# Modeling Of SI Engine Modification for Higher Ethanol Blended Gasoline Engine Applications: Part I - Parametric Study Using Port Flow Simulation

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## ABSTRACT

In the search for alternative fuels for transportation and emission reduction, internal combustion (IC) engine downsizing and utilization of higher ethanol blended fuel are the best candidates. Downsizing and utilization of higher ethanol blending method decrease fuel consumption as well as reduces emissions significantly. An efficient IC engine can be achieved by controlling the pre-combustion phenomena like swirl and tumble, which are best for uniform air-fuel mixture and convenient for efficient combustion. An intake modification system was used to inject higher ethanol content into the intake port of a single cylinder four stroke Spark Ignition (SI) engine that has been studied using Computational fluid dynamics (CFD). An engine modification at the inlet port has been inserted to increase the swirl and tumble ratios. The in-port utility with port fuel injection (PFI) contains three-swirl blades to achieve a swirl velocity component with minimum pressure drop expense during suction. Port flow simulation (PFS) for a model engine of single cylinder four stroke SI engine predicted fluid dynamics and airflow rate within the cylinder during the suction process. Comparisons have been made for models with and without in-port utility for an IC engine using ANSYS/ICE modeling package and found a significant improvement on in-cylinder swirl and tumble turbulence that affect the combustion process. An in-port utility design with port fuel injection (PFI) with 30mm length, 90mm pitch and blade radial length (BRL) of 10mm related with 2/3 of radius of the inlet valve has shown the best alternative in the design parametric study.

**Keywords:** Internal combustion engine, IC engine modeling, Port flow simulation, Swirl, Turbulence.

## INTRODUCTION

Economics, availability and environmental impact of fossil fuel use in IC engines, especially vehicles, are the current issues to be addressed. The price of fossil fuel is increasing continuously and the availability of this non-renewable source of energy is in doubt. The environmental impact of the emissions from fossil fuel use is a critical point to be considered to let the next generation enjoy living on the planet Earth.

Biofuels obtained from cellulose, non-food resources, are the best options for minimizing fossil fuel use for engine drive. Even though biofuels obtained from resources used for food created a controversy in challenging food security, sources like cellulose or by-products of other processes are becoming sustainable sources of ethanol without compromising food security. Ethiopia produces sugar from sugarcane and Ethanol from the bagasse obtained as waste from the sugar industries. The production of sugar and ethanol is expected to grow and contribute to the country's economy in terms of sugar export and increase ethanol blending ratios to reduce the currency exchange in fossil fuel import.

Many researchers have investigated the use of blended ethanol with gasoline fuel for Spark ignition engines (De Simio, Gambino, and Iannaccone 2012; Masum et al. 2013; Wallner and Miers 2008; Costa and Sodré 2011; Yücesu et al. 2006; Turner et al. 2011; Costagliola et al. 2013; Park et al. 2010; Jr 2007). The use of ethanol blended fuel for existing vehicles has been implemented in Ethiopia to a ratio of 10% ethanol and 90% gasoline resulted a significant save in currency exchange for gasoline purchase. Efficiency studies show that kilometers per mega Joule of fuel (km/MJfuel) are better for ethanol blended fuel than conventional gasoline whereas volumetric based mileage (km/l) with ethanol is lower. Increasing the contribution of ethanol in SI engines needs a thorough study of the combustion characteristics and develop a modification on the existing vehicle engine; otherwise, merely increasing the ethanol ratio wouldn't result in the same benefit as in the low ratios. The need for engine system modification for high ethanol blended gasoline has been considered for new vehicle engines, as in Figure 1. However, there is limited work on engine modifications for existing used engines to use high blending ratios.

Importing gasoline fuel for transportation and portable electric generators is the inevitable cost for Ethiopia. Ethiopia has more than 344,000 vehicles, of which 49.9% run on gasoline fuel (Amibe, 2012). Only in Addis Ababa are more than 87,000 gasoline engine vehicles, of which 42% are Carbureted engines (Redda 2012). Leakage and poor air/fuel mixing from the carburetor mainly contribute to unburned hydrocarbon emissions in old vehicles.

