Selection of Optimum Compression Ratio – MCDM Approach

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Abstract— **In this paper the combustion and emission characteristics were studied when the engine operated by varying compression ratios at 17.5:1, 16.4:1, 15.37:1, 14.5:1 and 13.7:1. The impact of compression ratio on fuel consumption, brake thermal efficiency, combustion pressure, heat release rates and exhaust gas emissions have been investigated and presented. Multi Criteria Decision Making methods like Graph Theory Matrix Approach, Simple Additive Weighting and Weighted Product Method and have also been adopted to find the optimum compression ratio. Application of Multi criteria decision making methods showed that 15.37 compression ratio forms the optimum compression ratio.**

Index Terms— **Compression ratio; Graph theory matrix approach; Multi criteria decision making; Simple additive weighting; Weighted product method**

I. INTRODUCTION

Compression ignition engines are generally preferred due to their undisputed benefit of fuel economy and higher torque output. In-cylinder solutions like reducing the compression ratio, modification in fuel injection, improvement in air intake system etc may be the areas to look into to reduce engine exhaust emissions[1].On low compression ratio engines, preheating the inlet air allows the control over the combustion process[2]. Carle et al[3] studied the effect of reducing compression ratio on compression ignition engine in-terms of thermodynamic parameters and found that the NOx emission was reduced with an increase in unburned hydro carbons. Cursente et al[4] studied the effects of reducing compression ratio on a high speed diesel engine and suggested the combustion system designs. On a low compression ratio engine, multiple injection strategies could be adopted to improve the fuel economy and reduce exhaust emissions[5]. Increasing the induction pressure ensure to squeeze the charge for higher output of the engine[6]. Swarup Kumar Nayak et al[7] studied the influence of compression ratio on combustion characteristics of a diesel engine using bio diesel and diesel at reduced compression ratio and found that the combustion duration was more while the ignition delay period was shorter. Biswajit De and R.S.Panua[8] analyzed the performance and emission characteristics of diesel and vegetable oil blends on a DI diesel engine at lower compression ratios and found that the optimum compression ratio which gives the best performance. They showed that the thermal efficiency, exhaust gas temperature and emission parameters such as NOx, HC and CO at optimum compression ratio 18 with blends containing up to 30%(volume) vegetable oil was satisfying to run an unmodified diesel engine. Santosh and Padmanabhan[9] studied the effect of compression ratio on the performance and emission characteristics of diesel and ethanol-diesel blend. They concluded that at lower compression ratio the carbon- monoxide (CO), Carbon-di-oxide (CO_2), Hydro carbon (HC) emission increases and Nitrogen oxides (NOx) decreases.

The present study investigates the performance and emission characteristics of a diesel engine by reducing compression ratio as 17.5:1, 16.4:1, 15.37:1, 14.5:1 and 13.7:1. Graph Theory Matrix Approach (GTMA)[10] is adopted to find the optimum compression ratio.

II. GRAPH THEORY MATRIX APPROACH

Graph theory matrix approach is a systematic and logical approach[10]. It consists of the following steps:

1. Digraph representation
2. Matrix representation
3. Permanent function representation

DIGRAPH REPRESENTATION

A directed graph is a graph with directed edges. The digraph gives graphical representation of the attributes and their relative importance for a quick visual appraisal. A performance attributes digraph is defined, which consists of a set of nodes V={vi} with i=1,2,3,….. M and a set of directed edges D= {dij}. A node Vi represents the ith performance attribute and edges dij represent the relative importance between the attributes. If a node ‘i’ has a relative importance over node ‘j’, then a directed edge is drawn from node i to node j (i.e dij). If a node j has a relative importance over i, then a directed edge is drawn from node j to i (i.e dji). The number of nodes M is equal to the number of attributes considered. In the present work, six attributes, Brake power(BP), Brake specific fuel consumption(BSFC), Brake thermal efficiency(BTE), Nitric oxide(NOx) and Hydro carbon(HC) and carbon monoxide

(CO) are taken as nodes and their inter-dependencies are represented as edges. The performance attributes digraph is shown in Figure 1.

