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Analysis And optimization of Intake System of An SI Engine Operating on Syngas

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***ABSTRACt**: The use of Syngas in place of petrol in SI engines reduces the power output of the engine due to the lower calorific value of syngas, lower volumetric efficiency and the fact that the engine is designed keeping the properties of petrol in mind. In this paper, analysis is conducted on a Honda GX-270 single cylinder SI engine and necessary optimizations are carried out in order to theoretically achieve the expected power output of 3 kW, while operating on syngas. Based on the results obtained, suggestions for improved design have been put forth. The optimization has been done in two stages; in the first stage, the intake manifold of the engine has been redesigned and optimized to theoretically obtain the required power output. In this stage, the mass flow rate of the air-fuel mixture and the air-fuel ratio obtained at the intake port are the parameters of importance.*

***Keywords**: syngas, optimization, volumetric efficiency, intake manifold, validation*

I. INTRODUCTION

Volumetric efficiency is an important parameter in determining engine performance characteristics. The overall effectiveness of four stroke engine can be expressed in the form of volumetric efficiency. Volumetric efficiency, in turn, is determined by design of intake manifold system, valve timing, valve lift, fuel and many more factors. Among these various factors intake manifold design has major influence on volumetric efficiency. During actual operation of engine, the flow of charge from intake manifold to cylinder keeps on varying with speed and time. This causes the generation of expansion waves in intake manifold. The generated expansion waves can get reflected at plenum of manifold. As a result the pressure waves get propogated away from manifold. The pressure waves are responsible for increasing the pressure above nominal inlet pressure at the inlet valve. The increase in pressure is during the end of intake process. The mass flow rate of charge in cylinder depends on pressure in manifold. Hence the rate of mass inducted during suction stroke gets increased and hence the volumetric efficiency. This is called as tuning of intake manifold.

Hence, in order to tune the intake manifold system and increase the volumetric efficiency, optimum geometric design of intake system is important. To understand the effect of intake manifold design and various parameters affecting volumetric efficiency many researchers have done experiments and analysis on engine. NeginMaftouni[1] carried the simulation on intake manifold of XU7 engine. In this paper length of intake manifold is changed by 110%, 120% and 130%. The effect on volumetric efficiency was analyzed for both steady and unsteady conditions. Suresh Aadepu[2] presented a paper determining factors affecting volumetric efficiency of twin cylinder diesel engine. The engine had volumetric efficiency of 84% at 2400rpm and rated torque. Mainly the effect of length and diameter of intake manifold was recorded. M MKhan[3] performed the CFD analysis on naturally aspired SI engine using Ansys Workbench 15 (Fluent) software. The simulation was carried for intake manifold using different steady state RANS turbulence models. Accordingly the computational time required for each case was analyzed.

This paper represents the design and simulation of three different intake manifold systems used for single cylinder four stroke petrol engine (Honda GX270). The engine has rated output power of 6KW using Petrol and 2.7 kW using Syngas. Syngas is mixture of different gases like nitrogen in 50%, carbon monoxide in 18%,carbon dioxide in 10%, hydrogen in15 % and methane in 7%. The design and simulation for the manifold is carried out for operation of engine on syngas. The design of manifold system for different length and diameter is done in Creo 2.2 modelling software and the simulation is being done in Ansys Workbench 15 (Fluent) software. For first manifold design the diameter for air inlet and syngas inlet are 20 mm and 22 mm respectively. For second design it is 18 and 20 mm respectively and for third it is 22 and 24 mm respectively.

The results obtained from the simulation are analyzed and validated using theoretical calculations. Hence comparing all different designs, optimum intake manifold system is suggested.

II. METHODOLOGY

The following are the important stages through which the analysis for inlet pipe optimization is accomplished:

1. Obtaining the ideal composition of Syngas based upon the purpose and application
2. Calculation of the calorific value of Syngas and ideal (Stoichiometric air-fuel ratio) for the composition obtained in Step 1
3. Calculation of required mass flow rate of Syngas and air based upon the final power requirement and the efficiencies
4. Fixing nominal inlet pipe dimensions for the purpose of comparative analysis
5. Calculation of inlet velocities required for air and fuel based upon pipe dimensions and mass flow rates
6. CAD modelling of inlet pipes based upon the dimensions fixed in Step 4 using Creo 2.2
7. CFD flow simulation of air-fuel flow through modelled pipes using Ansys Workbench 15 and analysis of the obtained results for the same

Selection of optimum design of inlet pipe based upon results from the flow analysis