**Nomenclature**

| | |
|---|---|
| RPM | Engine speed in revolutions per minute |
| BRL | Blade Radial Length |
| BIR | Blade Inner Radius |
| PFS | Port Flow Simulation |
| CFS | Cold Flow Simulation |
| CS | Combustion Simulation |
| LHV | Lower heating value |
| IVO | Inlet Valve Open |
| DM | Design Modeller |
| TDC | Top Dead Centre |

| | | Vehicle component | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Carburetor | Fuel injection | Fuel pump | Fuel pressure device | Fuel filter | Ignition system | Evaporative system | Fuel tank | Catalytic converter | Basic engine | Motor oil | Intake manifold | Exhaust system | Cold start system |
| Ethanol blend | ≤ 5% | | | | | For any vehicle | | | | | | | | | |
| | 5-10% | | | | for vehicles up to 15-20 years old | | | | | | | | | | |
| | 10-25% | | | | | | | | | | | | | | |
| | 25-85% | | | **For specially designed vehicles** | | | | | | | | | | | |
| | ≥ 85% | | | | | | | | | | | | | | |

Not necessary Probably necessary

**Figure 1**. Necessary vehicle modifications based on level of ethanol content (after (Jr 2007))

There are a considerable number of old versions (baseline study made in 2012G.C.) of vehicles in Ethiopia with high levels of pollutant gases including unburned hydrocarbons due to poor fuel quality, fuel/air mixing and fuel leakage at the carburetor section. The assessment further indicates that 55.3% of the gasoline vehicles in Addis Ababa have an engine size range of 1000-1300 cc and 52.8% of the gasoline engine vehicles are made on or before 1989. whereas 81.3% of the gasoline engine are made before 2000. (Lemma 2012). The fuel consumption of these vehicles with 1300 cc (Light duty vehicle) cylinder size is 8.4 liters per 100 km and the country imports 200,000 metric tons of gasoline per year and more than 1,200,000 metric tons of diesel fuel for the year 2012 (Amibe, 2012; Lemma, 2012).

Studies on the production of ethanol from molasses, by-product of sugar manufacturing, show that the average ethanol yield from final molasses (called C-grade molasses), which contains 32%

fermentable sugar is about 235 liters per tonne. Higher grades of molasses like B-molasses containing 60% fermentable sugar yields 297 liters per tonne (Sakthivel, Subramanian, and Mathai 2018). From reports from Ministry of Energy, Ethiopia benefited from using ethanol by 10.2 million USD foreign currency save from 12.5 million liters ethanol in one fiscal year of 2014/15. The government is working in multiple ways like increasing ethanol production from sugar cane and encouraging the import of fuel flexible vehicles so that more percentage of ethanol blended gasoline fuel can be used [Biofuel strategy, 2007, MoM & E].

**Port Injection Mixing**

Valve lift significantly influences the level of turbulence intensity and mixture formation inside engine cylinder (Begg et al. 2009) studied the effect of low valve lift in a port injected engine and find out airflow for a low valve lifts of 0.4 mm resulted 4 times higher turbulence intensity than full lift conditions. Jet flow in low valve lift gap significantly reduced mean droplet diameter, producing homogenous-like conditions down within the cylinder.

Convection Mass transfer in controls vapor formation in case of cold start conditions. For quick start and efficient combustion of fuel with less pollutant emissions, the first start of the cycle is critical specially when there is a need to start/stop the engine frequently like hybrid vehicles (Meyer and Heywood 1999; Cowart, 2003; Deng et al. 2011; Luan and Tagomori 2006). Convective mass transfer is more dominant in vapour formation mechanism in case of ambient temperature starting conditions. In case of hot temperatures start up, the fuel evaporation is accompanied by distillation and convection mass transfer. Other forms of mas transfer like diffusion and liquid film are relatively negligible (Cowart 2003).

Mid-valve open injection option is recommended in case of cold start up or quick start up. In case of hot start, three options like closed valve, mid-valve opening or fully open intake valve injection options resulted the same combustion characteristics. The latter two options with open intake valve injection are recommended to increase fuel transport (Deng et al. 2011).

(Luan and Tagomori 2006) analysed formation of fuel vapour mechanisms to predict the amount of fuel vaporized in the intake port at any crank angle degree and in the cylinder on cycle-by-cycle basis for the first few cycles at the beginning of a cold start process. Out of five different fuel vaporization mechanisms modeled, droplet evaporation by hot exhaust gas backflow occurred by fuel injection during the valve overlap period becomes the most dominating mechanism of fuel vapor formation.

A strong tumble motion starts to develop when the inlet valve lift increases above 5mm. The higher in-valve lifts increase mass flow rate of air admitted that changes the direction of rotation of the fluid inside the cylinder resulting in a positive circuiting motion to form a higher non-dimensional tumble-rig. Air mass flow rate reached a maximum value at in-valve lift of 9 mm with lower coefficient of discharge (El-Adawy et al. 2017).

Liquid fuel transported to in-cylinder during start up and warm up is influenced by several engine and injector design variables, and fuel parameters (Meyer and Heywood 1999). Injection timing significantly influences in-cylinder droplet size only for open and closed valve injection timing cases in which closed valve injection (with the longest possible time between injection and IVO) reduces in-cylinder liquid fuel occurrence. Locating the Ethanol fuel injector closer to the inlet valve in PFI system positively impacts engine stability and emission reduction by reducing HC and CO attributed to lower wall wetting phenomenon as ethanol vaporization increases closer to the hot valves (Padala and Hawkes, 2014).

