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Original Research Article

The fuzzy logic modeling of diesel engine emissions using fuel mixed with different ratios of hydrogen

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ABSTRACT

In this study a Rule Based Mamdani-Type Fuzzy Modelling (RBMTF) was used to model and determine exhaust gas emissions of CO, CO_2 and NO_x of a single cylinder, four strokes, air cooled engine where a certain amount of hydrogen was mixed with the fuel. The RBMTF was developed on MATLAB Fuzzy Logic Toolbox software and supported with additional programs written on the MATLAB. The RBMTF model was designed to have two input parameters (the amount of hydrogen mixed into the diesel fuel and the engine speed) and one output parameter (the emission rates of CO, CO_2 and NO_x) described by the 'if then rules'. When the results obtained from RBMTF and statistical analyses of experimental data were compared, it was determined that R^2 values were 97.7 % in CO, 96.84 CO_2 and 97.31 % in NO_x. These results were considered to be statistically acceptable and the exhaust emission values in hydrogen mixture rates not performed in experimental studies were predicted using RBMTF. As a result, the best results were obtained at the engine speed of 2400 rpm and 20% hydrogen by volume of the fuel.

Keywords: fuzzy expert system; hydrogen mixture rate; alternative fuels; exhaust emissions.

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1. INTRODUCTION

Hydrogen attracts interests of researchers due to its numerous advantantages like its abundance in nature, being environmentally friendly and being a portable energy resource. Studies on the use of hydrogen in vehicles as an alternative to petroleum based fuels have reached to an encouraging stage. The restrictions on the use of hydrogen instead of petrol in the existing motorized vehicles are based on economic reasons and insufficient infrastructure than technical grounds. The fear that the current motor vehicles that use petroleum based fuels will soon be a history is an example of this situation. On top of that, environmental regulations obligate immediate use of clean energy. This obligation accounts for positive advances on shifting from pure petroleum fuels to the one mixed with hydrogen. Countries advanced in the automotive sector like the USA and Germany lead the way in the studies conducted on the uses of fuels mixed with hydrogen. The aim of this study is show that different ratios of hydrogen emissions of diesel engine with RBMTF to determinate successfully are made.

Some of the researchers worked on this topic include; Bari and Esmaeil [1], in their experimental studies carried out under constant speed with varying load and amount of H_2/O_2 mixture. They attempted to to improve the performance of a diesel engine through the addition of H_2/O_2 mixture via generated water electrolysis. Bose and Maji [2], have developed a timed manifold induction system which is electronically controlled using diesel–hydrogen blend to deliver hydrogen on to intake manifold. Murcak [3], conducted an analysis on the engine performance and effects of exhaust gas emissions on diesel engines when hydrogen is used as a fuel. Another study by Batmaz and Murcak [4], investigated performance of a diesel engine that uses hydrogen as a fuel and also on the effects of emission gases therein. Akar [5], who conducted a study on a servo motor control where fuzzy logic technique and the conventional method were used and the results from the two compared. Wu and Wu [6], investigated combustion characteristics and optimal factors determination with Taguchi method for diesel engines port-injecting hydrogen. They noted that the predictions made using Taguchi's parameter design technique agreed with the confirmation results on 95% confidence interval. Miyamoto and et al. [7], conducted a study on effect of hydrogen addition to intake gas on combustion and exhaust emission characteristics of a diesel engine. They found that NO_x emission for hydrogen fraction of at 10% vol. was smaller than that without hydrogen at middle and high loads as the diesel-fuel injection timing was delayed until the expansion stroke. Lata and et al. [8], provided investigations on the combustion parameters of a dual fuel diesel engine with hydrogen and LPG as secondary fuels. Sitshebo and et al. [9], carried out promoting hydrocarbon-SCR of NO_x in diesel engine exhaust by hydrogen and fuel reforming. Tasdemir and et al. [10], conducted a study on an application of artificial neural networks in determination of performance of a petrol engine. Another study is the one conducted by Salman and et al. [11], where the performance of a plug ignited engine that uses hydrogen as fuel and the emission gas analysis were investigated. In this study, data from a study that investigated effects of exhaust emission and performance of an engine that used a mixture of motorin and hydrogen in internal combustion were used to model emission values of unused hydrogen ratios by using fuzzy expert system. The model used the volumetric ratio of mixed hydrogen and the engine speed as input parameters whereas emission rates of CO, CO_2 and NO_x were used as input parameter. The fuzzy logic expert system was programmed on MATLAB software where the use of the Fuzzy Tool Box was made. The results obtained from the program were compared to those obtained from experiments and the two were found to have close results. This suggests that RBMTF can be successfully used for the determination of the emissions of a diesel engine that uses hydrogen fuel. Many other engineering problems can be formulated using the RBMTF methodology suggested in this study.

