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Development of a Simulation Model for Fault Diagnosis of a Diesel Fuelled Engine

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Abstract

Several researchers including Antonic, [1,2,3] have worked on diesel engine in the area of fault diagnosis using various base data (vibration, voltage, temperature, and so on) measured from the diesel engine. However, little attention has been paid to data obtained from diesel engine exhaust gases. Diesel engine exhaust contains carbon-based particles and other gaseous components in different proportion according to the working condition of the engine with particular reference to the diesel engines combustion chamber. A STELLA based simulation model was developed and trained using the data obtained from an earlier work [4] for a normal diesel engine as a base-line data. This work presents results of experiments based on the data (700 x 5 samples each for seven (7) fault classes) from the developed diesel engine Fault Diagnosis simulation model. Curves showing relationship, interactions and proportion of gaseous components of the diesel engine exhaust fumes were presented and discussed. In addition, the model is able to predict the fault associated with various data used to experiment with the model.

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This work is limited to the development of a simulation model for diesel fuelled engine fault diagnosis using STELLA modelling software, and discussed the developed model under two categories of faults, namely loss of compression fault and nozzle fault.

Keywords: STELLA; Simulation Model; Faults; Diesel Engine; Exhaust Fumes; Carbon-Based Particles

1. Introduction

Diagnosis is the identification of the nature and cause of a certain phenomenon. In system engineering, diagnosis is typically used to determine the causes of symptoms, mitigation, and solutions.

Fault detection and isolation is a subfield of control engineering, which concerns itself with monitoring a system, identifying when a fault has occurred, and pinpointing the type of fault and its location. Two approaches can be distinguished: a direct pattern recognition of sensor readings that indicate a fault and an analysis of the discrepancy between the sensor readings and expected values, derived from some model. In the latter case, it is typical that a fault is said to be detected if the discrepancy or residual goes above a certain threshold. It is then the task of fault isolation to categorize the type of fault and its location in the machinery [5]. Thus, based on the second approach of fault detection and isolation, this work seeks to build a model for simulation of fault diagnosis of a diesel fuelled engine, and to simulate the developed model using numeric data obtained from diesel engine exhaust fumes analysis using STELLA modelling software.

2. Methodology

In the course of this work, the following methods were adopted:

- Acquisition of data through the use of sensors (Electronic nose)
- Physical observation of faults that is associated with diesel fuelled engine
- Book, Journal, articles and online material were consulted in understanding and writing of the thesis

2.1. Definition of Terms

1. Symptoms: The effect of a fault noticed by a technician
2. Fault: The root cause of a symptom or problem
3. Building Blocks: It describes the building block available in the interface, map and model layers
4. Stock: These are accumulator, which collect whatever flows into them and nets-off whatever flows out of them.
5. Flow: The job of flows is to fill and drain accumulators.
6. Converters: The converters holds value for constants, define external input to the model, calculate algebraic relationship and serves as the repository for graphical function. In general, it converts input to output.

7. Connectors: It connects model elements.
8. Diesel Fumes (diesel engine exhaust emission): these are the mixture of gases, vapours, liquid, aerosols and substances made up of particles.
9. STELLA: is a modelling software which offers a practical way to dynamically visualize and communicate how complex systems and ideas really work, design and developed by **isee** systems

2.2. Simulation

Simulation is the imitation of the operation of a real-world process or system over time [6]. The act of simulating something first requires that a model be developed; this model represents the key characteristics or behaviours/functions of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time.

2.3. Operations of a Diesel Fuelled Engine

Most diesel engines use a four-stroke cycle: the piston's first, downward stroke draws in air; the second, upward stroke compresses it; the third, downward stroke, following combustion, delivers power; and the fourth, upward stroke expels waste gases.

At the end of a piston's compression stroke, a fuel injector sprays fuel into the combustion chamber. Air temperature inside the chamber at that point is about 540° C (about 1000° F). The fuel ignites, causing a rapid expansion of hot air that forcefully pushes the piston downward. That downward power stroke turns the crankshaft. Figure 1 bellows shows a cross-sectional schema of an internal combustion chamber (cylinder) [7].

2.4. Exhaust System

The Exhaust system carries exhaust gases from the engine's combustion chamber to the atmosphere and reduces or muffles the engine's noise. Exhausts gases leaves the engine in a pipe, travelling through a catalytic converter and a muffler before exiting the pipe. Chemical reactions inside the catalytic converter changes most of the hazardous hydrocarbons and carbon monoxide produced by the engine into water vapour and carbon dioxide [9][10][11].

2.4.1. Components of Diesel Engine Exhaust Emission

Diesel Engine exhaust emission (commonly known as ‘’ diesel fumes’’) are a mixture of gases, vapours, liquid aerosol and substances made up of particles. These include, carbon (soot), Nitrogen, Water vapour, Carbon monoxide, Aldehydes, Nitrogen dioxide, Sulphur dioxide and Polycyclic Aromatic Hydrocarbons

2.4.2. Colour of Diesel Engine Exhaust Smoke

There are three (3) types of smoke emitted from diesel engine. These are Black Smoke, Blue Smoke and White Smoke.

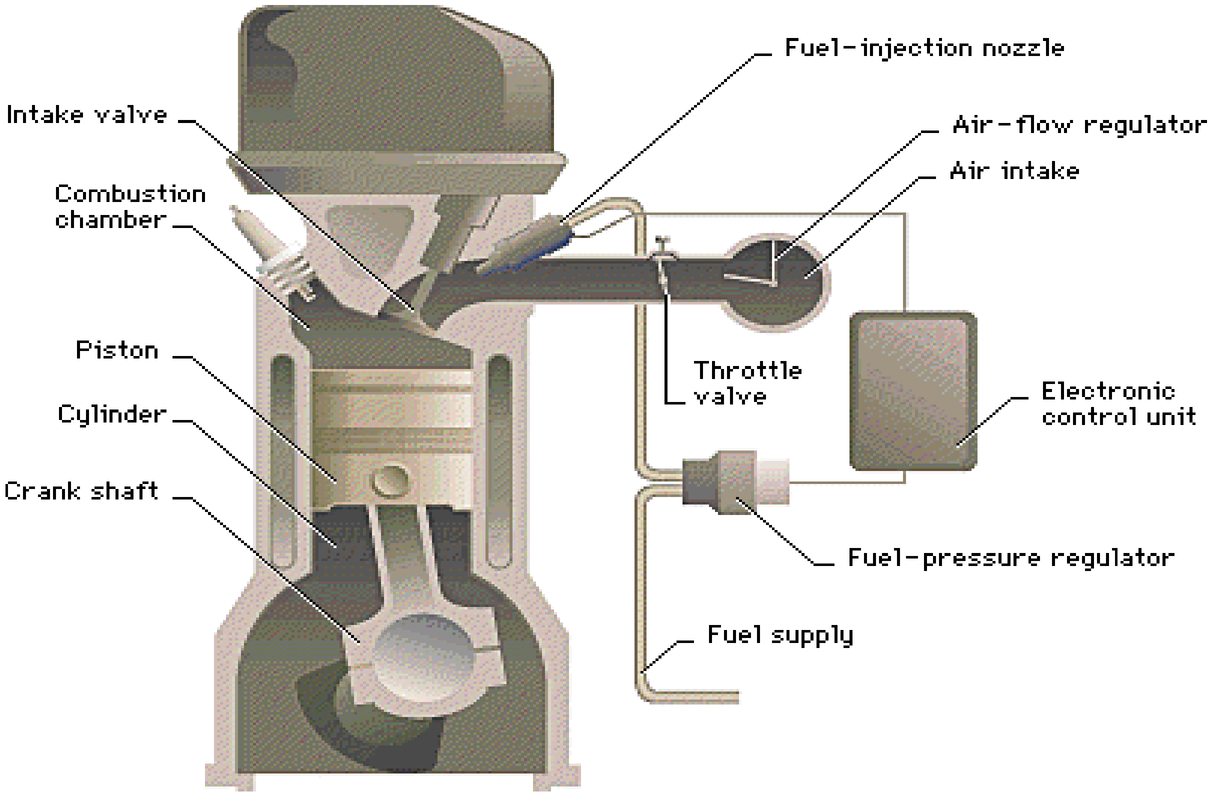

Fig. 1. cross-sectional view of a diesel engine showing piston and ring. (Source: [8])

