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EXPERIMENTAL AND NUMERICAL ANALYSIS OF PRODUCER GAS-AIR MIXER FOR GASIFIER-ENGINE SYSTEM.

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Abstract

For use of gaseous biofuels in existing IC engines, an air-fuel mixing device is necessary to avoid separation of gases due to density difference and for proper mixing at a desired air-fuel ratio with least pressure drop during intake. The aim of the present work is development of an effective mixer using CFD and experiments. The CFD simulations are carried out for a Venturi mixer of a 32kW CUMMINS producer gas engine. The CFD results show that the mixing quality degrades with increase in throat diameter and decrease in number of gas holes while unaffected by their cross-sectional area. Moreover, the pressure losses increase as the number of gas holes are increased while throat diameter and cross sectional area of gas holes are reduced. The air fuel mixer tends to becomes rich when throat diameter and number of holes are reduced. An effective mixer is fabricated with parameters chosen based on the CFD analysis. For experimental validation, the test bench with air blower is installed to analyze pressure losses and velocity profile in the mixer. Furthermore, rice husk gasifier test setup is installed to study the gas-air mixing quality. The simulated results have good agreement with the experimental results.

Keywords: biofuels; air-gas mixer; gasifier; CFD

Introduction

Biomass is one of the important renewable energy sources in developing countries like India, where majority of population depends on agriculture. Deployment of biomass gasification technology can be helpful for development of economy as well as it may be solution for energy crises in remote areas. It also helps to decentralize generation of the electricity. The electricity generated from biomass gasification is a potential source to meet the rural energy needs. The biomass gasification systems are known to generate producer gas as the combustible fuel that is clean enough to be used in I C engines[1][2]. It consists of carbon monoxide (CO), hydrogen (H_2), nitrogen (N_2) and carbon dioxide (CO_2).

Gaseous fuels have a number of advantages as compared to liquid fuels. However, they face certain key problems in regards to their widespread usability. One important aspect of the producer gas is that the compositions and properties of gaseous fuels vary from source to source as well as from time to time.[3] Also, the availability of a certain gaseous fuel differs drastically from place to place. These variations are known to affect engine performance and emissions through changes in

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fuel metering characteristics and knock resistance of the fuel[4][5] [6]. Moreover, a few modifications are needed to use IC engines for the biomass power plants. The air fuel ratio is one of the most important variables for an IC Engine metering and, hence, a mixing device is needed for effective mixing of air and fuel. A good producer gas-air mixer, should be able to adjust the air to fuel ratio easily and reproduce the performance while having a simple and rugged design[3]. The mixer designed for producer gas must have an ability to maintain the required air-to-fuel ratio near to stoichiometric with varying load conditions, smooth operation with minimal pressure loss and on-line provision for air/fuel tuning during the operation.

When fuel gas consists of different compositions of gases with variation in densities, there are possibilities of improper mixing and separation of gases and air in intake system. For proper combustion it is necessary to ensure the variation of air fuel ratio in the combustible mixture is within the permissible limit. The local air-fuel ratio variation cause the incomplete combustion and the fuel gas may escape through exhaust[7]. So it is necessary to study the flow patterns along with overall air fuel ratio and pressure drop across the gas mixer. It is also important to note that the gaseous fuels such as producer gas and biogas, derived from biomass, are generally available at low pressure i.e. near to atmosphere. This brings in the issue of proper mixing of gas-air mixture particularly when gas is not available at high pressure. For development of the engines for such applications, the design of effective metering and mixing device becomes crucial[8][9].

The technology for high pressure gas mixer is quite mature, also lot of literature is available for these gases such as CNG, LPG or LNG. [10][11][12][13][14]. The position of injector and orientation of gas injection is also studied for CNG and H_2 gas to discuss the effect of homogeneity on engine performance[9][15][16]. The performance of LNG and LPG engines are improved by intake system modification and proper designing of mixing devices for homogeneity of mixture[17][18]. However, for biomass derived low pressure gases like producer gas and bio gas [2] [19][20][21] literature is relatively rare. Danardono and et al [19] have developed mixer for SI engine using syngas as a fuel and for experimentation they have used the blowers. Similar study was performed by Chandekar et al [20] for biogas as fuel. They have studied amount of biogas variation for various load and biogas compositions by using CFD analysis. However, experimental analysis with continuous variation arising due to use of gasifier is not carried out in this work. Also, literature discussing the homogeneity of producer gas with air at the outlet mixer is relatively rare. As can be seen, most of the literature available on producer gas is using syngas for experimentation. Unlike syngas, the properties of producer gas, which is derived from gasifier and used in IC engine, is very sensitive to the load change[6]. For biomass gasifier connected to engine, it is difficult to achieve steady state to get a stable composition and flow pattern. Such experimental studies with gasifier and IC engine are not available in literature. Therefore, it is essential to test the performance of a mixer with gasifier coupled with IC engine as well as stable blower conditions.

To ensure the proper mixing of gas and air during intake at an optimum ratio, the main challenge is designing a mixing device. Venturi type gas mixer is one of the most used gas mixer. Number of holes, throat diameter and cross-section area of gas exit hole can be varied to get desired quantity of gas and air and their mixing for the particular engine[19]. The present work deals with the use of multi-dimensional CFD simulations of turbulent mixing of producer gas and air in order to design a Venturi mixer for 32 kW CUMMINS producer gas engine. It is aimed at further understanding of the air and fuel distribution by performing CFD studies using the ANSYS-FLUENT software. A few Venturi type mixers designed during the current study have been simulated. The Venturi with optimum parameter has been fabricated and validated with experimentation carried out in the laboratory. For experimental validation, the test bench was prepared with blowers. Engine conditions are maintained during test. During these experimentations, the readings are noted with air for pressure losses and velocity profile. Then risk husk gasifier test set up is installed to study the producer gas-air mixing quality with blower as well as with engine.

Design of Mixer

The Venturi mixer design should be compact, with minimum pressure loss across the Venturi-mixer, good suction pressure mainly in the throat due to the Venturi effect from the pressure difference, and homogeneous or good mixing quality. Figure 1 shows the conceptual mixer design based on the Venturi. Higher pressure at the mixer throat leads to lower velocity. This results in poor suction of gas from the tube and air from the inlet. The poor mixing, in turn, degrades the engine performance because of the air fuel ratio variations.

