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RESEARCH NOTE

Experimental and Numerical Flow Investigation of Intake Manifold and Multi Criteria Decision Making on 3-cylinder SI Engine using Technique for Order of Preference by Similarity to Ideal Solution

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ABSTRACT

In this paper, technique for order of preference by similarity to ideal solution(TOPSIS) method is used to find the best compromising design of intake manifold for a 3-cylinder engine considering mean value of torque, torque at 3500 rpm, mean value of brake mean specific consumption (BSFC) and BSFC at 3500 rpmas four objective functions. To calculate the objective functions, engine simulation is carried out using GT-SUITE software. The engine simulation code (ESC) is built from experimental combustion pressure data which come from engine test bench. Results of such simulations are then used to perform TOPSIS and some design points are obtained considering similar values for the objective functions weights. Due to high value of torque and low value of BSFC one of the obtained designs is selected as the best compromising design. To evaluate performance of the selected design, the flow rate is completely investigated experimentally and numerically. Results show that the flow is distributed in three runners as uniform, so that the maximum difference of flow rate is 0.49% which means the uniform air charging for all the three cylinders. Also, good compatibiliy is found between the CFD and experimenal results from flow rate point of view.

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NOMENCLATURE

BSFC	Brake mean specific consumption	**TOPSIS**	Technique for order of preference by similarity to ideal solution
ESC	Engine simulation code	**rpm**	Revolution per minutes
MCDM	Multi criteria decision making	**IM**	Intake manifold
I4	Inline four cylinder engine	**I3**	Inline three cylinder engine
CF	Coefficient of flow	**DOE**	Design of experiments
S-N	Signal to noise	**3D**	Three dimentional
CFD	Computational fluid daynamics	**ICE**	Internal combustion engine
R1	First runner	**R2**	Second runner
R3	Third runner		

1. INTRODUCTION

The numbers of petrol cars with three-cylinder engines are increasing these days. However, there's a perception that three-cylinder engines are inferior to four-cylinder engines. The basic advantage of a three-cylinder engine over a four-cylinder is that it is inherently more fuel efficient (as there's one cylinder less of volume of fuel to burn). The smaller engine sizes need less fuel to burn and hence are more fuel efficient. The engine optimization could have two base targets; one is having good performance and the other is obtaining minimum BSFC.

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Many researchers have tried to decrease fuel consumption of the internal combustion engine (ICE). The increasing amount of ground transportation units and simultaneous short comings in energy consumption and minimization of pollutant generation in transport forced the researchers to design more efficient engines. It is well known that it is possible to achieve a reduction in fuel consumption by downsizing the ICE.

Some engine designers have worked on blending the fuels together. Yousufuddin et al. studied the effects of blending the ethanol and hydrogen on improving the engine pollutant [1]. Semin et al. showed that the intake manifold has the main role to charge the engine cylinders especially in natural aspirated engines [2]. Nazoktabar et al. worked on combustion phasing in order to investigate the performance of engine [3]. Some researchers followed the fuel economy with dual fuel strategies in ICE. Pirouzpanah et al. showed that the injector phase has not a dominant role in the combustion parameters [4]. Akhlaghi investigated the effect of the air fuel ratio on decreasing emission and engine vibration [5]. Khoshbaktisaray with application of a combustion model showed that the pilot injection of fuel could have good effect on performance of engine [6].

Among this research, the authors have decided to improve engine performance with decreasing cylinder quantity. In this regards, a four- cylinder engine converted to a three-cylinder conceptually and optimized the air filling systems.

Fuel consumption and performance of an engine, are two important goals that should be achieved in the process of designing. It is clear that BSFC and torque are two conflicting functions. This implies that a multi-criteria decision making (MCDM) approach can be adopted as a useful method to handle such challenge. There is a substantial body of literature on MCDM methods and their applications in real world problems. One of the earliest methods, which were applied to problems of ranking and sorting, is the elimination et choixtraduisant la realité (ELECTRE) method that was proposed by Roy et al. [7].

