

Numerical Analysis of a Downsized 2-Stroke Uniflow Engine

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ABSTRACT

In order to optimize the 2-stroke uniflow engine performance on vehicle applications, numerical analysis has been introduced, 3D CFD model has been built for the optimization of intake charge organization. The scavenging process was investigated and the intake port design details were improved. Then the output data from 3D CFD calculation were applied to a 1D engine model to process the analysis on engine performance. The boost system optimization of the engine has been carried out also. Furthermore, a vehicle model was also set up to investigate the engine in-vehicle performance.

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INTRODUCTION

Aggressive downsizing of four-stroke gasoline engines at 50% has been recently published by a number of companies claiming fuel savings of 25%. Downsizing to 50% and beyond presents severe challenges e.g. max. boost capability, knocking combustion, transient performance, high peak cylinder pressure and associated mechanical and thermal load issues. The 2-stroke engine has double the firing frequency of the 4-stroke, for the same output torque the 2-stroke engine IMEP and the peak pressure are approximately halved and the safety margin from combustion knock is wider. Thus, the 2-stroke engine has much greater potential than the 4-stroke for aggressive downsizing, without having to increase boost to the same level.

2-stroke uniflow engines are widely used in large marine diesel engines [eg. MAN, Wärtsilä-Sulzer] and in some diesel locomotives (Electro-Motive Diesel). Detroit Diesel had been manufacturing uniflow 2-stroke direct injection diesel engines for heavy duty vehicles until late 1990s as well as for military vehicles requiring very high power density engines. In recent years, many companies and research groups have built 2-stroke engine prototypes[1, 2, 3,4], and also many groups has dedicated to numerical analysis[5, 6].

In this project, a 3-D CFD model has been built to investigate the scavenging process of a downsized 2-stroke uniflow engine numerical model. A 1-D numerical model has also been built up for the purpose of engine performance prediction.

SCAVENGING PROCESS OPTIMIZATION

The performance of 2-stroke engines is reply on the scavenging process to a great extent. There are mainly 3 ways to scavenge a 2-stroke engine, crossflow, loopflow and uniflow. Among these methods, the uniflow method shows the best scavenging efficiency. Furthermore, for a uniflow 2-stroke engine, the intake ports govern the intake fresh charge mass flow rate, the scavenging performance, and the swirl generation of in-cylinder flow.

At the start of the project, a single cylinder 2-stroke uniflow engine model was set up for the study of scavenging process and the optimized design of the intake ports. The engine model features intake ports at the bottom of cylinder liner. Exhaust valves are included in cylinder head and actuated by a camshaft. A set of parameters are introduced [7] to define the intake port configuration settings of the 2-stroke uniflow engine, as shown in [Figure 1](#) and [Table 1](#).



In order to set a ground for simulation work, a 2-D model was first used to predict the effect of axis inclination angle, A_i , on in-cylinder flow and scavenging process during the overlap period of intake port opening and exhaust valve opening. The 2-D model is shown in [Figure 2](#).

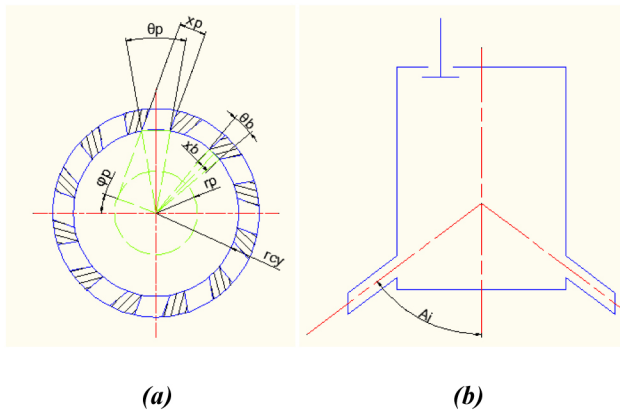


Figure 1. The intake port geometry parameter

Table 1. The intake port geometry parameter

Parameter	Definition
r_{cy}	engine bore radius
r_p	radius of swirl circle
θ_p	port width angle
N	Number of ports
A_i	Axis inclination angle
φ_p	Swirl orientation angle $= 90^\circ - \cos^{-1}(r_{cy}/r_p) - \theta_p/2$
x_p	Effective port width $= r_{cy} \times \sin(\theta_p/2) \times \cos \varphi_p$
θ_b	Port shoulder width angle $= 360/N - \theta_p$
x_b	Effective port shoulder width $= 2 \times r_{cy} \times \sin \theta_b/2$