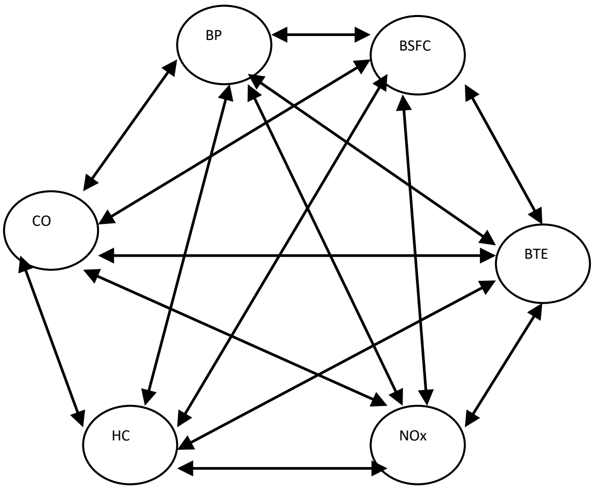


Fig. 1. Attributes digraph

In digraph model, the qualitative parameters can be given different numerical values and be made part of the model. To give better appreciation, the inter-dependencies are considered. As the number of nodes and their relative importance increases, the digraph becomes complex. To overcome this difficulty, the digraph is represented in matrix form.

MATRIX REPRESENTATION

The one-to-one representation of the attributes in digraph is presented in attributes matrix. It is an M x M matrix which considers all attributes (Ri) and their relative importance(aij). The Attributes Matrix, P, is shown in Eq. 1.

$$P = \begin{bmatrix} R_1 & a_{12} & a_{13} & \dots & \dots & a_{1m} \\ a_{21} & R_2 & a_{23} & \dots & \dots & a_{2m} \\ a_{31} & a_{32} & R_3 & \dots & \dots & a_{3m} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & a_{m3} & \dots & \dots & R_m \end{bmatrix} \quad (1)$$

Where Ri is the normalized value of ith attribute represented by node Vi and aij is the relative importance of the ith attribute over the jth attribute of edge dij. The normalized value of Ri can be calculated by Ri/Riu in the case of beneficial attribute and by Ril/ Ri in the case of non beneficial attribute. Where Ril and Riu are the lowest and highest range values of attributes respectively. The normalized values of the attributes are shown in Table 1.

Table1. Normalized values of attributes.

Exp No	Operating Parameters		Normalized Performance Characteristics					
	CR	Load (%)	B.P (kW)	BSFC (kg/h kW)	BTE (%)	Nox (ppm)	HC (ppm)	CO (%)
1	17.5	25	0.268	0.833	0.554	0.336	0.714	0.429
2	17.5	50	0.543	0.559	0.825	0.598	0.755	0.286
3	17.5	75	0.789	0.461	1.000	0.829	0.898	0.429
4	17.5	100	1.000	0.464	0.994	1.000	1.000	0.571
5	16.4	25	0.261	0.856	0.554	0.289	0.592	0.429
6	16.4	50	0.538	0.559	0.825	0.515	0.633	0.429
7	16.4	75	0.782	0.486	1.000	0.527	0.735	0.429
8	16.4	100	0.948	0.505	0.924	0.634	0.837	0.714
9	15.37	25	0.256	0.863	0.533	0.262	0.429	0.571
10	15.37	50	0.536	0.558	0.827	0.513	0.490	0.429
11	15.37	75	0.773	0.494	0.935	0.560	0.592	0.571
12	15.37	100	0.986	0.553	0.833	0.699	0.714	0.857

13	14.5	25	0.261	0.909	0.523	0.253	0.388	0.571
14	14.5	50	0.536	0.559	0.723	0.357	0.429	0.571
15	14.5	75	0.775	0.617	0.756	0.491	0.490	0.714
16	14.5	100	0.943	0.684	0.675	0.587	0.633	1.000
17	13.7	25	0.256	0.992	0.524	0.078	0.306	0.714
18	13.7	50	0.528	0.591	0.658	0.130	0.367	0.714
19	13.7	75	0.749	0.681	0.677	0.229	0.429	0.857

The values of relative importance between two attributes (a_{ij}) are also assigned on the scale of 0 to 1. The relative importance between i,j and j,i is given in Eq.2,

$$a_{ji} = 1/ a_{ij} \quad (2)$$

The relative importance values of attributes are shown in Table 2.