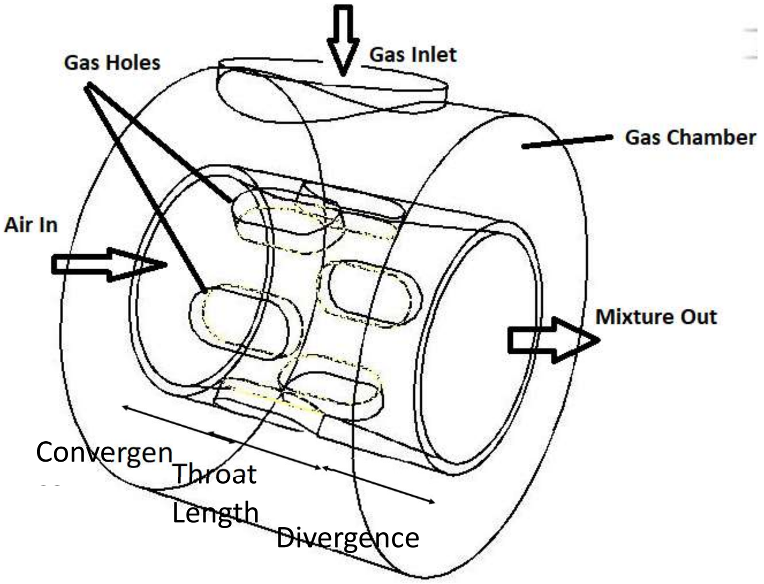

Fig 1 Conceptual Venturi Type Mixer

CFD Analysis

Based on the preliminary design shown in Figure 1, three dimensional CFD simulations of mixer are performed by using ANSYS-FLUENT. The flow parameters like flow rate of air and gas, pressure drop across the air and fuel line, velocity profile and concentration distribution of gas in air are studied.

The two major design parameters, i.e. number of holes and throat diameter, which affects the performance of mixer, are varied. The divergence and convergence angles have been fixed to 5^0. The mixer is modeled and simulated for different values of various parameters as given in Table 1. The effect of these parameters on air fuel ratio and pressure drop across air are studied to design an air- producer gas mixer. For the simulations, the geometry is prepared in GAMBIT in two volumes, first volume for the outer gallery for gas and second for Venturi, inlet and outlet pipes as shown in Figure 2. Two types of mesh were selected for above mentioned volumes, namely, hybrid and hexahedral. Hybrid meshes have a hexahedral core with pyramidal and tetrahedral cells that produce a high quality versatile grid for gas gallery where the flow parameters to study are of less interest. The cell size of 0.002 grid size was found to give reasonably accurate results and hence chosen for the detailed simulations. While for Venturi, the mesh scheme selected is hex/wedge and cooper type with mesh size of 0.001 to cover the smallest space in geometry. The solutions are found to be quite accurate with these grid sizes.

Table 1 Variation in the Parameters for Simulation

	Gas holes variation								
Throat diameter	No of holes = 4			No of holes = 6			No of holes = 8		
	Dia.	Total area	Throat length of the mixer	Dia.	Total area	Throat length of the mixer	Dia.	Total area	Throat length of the mixer
m	m	m^2	m	m	m^2	m	m	m^2	m
0.07	0.016	0.00301	0.049	0.016	0.00301	0.045	0.016	0.00301	0.041
0.08	0.021	0.00422	0.05	0.021	0.00422	0.048	0.021	0.00422	0.043
0.09	0.025	0.00606	0.062	0.025	0.00606	0.055	0.025	0.00606	0.049
0.095	0.029	0.00747	0.067	0.029	0.00747	0.059	0.029	0.00747	0.052

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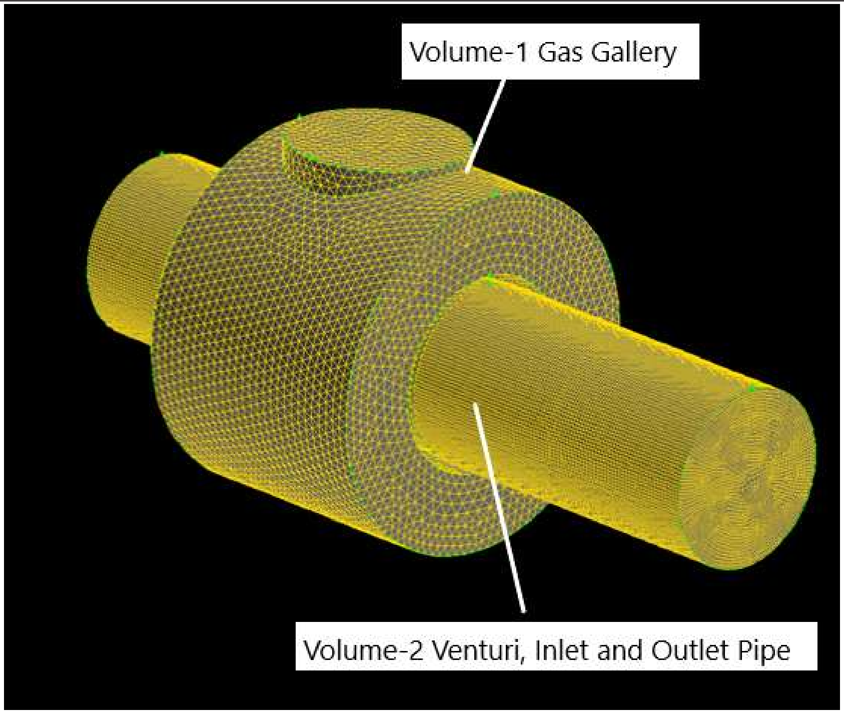


Fig 2 Mixer Geometry with Mesh

The computation models were run in the steady state conditions. The turbulence model used in this calculation is the Standard k-ε model because it is the most widely used and quite well validated model in terms of consistency and reliability, and it also consumes less computer time[19] [12] [20]. Near the wall, enhanced wall treatment model with pressure gradient effects are used, which gives reasonably accurate results for a wall bounded with high Reynolds number flow. SIMPLE (Semi-implicit method for pressure link equation) method was used as the solution algorithm. The SIMPLE method was chosen because it is used solely for steady state calculations in the iterative mode. Pressure boundary conditions were applied on the air inlet, gas inlet and outlet of the Venturi mixer. The pressure boundary type was selected to obtain a model reflecting experimental conditions. The turbulent intensity is set to 4% at all boundaries with hydraulic diameter conditions.

CFD Results

It is observed that as throat diameter is increased, the total area required for gas entry also increases. For the same diameter of the gas holes, the throat length increases with decrease in number of holes. Hence for less number of holes the overall length of the mixer increases.

The results obtained from simulations are discussed in subsequent sections.

