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Performance Modelling of Steam Turbine Performance using Fuzzy Logic Membership Functions.

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KEYWORDS: Steam turbine, performance prediction, Fuzzy Inference System, defuzzification, membership function.

ABSTRACT: A Fuzzy Inference System for predicting the performance of steam turbine based on Rankine cycle is developed using a 144-rule based in analyzing the generated data for different inlet and outlet conditions. The result of efficiency for different types of membership functions and defuzzification method was obtained. Centroid method of defuzzification gave good results irrespective of the type of membership function with error less than 5%. However, other defuzzification methods gave good result for some types of membership functions. Result of different input data tested do not vary significantly ($P<<0.05$). It can therefore be concluded that Fuzzy logic can be used to effectively predict performance of a steam turbine. ©JASEM

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Introduction

Performance prediction tends to estimate useful parameters such as efficiency based on certain input parameters (Benner, Sjolander, and Moustapha, 2006a, Benner, Sjolander, and Moustapha, 2006b, Benner, Sjolander, and Moustapha, 2004, Dunham and Came, 1970, Živković, 2000). Steam turbine is mostly used for generating mechanical energy due to its advanced features and outstanding qualities (Mathis, 2003). Currently, researchers are working assiduously towards improving efficiency of steam turbine by developing better metallurgical materials that can withstand steam at temperature as high as 600^0C and beyond critical pressure (Brooks,2012). However, not much improvement on its efficiency has been observed in recent times, due to the long technological history of efficiency of turbine cycles being about 52%, which is about 30% higher than that of a simple gas cycle, and about 40% as reported by General Electric (Organoski, 1990). One challenge faced by end-users is turbine operating at off-design conditions almost throughout its life, therefore, manufacturers need to accurately predict performance at varying operating conditions and incorporate a control system performance monitoring.

Performance prediction has graduated from qualitative guess checks to several empirical, analytical and numerical methods. Empirical methods suitable for gas turbines (Ainley and Mathieson, 1951, Dunham and Came, 1970, and Craig and Cox, 1971) can be modified with suitable correlations for non-condensing steam turbine modeling (Denton, 1993). However, Dixon (2005) argued that the empirical methods lack first principle in their derivations, and he developed a model that cannot be implemented because it requires quantifying all losses which is practically impossible. Existing analytical methods in standard literature (Horlock and Denton, 2003) come with rigorous mathematical complexities and require requisite knowledge of turbo-machinery physics for their application. There are well developed numerical methods such as Computational Fluid Dynamics (CFD), but they are very expensive and time consuming. Besides, their results are not accurate as reported by Denton (Emami, 1997). Current market trend of steam turbines has necessitated the development of easy to use performance prediction methods that give good result. Methods that do not require mathematical formulation such as Fuzzy logic, genetic algorithm and artificial neural network are therefore good alternatives.

Fuzzy Logic is one of the best methods that do not require mathematical formulation. It replaces rigorous, mathematical formulations with ambiguous,

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qualitative and random conceptions (Ariavie, Ovuworie and Ariavie, 2011). It is easy to use and has been applied to various systems ranging from linear to high level non-linear systems. Fuzzy logic tends to map a set of inputs to a set of outputs, obeying a list of rules (combination of statements with inference). The rules are formed from the variables (members of input and output sets) and the adjectives that describe those variables (membership functions). Before one can build a system that interprets rules, it is imperative to define all the terms to be used and the adjectives that describe them. To say that the pressure is high, one needs to define the range that the steam pressure can be expected to vary as well as what is implied by the word *high* (Harris, 2006). Due to its advantages and wide applicability, the method has gained much development and is discussed in detail as a subject in standard literature (Cox, 1994, Perfilieva and Mockr, 1999, Sivanandam et al., 2001, Yager and Filer,1994, Micheal and Shapiro, 2006). This work investigated the application of Fuzzy Logic to performance prediction of steam turbine. A Fuzzy Inference System (FIS) was developed. The FIS can be used to determine the thermodynamic efficiency of a steam turbine from the steam inlet pressure, inlet temperature and exit pressure as input variables. The FIS was trained with analyzed data generated from developed MATLAB simulation code that estimates efficiency, back work ratio and specific steam consumption based on the Rankine Cycle. The effect of different types of membership functions and defuzzification methods available in the MTALB FIS development environment was investigated and compared to the analytical result.