Fuzzy logic is a superset of Boolean-conventional logic that has been expanded to handle the concept of partial truth and truth values between ‘‘completely true’’ and ‘‘completely false’’. Fuzzy theory should be seen as a methodology to generalize any specific theory from crisp to continuous. Fuzzy modelling opens the possibility for straightforward translation of statements in natural language-verbal formulation of the observed problem-into a fuzzy system. Its functioning is based on mathematical tools. Over the last few years, there have been many investigations on application of fuzzy logic. Some are briefly mentioned below. Shakhawat, Tahir, and Neil studied fuzzy rule-based modelling for human health risk from naturally occurring radioactive materials in produced water. They noted that the variable range of the cancer risk criteria makes the comparison difficult. The approach for such comparison is yet to be developed. A simplification can be made through incorporation of intermediate crisp values as criteria (10^{-4}, 10^{-5} and 10^{-6}) until comparison approach with fuzzy criteria is developed. Keshwani, Jones, Meyer, and Brand studied rule-based Mamdani-type fuzzy modelling of skin permeability. It was shown by their study that the three-input model predicted over 70% of the test data within one-half of a fuzzy class of the published data and the two-input models predicted over 40 % of the test data within one-half of a fuzzy class of the published data. They noted that comparison of the models show that the three-input model exhibited less entropy than the two-input model [12].

2. MATERIAL and METHODS

The fuzzy subsets theory was introduced by Zadeh in 1965 as an extension of the set theory by the replacement of the characteristic function of a set by a membership function whose values range from 0 to 1. RBMTF is basically a multi-valued logic that allows intermediate values to be defined between conventional evaluations like yes/no, true/false, black/white, large/small, etc. Notions like “rather warm” or “pretty cold” can be formulated mathematically and processed with computers. A fuzzy system is based on a fuzzy set, fuzzy membership and fuzzy variable, which are the three basic concepts of fuzzy logic. According to the classic theory of sets, an element is in the set (logical value “1”) or is not in the set (logical value “0”). The knowledge base of RBMTF is a collection of fuzzy IF-THEN rules. The term fuzzy logic denotes a modeling approach, where functional dependencies between the input and output variables are described by means of a set of IF–THEN rules following the reasoning with the operators AND, OR and NOT in general linguistic usage. In this study, hydrogen at various ratios was introduced into a combustion chamber of a diesel engine and the CO, CO_2 and NO_x emissions exhausted at different engine speeds were predicted with a help of a RBMTF technique. To achieve the goal, the data obtained from an experimental study conducted on a four stroke, single cylinder and engine volume 395 cm^3 6LD400 model Lombardini diesel engine were used [3]. Experimental study was conducted with hydrogen volumetric ratios of 0, 5, 10, 15, 20 and engine speeds of 1800, 2000, 2200, 2400, 2600 rpm. These two (hydrogen ratios and engine rpms) were used as input parameters of the RBMTF modelling while the output parameter was the emissions of CO, CO_2 and NO_x. Therefore; to obtain three different emission values, three separate tests were carried out. For every test, the hydrogen volumetric rates were 0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20 and the engine speeds were given as 1800, 1900, 2000, 2100, 2200, 2300, 2400, 2500, 2600 rpm. Corresponding to the given inputs, the CO, CO_2 and NO_x emission gases (output parameter) were predicted each separately.

When the results from the fuzzy expert system were statistically compared with the experimental results, it was found that correlation coefficients are at the rates of 97.7% on CO, 96.84% on CO_2 and 97.31% on NO_x. These results were found to be acceptable and the CO, CO_2 and NO_x emissions for hydrogen ratios not performed in the experimental study were predicted with the fuzzy expert system. The values obtained from the fuzzy expert system were plotted on the graphs.

