APPLICATION OF ARTIFICIAL NEURAL NETWORK TO CLASSIFY FUEL OCTANE NUMBER USING ESSENTIAL ENGINE OPERATING PARAMETERS

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Dedicated to My Beloved Family, Zahra and Paliz

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ABSTRACT

Real-time fuel octane number classification is essential to ensure that spark ignition engines operation are free of knock at best combustion efficiency. Combustion with knock is an abnormal phenomenon which constrains the engine performance, thermal efficiency and longevity. The advance timing of the ignition system requires it to be updated with respect to fuel octane number variation. The production series engines are calibrated by the manufacturer to run with a special fuel octane number. Presently, there is no research which takes into account the fuel tendency to knock in real-time engine operation. This research proposed the use of on-board detection of fuel octane number by implementing a simple methodology and use of a non-intrusive sensor. In the experiment, the engine was operated at different speeds, load, spark advance and consumed commercial gasoline with research octane numbers (RON) 95, 97 and 100. The RON classification procedure was investigated using regression analysis as a classic pattern recognition methodology and artificial neural network (ANN) by executing combustion properties derived from in-cylinder pressure signal and engine rotational speed signal. The in-cylinder pressure analysis illustrated the knock-free, light-knock and heavy-knock regions for all engine operating points. The results showed a special pattern for each fuel RON using peak in-cylinder pressure, maximum rate of pressure rise and maximum amplitude of pressure oscillations. Besides, there is a requirement for pre-defined threshold or formula to restrict the implementation of these parameters for on-board fuel identification. The ANN model efficiency with pressure signal as network input had the highest accuracy for all spark advance timing. However, the ANN model with rotational speed signal input only had the ability to identify the fuel octane number after a specific advance timing which was detected at the beginning of noisy combustion due to knock. The confusion matrix for the ANN with speed signal input had increased from 68.1% to 100% by advancing the ignition from -10° to -30° before top dead centre. The results established the ability of rotational speed signal for fuel octane classification using the relation between knock and RON. The implication is that all the production spark ignition engines are equipped with engine speed sensor, thus, this technique can be applied to all engines with any number of cylinders.

ABSTRAK

Masa sebenar klasifikasi nombor oktana bahan api adalah penting untuk memastikan operasi enjin pencucuhan percikan adalah bebas daripada ketukan pembakaran yang efisien. Pembakaran dengan ketukan adalah satu fenomena yang tidak normal yang mengekang prestasi enjin, kecekapan haba dan jangka hayat. Masa awal daripada sistem penyalaan memerlukan ia dikemas kini berdasarkan variasi nombor oktana bahan api. Enjin siri pengeluaran ditentukur oleh pengilang untuk beroperasi dengan nombor oktana bahan api khas. Pada masa ini, tidak ada penyelidikan yang mengambil kira kecenderungan bahan api untuk ketukan semasa enjin operasi. Kajian ini mencadangkan pengesanan penggunaan ofon-lembaga nombor oktana bahan api dengan melaksanakan kaedah yang mudah dan penggunaan sensor yang tidak mengganggu. Dalam eksperimen ini, enjin beroperasi pada kelajuan yang berbeza, beban, menganjakkan percikan berdasarkan petrol komersial dengan nombor penyelidikan oktana (RON) 95, 97 dan 100. Prosedur klasifikasi RON telah dikaji dengan menggunakan analisis regresi sebagai satu kaedah pengiktirafan corak klasik dan rangkaian neural buatan (ANN) dengan melaksanakan ciri-ciri pembakaran yang diperoleh daripada isyarat tekanan dalam silinder dan isyarat kelajuan putaran enjin. Analisis tekanan dalam silinder digambarkan berdasarkan kawasan ketukan bebas, ketukan kecil dan ketukan kuat pada semua kondisi operasi enjin. Hasil kajian menunjukkan satu corak khas bagi setiap bahan api RON yang menggunakan tekanan dalam silinder, kenaikan tekanan pada kadar maksimum dan ayunan tekanan pada amplitud maksimum. Selain itu, terdapat keperluan untuk ambang atau formula yang telah ditetapkan untuk menyekat pelaksanaan parameter ini untuk mengenal pasti bahan api sebenar. Kecekapan model ANN dengan isyarat tekanan sebagai input rangkaian mempunyai ketepatan tertinggi untuk semua pemasaan awal percikan. Walau bagaimanapun, model ANN dengan isyarat putaran input kelajuan hanya mempunyai keupayaan untuk mengenal pasti nombor oktana bahan api selepas menganjakkan pemasaan yang spesifik yang telah menyebabkan permulaan untuk pembakaran yang bising berpunca daripada ketukan. Matriks kekeliruan bagi ANN dengan input isyarat kelajuan telah meningkat dari 68.1% kepada 100% dengan menganjakkan pencucuhan dari -10 ° hingga -30 ° sebelum titik mati atas. Keputusan menunjukkan keupayaan isyarat kelajuan putaran untuk pengelasan oktana bahan api menggunakan hubungan antara ketukan dan RON. Implikasinya adalah bahawa semua enjin pengeluaran cucuhan percikan dilengkapi dengan isyarat kelajuan enjin, dengan itu, teknik ini boleh digunakan untuk semua enjin tanpa mengira bilangan silinder.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