Effect of throat diameter

As shown in Figure 3, pressure drop increases with reduction in the throat diameter. This pressure drop is even more when flow rate is more. Also it is observed that air fuel ratio is greatly affected by throat diameter. As throat diameter increases mixture becomes leaner. For the pressure drop considered for simulation, the desired air fuel ratio of close to one can be achieved with the throat diameter of 0.9m. As throat diameter further increases mixture tends to be leaner.

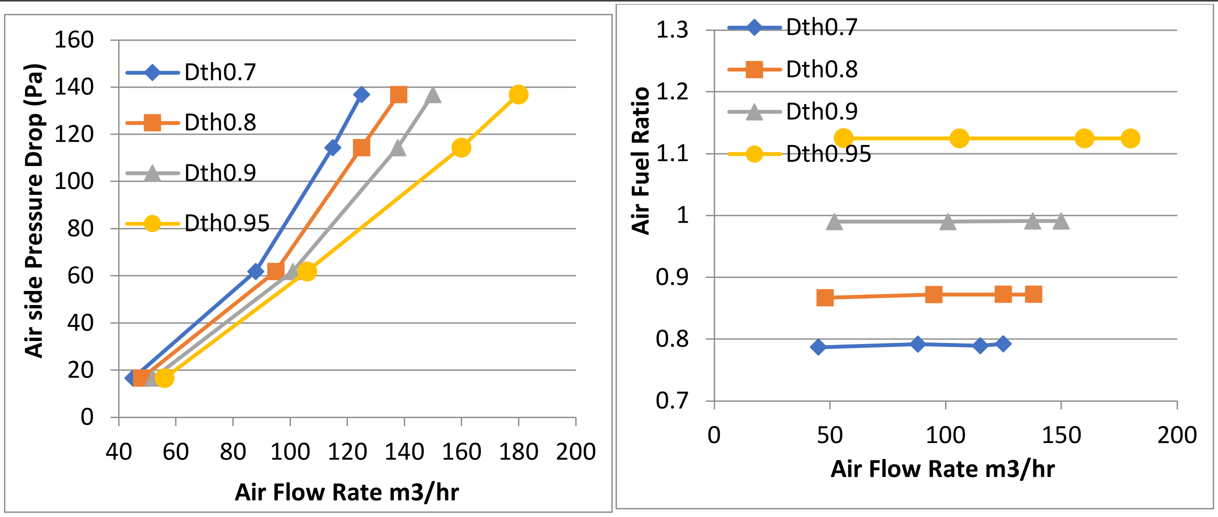


Fig 3 Effect of Throat Diameter on Pressure Drop and Air Fuel Ratio for Six Numbers of Holes

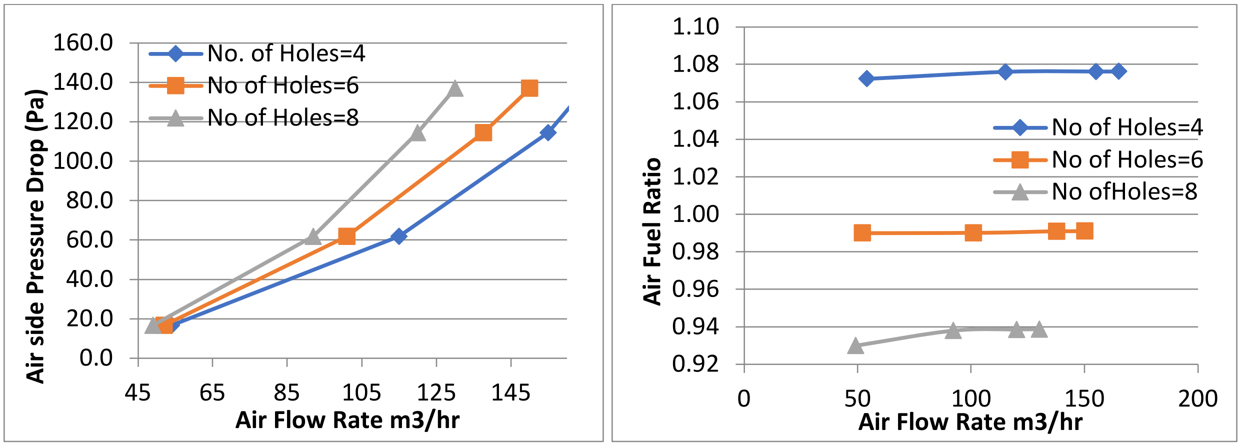
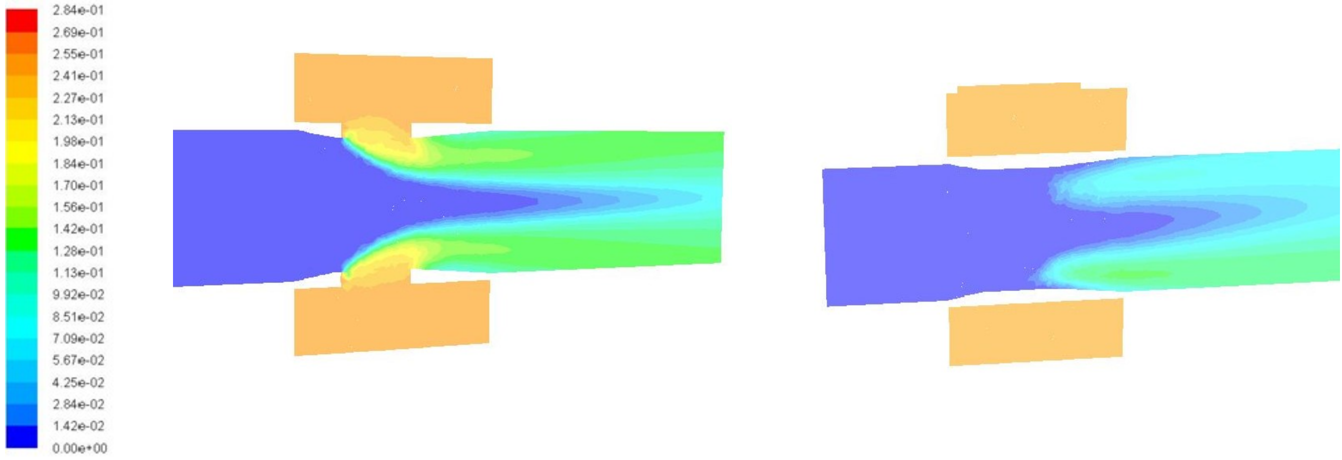