2.4.2.1. Black Smoke

Black Smoke is the most common emitted from diesel engines and indicate incomplete combustion of the fuel. The cause of black smoke can vary widely and include:

- Incorrect fuel injection timing
- Dirty or worn out fuel injectors
- Over fuelling
- Faulty turbocharger
- Faulty or dirty exhaust gas recycling (EGR) system
- Incorrect valve clearance
- Incorrect fuel-air ratio
- Dirty or restricted air cleaner system
- Overload the engine
- Poor fuel quality
- Cool operating temperature
- High altitude operation
- Excessive carbon build-up in combustion and exhaust spaces

Black smoke occurs across the entire operating range, but is usually most under full power, or during the lag before turbo-charger boosts air supply to match the fuel usage such as in the early stages of acceleration and during gear changes. Black smoke should hardly be visible in a correct running engine.

2.4.2.2. Blue Smoke

- Blue smoke is caused by engine lubricating oil burning. The oil can enter the combustion chamber from several sources including:
- Worn valve guide or seals
- Cylinder and/or piston ring wear
- Cylinder glaze
- Piston ring sticking
- Incorrect grade of oil, too thin and getting past rings, or valves

2.4.2.3. White Smoke

White smoke is caused by raw, un-burnt fuel passing into the exhaust stream. Common causes include:

- Incorrect injection timing
- Defective fuel injector
- Low cylinder compression

Note: Low cylinder compression may be caused by leaking valves, sticking piston rings, ring wear, cylinder wear or cylinder gaze. When white smoke occurs and disappears, the engine warms up, the most common causes are fuelling deposits around piston and rings and /or cylinder glazing.

2.5. Faults in Diesel Engine

Faults in Diesel engine describe or implies a state of operational incapacity in the engine as a result of foul condition of some components in the engine [5]. For the purpose of this work and ease of analysis, faults in diesel engine will be discussed under two broad categories. The categories are:

- Fuel system related faults, specifically faulty injection nozzle
- Combustion chamber related fault, this may be worn-out compression rings, piston or both and worn cylinder.

2.5.1 Faulty Injector Nozzle

The fuel injector nozzle is set to inject at a pressure of about 149 atmospheres, which amount to 2,200 lbs, per square inch. Failure of the nozzle to maintain this standard will result in either a Rich Air-fuel mixture or Lean Air-fuel mixture depending on the state of the nozzle. The air-fuel mixture ratio will in turn have an effect on the exhaust fumes of the engine in terms of it gaseous content composition [2].

2.5.2. Worn-out Compression Rings and/or Piston

Worn-out compression Ring and/or Piston allow the passage of lubricating oil from inside the crankcase into the combustion chamber and mixes with the Air-fuel mixture in the chamber. This results in defective combustion and equally affects the composition of the exhaust [12].

3. Fault Diagnosis in Diesel Engine

This work conducted an investigation into components of the exhaust fumes as a means of fault diagnosis in diesel engine, using mathematical modelling and simulation. Building a mathematical model for a system depends on the knowledge of the physical and chemical laws governing the process taking place within the boundaries of the system.

The process of modelling involves these stages;

1. Problem Formulation: This stage entails problem description and recognition of the specifics of individual aspects of the problem.
2. Model Assumption: This consists of the Technical Assumptions, Quantitative Assumption and Qualitative Assumptions.
3. Formulate Mathematical Model: this stage involves development of model equations and transfer function that describe the model.
4. Model Validating: This stage involves the use of training data to generate first-hand model result.
5. Result interpretation: At this stage, the result of the model is interpreted either numerically or graphically.
6. Solve Mathematical Problem: the Model was used to solve problems.
7. Use of the model to explain, Predict, decode or design: This is the stage where the model is put to its actual use of wither to predict, explain, decide or design a useful utility.

The diagrammatic representation of a modelling sequence is presented in figure 2.

3.1. Model Formulation

Using the data obtained from previous work (Akapo and Fasiku, 2008) as base-line data for standard engine condition, this work develops an ad-hoc model for fault diagnosis of diesel engine using numeric data obtained from the analysis of various gaseous composition of exhaust fumes of diesel engine using electronic nose based condition monitoring scheme for diesel engine. Tabulated in table 1 are various Electronic Nose based gas sensors, (some of which are gas specific) and the gases to which they are sensitive.

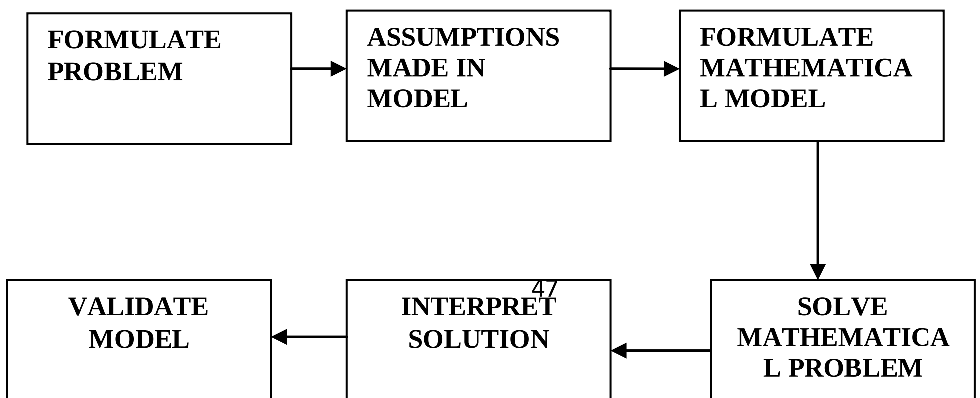

Fig. 2. Schematics of a modelling sequence

Table 1. Electronic Nose gas sensors and subject gases

SN	Electronic Nose Sensors	Gas(es)
1	TGS 816	Carbon monoxide
2	TGS 813	Water Vapour ($H_20_{(g)}$)
3	TGS5042	Nitrogen
4	TGS2201	Nitrogen IV Oxide (NO2)
5	TGS2104	Hydrocarbons (CxHy e.g. C10H22)
6	TGS822	n-Hexane, Benzene and Alcohol e.g. (C2H5OH)
7	TGS2602	Sulphur IV Oxide (SO2), Hydrogen Sulphide (H2S)

3.2 Model Assumptions

These are restrictions laid on the various units or compartment that make up the engines internal combustion chamber. They are Technical Assumptions and Constitutive Assumptions.

3.2.1 Technical Assumptions

1. The interacting components of the combustion chamber were assumed to be degrading under standard condition.

2. The combustion chamber is free from interference of external factors.
3. Recommended grade of fuels is assumed to be used
4. Recommended grade of lubricating oil is assumed to be used
5. All ancillary components to the combustion unit are working in conformity to standard specification
6. The engine is assumed to be four stroke internal combustion engine

3.2.2 Constitutive Assumptions

1. Air-fuel mixture is ideal
2. Compression ratio is optimal
3. Temperature requirement of combustion chamber is attained
4. Fuel injection is set to inject at a pressure of 149 atmosphere amounting to 2,200 lbs per square inch of the piston

4. Model Building

The model was built using STELLA modelling software. The modelling procedure featured the following stages; Mapping and Modelling, Simulation and Analysis, Database file, and Communication.