aTDC	-	*After Top Dead Center*
AC		*Alternating Current*
AI	-	*Artificial Intelligence*
ANN	-	*Artificial Neural Network*
ARMA		*Auto Regressive Moving Average*
BMEP		*Brake Mean Effective Pressure*
BP	-	*Back Propagation*
BSFC		*Brake Specific Fuel Consumption*
bTDC	-	*Before Top Dead Center*
CAD	-	*Crank Angle Degree*
CA50	-	*Crank Angle For 50% of Mass Fraction Burnt*
CA90	-	*Crank Angle For 90% of Mass Fraction Burnt*
CAx	-	*Crank Angle For x% of Mass Fraction Burnt*
CFR	-	*Cooperative Fuel Research (Engine)*
CI	-	*Compression Ignition (Engine)*
CNG	-	*Compressed Natural Gas*
DAQ	-	*Data Acquisition System*
DC		*Direct Current (Voltage)*
DoE	-	*Design of Experiment*
DSP		*Digital Signal Processing*
DWT		*Discrete Wavelet Transform*
E85	-	*A fuel with 85% Ethanol and 15% gasoline*
ECU	-	*Electronic Control Unit*
EGR	-	*Exhaust Gas Recirculation*
EGT	-	*Exhaust Gas Temperature*
FFT		*Fast Fourier Transform*
FL	-	*Fuzzy Logic*

FRF		*Frequency Response Function*
GA	-	*Genetic Algorithm*
GUI	-	*Graphical User Interface*
HCCI	-	*Homogeneous Charge Compression Ignition*
HIL		*Hardware in the Loop*
ICE	-	*Internal Combustion Engine*
IMEP	-	*Indicated Mean Effective Pressure*
KI	-	*Knock Index*
LKI		*Logarithmic Knock Intensity*
LOLIMOT	-	*Local Linear Model Tree Networks*
LPG	-	*Liquid Petroleum Gas*
LPP	-	*Location of Peak Pressure*
MAP	-	*Manifold Air Pressure*
MAHRO		*Maximum Amplitude of Heat Release Oscillation*
MAPO	-	*Maximum Amplitude of Pressure Oscillation*
MBT	-	*Maximum Brake Torque or Minimum Spark Advance for Best Torque*
MFB	-	*Mass Fraction Burned*
MLP	-	*Multi-Layer Perceptron*
MVM		*Mean Value Model*
NO_x	-	*Oxides of Nitrogen*
PI		*proportional and integral (controller)*
PLM	-	*Professional Lambda Meter*
PLRBF	-	*Pseudo-Linear Radial Basis Function*
RBF	-	*Radial Basis Function*
PFI		*Port Fuel Injection*
PLM	-	*professional lambda meter*
P_{max}	-	*Peak In-cylinder Pressure*
RON	-	*Research Octane Number*
RPM	-	*Revolution Per Minute*
SA	-	*Spark Advance*
SEHRO		*Signal Energy of Heat Release Oscillations*
SEPO		*Signal Energy of Pressure Oscillations*
SG		*Savitzky-Golay (Filter)*