Saaty et al. [8] developed the analytic hierarchy process (AHP) as a technique for analyzing complex decisions. The analytic network process (ANP) was introduced by Saaty [9] as a general form of AHP which structures a decision problem as a network and finally ranks the alternatives in the decision. Po-Lung Yu [10] and Zeleny [11] introduced the idea of compromise solution in MCDM. Opricovic [12] developed the VIKOR method to solve decision problems with conflicting criteria. Using VIKOR, alternatives can be ranked and the compromise solution, which is the closest to the ideal solution, can be determined. TOPSIS is a suitable method for solving real world MCDM problems and was first introduced by Hwang et al. [13]. TOPSIS method is based on choosing the alternative which is closest to the positive ideal solution and the farthest from the negative ideal solution. Azizmohammadi et al. showed that MCDM can be used for several mutually conflicting objectives which cannot combine in one single objective function [14]. Also, Delkhosh et al. investigated the multi objective optimization in transmission for reducing the fuel consumption [15]. Eskandarpour et al. investigated that the TOPSIS method is also an effective way to solve MCDM in many fields of automotive industry, so that the quality and cost can be compromised with very good accuracy [16].

Based on researchers' literatures review, there are no detail investigations onintake manifold (IM) geometry dimensions for plenum and runner profile.

In this paper, the air filling system is investigated in details with taking account the effective parameters in IM. L_1, L_2 and VP which are length of first part of runner, second part of runner and volume of plenum respectively, are selected as design variables. The ESC is carried out using the software GT-SUITE to calculate the engine performance through the different cases of design variables. This model is developed and verified for I4 engine and then developed and applied for I3 engine. After verifying the model, design of experiment (DOE) is performed on a desired domain of input variables using four output functions including, mean torque, mean BSFC, torque at 3500 rpm and BSFC at 3500 rpm. Then, the TOPSIS as a multi-criteria decision making method is applied to select the best compromising design of the engine, considering the same strategies of objective functions. Finally, the new IM is manufactured and tested on flow bench to measure the flow rate in each runner individually.

2. ENGINE MODELING

The air coming to the engine should be modeled in the simulation software till exhaust is getting out from the engine as shown in Figure 1. The all data including dimension, and thermodynamics properties are related to research engine as shown in Figure 2. Figure 3 shows the fluid path through engine channels which is considered in the present research.

The whole air system is discretized into many volumes, where each flow split is considered by a single volume, and pipes are divided into one or more sections. These volumes and sections are connected by different boundaries. In the software, the scalar variables are assumed to be uniform over each volume and are computed for the center of each volume. The primary scalar variables are the density and total internal energy and the secondary scalar variables are the pressure, temperature, total enthalpy and species concentrations.

The Three-cylinder engine which is investigated in this study is built up from a four-cylinder engine by cutting away one of the cylinders. Hence, to validate the simulation model, first, simulation of I4 engine is performed using GT-SUITE software and the results are compared with the experimental results. After such comparison and validation, one cylinder of the model is eliminated, and the I3 model, consequently is developed.