METHODS AND MATERIALS

Data was generated using Matlab simulation code for steam turbine modeling; however some suitable assumptions were made. The data was analyzed, filtered and then used to train the fuzzy inference systems developed for steam turbine performance predictions.

MATLAB Simulation program based on the Rankine combine cycle for steam turbine modeling was developed. Basic assumptions for applying the Rankine cycle to steam turbine modeling given in standard literature (Celgel, and Boles,2006, Potter and Somerton, 2004) were made. Optimum reheat temperature of one-fourth inlet conditions (Celgel, and Boles, 2006) was adopted, and varying conditions were adopted for the regenerative cycle. Turbine and pump isentropic efficiency were taken as 85%. The code was used to simulate result for varying turbine conditions. The data was analyzed in order to ascertain the rules for the fuzzy inference system. Turbine inlet and outlet conditions (pressure and temperature), and their effects on the turbine efficiency were investigated.

Development of Fuzzy Inference System: The Mandini type of Fuzzy Inference System was adopted for this work. The turbine inlet conditions (Boiler pressure (P1) and temperature (T1) respectively) and the turbine exit pressure (Condenser pressure (P2)) were taken as the three inputs variables while the efficiency of the turbine was taken as the output of the Fuzzy Inference System (FIS) for performance prediction of steam turbine. This is shown in figure

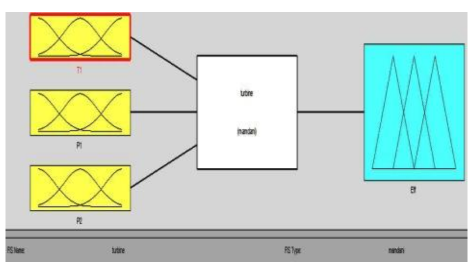

Fig .1 Mandini Fuzzy Inference System for Performance Prediction of Steam Turbine.

The membership functions for each variable was designed with the following range of values as seen best for developing rules for the turbine based on the data analyzed.

Table 1. Range Values of membership function for Turbine inlet temperature (T1)

Values in degree Celsius	100 – 320	250 – 400	320 – 450	400 – 500	450 – 600
Designation	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)

Table 2. Range Values of membership function for Turbine Inlet Pressure (P1)

Values in MPa	1 – 4	2 – 8	5 – 12	7 – 18	12 – 20	16 – 24
Designation	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)	Very High (VVH)

Table 3. Turbine Exit Pressure (P2)

Values in MPa	0.0015 – 0.015	0.01 – 0.05	0.04 – 0.1	0.08 – 0.5	0.3 – 1.2
Designation	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)

Table .4 Range Values of membership function for Efficiency

Values	-0.2 – 0.2	0 – 0. 4	0.2 – 0.6	0.4 – 0.8	0.6 – 1.0
Designation	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)

Four (4) different membership functions which includes the triangular (trimf), Gaussian (gausmf), Polynomial (Pmf) and the modified Gaussian (Gauss2mf) were tested with each generating its unique curve based on the function it describes. Their default parameters for each of the curves were adopted. The output (Efficiency) for each selected membership function was recorded. A sample dialog box for editing the type membership function and its parameters is shown in figure 2.2.

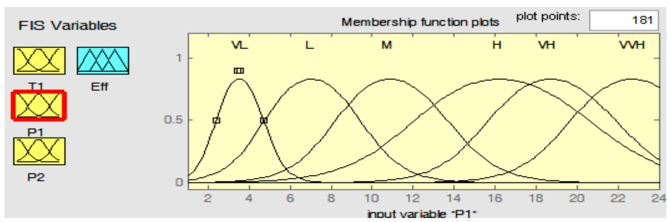

Fig 2. The Polynomial membership function (Pmf) for the Inlet temperature (T1)

Five (5) different defuzzification methods (the Centroid, Bisector of Area (BOA), Middle of maximum (MOM), Largest of maximum (LOM) and Smallest of maximum (SOM)) were also tested and corresponding values of efficiencies recorded. They include One hundred and forty four (144) rules were selected based on analysis of the generated data and a few is shown in figures 2.3 and 2.4, while Figures 2.5, 2.6, 2.7 and 2.8 shows the surface plots representing the rules. The minimum values and maximum values were used for the 'and' and 'or' combination respectively. The FIS developed was tested with the data below.

