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A Review of Swirl Air Intake Effect on the Performance of a Compression Ignition Engine

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ABSTRACT

Compression Ignition (CI) engines are highly efficient power sources compared to Spark Ignition (SI) engines and currently play a significant role in the transportation and industrial sectors. However, the engine has constraints with low engine performance, high fuel consumption and emissions levels which require continuous improvement. There are various designs of air intake systems to meet a specific engine operating range, still, there will be less actual amount of fresh charge entering the cylinder compared to the theoretical value due to the short cycle time available. The application of the existing air intake system becomes the main focus since the air resistance presented in the system is causing more pressure drop, reducing volumetric efficiency. This requires a comprehensive review of the patented or commercial air intake devices in proposing an improved air intake manifold design. Swirl in the intake air is an additional characteristic knowingly able to increase the fuel and air mixing rate for better combustion, thus reducing the exhaust gas emissions. However, the air resistance may also reduce the efficiency of the air swirl formed within the intake manifold, thus restricting the potential for combustion improvement. Numerous studies have been conducted to evaluate the effect of swirl air intake in the compression ignition engine due to the continuous issue of emission quality. Differences in intake designs, flow characteristics, numerical study, and other issues associated with engine performance are also thoroughly discussed in this review paper.

Keywords: Compression ignition; intake manifold; swirl air; engine performance; emission

INTRODUCTION

The performance of a Compression Ignition (CI) engine is very much related to the combustion characteristics. In a conventional four-stroke CI engine, the fuel and air are mixed homogeneously in the combustion chamber which is then compressed after the intake stroke. In normal conditions, the combustion is initiated near the end of the compression stroke at the phase in which the heat release rate is maximum and the pressure rise is rapid. This phase is known as the period of rapid combustion or uncontrolled combustion.

The combustion continues to the next stage of controlled combustion where it is assumed to be ended at the maximum in-cylinder pressure and temperature. The combustion does not finish with the injection process completion. The partially burnt and unburnt fuel particles remaining in the combustion chamber will start to burn shortly when they interact with the oxygen and continue for a certain duration. This duration is known as the after-burning period. The rate of after-burning is subjected to the partially burnt and unburnt fuel turbulent mixing with air and velocity diffusion. The after-burning period is relatively critical to the emissions level as they may not be efficient enough to let all the unburnt or partially burnt fuel particles settle before the new engine cycle begins. The presence of unburnt fuel particles after the end of the combustion cycle will appear as the UHC emission (Unburnt Hydrocarbon) along with the other elements such as CO and NO_x (Macor et al. 2011; Solangi et al. 2024).

The main concern of the emissions levels as well as the performance of the CI engine is none other than the effect of the quality of fuel-air mixing and the presence of turbulence flow in the combustion chamber after the intake stroke. Intake air without sufficient turbulence flow will not help to achieve a homogeneous fuel-air mixture in a shorter time and combustion without proper fuel-air mixing causes a lot of inefficiencies in the engine operation.

In improving engine efficiencies and reducing emissions, various strategies have been explored with the key focus being to observe the effect of a different setting or combination of fuel injections, ignition control and fluid flow mixing. While the fuel injection and ignition control may improve the fuel-air mixture through the combustion reactivity in the cylinder, the fluid flow mixing strategy, however, focuses on improving both external and in-cylinder flow characteristics to increase the mixing capability to promote fuel-air mixture homogeneity.

STRATEGIES FOR HOMOGENEOUS MIXTURE IN CI ENGINES

The effect of fuel-air mixing on the efficiencies of the CI engine has been widely discussed and investigated. The objective of the investigation is mainly to achieve a better homogeneous mixture of the fuel and air before the combustion starts. Table 1 shows some of the recent studies of the fuel-air mixing effect using various strategies on the CI engine characteristics.

FUEL INJECTIONS STRATEGY

Achieving a better air-fuel mixture is possible by extending the ignition delay time. When the ignition delay is longer, the fuel mixes more homogeneously with the air, resulting in more fuel being burned together after ignition. Ignition characteristics are largely affected by the fuel injection timing, where the timing of the injection as well as the fuel properties greatly affect the ignition delay and combustion duration (Erman et al. 2020). Ignition delay can be extended by applying different fuel injection strategies as performed by Qian et al. (2023) and Wang et al. (2022).

TABLE 1. Investigation of fuel-air mixing effect using various strategies on the CI engine efficiencies

No	Reference	Mode of Combustion	The strategy to form a better air-fuel mixture	Effect on engine characteristics/ efficiencies
1	Kesharvani et al. (2023)	Compression-Ignition	Fuel pre-mixed with nanoparticles	Approx. 2% increase in BTE
2	Qian et al. (2023)	Gasoline Compression-Ignition	Fuel dual-direct injection	Min. 7.7% increase in ITE
3	Vasanthakumar et al. (2023)	Compression-Ignition	Hydrogen-enriched intake air and ethanol blend	Min. 3.8% increase in BTE
4	Honecker et al. (2023)	Compression-Ignition	Molecularly-Controlled high swirl Combustion	Approx. 2.5% increase in ITE
5	Kang et al. (2022)	Compression-Ignition	Double swirl combustion system	Max. 4.8% increase in air-fuel uniformity index
6	Wang et al. (2022)	Gasoline Compression-Ignition	Fuel pre-injection	Min. 14.4% increase in BTE
7	Şener & Gül (2021)	Compression-Ignition	Double swirl combustion system	Approx. 3.2% increase in BP
8	Hamid et al. (2020)	Compression-Ignition	Guide vane intake manifold	Max. 5% increase in In-Cylinder airflow efficiency

Qian et al. (2023) state that the medium-pressure single-direction injection mode is appropriate for IMEP of 4 to 10 bar. However, at higher loads, the indicated thermal efficiency is decreased. Single DI mode combustion is limited by the rate of fuel mixing at a medium injection pressure. Thus, to improve the efficiency at high loads, a medium-pressure dual direct injection is much preferable for IMEP of 10 to 12 bar. The dual injection strategy is causing an improvement in the fuel-air mixing rate by having a slightly shorter ignition delay than that of a single

DI mode. This strategy increases the heat release rate and further improves the engine efficiency.

