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Numerical Optimization of a Premixer for an Internal Combustion Engine using Producer Gas as a Fuel

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Gasification seems to be one of the sustainable green energy solutions to fulfill the current and future energy needs. For efficient utilization of producer gas on existing IC Engines, carburetor/premixer needs to be carefully designed and developed to achieve uniform mixing quality. A long radius nozzle type premixer has been designed for natural gas engine to be operated on producer gas as an alternate fuel. Different configurations of T – Type premixers with single air entry and twin air entry with different throat diameters and hole sizes are numerically analysed using ANSYS® CFX. Turbulence is modelled using RNG k - ε closure model. Mixer performance is compared in terms of constituents' mass fraction, flow Uniformity Index (*UI*) and pressure penalty. Numerical analysis reveals that throat diameter, air entry type and air hole diameter governs mixing and pressure drop. Out of all configurations, twin air entry type premixer provides better mixing of producer gas and air. The optimized design of premixer shows that the absolute deviation in mass fraction of individual constituent lies in the range of ± 1.73% with respect to the actual mass fractions obtained. The average absolute deviation calculated is 1.37% with Uniformity Index 0.958 at the exit plane while the pressure drop across the premixer is 951 Pa.

Keywords: CFD, Homogeneity, Producer gas, Twin air entry

Introduction

With the increasing energy demand and stringent emissions norms in the current and near future, it is necessary to find green energy solutions to manage the current and future energy demands within the emissions norms. After conquering the problems associated with conventional gasification technology, gasification seems to be a truly economic and ecologically sustainable green energy solution with lesser emissions.[1–4] "Zero Effluent Discharge Gasification Technology" has been developed which is not only environment friendly but also more efficient than the conventional gasification system.[5,6] Clean producer gas of gasification can also be utilized as a green fuel in IC Engines.[7,8]

However, for its use in IC Engines, proper mixing of air and gaseous fuel is absolutely necessary. This calls for numerically and experimentally verified design of pre-mixture. This research addresses this aspect.

Literature Review

Homogenous mixture of air and fuel is one of the prerequisite for efficient and clean burning. Carburetors employed for other gaseous fuels (like natural gas, biogas, etc.) are not suitable for producer gas due to lower stoichiometric air-fuel ratio.[7] Developing optimum gas carburetor for producer gas fuel is a major challenge as there is no ready solution available for such a low air-fuel ratio. A simple carburetor was developed for producer gas engine in conjunction with zero pressure regulator by Shridhar *et al*.[7] This carburetor has separate individual ports for air and fuel (can be modified or tuned to achieve the required air – fuel ratio) without any moving components. Shashikanta *et al.*[8] designed and incorporated Venturi type – gas carburetor mixer with reduction ratio of 0.77 and pressure drop across Venturi in the range of 50 – 250 mm WC. Kumar *et al.*[9] has designed and developed gas carburetor for a gasifier – engine System by CFD approach with separate tangential entry for mixing gas and air whereas the diameter of the mixing chamber is decreased gently along the flow to minimize pressure drop along the path and the bottom side of carburetor is used to offer cyclone action. Suryawanshi *et al.*[10] has carried out the Mixing Performance Analysis of T shape, Y shape and Venturi shape Producer Gas Carburetor using CFD simulation and concluded that Venturi type premixer provides better mixing performance and homogeneous air–fuel mixture. Bhoi

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et al.[11] had developed concentric tube type premixed burner for producer gas with the provision of swirl vane for thorough mixing of air and gas and bluff body was provided for flame stabilization. The optimal performance is reported with conventional bluff body having blockage ratio of 0.65 out of different diameters of the bluff body.

Research Gap and Objectives

For efficient utilization of producer gas as a fuel in existing IC Engines, a premixer needs to be incorporated in the intake to achieve homogeneous charge. T-type pre-mixer is widely used for mixing fuel and air.[9] The pressure drop across the premixer should be as minimum as possible along with a homogeneous mixture of the charge after mixing so that the breathing capacity of the engine and its performance is not affected much. Apart from this, the shape of the premixer is also very important and crucial. Unfortunately, the standard methods for the design of the premixer and how to select the shape of the premixer are not available in published literature.