SI	-	*Spark Ignition (Engine)*
SKM		*Standalone Knock Module*
TDC	-	*Top Dead Center*
TWC		*Three-Way Catalyst*
TVE	-	*Threshold Value Exceeded*
UTC		*USB-to-CAN*
ULSD		*Ultra Low Sulfur Diesel*
VVT	-	*Variable Valve Timing*

LIST OF SYMBOLS

A	-	*Activation energy multiplier*
A_e	-	*Entrainment surface area at the edge of the flame front*
$AEFD_{f_1-f_2}$	-	*Average energy of the heat release*
a_i	-	*Network real output*
B	-	*Cylinder bore*
c	-	*Speed of sound*
dP_{max}	-	*Rate of pressure rise*
f	-	*Frequency*
$f_{m,n}$	-	*Specific frequencies of the acoustic modes*
I	-	*Induction time integral*
I_j	-	*Knock intensity for cycle* j
I_{tot}	-	*Total energy intensity*
IVC	-	*Crank angle at intake valve closed*
KI	-	*Knock index*
KO		*Knock onset*
M	-	*Knock index multiplier*
m	-	*Numbers of circumferential pressures nodes*
M_b	-	*Burned mass*
M_e	-	*Entrained mass of the unburned mixture*
mse		*Mean Square Error*
N_{cyc}	-	*Number of cycles*
n	-	*Numbers of circumferential pressures nodes*
ON	-	*Fuel octane number*
P	-	*Knock induction time multiplier*
p	-	*Average cylinder pressure*

$\overline{P}$	-	*Filtered in-cylinder pressure signal*
P_{max}	-	*Peak in-cylinder pressure*
P_{ave}	-	*Pressure mean value*
p_i	-	*Instantaneous cylinder pressure*
R^2		*R-squared*
S_L	-	*Laminar flame speed*
S_t	-	*Turbulent flame speed*
T	-	*Bulk unburned gas temperature*
t	-	*Time*
T_u	-	*Instantaneous unburned gas temperature*
t_i	-	*Network-predicted output*
V		*Cylinder volume*
V_{TDC}	-	*Cylinder volume at top dead center*
Φ	-	*Equivalence ratio*
θ_0	-	*Crank angle corresponding to the beginning of the window of calculation for MAPO*
$\rho_{m,n}$		*Corresponding wave number*
ρ_u	-	*Unburned density*
γ	-	*Ratio of specific heat*
λ	-	*Lambda signal from oxygen sensor*
ς	-	*Taylor microscale length*
τ	-	*Time constant*
τ_i	-	*Induction time*
$\wp$	-	*Pressure power spectrum*

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Foreword

Based on global statistics for passenger car production in 2012, more than 165,000 passenger cars were produced per day (60 million per year). Over one billion passenger cars are driven in the world today [1]. Passenger cars and all types of trucks use internal combustion engine as their power source. Such vehicles are able to travel on roads by converting chemical energy of various types of fuels during the combustion process to kinetic energy. Gasoline, gasoil, ethanol, compressed natural gas (CNG), and liquid petroleum gas (LPG) are general fuels used in internal combustion engine (ICE). Low efficiency and exhaust emissions produced during combustion process are the most damaging output of internal combustion engine. In spark ignition (SI) engines, the ideal cycle efficiency is between 56% and 61%, and in car production, just 14%-30% of the energy generated from the consumed fuel is used to drive the car. However, practical compression ignition (CI) engines work 30%-35% more efficiently than SI engines [2]. In the 1970's, electronic technologies were introduced to automobile system controllers and mechanical control systems were replaced with electronic type in SI engines [3]. The engine electronic control unit (ECU) does the same task for ignition system after removing the distributer and also ECU excites the electrical injectors which exchanging with engine carburettor. The use of electronic control system resulted in improving the fuel efficiency, emission reduction, and torque production [4]. The number of engine systems components and controllers increased due to improvement in fuel economy and emission reduction. In addition, legislation related to decreasing the amount of exhaust emission tightened.

