

A Review on Second Law Analysis of Single Cylinder Four Stroke Diesel Engine utilizing Residual Trapped Gases Via Reduced Valve Lift

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ABSTRACT:The engine analysis is usually on the traditional first law analysis. The second law analysis is also done by new researchers recently. Engine modeling is done to analyze the critical features of the process. The paper presents the research work done by different researchers to study the first and second law analysis of diesel engine. It is found out that the second law analysis is very good tool to understand the better insights of the engine processes and thermodynamic cycle. Hence, the analysis can be used to determine the optimized valve lift in the diesel engine. For this purpose various correlations like Annand, Wolfer, Arrhenius, Watson, Hardenberg and Hase, Woschni, Hohenberg and Eichelberg can be used to determine the optimized valve lift.

KEYWORDS: Second Law analysis, Diesel Engine, Residual Trapped gases, Modelling.

I. INTRODUCTION

Diesel Engines often during combustion result into accumulation of residual trapped gases in the engine cylinder. In compression ignition engines, high nitrogen oxides (NO_x) and their particulate matter (PM) emissions are the biggest handicap. It is not possible to reduce both of NO_x and PM emissions simultaneously in conventional compression ignition combustion. Complex and expensive after treatment exhaust emission systems are required to eliminate these emissions. However, emission norms get harder and harder with each passing day. The current after treatment systems may be insufficient in the near future to meet stringent emission regulations. Another problem of the after treatment systems such as diesel particulate filters, lean NO_x trap and selective catalytic reduction is cost and durability. Therefore, it is required to improve combustion process. For this reason a great deal of importance is given to the in cylinder combustion processes.

Presently, compression ignition engines have attracted a great interest due to their high thermal efficiency, reliability, durability and high specific power compared to spark ignition engines. In spite of these advantages of compression ignition engines, high nitrogen oxides (NO_x) and their particulate matter (PM) emissions are the biggest handicap. It is not possible to reduce both of NO_x and PM emissions simultaneously in conventional compression ignition combustion. Complex and expensive after treatment exhaust emission systems are required to eliminate these emissions. However, emission restrictions get harder and harder with each passing day. The current after treatment systems may be insufficient in the near future to meet stringent emission regulations. Another problem of the after treatment systems such as diesel particulate filters, lean NO_x trap and selective catalytic reduction is cost and durability. Therefore, it is required to improve combustion process. For this reason a great deal of importance is given to the in cylinder combustion processes.

II. LITERATURE REVIEW

Tianyou Wang, Daming Liu, Gangde Wang, Bingqian Tan and Zhijun Peng [1] have given the Effects of Variable Valve Lift on In-Cylinder Air Motion. The experimental work conducted in the modified four-valve optical spark-ignition (SI) test engine with three different MVL. Particle image velocimetry (PIV) was employed for measuring in-cylinder air motion and measurement results were analyzed for examining flow field, swirl and tumble ratio variation and fluctuating kinetic energy distribution. Results of ensemble-averaged flow fields show that reduced MVL could produce strong swirl flow velocity, and then resulted in very regular swirl motion in the late stage of the intake process. The strong swirl flow can maintain very well until the late compression stage. The reduction of MVL can also increase both high-frequency and low-frequency swirl flow fluctuating kinetic energy remarkably.

Zhilong Hu, Yong Gui, Min Xu, Kangyao Deng, Yi Cui and Jiayong Dou [2] have done a design of a variable valve hydraulic lift system for diesel engine. The hydraulic mechanism, which consists of a driving plunger, a driven plunger, a hydraulic cylinder, and a hydraulic oil tank, is the key part of the VVL mechanism. Simulation is conducted to study the relationship between maximum valve lift and rotation angle of driving plunger. Calculation results indicate that the maximum valve lift decreases with increasing rotation angle. A prototype was manufactured and successfully tested in a single-cylinder diesel engine.

Emad Monemian, M.H. Shojaeefard, Amir Hossein Parivar [3] have demonstrated the Potentials of Variable Valve Lift for improving full load operation in gasoline engine. Based on the final results, VVL with association of variable valve timing (VVT) could result in 3% increase in brake torque and 15.5% in nitrogen oxides emission averagely and also upto 4.5% reduction of BSFC at full load operation.