Table 2.5 Test data for fuzzy inference system

T1	P1	P2	Efficiency
360	4	0.05	0.371
600	24	0.02	0.502

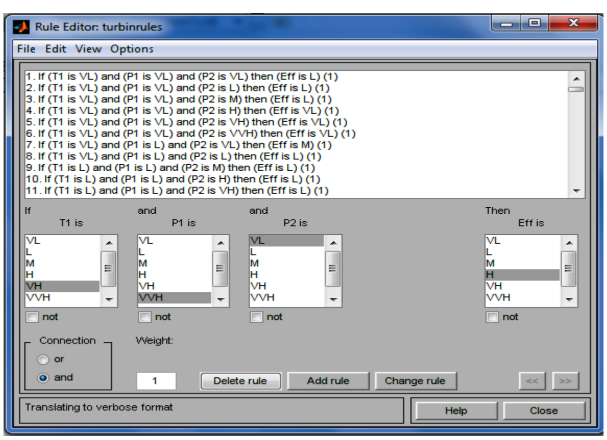

Fig .3

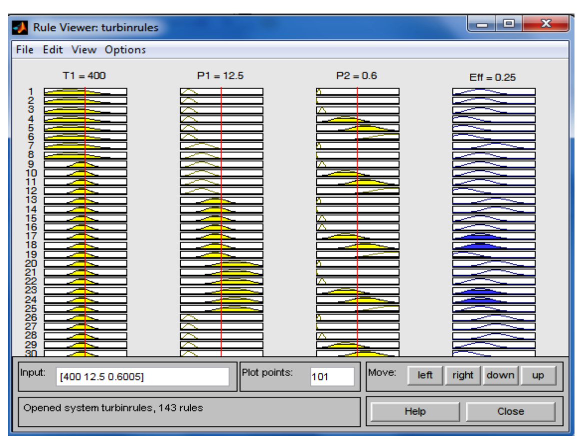

Fig 4

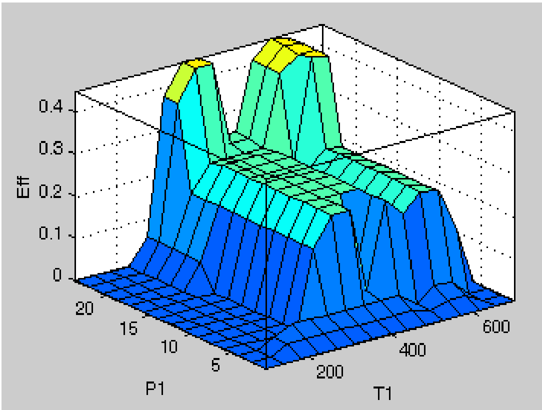

Fig .5

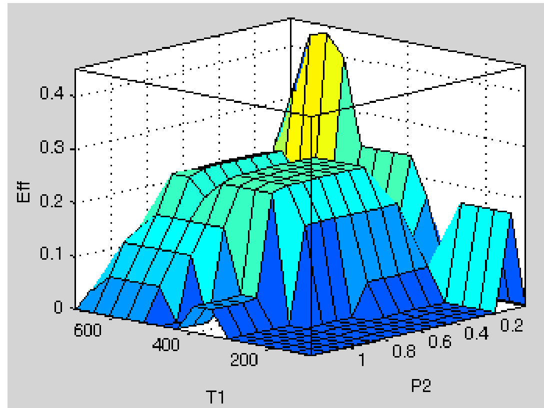

Fig .6

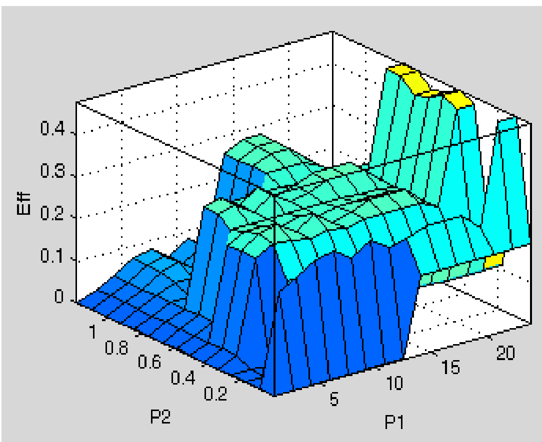

Fig .7

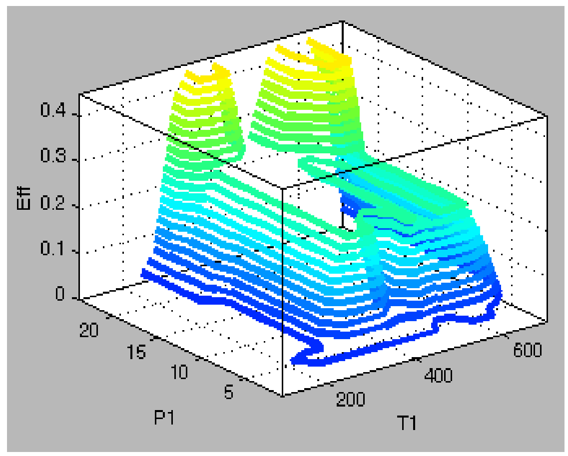

Fig .8

RESULTS AND DISCUSSION

Data Analysis: Plot of Turbine exit pressure (P2) versus Efficiency for different inlet pressures (Figure 3.1) shows that efficiency tends to decrease non-linearly as condenser pressure increases. This is explained by the fact that much more of the energy possessed by the body would have been converted to work at a more reduced pressure. This is further explained by specific enthalpy being lower values at lower pressure values and vice versa. Lower exit pressures give higher efficiency, and lower steam quality. There is a limit to which condenser pressure may be reduced since it affects the steam quality. For modern steam turbines design, steam at the exit of the turbine must be at least 90% dry. That is the dryness fraction which must be between 0.9 and 1 (Celgel and Boles, 2006) Contrary to decrease in efficiency with increasing exit pressure (Figure 3.1), efficiency tends to increase non-linearly with increasing inlet pressure (Figure 3.2). This increase in efficiency is due to