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Enhancing Spark Ignition Engine Efficiency and Emission Reduction through Nanoparticle Augmented Combustion

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ABSTRACT

Internal combustion engines operate by utilizing byproducts from combustion, as opposed to utilizing them solely for heat transfer purposes. The significance of turbulence in combustion cannot be overstated like turbulence of mixture is directly proportional to flame speed.Nanotechnology plays a vital role in advancing materials and processes in the automotive sector. Major advantages encompass the advancement of lighter yet more durable materials, heightened engine efficiency as well as enhanced and compact electronic systems for improved economy. The in-cylinder combustion process is simulated in Fluent, considering actual engine specifications. The simulation covers equivalence ratios ranging from 0.4 to 1.2 to determine the point of maximum engine efficiency, identified at an equivalence ratio of 1.2. Sisal nanoparticles, derived from chemically treated and ball-milled sisal fibers, are introduced into the combustion chamber. The in-cylinder temperature rises with increasing nanoparticle weight, peaking at 1.2gm, indicating optimal combustion. Beyond 1.3gm, a temperature drop is observed, and engine cessation occurs, suggesting an excessive volume of particles. Exhaust gas analysis demonstrates a reduction in CO and HC pollutants with the addition of nanoparticles.

Keywords: Nanotechnology, IC Engine, turbulence, combustion, sisal fibers

INTRODUCTION

Burning, or combustion, is a simple chemical process that lets out energy from mixing fuel and air. Initially, engines used an outside process to heat water and create steam, which was then used to make engines work. These engines were called external combustion engines. Around the 1860s, the internal combustion engine, which we commonly use today, became a practical invention.J. J. E. Lenoir created the first practical engine igniting gas and air in a cylinder [1]. About 5,000 of these engines were built between 1860 and 1865, with an efficiency of around 5%.Recent research focuses on understanding engine combustion and emission formation within the engine cylinder, influenced by factors like fuel spray, air motion inside the cylinder, and fuel type.

Spark-Ignition Engine

For cars, the air's temperature entering the carburetor helps control the right amount of fuel for the engine's airflow. The airflow through a part called the venturi sets up a pressure difference that helps control the fuel flow from the float chamber. By adjusting this valve, the intake flow is controlled, usually reduced below normal pressure when the engine doesn't need its maximum power. The intake manifold is often warmed to make the liquid fuel evaporate faster, ensuring a more even fuel mix for better combustion.This means that the unburnt gas, which accounts for 70% of the total, is compressed into only 40% of the chamber. This compression increases its temperature, accelerating the combustion rate.

Studies On S.I Engine

In recent years, significant research has accumulated regarding Spark-Ignition Engine Combustion. This progress is due to the use of advanced computational tools and growing interest in enhancing combustion efficiency while reducing pollutants. As a result, research on SI engine combustion has been progressing with increased enthusiasm and focus.

Studies On Flame Propagation In S.I. Engine

Ricardo's work [2] on SI engine development has been highly influential. He proposed that SI combustion occurs in two stages: the initial stage involving flame nucleus formation and growth, and the second stage involving normal flame spread. Withrow et al [3-5], Rassweiler, Marvin et al [6-7], and Bouchard [8] laid the foundation for SI engine combustion research.According to the studies by Withrow, Rassweiler et al [5][9-10], and their peers, the pressure increase from combustion is connected to the amount of fuel burned and ignition timing at a given speed. Marvin's work sheds light on how fuel type and spark plug placement affect the flame's growth and spread in the engine.Researchers, such as Curry et al [11], studied flame profiles under various engine conditions like speed. They found that without a swirl, the flame shape is typically spherical but becomes distorted due to the swirl induced by the shrouded intake valve.

Cyclic Pressure Fluctuation

Cyclic fluctuations in-cylinder pressure pose a significant challenge in analyzing cylinder pressure patterns for SI engines. Numerous studies [12-13] have investigated the nature and extent of these pressure variations and their dependency on different engine parameters.Research indicates that certain conditions, like using a maximum flame velocity mixture and employing a shrouded intake valve, can reduce cyclic fluctuations at peak pressures by enhancing burning rates.Studies by Patterson [14] and Barton et al [13] demonstrated that variations in gas velocity near the spark plug during ignition influence the initial burning duration, playing a crucial role in observed combustion variations.Additionally, research by Peters and Borman [15] found that cyclic pressure fluctuations have only a minor impact on power output.