4.1 Mapping and Modelling

- Intuitive icon-based graphical interface simplifies model building
- Stock and Flow diagrams support the common language of Systems Thinking and provide insight into how systems work
- Enhanced stock types enable discrete and continuous processes with support for queues, ovens, and enhanced conveyors
- Causal Loop Diagrams present overall causal relationships
- Model equations are automatically generated and made accessible beneath the model layer
- Built-in functions facilitate mathematical, statistical, and logical operations
- Multi-dimensional arrays simply represent repeated model structure
- Modules support multi-level, hierarchical model structures that can serve as “building blocks” for model construction
- XML-based model files support the new industry standard for common interchange of system dynamics models

4.2 Simulation and Analysis

- Simulations "run" systems over time
- Sensitivity analysis reveals key leverage points and optimal conditions
- Partial model simulations focus analysis on specific sectors or modules of the model

- Results presented as graphs, tables, animations, QuickTime movies, and files
- Data Manager archives and recalls simulation run data stored in a separate SQLite

4.3 Database file

- Dynamic data import/export links to Microsoft Excel files

4.4 Communication

- Flight simulators and dashboards describe model components and facilitate manipulation
- Input devices include knobs, sliders, switches, and buttons
- Output devices highlight outcomes with warning flashers, text, graphs, tables, and reports
- Causal Loop Diagrams present dominant feedback loops within structure
- Multimedia support for graphics, movies, sounds, and text messages
- Model security features allow locking or password protection

4.5 Model Equation

These are the mathematical equation, which described the configuration of Stock and Flow (STELLA based utilities) used in the model development. They are:

4.5.1 Stock Model (Stella Based Equation)

TGS2201NO2(t) = TGS2201NO2(t - dt) + (NO2\input - NO2\output) * dt

TGS2602SO2(t) = TGS2602SO2(t - dt) + (SO2\input - SO2\output) * dt

TGS5042CO(t) = TGS5042CO(t - dt) + (CO\input - CO\output) * dt

4.5.2 Flow Model (Stella Based Equation)

CxHy\input = TGS2201NO2*CxHy\input_rate=1

NO2\input = NO2\input_rate=1

CO\input_1 = CO\input+CO\input_rate1=1

5. Results and Discussion

5.1. Results

The developed Stella model was experimented using data obtained in earlier research work (Akapo and Fasiku, 2008) as the base line data for an engine operating in normal condition. The data obtained from the electronic nose from an engine operating in various induced faulty conditions were applied in turn. The result of experiment is shown in figure 4-9.

Further Experiments were conducted on the developed model to see its performance in the presence of five (known) unlabelled data sample A-E. The results were shown in figures 10-14:

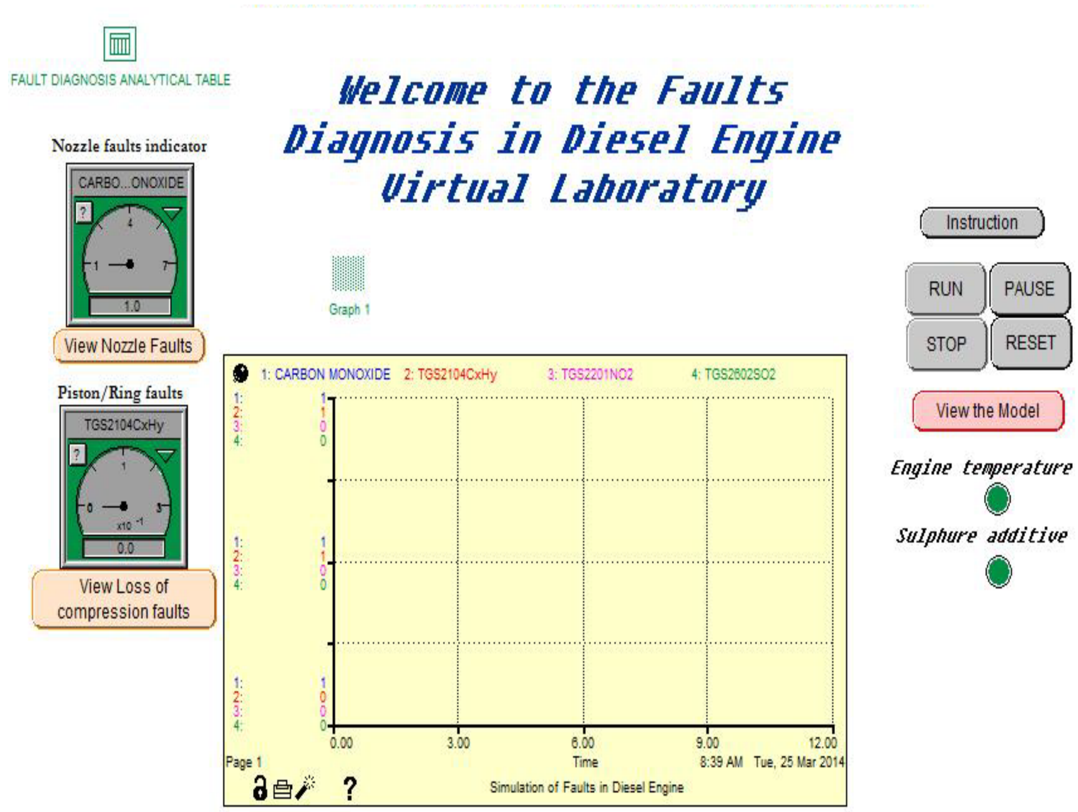

Fig. 3. Diagram showing default model interface

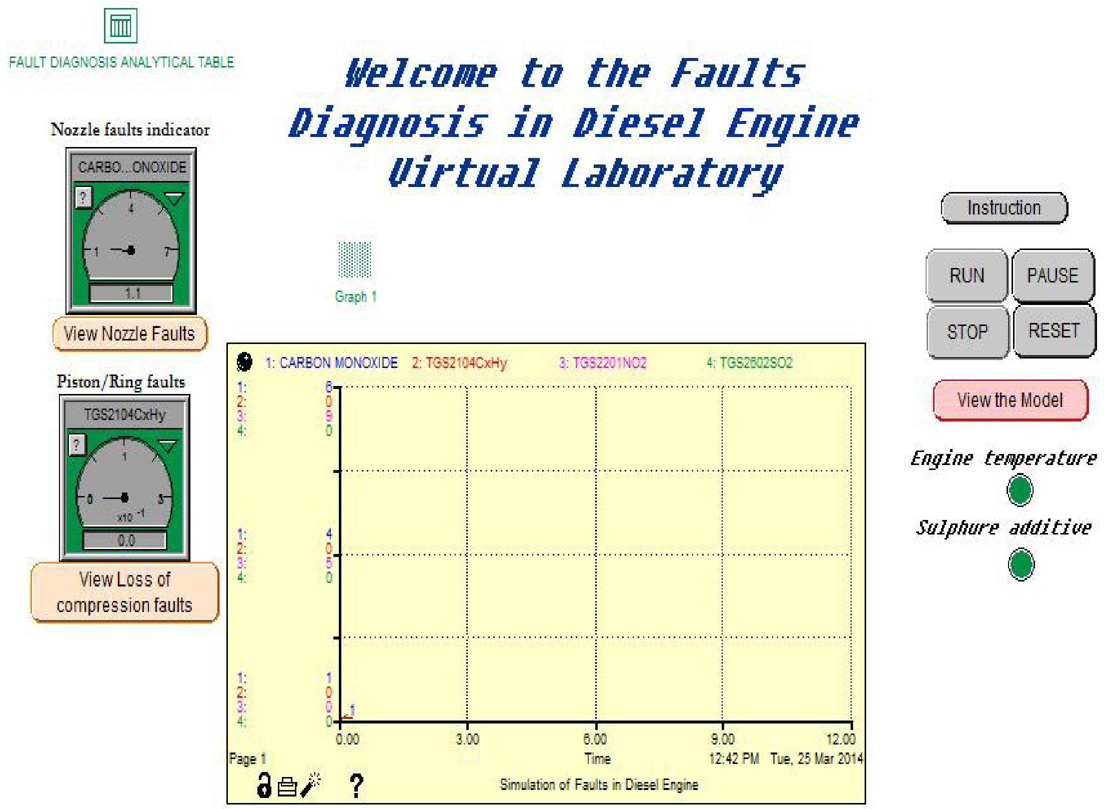

Fig. 4. Ideal Engine Condition

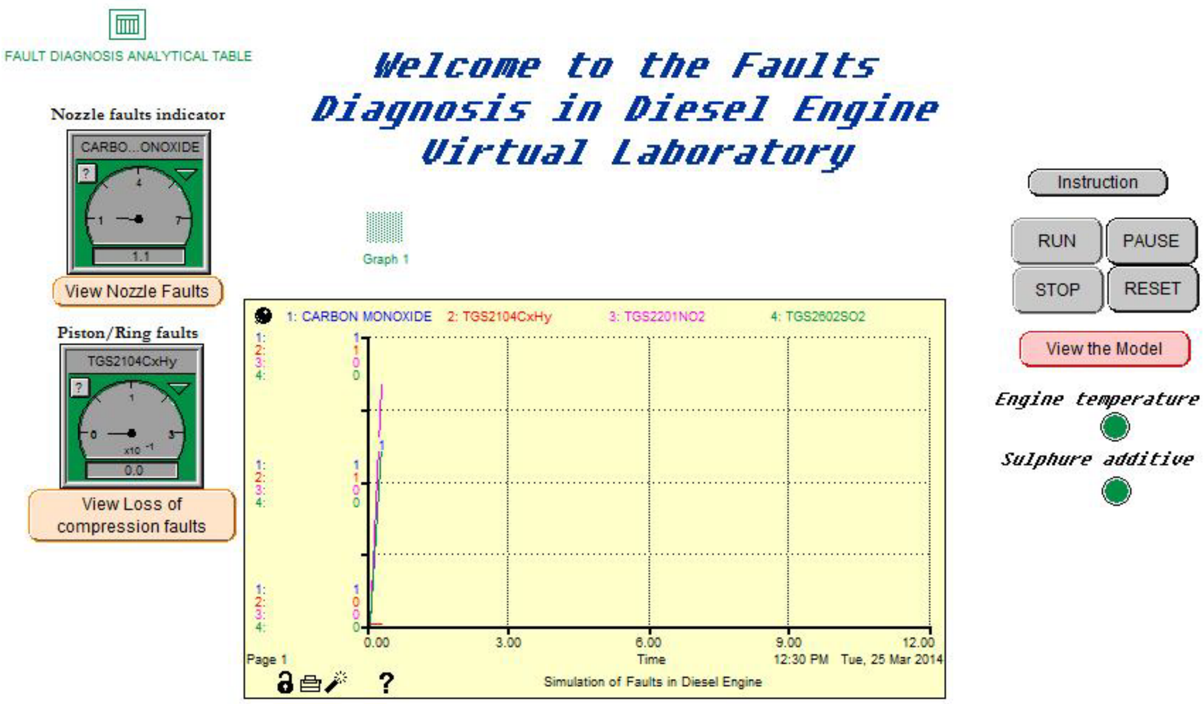

Fig. 5. Increasing carbon monoxide content (10% loss of compression ring)

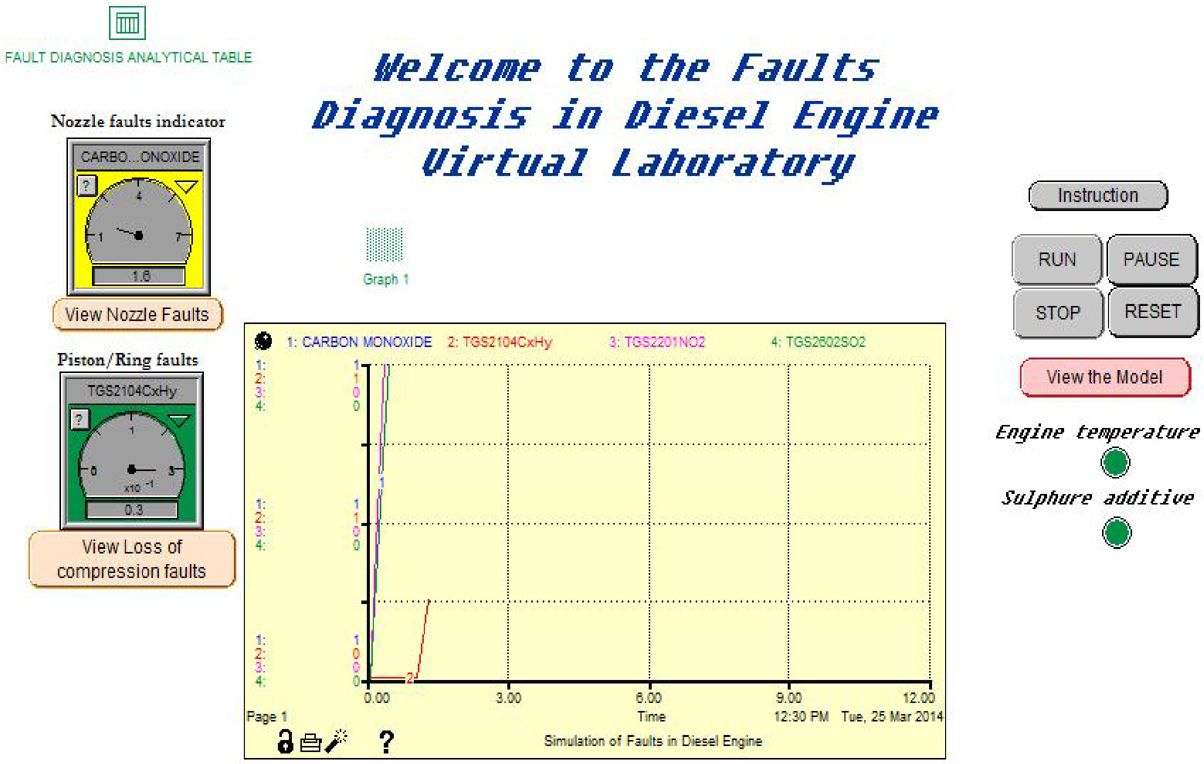

Fig. 6. Formation of Carbon Shoot (20% Loss of Compression)