higher energy of steam entering the turbine. From steam tables, the higher the pressure the higher the specific enthalpy. Efficiencies are therefore expected to be high for higher values of inlet pressure provided other conditions are kept constant as shown in Figure 3.1. There is a limit to which the pressure can be increased due to metallurgical strength for piping materials. However there are newly developed materials with strength high enough to withstand steam at critical pressure (Potter and Somerton, 2004). The efficiency of turbine increases linearly with inlet temperature of steam as shown in Fig. 3.3. This is however expected because heat is directly proportional to temperature. So steam at higher temperature possesses more heat energy that will be converted to work leading to higher efficiency values when other conditions are kept constant (Fig 3.2). So heating steam to high temperatures can increase the efficiency of the turbine, however this is however limited by the thermal properties of the material. There are modern developed materials that can withstand steam temperatures as high as 600^{o}C (Potter and Somerton, 2004).

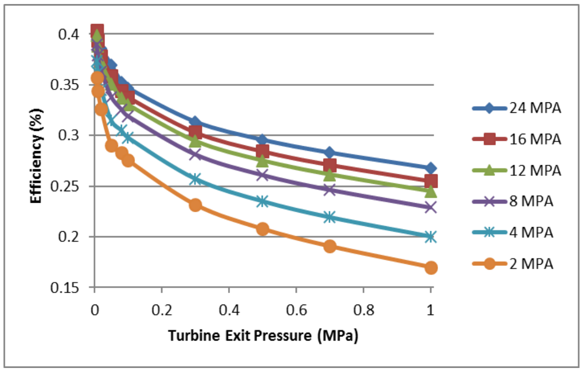

Fig 3. Plot of Steam exit pressure (MPa) versus efficiency for different inlet Pressure at 600^0C

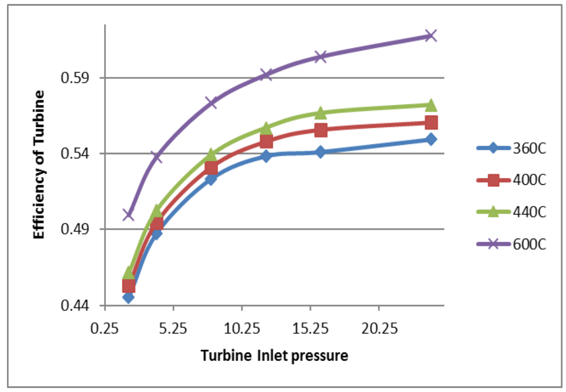

Fig. 4 Effect of Boiler Pressure on the efficiency of Turbine for different Temperatures