The fuel injection strategy further promotes complete combustion by implementing different injection pulses to regulate the fuel reactivity in the combustion chamber. A different fuel ratio with different reactivity is premixed with air before charging into the combustion chamber. This improves the ignition delay with respect to the fuel ratio in achieving a better air-fuel mixture in the cylinder and emissions due to more homogeneous combustion (Yusof et al. 2019)

IGNITION CONTROL STRATEGIES

The study by Kesharvani et al. (2023) evaluated the cerium oxide nanoparticles doped water diesel emulsion fuel effect on multi-cylinder compression ignition engines. The investigation found that the nano-particles help to improve engine performance with approximately a 2% increase in brake thermal efficiency while lowering harmful engine pollutants. This strategy results in the rapid mixing of fuel with air by the increase of the evaporation speed due to the nanoparticle sheath.

A similar strategy of using premixed fuel in improving the fuel-air mixing is also investigated by Vasanthakumar et al. (2023). They work on a dual fuel mode by ethanol-diesel blends with hydrogen-enriched intake air operating on a diesel engine with the aim is replacing conventional diesel fuel with low and no-carbon fuels. The use of the premixed fuel enriched with hydrogen results in an increase of a minimum of 3.8 % in brake thermal efficiency.

The improvement of engine efficiency is found to be due to the high diffusivity and volatility characteristic of hydrogen that ensures better homogeneous combustible mixture formation. This leads to faster propagation of flame and better combustion. The excess oxygen in ethanol also improves the formation of an air-fuel mixture. Based on Vasanthakumar et al. (2023), the lower heating value (LHV) of ethanol induces the effect of cooling on the intake charge compared to diesel. This increases the density of the intake charge, leading to better formation of the fuel-air mixture.

FLUID FLOW MIXING STRATEGY

Better fuel and air mixing can also be achieved by applying different fluid flow mixing approaches. This approach can be done at various locations from the intake system to the in-cylinder area through a certain mechanism. For the external approach, the air intake will be guided to the inlet port through a certain intake manifold design or with a separate device to automatically form the air swirl. The air swirl generated by the device will be drawn into the cylinder and expected to increase the fuel-air mixing rate for a homogeneous mixture.

For the in-cylinder approach, this method will involve the motion of the gas charge within the cylinder. It is necessary to use a swirling airflow that rotates about the cylinder axis to achieve adequate fuel-air mixing. The swirl airflow is created by force with the appropriate helical inlet port and valve design. The in-cylinder flow pattern initially set up by this intake process may be significantly modified during compression by the piston bowl. The use of bowl-in-piston influences the movement of air and fuel during the compression stroke, and increases the swirl rate, thereby affecting the fuel-air mixture (Caeses, 2017; Heywood, 2018).

Among the studies that focus on fuel-air mixing through the fluid flow mixing strategies are done by Honecker et al. (2023), Kang et al. (2022), Şener & Gül (2021) and Hamid et al. (2020). Kang et al. (2022) investigated the effect of optimizing the double swirl combustion system (DSCS) diameter on the fuel-air mixing process in a diesel engine. The improvement to the fluid swirl motion characteristics has contributed to the rapid fuel-air mixing in the outer chamber and the clearance. Low soot generation and high indicated power are also observed based on the study. They found that the whole-chamber uniformity index by optimizing the DSCS has increased up to 4.8 %. The increase is due to the improved air entrainment and the reverse squish together with the effects of wall-flow-guiding and in-cylinder motion. The effect of DSCS on the CI engine was also studied by Şener & Gül (2021). They observed that by the improved utilization of in-cylinder air and fast mixing-controlled combustion in the optimum DSCS design, there are improvements in combustion efficiency and engine performance with a decrease in exhaust emissions.

In the study conducted by Hamid et al. (2020) study, they incorporated the guide vane design (GVD) with a shallow depth re-entrance combustion piston (SCC) to improve the engine performance. Before the air is induced into the cylinder, a separate device of GVD is installed in the intake runner of the engine to direct the airflow. The GVD vanes guide the airflow and consequently generate more turbulence and create the necessary momentum to sustain the swirl until the end of the expansion stroke (Hamid et al. 2020). Due to the capability of the turbulent airflow to break down the heavier molecules viscosity, there will be a tendency of the airflow to accelerate and improve the fuel-air mixing process (Hamid et al. 2020; B. V. V. S. U. Prasad et al. 2011).

One of the variables that determine the in-cylinder turbulence flow improvement is the turbulence kinetic energy (TKE). Higher turbulence airflow can be indicated by the higher TKE. Higher TKE will increase the speed and the ability to assist the molecule's atomization during spraying and, thus, have a greater ability to break down the fuel molecules (Hamid et al. 2020). The use of GVD and SCC pistons has shown a higher in-cylinder TKE compared to that of the engine without the GVD. The increase of TKE, among others, contributes to the result of a 5% increase in the in-cylinder airflow efficiencies.

PERFORMANCE COMPARISON

STATE OF THE ART OF CURRENT AIR INTAKE SYSTEMS IN IC ENGINES

The fluid flow mixing strategy has attracted the attention of researchers due to its proven effectiveness in improving combustion processes and fuel-air mixing. This strategy has a lot of potential to reduce emissions and improve engine performance by implementing various designs on important components such as an air intake manifold for guiding and controlling the external airflow. For establishing the in-cylinder turbulence flow, an intake port shape, an intake valve, and a piston crown may have a different design to assist in creating the swirl and tumble motions. In comparing the performance and emissions of current engines, this paper, however, will focus on the design of an air intake system in an internal combustion (IC) engine.

