulic system. NOx and smoke emissions were not affected by CR and were generally very low. However, an increased CR resulted in higher HC emissions and a decrease in combustion efficiency [8]. Others [9] reported that decreasing inlet temperatures and lambdas, higher CRs were need to maintain correct maximum brake torque and concluded that variable CR can be used instead of inlet heating to achieve HCCI combustion. Furthermore, the effect of CR on HCCI combustion in a direct-injection diesel engine was also investigated [10]. The CR could be varied from 7:5:1 to 17:1 by moving the head and cylinder liner assembly relative to the centerline of the crankshaft. Acceptable HCCI combustion was achieved with ignition timing occurring before TDC – with misfire being exhibited if ignition timing was further delayed – with CRs from 8:1 to14:1. However, with a knocking intensity of 4 (where audible knock occurs at 5 on a scale from zero to ten), the acceptable HCCI operation was limited at CRs from 8:1 to 11:1.

Supercharging and Turbo charging

Supercharging (2bar boost pressure) was shown to increase the Indicated Mean Effective Pressure (IMEP) of an engine under HCCI combustion to 14bar [11]. Supercharging was used because of its capability to deliver increased density and pressure at all engine speeds while turbo charging depends on the speed of the engine. However, this resulted in lower efficiency due to the power used for supercharging. Supercharging resulted in greater emissions of CO and HC, greater cylinder pressure, longer combustion duration and lower NOx emissions. There were no combustion related problems in operating HCCI with supercharging and the maximum net indicated efficiency achieved was 59%. On the contrary, others [12] investigated the effect of turbo charging on HCCI combustion. A Brake Mean Effective Pressure (BMEP) of 16bar (compared to 6bar without turbo charging and 21bar with the unmodified diesel engine) and an efficiency of 41.2% (compared to 45.3% with the unmodified diesel engine) were achieved.

Furthermore, CO and HC emissions decreased with increasing load, but NOx emissions increased. However, at higher loads, as the rate of pressure increased and the peak pressure approached their set limit (i.e. peak pressure greater than 200bar); ignition timing was retarded at the expense of combustion efficiency. Thus, in order to improve the combustion efficiency at high boost levels, cooled EGR rates was introduced [13], and it was shown that under those conditions, the combustion efficiency increased only slightly.

Variable Induction Temperature

In HCCI engines, the autoignition event is highly sensitive to temperature. Various methods have been developed which use temperature to control combustion timing. The simplest method uses resistance heaters to vary the inlet temperature, but this approach is slow (cannot change on a cycle-to-cycle basis). Another technique is known as fast thermal management (FTM). It is accomplished by rapidly varying the cycle to cycle intake charge temperature by rapidly mixing hot and cold air streams. It is also expensive to implement and has limited bandwidth associated with actuator energy.

Variable Exhaust Gas Percentage

Exhaust gas can be very hot if retained or re-inducted from the previous combustion cycle or cool if recirculated through the intake as in conventional EGR systems. The exhaust has dual effects on HCCI combustion. It dilutes the fresh charge, delaying ignition and reducing the chemical energy and engine work. Hot combustion products conversely will increase the temperature of the gases in the cylinder and advance ignition. Control of combustion timing HCCI engines using EGR has been shown experimentally.

Variable Valve Actuation

Variable valve actuation (VVA) has been proven to extend the HCCI operating region by giving finer control over the temperature-pressure-time history within the combustion chamber. VVA can achieve this via two distinct methods:

- Controlling the effective compression ratio: A variable duration VVA system on intake can control the point at which the intake valve closes. If this is retarded past bottom dead center (BDC), then the compression ratio will change, altering the in-cylinder pressure-time history prior to combustion.

- Controlling the amount of hot exhaust gas retained in the combustion chamber: A VVA system can be used to control the amount of hot internal exhaust gas recirculation (EGR) within the combustion chamber. This can be achieved with several methods, including valve re-opening and changes in valve overlap. By balancing the percentage of cooled external EGR with the hot internal EGR generated by a VVA system, it may be possible to control the in-cylinder temperature.