Table 2. Relative importance of attributes

Description	Relative importance	
	a_{ij}	$a_{ji} = 1/a_{ij}$
Two attributes are equally important	0.5	2.000
One attribute is slightly more important over the other	0.6	1.666
One attribute is strongly more important over the other	0.7	1.428
One attribute is very strongly important over the other	0.8	1.250
One attribute is extremely important over the other	0.9	1.111
One attribute is exceptionally more important over the other	1.0	1.000

PERMANENT FUNCTION

The permanent function of the parameter matrix is a standard matrix function used in Combinatorial mathematics. The concept of permanent leads to a better appreciation as no negative sign will appear in the expression and hence no information will be lost. The parameter index is a measure of the ease with which the optimum operating parameter can be chosen. The parameter index for each experiment is evaluated using the Eq. 3, which contains the measures of attributes and their relative importance.

$$\mathrm{Per(P)} = \prod_{i=1}^{M} Si + \sum_i \sum_j \sum_k \ldots \sum_m (a_{ij}a_{ji})R_k R_l \ldots R_m + \sum_i \sum_j \sum_k \ldots \sum_m (a_{ij}a_{ji}a_{ki} + a_{ik}a_{kj}a_{ji})R_l R_m \ldots R_m + \left(\sum\sum\sum \ldots \sum (a_{ij}a_{ji})(a_{kl}a_{lk})R_m R_n \ldots R_m + \sum_i \sum_j \sum_k \ldots \sum_m (a_{ij}a_{jk}a_{kl}a_{li} + a_{il}a_{lk}a_{kj}a_{ji})R_m R_n \ldots R_m \right) + \left(\sum_i \sum_j \sum_k \ldots \sum_m (a_{ij}a_{ji})(a_{kl}a_{lm}a_{mk} + a_{km}a_{ml}a_{lk})R_n R_o \ldots R_m + \sum_i \sum_j \sum_k \ldots \sum_m (a_{ij}a_{jk}a_{kl}a_{lm}a_{mi} + a_{im}a_{ml}a_{lk}a_{kj}a_{ji})R_n R_o \ldots R_m + \ldots\ldots \right) \quad (3)$$