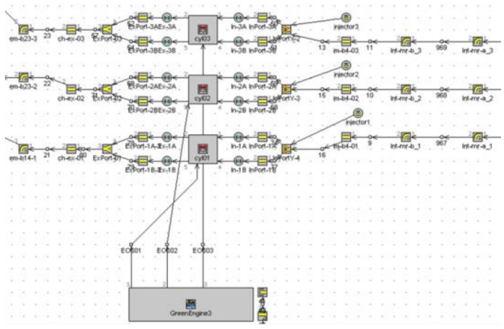

Figure 1. Engine simulation model

Figure 2. Research engine on dynamometer

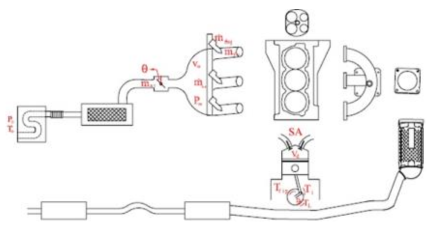

Figure 3. Schematic of fluid path for engine simulation

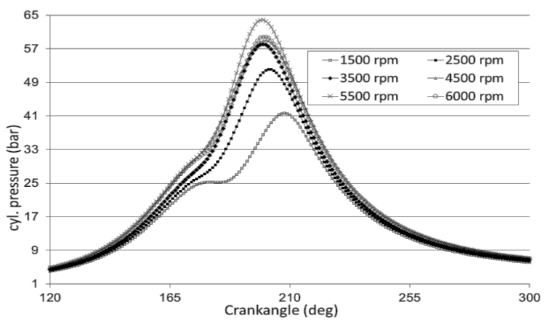

Figure 4. Schematic of fluid path for engine simulation

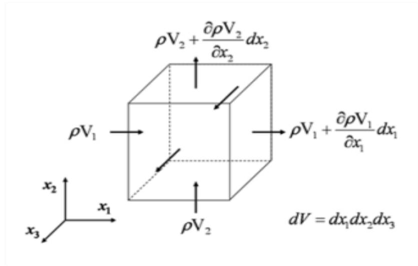

Figure 5. Control volume element

TABLE 1. Engine specification

Parameter	Engine	
	I3	I4
Type	3cylider Linear -4 stroke	4cylinder Linear -4 stroke
Displacement	1.3 L	1.65 L
No. Valve	4	4
Compression ratio	11	11
S/B ratio	86/78.6=1.08	86/78.6=1.08
Fuel System	Gasoline MPFI	Gasoline MPFI
Power(KW)	69.45*@6500	83@6500
Torque(N.m)	123.496*(4000)	150@4000

*After optimization

The main data of the I3 and I4 engines are listed in Table 1. Inlet and exhaust flow coefficients are obtained experimentally and imported to the software as input parameters. The combustion profiles which are shown in Figure 4 at all speeds of engine are measured on engine dynamometer and applied to ESC as input parameters. The heat release has been set up to be calculated from experimental combustion profiles at each rpms in the ESC.

The ESC (GT-SUITE) includes the capability to model exhaust emission and also knock. By default, it predicts 11 products of combustion (N_2, O_2, CO_2, H_2O, H_2, H, O, OH, NO, N) using equilibrium and chemical chemistry. Since it is accepted among researchers to develop an engine with good performance and then trade off the objective functions with pollutant, the authors' focus in this paper will be on the engine performance. So, the emission will be calculate by software but will not be investigated in detail at the present rsearch.

After completing the flow model, the equations of the continuity, momentum and energy are solved simultaneously by the simulation software. The continuity equation states that the changes of fluid mass in each control volume (see Figure 5) shall be equal to the net rate of the input and output fluid flow. The main equations which have been solved in ESC are as following:

Physically, the mass is neither created nor passed away in the each volume and can be written into the integral form of the continuity Equation (1):

$$\frac{\partial}{\partial t}\iiint_V \rho dV = -\oiint_s \rho u.dS \quad (1)$$

where, ρ is the fluid density, u is a velocity vector, and t is time. Another equation is conservation of momentum (Equation (2)). Newton's second law of motion describes that any change in momentum of the air within a control volume shall be equal to the net flow of air into the control volume and the action of external forces. In this form of equation the body forces per unit of mass are denoted by fbody and the F_{surf} is the surface force:

$$\frac{\partial}{\partial t}\iiint_V \rho u dV = -\oiint_s (\rho u.dS)u - \oiint_s pdS + \iiint_V \rho ff_{body} dV + F_{surf} \quad (2)$$

The final equation in the software which shall be solved and analyzed is energy. Equation (3) shows the parameters which are effective in conservation of energy:

$$\rho\frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla.(k\nabla T) + \Phi \quad (3)$$

where, the variables h, k, T and Φ are enthalpy, thermal conductivity of the fluid, temperature, and the viscous dissipation function, respectively.

As it was mentioned earlier, for initial work the simulation is carried out for the I4 version. Then, the experimental torque of this engine is measured by dynamometer. Figure 6, shows that the I4 model has a good compatibility to the simulation.

The maximum deviation between the model and experimental data is 5.16% at 4000 rpm. At the engine lab, the procedure of measuring the power is so that, 60 points at each engine revolution are measured and then averaged in these cycles. The engine revolution fluctuation is kept in +/-3 rpm. The CL (Confident Level) is chosen to be 0.95.