1. Inlet Pipe Optimization

1.1 Ideal composition of Syngas

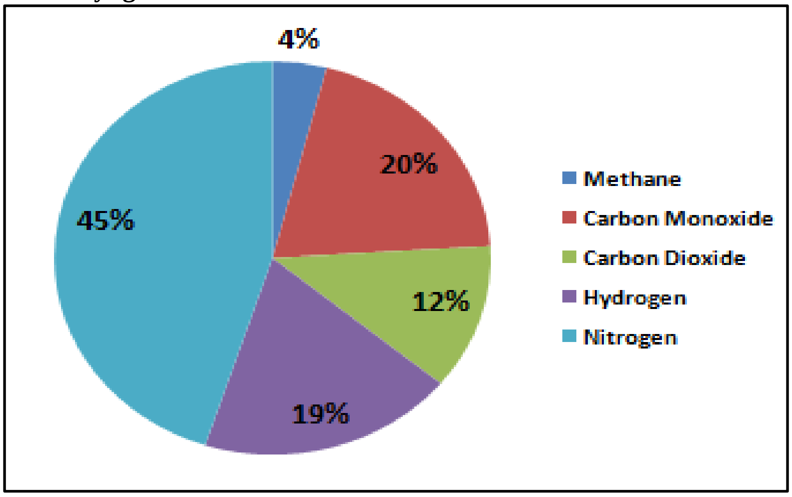

Fig 1. Composition of Syngas (% by volume)

The basic purpose of developing an engine operating on Syngas is to exploit the easy availability of biogas in rural areas from which Syngas can be easily obtained. This conversion is described by the following equation.
Biogas → Catalytic reformation → Syngas
(Catalyst used: γ-Al_2O_3 with 10% Nickel)
Hence, the composition of Syngas to be used is the one derived from biogas conversion. This composition is shown in Fig. 1 in terms of % by volume.

1.2 Calculation of calorific value of syngas

For the purpose of calculation, the mass of Syngas is assumed to be 1 kg.
Hence, mass of syngas = 1 kg
Density of Syngas= Σ (Density of component * % by volume of component)
The density and volume percentages are given as follows in Table 1.

Table 1.Density of syngas components

Component	Density (kg/m^3)	% by volume of Syngas
CH_4	0.668	4
CO	1.165	20
CO_2	1.842	12
H_2	0.0899	19
N_2	1.165	45

Based on equation and values from Table 1,
Density of Syngas = 1.022 kg/m^3

Volume of 1 kg Syngas = Mass / Density
= 1 / 1.022
= 0.9785 m^3

Mass fractions of components are obtained as follows from Table 2.

Table 2. Mass fractions of syngas components

Component	% by volume	Volume present in 0.9785 m^3 Syngas (m^3)	Mass present in 1 kg Syngas
CH_4	4	0.03914	0.0261
CO	20	0.1957	0.2279
CO_2	12	0.11742	0.2162
H_2	19	0.1859	0.0167
N_2	45	0.440325	0.5129

The working reactions for the complete combustion of Syngas alongwith the heat release rates are as follows:
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + 882 kJ/mole
$CO + O_2 \rightarrow CO_2$ + 276.8 kJ/mole
$H_2 + O_2 \rightarrow H_2O$ + 285.8 kJ/mole

Table 3. Heat release rates of syngas components

Components	Mol. weight (kg)	Heat released by 1 mole (kJ)	Heat released by mass in 1 kg Syngas (kJ)
CH_4	0.016	882	1435.17
CO	0.028	276.8	2252.95
H_2	0.002016	285.8	2367.49

Higher calorific value
= Heat released by (CH_4 + CO + H_2)
= 6055.61 kJ / kg

Heat carried away by the steam
= 1130.12 kJ/kg

Lower calorific value
= 6055.61 – 1130.12
= 4925.49 kJ/kg

1.3 Calculation of stoichiometric air-fuel ratio

The overall chemical reaction of Syngas and air is given as:
$CH_4 + 5CO + 4.75H_2 + 11.25N_2 + 3CO_2 + 6.875[O_2 + 3.773N_2 \rightarrow 9CO_2 + 6.75H_2O + 32.472N_2$

From the above reaction, the stoichiometric air-fuel ratio is defined as:
= [6.875(1 * MW of O_2 + 3.773 * MW of N_2)] / [(1 * MW of CH_4) + (5 * MW of CO) + (4.75 * MW of H_2) + (11.25 * MW of N_2) + (3 * MW of CO_2)]
= 1.545
(Where MW stands for Molecular weight)

1.4 Calculation of mass flow rates of fuel

$$\eta_{th} = \frac{BP}{mf \text{ x } CV} \qquad (1)$$

whereη_{th}= "Brake thermal efficiency"
= 20.39 %
BP = "Brake power" (required)
= 3 kW