Fig 4 Effect of Number of Holes on Pressure Drop and Air Fuel Ratio for Throat Diameter 0.9m

Effect of number of holes

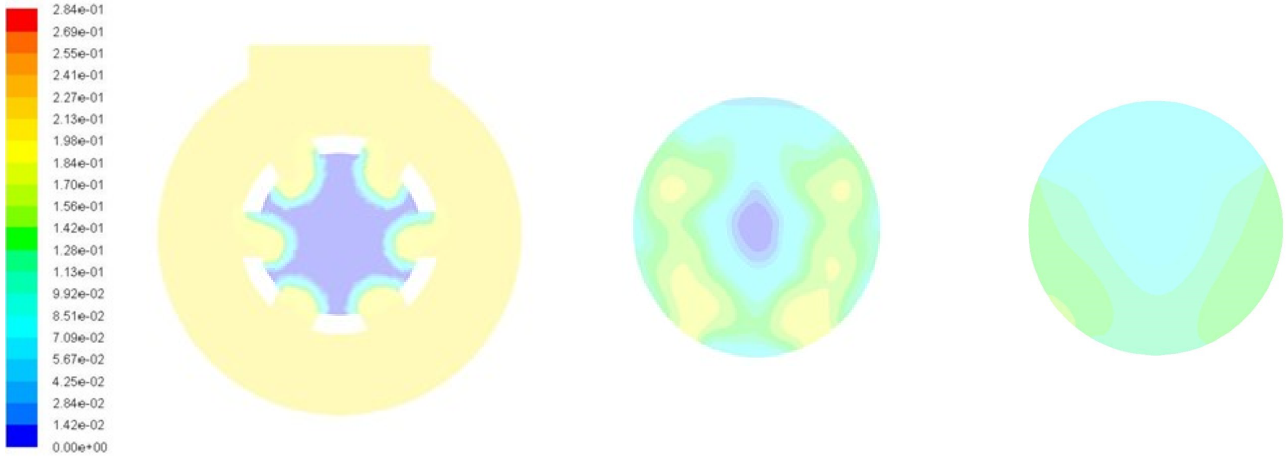
Figure 4 shows, the effect of number of holes on pressure drop on air side and air fuel ratio. As number of holes increases, pressure losses increase, also the mixture tends to be richer. For six numbers of holes with the pressure drop, the air fuel ratio is near to one, which is desired

Fig 5 Counters of Mass Fraction of CO along the Length a) Horizontal b) Vertical Cross Section



(a) (b)

for Mixer of 0.9m Throat Diameter with 6 Holes



(a) (b) (c)

Fig 6 Counters of Mass Fraction of CO at a) Center of the Throat, b) Exit of Mixer and c) 10cm from Exit for the Mixer of 0.9m Throat Diameter with 6 Holes

Distribution of CO and H_2

Moreover, the gas distribution is observed from CFD simulation of mixer with throat diameter of 0.9 and number of holes is kept at 6 as shown in Figures 5 and 6. It is seen that the mixing quality is better than mixer with that obtained with throat diameter 0.9 and 4 numbers of holes. However, the pressure drop for this mixer is less than the mixer with throat diameters of 0.7 or 0.8 with 8 numbers of holes. Hence, based on this study the mixer with six numbers of holes and throat diameter of 0.9m has been selected as an effective model for further experimentations. The mixer is manufactured with dimensions as shown in Figure 5.

Experimental Validation

The experiments are carried out in three phases, in the first phase mixer is connected to only blowers. In second phase Gasifier is used along with blower while in third phase, mixer is connected to gasifier along with IC engine. The details are discussed subsequently in this section.

Phase –I

For experimentation purpose in phase-I, instead of taking producer gas, air is used for blower test set up where pressure gradient and velocity profiles are validated at similar experimental conditions as that of engine. The simulations are also carried out for similar conditions for comparison with experimental results. In first phase, the experimentation had been done on fabricated setup (as shown in Figure 8) to validate the simulated data. The test setup consists of two blowers one for mixture suction and another for gas side pressure rise.

Phase-II

During this second phase, the experimentation is performed to study the gas distribution along the suction pipe of the engine as well as pressure losses with producer gas. The rice-husk down draft gasifier is installed with thermal capacity of 40 kW. The gasifier is attached with flair mode with blowers instead of engine. The suction pressures of engine for different load conditions are provided to mixer inlet with the help of the blower. The blower instead of engine is used to get steady state conditions and to avoid the effect of engine fluctuations on gasification so that the same quality and quantity of gas should generate. The experimental setup is shown in Figure 9.

Phase –III

To check the performance of mixer with the engine, the mixer is fitted on 32 kW CUMMINS engine. Tests are conducted to check the pressure drop and response of mixer to air fuel ration with variation in load. It is observed that for higher loads, the gasifier becomes unstable in terms of the composition of the producer gas. Hence, readings are taken for stable conditions for the engine load of 0, 5, 10, 15, 20 and 28kW. The test is conducted for one hour run for each load. During experimentation of phase-III, for different load conditions of engine the gas flow rate and air flow rate are noted as given in Table 2. As during experimentation in phase-I and II the gas and air flow rates are varied, the results are compared and discussed based on basis of the gas and air flow rate instead of load.

Table 2. Gas and Air Flow Rate for Various Load Conditions

Load (kW)	Gas Flow Rate m3/hr	Air Flow Rate m3/hr
0	51	52
4.5	57	57
10	60	64
15	69	73
20	84	91
25	89	94
28	101	95