IC engine performance can also be increased by inserting swirl generating blades to enhance the turbulence and mixing level between fuel and air. Previously, multiple blade swirl generator for intake system has been developed by several patents (Hunt 1997; Lee and Heywood, 2017; Cheng 2003). Swirl generator compressor blades assembled on the valve have been tried as an internal turbocharger (DiMarco 2002). Two blade swirl generator has been tried (Lyssy, 1986). Chocking system for swirl control has been tried (Fornara and Schiavina, 2010). The corresponding increase in swirl velocity and the expense of pressure drop must be studied in detail to design an optimum blade profile and length for the in-port utility.

**Engine Specification**

As presented in Table 1, the engine test setup for verification is a single cylinder engine with a possibility to vary the compression ratio, ignition timing, carburetor setting, with turbocharger effect, as well as dynamometer coupled to measure and control the engine speed/loading conditions.

Table 1. Variable compression test rig engine specification

| Parameter | Description (Value) |
|---|---|
| No. of Cylinders | One |
| Engine type | Spark Ignition |
| Bore x Stroke | 95mm x 82mm |
| Inlet valve diameter | 30mm |
| Swept Volume | 582cm$^3$ |
| Ignition timing | 25$^o$BTD to 10$^o$ATDC |
| Compression ratio | 6:1 to 11:1 |
| Cooling system | Water cooled |
| Engine Speed | 1000RPM to 2750RPM |
| Fuel type | Gasoline-Ethanol Blends |

**IC Engine modeling**

Two universal engine models without modification (base model) and with in-port modification have been prepared. Cylinder bore size is taken as geometry parameter to study for different bore to stroke ratio engine cylinders with a single universal engine model. ANSYS/ Design Modeler is used as a tool to prepare a parameter based unified IC engine geometry. ANSYS/ICE Analysis System has been used for geometry decomposition, meshing and parametric solving. The same Geometry preparation, decomposition setting, mesh setting, solver setup and iterations of convergence criteria are used for both models, as represented in Figure 3(B& C).

The model is prepared with flexible geometric parameters to investigate different compression ratios and cylinder sizes. The engine model has a combustion chamber of variable cylinder bore and stroke length, fixed canted valve inclination angle of 28°, variable clearance height (3mm as default), fixed piston bowel depth of 2mm, and fixed piston bowel radius 35 mm. The model involves key sketch constraints and geometry operations on the design modeler (DM) to be followed to achieve a generalized design geometry accounting variability of engine sizes for parametric investigation.

### IC engine simulation

The performance of IC engines depends on several factors of which combustion chamber design, operating variables and intake conditions are factors directly affect the fluid dynamics inside the cylinder. Combustion chamber design and intake conditions directly influence the fluid dynamics inside the cylinder creating turbulent conditions before combustion starts. Turbulence helps to mix the air and fuel uniformly to improve combustion efficiency and reduce emissions of pollutants due to incomplete combustion. In IC engine Swirl, the component of fluid rotational motion around the center of the engine cylinder, directly affects the performance of the engine via affecting the turbulence level inside the cylinder (Bonatesta 2013; Heywood 1988). Engine modification involves to analyze the current pros and cons of the existing engine on the basis of combustion chamber geometry, fuel type, fuel mixing, combustion parameter optimization – ignition timing, compression ratio, engine load conditions and emission standard criterion. Engine design involves three types of engine process simulations- port flow simulation (PFS), cold flow simulations (CFS) and in-cylinder combustion simulations (CS) (ANSYS Inc. 2016; Canonsburg 2015).

In CS, the power process starting from closing of inlet valve to the end of compression process is simulated taking input fluid dynamic parameters results from cold flow and port flow simulation results. In PFS, the effect of fluid flow in the intake port on in-cylinder flow phenomenon during suction stroke will be studied. Parameters to be considered during port flow analysis are swirl, valve lift, pressure drop, fluid flow rate.

PFS for a model single cylinder four stroke SI engine has been done to predict air flow rate and fluid dynamics within the cylinder during suction. An engine modification at the inlet port has been designed to increase the swirl and tumble ratios. Comparisons have been made with and without in-port utility for the suction process using ANSYS/ICE modeling package and found a significant improvement that enhances the combustion process.

