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Design and Simulate Mixing of Compressed Natural Gas with Air in a mixing device

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Abstract — Gas mixer is a device used to determine the amount of natural gas and air before entering the engine. It injects the gas into the intake air stream of an internal combustion chamber using a combination of radial holes and radial tubes located around the perimeter of an air flow passage. The size of intake air passage, the number and size of the radial holes and tubes varies to achieve adequate gas or air mixing for the particular engine. Measurement of air flow necessary for engine operation is the selection criteria of mixers. The power obtained from engine is dependent on the size of the mixer. It can be seen from the experimental result that a smaller mixer caused higher pressure at the throat in compare to the analytical result. High pressure caused low velocity at the throat. Both smaller and larger mixer was able to promote the methane into the outlet from the inlet tube. Smaller size throat mixer at the throat restricted caused undesirable results.

Keywords**:** Compress natural gas (CNG), internal combustion chamber, air flow.

I. Introduction

Compressed natural gas is a growing alternative fuel which was introduced to reduce the dependent on conventional fuel. It has been found that natural gas vehicle (NGV) gives good performance and can be use for long travel. Unlike gasoline or petrol, natural gas does not contain lead because of its high octane rating, 120-130. As combustion is more complete, the contaminating effects of exhaust emission are reduced. In Malaysia, the number of natural gas vehicle has increases and are projected to be more in the future based on the government policies to encourage the use of alternative fuel in the transportation sector [1].

With the increasing concern on the use of alternative fuel for engine application, various studies have been done concerning the performance of the engine. Mixing of the compressed natural gas (CNG) with air is necessary to achieve adequate mixing in order for combustion. Too lean or too rich mixture will cause poor performance of the engine or combustion will not occur at all. The mixer should provide an air-fuel ratio in accordance with the engine operating requirements and this ratio must be within the combustible range. Therefore the research for a proper mixing device is essential in order to achieve this objective [1].

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II. Mixer Design

The conceptual mixer design of the proposed mixer is based on the venturi effect, whereas Bernoulli's principle is applied [2].

Figure 1 shows the overview of the venturi. A venturi consist of a tube with a constricted throat which produces an increased velocity accompanied by a reduction in pressure followed by gradually diverging portion in which the velocity is transformed into pressure with slight friction loss[2].

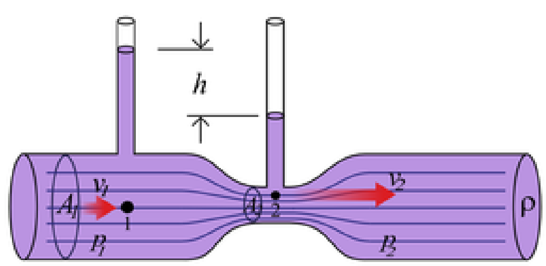

Figure 1: Basic venturi overview

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} \qquad (1)$$

Figure 2 shows the conceptual mixer design based on the venturi. Higher pressure at the mixer throat will cause lower velocity. This will results in poor suction of compressed natural gas from the tube and air from the inlet. Poor mixing will degrade the engine performance because of the air fuel ratio that is being produced.

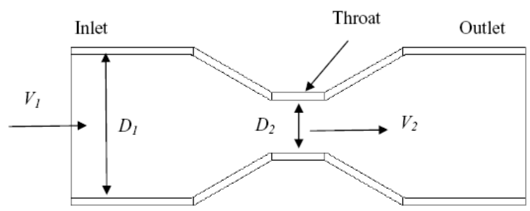

Figure 2: Conceptual mixer

Too small throat causes air flow restriction at the throat which is undesirable for better mixing fuel and air. The mixer should produce better mixing in order for combustion. Required air flow rate for the engine operation has to be determine, it can be found by solving the equation below[3]:

$$Q_a = \frac{\eta_v V_d N}{n} \tag{2}$$

Where,

Q_a = Required airflow rate (m^3/s)
η_v = Volumetric efficiency, assumed to be 85%
V_d =Volume displacement (m)
N= Engine speed (rpm)
n = 2 for 4 stoke engine