A. Vamshikrishna Reddy, T. Sharathkumar, D.K. Tharunkumar, B. Dinesh and Y.V.S. Sai Santosh [4] have done Energy and Exergy Analysis of I.C. Engines. In this paper the author has carried out energy and exergy analysis of the biogas run dual fuelled diesel engine. The study is done by coupling 1st law and 2nd law of thermodynamics. This gives a clear picture on fuel consumption, brake thermal efficiency, exergy efficiency and different availabilities with the varying load and compared to the corresponding diesel values.

C. D. Rakopoulos and E. G. Giakoumis [5] have studied speed and load effects on the availability balances and irreversibilities production in a multi-cylinder turbocharged diesel engine. They used a multi-cylinder, turbocharged, in direct injection diesel engine from a view based on second-law analysis. A single-zone thermodynamics model is developed following the filling and emptying modeling technique. In all parts of the diesel engine plant a second-law analysis is performed, that provides all the present availability terms and accounts for the analysis of each component's irreversibilities. The results by first law and second law are compared. To simulate the heat loss to the cylinder walls for each the main chamber and therefore the pre-chamber, the model of Annand is employed. They highlighted however the two basic engine operation parameters, i.e. speed and load, have an effect on the operation of this engine below a second-law perspective.

C. D. Rakopoulos and E. G. Giakoumis [8] developed a computer model for studying the first- and second-law (availability) balances of a turbocharged diesel engine, operating under transient load conditions. They use the model of Annand to simulate the heat loss to the cylinder walls. They declared that second-law analysis results don't invariably go together with the first-law ones, strengthening the idea that a joint improvement of first and second-law could also be an awfully sensible choice for establishing best engine performance.

Zehra Sahin and Orhan Durgun [9] have done multi-zone combustion modeling for the prediction of diesel engine cycles and engine performance parameters. In this, quasi-dimensional phenomenological combustion model developed by Shahed and Ottikkutti are used and developed with new assumptions. Annand's correlation is employed to calculate the instantaneous total heat transfer from the cylinder contents to the combustion chamber walls. They explicit that the given model will predict the engine behaviour in sensible agreement with the theoretical and experimental results.

F. Payri, P. Olmeda, J. Martín and A. García [10] have done a complete 0D thermodynamic predictive model for direct injection diesel engines. In this, a variation of the expression given by Woschni is employed to calculate the heat transfer constant. Many efforts are taken to improve the original model of Woschni. Finally the justification have been given to include the proposed sub-models for correct prediction of the engine performance and it's been quantified the error within the simulation results if these sub-model weren't enclosed.

Maher M Abou Al-Sood, Mahmoud Ahmed and Yousef M Abdel-Rahim [11] have developed rapid thermodynamic simulation model for optimum performance of a four-stroke, direct-injection, and variable-

compression-ratio diesel engine. For the performance of a four-stroke, DI diesel engine a thermodynamic simulation model is developed. The Eichelberg model as changed by Rakopoulos and Hountalas is employed. The comparisons between foreseen and experimental results for various engines, in operation beneath different conditions show that there is a decent concurrence between foreseen and measured values.

Claude Valery Ngayihi Abbe, Robert Nzengwa, Raidandi Danwe, Zacharie Merlin Ayissi and Marcel Obonou [12] have done a study on the 0D phenomenological model for diesel engine simulation with application to combustion of Neem methyl ester biodiesel. The Woschni approach is planned to formulate heat transfer model. They state that the model is ready to predict engine operation characteristics in several operation points with fair accuracy and few adjusting numerical coefficients. The results obtained were satisfactory in terms of accuracy, simplicity and computer price.

C.D. Rakopoulos and E.G. Giakoumis [13] have done second-law analyses applied to internal combustion engines operation. This paper surveys the publications offered within the literature regarding the applying of the second-law of thermodynamics to IC engines. A close reference is created to the findings of different researchers within the field over the last forty years regarding all sorts of IC engines, i.e. SI, CI, turbocharged or naturally aspirated, throughout steady state and transient operation. Main variations between the results of second and first law analyses are highlighted and mentioned. It is believed that engine operation optimization supported the second-law of thermodynamics will function as a strong tool to the engine designer.