Engine controllers regulated all combustion details to reduce accurately exhaust emission. The design process and the addition of any new systems to the engine increase the complexity and production cost. Systems such as variable valve timing (VVT), exhaust gas recirculation (EGR) and charge-boosting systems (i.e., supercharger, turbocharger, and intercooler) influence the in-cylinder charge composition. Complexities of combustion control increase by controller objectives such as fuel efficiency, emission reduction, misfire and knock detection. Distinguishing between effects of several parameters that influence the combustion process has become more difficult with the increased number of engine systems. Furthermore, fuel octane number variation and the introduction of new bio-fuel increase such complexity.

ECU of the SI engines has two main tasks: managing the fuel injection and managing spark ignition (or injection timing in CI engine). The engine ignition system task is to ignite the air-fuel mixture in the combustion chamber at the ignition timing with adequate energy. Ignition timing depends on several factors such as engine speed and load (by measuring the manifold air pressure), engine warm-up condition, and knock occurrence. For instance, by providing a rich mixture and retard ignition, the combustion continues into the exhaust system, resulting in speeding up the warm-up process of three-way catalyst (TWC). The early electronic ignition control system was an open-loop system that used a look-up table provided in engine test procedure with dynamometer. The ignition timing look-up table consisted of a matrix that considered required advance ignition for every engine speed and load. The benefit of this approach was to overcome the non-linearity of engine phenomena. In addition, engine ignition timing is affected by in-cylinder mixture properties. The fuel octane number, laminar flame speed, turbulent intensity, residual fraction, temperature, and equivalence ratio affect the ignition timing. Any change in these parameters requires that the look-up table data be updated to adjust the ignition to achieve maximum brake torque (MBT) timing [5].

A combustion closed-loop control system requires a feedback signal from combustion process and also uses look-up table as a reference for adjusting the ignition. It prevents the engine from operating in knock region by monitoring the vibration signal from a knock sensor installed on engine cylinder block. The controller *works as a closed-loop control system, and ignition timing is retarded when a knock event is detected. However, retard ignition reduces the combustion efficiency and engine works far from MBT timing [6].*

1.2 Background

Ideally, nearly all of the fuel energy would be released in ICEs when the piston was at top dead centre (TDC) and ready to begin the power stroke. In SI engines with port fuel injection (PFI), the fuel is premixed with air before entering the combustion chamber and energy release begins when the spark plug is fired. Significant time is required for the flame front to progress from the spark plug to the far side of the combustion chamber; thus, the spark plug must be fired before TDC. Spark advance refers to the number of crankshaft degrees before TDC at which the spark plug fires. Because initial flame speed is nearly constant, greater spark advance is required at higher engine speeds to allow sufficient time for the flame front to cross the combustion chamber. The unstretched laminar burning velocity depends on fuel type and equivalence ratio, 33.3 cm/s for iso-octane and 38.9 cm/s for n-heptane at stoichiometric mixture. Greater spark advance is also required for leaner mixtures, because they burn more slowly than chemically correct mixtures. A lean mixture is one in which the fuel-to-air ratio is less than the chemically correct ratio [7]. The ignition control system target is to set the MBT timing at CA50 (crank angle which 50 percent of mixture burned); therefore, the spark advance strategy after this value or the occurrence of the audible knock should be stopped.

Ignition timing is one of the major factors that directly affects the combustion process. Combustion phasing, such as crank angle for the consumption of 50% of the fuel mass (CA50), crank angle for the consumption of 90% of the fuel mass (CA90), the duration from consumption of 10% to 90% of the air/fuel mixture (CA10-CA90 duration), and location of peak pressure (LPP), is influenced by advancing the ignition as the starting point of combustion. The general combustion phasing location is CA50, the point when 50% of in-cylinder mixture mass burned in crank angle degree (CAD). The indicated mean effective pressure (IMEP) is most relevant parameter in terms of engine efficiency and CA50 location defines the MBT timing point. Another definition *for MBT is "minimum spark advance for best torque", illustrating that ignition timing is restricted by knock phenomena. At MBT timing, the maximum acceleration point of mass fraction burned (MFB) is located at around top dead centre. The optimized CA50 is 8-10° aTDC, and the peak cylinder pressure location is around 15° aTDC. Consequently, the only requirement for handling the combustion into MBT timing is adjusting the ignition in such a way that CA50 can occur around 8-10° aTDC [8-9]. Therefore, the main target of combustion control designer for ignition advance timing is to set the CA50 at MBT timing [5,10].*