Pre-Combustion Energy Release

Johnson et al [16] conducted a study on the amount of chemical energy released before actual combustion, and their findings are documented in the available literature. The rates of chemical energy release computed were linked to a chain reaction type kinetic model. Their study revealed that, typically, around 10% of the energy in the fuel was released before the flame front arrived.

Turbulent Combustion In S.I. Engines

Semenov E.S et al [17] conducted extensive research on turbulent combustion in reciprocating Spark-Ignition (S.I.) engines. By adjusting the spark advance, they found that the duration of the second stage isn't heavily influenced by mixture strength. They discovered that the mean turbulent flame velocity within the cylinder could surpass the turbulent fluctuating velocities measured under motoring conditions.Since the initial works of Rassweiler and Withrow [5][9][18], substantial progress has been made in the S.I. engine cycle analysis. Advanced computational techniques [19-20] have been developed, including the application of Semenov's Thermal model [21] for estimating flame propagation rates. Moreover, various formulations are available for estimating instantaneous heat transfer in the reciprocating engine.Ganesan [22] explores thermodynamic modeling of combustion in spark ignition engines, categorizing techniques into thermodynamic, phenomenological, and multi-dimensional models. Ten combustion models are detailed, and a software tool named 'GANESH' (Graphical and Numerical Software Hub) is introduced for simulating engine processes [23].Jehad A. A. Yamin [24] addresses the urgent need for environmentally friendly and renewable energy sources in light of petroleum depletion and associated environmental pollution. The findings reveal a specific combustion duration crucial for achieving desired engine output, emphasizing the importance of maintaining this duration in the design and optimization of engines utilizing propane as a fuel [25].In the research conducted by Yousef S.H. Najjar [26], three categories of alternative fuels—alcoholic, gaseous, and liquid fuels—were studied. Verhelst and Sheppard [27] the term 'Multi-zone thermodynamic engine model' encompasses quasi-dimensional, two-zone, three-zone models. K Rezapour's [28] the model predicts various performance parameters, including temperature, pressure. Experimental validation demonstrates the model's effectiveness in optimizing engine performance and minimizing emissions. P.V.K. Murthy [29] conducted an experimental investigation on combustion parameters in a two-stroke spark ignition engine with a copper-coated piston crown and cylinder head.

Through past literature, it's evident that turbulence significantly improves the combustion process in engines, resulting in increased efficiency and reduced pollutants.In recent times, nanoparticles like Cupric oxide, Silicon carbide, Aluminium Oxide, Manganese, cerium oxide, and platinum have been introduced as additives to enhance combustion. However, their impact on pollutants remains uncertain. Therefore, there's a growing interest in exploring the use of biodegradable nanoparticles to improve combustion without contributing to pollutant production. The aim is to test these biodegradable nanoparticles to ascertain their potential to enhance combustion without the adverse environmental effects typically associated with regular nanoparticles.For any engine, achieving optimal combustion relies on the air-fuel ratio, often expressed as the equivalence ratio. To evaluate this ratio, we simulated the in-cylinder combustion process using ANSYS, taking into account the actual dimensions of the engine. We validated the test rig against the simulated results.During engine operation at a specific equivalence ratio, we introduced sisal nanoparticles into the cylinder and recorded in-cylinder temperatures. We conducted exhaust gas analysis before and after adding the nanoparticles.

SIMULATION AND MODELING

The improvement of Internal Combustion (IC) Engines faces substantial challenges. The future engines are expected to be smaller, lighter, more potent, adaptable, and simultaneously eco-friendly while consuming less fuel. To meet these demanding criteria, innovative engine designs are crucial. Accurate and swift analysis of various engine designs is essential. Utilizing simulated modeling in ANSYS has helped outline the crucial elements needed for combustion in spark ignition engines.The simulation was conducted across various air-fuel ratios to determine the engine's most efficient air-fuel ratio, measured in terms of equivalence ratio. The entire combustion simulation within the cylinder adheres to these specific conditions, commencing at IVC. Therefore, the results are presented spanning from 0 to 252 crank angles. The velocity magnitude was depicted for equivalence ratio $\Phi = 1.2$, while the plots of mass average static temperature were showcased for equivalence ratios $\Phi = 0.4, 0.6, 0.8, 1.0$, and 1.2.