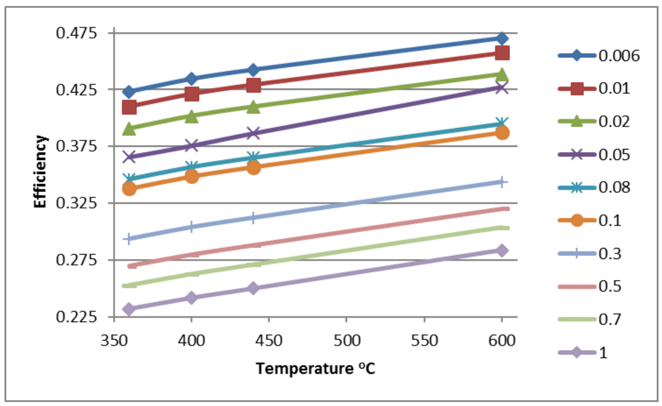

Fig. 5. Temperature versus Efficiency for Different Exit Pressure at 16MPa inlet pressure

Fuzzy Inference System: Figures 3.4 and 3.5 are bar charts showing the values of efficiency for different membership function and method of defuzzification. Their respective percentage error computed is shown in table 3.1. The Centroid method of defuzzification gives good result, that when compared to analytical values with efficiency less than 5%. The bisector method gives very good result for all membership function except the polynomial membership function in which the percentage error is about 7%. The other three methods of defuzzification: LOM, NOM and SOM respectively gave poor results irrespective of the type of membership function used, with their respective percentage error more than 5% for all cases. LOM method of defuzzification gave the worst result with percentage error of about 34% for triangular membership function. The triangular membership function with centroid method of defuzzification gave the best result with percentage error being about 0.5%, followed by the modified Gaussian method with percentage error of about 0.8%.

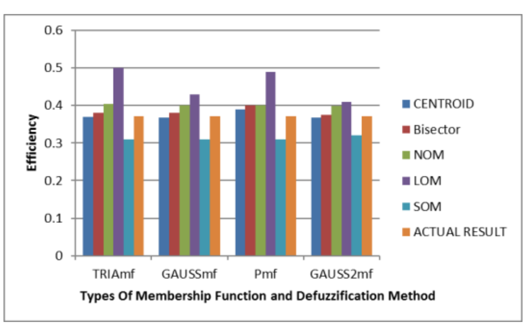

Fig 6 Chart of efficiency for different Membership functions and Defuzzification Methods compared to actual Efficiency for second case study.

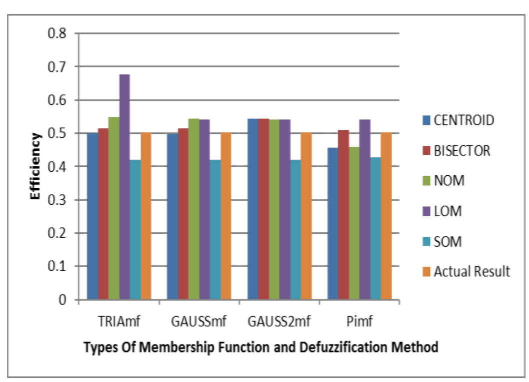

Table 3.1 Efficiency computed for the different methods

	TRIAmf	GAUSSmf	Pmf	GAUSS2mf
CENTROID	0.539084	1.078167	5.012129	0.8086253
Bisector	2.425876	2.425876	7.816712	1.3477089
NOM	9.16442	7.816712	7.816712	7.5471698
LOM	34.77089	15.90296	32.07547	10.512129
SOM	16.44205	16.44205	16.44205	13.746631

Table 3.2 Statistical analysis of results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Rows	0.110784	24	0.004616	40.69481	3.83E-14	1.98376
Columns	0.219085	1	0.219085	1931.455	1.89E-24	4.259677
Error	0.002722	24	0.000113			
Total	0.332591	49				

Conclussion: In conclusion, Fuzzy logic can be effectively used for predicting performance of steam turbine. The efficiency of the Fuzzy Inference System depends on the method of defuzzification, and type of membership function and its parameter used in developing the system. However, the parameters of membership function and range can be adjusted to improve efficiency of the system.

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