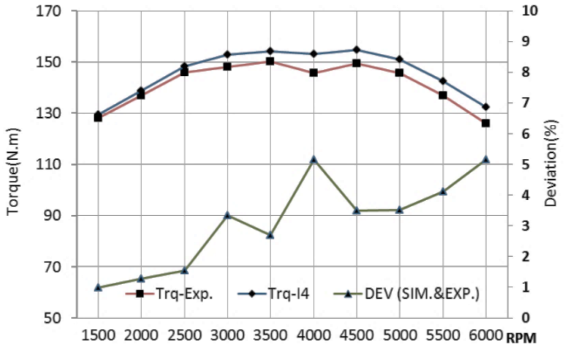

Figure 6. Simulation model validation

Also, the simulation software is set up to calculate 25 periods at each engine revolution and to consider the average of thermodynamic characteristics of the engine in different rpms. The error range between the experimental and simulation results for power and torque are 0.98- 5.16%. The lowest deviation between the experimental and simulation results is found at low rpms. So, these data can prove that the engine model and simulation is capable of predicting the engine behavior with a good accuracy .

Since the most important factors exported from the experimental data resulted in a trustable ESC, The I4 engine shows a very good compatibility with the simulation results. Also, the inputs required to simulate the I3 engine performance are related to the experimental data from single cylinder, (i.e combustion pressure) so, it is acceptable that the model could be valid and work with a good accuracy like I4 version and could be trustable with the same accuracy. Besides, the cylinder ports, combustion geometry, air fuel ratio and specification of the fuel and air have not been changed compared to I4 version. So, the I3 model with measured combustion profiles with these mentioned constant characterestics produces the same heat releases and can be supposed to work and perform as accuracy as I4 model.

3. TOPSIS METHOD APPLICATION

To conduct MCDM, different designs of IM with three runners are generated using factorial design. Mean of torque, mean of BSFC, torque at 3500 and BSFC at 3500 for corresponding design parameters are then calculated by performing ESC according to section 2. Some rows of MCDM data table are shown in the Table 2. In this paper, the TOPSIS is used as a wellknown MCDM approach.

The objective of TOPSIS is to determine the best compromise solution based on its distance from the positive, (S^+), and negative, (S^-), ideal solutions according to the weights appointed for every criterion. The best solution is the closest one to the positive ideal solution and the farthest one from the negative ideal solution. The process in TOPSIS is as follows :

1) Evaluation matrix S, in which the element s_{ij} is created from the jth criterion value and the ith alternative.

2) Normalized rating $\tilde{s}_{ij}$ is calculated according to the following equation:

$$\tilde{s}_{ij} = \frac{s_{ij}}{\sqrt{\sum_{i=1}^{m} s_{ij}^2}} \; i = 1,\ldots,m;\; j = 1,\ldots,n \quad (4)$$

3) The weighted normalized values $\hat{s}_{ij}$ are constructed using the following equation:

$$\hat{s}_{ij} = w_j \times \hat{s}_{ij} \qquad i = 1,\ldots,m;\ j = 1,\ldots,n \tag{5}$$

where, w_j is the weight value appointed for jth criterion and satisfies:

$$\sum_{j=1}^{n} w_j = 1 \tag{6}$$

4) S^+ and S^- are determined as follow:

$$S^+ = \{(\min \hat{s}_{ij} | j \in J_1), (\max \hat{s}_{ij} | j \in J_2), i = 1,2,\ldots,m\} \tag{7}$$

$$S^- = \{(\min \hat{s}_{ij} | j \in J_1), (\max \hat{s}_{ij} | j \in J_2), i = 1,2,\ldots,m\} \tag{8}$$

where, J_1 and J_2 are associated, respectively, with the benefit and the cost criterion.