Maximum air flow rate of the engine was used to find the throat size. The gas was assumed to be an incompressible fluid where the Mach number is less than 0.1. By knowing the air flow rate for the engine operation, the initial approximation of the throat size was computed by using continuity equation.

$$Q = AV \tag{3}$$

Where,

Q = Required air flow rate (m^3/s)
A = Area at the throat (m^2)
V = Velocity at the inlet (m/s)

The velocity at the throat is predetermined by using the Mach number which was assumed to be 0.1 in order for the gas to be considered as an incompressible fluid[4].

$$v = Mc \tag{4}$$

Where,

v = Velocity (m/s)
M = Mach no.
c = Speed of sound (m/s)

To find the initial size where the natural gas is introduced, several calculations have been made. Based on the air-fuel ratio equation we can find the area of the tube.

$$A/F \ ratio = \frac{\dot{m}_a}{\dot{m}_f} \tag{5}$$

Where,

A/F= Air to fuel ratio
$\dot{m}_a$ = mass flow rate of air
$\dot{m}_f$ = mass flow rate of fuel

From the combustion equation, the stoichiometric air fuel ratio for natural gas is determined [5].

$$A/F = \frac{(1 + y/4)(32 + 3.773 \times 28.16)}{12.011 + 1.008\,y} \tag{6}$$

Since the gas is considered as incompressible, Bernoulli's theorem is applicable to the air flow also. Thus,

$$\frac{\dot{m}_a}{\dot{m}_f} = \frac{C_{da}}{C_{df}} \frac{A_2}{A_f} \sqrt{\frac{\rho_a}{\rho_f}} = \frac{A_2}{A_f} \sqrt{\frac{\rho_a}{\rho_f}} \tag{7}$$

Where,

ρ_a = air density (kg/m^3)
ρ_f = fuel density (kg/m^3)
A_2 = Throat area (m^2)
A_f = Inlet tube area (m^2)

Figure 3 shows the overall mixer that has been design based on the dimension calculation. The mixer is designed from parts for ease of assembly [6]

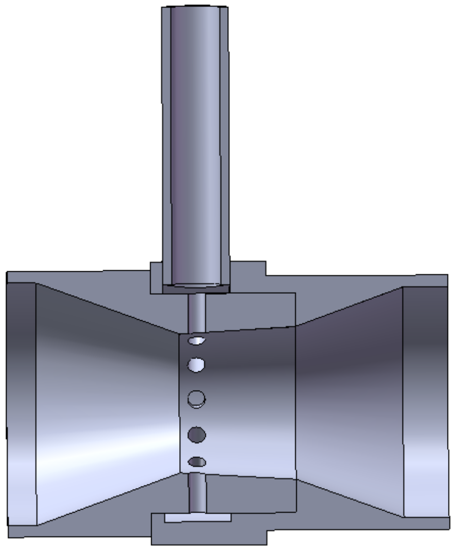

Figure 3: Mixer design

III. Simulation Procedure

The simulation was done using COSMOS FloWorks for validation of the proposed mixer design. There are 3 boundary conditions that are taken measure in the simulation. The accuracy of the conditions is important as it will affect the simulation outcomes.

i. Air inlet

The first boundary condition is the air at the mixer inlet. The air is assumed to be at ambient temperature.

ii. Flow rate at outlet

Flow rate at the mixer outlet is determined based on the engine operating requirement. A range of 1000 rpm of engine speed is being used and by solving equation (2), the flow rate is determined

iii. CNG inlet tube

The inlet tube is where the natural gas is introduced into the air flow stream at the mixer throat. The pressure of compressed natural gas is set to be at 1 bar.

Table 1 listed the initial condition that is being used for the simulation process of the proposed design.

Table 1: Initial simulation condition

Parameters	Value
Air pressure (bar)	1
Methane pressure (bar)	1
Flow rate (m^3/s)	0.01697
Engine speed (rpm)	6000
Temperature (K)	292.3
Substance fraction by mass Air	1
Substance fraction by mass Methane	1

Table 2 listed the boundary condition at the mixer inlet. The air is at ambient condition and the air concentration is set at 1 and methane at 0 which shows that no natural gas is introduced from the mixer inlet at the beginning.