Maro Jelić and Neven Ninić [14] have done analysis of internal combustion engine using the second law of thermodynamics. The paper presents the research work done by various authors who have done research in the application of the second law of thermodynamics in analysis of the internal combustion engine and in analysis of the thermodynamics of the combustion process in an engine cylinder in spark- and compression-ignition engines. For several decades now, various authors have been trying to optimize processes in the internal combustion engine, where energy degradations occurs during combustion. It is essential to get a better insight and understanding of the sources for this energy degradation to avoid or diminish them, striving to achieve higher efficiencies of internal combustion engines as the most effective heat engine. One of the most suitable ways in research of energy degradation is application of the second law of thermodynamics in analysis of the process in internal combustion engines. Through the application of the second law of thermodynamics in analysis of the combustion process, the connection between all thermodynamic data with entropy was achieved. By applying the numerical simulations in modeling the ICE engine processes together with the analysis by the second law of thermodynamics, we get a very potent tool for better insight and optimization of spark- and compression-ignition engines achieving lower fuel consumption and lower emissions.

N. Watson and A. D. Pilley [15] in the paper has given the combustion correlation for diesel engine simulation. The use of cycle simulation computer programs has become an established part of turbocharged diesel engine research and development. However, the utility of these programs has in the past been limited by the need for combustion information at the operating point. This difficulty has been overcome by the development of an empirical correlation simulating the combustion process (heat release) via an analytical expression whose governing parameters are linked to in-cylinder conditions. A method of deriving the governing parameters from only a minimum of experimental test data is presented, but enabling performance to be predicted over a wide range of operating conditions. The use of the combustion correlation enables the effects of changing ambient conditions, turbocharger match, valve timing and other engine design parameters to be predicted automatically, and includes their influence on combustion as well as the turbocharging process in an engine design as well as ambient conditions to be predicted, including their effects on the combustion process. The correlation is based on experimental AHRR data, and was initially derived from a large quantity of such information obtained from a typical truck type engine. However, it will be shown that the correlation can be applied to other engines for which only a limited amount of experimental data is available.

N. D. Whitehouse and E. Clough [16] in their paper have obtained Heat release data from a 5 in bore direct injection diesel engine operating over a range of conditions including off-design conditions, such as running at low air to fuel ratios, using six-hole injector nozzles in place of the standard three-hole nozzles, and reducing compression ratio and thereby swirl ratio at TDC. The paper shows that when operating with adequate utilized air fuel ratios (A/Fs) the experimental heat release data could be correlated with a single zone combustion model and that changing the number of nozzle holes or compression/swirl ratio had little effect on the correlation after the initial period of heat release. At inadequate A/Fs a modification to the model to allow for partial combustion was introduced. This improved correlation

and enabled reasonable heat release prediction in the cycle synthesis program.

Donald J. Patterson [17] Cylinder pressure variation is a fundamental and widespread combustion problem in spark-ignited engines. The basic factors causing this problem are variations both in the start and in the rate of combustion. These variations occur not only from cycle to cycle within each cylinder but may also show up as consistent differences between cylinders. Our test results indicate that the major cause of cyclic combustion rate variation is the mixture velocity differences that exist within the cylinder near the spark plug at the time of ignition. As yet we do not know how to reduce the cyclic mixture velocity variations and thus reduce the problem at its origin. However, it is possible to circumvent some effects of cyclic pressure variation by increasing the average combustion rate.

H. Hiroyasu and T. Kadota [18] In order to determine spray droplet size in a diesel engine, fuel was injected into high-pressure, room-temperature gaseous environments with a diesel engine injection system. Droplet size was measured using the liquid immersion sampling technique with a mixture of water-methylcellulose solution and ethanol used as an immersion liquid for diesel fuel oil. The volume distribution of diesel spray droplets is well correlated with chi square distribution with freedom, $\phi = 8$, in the range of this investigation. The Sauter mean diameter increased with increasing back pressure, with the amount of fuel in a spray, and with decrease in pump speed. An empirical correlation was developed between effective injection pressures, air density, the quantity of the fuel delivery, and the Sauter mean diameter of spray droplets, the swirl atomizer, air blast atomizer, and rotating-cup atomizer has been measured by numerous investigators, but only a few studies of droplet size in the diesel combustion chamber have been made. The lack of sufficient data of droplet size distribution in diesel spray is due to the difficulty in measurement which arises from the large number of droplets to be sampled, intermittent characteristics of the spray, and its liquidity.