CV= "Calorific value"
= 4925.49 kJ/kg
m_f = Syngas mass flow rate

Hence, we obtain syngas mass flow rate = 0.0029871 kg/s

$$\eta_{vol} = \frac{ma}{\left(\frac{\Pi}{4}\right) x\ \rho\ x\ d\ x\ d\ x\ l\ x \frac{N}{120}} \quad (2)$$

whereη_{vol} = Volumetric efficieny
= 70 %
d = Cylinder bore
= 77 mm
l = Stroke length
= 58 mm
m_a = Air mass flow rate
ρ = 1.18 kg/m^3
N = Required rpm of engine
= 3000 rpm

Hence, we obtain air mass flow rate = 0.00467 kg/s

1.5 Fixing the inlet pipe diameter

The intake manifold allows the air to pass to the engine. To ensure maximum possible air reaching the engine, optimization of air intake manifold is necessary. Fixing the dimensions of the manifold can be done by trial and error. But this method will be time consuming as well as expensive. Also, it will not give a clear picture of how the flow is actually taking place inside the pipes.

Therefore there is a need for CFD (Computational Fluid Dynamics) analysis which can approximate the air-fuel ratio being supplied to the engine during the design stage itself.

Three manifolds were designed. The requirements were as follows: the outlet of the manifold should be 25 mm in diameter and there should be two inlets; one for intake of syngas and the other for air. The diameters of pipes should be such that the fuel supplied to the engine should be at the required air-fuel ratio.
In the earlier design, both intake pipes were set at 20 mm diameter. Three alternative designs were made in which the dimensions of inlet pipes were identified as given in Table 4 below. These designs were modelled and analyzed in Fluent.

1.6 CAD modelling of inlet pipes

CAD modelling is completed using Creo 2.2. Based on previous work, the basic dimensions of inlet pipe are available. In order to carry out the optimization of the inlet pipe, three different pipe designs are proposed having three sets of dimensions.

Standard inlet pipe designs make use of a plenum in order to carry out the mixing of the air and fuel. However, as the densities of air (1.18) and Syngas (1.022) are closer in value, the plenum can be neglected as the fluid mixing does not pose as much of a problem as with earlier designs.

Different models of the manifold are made using the dimensions fixed earlier. The manifolds were designed in a shape of "Y" in which the angle between the two intake arms was kept as 25^o.Two intake pipes will combine to give a single outlet pipe which will be connected to the engine.

Table 4. Inlet pipe dimensions

Model No.	Air inlet diameter (mm)	Syngas inlet diameter (mm)	Charge outlet diameter (mm)
1	20	22	25
2	18	20	25
3	22	24	25

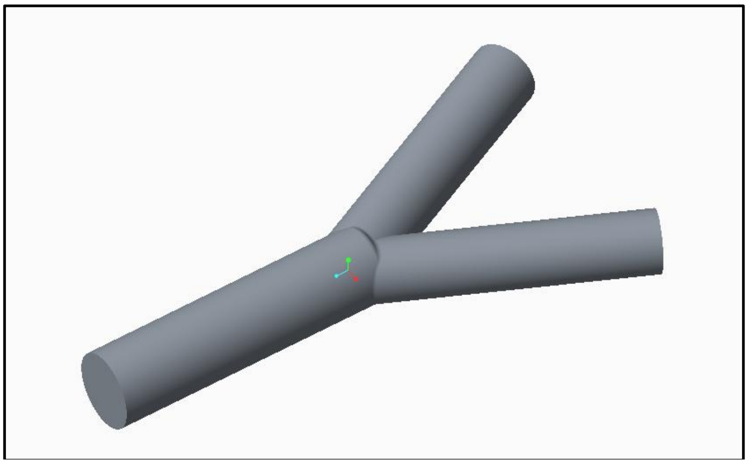

Fig 2. Inlet pipe model 1

1.7 Calculation of inlet velocities

Calculation of air inlet velocity

$$\nu_a = \frac{ma}{\rho \times \left(\frac{\Pi}{4}\right) \times d \times d} \qquad (3)$$

where m_a = Air mass flow rate
= 0.00467 kg/s
ρ = Density of air
= 1.18 kg/m^3
d = Air inlet diameter of pipe
= 20 mm

Hence, we obtain velocity of air = 12.6 m/s

Calculation of fuel intake velocity

$$\nu_f = \frac{mf}{\rho \times \left(\frac{\Pi}{4}\right) \times d \times d} \qquad (4)$$

where m_f = Syngas mass flow rate
= 0.0029871 kg/s
ρ = Density of Syngas
= 1.022 kg/m^3
d = Syngas inlet diameter of pipe
= 22 mm

