Mathematical Model Formulation for Investigation of Influence of Air Induction Pressure as an Operating Variable on a Stationary Compression Ignition Engine Performance

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Abstract— ***Operating parameters of any particular Compression Ignition engine are firstly critically reviewed. Then by using the theories of engineering experimentation design of experiments is done. Dimensional analysis technique is used for formulation of mathematical model. Internal Combustion engines subject area is especially important as per the environmental aspects are concerned. Design of each machine is having common objectives, first is to obtain highest possible efficiency and another is to obtain minimum possible environmental degradation. The Induction pressure acting on engine is most important operating parameter of engine. The present work Shows vital scope for improvement of operating performance of engines by taking wider operating range in case of each engine.***

Keywords— **Air Induction Pressure, Efficiency, Compression Ignition Engine, Performance**

I. INTRODUCTION

Operating parameters of an internal combustion engine are discussed here, for the study of the effects of different parameters on engine performance. Engine performance is dependent on fuel consumption, which bears direct influence on efficiency and engine out emissions. So, fuel consumption rate is a basic dependent variable, It is an important parameter of an engine, varies because of any possible variable variations such as engine design (its operating conditions) & fuel (type of fuel) and After treatment system(flow resistance offered by exhaust system). Based upon the literature reviews, the following different variables are selected for reduction of variables using dimensional analysis technique. Different *л- terms* are obtained, using Buckingham`s *л* –theorem. Let us begin here with a basic but essential step in the experimental investigation, different input and output variables are briefly discussed below.

The indicator diagram of a four-stroke diesel engine cycle, as shown in the figure-1, consists of two enclosed areas. The large area represents the gross work done. The smaller shaded area, formed by the suction and exhaust operations is called pumping loop and represents the loss of work due to exhausting of burnt gases and admission of new unburnt gas or charge. This work obtained from the negative area is to be deducted from the gross work to obtain the net work done. The pumping loop is shown magnified in figure for explanation purpose. The gas exchange processes affects the volumetric efficiency of the engine. The performance of the engine, to a great deal, depends on the volumetric efficiency.

During the exhaust stroke when the piston moves from bottom dead centre to top dead centre, pressure rises and gases are pushed into exhaust pipe. Thus the power required to drive the exhaust gases is called the exhaust stroke loss and increase in speed increases the exhaust stroke loss. The indicator diagram of a diesel four-stroke cycle engine shows the suction line “ea” lies below the atmospheric pressure line. This fall of pressure below the atmospheric pressure is a result of the restricted area of the inlet passages, due to the restricted area, the entering air cannot flow into the cylinder in sufficient quantity to keep the pressure with the rapidly moving piston. With the use of supercharger the air pressure of the inlet on I.C. engine can be increased which results in decrease in the negative loop of the indicator diagram of a 4- stroke diesel engine cycle. This can increase the net work done.

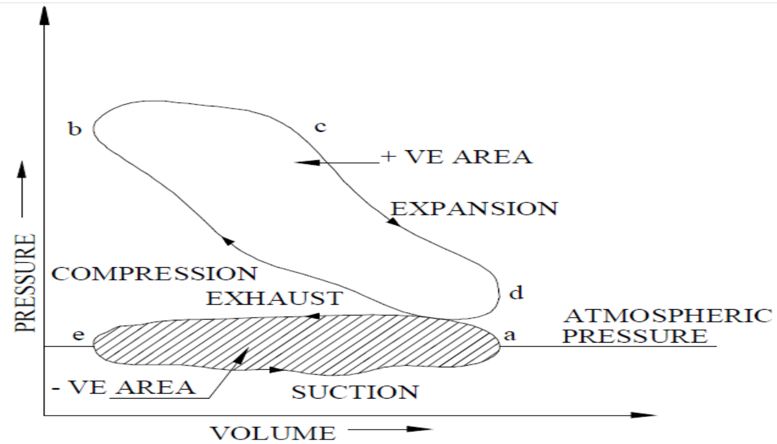

Figure 1: Theoretical Indicator diagram of a four-stroke diesel engine cycle

II. OPERATING VARIABLES FOR COMPRESSION IGNITION ENGINE

Operating parameters of an internal combustion engine are reviewed and summary of important operating variables is given below [2-6].