SYNTHESIS AND CHARACTERIZATION OF NANOPARTICLES

Nanotechnology focuses on crafting and utilizing systems at an incredibly tiny scale—atomic or molecular to submicron dimensions. It involves making tiny structures and integrating them into larger systems. These materials often change in surprising ways because of their incredibly small sizes. Nanotechnology holds potential in fields like materials and manufacturing. Nanoparticles, show distinct properties, especially when added to larger materials, which greatly impact how these materials work.Materials exhibit unique behavior when their size is within the atomic scale. Nanomaterials have a heightened surface area, making them exceptionally useful in composites, reactive systems, and energy storage. At the nanoscale, gravitational forces diminish, while electromagnetic forces take precedence.

Nano-Particles For Coolant

Kumar et al. [30] discovered the employing nanofluids with high thermal conductivity in the radiator may decrease the radiator's frontal area by up to 10%. This reduction in component size can enhance fuel efficiency and vehicle performance.Ravikanth et al. [31] conducted a study using CuO and Al2O3 nanofluids in radiators to analyze heat transfer performance. Their study also highlighted a reduction of up to 80% in required pumping power with an increase in particle concentration. Specifically, an 82% reduction in pumping power was observed using a 10% concentration of Al2O3 nanofluid and a 77% reduction using a 6% concentration of CuO nanofluids.

Nano-Particles For Lubricant

Osorio et al. [32] tests are conducted under specific conditions, and worn surfaces were analyzed using EDS and XPS. The findings indicate that all tested nano lubricants demonstrated reduced friction compared to the base oil [33]. Mu-Jun Kao et al. [34] investigate the tribological properties of cast iron using a reciprocating sliding tester with base oil and titanium oxide nanoparticles as additives. Friction and wear experiments were conducted at temperatures ranging from 30 to 130 °C using homemade titanium nano oil.

Natural Fibers

Natural fibers are an excellent renewable resource, having been replenished by nature and human creativity for ages. They are considered carbon neutral, as they absorb as much carbon dioxide as they emit. Their processing primarily results in organic waste, leaving residues that can be repurposed for generating electricity or creating eco-friendly building materials. Furthermore, at the end of their lifecycle, these fibers are entirely biodegradable, according to the FAO.The advantages of natural fiber products go beyond just their production. Materials like hemp, flax, and sisal are increasingly replacing glass fibers in thermoplastic panels in automobiles. As these fibers are lighter, they contribute to reducing fuel consumption, subsequently lowering carbon dioxide emissions and air pollution.

Sisal Fiber

Sisal fiber, derived from the Agave sisalana plant, originally hails from Mexico. Thriving in various hot climates, including arid regions unfavorable for many other plants, this sturdy plant's leaves are harvested and processed to extract the pulp and fibers—sisalfibers, which are lustrous and whitish. While not suitable for textiles due to their coarse and tough nature, these fibers possess excellent strength, durability, and elasticity. They resist moisture absorption, and saltwater damage, and have a smooth surface ideal for dyeing a wide range of colors. Figure 3.1 shows the Sisal Plant and Fiber.

Fig3.1SisalPlant&Fiber

In the automotive industry, people are paying a lot of attention to using natural fibers, like flax and hemp, in making car parts. These fibers are used in creating trim panels and dashboards using a special molding process. This method is easier and more efficient than using traditional textiles. Using these natural fibers instead of glass ones makes the car parts lighter, helping cars use less fuel. It also helps decrease wear on manufacturing equipment and makes it easier to recycle the parts when they're no longer used.