3. RESULT and DISCUSSION

In this study determination of amounts of CO, CO_2, and NO_x emissions in exhaust gases was modelled using RBMTF by mixing certain amounts of hydrogen in the fuel. This stimulus model is constructed into RBMTF using the amount of hydrogen mixed into the diesel fuel and number of revolutions per minute as input parameters, and output parameter was the emission rates of CO, CO_2 and NO_x described by RBMTF if-then rules. The study consisted of three different tests where in the first test, the amount of hydrogen and the engine speed were used as the input and the amount of CO as output parameter. The variation of CO emission with respect to the amount of hydrogen and engine rpm is shown on Fig. 1.

It is clearly seen from Fig.1 that there is a close correlation between actual CO emission values and those obtained from the RBMTF modelling. As it is also seen on the figure, as the hydrogen additive increases the CO emissions tend to decrease.

It is also seen that the lowest CO emission occurred at engine speed of 2400 rpm and the highest CO emission rate is observed at 2600 rpm. In other words, the best engine performance took place at 2400 rpm. This can be described as due to complete combustion as the result of the best hydrogen-fuel mixture. At higher engine speeds, the air-fuel mixture tends to leave the combustion chamber before complete combustion is achieved.

In the second study, percentages of hydrogen and engine speed are given as input parameters while the output parameter is the percentage of CO_2. In Figure 2, the variation of CO_2 emission with respect to hydrogen ratios and engine speed is shown.

Though the situation in this case is not as those obtained for CO emission, the results for CO_2 are still close to the experimental results. When the figures are studied closely, it is seen that as the amount of hydrogen increases the CO_2 ratio increase too. Again, at the engine speed of 2400 rpm the CO_2 is maximum and the rate is minimum when the engine speed reaches 2600 rpm. Here, it can be concluded that the best combustion takes place at the speed of 2400 rpm. This means while the ratio of CO was minimum at this speed, it reaches maximum for CO_2. Complete combustion does not take place due to high-speed at the value of 2600 rpm. Incomplete combustion is caused the high rate of CO and the lower the rate of CO_2.

Common evaluation of Figure 2 shows that there are slight discrepancies in the CO_2 emissions at 1800 rpm and 2000 rpm from the actual curves. This is considered to be due to possible experimental errors. Otherwise, the same situation should have occurred for CO.

As for the third situation, amount of hydrogen and engine speed were used as the input parameters whereas the output parameter was the amount of NO_x. Figure 3 shows the graphs of NO_x emission based on the hydrogen rates and engine speeds rated at 1800, 2000, 2200, 2400 and 2600 rpm. By looking at the figure, a good match can be said to exist between the NO_x emission values from the RBMTF with those obtained experimentally.

It is seen from the graphs, that when the hydrogen increases at engine speeds of 1800, 2000 and 2200 rpm, the amount of NO_x emission first increases slightly and then drops. And as for the speed of 2400 rpm and 2600 rpm, generally the CO_2 ratio is also seen to increase. Once more, at the speed of 2400 rpm, CO_2 exhibits maximum ratio while at 2600 rpm, the graphs maintain a horizontal trend, that is the amount of NO_x remains constant. We can say, from these graphs, that there is an increasing trend of NO_x as a result of increasing amount of hydrogen. The reason being the high thermal value and high combustion efficiency of hydrogen which led to increasing temperatures of the gases within the combustion chamber.