Looking at these facts, the principal objective of the present work is to design a premixer and carry out 3-D numerical analysis and optimization of it to achieve the homogeneous mixture of air and producer gas with a minimum pressure drop.

Methodology

With these objectives, in the present work, a novel twin air entry, long radius type producer gas premixer has been designed based on the capacity of the engine, the composition of the producer gas, Reynolds number of the flowing fluid with allowable/desired pressure drop across the throat. Limiting diameter ratio of the nozzle, pressure drop and shape of the premixer is decided based on IS standard.[12]

The engine data and producer gas composition utilized for design of various configurations of the premixer is taken from available literature[13] and given in Table 1 and Table 2, respectively.

Various configurations of single air and twin air entry premixer designed based on this data is given in Table 3. The general configurations of single air entry and twin air entry premixers are shown in Fig. 1 and Fig. 2, respectively.

Numerical Investigation of Premixer

Three dimensional CFD analysis of producer gas mixer is carried out to investigate the effect of air entry, throat diameter, diameter ratio, diameter of air holes and number of holes on mixture uniformity and pressure drop. Total 9 numbers of T-Type premixers, as shown in Table 3, with single air entry and twin air entry are analysed numerically. Commercially available CFD tool ANSYS-CFX is used for analysis. Diameter of air holes in premixers is selected such that air velocity in the throat region remains higher than that of the producer gas velocity. This prevents the backflow of the producer gas in to the air inlet lines through air holes at the throat section.

At the air inlet plane (blue arrow in Fig. 1) and producer gas inlet plane (red arrow in Fig. 1) mass flow rates are specified. At the outlet plane (black arrow in Fig. 1) of the domain pressure boundary condition is assigned. The remaining surfaces of premixer are considered as a wall.[9,14] The RNG k - ε model for turbulence with isothermal heat transfer

Table 1 — Engine specifications

Make	Cummins
Power	69 bhp
Bore × Stroke	102 mm × 120 mm
Compression ratio	10.5
Swept volume	5.9 litre
Fuel	Natural gas/ Producer gas
Cooling	Liquid cooled
Aspiration	Natural aspirated
No. of cylinders	6, in – line

Table 2 — Producer gas composition[13]

Constituents	CO	H_2	CO_2	CH_4	N_2
Molar (%)	19	20	9	1.5	50.5
Mass (%)	22.11	1.68	16.46	1	58.76

Table 3 — Summary of designed premixers' configurations

Premixer	Throat diameter of premixer (in mm)	Diameter ratio	Air entry holes at premixer throat section		Remarks
			Diameter (in mm)	No of holes	
1	36	0.6574	8.2	18	Single air entry
2	42	0.7669	9.0	18	Single air entry
3	42	0.7669	8.5	18	Single air entry
4	42	0.7669	8.8	18	Single air entry
5	36	0.6574	8.2	18	Twin air entry at premixer centre
6	36	0.6574	8.2	18	Twin air entry at throat centre
7	42	0.7669	9.0	18	Twin air entry at throat centre
8	42	0.7669	8.5	18	Twin air entry at throat centre
9	42	0.7669	8.8	18	Twin air entry at throat centre

