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Standardization of Methodology for the Effective Selection of CAC (Charge Air Coolers) for Diesel Engine Testing using Statistical Analysis

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***Abstract*— In Engine Testing and Laboratory Operations, selection of a specific CAC (Charge Air Cooler/ Intercooler) based on the requirements of different series engine being tested in HMLD *(Heavy duty-Mid range-Light Duty engines)* and HHP *(High Horse Power engines)* test cells is very critical especially when the CAC are sourced from multiple sources and are of different configurations. This demands for a standard methodology to select the best one for testing purpose within minimum time in order avoid the test cell downtime issues due to CAC incompatibility and to meet the ultimate aim of minimizing the downtime associated with effective selection of CAC based on its compatibility with the particular engine with an effect to improve the efficiency & productive utilization of engine test cells. In order to decide upon compatibility, Statistics, mainly the Regression Analysis played a major role to resolve the issue. The project also demands for standardizing the piping associated with CAC which will help in bringing about the standardization in air intake system in Diesel engine test cell.**

Index Terms—CAC (Charge Air Cooler), Statistics, Regression Analysis, Regression ANOVA, Box Plot

I. INTRODUCTION

The main function of Diesel Engine Lab-Ops (Laboratory Operations) team is to support Engine R&D projects by simulating desired favorable working conditions inside the test cells. Different Endurance, & Performance .Before claiming for approval of any newly launched engine from Govt. Regulatory authority in India like ARAI we need to validate the performance of engine in-house in Test Cells. It is the responsibility of Lab-Ops team to facilitate all required utilities & equipment support, and robust technology for consistently recording accurate data as per mentioned in test plan for the particular engine. Equipment & Utility support consisting of sophisticated devices such as CCU (Coolant Conditioning Unit), FCU (Fuel Conditioning Unit), CAC (Charge Air Cooler) unit, ACS (Air Conditioning System), AHU (Air Handling Unit), Hydraulic/Transient Dynamometer etc. and a robust Control system to synchronize all these devices as per the test's requirement.

Charge air coolers (CAC's) used in test cells uses *50-50 mixture of Ethylene Glycol and water* to absorb the heat content of charged air (i.e. compressed air by the means of turbo-charger to increase the density of air) from turbo-compressor to bring down its temperature to desired range i.e. from (200ºC to 45ºC) before supplying it to the engine intake manifold. This coolant is then passed through *shell & tube type HE or PHE* to which raw water is supplied from cold well below the Cooling Tower as mentioned above. Shell & Tube HE are robust in nature can handle raw water mostly used in Endurance testing while Plate Type HE are more efficient and provides precise control over IMT of engine only when water supplied to its secondary circuit is softened by the means of softener plant as they clog early if raw water is used instead. CAC consists of *PID control valve* on air side which maintains the IMT in prescribed range.

Fig1 Charge Air Coolers different configurations

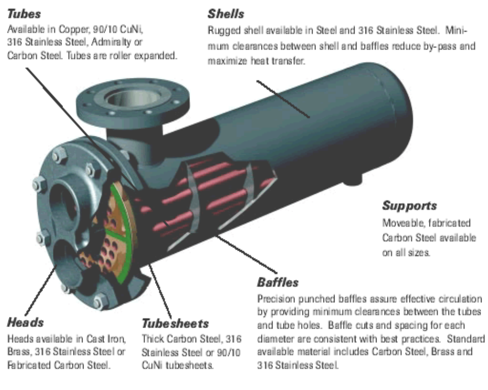


Fig 2 Typical Shell & Tube Type Heat Exchanger

A PID controller is used to calculate the error value as measured process variable minus desired set point. It is the main function of the controller to minimize this error by supplying controlled process signal to the actuators used in the CAC circuit.

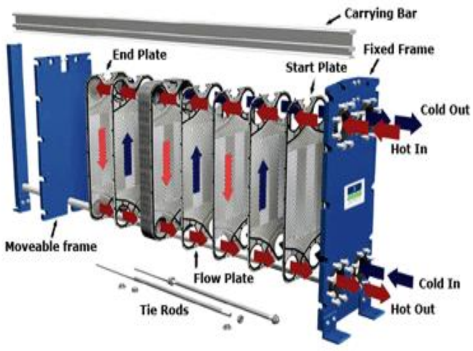


Fig 3 Typical Plate Type Heat Exchanger

On coolant side of CAC there is *3-way control valve* which helps in maintaining the temperature as well as to control the flow rates as per the requirement. Control valves used to control flow conditions by fully or partially opening or closing in response to processed & conditioned input signals received from controllers that minimizes error. Spool of the control valves are usually positioned automatically by, hydraulic or electrical or pneumatic actuators.