Table 2: Boundary condition at mixer inlet

Type	Static Pressure
Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Concentrations	Substance by fraction mass Air:1 Methane: 0
Boundary layer parameters	Turbulent

Table 3 listed the condition of natural gas from the CNG inlet tube that will be introduced into the air intake passage.

Table 3: Boundary condition at CNG inlet tube

Type	Static Pressure
Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Concentrations	Substance by fraction mass Air: 0 Methane:1
Boundary layer parameters	Turbulent

Mesh analysis is also been done to determine the correct flow in the mixer.

IV. Results And Discussion

There are several design considerations and factors that have been made. Each consideration is designed using designing software and will undergo simulation to identify the most suitable mixer design.

i.Inlet and outlet angle

The mixer design is first analyzed based on the angle of the inlet and outlet of the mixer. From the venturi principle, it is necessary for the mixer to produce lower pressure and higher velocity at the mixer throat. The air fuel ratio produced at the outlet is the selection criteria.

Based on the figure 4, we choose the angle that produces the lowest pressure. We can also see that at a length of 0.3 m, the lowest pressure is achieved which shows the location of the radial holes at the mixer throat.

Figure 4 shows the pressure differences for each different angle of mixer inlet and outlet.

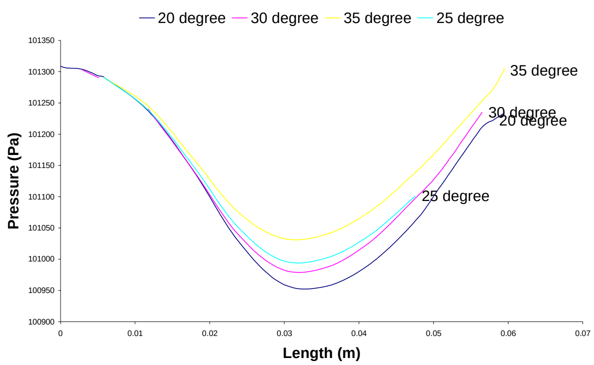

Figure 4: Pressure difference at different angle

ii.Mixer throat diameter

From the calculation, the initial mixer throat diameter was 22 mm. An increase of 2 mm is being made in choosing the mixer diameter. The selection criteria are the air fuel ratio that is being produced by each mixer throat. The maximum diameter is 28 mm, as bigger diameter is undesirable and affects the mixer design.

Based on table 4, we can conclude that the oversized mixer produced is a too lean mixture. At this range, combustion would not occur. Mixer diameter which produces not too rich or too lean mixture is chosen. The 24 mm diameter produces air fuel ratio near the stoichiometric air fuel ratio for natural gas which is 17.23. Thus two criteria has been chosen, an angle of 20 degree and a 24 mm diameter mixer throat will be selected for analyzing the other design consideration.

Table 4: Air fuel ratio for different mixer throat diameter

Diameter	Air fuel ratio
22 mm	15.09
24 mm	15.8
26 mm	20.93
28 mm	26.63

iii. Number of holes

The size of the radial holes at the mixer throat is 3 mm for designing purpose. For the analysis, a range of 8 to 12 radial holes is designed with an angle of 20 degree and a mixer throat diameter to be 24 mm.

From table 5, the 10 radial holes produce the most optimum air fuel ratio. Although, the simulation is being made based on the maximum engine speed 12 radial holes produces a slight rich mixture. 8 radial holes are chosen because it produces a slight increase from the stoichiometric ratio and is still in the combustible range. The mixer will then being analyze based on the other engine operating speed to optimize the mixer design and validate whether the proposed design based on the results is suitable for range of the engine.

Table 5: Air fuel ratio for different number of holes

No. of holes	Air fuel ratio
8	18.18
10	17.04
12	15.81

From the graph from figure 5, at 1000 rpm the mixer produces the lowest air at the outlet. We can conclude that at lower engine speed, it requires smaller portion of air.