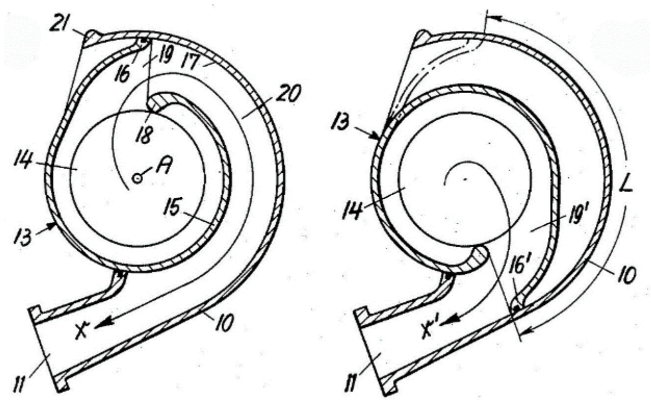
Producing homogeneous mixtures to achieve near-complete combustion is the target of every engine manufacturer. In the current air intake systems, major improvements have been made to the arrangement and location of the intake pipe. The majority of the current vehicles have arranged their air duct far from the engine side. This is to minimize the effect of the hot air that surrounds the engine while it runs. The cold intake air provides denser air, which means more oxygen to be supplied to the engine cylinder. More oxygen will result in better combustion efficiency. This air duct arrangement can be seen in most of any vehicle nowadays, among others to be named, Mercedes Benz C200 (petrol or diesel), Proton Preve (petrol only), Volkswagen Golf (petrol or diesel), Honda City (petrol or diesel) and Toyota Camry (petrol only).

There are other methods commercially available to increase the performance and fuel efficiency. Methods such as cold air intake and ram air intake are among the popular performance choices. However, the cold air intake and short ram air intake methods are mainly considered the aftermarket replacement primarily for performance upgrades due to the elimination of the standard airbox component. In consideration of the overall NVH (Noise, Vibration and Harshness) level, comfort, reliability, cleanliness and maintenance cost of the engine, the existing air intake manifold is often installed with a standard airbox that restricts the laminar airflow to the engine, thereby limiting the actual capability of the engine. The standard airbox still can be seen in modern vehicles mentioned previously.

To ensure optimum combustion efficiency in a standard engine, proper fuel-air mixing is therefore assisted by the use of the MAF sensor in a petrol engine to calculate the correct amount of fuel that matches the amount of incoming air. In the case of a diesel engine, the exhaust pipe is equipped with an oxygen sensor to evaluate the amount of oxygen from the exhaust gas. The ECU will calculate a proper air-fuel ratio based on the oxygen content. This will help to achieve better homogeneous mixtures for a near-complete combustion.

In the other part of the air intake system, there are several air intake manifold designs used to optimize the flow of the intake air at both higher and lower engine speeds. The IC engine manifold technology referred to as the Variable Intake Manifold (VIM), Variable-Length Intake Manifold (VLIM) or Variable Intake System (VIS) is vital to the IC engine operation to enhance power and torque across the engine speed operation range, as well as offering better fuel efficiency.

The VLIM, VIM or VIS is operated by varying the intake tract length for optimized intake flow. An earlier patent issued for a VLIM was published by Daimler Benz AG in 1958 with the US Patent US2835235 as shown in Figure 1 (Gassmann, 1958). The VLIM used to be controlled by a valve, that would open two different runners at various loads or engine speeds. At full engine load, the VLIM will work with a short runner to gain more power as shown in Figure 2. Meanwhile, at a lower load, it will change to a longer runner to achieve slower airflow to promote better mixing with fuel. The main effects of this variable-length mechanism will create beneficial air turbulence in the combustion chamber and a light pressuring effect which has further increased the engine output.



(a) (b)

FIGURE 1. Patented VLIM designed by Daimler Benz AG, (a) Cross-section of an intake pipe adjusted to the greatest length, (b) Cross-section of an intake pipe adjusted to the shortest length (Gassmann, 1958)

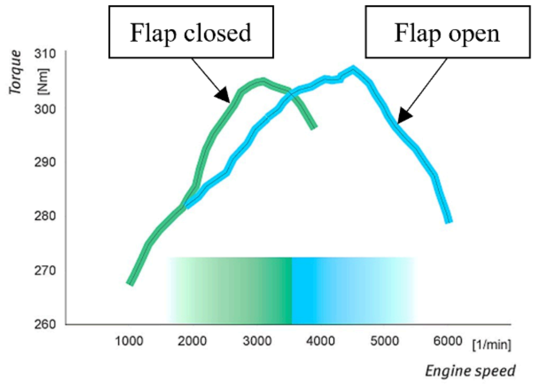


FIGURE 2. Performance Curve (Torque) of the Mercedes-Benz V6 3.2 litre Engine under Two Different Modes of Flap Position (MS Rheinmetall Automotive, 2017).

Three (3) stages of VLIM are also introduced to broaden the torque curve compared to a typical two (2) stages of variable length (Wan, 2011). The effect of using the three stages of VLIM can be seen in Figure 3, where there are three different torque curves at different engine load conditions. This design was used in the Audi 4.1 litre V8 engines (Wan, 2011). However, as the 3-stage system is more complex than the 2-stage system, the 2-stage system is more common for most of the VLIM designs.