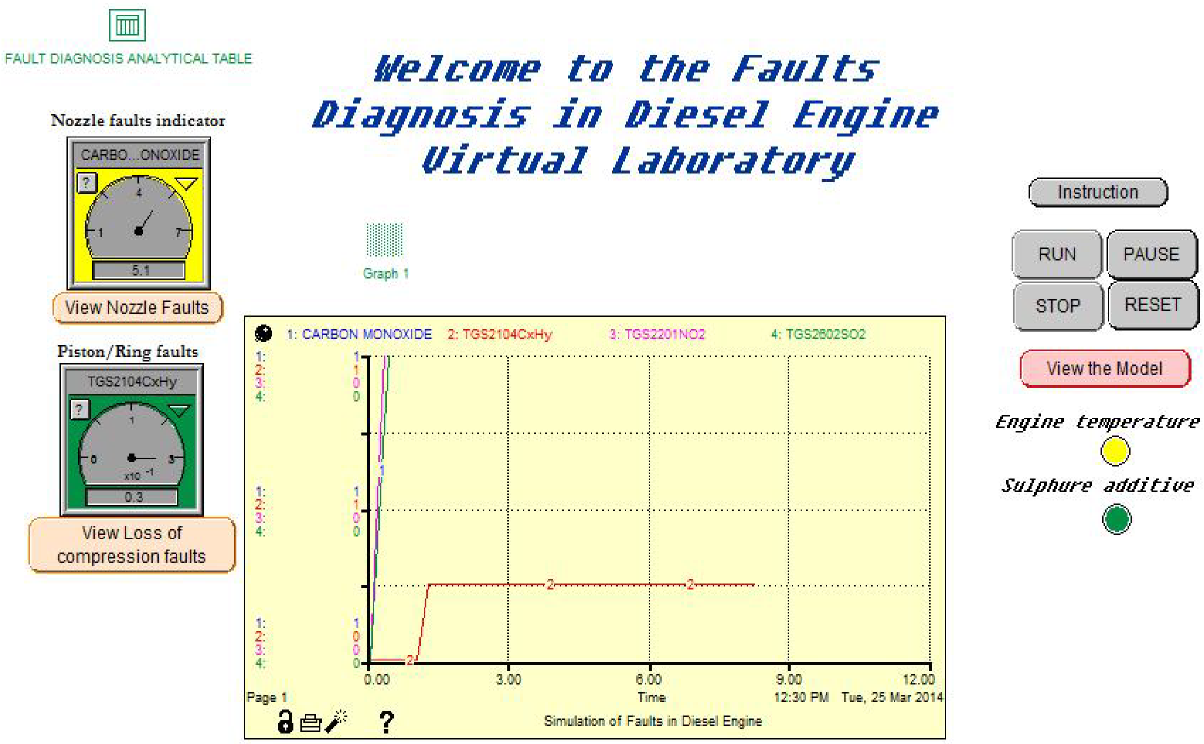

Fig. 7. Graph showing 30 – 70% loss of compression

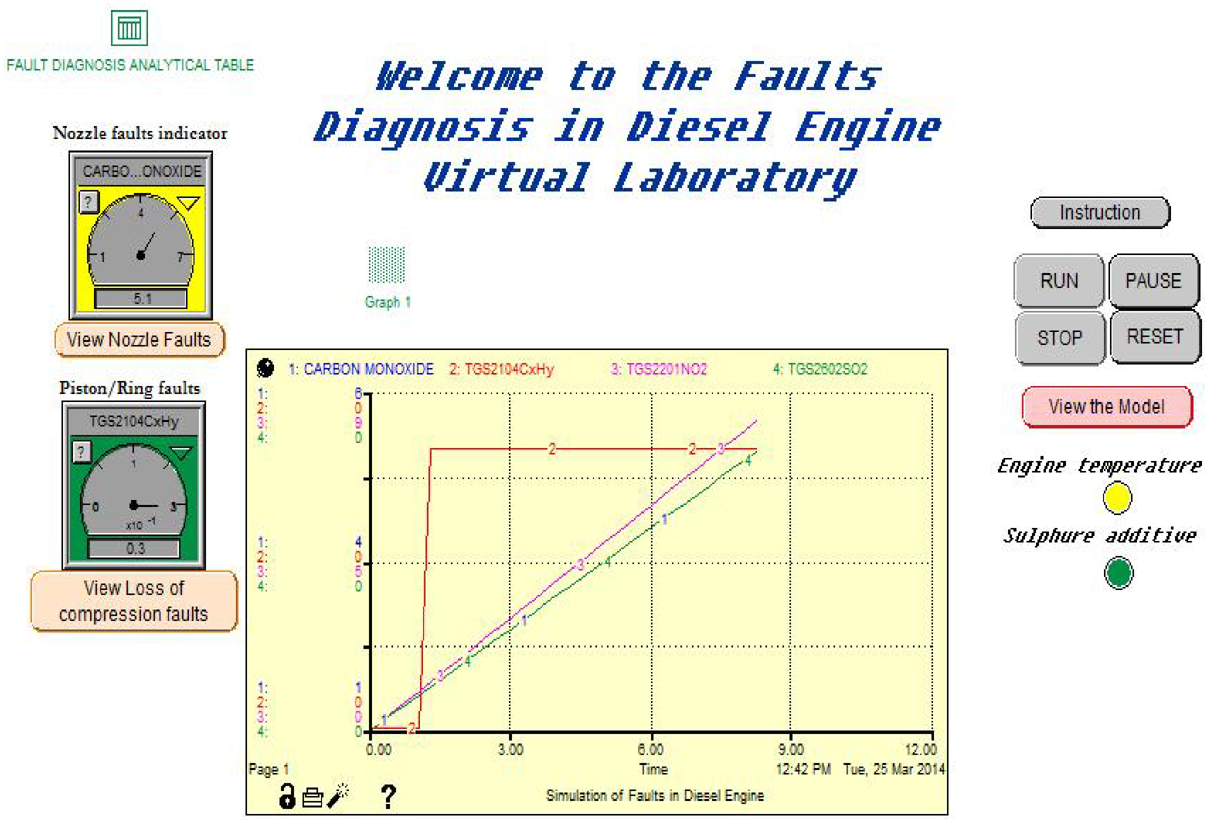

Fig. 8. Increased nitrogen IV oxide (NO_2)