Table No I:-Operating Parameters of an Internal Combustion Engine [2-6]

Sr. No	Parameters	Type of variable	Causes of variations
1	Fuel consumption rate	Basic dependent variable	It is a dependent & essential Input parameter of an engine varies because of any possible variable variations such as engine design (type of engine) & fuel (type of fuel) and After treatment system(type of devices used and flow resistance offered by exhaust system)
2	Load on engine	Independent variable	As per the output power requirements such as vehicle weight, No. of persons seating, road resistance or slope condition, drag force because of air while in motion.
3	Speed	Independent variable	As per the availability of time or time requirements. Speed can be kept constant as in case of electric generator applications with the help of a governor.
4	back pressure on the engine	Independent variable	As per the complete exhaust system designs and their maintenance aspects because of aging effects. Particulate Matter accumulations causes variations of pressure drop across each component of exhaust system.
5	Air induction pressure	Independent variable	As per the design of air intake system and its maintenance aspects because of aging effects. Dust particles accumulation in air filter causes variations of pressure drop across each component of induction system. Turbocharger or Supercharger like air induction system components also affects on air induction pressure at the inlet to C.I. engine.

III. REDUCTION OF VARIABLES

The theory of experimentation as suggested by Hilbert (1961) is a good approach of representing the response of any phenomenon in terms of proper interaction of various inputs of the phenomenon. In fact, it is felt that such an approach is not yet seen towards research on engines. This approach finally establishes an experimental data based model for any phenomenon. It is felt in this investigation to adopt this approach for formulating the model correlating various inputs to a phenomenon of engine operation. The response variable of the phenomenon is fuel consumption during experimentation. A quantitative relationship is decided to be established amongst the response and the Inputs. The inputs are varied experimentally and the corresponding responses are measured. Such relationships are known as models.

The data of the independent and dependent parameters of the system has been gathered during the experimentation. The optimum values of the independent pi terms can be decided by optimization of these models for maximum efficiency and minimum fuel energy. Future modifications must be done in such a way that each alternation should not cause air induction fall.

Finally in this analysis the fuel consumption ($\boldsymbol{F_c}$) of four stroke, single cylinder C.I. engine during a test run can be considered as dependent upon load ($\boldsymbol{l_d}$), speed ($\boldsymbol{N}$), back pressure ($\boldsymbol{P_b}$) and suction pressure of intake air ($\boldsymbol{P_1}$) of the engine. Hence F_c is a function of l_d, N and P_b, P_1. Using Buckingham`s Pi theorem, Mathematically,

$$F_c = f(l_d, N, P_b, P_1) \quad \ldots\ldots(\text{I})$$

Or it can be written as

$$f_1(F_c, l_d, N, P_b, P_1) = 0 \quad \ldots\ldots(\text{II})$$

Therefore, total number of variables, n = 5
No of fundamentals dimensions, m = 3
(m is obtained by writing dimensions of each variables)

Table No II:-Dimensions of Operating Parameters of an IC Engine

Sr. No	Parameters	Symbols	MLT
1	Fuel consumption rate	F_c	MT^{-1}
2	Load on engine	l_d	MLT^{-2}
3	Speed	N	T^{-1}
4	Back pressure on the engine	P_b	$ML^{-1}T^{-2}$
5	Air induction pressure	P_1	$ML^{-1}T^{-2}$

Thus, the fundamental dimensions in the problems are M, L, T and hence m = 3).
Therefore the number of dimensionless π– terms = n – m
= 5 – 3 = 2

Thus, two π– terms say π_1, π_2 are formed.
Hence equation (II) is written as,

$$f_1(\pi_1, \pi_2) = 0 \ldots\ldots\ldots\ldots.(\text{III})$$

Each π– terms = m + 1 variables
Where m is equal to 3 and also called repeating variables. Out of five variables $F_c, l_d, N, P_b, and\ P_1$, three variables are to be selected as repeating variables; F_c is dependent variable and should not be selected as repeating variables. Out of 4 remaining variables (One variable should have geometric property, the second variable should flow property and third one should have fluid property. These requirements must be fulfilled.) the variables l_d, N and P_b are selected as repeating variables. The variables themselves should not form a dimensionless term and should have themselves fundamental dimensions equal to m, i.e. 3 here. Dimensions of l_d, N and P_b are MLT^{-2}, T^{-1}, $ML^{-1}T^{-2}$ and hence the 3 fundamental dimensions exists in l_d, N and P_b and they themselves do not form dimensionless group.