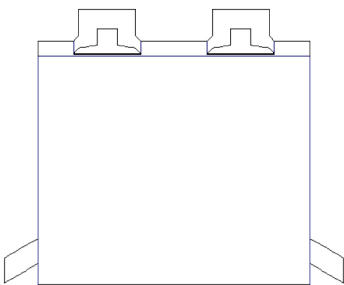


Figure 2. The 2-D CFD model

The following parameters are used to characterize the quality of scavenging process [8]:

Delivery ratio (DR): defined as the ratio of delivered fresh charge mass to reference mass. The reference mass is calculated by the displaced volume multiplies ambient air density.

Trapping efficiency (TE): defined as the ratio of mass of delivered fresh charge retained in the in-cylinder to the total mass of delivered fresh charge.

Scavenging efficiency (SE): defined as the ratio of mass of delivered fresh charge retained in the cylinder to the total trapped cylinder charge.

Charging efficiency (CE): defined as the ratio of mass of delivered air retained in the cylinder to the reference mass.

The calculations started from 120°ATDC, at which exhaust valves start to open, to 250°ATDC, when the intake ports are fully covered by the piston. A 1.5bar absolute boost pressure was applied to the intake flow, the initial in-cylinder pressure was set to 1.2bar @120°ATDC, and in-cylinder temperature was set to 500K. The initial in-cylinder charge was assumed with no motion. The exhaust backpressure was set at ambient pressure.

[Figure 3](#) shows the accumulative values of the scavenging parameters at the end of the scavenging process. One of the most common issues of 2-stroke engine scavenging process is known as “short circuiting” [7], the fresh charge goes directly out of the cylinder through the exhaust valve/port. As shown in [figure 4](#), when the intake port inclination angle is small, the intake charge goes up towards the exhaust valves along the cylinder wall, which shows poor capacity of blowing residual gas out of cylinder and strong “short circuiting”. But if the intake port inclination angle is too big, the intake flow goes directly towards the centre of the cylinder, crashes into the fresh charge flow from the opposite side, then goes up to the exhaust valve, which also leads to a poor scavenging performance.

In comparison, the 60° axis inclination angle design produces best compromise of delivery ratio and trapping efficiency and achieves the best charging efficiency and scavenging efficiency in this case. Since charging efficiency determines the mount of air available for combustion, a greater charging efficiency will lead to more engine output for a given engine.

In addition, the higher the scavenging efficiency the lower of residual gas, which would be required to minimize the knocking combustion at full load operations.

The 3-D CFD calculation model was then built up based on the 2-D calculation result, as shown in [Figure 5](#). The initial conditions are kept the same as the previous 2-D analysis, and 60° axis inclination angle was applied to the CFD model.

In order to maximize intake flow through the intake ports, the number of intake ports and their geometry need to be designed to give the highest flow efficiency. For a given number of intake ports N , the port width ratio C_{pb} can be used to describe the port's geometry effect on flow and can be calculated as follow,