## IC Engine Modification Using Port Flow Simulation

The engine modification is done on the inlet port section to control the proportion of fuel mixing and the flow phenomenon of suction process as in Figure 2. Ethanol fuel is injected at the import utility after the swirl blades to entrain the fuel in the process of vaporization during suction process represented as inFigure 2b. The injector orientation in PFI is set to be as close as possible to hit the backside of the inlet valve to reduce formation of liquid fuel film on the walls of the intake port (Kim, Cho, and Min 2015; Heywood 1988).

### Swirl generating blades

Swirl blade generator is done considering to achieve a swirl velocity component with minimum pressure drop expenses. The number of blades is set to three to minimize the frictional pressure drop.

The swirl generating blade development covers six different cases of blade profiles. All have been modeled based on parametric study method to compare the resulting change in mass flow rate and turbulence enhancement achieved as well as pressure drop occurred due to the stator blades. The width of the swirl generator is limited to 30mm based on the space available at the real engine suction section. The pitch of the spiral blade is tasted for 30mm for full one round spiral, 60mm for half round spiral and 90mm pitch length, as shown inFigure 3A. Whereas BRL of 15, 10, 5 and 2mm are studied, i.e. blade inner radius (BIR) of 0, 5, 10 and 2mm thick spiral rough surface, respectively. Only single blade spiral is shown for a simple representation of the spiral blades.

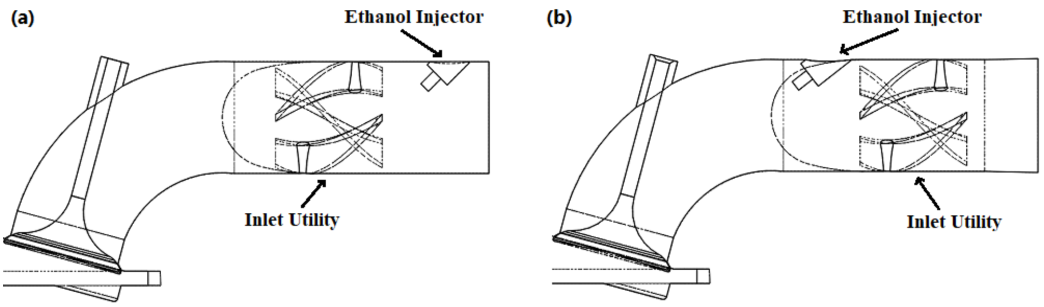



**Figure 2.** Port injection utility indicating; (a) Ethanol port injector and swirl generator blades, (b) Injector placed after the swirl blades

**Ethanol Port Injection Utility**

Carburetted engine vehicles will be equipped with an inlet port injection utility/adapter to facilitate a premixed ethanol-gasoline blend of required proportion right at the intake port. To enhance the mixing quality, multiport injectors are used for supplying pressurized ethanol fuel. In addition to injection mixing, the utility has second objective as a swirl generator to increase combustion efficiency inside the cylinder. As in Figure 2a, ethanol fuel is injected before the mixture gets in to the swirl enhancing blades. The swirl enhancing blades are stationary with the inner surface of the inlet port utility. The mixture fluid rotates as it passes through the stationary blades before entering the cylinder. Where as in the second case, the incoming mixture of fuel and air gets rotational motion as it moves through the swirl guide vanes then ethanol is injected into the swirling mixture at the inlet valves, as shown in Figure 2b.