5) The separation measures are determined using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is determined as follows:

$$D_i^+ = \sqrt{\sum_j (\hat{s}_{ij} - S_j^+)^2} \tag{9}$$

$$D_i^- = \sqrt{\sum_j (\hat{s}_{ij} - S_j^-)^2} \tag{10}$$

TABLE 2. Experimental layout L16 orthogonal array with objective functions

Row	A	B	C	T3500	BSFC3500	T-mean	BSFC-mean
1	1	1	1	112.2604	265.9966	108.4848	289.7368
2	1	2	2	115.8638	265.7539	108.7176	289.9134
3	1	3	3	121.0839	265.0939	109.8818	289.7624
4	1	4	4	116.5318	265.9201	107.956	292.2666
5	2	1	2	111.9247	265.8253	108.3994	289.9488
6	2	2	1	117.6588	265.5315	108.9166	289.4998
7	2	3	4	119.7246	264.2877	109.1706	289.5152
8	2	4	3	116.8015	266.2598	109.2836	291.9041
9	3	1	3	114.8864	264.6937	108.8199	289.139
10	3	2	4	121.0261	264.9736	109.4478	289.6192
11	3	3	1	116.4377	265.9793	107.6605	290.2372
12	3	4	2	118.6672	266.4301	107.1377	291.4885
13	4	1	4	118.3575	265.1918	109.077	289.1571
14	4	2	3	120.1372	265.9663	110.2455	289.276
15	4	3	2	116.5406	266.1823	107.7915	290.614
16	4	4	1	119.7599	266.8432	106.5198	292.3116

TABLE 3. TOPSIS output for the same weight of objective functions (wi= 0.25 , i=1 to 4)

Selected design (TOPSIS)			Objective functions' values			
L_1	L_2	Vp	F1	F2	F3	F4
176.667	256.664	500000	122.76	260.78	112.45	280.12

TABLE 4. Flow bench system specification

Parameter	Value
Make and model	SF-1020
Flow measurements accuracy	+/-0.05%
Flow repeatability	+/-0.5%
Flow range	12-470 l/s
Pressure accuracy	+/-12 Pa
Temperature accuracy	+/-0.3 Centigrade
Delta pressure range	0-16 KPa

6) The relative closeness D_i of each alternative to the ideal solution is calculated according to the following equation:

$$D_i = \frac{D^-}{D^- + D^+} \qquad i = 1,\ldots,m \tag{11}$$

7) The solution whose relative closeness D_i is the closest to 1 is determined as the best compromise solution.

Table 3 illustrates the selected designs with the same strategies for performance and fuel economy. The TOPSIS method introduced a trade-off design, corresponding to each set of different weights for the objective functions. Designing an engine could be considered depending on what a designer or customer anticipates from the engine. The case of equivalent importance of each objective function shows that, the importance of power produced by the engine in all working speeds is the same as that of BSFC in all working speeds and the weight functions are considered as 0.25 for all of the four objective functions. In the case of this study, regarding to have very good torque along with minimum fuel consumption in all working speeds, specially at 3500 rpm, this case is selected as the desired and best compromising design. This design could lead to the maximum torque of 123.496 N.m and BSFC of 259.778 in order to achieve maximum gain in fuel economy target. Based on the mentioned exclusivity, this design has been considered for 3D calculation and further investigations.

4. EXPERIMENTAL AND NUMERICAL INVESTIGATION ON SELECTED DESIGN

In this section, the selected design which was introduced in the previous section, is investigated for more detailed flow characteristics and behavior. Therefore, 3D calculation and flow bench test are carried out. Also, the new IM is manufactured and tested on flow bench equipment. The specifications of flow bench are demonstrated in Table 4. The valve is kept 10 mm in order to measure the flow rate experimentally in all three runners individually.

The variation of flow rate is very important between the cylinders to make the charge and power values closer to each other as much as possible.

To study the effect of flow rate in IM and the cylinder head, it is decided to test the cylinder head (see Figure 7) assembled to IM.

The main equations which have been solved in ESC are as following:

The data are so important to assessment of cylinder filling, and also the deviation between different cylinders is not too high, so it has been decided to repeat the data measuring for 5 times and after 5 minutes in order to have steady state value for flow rate.