While electro-hydraulic and camless VVA systems can be used to give a great deal of control over the valve event, the component for such systems is currently complicated and expensive. Mechanical variable lift and duration systems, however, although still being more complex than a standard valve train, are far cheaper and less complicated. If the desired VVA characteristic is known, then it is relatively simple to configure such systems to achieve the necessary control over the valve lift curve. Also see variable valve timing.

Variable Fuel Ignition Quality

Another means to extend the operating range is to control the onset of ignition and the heat release rate by manipulating the fuel itself. This is usually carried out by adopting multiple fuels and blending them "on the fly" for the same engine. Examples could be blending of commercial gasoline and diesel fuels, adopting natural gas or ethanol ". This can be achieved in a number of ways;

- Blending fuels upstream of the engine: Two fuels are mixed in the liquid phase, one with low resistance to ignition (such as diesel fuel) and a second with a greater resistance (gasoline), the timing of ignition is controlled by varying the compositional ratio of these fuels. Fuel is then delivered using either a port or direct injection event.
- Having two fuel circuits: Fuel A can be injected in the intake duct (port injection) and Fuel B using a direct injection (in-cylinder) event, the proportion of these fuels can be used to control ignition, heat release rate as well as exhaust gas emissions.

OPERATIONIONAL METHODS

A mixture of fuel and air will ignite when the concentration and temperature of reactants is sufficiently high. The concentration and/or temperature can be increased by several ways.

- High compression ratio
- Pre-heating of induction gases
- Forced induction
- Retained or re-inducted exhaust gases

Once ignited, combustion occurs very quickly. When auto-ignition occurs too early or with too much chemical energy, combustion is too fast and high in-cylinder pressures can destroy an engine. For this reason, HCCI is typically operated at lean overall fuel mixtures.

Advantages

- HCCI provides up to a 30-percent fuel savings, while meeting current emissions standards.
- Since HCCI engines are fuel-lean, they can operate at a Diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional spark-ignited gasoline engines.
- Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. Actually, because peak temperatures are significantly lower than in typical spark ignited engines, NOx levels are almost negligible. Additionally, the premixed lean mixture does not produce soot.
- HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels.
- In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency.

Disadvantages

- High in-cylinder peak pressures may cause damage to the engine.
- High heat release and pressure rise rates contribute to engine wear.
- The auto ignition event is difficult to control, unlike the ignition event in spark ignition (SI) and diesel engines which are controlled by spark plugs and in-cylinder fuel injectors, respectively.[5]
- HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions.
- Carbon monoxide (CO) and hydrocarbon (HC) pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation (due to the rapid combustion event and low in-cylinder temperatures) and trapped crevice gases, respectively.

CONTROL

Controlling HCCI is a major hurdle to more widespread commercialization. HCCI is more difficult to control than other popular modern combustion engines, such as Spark Ignition (SI) and Diesel. In a typical gasoline engine, a spark is used to ignite the pre-mixed fuel and air. In Diesel engines, combustion begins when the fuel is injected into compressed air. In both cases, the timing of combustion is explicitly controlled. In an HCCI engine, however, the homogeneous mixture of fuel and air is compressed and combustion begins whenever the appropriate conditions are reached. This means that there is no well-defined combustion initiator that can be directly controlled. Engines can be designed so that the ignition conditions occur at a desirable timing. To achieve dynamic operation in an HCCI engine, the control system must change the conditions that induce combustion. Thus, the engine must control the compression ratio, inducted gas temperature, inducted gas pressure, fuel-air ratio, or quantity of retained or re-inducted exhaust. Several control approaches are discussed below.

High peak Pressures and Heat release Rates

In a typical gasoline or diesel engine, combustion occurs via a flame. Hence at any point in time, only a fraction of the total fuel is burning. This results in low peak pressures and low energy release rates. In HCCI, however, the entire fuel/air mixture ignites and burns nearly simultaneously resulting in high peak pressures and high energy release rates. To withstand the higher pressures, the engine has to be structurally stronger and therefore heavier. Several strategies have been proposed to lower the rate of combustion. Two different fuels, with different auto ignition properties, can be used to lower the combustion speed. However, this requires significant infrastructure to implement. Another approach uses dilution (i.e. with exhaust gases) to reduce the pressure and combustion rates at the cost of work production.