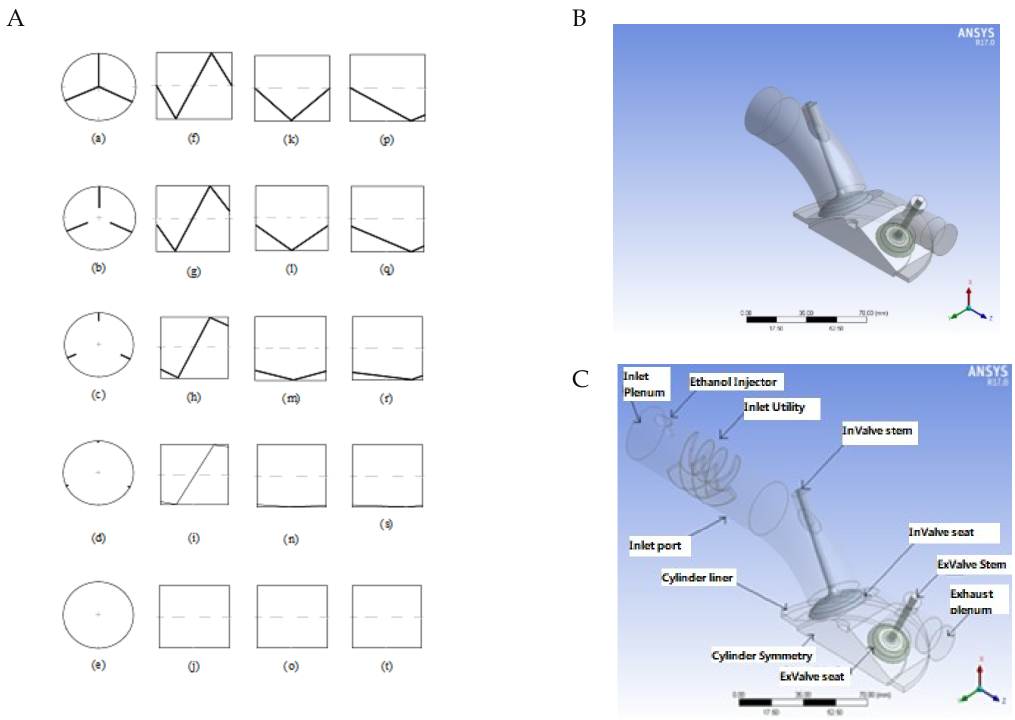



**Figure 3.** (A) Representation of radial blade profile and spiral pitch length for three cases for 30mm long inlet port utility with BRL of; (a) Blade through-15mm, (b) 10mm, (c) 5mm, (d) 2mm thick spiral, (e) plane connector, and (f-t) pitch length of 30, 60 & 90; (B) base model, and (C) model with inlet utility.

**Table 2.** IC Engine PFS Simulation setup and boundary conditions

| Model Type | Description/ Value |
|---|---|
| Solver Type/ Simulation Type | ANSYS/ICE(Fluent)/ PFS |
| Number of mesh nodes/ Elements | 180,999/ 431,679 |
| Mesh size Minimum/ Maximum | Fine mesh: 0.531/ 10.6221 |
| Model | 3D, Steady state, Pressure based |
| Viscous turbulence model | Standard k-omega |
| Boundary conditions inlet/ outlet | Pressure inlet/ Pressure outlet: 0/ 5kPa Vacuum Gauge |
| Pressure-velocity coupling method | Coupled, Pseudo Transient |
| Discretization - turbulent kinetic energy | First Order Upwind |
| Initialization | Cold flow conditions: 300K, zero velocity and 101,325Pa |
| Ethanol Injection model | Rosin-rammler, Spherical, 673.7 m/s at 300 K |
| Convergence conditions | Continuity equation/ Monitor Parameters: 1e-4 |

**Solver setup**

In the current IC Engine PFS, 3D steady state turbulent flow with discrete model has been used to simulate the fluid dynamics effect due to the inlet port modification. The ICE(Fluent)setup used to solve the governing equations like continuity, Navier-Stokes, discrete phase, and energy equations has been described as in Table 2 with key boundary conditions.

## RESULTS AND DISCUSSION

The inlet utility creates swirling motion to the fluid during suction process as represented by projected velocity vectors just leaving the blades and just leaving the inlet utility after ethanol injection as shown in Figure 4(b & d) respectively. From flow simulation of PFI, the results from locating the injector after the swirl generating blades and directing in-line with the back side of the inlet valves showed better design alternative than installing the port injector before the swirl blades as represented in Figure 4c. Injector is aligned with inlet valve port orientation resulting a strong throw directing into the back side of the inlet valves. The inlet port fuel injection of ethanol using the developed utility enhanced mixing and swirl generation as shown in Figure 4a.