Each π – term is written as according to the equation

$$\pi_1 = {l_d}^{a_1} * N^{b_1} * {P_b}^{c_1} * F_c \quad \ldots\ldots\ldots. (\text{IV})$$
$$\pi_2 = {l_d}^{a_2} * N^{b_2} * {P_b}^{c_2} * P_1 \quad \ldots\ldots\ldots. (\text{V})$$

π –terms are determined by the principle of dimensional homogeneity.
For the π – term, we have

$$\pi_1 = M^0 * L^0 * T^0$$

$$\pi_1 = (MLT^{-2})^{a_1} * (T^{-1})^{b_1} * (ML^{-1}T^{-2})^{c_1} * (MT^{-1})$$

Equating the powers of M, L, and T on both sides, we get
Power of M,

$$0 = a_1 + b_1 + 1$$
$$a_1 + b_1 = -1 \quad \ldots.(\text{i})$$

Power of L,

$$0 = a_1 - c_1 \quad \ldots (\text{ii})$$

Subtracting equation (ii) from (i),
$c_1 = -\frac{1}{2}$ and by putting this value in equation (i), $a_1 = -\frac{1}{2}$
Power of T,

$$0 = -2a_1 - b_1 - 2c_1 - 1$$

$$-1 = 2a_1 + b_1 + 2c_1 \quad \ldots (\text{iii})$$

Putting values of a_1 & c_1, we get

$$2\left(-\frac{1}{2}\right)+b_1+2\left(-\frac{1}{2}\right)=-1$$
$$-1+b_1-1=-1$$

$$b_1=-1+2=1$$

Substituting the values of a_1, b_1 and c_1 in equation (IV),

$$\pi_1 = l_d{}^{-1/2} * N^1 * P_b{}^{-1/2} * F_c$$

$$\pi_1 = \frac{N.F_c}{\sqrt{P_b l_d}}$$

$$\pi_2 = l_d{}^{a_2} * N^{b_2} * P_b{}^{c_2} * P_1$$
$$\pi_2 = M^0 * L^0 * T^0$$

$$\pi_2 = (MLT^{-2})^{a_2} * (T^{-1})^{b_2} * (ML^{-1}T^{-2})^{c_2} * (ML^{-1}T^{-2})$$

Equating the powers of M, L, and T on both sides, we get

Power of M,

$$0 = a_2 + c_2 + 1$$
$$a_2 + c_2 = -1 \; \text{.... (iv)}$$

Power of L,

$$0 = a_2 - c_2 - 1$$
$$a_2 - c_2 = 1 \quad \text{... (v)}$$

Subtracting equation (iv) from (v),

$c_2 = -1$ and by putting this value in equation (iv), $a_2 = 0$

Power of T,

$$0 = -2a_2 - b_2 - 2c_2 - 2$$

$$-2 = 2a_2 + b_2 + 2c_2 \quad \text{... (vi)}$$

Putting values of a_2 & c_2, we get

$$2(0) + b_2 + 2(-1) = -2$$
$$0 + b_2 - 2 = -2$$

$$b_2 = -2 + 2 = 0$$
$$b_2 = 0$$

Substituting the values of a_2, b_2 and c_2 in equation (V),

$$\pi_2 = l_d{}^0 * N^0 * P_b{}^{-1} * P_1$$
$$\pi_2 = \frac{P_1}{P_b}$$

Substituting the value of π - terms in equation (III),

$$f_1(\pi_1, \pi_2) = 0$$

$$f_1\left(\frac{N * F_c}{\sqrt{p_b l_d}}, \frac{P_1}{P_b}\right) = 0$$

$$\text{or } \frac{N*F_c}{\sqrt{p_b * l_d}} = f_1\left(\frac{P_1}{P_b}\right)$$

$$\text{or } F_c = \frac{\sqrt{p_b l_d}}{N} * f_1\left(\frac{P_1}{P_b}\right)$$

IV. EXPERIMENTATION

In the present work, throughout the complete trials conducted, engine jacket cooling water is kept constant at 0.1666 liters/sec, so as to provide ease in comparison of different parameters. Perforated circular copper plates arrangement in Diesel Particulate Filter is used as a test piece for back pressure variations, in some cases by varying the load and speed of the engine also. Further during the trials on DPF, each times the fresh perforated plates and rings are used. To reduce the backpressure on the engine, maximum no. of plates (i.e. 20 plates) provided with extra 8 no. of holes, of 5 mm diameter are used for determining the effect, that is of back pressure reduction mainly. The different parameters are compared with the values of same parameters without using DPF, for the same engine output conditions [9,11,12].

During the trials, 10 test runs are conducted and distinct observations are obtained. These deviations may be a result of the lack of control in holding the variables at their planned levels, or simple lack of precision in the measurements [7]. Each observation is taken when the engine setup reaches at steady state condition to minimize error (See Appendix calculation table). [8-14].