Hence, we obtain velocity of Syngas = 7.68 m/s

Table 5. Inlet velocities of air and syngas

Model No.	Air intake		Fuel intake	
	Dia. (mm)	Flow vel. (m/s)	Dia. (mm)	Flow vel. (m/s)
1	20	12.6	22	7.68
2	18	15.55	20	8.05
3	22	10.41	24	5.59

3.8 CFD flow simulation of inlet pipe

For the purpose of flow simulation Ansys Workbench 15 (Fluent) is used. The models of the three inlet pipes are analyzed under flow conditions specific to their dimensions to obtain results regarding mass flow rates and air-fuel ratio obtained at the inlet to the engine.

In order to use the Syngas mixture in the simulation, a Species transport is activated in Fluent, in which the components of Syngas are defined based on their individual mass fractions as shown in Fig 4 and Fig 5 below.

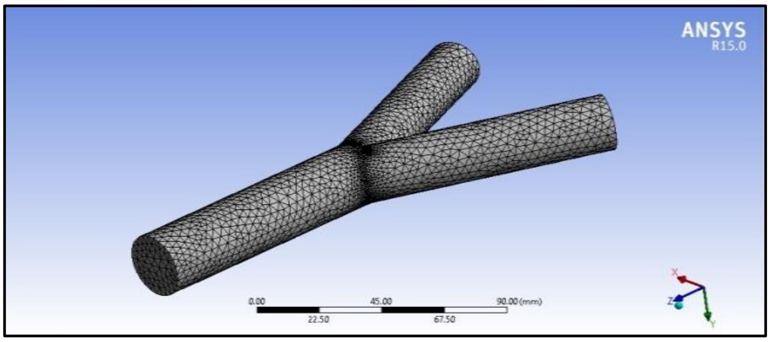

Fig 3. Meshed model of Inlet Pipe 1

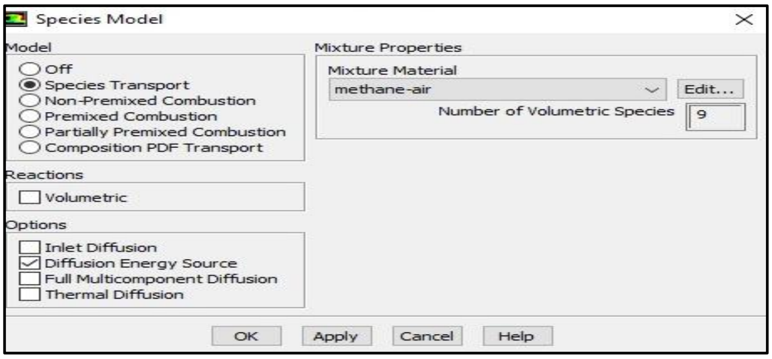

Fig 4. Species transport model in Fluent

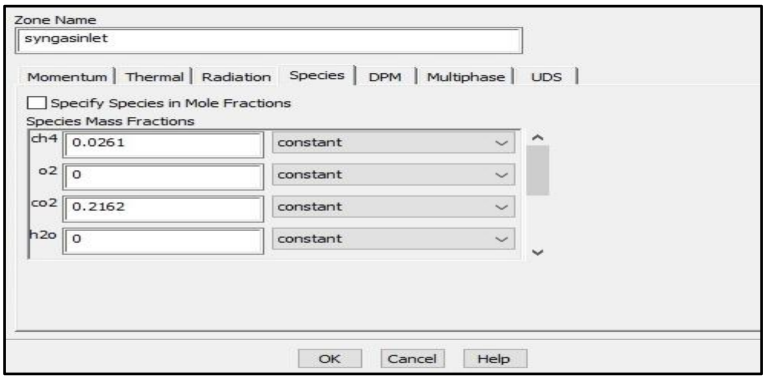

Fig 5. Syngas inlet in Fluent

For the purpose of using Syngas in the flow simulation, Syngas is defined in the Fluent materials library as a new fluid mixture of Methane and air, consisting of the additional elements, i.e., carbon monoxide, carbon dioxide and nitrogen as shown in Fig 6 below.