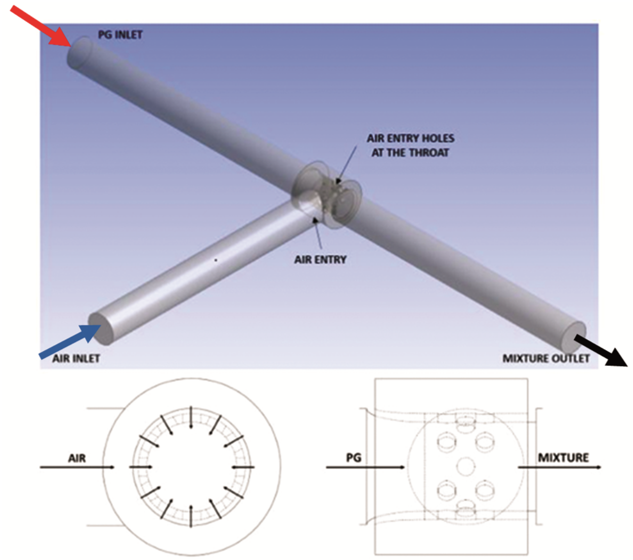

Fig. 1 — Single air entry premixer model

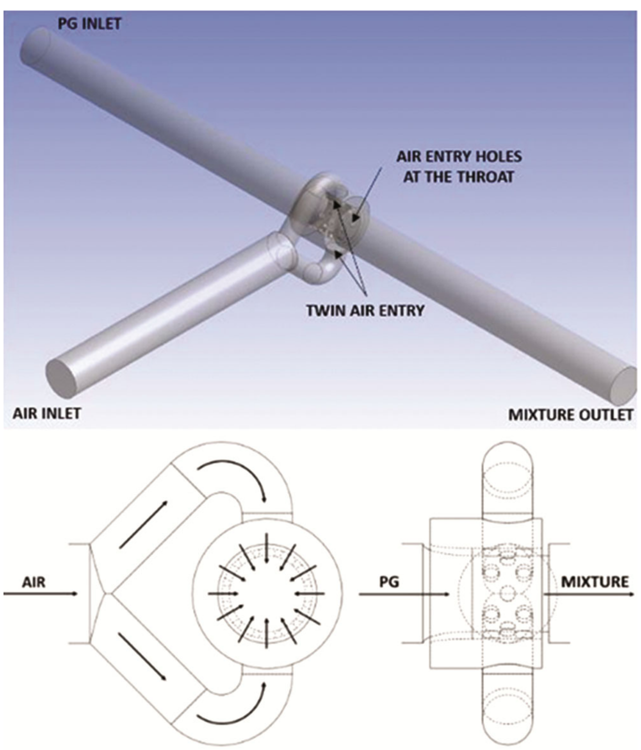

Fig. 2 — Twin air entry premixer model

conditions has been used for investigations.[9,15] The inlet and outlet pipe length has been taken as 10D (where D is the internal pipe diameter) to ensure fully developed flow conditions. The turbulent intensity value of 5 % is assigned to incoming flow stream into the domain. Variation in grid size is considered such that flow physics is captured effectively. The minimum and maximum sizes of grid cells in the computational domain are 3.8591E-2 mm and 3.8581 mm, respectively.

For all the nine different cases, air and fuel mass flow rate are kept constant at 35.1 g/s and 27.5 g/s based on available maximum engine load data of literature.[13] Static pressure of 1 bar is applied on exit plane for all cases.

To evaluate the mixing performance of premixer, the quantitative parameter flow UI has been used.[14] UI is calculated as follows:

$$UI = 1 - \frac{1}{2}\frac{\sum_{i=1}^{n}|m_i - m_{mean}|A_i}{A m_{mean}} \qquad \dots (1)$$

where, m_i : local mass fraction; A_i : local area; A : the cross area where UI is evaluated and mean mass fraction was computed as:

$$m_{mean} = \frac{1}{A}\sum_{i=1}^{n} m_i A_i \qquad \dots (2)$$

where, i is the local grid cell and n is the number of grid cells within the cross-section plane.