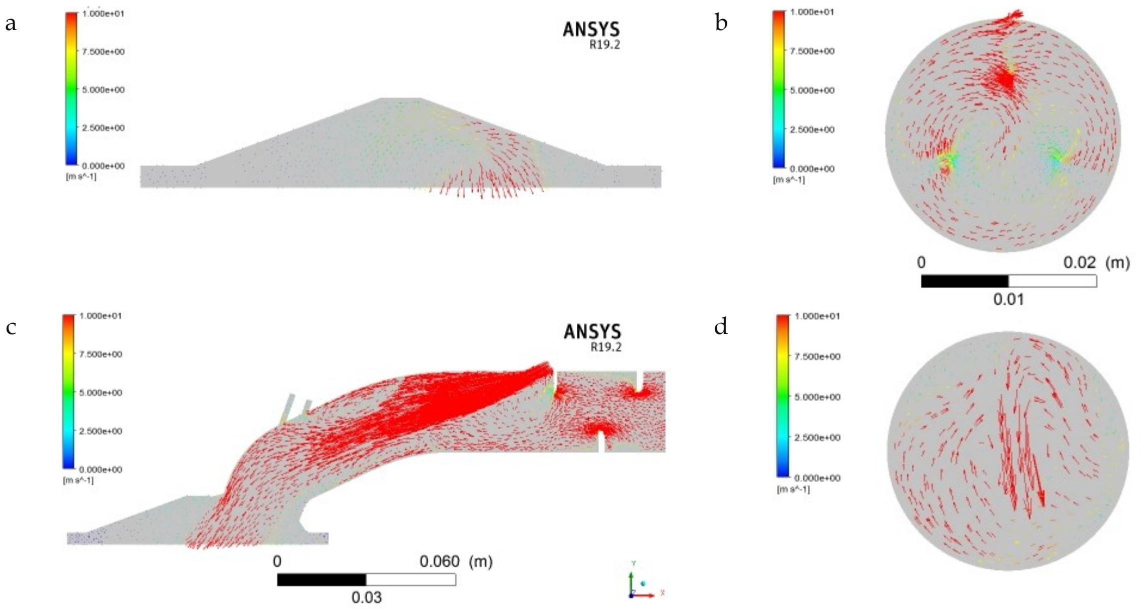



**Figure 4**. Velocity vector for Ethanol PFI simulation for inlet port with inlet utility at (a) cylinder cut plane; (b) exit of swirl blades; (c) inlet port; and (d) after injector

The result of PFS for inlet utility with 60 mm pitch at 10mm blade radial length and half revolution spiral resulted 65% of the mass flow rate of the base model at higher inlet valve opening condition of 10mm as shown in Figure 5(a – c). At lower valve opening, the mass flow rate change decreases to a value of 98% for 2 mm inlet valve opening and 77% for mid-valve opening of 6mm. Mass flow rate of the case 30mm pitch, 5mm BRL and full revolve spiral blade showed a significant decrease below that of 60mm and 90mm pitch under similar conditions.

Application of swirl generating blades resulted a decrease in mass flow rate at specific inlet valve lifts, however this does not need direct increase in the size of the cylinder as ethanol is an oxygenated fuel. Mass flow rate of mixture admitted can be increased to match the base engine without changing the size of the engine by multiple methods; increasing the inlet valve opening duration profile or using turbochargers that increase the inlet velocity of air via the inlet port utility compensating the pressure drop incurred due to the inlet port modification component as well as to compensate the decrease in the LHV due to fuel change in case of higher power demand.

From PFS results using area weighted velocity magnitude as a monitors shown in Figure 5d, the velocity magnitude for the model with modification utility increases resulting in a further decrease in flow utility shows a decrease by 1m/s for 30mm pitch and 0.5m/s for 60mm pitch due to the additional pressure drop at the inserted utility containing injector and swirl blades. From the velocity magnitude and the level of turbulence predicted by PFS, the optimum size and quantified benefits in improving the pre-combustion phenomenon is obtained. PFS results presented in Figure 6 are velocity magnitude on Cut plane (symmetry of the cylinder) and Velocity magnitude with Vectors overlaid on Swirl Plane located 45mm from the reference location at TDC for determining the optimum BRL of swirl generator utility. The velocity magnitude in case of shorter BRL are larger as expected due to lower flow resistance. However, the turbulence level created i.e. the swirl and tumble components are significantly higher in case of longer BRL cases: 15 mm and 10 mm as in Figure 6(a-d). The inlet utility design with 30 mm length, 90mm pitch and BRL of 10 mm related with 2/3 of radius of the inlet valve showed the best alternative in the design parametric study evident in Figure 6(c & d).

As Figure 7(a & b) indicates, the pressure distribution through the intake port with and without the inlet modification gives key information about how the intake mass flow rate is reduced in case of swirl generating blades at the intake utility. As the BRL increases, the pressure drop through the intake rate at the instant of valve lift which is evident from the direct proportionality between flow rate and driving pressure gauge between in-cylinder and ambient pressure.