The intake manifold model (see Figure 8) has been made in CATIA V5R21 and then imported to ANSYSFLUENT for CFD calculation. Table 5 shows the CFD boundary and meshing condition. The adaptive meshing method has been selected in ANSYSFLUENT. The type of mesh configuration is unstructural and Tet/Hybrid. The most meshing configuration has four faces, except in corners with six faces and 8 nodes which has been applied. For investigation of independency of element quantity, the adaptive meshing with 290,000 & 330,000 & 350.000 and 365.000 elements which have automaticlly been used by software in order to come with at least 1e-06 accuracy for velocity and mass flow rate (see Figure 9).

Since the experimental set up for flow rate measuring has been done in local condition (i.e, Tehran which has 88.57kpa air pressure), so, it has been decided to apply local condition pressure for comparing CFD analysis results.

Figure 10 shows that the CFD and experimental data have good compatibility, specially for second runner. Also, the deviation of mass flow rate from mean value is limited for three runners by 0.49%. Although the runner one can charge a little more air to cylinder; but it could be in acceptable range.

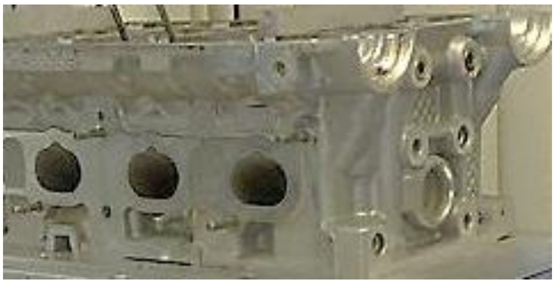

Figure 7. Cylinder head on flow bench equipment

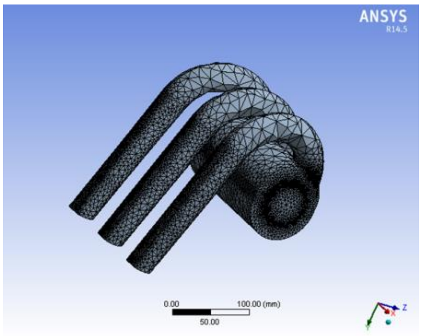

Figure 8.3D model meshed of IM

TABLE 5. CFD condition

Inlet pressure	Outlet pressure	Meshing method
88.57kpa	83.57kpa	Adaptive meshing

CFD calculations have a good compatibility with experimental flow rate which comes from the flow bench test. Theoretical and experimental data have maximum deviation by 4.58% in valve lift 10mm. CFD analysis has a good compatibility with experimental data. Investigation of air path performance in third runner as shown in Figure 10 showed that better flow rate occurs for second and third runners experimentally and numerically point of view, respectively.

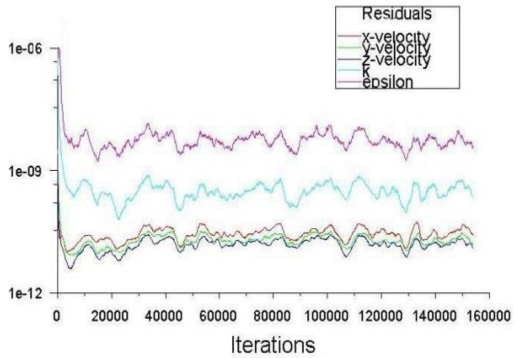

Figure 9. CFD residuals and accuracy

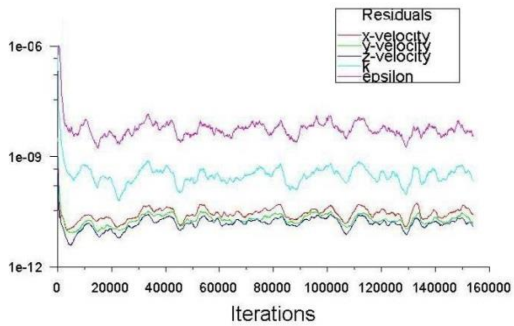

Figure 10. Experimental and numerical flow assessment

TABLE 6. Mass flow rate (Kg/s) in the new IM'Runners

	R1	R2	R3	Variance
I3 IM CFD	0.07204	0.072072	0.072075	1.63E-5
I3 IM EXP.	0.06874	0.0693	0.06884	2.438E-4
Errors (%)	4.58	3.84	4.48	-
Dev.from mean value (%)	-0.32005	0.49062	-0.17432	