Power

In both a spark ignition engine and diesel engine, power can be increased by introducing more fuel into the combustion chamber. These engines can withstand a boost in power because the heat release rate in these engines is slow. However, in HCCI engines the entire mixture burns nearly simultaneously. Increasing the fuel/air ratio will result in even higher peak pressures and heat release rates. In addition, many of the viable control strategies for HCCI require thermal preheating of the charge which reduces the density and hence the mass of the air/fuel charge in the combustion chamber, reducing power. These factors make increasing the power in HCCI engines challenging.

One way to increase power is to use fuels with different autoignition properties. This will lower the heat release rate and peak pressures and will make it possible to increase the equivalence ratio. Another way is to thermally stratify the charge so that different points in the compressed charge will have different temperatures and will burn at different times lowering the heat release rate making it possible to increase power. A third way is to run the engine in HCCI mode only at part load conditions and run it as a diesel or spark ignition engine at full or near full load conditions. Since much more research is required to successfully implement thermal stratification in the compressed charge, the last approach is being studied more intensively.

Emissions

Because HCCI operates on lean mixtures, the peak temperatures are lower in comparison to spark ignition (SI) and Diesel engines. The low peak temperatures prevent the formation of NOx. This leads to NOx emissions at levels far less than those found in traditional engines. However, the low peak temperatures also lead to incomplete burning of fuel, especially near the walls of the combustion chamber. This leads to high carbon monoxide and hydrocarbon emissions. An oxidizing catalyst would be effective at removing the regulated species because the exhaust is still oxygen rich.

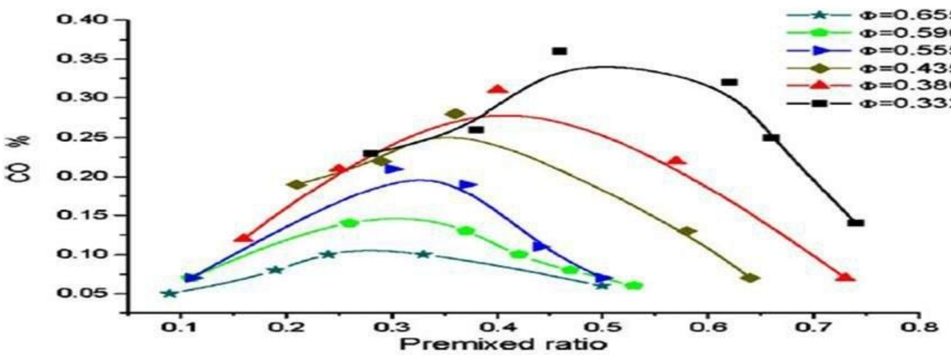

Fig: 1- Effects of Premixed combustion ratio on CO emissions on HCCI- DI

Difference from Knock

Engine knock or pinging occurs when some of the unburnt gases ahead of the flame in a spark ignited engine spontaneously ignite. The unburnt gas ahead of the flame is compressed as the flame propagates and the pressure in the combustion chamber rises. The high pressure and corresponding high temperature of unburnt reactants can cause them to spontaneously ignite. This causes a shock wave to traverse from the end gas region and an expansion wave to traverse into the end gas region. The two waves reflect off the boundaries of the combustion chamber and interact to produce high amplitude standing waves.

A similar ignition process occurs in HCCI. However, rather than part of the reactant mixture being ignited by compression ahead of a flame front, ignition in HCCI engines occurs due to piston compression. In HCCI, the entire reactant mixture ignites (nearly) simultaneously. Since there are very little or no pressure differences between the different regions of the gas, there is no shock wave propagation and hence no knocking. However, at high loads (i.e. high fuel/air ratios), knocking is a possibility even in HCCI.

Simulation of HCCI Engines

The development of computational models for simulating combustion and heat release rates of HCCI engines has required the advancement of detailed chemistry models. This is largely because ignition is most sensitive to chemical kinetics rather than turbulence/spray or spark processes as are typical in direct injection compression ignition or spark ignition engines. Computational models have demonstrated the importance of accounting for the fact that the in-cylinder mixture is actually in-homogeneous, particularly in terms of temperature. This in-homogeneity is driven by turbulent mixing and heat transfer from the combustion chamber walls, the amount of temperature stratification dictates the rate of heat release and thus tendency to knock. This limits the applicability of considering the in-cylinder mixture as a single zone resulting in the uptake of 3D computational fluid dynamics codes such as Los Alamos National Laboratory's KIVA CFD code and faster solving probability density function modeling codes.