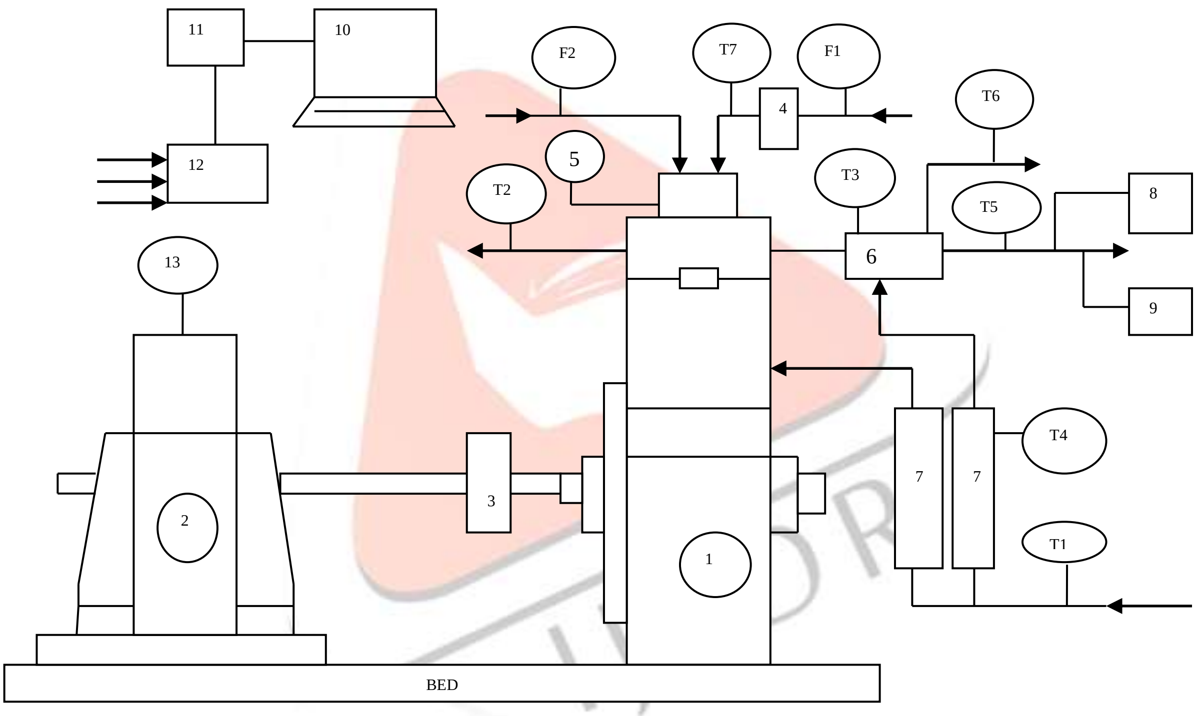
A computer program is developed to evaluate the parameter index for all experiments and these values are arranged in the descending order. The experiment, for which the parameter index is highest, forms the optimal combination of operating parameters of the engine. The parameter index values for 19 experiments are shown in Table 4.

III. EXPERIMENTAL SETUP AND PROCEDURE

The schematic diagram of the engine test rig used for experimentation with necessary instrumentation and computer interface is shown in Fig. 2. This test rig comprises of a single cylinder, four stroke, direct injection water cooled diesel engine of Kirloskar make. The specifications of the engine can be referred from Table 3, where the engine displacement is 661 cc. The engine is coupled with eddy current dynamometer. Strain gauge type load cell is used to measure the load and rotary encoder enables the measurement of speed. Rotameter, between 40 to 400L per hour operates for engine cooling and enhances calorimeter cooling in the range of 25 to 250 L per hour. K- Chromel type thermocouples are fitted to measure the temperature of cooling water inlet, outlet, exhaust gas, calorimeter exhaust, calorimeter inlet & outlet, ambient temperature. The fuel flow is measured by 20 cc burette and stopwatch with level sensors. The pressure inside the combustion chamber is measured using an AVLGH12D miniature pressure transducer. Piezo electric sensor in the range of 5000 PSI is used for measuring fuel inlet pressure in the combustion chamber. The engine is equipped with AVL Digas 444, a five gas analyzer and a smoke meter. All the sensors are connected to the data acquisition system. Engine performance analysis software, AVL INDIMICRA -602-T10602A, version V2.5 is interfaced between engine and the data acquisition system for P-V, P-Ɵ and heatrelease rate diagrams. Before starting the engine, lubricating oil level and cooling water flow were ensured. The engine was started and run at 0A load till the warm up period ends, that the cooling water temp is stabilized at 60C. The tests are conducted from 0A load to the rated load of 18A at the rated speed of 1500rpm. The compression ratio was changed by changing the clearance volume at cylinder head by adding spacers. The fresh air supplied to the engine was preheated when the compression ratio was reduced to 16.4:1, 15.37:1, 14.5:1 and 13.7:1 to ensure control over compression and combustion process. In every test, fuel consumption, air consumption, torque, speed, exhaust gas emissions like NOx, CO, HC, CO_2, O_2 and exhaust gas temperature are recorded. At each load, the experiment was repeated three times to check the repeatability of measurements. From the recorded readings, the performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, mechanical efficiency are calculated. Combustion parameters such as in-cylinder pressure, heat release rates, rate of pressure rise, P-V and P- ϴ diagrams were recorded and analyzed at various compression ratios like 17.5:1, 16.4:1, 15.37:1, 14.5:1 and 13.7:1.