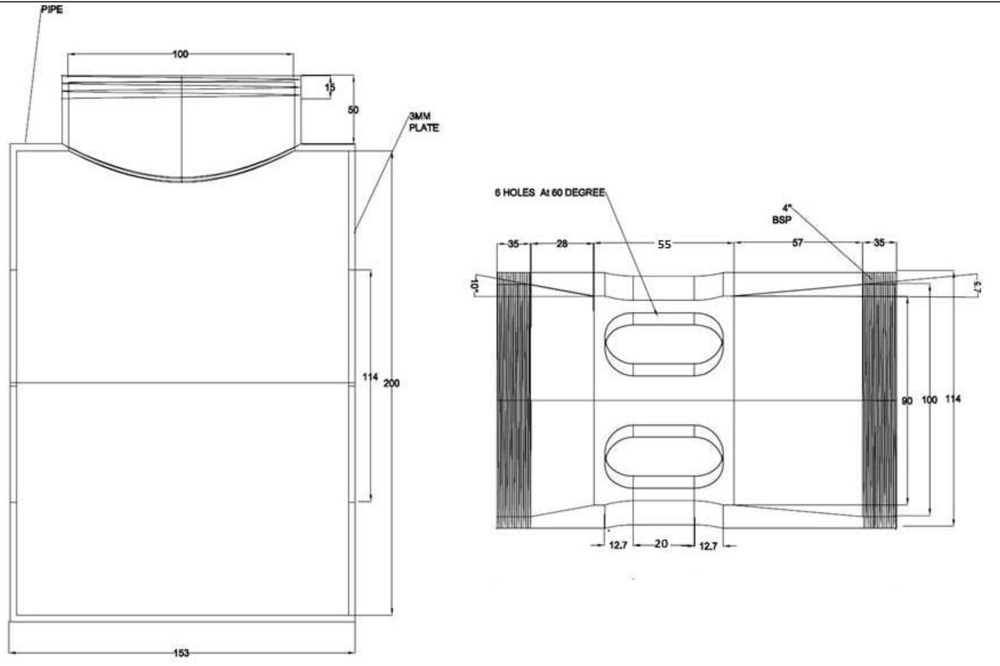


Fig 7 Mixer with Optimum Dimensions

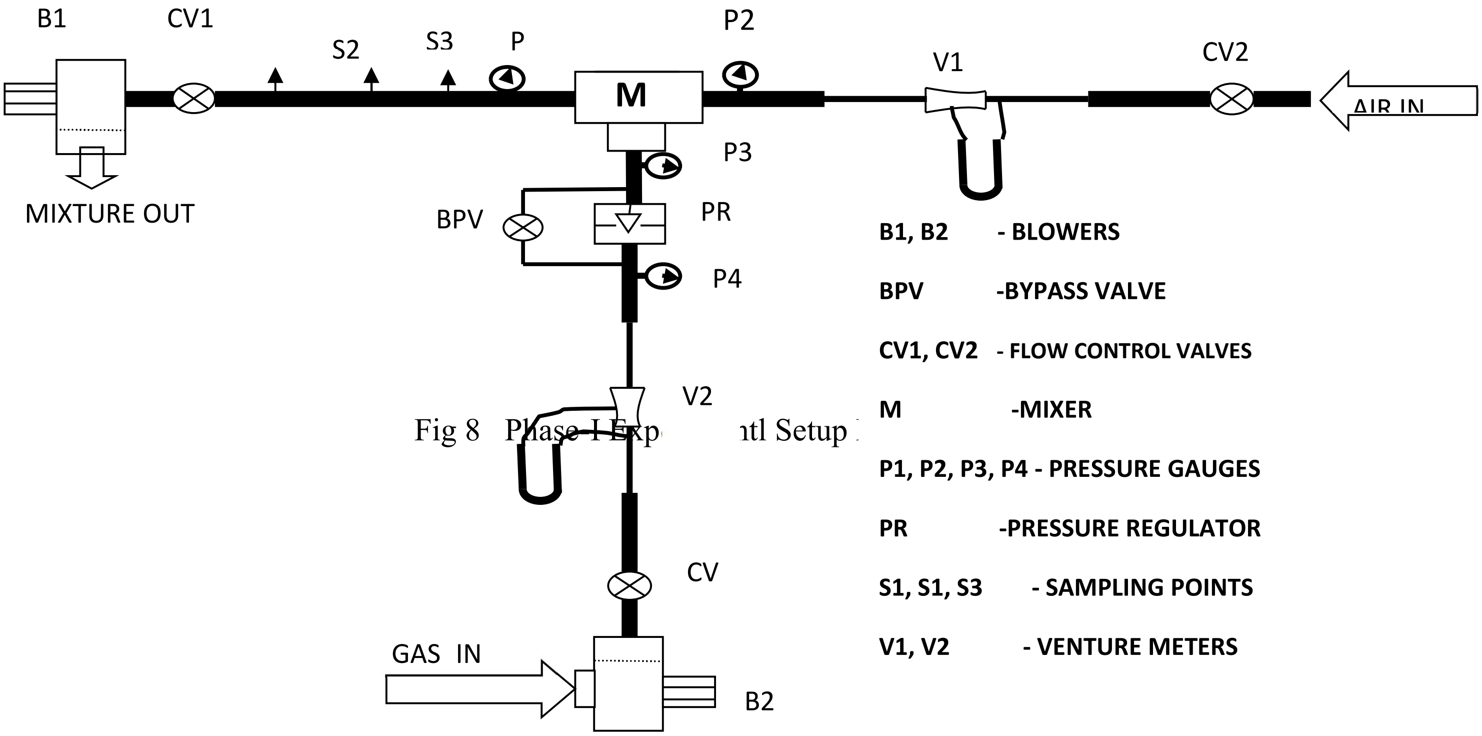


Fig 8 Phase-I Exp ntl Setup

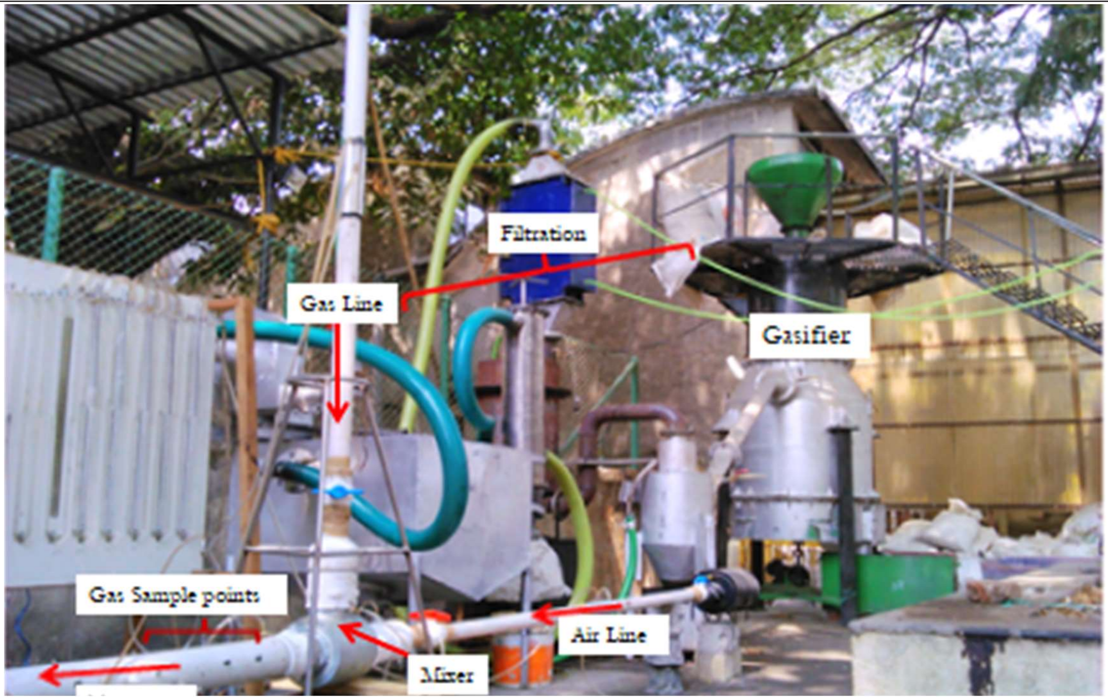


Fig 9 Phase-II Experiment Setup Layout

Results and Discussions

Effect of Volume Flow Rate on Pressure Drop

From the experimental results shown in Figure 10, it is observed that the results of experiments in phase-II, Phase-III and simulated results for pressure drop are in