Results and Discussion

The mass average fraction of mixture constituents on the exit plane are given in Table 4. Initially premixer-1 is analyzed with throat diameter of 36 mm (diameter ratio 0.6574) with single air entry. Comparison of numerically predicted mass fraction with that of the reported experimental results[13] indicates deviation between these results and not in good agreement with the actual mass fraction of air and fuel. The percentage deviation of the numerically obtained constituents with the reported one is in the range of ± 5.5% with average absolute deviation of 4.3%. Pressure drop across premixer-1 is of order of 1587 Pa. The mixture UI on exit plane is evaluated as 0.919. This larger deviation of mixture constituents and higher pressure drop suggest that premixer needs to be modified to achieve better mixing with optimum pressure drop. Based on above observation, another eight different configurations are developed as described in Table 3 taking into account flow Reynolds number and pressure drop.[12]

The throat diameter of 42 mm (diameter ratio 0.7669) with single air entry is utilized in second variant of premixer. The results in terms of mixture constituents and pressure drop indicate refinement compare to premixer-1. The percentage deviation of the numerically obtained constituents with the reported constituents is in the range of ± 3.5% with average absolute deviation of 2.824%. The pressure

Table 4 — Summary of the numerical results of the premixers

Premixer	Pressure drop across premixer (Pa)	Mass Fraction of Constituents					
		Constituents	Exit plane	Actual[15]	Dev. (%)	Avg. absolute Dev. (%)	UI
1	1587	CO	0.09186	0.09712	−5.420%	4.426%	0.919022
		H2	0.00696	0.00736	−5.386%		
		CH4	0.00415	0.00439	−5.451%		
		CO2	0.06837	0.07229	−5.419%		
		O2	0.13444	0.12896	4.249%		
		N2	0.69422	0.68988	0.629%		
2	871.1	CO	0.09376	0.09712	−3.456%	2.824%	0.875603
		H2	0.00711	0.00736	−3.422%		
		CH4	0.00424	0.00439	−3.487%		
		CO2	0.06979	0.07229	−3.455%		
		O2	0.13248	0.12896	2.728%		
		N2	0.69262	0.68988	0.397%		
3	888.5	CO	0.09414	0.09712	−3.065%	2.504%	0.89032
		H2	0.00714	0.00736	−3.030%		
		CH4	0.00425	0.00439	−3.096%		
		CO2	0.07008	0.07229	−3.063%		
		O2	0.13207	0.12896	2.414%		
		N2	0.69232	0.68988	0.353%		
4	878.8	CO	0.09384	0.09712	−3.381%	2.762%	0.875853
		H2	0.00711	0.00736	−3.346%		
		CH4	0.00424	0.00439	−3.412%		
		CO2	0.06985	0.07229	−3.380%		
		O2	0.13240	0.12896	2.666%		
		N2	0.69256	0.68988	0.389%		
5	1625.3	CO	0.09461	0.09712	−2.583%	2.104%	0.978917
		H2	0.00717	0.00736	−2.548%		
		CH4	0.00428	0.00439	−2.614%		
		CO2	0.07042	0.07229	−2.582%		
		O2	0.13153	0.12896	1.993%		
		N2	0.69199	0.68988	0.305%		
6	1726.7	CO	0.09607	0.09712	−1.086%	0.877%	0.987712
		H2	0.00728	0.00736	−1.050%		
		CH4	0.00434	0.00439	−1.118%		
		CO2	0.07151	0.07229	−1.085%		
		O2	0.12997	0.12896	0.785%		
		N2	0.69083	0.68988	0.138%		
7	950.8	CO	0.09344	0.09712	−3.785%	3.078%	0.941464
		H2	0.00708	0.00736	−3.751%		
		CH4	0.00422	0.00439	−3.816%		
		CO2	0.06955	0.07229	−3.784%		
		O2	0.13267	0.12896	2.875%		
		N2	0.69303	0.68988	0.456%		
8	951.1	CO	0.09547	0.09712	−1.696%	1.373%	0.95841
		H2	0.00724	0.00736	−1.661%		
		CH4	0.00431	0.00439	−1.728%		
		CO2	0.07106	0.07229	−1.695%		
		O2	0.13056	0.12896	1.244%		
		N2	0.69135	0.68988	0.213%		
9	955.7	CO	0.09381	0.09712	−3.405%	2.766%	0.942681
		H2	0.00711	0.00736	−3.371%		
		CH4	0.00424	0.00439	−3.436%		
		CO2	0.06983	0.07229	−3.404%		
		O2	0.13227	0.12896	2.565%		
		N2	0.69274	0.68988	0.414%		