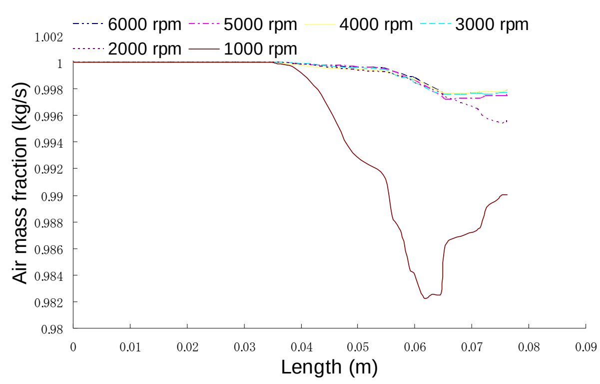

Figure 5: Air mass fraction at different engine speed

From figure 6, we can see that the lower engine speed, more methane is introduced at the mixer outlet. This is conversely from the air intake.

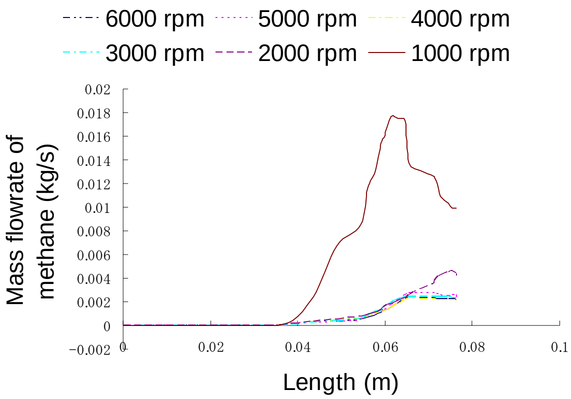

Figure 6: Methane mass fraction at different engine speed

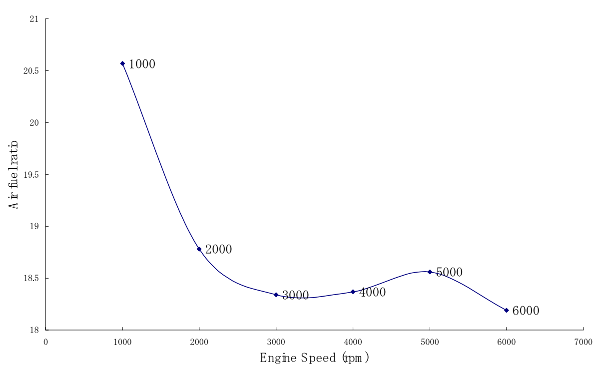

Figure 7: Air fuel ratio at different engine speed

Based on the graph from figure 7 we can conclude that the proposed mixer design was able to introduce a good portion of natural gas and ia at the outlet. The highest air fuel ratio was at the lowest engine speed and it decreases as the engine speed decreases. We can also conclude that the mixer was able to produce air fuel ratio at the range of combustile, where combustion would most likely to happen because the current proposed mixer design do not produce either too lean or too rich mixture of natural gas and air.

Based on the analysis and the discussion, the table 6 listed the recommended dimension for the mixer design.

Table 6 Recommended dimension of CNG mixer

Parameter	Value
Inlet Diameter	42 mm
Outlet Diameter	42 mm
Throat Diameter	24 mm
Inlet and Outlet Angle	20 degree
CNG Inlet Tube Size	10 mm
Size of hole	3 mm
Number of holes	8 holes

V. Conclusion

Some factors were considered in order to mix the fuel and air. Those factors are throat size, angle of the inlet and outlet, size and location of the holes at the throat and others. Smaller size throat causes restriction to the throat causing less air into the throat. The angle affects overall pressure, need to consider the angle which produces less pressure in order to create higher velocity that flows in the mixer. The size and location of the holes give different results as it's where the methane or natural gas goes through before introduced to the throat. It is recommended that the throat should be slightly larger. Different angle size causes different pressure.

Acknowledgment

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