reasonably good agreement. The max deviation is about 10% for air side pressure drop while for gas side it is 12%. It also seen that as flow rate of air and gas increases the pressure drop tends to increase as per expectations.

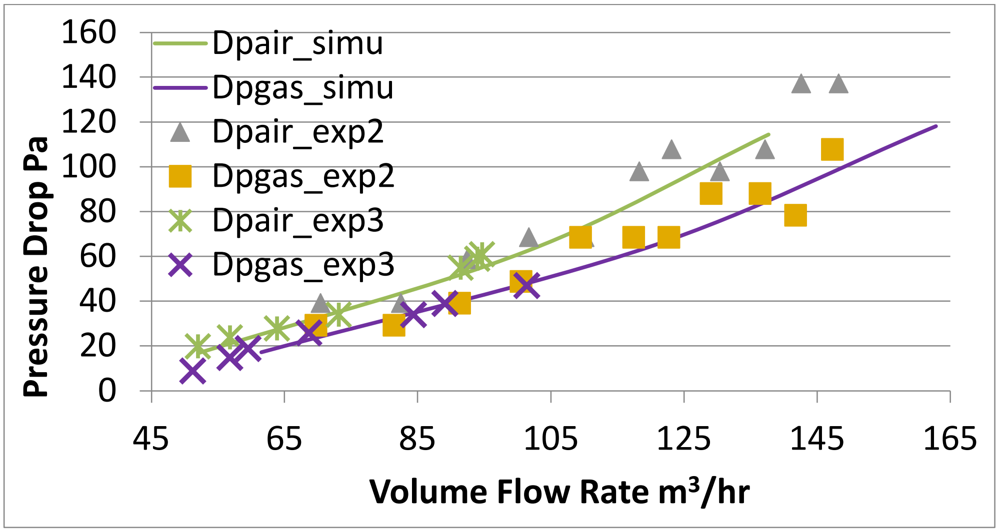
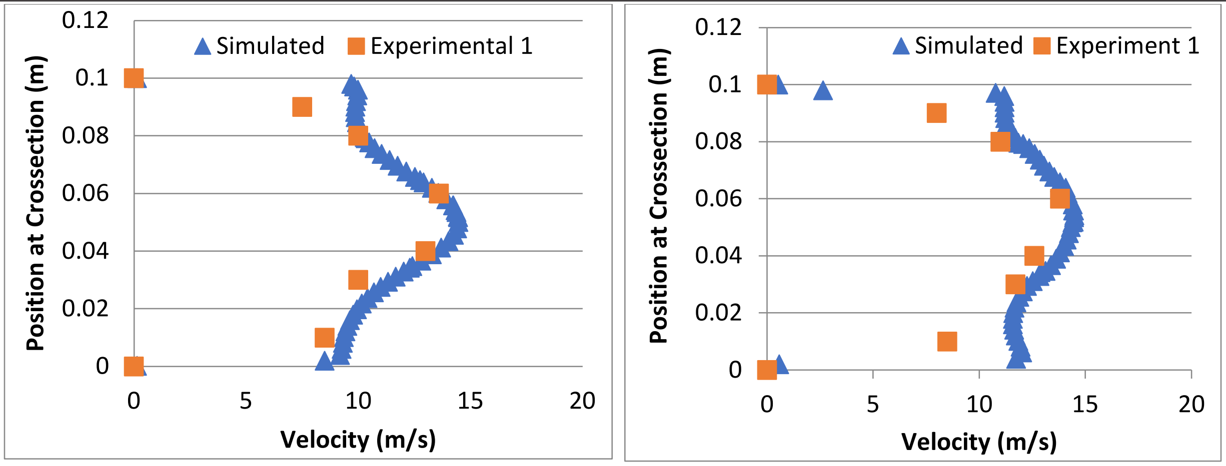


Fig 10 Comparison of Simulated and Experimental Results for Pressure Drop Vs Volume Flow Rate

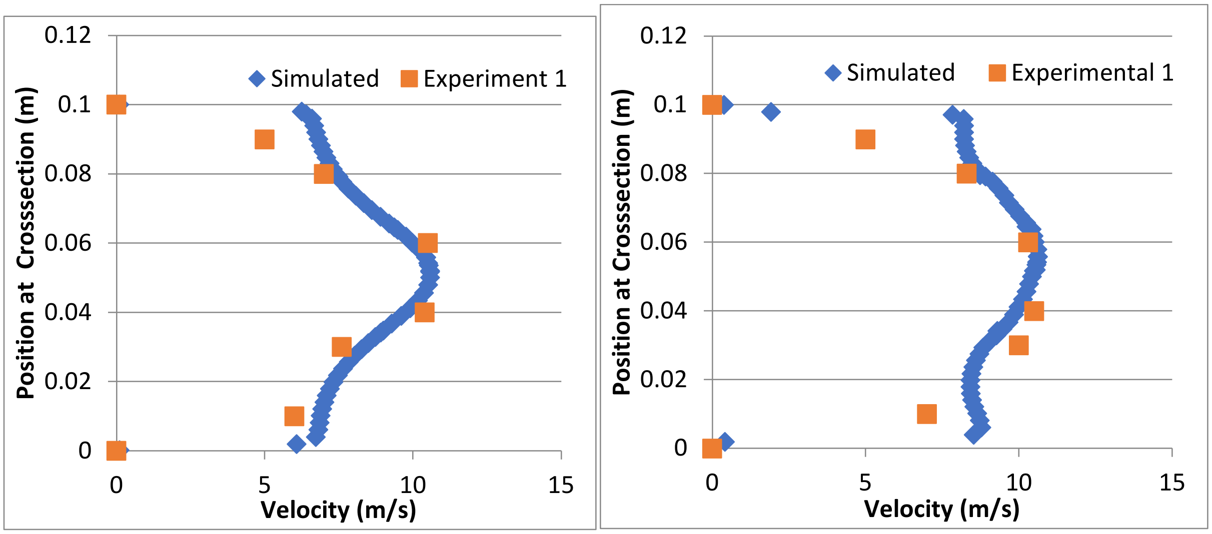
Velocity profile



a) b)