To adjust the ignition on MBT location, look-up table (or map) based ignition control system is introduced. It is quite hard and time consuming to prepare the ignition timing map. However, it is easy to implement it on the engine ignition system. Since maps are developed in laboratory measurements, data are only acceptable for that condition, i.e., engine wearing and production tolerances decrease the control accuracy. Several parameters reduce or disable the map-based control system during the engine operation such as fuel octane number, engine subsystems alteration, environment variety, etc.

A look-up table structure consists of a matrix that defines the optimum ignition timing for each engine operation point with respect to manifold air pressure (MAP) and engine speed. A microprocessor serves to apply map data by receiving the engine speed and load signal from related sensors. Moreover, the correction for engine warm-up condition and torque reduction request from automobile stability system is applied during engine operation. Additionally, in a closed-loop map-based ignition control system, an extra correction has been done with respect to knock sensor signals for preventing repetitive knock events. A new window is opened for such system improvement by transition from mechanical system to map-based electronic system that conquered the engine non-linear phenomena.

SI engines consume a wide variety of fuel with different characteristics such as octane number and laminar flame speed, which directly affect the ignition timing. Gasoline, LPG, CNG, Hydrogen, and E85 (a blend of 85% ethanol and 15% gasoline) are common fuels commercially used in SI engines. Different burning rate and knock tendency increase the complexity of the ignition timing map; thus, an individual map for each fuel should be designed. In conclusion, an essential control algorithm capable *of detecting and predicting the properties of fuel with respect to fuel efficiency and emission reduction is required. For introducing a new control algorithm for real-time ignition adjustment, knock and misfire limitation, MBT settles, and emission reduction should be taken into account. By implementing the model-based spark advance controller, SI engines can work with a wide range of fuel octane number; an approach that improves the use of new energy sources and severely reduces the research cost for new fuel utilization. The overall cost of improving the octane number and fuel production process, essentially for bio-fuel, can be reduced by this approach. Therefore, the engine performance and efficiency can be enhanced when various types of fuel are applied.*

1.3 Statement of the Problem

This research aims at finding a useful feed-back signal from combustion process for designing a closed-loop control system. The in-cylinder pressure measurement, using pressure transducer or ion current sensor, has been applied to several studies on knock detection. However, the complexity of signal analysis, high expense, low precision, and poor stability have limited the implementation of such controllers that use such signals. Furthermore, cylinder-to-cylinder variations have been ignored because the system needs individual combustion analysis for each cylinder. Several sample sets are needed to increase the accuracy in steady state condition, making it difficult to consider engine transient condition [11-15].

Numerous techniques have been adopted to reconstruct the cylinder pressure from the instantaneous crankshaft speed measurement [16-17]. The engine angular velocity and its derivative has been implemented as inputs in artificial neural network (ANN) to estimate the LPP [18], finding the correlation between torque and engine speed [19], instantaneous pressure estimation [20], IMEP estimation [21] and different diesel fuel identifier [22]. In this research, the engine rotational speed has been implemented as the input into an ANN to identify different fuel octane numbers. The objectives of an adaptive model-based ignition control system are to adjust the spark advance to locate the MBT timing on CA50 and to prevent knock occurrence or knock repetition at all engine operating conditions. Therefore, the main targets of this *research are to develop a neural network structure that is able to identify the fuel octane number and to determine the correction requirement for spark advance with a high degree of freedom related to variation in fuel properties and combustion chamber tendency to surface ignition.*

1.4 Hypothesis

When the engine control unit technology evolves and when a new fuel is introduced to be used in an internal combustion engine, the most important issue is how to update the engine maps with new conditions. For instance, engines that simultaneously consume gasoline and CNG need two different spark timing look-up tables for each type of fuel. Furthermore, engine controllers need to be updated with current engine operation parameter; in other words, if the octane number is defined as a fixed parameter in the laboratory, the controller operation will be corrected for that situation and pump-to-pump fuel properties will be varied to enhance the engine efficiency.