II.NEED

All Heavy duty-Mid range-Light Duty engines and few High Horse Power engines must be equipped externally with air intake systems before initiating any performance or Endurance test. This external air handling system consists of CAC used in conjunction with Heat Exchanger setup, intake restriction/brake, flow control valves, connected with each other with Rigid M.S. piping and Flexible hoses and synchronized by means of a robust control systems. Test Facility support consists of different configuration CAC's some of them are outsourced such as AVL (HD), AVL (MR) while few of them are customized in house to suit the test cell needs such as QST 30, N-14, K-19. So it is the duty of Lab-Ops team to decide upon which CAC is compatible with which engine. Since the heat rejection capacities of most of the CAC's used in test cells as well as the air heat to be rejected from most of the engines is not known directly, thus it becomes a difficult task for the facility providers to decide upon the compatibility. Thus to have a standardized methodology for the effective selection of CAC within minimum time and that too by using readily available engine data i.e. engine power in KW so that even a unskilled test operator could easily decide upon the best compatible CAC which will avoid any trial & error CAC installation practices.

III. OBJECTIVE

Ultimate aim of this is to minimize the downtime or idle time associated with effective selection of CAC based on its compatibility with the particular engine by developing a standard methodology. By following the standard methodology one could easily decide upon the compatibility of CAC and could effectively select the best compatible CAC within minimum time. This will improve the effectiveness and overall utilization of test cells.

IV. MAJOR HURDLES

Data generation need of the project:
In order to decide upon the compatibility we need to have maximum data mainly regarding:

1. Maximum heat to be rejected by air to the coolant
2. Types of CAC availability
3. Capacities of CAC
4. Capacities of HE used in conjunction with CAC
5. Mass flow rates of coolant through CAC & it's HE.
6. Effectiveness of CAC is Unknown
7. Maximum Drop in temperature and pressure drop of coolant on CAC as well as HE side is not known.
8. Cooling tower efficiencies and raw water quality unknown.

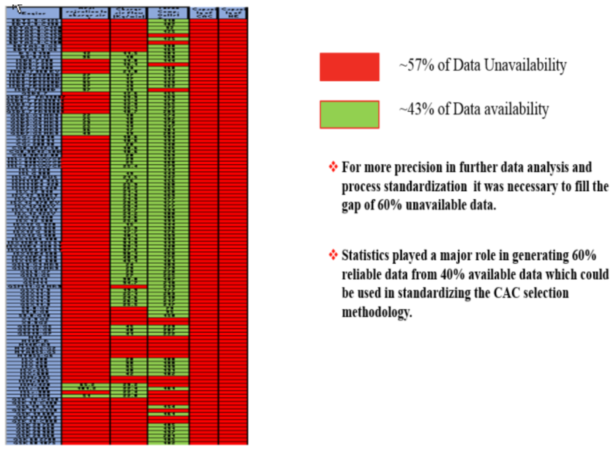


Fig 4. Data sheet for engine heat rejection

From the overview of data sheet shown in Fig.4 for most of the HHP & HMLD engines it is seen that nearly 57% of the air heat rejection data is missing while we have only 43% of data in hand, thus from the project point of view it become necessary to generate the missing data for other engines .

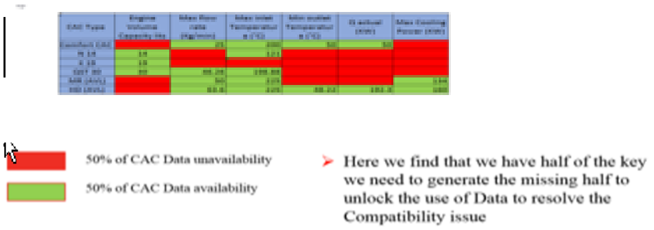


Fig 5 Data for CAC heat removal rate capacity

Similarly from the overview of details for CAC heat rejection capacity for only two out of six of the CAC's were available as shown in Fig. 5 ,also in all 50% of data was missing thus we need to generate the remaining 50% which was a major loop hole in the project.