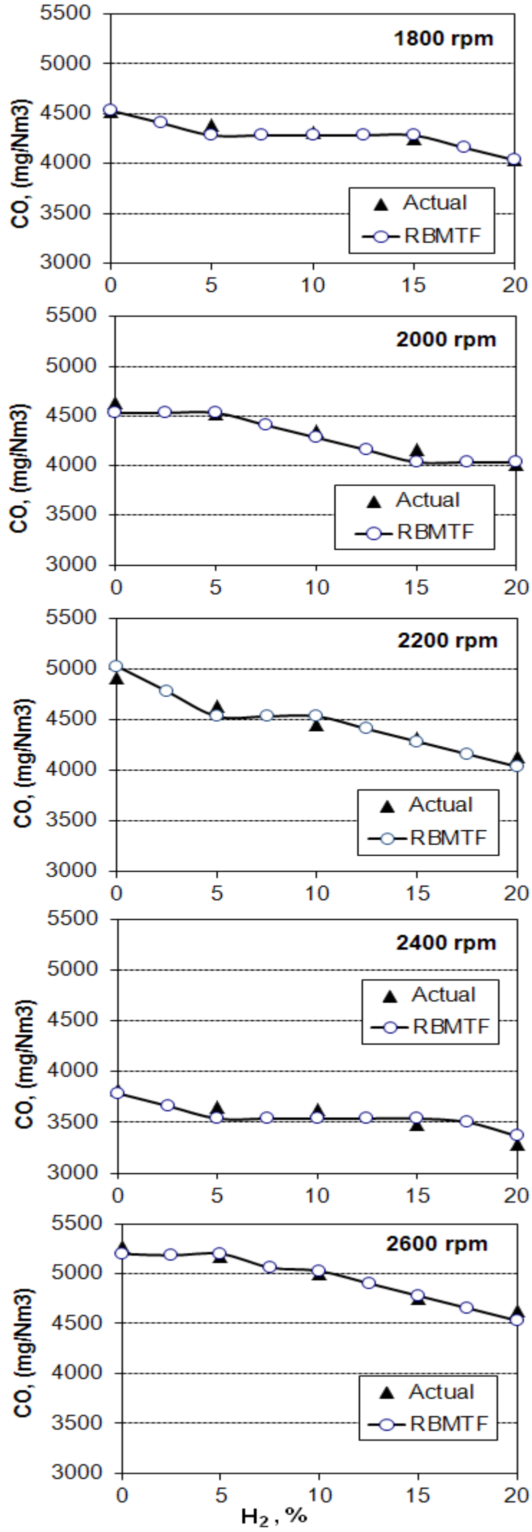

Figure 1. Change the amount of CO emissions depending on the ratio of hydrogen

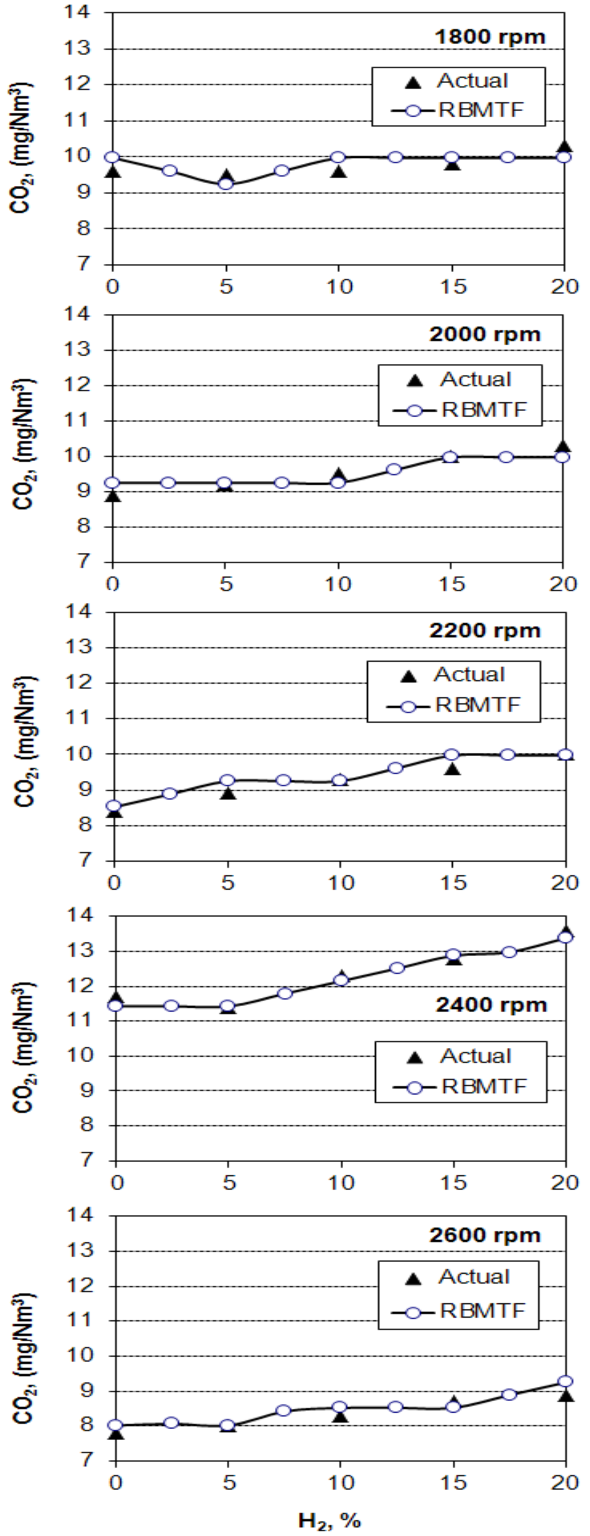

Figure 2. Change the amount of CO_2 emissions depending on the ratio of hydrogen

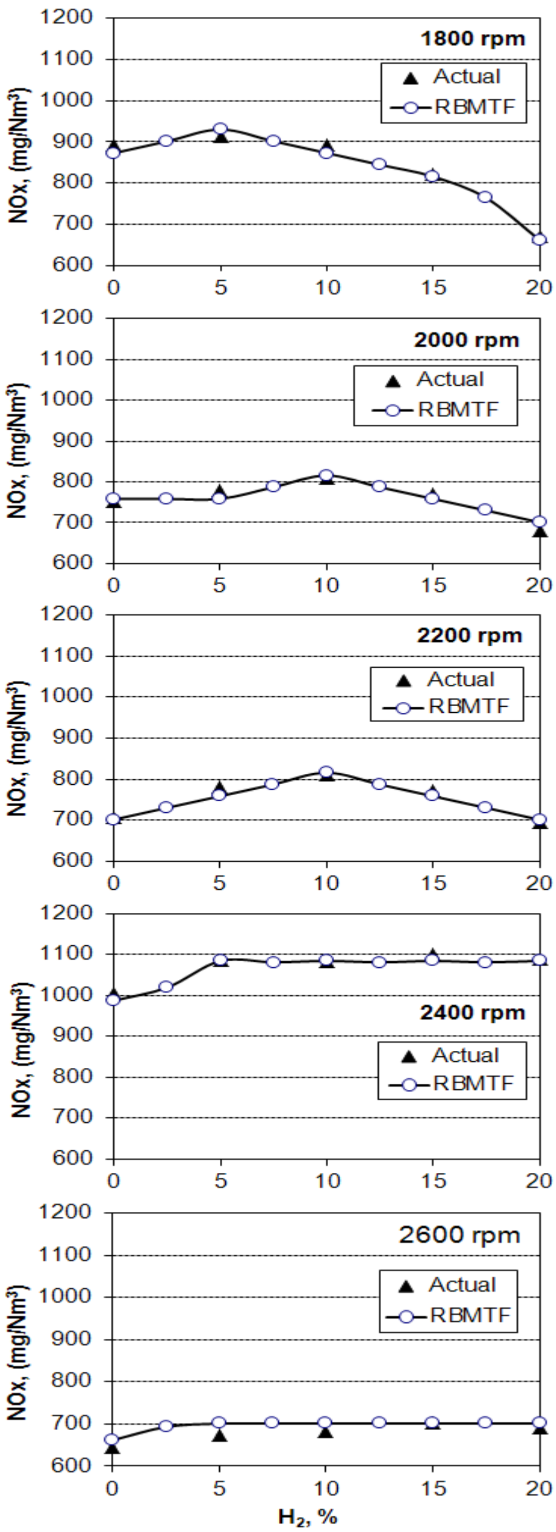

Figure 3. Change the amount of NO_x emissions depending on the ratio of hydrogen

For example, for the speed of 2400 rpm while the amount of CO was little, that of CO_2 appeared to be high. And this is also another proof that the combustion was perfect. However; the result of good combustion leads to NO_x formation as a result of increasing temperature. For this reason, the highest amount of NO_x is obtained at the engine speed of 2400 rpm. Similarly, the reason for the relatively lower NO_x emissions at the engine speed of 2600 rpm is the incomplete combustion taking place at that speed and hence the temperature does not reach its peak value. Consequently being not a cause for the NO_x formations.

4. CONCLUSION

In this study, fuzzy expert system of RBMTF was used to analyze and predict emission of CO, CO_2 and NO_x exhaust gases of a single cylinder diesel engine that uses fuel mixed with hydrogen gas. To perform this, results of an experimental study were used. The results obtained from the fuzzy modeling were found to match well with those from the experiments. A program was developed in MATLAB software where the Fuzzy Logic Tool Box was made use of. The best results in the study were obtained at an engine speed of 2400 rpm and when 20% of hydrogen was mixed with the fuel. More hydrogen would cause a drop in the volumetric efficiency of the engine. While addition of hydrogen gas into the fuel causes positive impacts in terms of CO and CO_2 emissions, it leads to an increase in the NO_x formation. It is most likely that this study and similar studies can prove equally effective when they are used with the artificial neural networks as well. Reliable results from numerical modeling would provide the experimental studies with economic and time saving advantages.

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