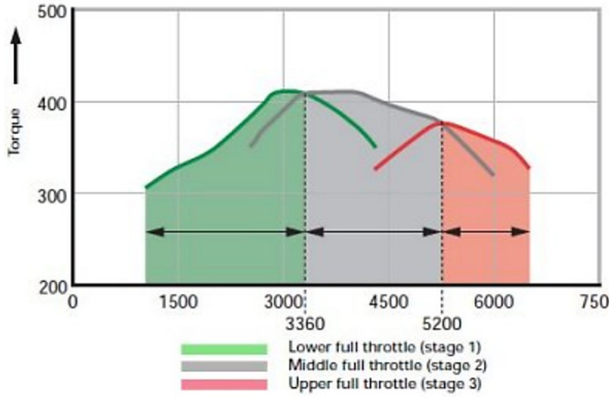


FIGURE 3. Performance Curve (torque) of Three (3) stages of VLIM (Wan, 2011)

VLIM technology has been used by many automobile manufacturers with different names. As example, but not limited to, the Mitsubishi Variable Induction Management (MVIM), Honda 2-Stage Variable Intake Manifold (VIM), Toyota Variable Induction System (T-VIS), Audi 3-Stage Variable Length Intake Manifold (VLIM), BMW Differential Variable Intake System (DIVA), Volvo Variable Induction System (V-VIS), Mazda Variable Resonance Induction System, Mercedes Benz M112 Variable Geometry Intake Manifold, Proton CPS Variable Intake Manifold (CPS-VIM) and Proton IAFM Variable Length Intake Manifold (IAFM-VLIM) (Edilan et al. 2014; Larsson et al. 1991; Lorio, 2019; Matsumoto & Ohata, 1986; Mitsubishi Motors, 2003; Motor Reviewer, 2022; Potul et al. 2014; Sachek, 2023; Soon, 2014). Each intake manifold may have a different working mechanism but the main principle behind these VLIMs is similar.

PATENT AND COMMERCIAL SWIRL AIR INTAKE DEVICE

The intake manifold is by far a highly suitable component to be continuously developed and improved since the inducted air may directly affect the volumetric efficiency and the overall engine performance. Table 2 shows a list of the patented, published or commercialized swirl air-generating devices as continuous development efforts. A higher power will be produced by a greater mass of inducted charge. Volumetric efficiency is a measure of the induction process effectiveness for an engine. Higher volumetric efficiency means the induction process is highly effective and this may increase the engine power. However, to have a near-complete combustion, the fuel-air mixture must be homogeneous and this requires a better fuel flow mixing strategy.

TABLE 2. Patented or Commercialized Swirl Air Generating Device

No	Reference	Patent No./DOI	Invention/Product Name
1	Selirio et al. (2022)	US11224846	Static mixer for fluid flow in a pipeline
2	S. Y. Kim (2021)	WO2021150025A1	Intake and exhaust swirling device for IC engine
3	Y. H. Kim (2021)	KR20210103189A	Device for decreasing flowing resistance of intake air of the engine
4	T. W. Kim & Yoon (2021)	KR102250955B1	Velocity increase device of intake and exhaust pipe for automobile
5	Arjunraj et al. (2021)	10.1007/s10973-021-10817-z	Novel intake manifold
6	J. Y. Kim (2018)	KR101921023B1	Swirl generator in air intake pipe and exhaust pipe for car
7	W. Zhang et al. (2018)	CN108757153 (A)	Variable swirl guiding supercharger
8	Liu et al. (2018)	CN207111268(U)	Swirler structure at air cleaner inlet end
9	Kimura & Shibata (2017)	JP6252774B2	Intake device
10	Anderson (2016)	US9228542B2	Swirl vane air duct cuff assembly and method of manufacture
11	Chen et al. (2016)	CN205605339UA	Variable vortex air intake manifold structure of engine
12	Saad & Bari (2015)	10.11113/jt.v75.5217	Guide Vane Design (GVD)
13	Il & Seob (2013)	KR20130075874	A swirl apparatus for combustion engine
14	Yao (2013)	US2013255616A1	Air-Guiding Device for Vehicles
15	Chang (2011)	US2011011370A1	Air Pressure Vortex Generator Structure for an IC Engine
16	Andreas & Josef (2011)	JP2011501024A	IC engine having intake system
17	Chang (2010)	GB2461995A	Air Inlet Device with Swirl Plates
18	Deok (2004)	KR20040069119A	Duct structure of super charger for automobiles
19	Woo (2004)	KR20040096709A	Intake pipe for diesel engine
20	Wijaya (2003)	US2003221662A1	Air flow-twisting device on an air inlet system of IC engine

One of the methods, as discussed in the previous section, is the external formation of swirl airflow generated by a certain mechanism in the intake manifold, for example, the swirl-generating device installed within the intake system. This device has been thoroughly studied by the researchers with some of them may successfully find the market as an aftermarket part. Some of the swirl air-generating devices that are substantial to the field are presented in the Table 2. The use of swirl air generating devices in IC engines is mainly applied to provide swirl air for better fuel-air mixing during the premixed phase.

Some of the swirl air intake devices are available as aftermarket replacement parts. The purpose is similar to the cold air intake which prioritizes the performance upgrade and tuning from a factory standard system. Among the examples of commercial swirl air intake devices that can be easily found in the open market are the ‘Flex-Force Performance Intake Kit’ (SpitFire Tuning, 2023) and the ‘Air Suction-Turbo’ (Surbo.net, 2022). These products are designed to work with the air intake system of an automobile. Based on the statement, these companies have claimed that their kit or device is capable of increasing the engine performance, improving throttle response, inducing more air, creating an air vortex and saving fuel (SpitFire Tuning, 2023; Surbo.net, 2022). Despite the claim, the product’s effectiveness cannot be independently verified or proven by the author.

The Flex-Force intake kit, as an example, has similarities to the design patented by Zhang et al. (2018) in terms of the tubular air-guiding pipe and the air-guiding structure. Zhang et al. (2018) patented a tubular air-guiding pipe, an airflow baffle plate and a swirl air-guiding structure to form a variable swirl as shown in Figure 4. The use of the internal guiding vanes with the baffle plate will allow the air-flow amount to be varied at different engine speeds.