drop across premixer-2 is 871.1 Pa. The mixture UI is reduced to 0.8756 for premixer-2. The results obtained from premixer-2 are improved compared to premixer-1. Throat hole diameters have been increased to 8.5 mm and 8.8 mm with throat diameter of 42 mm. These variant of premixers are referred as premixer-3 and premixer-4. Out of these two variants premixer-3 performs better with the percentage deviation of the constituents with the actual constituents in the range of ± 3.5% and average absolute deviation of 2.504%. *UI* seems to be improved in comparison to two with comparable pressure drop. To further improve the value of *UI*, there is a need to device different air introduction strategy for better mixing of air and producer gas. The twin air entry concept has been proposed as shown in Fig. 2.

Twin air entry has two different variants with constant throat diameter of 8.2 mm. In first case (premixer-5) air is introduce at the center of the overall premixer while in second case (premixer-6) the twin air entry has been provided at the center of the throat of the premixer. Mass fraction constituents are obtained for both variant and same are tabulated in Table 4. Comparison of mass fraction constituents and *UI* for twin entry premixers with single air entry premixers indicates that twin air entry outperforms in terms of improved *UI* at the cost of higher pressure penalty. Among the twin air entry premixer, twin air entry at the throat (premixer-6) performs better in terms of mixture quality with comparable pressure drop. *UI* value obtained in premixer-6 is close to 0.99 which is very close to ideal value of 1. Higher pressure drop in premixer-6 can be reduced by increasing throat diameter and diameter of air entry holes.

In premixer-7, 8 and 9 air entry hole of diameter 9.5 mm, 8.5 mm and 8.8 mm are considered respectively. Throat diameter is increased from 38 mm to 42 mm with twin air entry at the throat. Comparison of results of Table 4 for premixer-7 to premixer-9 indicates that these variants of premixer perform better than premixer-6. Premixer-8 provides optimal performance in terms of UI and pressure drop. For Premixer-8, percentage deviation of the constituents is within the ± 1.73% with average absolute deviation 1.373%. Pressure drop across premixer is 951.10 Pa with fuel UI 0.958.

Further, the results show that the pressure drop in twin air entry premixer-7 is marginally higher compared to their counterpart single air entry premixer-3. This is due to fact that two air entry entries have higher flow losses than single air entry flow losses.[16] Overall comparison of data tabulated in table 4 indicates that premixer-6 provides best mixing performance for producer gas and air with a uniformity index 0.9877 whereas the premixer-8 considered as optimal design with pressure drop 45% lower than premixer-6 and comparable *UI*. The lower pressure drop across the premixers is due to higher diameter ratio at the throat.

Contour plots for various constituents of mixture on outlet plane of the premixer-7 are shown in Fig 3. Fig. 3(a) and Fig. 3(b) shows the mass fraction contours of constituents at premixer exit plane (plane at the premixer's nozzle throat) and at exit plane (located at the distance of 10D, D is the inlet pipe diameter) where flow becomes fully developed. The contours of the mass fraction of the constituents reveal that the constituents of the producer gas are rich in the vicinity of the centre of the exit plane and gradually become leaner in radially outward direction. The constituents of the air are richer near the circumference of the throat and become gradually leaner in radially inward directions. This is due to fact that producer gas is flowing through core region and air is entering through circumferentially located air holes in the throat region.

In the downstream of the throat plane mixing takes plane between producer gas and air due to diffusion of species and due to turbulence mixing between air and producer gas. The mixing progresses gradually spread across the entire planes till the flow becomes fully developed. After this, mixture achieves state of homogenous UI. The same has been shown for O_2 mass fraction contours at different planes in Fig. 4.