J. C. Dent and Pramod S. Mehta [19] A phenomenological model is presented for prediction of the combustion characteristics of a Quiescent Chamber Diesel engine. Predictions with the model have shown acceptable agreement with a range of experimental data. The major physical processes controlling combustion have been characterized, and the dominant role of air entrainment and turbulent mixing confirmed quantitatively.

N. Watson and M. Kamel [20] The lower efficiency of the indirect-injection diesel engine, with respect to the direct injection type, is due to additional heat transfer from the combustion chamber, gas pumping between chambers, later injection timing and a different burning rate schedule. The paper describes a project to isolate and quantify these reasons for low efficiencies, using a mathematical model, supported by experimental verification. The model is based on a two-zone system (main and pre-chamber), with component models for heat transfer, gas flow through the passage etc. Experimentally derived heat release schedules in main and pre-chamber are used. It is shown that for a 0-1 m bore engine, with a Ricardo Comet Vb pre-chamber, the different burning rate schedule is the major contribution to the difference in efficiency, with injection timing and gas pumping being the least significant.

W. T. Lyn and E. Valdmanis [21] The effects of physical factors on ignition delay have been studied on a motored research engine using a single injection technique. The fuels used included a high cetane number reference fuel, gas oil and M.T. 80 petrol. The primary factors investigated are those pertaining to the fuel spray, such as injection timing, quantity, and pressure (affecting drop size, velocity and injection rate) hole diameter (affecting drop size and injection rate) and spray form (nozzle type); and those pertaining to the engine, such as temperature, pressure and air velocity. Engine operating variables such as speed and load affect the ignition delay because they change the primary factors such as injection pressure, compression temperature, pressure and air velocity. It has been found that under normal running conditions, compression temperature and pressure are the major factors. All other factors have only secondary effects. Under starting conditions, when ignition is marginal, mixture formation becomes as important as compression temperature and pressure. Such factors as air velocity and spray form which affect the mixing pattern can have a very pronounced effect on ignition delay. Published data on ignition delay are compared with those obtained in the present investigation and a generalization of the data is recommended for engine design and computational work.

III. THE CORRELATIONS USED BY VARIOUS RESEARCHERS

For diesel fuels a reasonable estimate of the delay, ID is achieved by Wolfer, [19]

$$ID = 3.45 \exp(2100/T_m) * P_m^{-1.02},$$

where, T_m and P_m are the mean temperature and pressure of the ambient during ignition delay.

The Arrhenius type of equation is used to describe ignition delay [7]

$$\tau_{id} = a \cdot \Phi \cdot k \cdot P \cdot n \cdot \exp\left(\frac{E_a}{R_u T_{cyl}}\right),$$

where, τ_{id} = Ignition delay, Φ = Equivalence ratio, E_a = Activation energy, T_{cyl} = Cylinder charge temperature, R_u = Gas constant, a , k and n = Empirical constants

The Watson model is given by [15]

$$\tau_{id} = A(BP) \cdot N \cdot P_{SOC}^{-B} \cdot \exp\left(\frac{E}{R_u T_{SOC}}\right),$$

the constants A , N and B are adjustable.

The correlation developed by Hardenberg and Hase is given by, [22]

$$\tau_{id}(A) = (0.36 + 0.22 \bar{S}_p) \exp\left[EA \left(\frac{1}{R \cdot T} - \frac{1}{17190}\right)\right] \cdot (21.2 / (P - 12.4))^{0.63},$$

where, \bar{S}_p = piston speed (m/s), R = Universal gas constant (8.3143 J/mol), EA = Apparent activation energy

$$EA = \frac{618840}{CN + 25},$$

where, CN = Cetane number

The Prakash et al equation for ignition delay for dual fuel diesel engine operated biogas as secondary fuel-[23]

$$\tau_{id(A)} = C \cdot (O_{O_2})^k \cdot (0.36 + 0.22 M_{F_2}) \exp\left[EA \left(\frac{1}{R T_m (r_c)^n} - \frac{1}{17190}\right) + \left(\frac{21.2}{P_m (r_c)^n - 12.4}\right)^{0.63}\right]$$

Where, C , k , O_{O_2} = modified coefficient constant and oxygen concentration of dual fuel engine respectively.