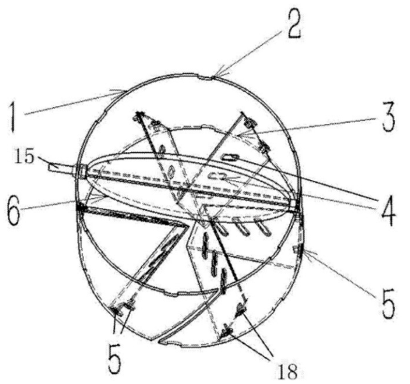


FIGURE 4. Patented design of a swirl guiding structure (W. Zhang et al. 2018)

S. Y. Kim (2021) has patented almost a similar concept of a swirl guiding pipe with an intake and exhaust swirling device for an IC engine as shown in Figure 5. This device can accelerate or increase the air swirling in addition to the reduction of the surface resistance of prior art, and increase flow velocity and flow rate. It can be installed inside an air intake system between the air cleaner and the intake manifold to reduce fluid resistance and increase the amount of fluid (S. Y. Kim, 2021).

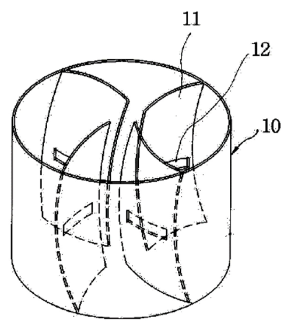


FIGURE 5. Patented intake and exhaust swirling device (S. Y. Kim 2021)

As shown in Figure 6, another patented air intake device was designed by Y. H. Kim (2021) to be used in the intake pipe to reduce the intake airflow resistance of an engine by concentrating the airflow to the centre. This part can be easily mounted in the intake system by inserting it into an intake pipe connected to the IC engine.

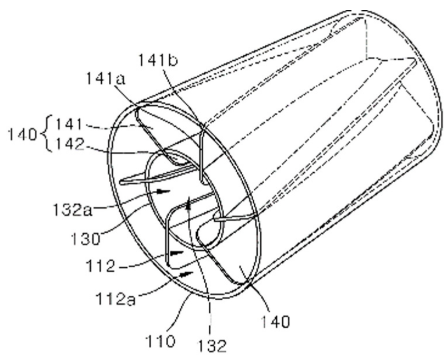


FIGURE 6. Patented design of an air intake device for an IC engine (Y. H. Kim, 2021)

COMBUSTION AND PERFORMANCE CHARACTERISTICS

The efficiency of the engine combustion is strongly reliant on the flow of the fluid in the chamber (Payri et al. 2004). The flow in the engine alters the output due to changes in the fluid structures in the cylinder and finally changes the combustion (Zaidi 2019). Secondary flow such as turbulence, swirls and tumble are significant for good fuel-air mixing, proper distribution of fluid inside the chamber, spreading of the combustion flame and increasing the efficiency. The flow in the intake manifold is one particular flow that has a large effect on engine combustion (Zaidi 2019). A good swirling fluid motion or strong vertical structures in the intake manifold leads to better fuel and air mixing and combustion efficiency (Giannakopoulos et al. 2017). The swirl air which initially developed in the inlet manifold can be characterized by the swirl number based on several definitions that are explained in the next section.

In terms of the engine performance, there is much evidence of the increased brake power for an engine induced with swirl air intake. As reported by Hairuddin and Shafanejad (2018), Naga Deepthi and Govinda Rajulu (2019) and Sharma et al. (2017), from 1.1% to 14.4% increase in the performance output is observed in their investigations. The volumetric efficiency may be improved by the optimum swirl and consequently enhances the combustion characteristics. However, several researchers also reported on the limitation of the fluid flow mixing method which may result in poor engine performance. The swirl air intake device, for example, may create undesirable air restrictions due to the internal swirl geometries and sizes as reported by Saad and Bari (2014) and Cahyono et al. (2016). With the swirl device obstructing the flow of the inducted air, the resistance of airflow increases at higher engine speed caused by the increase of airspeed entering the combustion chamber (Cahyono et al. 2016). It is necessary to consider all the factors that can cause air restriction in applying any swirl air intake mechanism into the air intake system. An overly design piston bowl geometry and helical intake port inducing more swirl and reversed squish formations may also have an adverse effect on the combustion characteristics and performance (Y. Chen et al. 2021; Kang et al. 2022). In a diesel DSCS engine as reported by Kang et al. (2022), although the air utilization is improved, however, the design may cause fuel accumulation problems due to air entrainment and wall-flow guiding effects leading to incomplete combustion and soot formation.

IN-CYLINDER PRESSURE AND TEMPERATURE

The performance of a CI engine operated with swirl air intake is expected to be affected by the increase of the fuel-air mixing rate before combustion. The variation in heat release rate due to the change in the fuel-air mixing rate will also affect the in-cylinder peak pressure and temperature. Typically, richer mixtures and higher load conditions will also produce higher peak pressures. Based on the report by Arjunraj et al. (2021) and Sadeq et al. (2019), increasing the engine load due to the increase in the injected fuel amount will increase the peak pressure, which results in higher in-cylinder pressure and temperature at higher engine load. Other than the engine load and speed, the in-cylinder pressure also depends on the energy of the fuel, temperature and pressure of the intake.

The effect of swirl air intake on the in-cylinder pressure and temperature needs to be properly investigated with consideration of turbulence. From the previous investigations, swirl intensity will always be associated with turbulence kinetic energy (TKE) when studying its effect on the peak pressure (Arjunraj et al. 2021; Bassiony et al. 2018; Hamid et al. 2020; Sadeq et al. 2019). The intake manifold that generates a strong swirl and a maximum TKE inside the cylinder may lead to more complete combustion as this reduces the physical ignition delay which includes the atomization, penetration, evaporation and fuel-air mixing. Reduction in the ignition delay, which is due to the enhanced fuel-air mixing may affect the maximum pressure due to the variation in the amount of burnt fuel during the rapid combustion period.