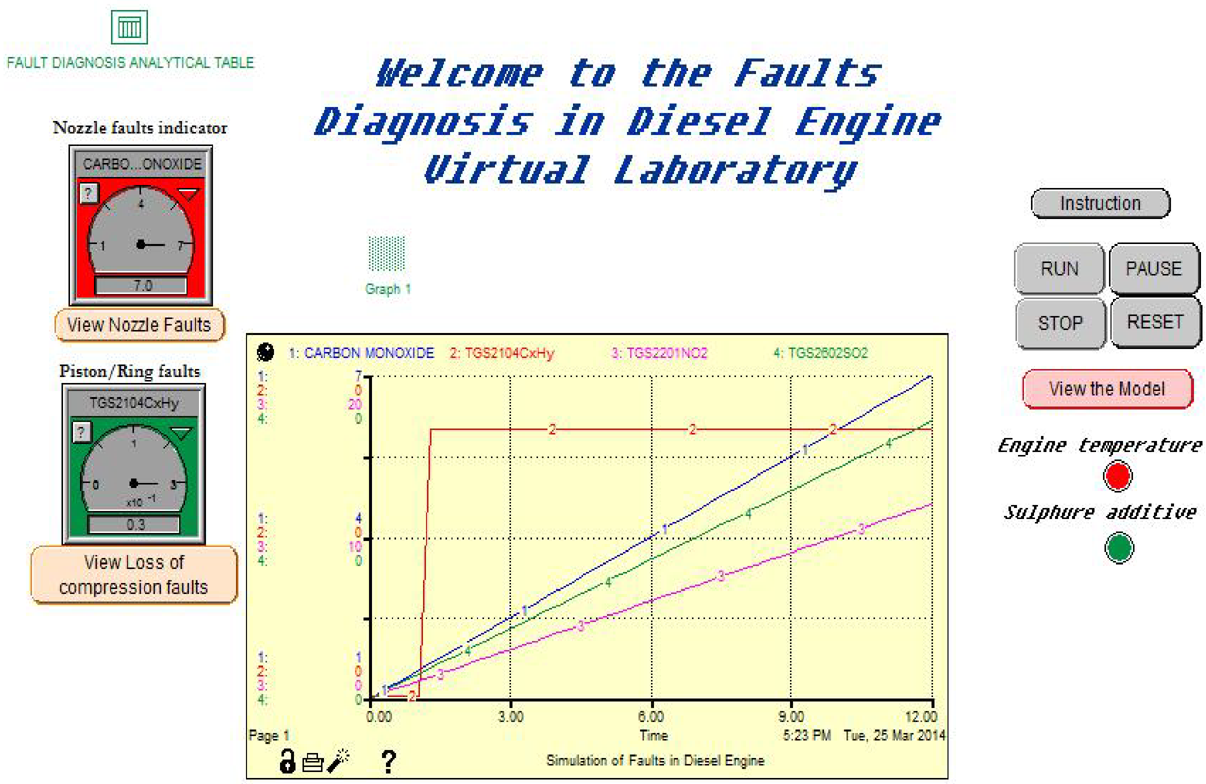

Fig. 9. Showing the steady state of the carbon shoot curve, which indicates a nozzle related fault