Shipinski et al attempted to correlate the Apparent heat release rate with the rate of injection by fitting a Wiebe function to experimentally determined heat release diagrams, over a range of engine test conditions. The Wiebe function can be expressed as:

$$M(\tau) = \frac{m(\tau)}{m_t} = 1 - \exp(-C_1 \tau^{C_2})$$

The Woschni correlation is given by [24]

$$h = 3.26 \cdot B^{-0.2} \cdot P^{0.8} \cdot T^{-0.53} \cdot w^{0.8},$$

where, B - cylinder bore (m), P - Instantaneous cylinder pressure (Pa), T - Temperature (\square), w -

Local avg. gas velocity,

$$w = C_1 \cdot S_p + C_2 \cdot \frac{V_d \cdot T_r}{P_r \cdot V_r} \cdot (P - P_m),$$

where, C_1 , C_2 - constants to adjust according to engine, S_p - Mean piston speed, V_d - Displaced volume, P_r , V_r , T_r - pressure, volume, temperature at reference state, P_m - Motored cylinder pressure at same crank angle as P .

The Hohenberg correlation is given by [25]

$$h = 3.26 \cdot P^{0.8} \cdot T^{-0.4} \cdot V^{-0.06} \cdot (\bar{S}_p + 1.4)^{0.8},$$

where, \bar{S}_p - Mean piston speed.

Eichelberg's correlation can be expressed as, [20]

$$h(\theta) = 7.67 \cdot 10^{-3} \cdot U_p^{1/3} \cdot \sqrt{P(\theta) \cdot T(\theta)}$$

The Annand's correlation is given as [26]

$$Q_{cyl} = A \left\{ \left[a \cdot \frac{K}{B} \cdot Re^{0.7} \cdot (T - T_w) \right] + [b_A (T^4 - T_w^4)] \right\},$$

where, B is the cylinder bore, A is the heat transfer area, K is the thermal conductivity of the cylinder gas, Re is Reynolds number based on piston speed and cylinder bore, T is the cylinder bulk gas temperature, T_w is the cylinder wall temperature, $b_A = 3.267 \times 10^{-11} \text{ W/m}^2 \text{ K}^4$, a is a constant ranging from 0.35-0.8 depending on the intensity of charge motion.

IV. CONCLUSION

Review work is undertaken to study the experimentation carried out by different researchers to calculate the heat release rate from engine cylinder by using first and second law analysis. It is found out that the second law analysis is the best way to study the thermodynamic processes and engine operations.

Most of the researchers justified the use of second law of thermodynamics to the engine analysis. They called it a very potent tool to for better insight and optimization of diesel engine. It is also observed that the correlations of Annand, Woschni, Wolfer, Arrhenius, Watson, Hardenberg and Hase, Hohenberg, Wiebe and Eichelberg are better to determine the optimized valve lift.