V. METHODOLOGY EMPLOYED TO GENERATE THE DATA

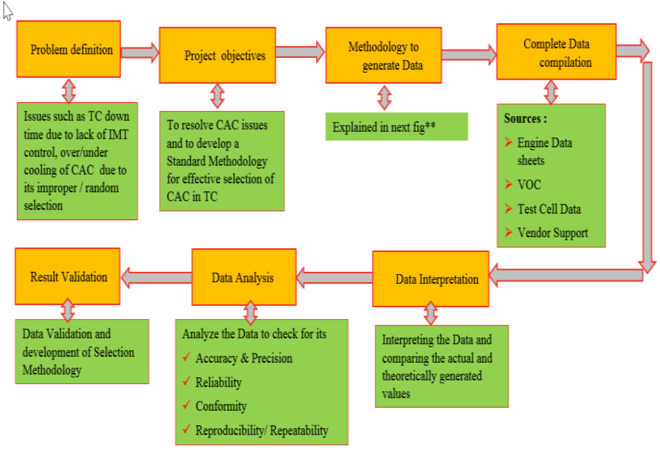


Fig 6 Research Methodology employed for data generation

The flow diagram in Fig.6 clearly indicates the methodology followed to generate the missing data for engine as well as CAC.

VI. DATA TESTING FOR RELIABILITY & TO PREDICT SINGNIFICANT PREDICTORS FOR THE PRE-ASSUMED RESPONSE VARIABLE

a. RESULT FROM BEST SUBSET REGRESSION ANALYSIS

Best Subsets Regression: Air Heat (KW) versus Power (KW), Air T

Response is Air Heat (KW)

Vars	R-Sq	R-Sq (adj)	R-Sq (pred)	Mallows Cp	S	Power (KW)	Air Temp.	air flow (Kg/min)	Displ (Lits)
1	91.4	91.0	89.2	37.3	2.4057			X	
1	89.2	88.6	86.8	51.5	2.7064		X		
2	97.5	97.2	96.4	1.7	1.3450		X	X	
2	93.4	92.6	90.5	27.5	2.1823	X		X	
3	97.5	97.1	95.9	3.5	1.3739	X	X	X	
3	97.5	97.0	96.1	3.7	1.3863		X	X	X
4	97.6	97.0	95.6	5.0	1.3974	X	X	X	X

Fig.8 Best Subset Regression Output from Minitab

From Fig 8. analysis it can be concluded that the best three predictors are Power, Air Flow and Compressor air out temperature.

b. RESULT FROM SCATTER PLOTS

Conclusion:

- From the above scatter plots it represents a strong positive correlation between Airflow , Power Vs Air Heat
- Represents fair correlation between Displacement Vs Air Heat
- Represents poor correlation between Charge Air temperature Vs Air Heat

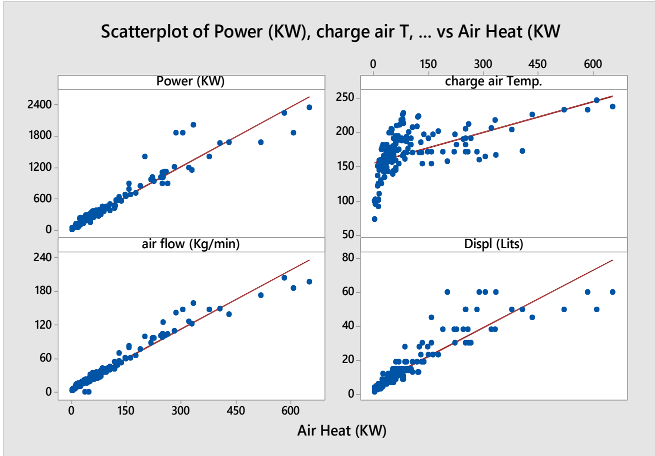


Fig 9 Scatter Plot Output from Minitab

Thus it can be concluded that there exists a strong correlation between Power Generated by the engine and the heat content in charge air.

V. EXISTING DATA MANIPULATION AND REQUIRED DATA GENERATION

Assumptions

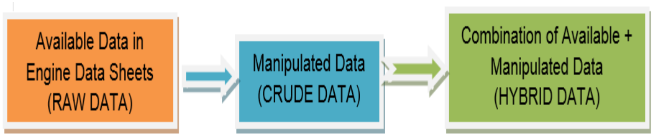
1.Cp air is assumed at mean temperature of air : For T mean= (60 to 100 °C) , Cp=1.009 KJ/kg°C for HMLD engines & T mean =(120 to 140 °C) , Cp= 1.013 KJ/kg°C for Hig Horse Power engines.