Table. 3. Engine specifications

Component	Specification
Make	Kirloskar Engines Ltd, Pune,India
Type of engine	Four Stroke Single Cylinder Water Cooled Engine
Bore and Stroke	87.5 mm & 110 mm
Compression ratio	17.5:1
BHP and rpm	4.4kW & 1500 rpm
Fuel injection pressure	200 N/mm^2
Fuel injection timing	23^0 BTDC
Dynamometer	Eddy Current Dynamometer



1-Engine 2- Eddy current dynamometer 3- Crank angle encoder 4- Air pre heater 5- Cylinder & Injection pressure sensor 6- Calorimeter 7- Rotameter 8- Gas analyzer 9- Smoke meter 10- Computer 11- Data Acquisition system 12- Charge amplifier 13- Load sensor F1 & F2- Air and Fuel flow sensor T1 to T7- Temperature sensors

IV. Results and Discussion

MCDM Results

Table 4: Results of MCDM

C R	Load (A)	GTMA			SAW			WPM		
		Exp no.	Permanent Index	Rank	Exp no.	Permanent Index	Rank	Exp no.	Permanent Index	Rank
15.4	18	12	1.1791	1	12	6.177	1	12	0.160	1
13.7	18	20	1.0586	2	20	6.152	2	20	0.150	2
14.5	18	16	1.0493	3	16	6.152	3	16	0.143	3
13.7	14	19	0.8012	4	19	6.104	4	18	0.132	4

13.7	9	18	0.6147	5	8	6.089	5	8	0.118	5
16.4	18	8	0.6049	6	4	6.06	6	2	0.104	6
13.7	4	17	0.5357	7	7	6.031	7	6	0.103	7
17.5	18	4	0.4681	8	18	6.027	8	7	0.094	8
17.5	14	3	0.4287	9	3	6.0100	9	1	0.042	9
16.4	14	7	0.4136	10	15	5.988	10	5	0.032	10
17.5	9	2	0.3804	11	11	5.969	11	3	0.000	11
15.4	4	9	0.3738	12	17	5.938	12	4	0.000	12
16.4	9	6	0.3683	13	2	5.9360	13	9	0.000	13
14.5	4	13	0.3615	14	6	5.932	14	10	0.000	14
17.5	5	1	0.2902	15	10	5.906	15	11	0.000	15
16.4	5	5	0.2758	16	14	5.893	16	13	0.000	16
14.5	14	15	0.2244	17	13	5.824	17	14	0.000	17
15.4	9	10	0.2015	18	9	5.815	18	15	0.000	18
15.4	14	11	0.2002	19	1	5.799	19	17	0.000	19
14.5	9	14	0.1917	20	5	5.797	20	19	0.000	20

The evaluation results yielded by the three MCDMs are shown in Table 4. The ranks of the alternatives out of all MCDMs are in agreement with each other. Experiment number 12 has the highest value of index as calculated by all MCDMs and ranked as No 1.

5. Conclusion

The following conclusion can be drawn:

15.37:1 compression ratio was found to be the optimum compression ratio by adopting Multi criteria decision making methods.

Nomenclature

BP : *Brake power*
BSFC : *Brake specific fuel consumption*
BTE : *Brake thermal efficiency*
CO : *Carbon monoxide*
CR : *Compression ratio*
GTMA : *Graph theory matrix approach*
HC : *Hydro carbon*
MCDM : *Multi criteria decision making*
NO_x : *Nitrogen oxides*
PM : *Particulate matter*
SAW : *Simple additive weighting*
WPM : *Weighted product method*

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