Comparison with the experimental Results

The performance of premixer-8 is compared with experimental data reported in literature.[13] Fuel (producer gas) mass flow rate is varied from minimum 11.9 g/s to 27.5 g/s to meet part to full load engine conditions. Numerical and experimental value of air-fuel ratio is compared for various engine loads. The same is shown in Table 5 and Fig. 5. The deviation observed is below 5 %.

Pressure drop is obtained numerically for optimally designed premixer (premixer-8) at different fuel mass flow rate as shown in Table 6. In Fig. 6 the variation in the pressure drop for different mass flow rate of producer gas is depicted. It can be observed from

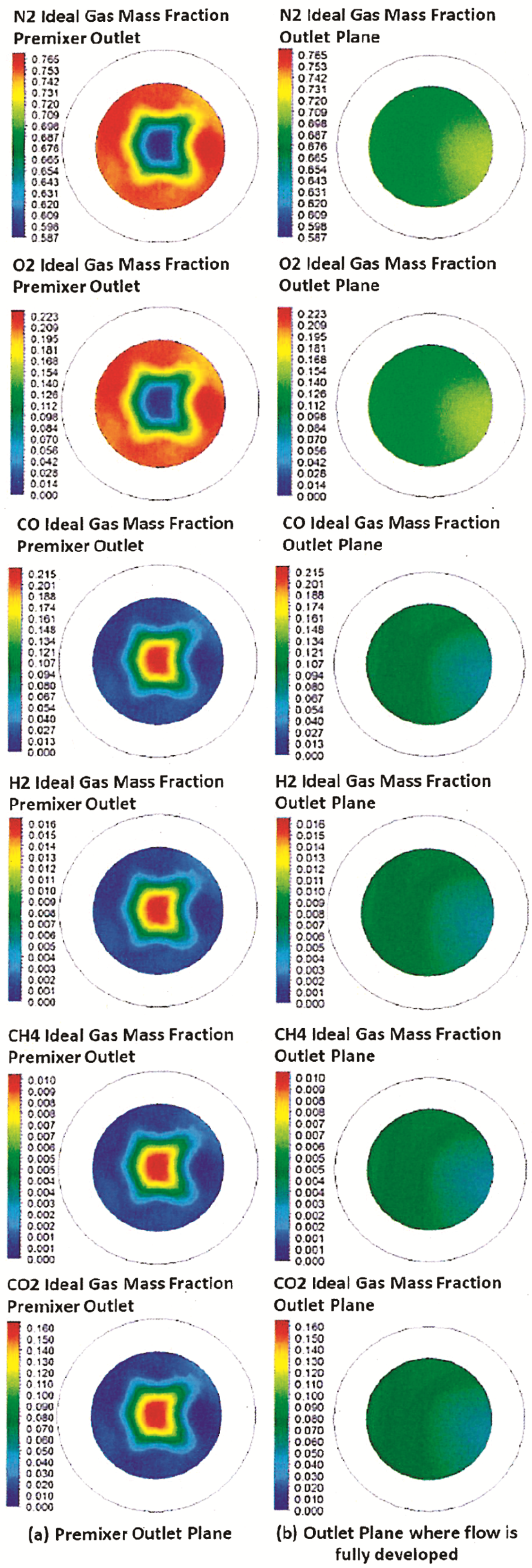

Fig. 3 — Mass fraction contours of constituents

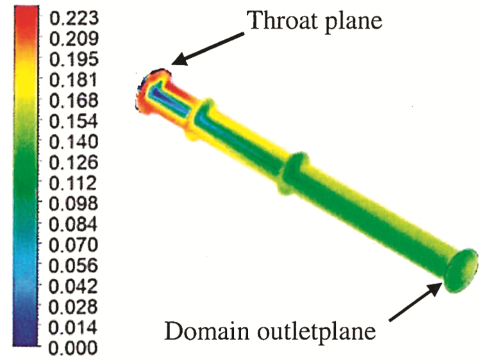

Fig. 4 — O_2 mass fraction on different planes in down stream of throat

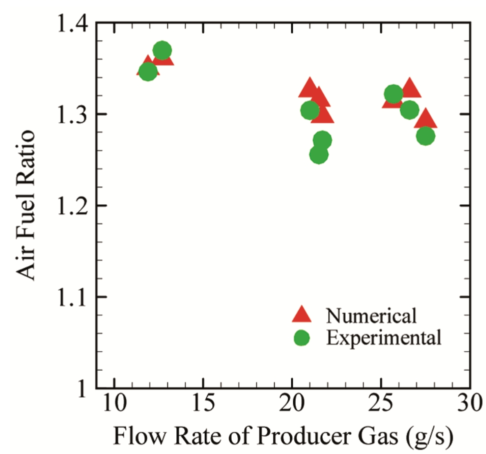

Fig 5 — Comparison of numerical and experimental air fuel ratio

Table 5 — Comparison of Numerical and Experimental Air Fuel Ratio

Fuel Flow Rate (g/s)	Numerical A/F	Experimental A/F	% Dev
11.9	1.350	1.346	0.297
12.7	1.361	1.370	−0.644
21	1.326	1.304	1.679
21.5	1.316	1.256	4.772
21.7	1.298	1.271	2.085
25.7	1.314	1.322	−0.605
26.6	1.326	1.305	1.627
27.5	1.292	1.276	1.285

Table 6 — Numerically obtained pressure drop for optimally designed premixer at different fuel flow rate

Fuel Flow Rate (g/s)	Pressure Drop across Premixer (Pa)
11.9	194.9
12.7	217.4
21	551.8
21.5	567.8
21.7	609.8
25.7	870.3
26.6	915.8
27.5	951.1

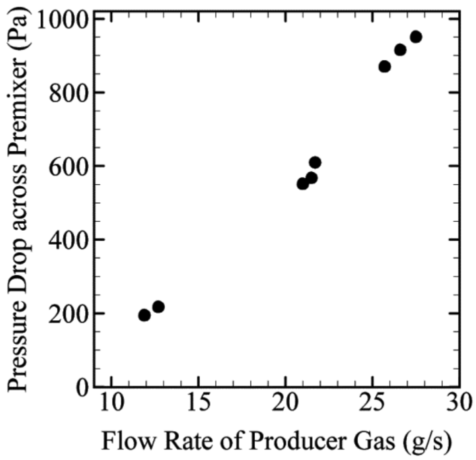

Fig. 6 — Pressure drop across premixer