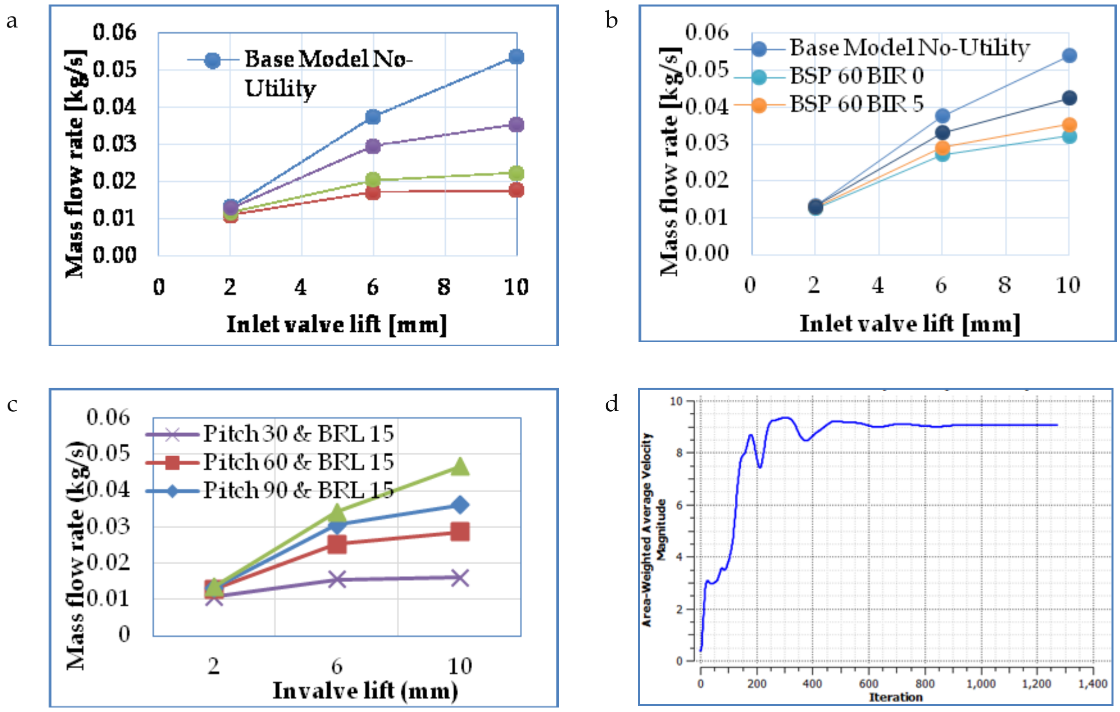
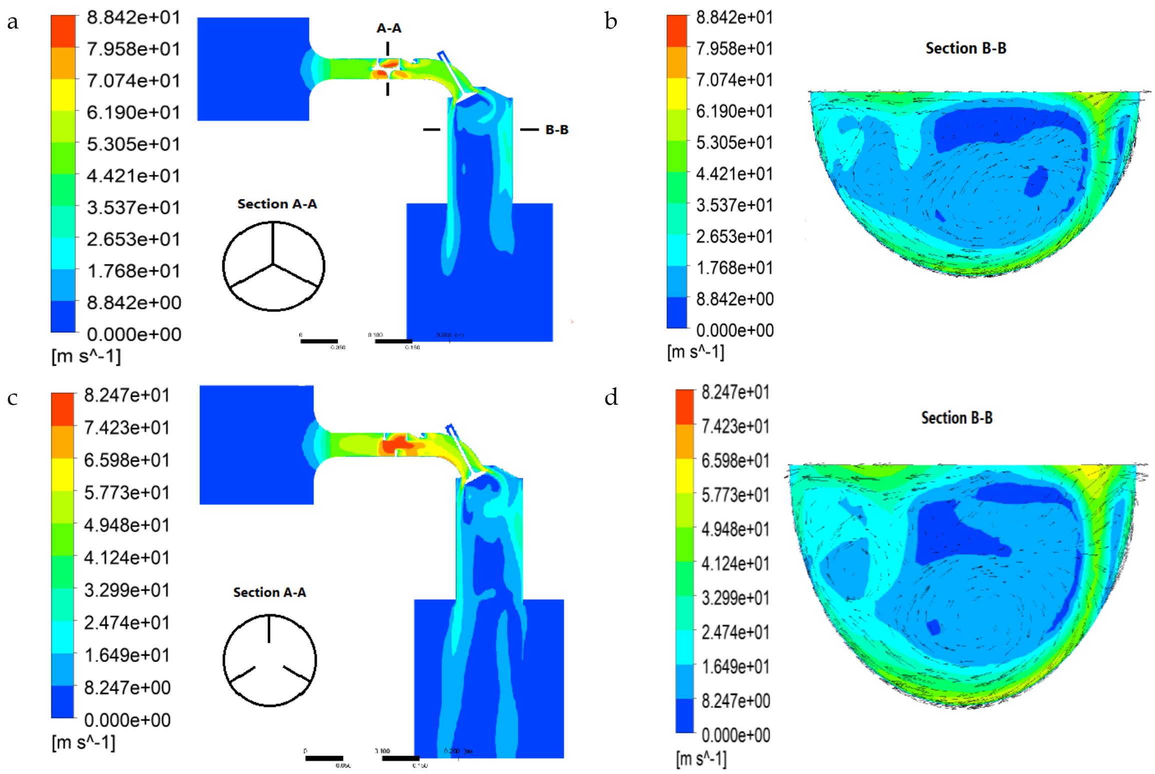



**Figure 5.** Mass flow rate for inlet modification design modeling of the Swirl Blades (a) Different BRL for spiral pitch of 30mm; (b) spiral pitch of 60mm; (c) different spiral pitch and BRL of 15mm; (d) velocity magnitude convergence on out-plenum.