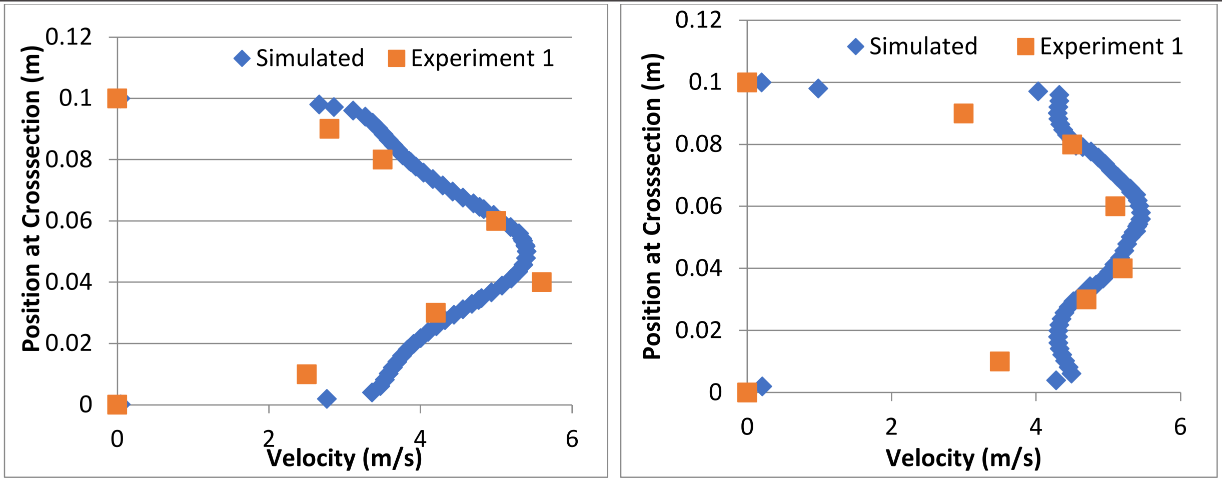
Fig 11 Velocity Distribution across Cross-section of Pipe for Volume Flow Rate=138 m^3/hr on a) Vertical line b) Horizontal line

During experimentation in phase-I, the velocity at different points along the cross sectional area of pipe is measured with help of a pitot tube. The Figures 11-13 show the comparison of velocity profile for at horizontal and vertical line on the cross section of pipe at 10 cm from the mixer outlet. It can be seen from the figures that the simulated and experimental velocity profiles are having good agreement. The experimental results are closer to simulated in case of low flow rate i.e. at 53m^3/hr, while those are deviating more when flow rates are higher.



a) b)

Fig 12 Velocity Distribution across Cross-section of Pipe for Volume Flow Rate =101 m^3/hr a) Vertical line b) Horizontal line



a) b)

Fig 13 Velocity Distribution across Cross-section of Pipe for Volume Flow Rate =52 m^3/hr a) Vertical line b) Horizontal line

Gas Distribution

Gas compositions are measured at the test point with gas analyser, at 10cm from mixer outlet, and are plotted in Figures 14 and 15. It shows simulated results are in reasonable agreement with experimental results for low flow rates i.e. at 52 m^3/hr. Also it can be seen that the developed mixer is capable to have desirable mixing quality.

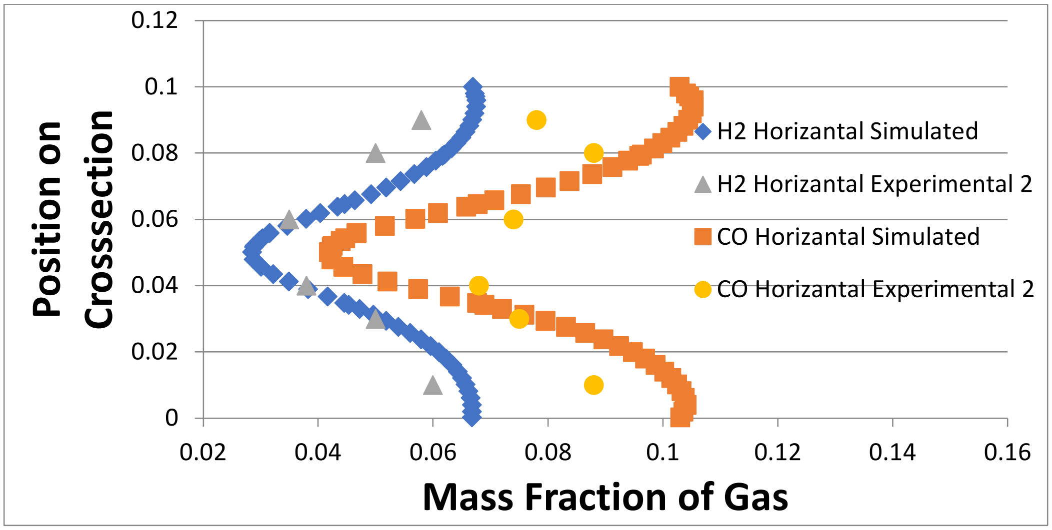


Fig 14 CO and H_2 Distribution along Horizontal Line on the Pipe Cross Section at 10 Cm from Mixer out for the Volume Flow Rate of 52 m^3/hr