Fig. 6 that at low engine load pressure drop is lowest. Pressure drop increases with increase in the engine load and becomes maximum at full load conditions. Similar trends were also reported by Kumar *et al*.[9] and Danardono *et al*.[15]

Conclusions

In present work, different configurations of long radius nozzle type premixers have been designed and numerically analyzed with single air entry and twin air entry with different sizes of the holes at the throat of premixer. From these studies, following conclusions can be summarized:

Twin Air Entry premixer provides better mixing of fuel and air than the single air entry premixer.

The twin air entry locations at the centre of throat section of premixer provided the better mixing than the locations at the centre of the overall premixer.

Increase in diameter ratio reduces pressure drop with compromise in *UI*.

Air entry hole diameter value primarily affect the *UI* while pressure drop value is mainly decided by the diameter ratio. Higher diameter ratio offers in general minimum pressure drop.

Premixer having twin air entry with diameter ratio 0.7669 and air entry diameter 8.5 mm (premixer-8) is the best fit for optimum performance.

In the optimized design, Uniformity Index is 0.958 while deviation in mass fraction of all constituents is observed to be in the range of ± 1.73% with respect to the actual mass fraction with average absolute deviation of 1.373% while pressure drop is of the order of 951 Pa.

The experimental validation of all numerical results could not be carried out due to lack of complete experimental data and set-up. This may be left as future scope.

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