Engine specifications:
1. Make: Kirloskar, single cylinder, four stroke Compression Ignition engine
2. Rated power output: 5 H.P
3. Stroke length: 110 mm
4. Bore diameter: 80mm
5. Loading type: Water resistance type load, with copper element and load changing arrangement
6. Moment arm: 0.2 meter
7. Orifice diameter (for air box): 25mm
8. Co-efficient of discharge of orifice: 0.64

V. DEVELOPMENT OF EXPERIMENTAL DATA BASED MODEL

One dependent π term (viz.π_1) and one independent π- term (viz.π_2) and have been recognized in the design of experimentation. These π-terms are accessible for the model formulation. Dependent π- term is assumed to be the function of the available independent π- term.

Model Development for dependent π- term (π_1):

For the dependent π- term, π_1 we have,

$$\pi_1 = f(\pi_2)$$

Where f stands for "function of"

A possible accurate numerical form for this phenomenon could be

$$\pi_1 = K_1 * (\pi_2)^{a_1} \quad \text{….1.1}$$

Equation (1.1) is one of the mainly significant and universal relations assumed in technical work and general functional relationship obtained as a result after applying dimensional analysis method.

In the equation 1.1, Constant of proportionality K_1 and indices a_1 are the two unknown terms. To obtain the values of these unknowns we require at least two sets of values of π_2. As per the experimental plan in design of experimentation we have n sets of these values. If any random one set from this table is selected and the values of unknowns, K_1 and a_1 are computed, then it may not result in one best unique solution representing a best-fit unique curve for the remaining set of the values.

To be very specific we can find out ^nC_r combinations of r sets taken together out of the available n sets of the values. The value ^nC_r in this case will be $^nC_2$. Solving these many sets and finding their solutions will be a extraordinary task. Hence, it was decided to solve this problem by curve fitting technique (Spiegel 1980). To follow this method it is necessary to have the equations in the form as under.

$$Z = a + b * x + c * y + d * z \quad \text{…………..1.2}$$

The equation 1.1 can be brought in the form of equation 1.2 by taking the log of both sides. By taking the log of both the sides of this equation we get,

$$\log \pi_1 = \log K_1 + a_1 * \log(\pi_2) \quad \text{…………..1.3}$$

$$\text{Let, } \log \pi_1 = Z_1,\ \log K_1 = K_1, \log(\pi_2) = A$$

Then the equation 1.3 can be written as

$$Z_1 = K_1 + a_1 * A \quad \text{…1.4}$$

Equation 1.4 is **a regression equation** of Z on A, In an n-dimensional co-ordinate system this represents a **regression hyper-plane**. To find out the regression hyper- plane we determine a_1 in equation 1.4 so that

$$\sum Z_1 = n\, K_1 + a_1 * \sum A$$

$$\sum Z_1 * A = K_1 \sum A + a_1 * \sum A * A \quad \text{……….1.5}$$

Where, n is the number of runs or the number of sets of the values.

These equations are called usual equations equivalent to the equation 1.4 and are obtained as per the definition. In the above sets of equation the values of the multipliers of K_1 and a_1 are substituted to calculate the values of the unknowns (viz. K_1 and a_1). The values of the terms on Left Hand Side and the multipliers of K_1 and a_1 in the sets of equation 1.5 are calculated. After substituting these values in the equation 1.5 we will get one set of equation which is to be solved simultaneously to get the values of K_1 and a_1.

The matrix method of solving these equations using MATLAB is given below.

Let, A = 2x2 matrix of the multipliers of K_1 and a_1.

B = 2x1 matrix of the terms on Left Hand Side and

C = 2x1 matrix of solutions or values of K_1 and a_1.

$$\text{Then, } C = inv\,(A) * B \quad \text{….1.6}$$

gives the unique values of K_1 and a_1, In our case –
Engine performance Model

$$\pi_1 = x\,(\pi_2)^y$$

VI. CONCLUSIONS

The data of the independent and dependent parameters of the system has been gathered during the experimentation. In this case there are dependent and independent pi terms. It is necessary to correlate quantitatively various independent and dependent pi terms involved in this man-machine-animal system. This correlation is nothing but a mathematical model as a design tool for such work station. The optimum values of the independent pi terms can be decided by optimization of these models for maximum efficiency and minimum fuel energy. Since induction pressure is one of the operating parameters of a particular engine, which must be maximized for overall engine performance improvement. It would be a challenge to continue to do this with future emission limits. In this paper an important correlation for C.I. engine operating variables, for limited test run region, is investigated & procedure of experimental data based modeling is shown for a C.I. engine. Further scope is, to check that the applicability of model and feasible operating regime, for any particular internal combustion engine and its utility for performance analysis & optimization.

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