EXPERIMENTATION AND RESULTS

The test rig used for the experiments, and the engine's validation was performed by simulating the in-cylinder combustion using ANSYS. The engine's specifications from the test rig were utilized for modeling. The simulation outcomes showed that the temp. is highest at an $\Phi = 1.2$. Consequently, this equivalence ratio was chosen for the experimentation.The synthesis and characterization of the sisal nanoparticles, used in the experimentation. Before the experimentation, the sisal nanoparticles were tested for their combustibility and the residual amount after combustion

Combustibility Test

The combustibility test was performed on raw sisal fiber, sisal fiber post-chemical treatment, and nanosisalfiber. A 1-gram sample of sisal fiber was used for the test, with a Bunsen burner serving as the heat source to ignite the particles in a crucible. The outcomes of the test are illustrated in Figure 4.1 below.

Fig4.1 (a) Fig 4.1(b)

Raw Sisal fiber weighing 1gm b. fiber clamped on the Stand

Fig 4.1 Combustibility Test

This figure depicts a 1-gram raw sisal fiber that was set on fire using a Bunsen burner. After combustion, the remaining residue weighed 0.01 grams. The treated sisal fiber, also 1 gram, was placed on a mesh and burned with a Bunsen burner, completely combusting with no residue. Similarly, the 1-gram nano sisalfiber sample burned entirely, leaving no residue. The experiment shows that the nanosisal fiber is completely combustible. In the engine's combustion chamber, temperatures are significantly higher than those produced in the experiment, ensuring complete combustion without leaving any residue.

Nanoparticle Regulating Unit

The sisal fiber undergoes a sequence of chemical treatments and is later processed through a high-energy ball milling procedure to achieve a nano-sized form. This nano sisal fiber is introduced into the engine to evaluate its impact on combustion efficiency. A built-in control unit is designed to manage the injection of nanoparticles in engine during the experimental procedure. The specific configuration control device as illustrated in Fig. 4.2.

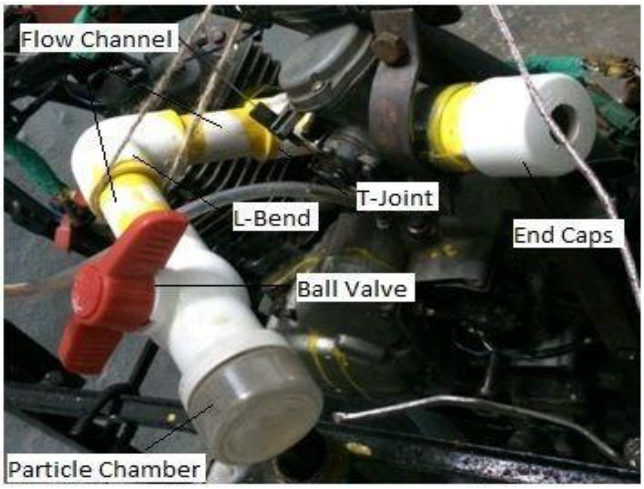


Fig. 4.2 Controldevice

PVC pipe, measuring one inch in diameter, is utilized to manage the particle flow. One end of the pipe houses a chamber for storing particles. The other end of the pipe is attached to the cylinder inlet through a T-joint assembly and securely fastened. The outlet from the L-bend is connected on one side to the cylinder inlet and on the other side to the nanoparticle chamber. To facilitate the fuel flow, a fuel channel using a 50-cc capacity burette is established. Engine acceleration is set by adjusting the knob near the Carburettor.

Combustion Efficiency

C.E. = amount that much heat liberated during the combustion of charge to actual heat to be liberated. This amount of charge used for the experiment is 20cc. The actual heat capacity of the fuel is measured by using Bomb calorimeter. The heat generated in the engine is calculated from the temperatures attained during the experimentation. The average value of the 6 trails before the addition of nanoparticles is considered. The readings from the bomb calorimeter and the engine are tabulated in table 4.1.