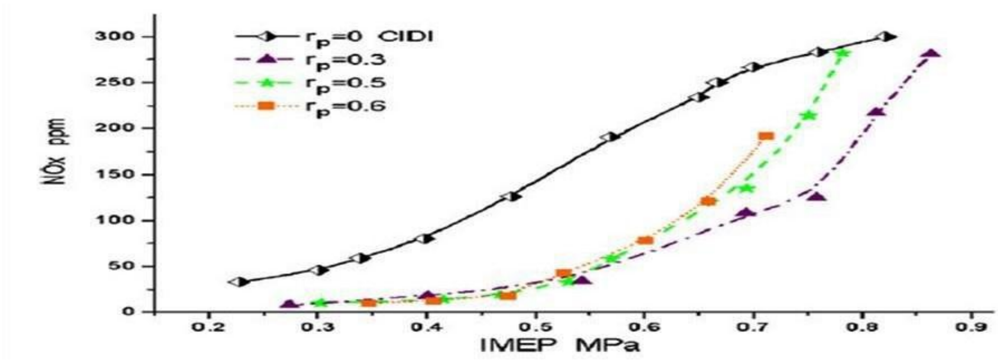

Fig: 1-NO_x emissions of HCCI-DI mode Vs CIDI mode for all loads

OTHER APPLICATIONS OF HCCI RESEARCH

To date, there have been few prototype engines running in HCCI mode; however, the research efforts invested into HCCI research have resulted in direct advancements in fuel and engine development. Examples include:

- PCCI/PPCI combustion - A hybrid of HCCI and conventional diesel combustion offering more control over ignition and heat release rates with lower soot and NOx emissions.
- Advancements in fuel modeling - HCCI combustion is driven mainly by chemical kinetics rather than turbulent mixing or injection, reducing the complexity of simulating the chemistry which results in fuel oxidation and emissions formation. This has led to increasing interest and development of chemical kinetics which describe hydrocarbon oxidation.
- Fuel blending applications - Due to the advancements in fuel modeling, it is now possible to carry out detailed simulations of hydrocarbon fuel oxidation, enabling simulations of practical fuels such as gasoline/diesel and ethanol. Engineers can now blend fuels virtually and determine how they will perform in an engine context.

OPERATIONAL LIMITS AND EMISSIONS

With stable HCCI combustion over a range of CRs, fuels, inlet temperatures and EGR rates, operation maps of HCCI operation have been produced by various researchers for a wide number of production engines. The effect of these parameters on BMEP, IMEP, combustion efficiency, fuel economy and NOx, HC and CO emissions has been analyzed in detail. There is a vast, and some time contradicting, background literature especially on emissions and in the present subsection, no assumptions have been made on the author’s behalf; the data is presented in this subsection as analyzed by the various researchers. This subsection is not aimed to act a complete review on all the experiments conducted on all engines, but to present to the reader the complexity in analyzing HCCI engine operation. The modified Scania DSC12 engine was used [47] to run a multi cylinder engine in HCCI mode and to provide quantitative figures of BMEP, emissions and cylinder-to-cylinder variations. The engine was run at 1000, 1500 and 2000RPM and various mixtures of n-heptane and isooctane were used to phase the combustion close to maximum BMEP. A BMEP of up to 5bar was achieved by supplying all cylinders with the same fuel, but for higher loads, the fuel injected in each cylinder had to be individually adjusted as small variations led to knocking in individual cylinders. A naturally-aspired Volkswagen TDI engine with propane as fuel, was used [71] to investigated the effect of different fuel flow rates and intake gas temperature on BMEP, IMEP, efficiency and CO, HC and NOx emissions. It was concluded that:

- Combustion efficiency increased with increasing fuel flow rate or increasing intake gas temperature.
- NOx emissions increased with increasing fuel flow rate and increasing intake gas temperature.
- CO and HC emissions decreased with increasing fuel flow rate and increasing intake gas temperature.