2. For simplicity Intake Manifold Temperature is assumed to be (minimum) constant as 40.5 °C (This value is considered as optimum minimum value to be on the safer side)

3. Rise in temperature of coolant across HE as well as CAC to be max as 10 deg Celsius.

By considering above assumptions and by data manipulations and by extensive Regression Analysis we have generated hybrid data which is the combination of actual & theoretically calculated data as follows .Engines were classified into four groups as

Heavy duty engines, Mid-range engines, Light Duty engines and High Horse Power engines and Regression Analysis was done to generate the unknowns which were utilized to derive the Hybrid data.



VI. COMPARISON BETWEEN REGRESSION MODELS USING ACTUAL, THEORETICAL, HYBRID DATA VALUES

Regression Analysis was also carried for actual available data values,theoretically generated data values and for hybrid data values considering the engine power & air heat content (i.e. P Vs Q) and the models are as shown in figure10

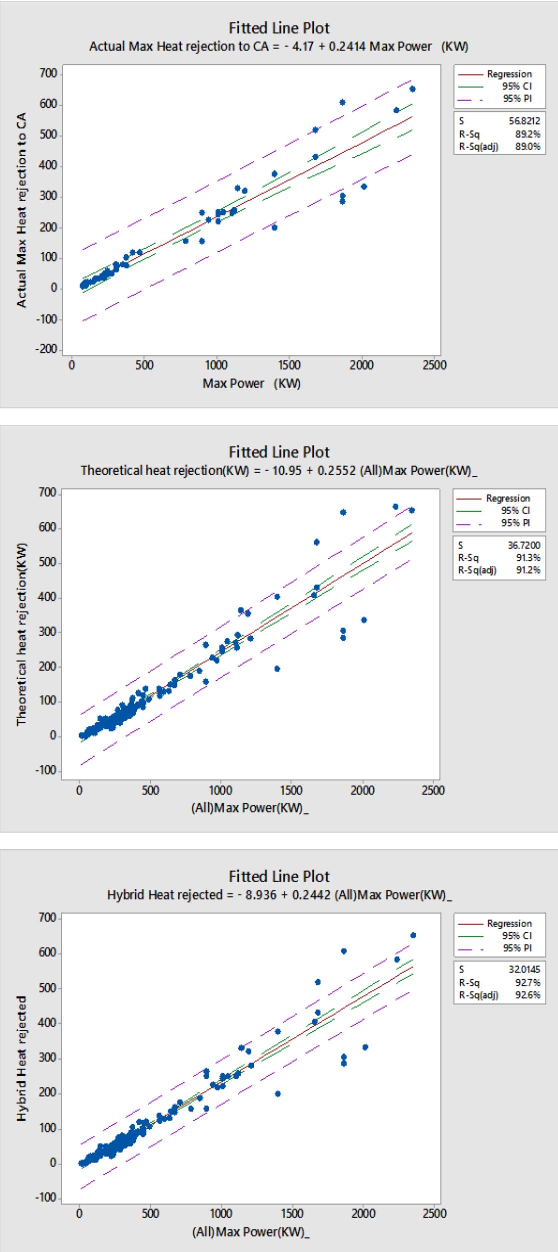


Fig.10 Comparison between Regression models based on Actual, Theoretical and Hybrid Data values

Table1. R-Sq. values for different Regression Models

Sr.no.	Regression model using following Data values	R-Sq. values
1	*Actual Data Values*	*89.2%*
2	*Theoretical Data Values*	*91.3%*
3	*Hybrid Data Values*	*92.7%*

From the above Regression Analysis it is clear that R-S q value is more for Hybrid data i.e. above 90% which indicates comparatively strong regression model within 95% confidence interval.