The heat of combustion can be calculated using the formula

$$Q = mc_p\Delta T \qquad (6.1)$$

where m is the mass of fuel in Kg
Cp is the specific heat KJ/Kg K
ΔT is the temperature difference K = T2-T1

where T_2 is the temperature after combustion in bomb calorimeter/engine K
T_1 is the temperature before combustion in bomb calorimeter/engine K

Table4.1HeatofcombustionfromBombCalorimeterandEngine

HeatofCombustionmeasuredfrom	m(Kg)	CpKJ/ KgK	T_2(K)	T_1(K)	Q(KJ)
BombCalorimeter	0.01445	2.2	592	302	9.147
Engine	0.01445	2.2	456	302	4.875

Combustion Efficiency of the engine before the addition of nanoparticles is found to be

$$\eta = 4.86/9.17 = 53.03\% \qquad (6.2)$$

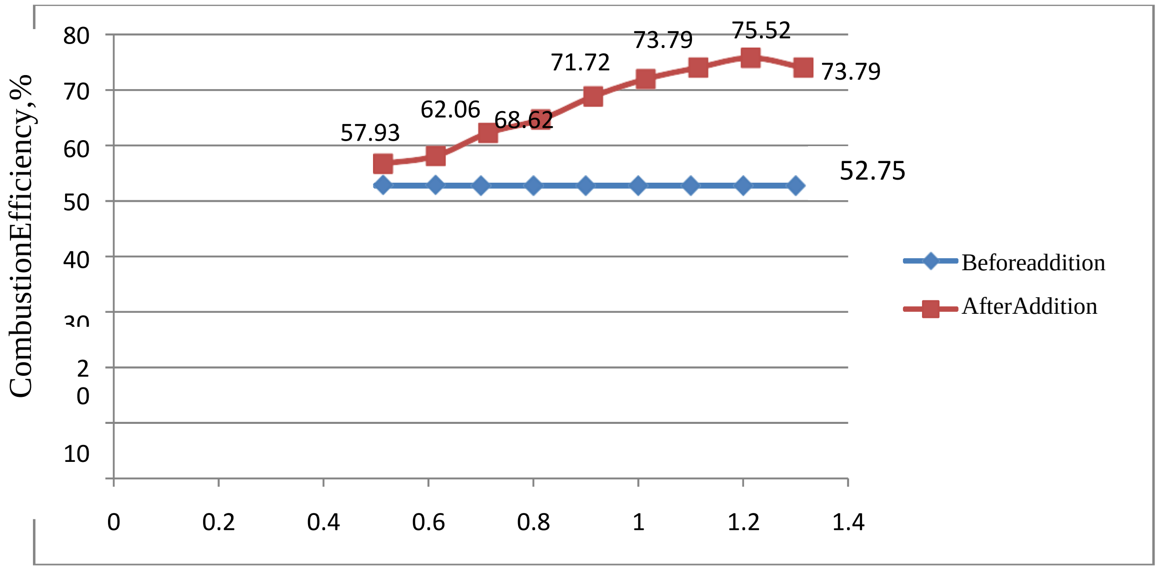
The calculation of combustion efficiency after incorporating nanoparticles involves utilizing equation 6.2 with the data obtained from the heat of combustion measured via a bomb calorimeter and experimental values. The resulting combustion efficiency figures are then organized and presented in table 4.2.

Table4.2CombustionEfficiency

HeatofCombustionmeasuredfromBomb calorimeter Q_b,KJ	HeatofCombustionmeasuredfromEngine Q_e,KJ	CombustionEfficiency h=Q_e/Q_b(%)
Before the Addition of nanoparticles		

9.147	4.83		53.03
After the Addition of nanoparticles			
HeatofCombustionmeasuredfromBomb calorimeter Q_b,KJ	WeightofthePartcilesadded, gm	Heat ofCombustionmeasured fromEngine Q_e,KJ	CombustionEfficiency h=Q_e/Q_b(%)
9.148	0.5	5.172	56.53
	0.6	5.299	57.92
	0.7	5.677	62.05
	0.8	5.898	64.47
	0.9	6.277	68.61
	1.0	6.560	71.71
	1.1	6.750	73.78
	1.2	6.908	75.51
	1.3	6.750	73.78

The engine's combustion efficiency is noted as 53.03% in the absence of nanoparticles. Upon adding 0.5gm of particles, the efficiency increases to 56.54%. As nanoparticles continue to be added, the combustion efficiency progressively rises until it reaches a peak at 1.2gm, achieving the maximum observed efficiency of 75.52%. These trends are visually represented in the provided Figure4.3.