Furthermore, at the lowest intake gas temperature operating point, the combustion process varied considerably from cylinder to cylinder, but became more consistent with time as the engine temperature increased. Allen and Law [72] produced operation maps of the modified Lotus engine under HCCI combustion when running at stoichiometric A/F ratio. The operational speed range was found to lie between 1000-4000RPM with loads of 0.5bar BMEP at higher speeds and 4.5bar at lower speeds. The limitation at high speeds was due to knocking while at low speeds it was thought to be due to insufficient thermal levels in the cylinder due to the very small amount of fuel being burned. It was concluded that compared with SI combustion:

- Fuel consumption was reduced by up to 32%.
- NOx emissions were reduced by up to 97%.
- HC emissions were reduced by up to 45%.
- CO emissions were reduced by up to 52%.

The HCCI operating range with regards to A/F ratio and EGR and their effect on knock limit, engine load, ignition timing, combustion rate and variability, Indicated Specific Fuel Consumption (ISFC) and emissions for the Ricardo E6 engine were also produced [7],[25]. Comprehensive operating maps for all conditions were produced and the results were compared with those obtained during normal spark-ignition operation. From their experiments they were able to conclude the following:

- A/F ratios in excess of 80:1 and EGR rates as high as 60% were achieved.
- ISFC decreased with increasing load.
- IMEP increased with decreasing lambda.
- NOx emissions were extremely low under all conditions.
- HC emissions increased near the misfire region at high EGR rates.
- CO emissions increased with increasing lambda and EGR rate.
- ISFC increased with increasing lambda due to oxygen dilution and decreasing combustion temperatures.

CONCLUSION

The oxidation mechanism behind auto ignition combustion and HCCI is analyzed, while in the third section, historical reviews on the early research on autoignition are presented. HCCI combustion is presented in more detail, including aspects such as the effect of fuels, and fuel additives, engine design, etc, as well as the HCCI engines in production are discussed elaborately. Experimentally has to investigate on controlling HCCI has to be presented, with emphasis on fuel injection strategies, Exhaust Gas Recirculation (EGR) and temperature in homogeneities.

Foot Notes:

Homogenous Charge Compression Ignition (HCCI)

Homogeneous charge compression ignition (HCCI) is a form of internal combustion in which well-mixed fuel and oxidizer (typically air) are compressed to the point of auto-ignition. As in other forms of combustion, this exothermic reaction releases chemical energy into a sensible form that can be transformed in an engine into work and heat.

Variable Compression Ratio (VCR)

Variable compression ratio is technology to adjust the compression ratio of an internal combustion engine while the engine is in operation. This is done to increase fuel efficiency while under varying loads. Higher loads require lower ratios to be more efficient and vice versa. Variable compression engines allow for the volume above the piston at 'Top dead centre' to be changed. For automotive use this needs to be done dynamically in response to the load and driving demands.

Exhaust Gas Recirculation (EGR)

The Exhaust Gas Recirculation (EGR) system is designed to reduce the amount of Oxides of Nitrogen (NO_x) created by the engine during operating periods that usually result in high combustion temperatures. NO_x is formed in high concentrations whenever combustion temperatures exceed about 2500° F. The EGR system reduces NO_x production by re-circulating small amounts of exhaust gases into the intake manifold where it mixes with the incoming air/fuel charge. By diluting the air/fuel mixture under these conditions, peak combustion temperatures and pressures are reduced, resulting in an overall reduction of NO_x output.

Turbocharger

A turbocharger or turbo (colloquialism), from the Greek "τύρβη" ("turbulence") is a turbine- driven forced induction device that makes an engine more efficient and produce more power for its size by forcing extra air into the combustion chamber. A turbocharged engine is more powerful and efficient than a naturally aspirated engine, because the turbine forces more air, and proportionately more fuel, into the combustion chamber than atmospheric pressure alone.

Supercharger

A supercharger is an air compressor that increases the pressure or density of air supplied to an internal combustion engine. This gives each intake cycle of the engine more oxygen, letting it burn more fuel and do more work, thus increasing power. Power for the supercharger can be provided mechanically by means of a belt, gear, shaft, or chain connected to the engine's crankshaft. When power is provided by a turbine powered by exhaust gas, a supercharger is known as a turbo supercharger typically referred to simply as a turbocharger or just turbo. Common usage restricts the term supercharger to mechanically driven units.

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