In terms of the turbulence level, higher swirl intensity does not mean the TKE is higher due to the variation in the fluid flow characteristics. Depending on the shape, structure and length of the device, the flow characteristics such as the turbulent drag and diffusion may be affected by the confined inflow condition and this will reduce the TKE further, even with the higher swirl intensity (Arjunraj et al. 2021; Sadeq et al. 2019). The effect of lower TKE inside the cylinder by changing the swirl air intake device, for example, may cause a different peak pressure level for the same engine. For this condition, the fuel properties effect such as low cetane number and high viscosity that affect the fuel atomization and droplet size becomes dominant to extend the ignition delay and produce high peak pressure (Sadeq et al. 2019). It should be mentioned that the turbulence energy level in the cylinder may further change with different designs of piston-bowl, combustion chamber and other parameters.

Arjunraj et al. (2021) investigated the effect of different sizes of intake manifold helical pipe diameter that can generate different intensities of swirl air (Intake manifold type 1D, 2D and 3D) on a CI engine. For the testing with a neat diesel fuel, intake manifold 1D results in a lower peak pressure of 6.2% as compared to the standard intake manifold, but the peak pressure for intake manifold 2D and 3D have higher peak pressure by 3.4% and 6.3% respectively. Intake manifold 1D has a strong swirl intensity with high TKE, while intake manifolds 2D and 3D, have stronger swirl intensity but with lower TKE based on the previous CFD simulation work (Bassiony et al. 2018; Sadeq et al. 2019). These findings show the importance of both strong swirl and turbulence intensity in achieving better combustion efficiency.

The effect of swirl air intake on the maximum temperature in the cylinder, by far, is not fully reported by the researchers. However, according to the gas law, pressure is directly proportional to the absolute temperature when the volume is constant (Oxford Reference, 2023). Therefore, it is expected with the decrease in maximum pressure, the maximum temperature inside the cylinder will also decrease.

BRAKE THERMAL EFFICIENCY AND BRAKE SPECIFIC FUEL CONSUMPTION

The increase in combustion efficiency can be achieved by higher turbulence and swirl air intake. The turbulence increases the rate of reaction by accelerating the chemical reaction by a thorough fuel mixing with oxygen in the air. Turbulence also produces a higher flame speed and increases the heat flow to the cylinder wall. The increase in flame speed due to the turbulence reduces the combustion period and also reduces the abnormal combustion tendency. All these factors contribute to the increase of BTE in a CI engine, where the BTE may be directly affected by the fuel-air rapid mixing. BTE is defined as the ratio of brake output to input power which describes the produced brake power by the engine with respect to the supplied energy by the fuel.

Numerous investigations have been done to study the impact of the swirl air intake on the engine. It is observed that the modification of the swirl air intake increases the brake thermal efficiency by 13.0 % to 25.6 % compared to the normal engine (A. R. Kumar et al. 2016; V. Prasad & Rangadu, 2011). The configuration of using a modified inlet manifold offers better thermal efficiency than a normal engine due to the improved mixing rate carried by the effects of swirl. Engine BTE is inversely related to brake specific fuel consumption (BSFC), whereby the lower the BSFC, the higher the thermal efficiency (Sadeq et al. 2019). It is expected to have a lower BSFC when the BTE is higher. Based on the previous findings, it is observed that the modified intake manifold with swirl air intake is 4.9 % to 25.8 % lower in BSFC when compared to a normal engine (Arjunraj et al. 2021; A. R. Kumar et al. 2016; Naga Deepthi & Govinda Rajulu, 2019; NShrirao & Sambhe, 2012; V. Prasad & Rangadu, 2011; Sharma et al. 2017). They conclude that this is due to more complete combustion by the enhanced swirl in the combustion chamber which increases the fuel-air mixture quality.

However, the engine running from high to low load may produce a different combustion characteristic. There are cases with no clear effect of the swirl air intake on the BSFC found when the engine load increases (Arjunraj et al. 2021; Sadeq et al. 2019). This is due to the considerable effect of the fuel density and calorific value when a high amount of fuel is injected at a higher load. The effect of fuel properties is more dominant with diesel-biodiesel blends. Arjunraj et al. (2021) and Sadeq et al. (2019) have investigated the effect of various diesel-biodiesel blends in a CI engine with swirl air intake and observed that the fuel properties have a considerable effect on the BSFC at higher load compared to the swirl effect.

EXHAUST GAS EMISSIONS

Exhaust emissions of a CI engine can be further reduced with the swirl air intake. Since better fuel-air mixing is generated with the swirl and turbulence flow inside the cylinder, more complete combustion of the fuel can be achieved in the combustion chamber. Unburnt hydrocarbon (UHC) is the emission element that is a direct result of incomplete combustion (Arjunraj et al. 2021; NShrirao & Sambhe, 2012). As the engine load increases, the hydrocarbon emission will slightly increase as two different factors work against each other; more fuel injected, and reduction of quenching (Sadeq et al. 2019). The increased incomplete combustion is due to more fuel injected which causes more unconsumed hydrocarbon. At the same time, quenching is reduced by a higher engine load that increases the temperature inside the cylinder. Flame quenching is an undesirable condition that happens during the oxidation process which causes the UHC to remain unconsumed (Heywood, 2018).

The UHC substantially decreases with the increase of turbulence inside the cylinder which results in more complete combustion. This is consistent with the previously reported results, where, in most cases, they found lower UHC emission using the swirl air intake manifold when correlated with the ordinary manifold (Arjunraj et al. 2021; A. R. Kumar et al. 2016; Naga Deepthi & Govinda Rajulu, 2019; NShrirao & Sambhe, 2012; Reddy et al. 2014; Sadeq et al. 2019).