WeightofSisalparticles,gm
Figure4.3WeightofSisalvsCombustionEfficiency

CONCLUSIONS

The digital model of a single-cylinder engine was created in ANSYS to simulate the combustion process. The simulation was conducted across different equivalence ratios ranging from 0.4 to 1.3. The observations revealed that the combustion temperature varies with the equivalence ratio and reaches its maximum at Φ=1.2.Through these simulations, a specific range of equivalence ratios for the experimental setup is determined: 0.4, 0.6, 0.8, 1.0, 1.2, and 1.3. Treatment of sisal fiber with 1M H_2SO_4 solution and subsequent drying before ball milling reduced the milling time by 70%. Characterization using XRD revealed that the size of the resulting sisal nano powder after ball milling is approximately 14 nanometres.Sisal particles are tested for combustibility before being introduced into the engine. Both the raw sisal fiber and the nano sisal particles are examined in laboratory conditions, revealing that the sisal fiber is entirely combustible. Upon the addition of 0.5gm of nanoparticles, the efficiency rose to 56.54%. At 1.2gm addition, the efficiency reached 75.52%, and at 1.3gm, the efficiency was 73.7%. This indicates a consistent increase in combustion efficiency from 0.5g to 1.2g due to improved turbulence inside the cylinder caused by the nanoparticles.This suggests that as the particle addition increases, the temperature rise becomes less significant.The exhaust gas analysis did not show any substantial change in emissions after adding sisal particles. Therefore, it can be concluded that sisal fibers have been entirely burned and are biodegradable.