Demand for high fuel efficiency and emission reduction has increased the demand for new engine actuators. VVT, EGR, and charge-boosting systems are the most popular and new technologies in SI engines [23-25]. The cost of implementing such systems is very high, which confines its application to engine. Therefore, a new approach for updating the control parameters during the engine operation is proposed in this research. This technique can detect any changes in the fuel properties or engine systems. While spark timing is the main issue in SI engines equipped with PFI system, the injection timing is the control parameter for CI engines. Similar to SI engines, CI engines can be reutilized via the proposed approach for their fuel injection timing.

1.5 Objectives of the Research

The present research mainly aims at utilizing a neural network structure for on-board identification of fuel octane number. The network has the ability to use an *operating parameter as the network input and the fuel octane number as the network output. The spark advance will be updated with regard to identification of the octane number. The specific objectives of this research are:*

1) *To investigate and validate the knock intensity for different fuel octane number at altered engine speed and load using in-cylinder pressure signal and cylinder block vibration signal.*
2) *To compare and validate the knock detection results using the experimental signals using knock prediction results obtained from GT-Power simulation software.*
3) *To investigate the engine operating parameter thus finding a reliable factor related to octane number variety.*
4) *To design and develop an ANN structure for fuel octane number identification using input-output data obtained experimentally.*

1.6 Scope of the Research

The scope of this research is categorized into four items as follow:

1) *Organization of test rig to run an SI engine at different speed and load with different fuels:*
    - *Modification of the engine harness and installation programmable ECU on a series production engine in order to adjust the injection duration and sweep the ignition timing;*
    - *Installation of in-cylinder pressure transducer and crank angle encoder to collect the experiment requirement for knock analysis.*
2) *To perform the test point considering:*
    - *The engine operation condition limited to low engine speed ranges (as knock intensity is high), the engine load increased from 20 to 60% of maximum brake torque with 20% interval;*

- *The octane number of fuels used in this research is limited to RON95, RON97, and RON100 (representing research octane number (RON) for commercial gasoline);*
- *The injection duration adjusted to operate the engine only at stoichiometric mixture along using a wide range oxygen sensor and a lambda module;*
- *The spark timing is swept till audible knock region using a programmable ECU.*

3) *To carry out the testing results analysis:*
   - *Frequency analysis of in-cylinder pressure and cylinder block vibration signals to define the domain of acoustic resonance frequency due to knock events;*
   - *Comparison and validation of knock envelope extracted from in-cylinder pressure signal by cylinder block vibration signal;*
   - *Modelling and simulation of combustion process using the SI turbulent flame entrainment model and Douaud and Eyzat knock predictor model in GT-Power environment.*
4) *To design and develop a fuel identifier algorithm:*
   - *Comparative and statistical analysis of combustion parameters for different fuel octane number.*
   - *Comparative and statistical analysis of in-cylinder pressure signal and engine rotational speed signal as the input signal into a neural network structure to identify the fuel types (different RONs).*

1.7 Significance and Contribution of the Research

The novelties of this research and test rig instrumentation are listed below:

1) *Reliable parameter to identify the fuel octane number has been selected and validated using in-cylinder pressure signal and engine rotational speed.*

2) *An ANN model has been trained, validated, and tested for on-board fuel octane classification by monitoring the pattern of instantaneous rotational speed.*

The other prospective contributions of this study include:

1) *The knock boundary prediction for engine operating range utilizing the validated combustion model in GT-Power.*
2) *The knock intensity determination for different fuel octane numbers and illustration of the differences.*

Figure 1.1 briefly presents the procedure of the study in four steps; experiment setup, simulation using GT-Power, data analysis, and fuel octane identifier using ANN.