Incomplete combustion also produces carbon monoxide (CO). CO is resulted as the product of incomplete combustion which increases with an increase in engine load. In a swirl air intake, generally, lower CO levels can be achieved for most cases as compared to a normal intake manifold due to the improvement in the fuel-air mixture and better combustion. This is consistent with the results from the similar reports. Meanwhile, Nitric Oxide (NO), this emission increases with the engine load due to the high combustion temperatures caused by the increased fuel amount. Therefore, it can be considered as a representative of NO_x emissions.

NUMERICAL STUDY BACKGROUND

NUMERICAL AND CFD ENVIRONMENTS

In predicting the fluid flow characteristics in IC engines, numerical study has been used extensively to simulate and analyse the behaviour of fluids inside the engine. The numerical method is used to discretise the governing equations and solve these equations numerically. Simulation works are based on mathematical models to describe the behaviour of the fluid flow and its interaction with the solid body depending on the boundary conditions and assumptions. Three categories of simulation are very common in the numerical study which are Zero-Dimensional, Quasi-Dimensional and Multi-Dimensional simulations (Hafizil et al. 2017; D. Zhang et al. 2023).

Zero-dimensional often referred to as '0D' simulation provides a simplified representation of the entire engine system, where the engine is considered as a single control volume with the fluid flow and combustion process represented by a set of simplified models derived from the governing equations. However, Zero-dimensional simulations have limited accuracy due to the simplified model which does not accurately represent more complex fluid flow and combustion process. This limitation can be improved by necessary modifications to the model in calculating the heat release rate in diesel engines (Feng et al. 2019).

Quasi-dimensional simulations provide a compromise between computational efficiency and spatial details where the simulation is done according to the multiple interconnected control volumes. Each simulation considers the inclusion of additional models to capture specific phenomena. This simulation provides a more accurate prediction with an additional model for capturing the turbulence within the intake pipe and cylinder. For a swirl prediction in a CI engine, the zero-dimensional model can be further developed with a sub-model working under the swirl environment in the heat release model (Broatch et al. 2019; Wu et al. 2022).

Multi-dimensional simulation provides the highest level of detail where the complex flow structures such as swirl, tumble and turbulence can be captured to observe the effect on combustion and emissions. CFD is used in the multi-dimensional simulation to solve the governing equations of fluid flow and combustions in three-dimensional distribution. CFD is extensively used in fluid flow analysis with the ability to provide a detailed and accurate representation of flow physics. This is a well-known method which has been widely used to simulate and analyse the flow characteristics, pressure difference, and other effects within the cylinder as well as in the intake systems.

COMBUSTION AND SWIRL FLOW MODELLING IN CI ENGINE

In CI engine study, the zero-dimensional model is often used in predicting the overall combustion behaviour with consideration of only one independent variable for each analysis. This is actually essential to isolate and assess the intermediate changes such as the heat transfer, real working fluid or gas, dynamic change of combustion velocity and phasing, effect of incomplete combustion and blow-by-losses as performed by Broatch et al. (2019). Not to mention the effect of the exhaust blowdown in actual cycles due to the advanced exhaust valve opening just right before BDC to decrease the pumping work before the exhaust stroke begins. Since it is impossible to isolate and evaluate these changes separately in the real engine, thus a zero-dimensional model is more suitable to be used for a parametric study (Broatch et al. 2019).

A heat transfer model is also normally applied in the zero-dimensional simulation. As an example, Woschni's heat transfer coefficient is used in the heat transfer model for the zero-dimensional simulation conducted by Wu et al. (2022) and Broatch et al. (2019). To predict the heat exchange process of the working fluid with consideration of the swirl parameters, Wu et al. (2022) and Broatch et al. (2019) employ the sub-models in their simulation as an improvement to the base zero-dimensional model. This improvement can be considered as a quasi-dimensional model where it can provide more precise prediction with an additional model for capturing the turbulence within the cylinder walls, as well as the heat transfer of the working fluid, the top surface of the piston, block wall, cylinder wall and cylinder bottom as presented by Wu et al. (2022).

In predicting the effect on emissions and combustion efficiency due to swirl formation using a multi-dimensional model, the work can be performed with the guidance of CFD. The CFD-based simulation has been employed by numerous researchers in analysing the combustion behaviour inside the combustion chamber involving a specific transport equation based on the energy, momentum and continuity equations. This includes the transport of species which comprise the turbulence characteristics for detailed analysis of the swirl effects (Sener & Gul, 2021).

Figure 7 shows the multi-dimensional simulation results as performed by Sener & Gul (2021) in investigating the effect of swirls on the in-cylinder temperature and velocity distribution through the injection parametric study. These distributions are caused by the movement of the swirls by the improved designs and better air-fuel mixing inside the cylinder. This shows the effectiveness of the multi-dimensional model in accurately predicting the behaviour of the combustion.

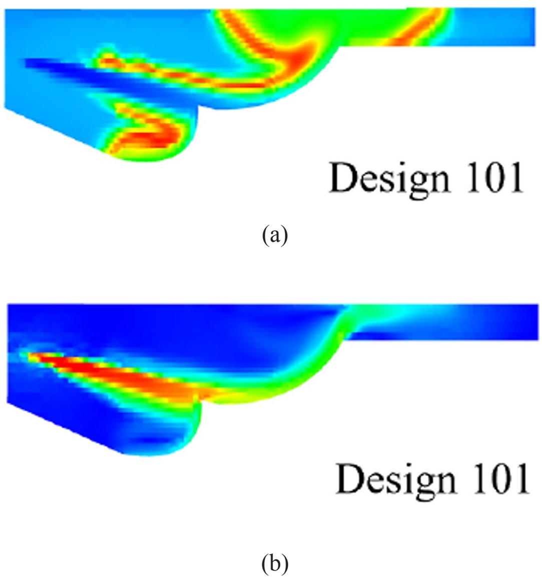


FIGURE 7. Temperature (a) and velocity (b) distributions of the selected optimum designs at TDC (Sener & Gul, 2021)

CFD is mainly used to study the flow behaviour inside the air intake system, where the analysis is done by focusing on the physical properties and flow conditions of the fluid with the specified wall boundary conditions. From the previous discussions, the flow behaviour of the inducted air charge has a substantial effect on the quality of the fuel-air mixing in the cylinder. Hence, the fluid flow study is important to be conducted in identifying the flow characteristics of the inducted air charge before any work related to combustion kinetics and thermodynamics.