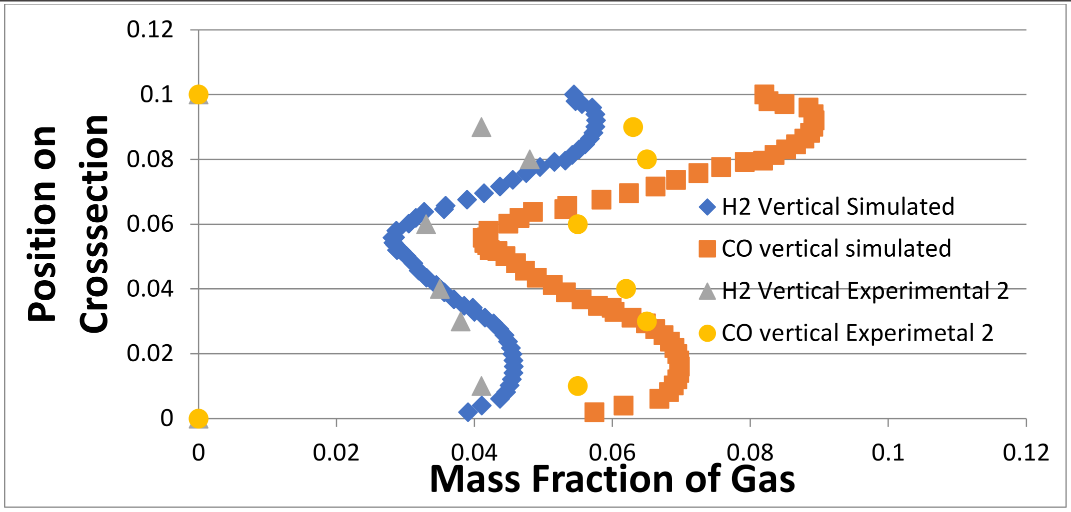


Fig 15 CO and H_2 Distribution along Vertical Line on the Pipe Cross Section at 10 cm From Mixer Out for the Volume Flow Rate of 52 m^3/hr.

Variation in Air Fuel Ratio

It is observed from the figure 16 that the variation in air fuel ratio is in between 0.93 to 1.1 for different engine conditions. The variation is in the range of 10% of the simulated results. This is due to the variation in the suction pressure. For constant suction pressure which is maintained during the Phase-II experiments, the air fuel ratio is having good agreement with simulated results.

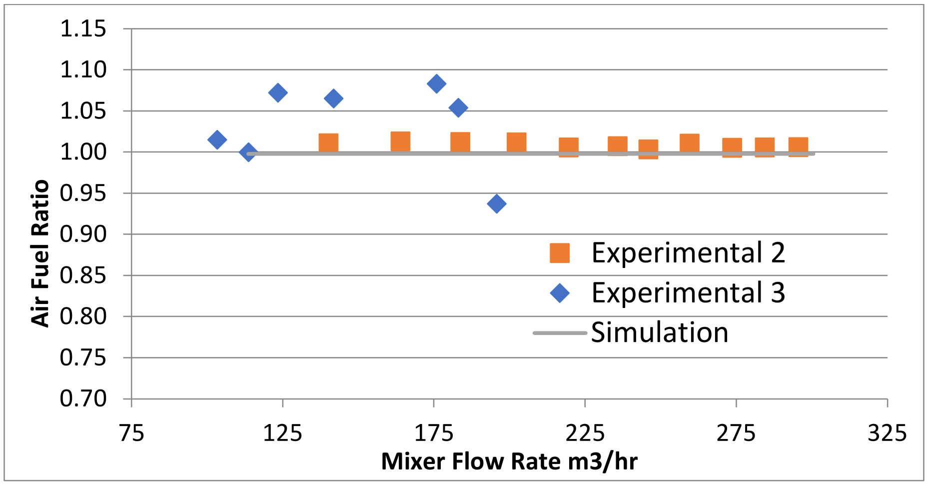


Fig 16 Variation in Air/Fuel Ratio with Mixer Flow Rate

Conclusion

In this study, various designs of mixer for producer gas are simulated using CFD. It is seen that the standard k-ε model with enhanced wall treatment is efficient for the venture mixer with a divergence angle of 5°[19][12]. From the CFD analyses following results are recorded,

1. Pressure drop increases with reduction in the throat diameter. Also air fuel ratio is greatly affected by throat diameter. As throat diameter increases mixture becomes leaner. The throat diameter of 0.9 m gives desired air fuel ratio with considerable amount of pressure drop.

2. As number of holes increases, pressure losses increases, also the mixture tends to richer. It is seen that the six numbers of holes with the considerable pressure drop, the air fuel ratio is near to 1, which is desired.
3. Also it is observed that as divergence angle increases the pressure losses increases. The ratio of inlet air pipe diameter to throat diameter can be selected near to 1, so the divergence angle can be kept below 5°.

Based on the above discussion, the mixer with six holes with throat diameter of 0.9m and divergent angle of 5° is fabricated. The experiments were carried out in three stages to validate the CFD analysis results. In first stage velocity profile and pressure losses are validated only with air on test bench consisting of blowers. The simulated results show agreement with experimental data with the maximum deviation in air flow rate calculation of 6-8%.

In second stage, the mixer is connected to gasifier and blower instead of engine to avoid the fluctuations. The steady conditions are used to measure the gas distribution along the pipe diameter. It is observed that the homogeneity in air- gas mixture can be achieved within short distance of 10cm. Moreover, separation of low density gases is avoided.

In third stage of experimentation, the developed mixer is tested for the actual engine conditions of 32 kW engine connected to gasifer. Fluctuations are observed in the working of gasifier. The response to load variation is governed by the engine governer by varying the total quantity of the mixture. The air fuel ratio is maintained near to 1. If the gas composition changes due to repsonse from gasifier then the fuel flow rate is controlled by another valve in the gas line. The variations in the overall air fule ratio is small and within range of 10% as that of stoichiometric.

It is found from CFD anlysis and experimental results that the devloped mixer is sufficient to provide the desired airfuel ratio for alomost all load conditions of the engine. Also it is effective in mixing of air fuel with acceptable pressure drop across the mixer.

Acknowledgments

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Appendix

A. Fuel Gas Properties Considered for Simulation

Gas Used	Producer Gas
Composition	CO (15%), H_2(12%), CO_2(12%), CH_4 (3.5%), Rest is N_2 (Volumetric composition)
Air Density (at 0°C, 101.325 kPa) kg/m³:	1.292
Gas Density (at 0°C, 101.325 kPa) kg/m³:	1.09476
Stoichiometric air/fuel ratio kg Air/kg Gas:	1.3431
Gas consumption in m3/hr	120

B. Engine Specifications

Make	Cummins India Ltd Pune
Model	C40PG5P
Type	Liquid cooled, 4 Stroke Gas Engine
Power	32kW
Number of Cylinder	6

C. Gas Analyser Specifications

Specification, Make- Electronic System Tech,
Model- Multi Gas Analyzer

Gas	Range (%Volume)	Resolution
CO	0-50	0.1%
CO_2	0-25	0.1%

H_2	0-50	0.1%
CH_4	0-100	0.1%
O_2	0-25	0.1%