This conclusion enables us to use the Hybrid model for the generation of missing air heat rejection values using Regression Equation as follows:

Charged air heat content (Q) in KW=
-8.936 + 0.2442 (P) Max Engine Power in KW .* *(1)*

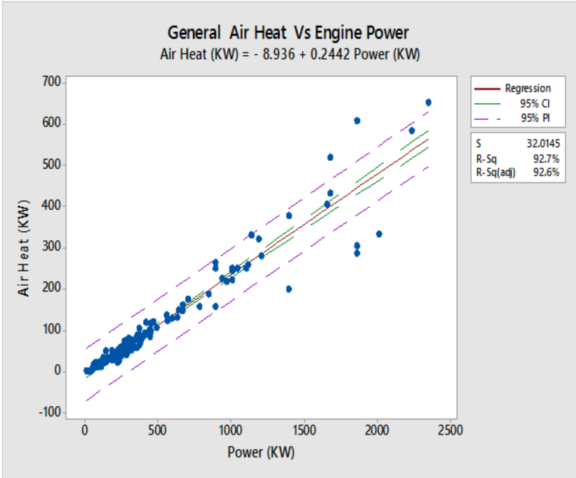


Fig11. Hybrid Regression Model

Interpretation:

From (fig.11) above model it is clear that most of the data points generated for HMLD engines are lying close to the best fit line with 92.7% R-Sq. value, within 95 % confidence level band.

Few outliers are also found in HHP region highlighted in fig above by circle, but they do not pose much potential threat as in most of the HHP engines CAC i.e. intercooler is used as an integral part of engine.

V. REGRESSION ANOVA FOR HYBRID SUPERIMPOSED DATA

From the generated Hybrid Data, Regression ANOVA was done in Minitab17 to get following results, when significance of all predictors i.e. Engine Power (P)in KW, air flow rate (M)kg/min and Displacement (D) in lits are taken into considerations. Thus more approximate equation to predict charge air heat content Q (KW) when values of all predictors are known is given by:

*Q ={-2.84 + (0.0897*P) +(2.845*M) –(3.305*D)}* *(2)*

VI. PREDICTION OF CAC HEAT REJECTION CAPACITIES

Similar methodology as above mentioned was employed to the available data for CAC to predict the Heat Rejection Rate i.e. capacities of CAC used in test cell. Since the available values were very limited

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in this case the model may be an over or under predictive model. To generate data the specifications of obsolete CAC was also used for Regression Analysis. Thus by Extensive application of Regression Analysis and by Data manipulation we are able to predict the missing data values in terms of air heat to be rejected from different engine series and the Heat Rejection Capacities of the different configuration CAC's.

By comparing the generated data values of engine air heat to be rejected with that of CAC capacities it can be determined that, those engines whose air heat to be rejected is less than the rated capacity of CAC ,then that CAC is considered as compatible with that particular engine.

Table 2. Predicted values of CAC capacities

Sr.no.	CAC Name	Heat Rejection Capacities (KW)
1	X	26.1
2	Y	58.5
3	Z	120.1
4	W	143.8
5	Q	192.3

VII. BOX PLOT OF THE GENERATED DATA FOR CAC CAPACITIES & ENGINE AIR HEAT CONTENT

From the above Regression Analysis we have the two main sets of data values i.e. CAC capacities & heat to be rejected from turbo-charged air, now to have an idea of which is widely used CAC in test labs so as to have more units of the same in buffer stock of facility stores, we need to study the spread of these two data values by plotting them against X-Y co-ordinates .This spread of data can be visualised by the means of Box Plot in Minitab as shown in figure 12 below.

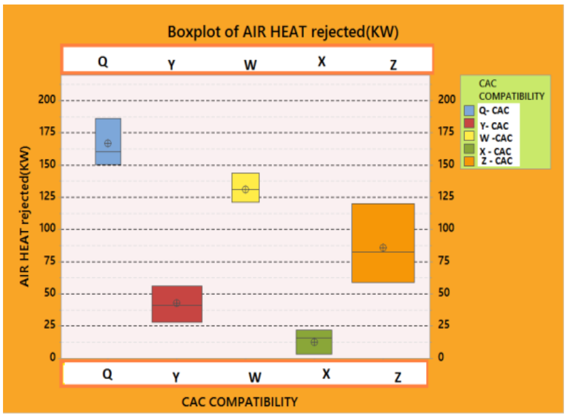

Fig 12 Box plot to predict the widely used CAC

From Box plot it can be concluded that Z is the widely used CAC on test cell, therefore it is recommended to keep more units of Z -CAC.

VIII. CONCLUSION

Thus by extensive use of Regression Analysis along with the other statistical tools like Regression ANOVA & Box Plot and by Data manipulation techniques it is possible to predict which CAC is compatible with the particular engine to be tested in test labs within minimum time. Also it is now possible to know the widely used CAC in testing so as to maintain buffer stock of the same.

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