The results show that there is an excellent compatibility between research data and experimental values. The results are shown in Table 6. The flow is distributed in three runners as uniform, so that the maximum difference of flow rate between runners is 0.49% which means the uniform air charging for all three cylinders. Hence, the experimental assessment of best compromising IM shows that the new design can send the maximum flow rate along with good distribution between cylinders. For authors it was important to evaluate the runners performance so that, the compromising design satisfies all the described objective functions with best performance.

5. RESULTS AND DISCUSION

Although eliminating one of the cylinders is expected to reduce the torque by 25% in speed range averagely, but the optimization of the air path leads to a torque loss remarkably smaller than the anticipated value. The TOPSIS method helped in a good effective manner to find the best compromising design variables, so that the peak torque loss reached to 17.66% and the power loss was limited to 16.32% compared to I4 base engine.

Experimental data for flow rate with CFD results, prove that at maximum valve lift, the ram effect and tuning phenomena are dominant and make good air charging with low flow resistance. Pressure pulsations inside the IM can create very strong acoustic resonance modes.

The ram effect at high engine speed also could improve engine charging, so that as air flows inside the runner, it plays the role of a velocity stack and the pressure keeps increasing with the raised air velocity (i.e, high rpm) inside it. This effect becomes progressively more important with increasing engine speed.

6. CONCLUSION

The main target at present research was to have more volumetric efficiency to come in maximum torque with a novel geometry of intake manifold. Based on the validated model in section 2, simulation of the three-cylinder engine was done in this research and the following items were achieved:

- The ESC showed that the original IM values are not good for the new-three cylinder engine and optimization is necessary for filling and emptyng systems.
- Finding the best compromising values for L_1, L_2 and V_P in this research along with four objective functions was novel and interesting. Also, it was shown that coupling the ESC to DOE and TOPSIS with MCDM method gives interesting results.
- Using resonance tuning effect, reflective wave tuning, inertia charging and ram effect phenomena in air path could show very good results in air charging. Researchers can claim that best compromising design which is obtained in the present study, benefits these mentioned advantages more than the I4 based version of design.
- TOPSIS application in MCDM method could lead to valuable results in point of engine optimization.

7. ACKNOWLEDGEMENT

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Experimental and Numerical Flow Investigation of Intake Manifold and Multi Criteria Decision Making on 3-cylinder SI Engine using Technique for Order of Preference by Similarity to Ideal Solution

RESEARCH NOTE

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چکیده

هدف از این پژوهش دستیابی به بهترین طرح بهینه (Best Compromising Design) با بکارگیری تکنیکTOPSIS در روش MCDM میباشد. فشار احتراق از مقادیر تجربی از یک سیلندر موتور در همه دورها از ۱۵۰۰ الی ۶۵۰۰ اندازه گیری و در مدل شبیه سازی موتور (GT-SUITE) بعنوان ورودی لحاظ شد. صحه گذاری با اندازه گیری گشتاور موتور پایه چهار سیلندر در آزمایشگاه انجام گردید. سپس با تعریف چهار تابع هدف از مصرف سوخت و گشتاور برای متوسط و در دور ۳۵۰۰ با وزن های برابر طرح بهینه بدست می آید.در ادامه بهترین طرح چند راهه ورودی ساخته و تحت آزمون میز جریان برای اندازه گیری دبی جرمی قرار گرفت. نتایج نشان میدهد که بکارگیری فشار تجربی در شبیه سازی موتور دقت خوبی نسبت به سایر مدلهای احتراقی استاندارد دارد. همچنین رفتار شاخه های بهترین طرح, در ارسال هوا به داخل موتور سه سیلندر بسیار شبیه بهم می باشد. بطوریکه حداکثر اختلاف شاخه ها در شارژ هوا به داخل سیلندر ها به ۰/۴۹ درصد رسیده است.

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