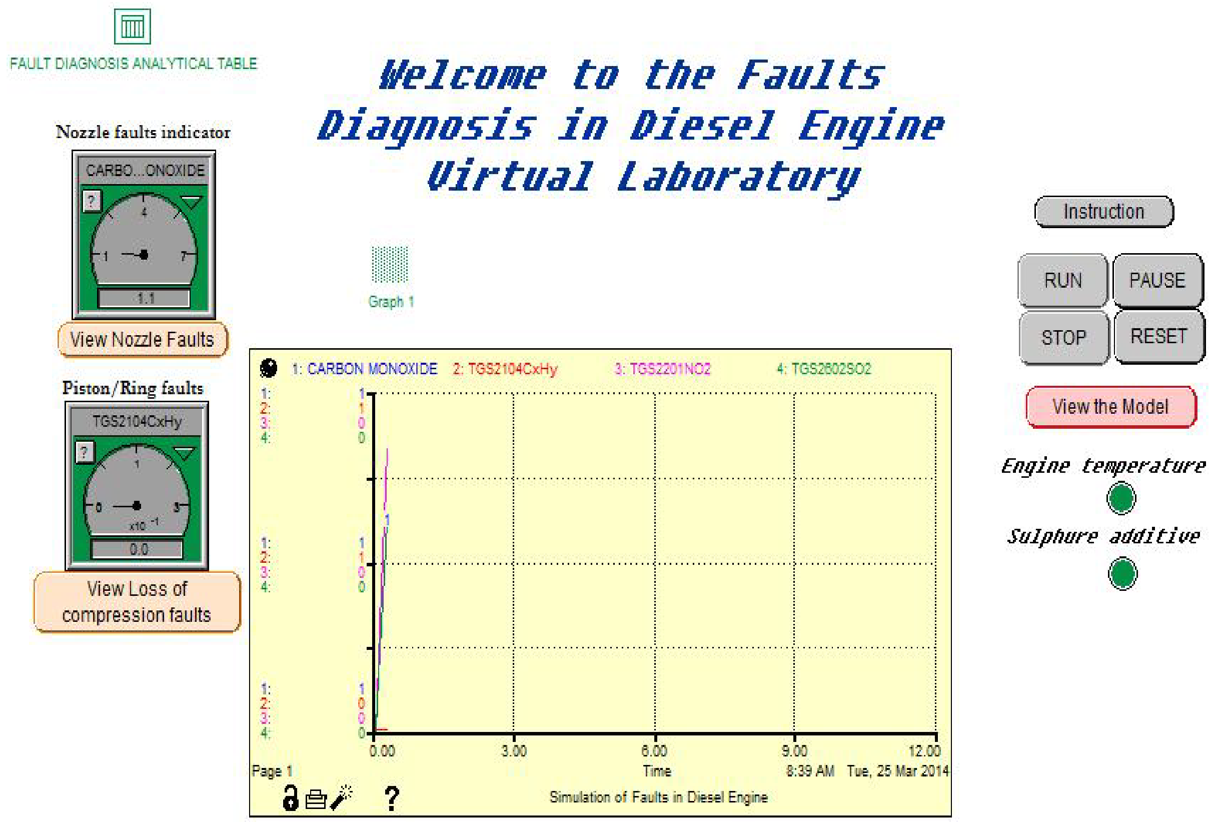

Fig. 10. Showing the curve for (known) unlabelled sample A

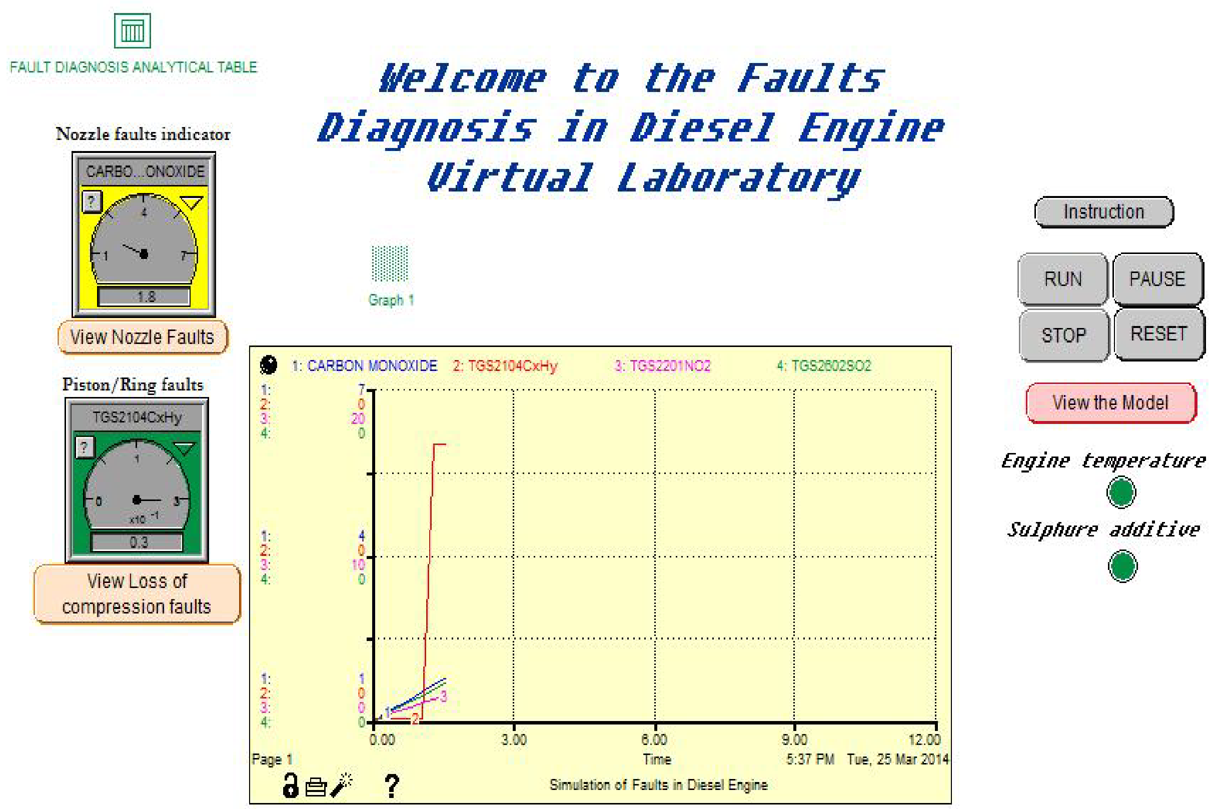

Fig. 11. Showing the curve for (known) unlabelled sample B

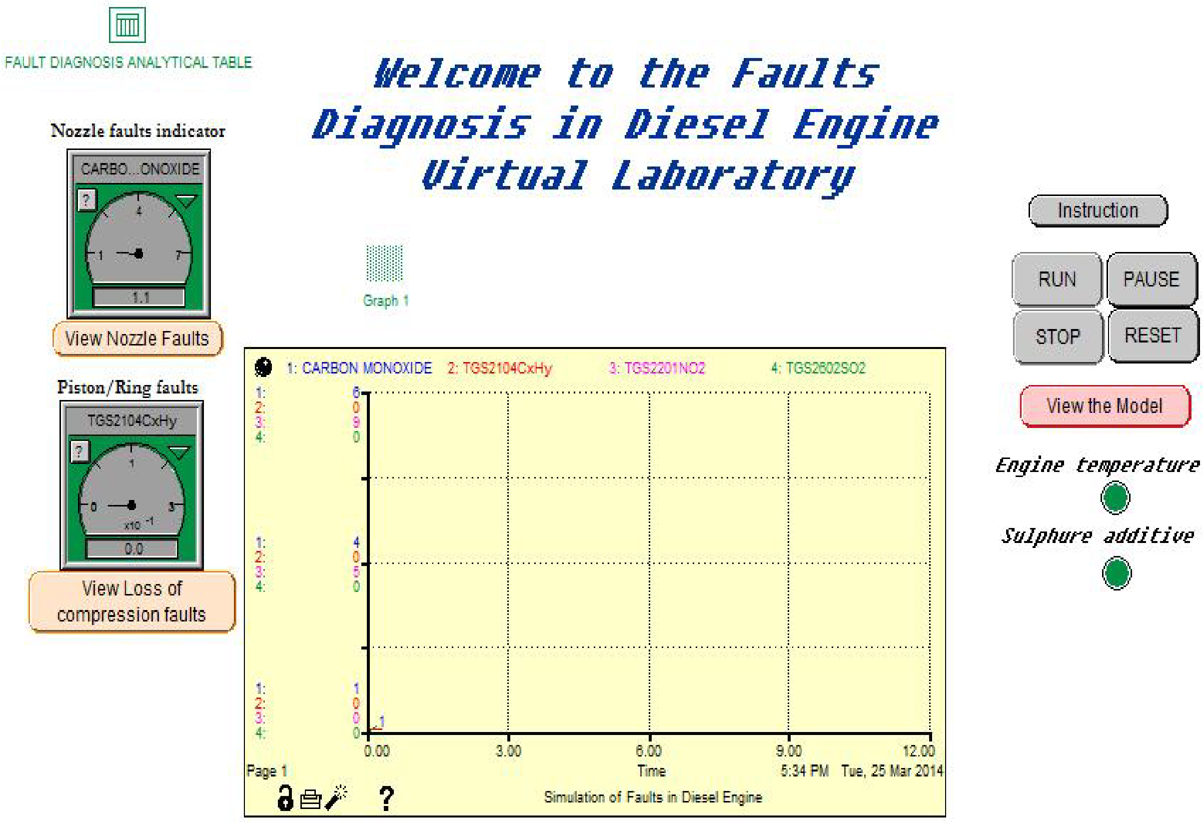

Fig. 12. Showing the curve for (known) unlabelled sample C

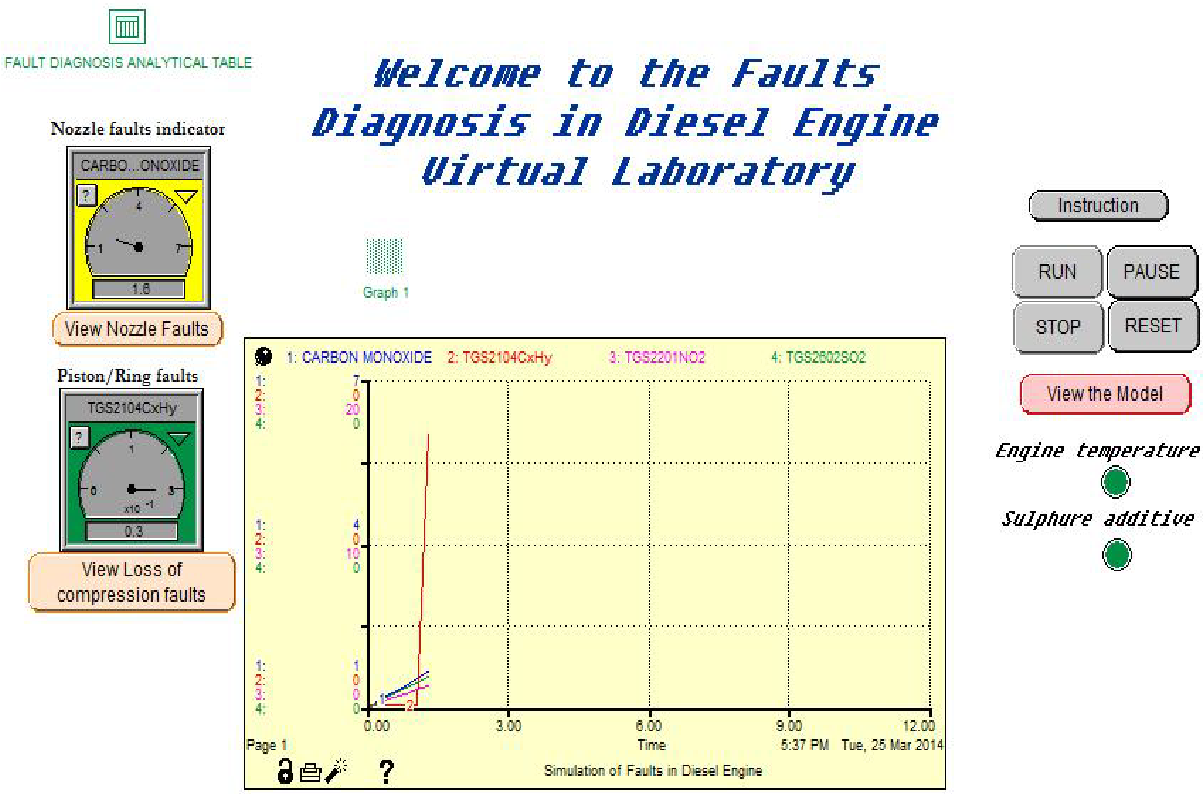

Fig. 13. Showing the curve for (known) unlabelled sample D

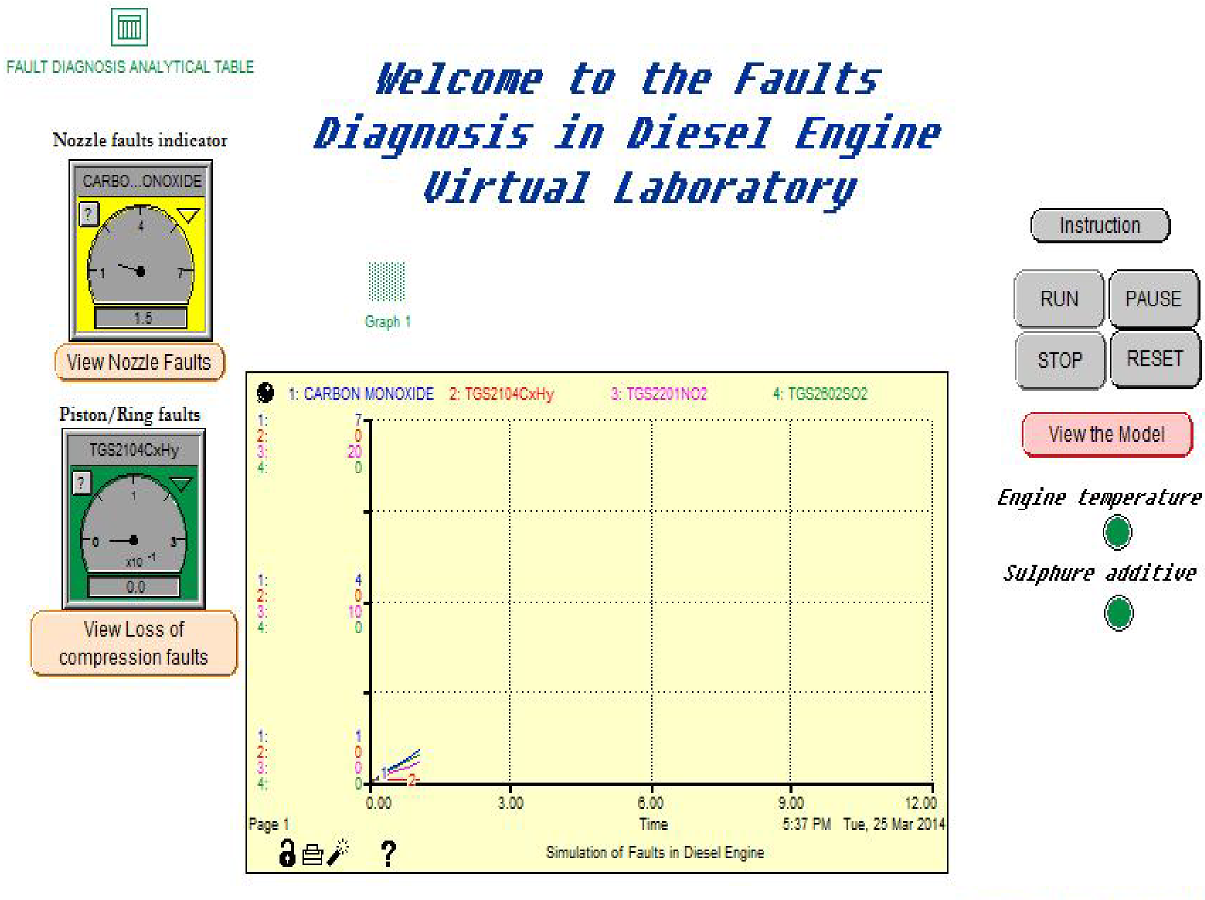

Fig. 14. Showing the curve for (known) unlabelled sample E

5.2. Discussion of Results

The simulation results of the developed model are presented in figures 3-10. Figure 3 shows the default mode of the developed simulation model. Figure 4 shows the variation in composition of the exhaust fume of a normal diesel engine. The curves labelled “2” in the graph shows that the graph rise from a negative value of “1” to zero after which the curve becomes steady. It indicates an idea level of carbon shoot presence. Curve labelled “1 shows an insignificant level of carbon monoxide which indicates a ‘no-fault condition.

In figure 5, a rise in curve labelled ‘2’ from – 1 to zero and it stay steady on zero; implies that the carbon soot content rises from practically zero (i.e. ‘no shoot”) to zero (another degree of “no shoot”). The engine condition is still very tolerable as it show a “mild compression – ring worn out” (i.e. 10% - loss of compression). The engine can be used by the user for a little while before services.

Figure 6, consider the curve labelled ‘2’ the carbon shoot content rises to about 0.3m^3 (from the graph) an it was stead all along on the axis. This indicates that every other component of the engine might be working correctly except for a wearing position ring. Engine service is recommended for optimum performance and reliability.

In figure 7, level of carbon shoot has risen to about 0.8m^3 per cubic metre of the exhaust fume. This suggests a ’critical’ level of warn–out compression ring. At this point engine is in a deplorable condition (with respect to the combustion chamber). Service of the engine is strongly recommended for smooth running and greater efficiency.

Figures 8 and 9 show a rising in the level of Nitrogen IV oxide content in the exhaust fume (from the curve labelled '3'). This indicates a certain degree of nozzle related fault. The services of an expert should be sought in order to precisely determine the level of damage done to the nozzle.

5.3. Discussion of Testing With Unknown Labelled Samples

Further experiments were conducted on the developed model to see its performance in the presence of five (known) unlabelled data sample A-E. The result are shown in figure 10-14 and summary of results given in table 3 while table 4 shown the actual label for the unlabeled sample.

Table 3. Summary of results of Known Unlabelled Samples

Unlabelled samples	Faults associated with samples
Sample A	Faulty Nozzles
Sample B	Two Nozzles bad
Sample C	Compression fault
Sample D	Three Nozzle fault
Sample E	Compression fault

Sample A

From the graph in figure 10, the engine temperature rises steadily as shown by curve labelled 3 and as such there is overheating due to incomplete combustion. But the carbon monoxide content of the exhaust rose (as indicated by curve labelled 1) beyond the recommended level of $0.03cm^3$ per cubic metre (as obtained from Normal engine data). This indicates a faulty nozzle condition (as also shown by the red colour of the indicator Nozzle Fault).