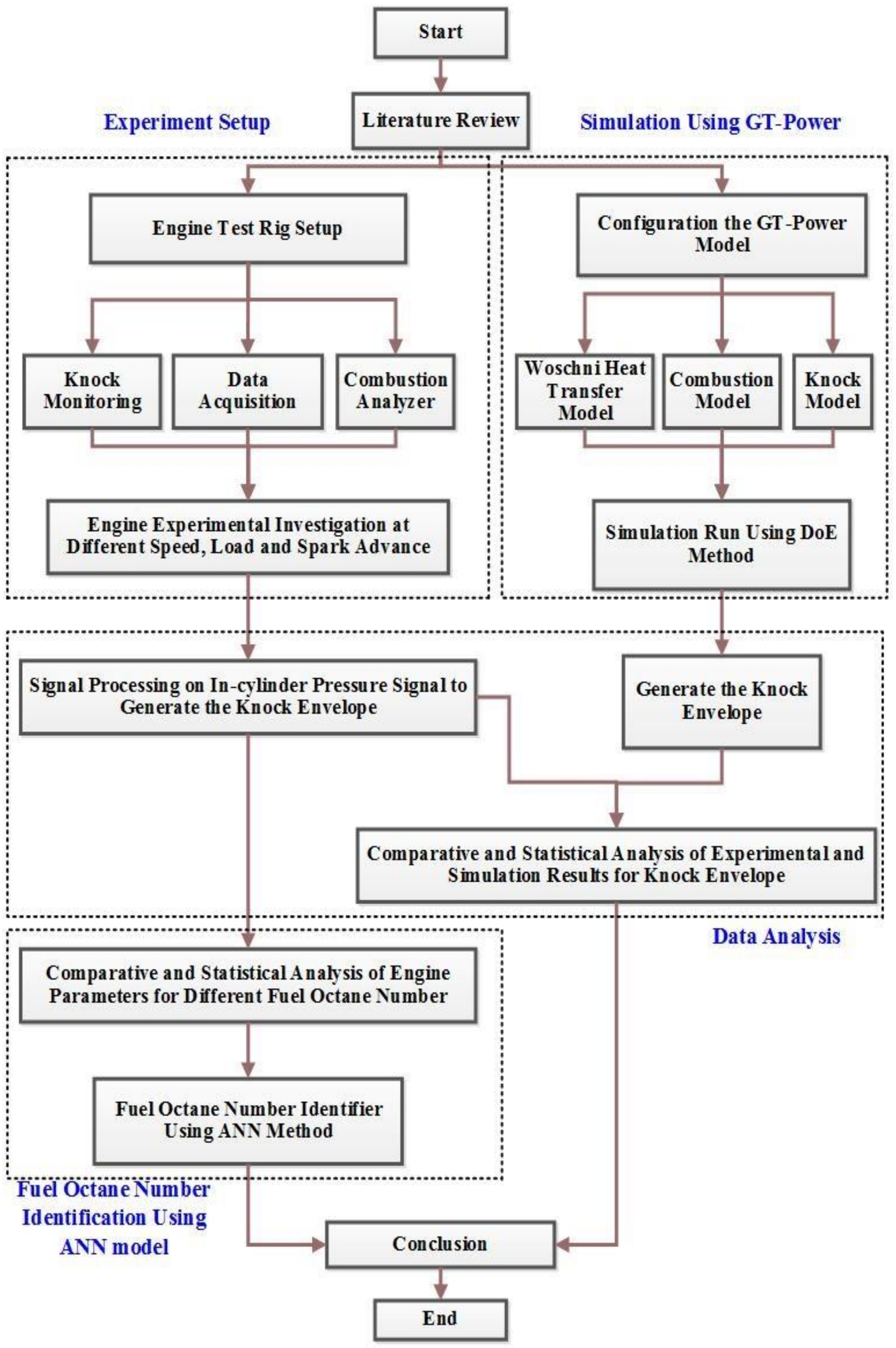

Figure 1.1 *Research procedure flowchart*

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