$$C_{pb} = Nx_p/2r_{cy}$$

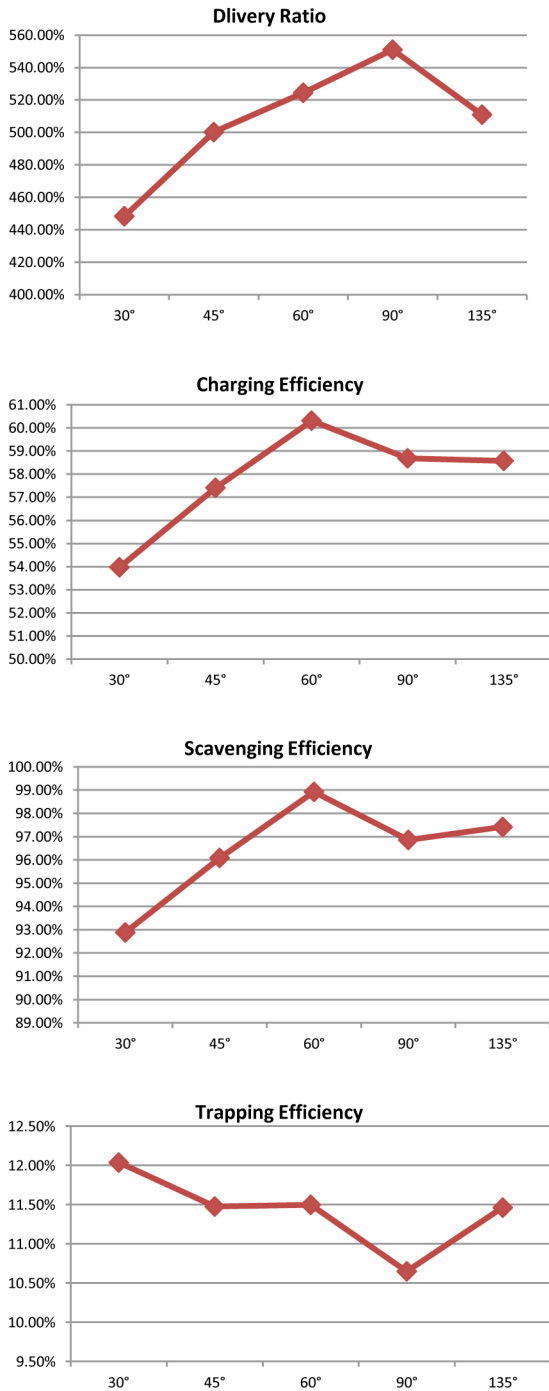


Figure 3. Scavenging performance as a function of axis inclination angle based on 2-D models

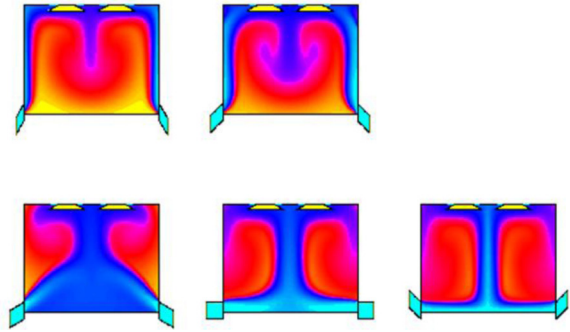


Figure 4. In-cylinder components distribution contour

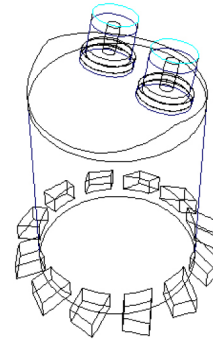


Figure 5. 3-D CFD base model

For a specific value of C_{pb} , the intake ports can be arranged with wider port width and less number of ports or narrower port width and more number of ports.

A 3-D CFD model simulation was set up to investigate the effect of the combination of port number N and effective port width x_p . Different combinations of N and x_p are evaluated as given in Table 2 and the definition of each parameter can be found in Table 1.

Table 2. The setting of combination of N and x_p

Setting	SET1	SET 2	SET 3	SET 4	SET 5
r_{cy} – mm	80	80	80	80	80
r_p – mm	40	45.7	51.4	55.5	61.2
ϕ_p – °	20	20	20	20	20
θ_p – °	20	30	40	48	60
θ_b – °	10	15	20	24	30
x_b – mm	13.94	20.88	27.78	33.27	41.41
x_p – mm	26.12	38.96	51.44	61.20	75.24
N	12	8	6	5	4
A_i – °	60	60	60	60	60
C_{pb}	1.9	1.9	1.9	1.9	1.9