Sample B

In sample B, the carbon soot content does not increase (as shown by the curve labelled 2) while the carbon monoxide content of the exhaust fume and the engine temperature increase steadily than (this is shown by the curve labelled) than in sample A, which indicates that nozzles are faulty.

Sample C

This indicate an unacceptable rise in carbon soot (indicated by curve labelled 2) and a steady increase in carbon monoxide content (given by curve labelled 1), but the engine temperature does not rise (the temperature is indicated by curve labelled 3). This graph had shown a compression fault.

Sample D

This sample shows a less rapid increase in carbon monoxide content of the fume (shown by curve 1) and there is more rapid increase in engine temperature (by curve labelled 3). This indicates a nozzle fault. This is similar to that of sample B.

Sample E

The graph of this sample behaves like that of sample C. It shows an unacceptable rise in carbon soot and a steady increase in carbon monoxide content. In this case, the engine temperature rises. These shows a loss of compression ring.

Table 4: Summary of results of Known labelled Samples

Unlabelled samples	Faults associated with samples
Sample A	Normal
Sample B	Two Nozzles out
Sample C	Compression fault
Sample D	Nozzle fault
Sample E	Nozzle fault

6.0 Conclusion and Recommendation

6.1 Conclusion

A dynamic model was developed for fault diagnosis in diesel engine using STELLA simulation software. STELLA based computer-generated model equations were obtained and used in the simulation. The model accounted for diesel engine combustion chamber related faults (Nozzle fault and various degrees of compression faults) and their symptoms. Known and labelled data's from faulty diesel engine were imported into the model and the results of the model behaviour were obtained and discussed. Further experiments were conducted with the model using known unlabelled samples. Results were also obtained and discussed. The result obtained with known unlabelled sample, four samples out of five were correctly identified as either block nozzle or compression fault by the model. This gives 80% classification accuracy from the model.

6.2 Recommendations

As a result of the knowledge and information gathered during the cause of caring out this project, the recommendations based on this work are as follows:

- Diesel engine standard fault matrix data should be obtained from a specific diesel engine manufacturer and visual inspection of the numeric should be made, noted and compared to the numeric obtained from the Electronic Nose based fault diagnosis data used for this work.
- The standard fault matrix data should be used to perform further experiments with the model developed in this project and the results should be obtained.
- A comparative analysis of the result obtained from this work and that obtained from experimenting with the standard fault matrix data should be carried out. This will bring about precision in the fault diagnosis and greater efficiency.

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