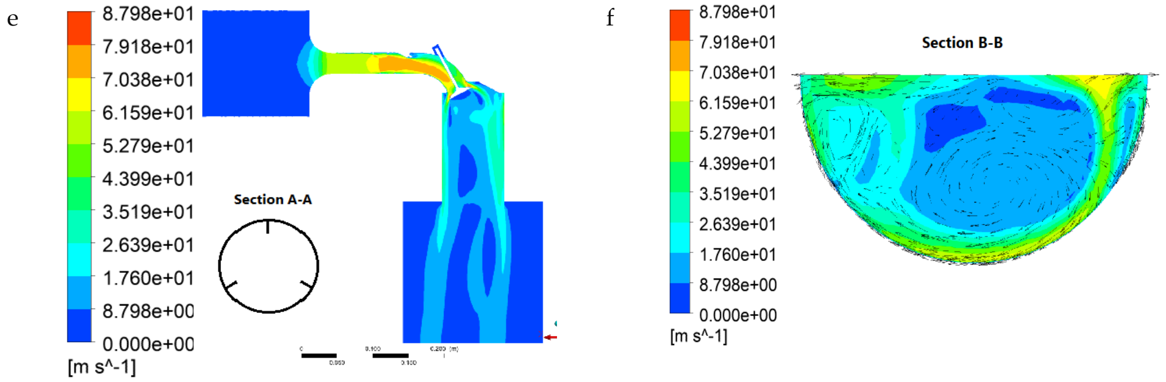



**Figure 6**. Velocity Magnitude on Cut plane 1 (symmetry of the cylinder) and Velocity Magnitude with Vectors on Swirl Plane 2 (45 mm from TDC) at 10mm Valve Lift for 90mm pitch Model with BRL of (a&b)15mm; (c&d) 10mm and (e&f) 5mm.

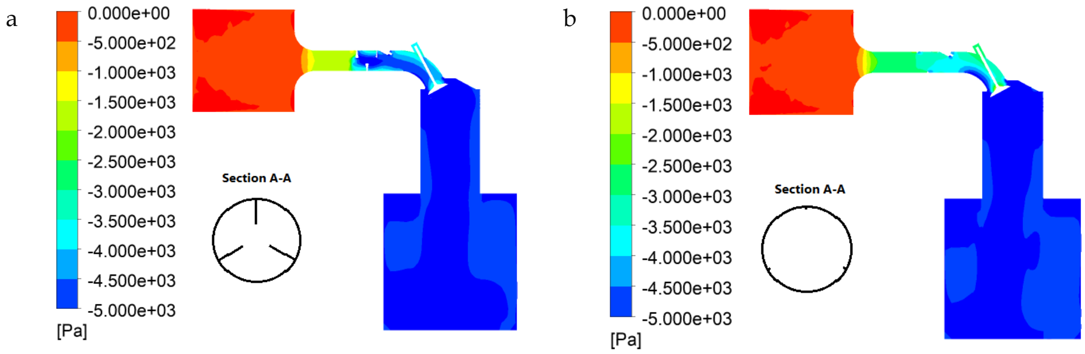



**Figure 7.** Pressure contour of flow through the intake port at 10mm valve lift with utility of; (a) 10 mm BRL and b) 2mm BRL

## CONCLUSIONS

PFS of IC engine with an inlet utility has been done to investigate its effect on the fluid dynamics inside the cylinder. For the analyzed engine modification and the base model, the turbulent flow components swirl and tumble motions have been improved, favoring the pre-combustion phenomenon. An inlet utility design with stator blade has been designed with the possibility of smaller fluid residence time on the blade by optimizing the blade length. The inlet utility design with 30 mm length, 90 mm pitch and blade radial length of 10 mm related to 2/3 of radius of the inlet valve showed the best alternative in the design parametric study. It is also observed that the flow in the in-port utility results in a pressure drop leading to a lower mass flow rate at the maximum inlet valve lift of 10mm. The lower mass flow rate affects the volumetric efficiency of the engine as well as the amount of power generated from the engine as the fuel admitted into the cylinder decreases proportionally to the quantity of air available into the cylinder. The decrease in mass flow rate at the largest valve lift of 10mm can be resolved by increasing the inlet valve opening duration profile or using turbochargers compared to base model with no-inlet utility. However, the thermal efficiency of the engine improves with better mixing quality and higher level of swirl turbulence prior to combustion start. As the ethanol fuel energy density is smaller than gasoline, the amount of fuel admitted into the cylinder should be higher to compensate the decrease in lower heating value of the fuel per each cycle of the engine. As a future direction, swirl modification results from the PFS need to be studied in different cases by patching or inserting it into the CS model.

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