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REFERENCES

[1]. Robert Ray Raine 1990,A performance model of the dual fuel (diesel/natural gas) engine, SAEpaper900387.
[2]. Guezennec,YG&Haurama,W1999,Twoheatreleaseanalysisofcombustiondataand calibrationofheattransfercorrelationinanI.C.engine,SAEpaper1999-01-0218.
[3]. Withrow,L.,Vovell,WG Boyd,A ,"FollowingCombustion byChemicalMeans",IndustrialandEngg.Chem.,V.22, No.9, (1930),P. 945.
[4]. Withrow,L.,Boyd,T.A.,"PhotographicFlameStudiesintheGasolineEngine",IndustrialandEngg.Chem.,V23, No.5, (1931),P.539.
[5]. Rassweiler,GM.,Withrow,L,"High-SpeedMotionPicturesofEngineFlamesCorrelatedtoPressureCards", SAE Trans.,V 33, (1938), P.185.
[6]. Marvin,C.F.,Best,R.D.,FlameMovementandPressureDevelopmentinaEngineCylinder
[7]. Marvin,C.F,Wharton,A,Roeder,CH,"FurtherStudiesofFlameMovementandPressureDevelopment ina EngineCylinder ",NACATech.Rep.No 556,(1936)
[8]. Bouchard,C.L.,Taylor,CF.,Taylor,ES.,"VariablesAffectingFlameSpeedintheOtto-CycleEngine ", JourSAE, V41,(1937),P514.
[9]. Withrow,L.,Rassweiler,GM,"SpectroscophicStudiesofEngineCombustion",IndustrialandEngg.Chem.,V23, No7, (1931), P.769. NACARep.No.399,(1931).
[10]. Withrow,L., Rassweiler, G.M., "Emission Spectra of Engine Flames", Industrialand Engg. Chem,V24,No5,(1932),P528.
[11]. Curry,S.,"Three-DimensionalStudyofFlamePropagationinSparkIgnitionEngine", SAETrans.,V.71,(1963),P 628.
[12]. Soltau,JP,"CylinderPressureVariationsinPetrolEngines",Proc.Auto.Div.,I.MechE,V2,(1960-61),P.99.
[13]. Samaga,B.S.,Murthy,BS,"InvestigationofaTurbulentFlamePropagationModelforApplicationforCombustionPredictionintheSIengine",SAEpaperno.760758InternalCombustionEngines",SAEPaper740191presentedatAutomotiveEngineeringCongress,Detroit,January1974.
[14]. Woschni,G1967,Auniversallyapplicableequationfortheinstantaneousheattransfercoefficientin theinternalcombustion engine, SAE670931
[15]. Barton,R K , Lestz,S.S. Meyer, W.E , "An Empirical Model for CorrelatingCycle to CycleCylinder Gas Motion and Combustion Variations of a Spark Ignition Engine", SAE Paper No710163,SAEAutomotiveEngg.Congress,Detroit,(1971),SAETrans.,V.80,Section1,P.695
[16]. ohnson,J.H.,Myers,PS.,Uyehara,O.A.,"End-GasTemperatures,Pressures,ReactionsRatesandKnock", SAEPaperNo650505,Mid- YearMeeting,Chicago,111.,(May1965)
[17]. Semenov,E.S.,"CombustioninTurbulentFlow",byIsraelprogramforScientificTranslations,Jerusalem,(1963), IPST Cat.No 812.
[18]. Rassweiler,G.M.,Withrow,L.,"High-SpeedMotionPicturesofEngineFlames", Industrialand Engg Chem, V28, (1936), P 672.
[19]. DeSoete,G,"ASurveyoftheEffectsofTurbulenceonEngineCumbustion",AdvancesinAutomobileEngineering(Part IV),PergamonPress, (1965),P 35 Huber,P.,Brown,JR,"ComputationofInstantaneousAirFlowandVolumetricEfficiency", SAETrans,V73,(1965),P698.
[20]. Lefebvre, A H., Eeid, R., "The Influence of Turbulence on the Structure and Propagation ofEnclosedFlames",Combustion andFlame, V.10, (1966),P.355.
[21]. Semenov,N.N.,"ThermalTheoryofCombustionandExplosionIIITheoryofNormalFlamePropagation", NACA, TM No.1026, 1942.
[22]. Merdjani, S 1996, Leeds university spark ignition engine computer model, version 6.1, UserManual.
[23]. Chow A & Wyszynski ML 1999,Thermodynamic modelling of complete engine systemsareview, Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 213:403.
[24]. Jehad A. A. Yamin "The Effect of Combustion Duration on The Performance and Emission Characteristics of Propane-Fueled 4-Stroke S. I. Engines", Emirates Journal for EngineeringResearch,8 (1), 1-14 (2003)
[25]. JieWANG"Simulationofcombustioninspark-ignitionenginefuelledwithnaturalgas-hydrogenblendscombinedwithEGR"Front.EnergyPowerEng.China2009,3(2):204–211.

[26]. Yousef S.H. Najjar) "Alternative Fuels for Spark Ignition Engines" The Open Fuels & EnergyScienceJournal, 2009, 2,1-9
[27]. Verhelst S & Sheppard, CGW 2009,Multi-zone thermodynamic modelling of spark-ignitionenginecombustionanoverview ,EnergyConversion&Management50,13261335.
[28]. K Rezapour"Bi-fuel SI Engine Model for Analysis and Optimization"Universal Journal ofMechanicalEngineering 2(2):71-82, 2014.
[29]. Dr.P.V.K.Murthy"CombustionModellingInATwo-StrokeCopperCoatedSparkIgnitionEngine" TheExperiment,October,2012.
[30]. D. Singh, J. Toutbourt, G. Chen et al, Annual report Argonee National lab (2006).
[31]. S. V. Ravikanth, K. D. Debendra and K. N. Praveen, Int. J. Heat Fluid Flow 31, 613 (2010). doi:10.1016/j.ijheat fluidflow.2010.02.016
[32]. J. A. Eastman, S. U. S. Choi, S. Li, W. Yu and L. J. Thompson, Appl. Phys. Lett. 78, 718 (2001). doi:10. 1063/1.1341218
[33]. A. Osorio ,B. A. Hernández, J. L.Viesca, R. González, D. Blanco, E. Asedegbega,, Wear 268, 325 (2010)
[34]. M. J. Kao and C. R. Lin, J. Alloy. Compd. 483, 456 (2009). doi:10.1016/j.jallcom.2008.07.223.