The study that focuses on the fluid behaviour inside the cylinder has been conducted by Oddiwar & Koshti (2017). Figure 8 shows the CFD result of the streamlined flow during the air induction process with the swirl measured inside the cylinder. The change of the valve lift changes the swirl ratio as well as the TKE and TED of the charged air intake inside the cylinder. The flow starts from the intake runner directly to the intake port and ends inside the cylinder.

There are also CFD simulation works related to the fluid flow before the air reaches the intake port (Gocmen & Soyhan, 2020; Ruqaiyah et al. 2023; Xu, 2017). Ruqaiyah et al. (2023) predicted the unevenness of the design and the vortex phenomenon which affects the intake airflow into the cylinder. Meanwhile, Gocmen & Soyhan (2020) simulated the new intake manifold geometry to improve the swirl intensity in the cylinder, thereby reducing exhaust emissions. These simulation works indicate the effectiveness of CFD as the simulation tool for fluid flow modelling in the CI engines.

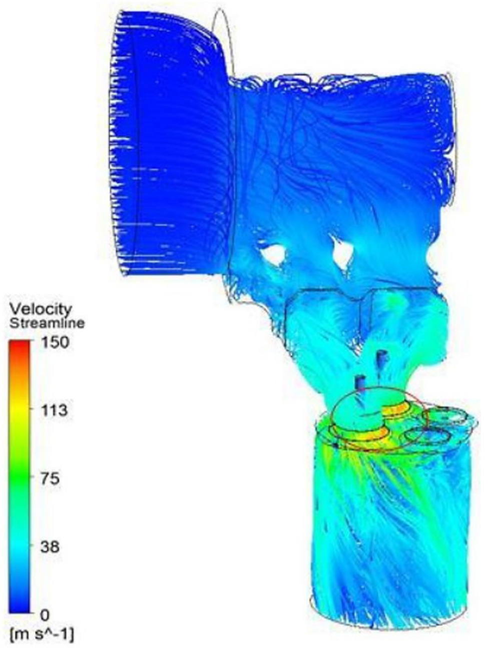


FIGURE 8. Streamline plot for 8mm valve lift in the CFD simulation of intake air swirl for diesel engine (Oddiwar & Koshti, 2017)

TURBULENCE MODELS

The k-epsilon (*k*-*ε*) model is regularly used as a standard turbulence model in the CFD in many simulations to predict the flow behaviour inside the intake manifold and cylinder of an engine (Gocmen & Soyhan, 2020; Oddiwar & Koshti, 2017; Xu, 2017). In previous investigations, researchers have pointed out that the *k*-*ε* is considered satisfactory compared to the experimental results (Gocmen & Soyhan, 2020). However, the *k*-*ε* accuracy may be limited in predicting complex flow phenomena such as flow separation and highly swirling flows, where this model is mainly applied in the steady-state simulations, and thus may not accurately capture the transient or unsteady flow phenomena.

Realizable *k*-*ε* has better accuracy than the other *k*-*ε* models for boundary layer flows that involve complex flow structures and high-pressure gradients (Araoye et al. 2017;

Qu et al. 2019). This turbulence model has been specifically employed by several fluid dynamics simulation works that cover various swirl flow strengths or intensities (Araoye et al. 2017; Kozlov et al. 2016; Pofalkar et al. 2017; Qu et al. 2019).

Another turbulence model may also perform better compared to the standard *k*-ε. Models such as RANS-RNG *k*-ε (Sener & Gul, 2021) and RNG *k*-ε (Z. Wang & Li, 2022) are more appropriate for more accurate and detailed turbulence modelling involving complex flow phenomena. K-omega (*k*-ω) (Zaidi, 2019), Shear Stress Transport (SST) (Ruqaiyah et al. 2023) and Transition-SST (*k*-ω) (K. Kumar et al. 2023) are the other types of turbulence model that are available to be used in simulating the fluid flow involving swirl airflow study. However, the choice of turbulence model is very much dependent on the specific flow characteristics aimed to be studied and higher computational cost and time should also be considered.

CONCLUSION

This review study discloses some of the recent findings on the study of swirl air intake to improve fuel-air mixing in the CI engine. Numerous strategies have been adopted in the air intake system to maximize the potential of the engine to achieve optimum combustion. From the fuel injection to fluid flow strategies, the objective is mainly to achieve a better homogeneous mixture during the fuel-air premixed phase in the combustion chamber. Their findings show that the improvement to the engine combustion characteristics increases the engine performance and subsequently reduces exhaust emissions. Many researchers have also reported higher brake or indicated thermal efficiency with the combustion-controlled parameters based on their investigations.

In the fluid flow strategy, various designs of air intake systems have been implemented in the engine. The list of recent patented, published or commercial swirl air intake devices as presented in Table 2 has shown that the current motivation in improving the engine performance is undeniably through the air induction method. Through the design of a swirl air device or induction pipe, inlet port and piston bowl, better combustion characteristics can be achieved with the increase of turbulence, formation of swirl and tumble motions that provide adequate mixing of air-fuel and proper circulation of fluid in the chamber. The swirl intensity or strength is indicated by the Swirl Number or Swirl Ratio and can be estimated based on several swirl definitions. However, several researchers also reported on the limitations of this method which may result in poor engine performance and exhaust emissions. This indicates that the effectiveness of generated swirl air through various designs of intake mechanisms needs to be further studied and investigated.

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DECLARATION OF COMPETING INTEREST

None.

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