REFERENCES

- [1] Tianyou Wang, Daming Liu, Gangde Wang, Bingqian Tanand ZhijunPeng, "Effects of Variable Valve Lift on In-Cylinder Air Motion", *Energies* (2015), 8, 13778–13795
- [2] Zhilong Hu, Yong Gui, Min Xu, Kangyao Deng, Yi Cui and Jiayong Dou, "Design of a variable valve hydraulic lift system for diesel engine", *Journal of Mechanical Science and Technology* 29 (4) (2015) 1799~1807
- [3] EmadMonemian, M.H. Shojaeefard, Amir HosseinParivar, "Potentials of Variable Valve Lift for improving full load operation in gasoline engine", *Mqat of the Ninth International Conference on Internal Combustion Engines and OilAt Petroleum Research Institute, Tehran, Iran* (2016)
- [4] A.Vamshikrishna Reddy, T.Sharathkumar, D.K.Tharunkumar, B. Dinesh and Y.V.S. SaiSantosh, "Energy and Exergy Analysis of I.C. Engines" *The International Journal Of Engineering And Science (IJES)* Volume no.3 Issue.5 Pages-07-26 (2014) ISSN (e): 2319 – 1813
- [5] C.D. Rakopoulos, E.G. Giakoumis, "Second-law analyses applied to internal combustion engines operation", *Progress in Energy and Combustion Science* 32 (2006) 2–47
- [6] John B. Heywood, "Internal Combustion Engine Operation", McGraw-Hill, 2007
- [7] C. D. Rakopoulos and E. G. Giakoumis, "Speed and load effects on the availability balances and irreversibilities production in a multi-cylinder turbocharged diesel engine", *Applied Thermal Engineering* Vol. 17, No. 3. pp. 299-313, 1997
- [8] C. D. Rakopoulos, E. G. Giakoumis, "Comparative first- and second-law parametric study of transient diesel engine operation", *Energy* 31 (2006) 1927–1942
- [9] Zehra Sahin and Orhan Durgun, "Multi-zone combustion modeling for the prediction of diesel engine cycles and engine performance parameters", *Applied Thermal Engineering* 28 (2008) 2245–2256
- [10] F. Payri, P. Olmeda, J. Martín, A. García, "A complete 0D thermodynamic predictive model for direct injection diesel engines", *Applied Energy* 88 (2011) 4632–4641
- [11] Maher M Abou Al-Sood, Mahmoud Ahmed and Yousef M Abdel-Rahim, "Rapid thermodynamic simulation model for optimum performance of a four-stroke, direct-injection, and variable-compression-ratio diesel engine", *International Journal of Energy and Environmental Engineering* 2012, 3:13
- [12] Claude Valery Ngayihi Abbe, Robert Nzengwa, Raidandi Danwe, Zacharie Merlin Ayissi Marcel Obonou, "A study on the 0D phenomenological model for diesel engine simulation: Application to combustion of Neem methyl ether biodiesel", *Energy Conversion and Management* 89 (2015) 568–576
- [13] C.D. Rakopoulos, E.G. Giakoumis, "Second-law analyses applied to internal combustion engines operation", *Progress in Energy and Combustion Science* 32 (2006) 2–47
- [14] Maro JELIĆ and Neven Ninić, "Analysis of internal combustion engine thermodynamic using the second law of thermodynamics", *ISSN 0562-1887, Strojarstvo* 50 (2) 85-94 (2008)
- [15] Watson, N., Pilley, A. D., and Marzouk, M.: "A Combustion Correlation for Diesel Engine Simulation," SAE paper 800029,1980.
- [16] Whitehouse, N. D., Clough, E., and Way, J. B.: "The Effect of Changes in Design and Operating Conditions on Heat Release in Direct-Injection Diesel Engines," SAE paper 740085, 1974.
- [17] Patterson, D. J.: "Cylinder Pressure Variations Present a Fundamental Combustion Problem, SAE paper 660129, *SAE Trans.*, vol. 75,1966.
- [18] Hiroyasu, H., and Kadota, T.: "Fuel Droplet Size Distribution in Diesel Combustion Chamber, SAE paper 740715, *SAE Trans.*, vol. 83,1974.
- [19] Dent, J. C., and Mehta, P. S.: "Phenomenological Combustion Model for a Quiscent Diesel Engine," SAE paper 811235, *SAE Trans.*, vol. 90,1981.
- [20] Watson, N., and Kamel, M.: "Thermodynamic Efficiency Evaluation of an Indirect Injection Diesel Engine," SAE paper 790039, *SAE Trans.*, vol.88,1979.
- [21] Lyn, W.-T., and Valdmans, E.: "Effects of Physical Factors on Ignition Delay," SAE paper 680102,1968.
- [22] Hardenberg HO, Hase FW. An empirical formula for computing the pressure rise delay of a fuel from its cetane number and from the relevant parameters of direct-injection diesel engines. In: SAE technical paper 790493; 2011p. 1823-1834.
- [23] Lata DB, Misra," A. Theoretical and experimental investigations on the performance of dual fuel diesel engine with hydrogen and LPG as secondary fuels." *Int J Hydrogen Energy* 2010;35:11918-31.
- [24] Aysegul Abusoglu, Mehmet Kanoglu, "First and second law analysis of diesel engine powered cogeneration systems", *Energy Conversion and Management* 49 (2008) 2026–2031
- [25] Claude Valery Ngayihi Abbe, Robert Nzengwa, Raidandi Danwe, Zacharie Merlin Ayissi Marcel Obonou, "A study on the 0D phenomenological model for diesel engine simulation: Application to combustion of Neem methyl ester biodiesel". *Energy Conversion and Management* 89 (2015) 568–576
- [26] C.D. Rakopoulos, E.G. Giakoumis, "Second-law analyses applied to internal combustion engines operation", *Progress in Energy and Combustion Science* 32 (2006) 2–47