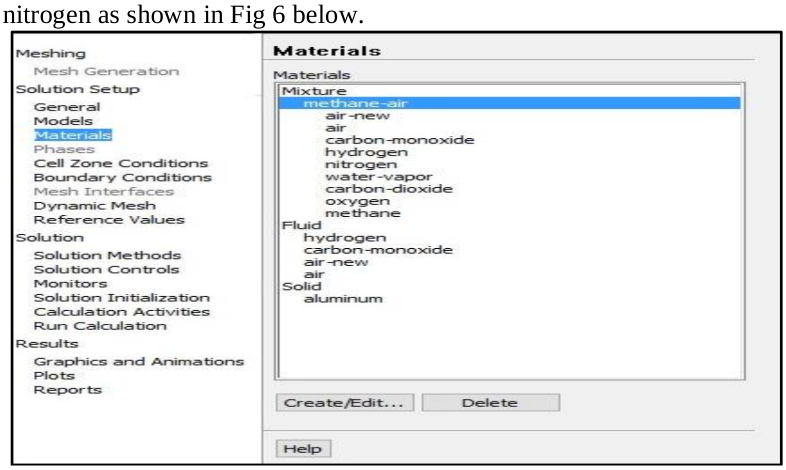

Fig 6. Material definition of Syngas in Fluent

One of the reasons for lower output power being obtained for theoretically correct amount of air-fuel mixture is the lower volumetric efficiency as compared to the theoretical value. Elimination of flow losses occurring in the inlet pipe is a possible solution for avoiding the lowering of volumetric efficiency. In order to monitor the losses, if any, in the inlet pipe, monitors were set up at the outlet of the pipe to calculate the mass flow rate at the exit. The monitor graph for Inlet pipe 1 is shown in Fig 7 below.

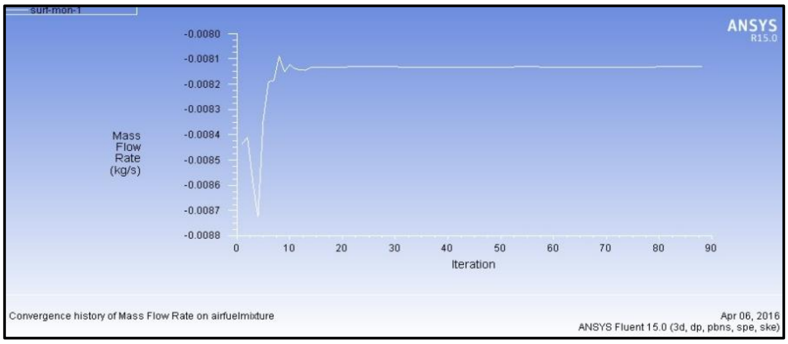

Fig 7. Outlet mass flow rate in Fluent

The mass flow rate data for the three designs is as given in Table 6 below.

Table 6. Obtained mass flow rate

Pipe Model No.	Expected outlet mass flow rate (kg/s)	Obtained mass flow rate (kg/s)
1	0.0076571	0.00815
2	0.0076571	0.00752
3	0.0076571	0.0075

As can be observed from the above table, the discrepancy between the expected and obtained values is negligible. This shows that the flow losses occurring in the inlet pipe are negligible and do not affect the volumetric performance of the engine adversely.

The main purpose of designing a suitable inlet pipe for the engine is to ensure that the required stoichiometric air-fuel ratio is available at the inlet to the engine. As already calculated above, the required air-fuel ratio is 1.545. In order to obtain the air-fuel ratio at the outlet of the pipe, an expression is created and inserted into Fluent to compute the final value of the air-fuel ratio as shown in Fig 8 below.
Table 7 shows the air-fuel ratios obtained for the pipe models.

Table 7. Air fuel ratio obtained

Pipe Model No.	Air fuel ratio required	Air fuel ratio obtained
1	1.545	1.54862
2		1.56374
3		1.56449

From Table 7, it is evident that the pipe design 1 is the optimum design as it supplies the required air fuel ratio at the inlet to the engine.

Fig 8. Air fuel ratio at engine inlet in Fluent

III. CONCLUSION

- The ideal composition of Syngas derived from biogas was identified
- The calorific value of Syngas was calculated for the obtained Syngas composition and the values were 6055.61kJ/kg (Higher calorific value) and 4925.49 kJ/kg (Lower calorific value)
- Stoichiometric air fuel ratio was calculated based on the overall chemical reaction and the value was found to be 1.545
- Mass flow rates of air and fuel were calculated based on the volumetric efficiencies and brake thermal efficiencies obtained from previous work and the required brake power value as defined in the problem statement.
- Three models of inlet pipes were modeled and analyzed for flow behavior with the view of optimizing the in parameters
- The values of mass flow rate and air fuel ratio obtained from flow analysis were found to be nearly matching with the theoretically calculated values
- The optimum inlet pipe model was found to be Model 1, which was determined based on the obtained mass flow rate and air fuel ratio

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