Thermodynamic simulation of performance of an endoreversible Dual cycle with variable specific heat ratio of working fluid

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Abstract: An endoreversible Dual heat engine model is established and used to investigate the influence of the variable specific heat ratio of the working fluid on the performance of the cycle. The net work output and thermal efficiency of the cycle are derived and optimized with respect to the specific heat ratio of the working fluid. The results shows that that if compression ratio is less than certain value, the increase of specific heat ratio of the working fluid makes the net work output bigger; on the contrary, if compression ratio exceeds certain value, the increase of specific heat ratio of the working fluid makes the net work output less. The thermal efficiency increases with the increase of specific heat ratio of the working fluid throughout the compression ratio range. One can see that the maximum net work output, the working range of the cycle and the optimal compression ratio corresponding to maximum net work output decrease when specific heat ratio of the working fluid increases. However, the effects of the specific heat ratio of the working fluid on the performance of the cycle are obvious and they should be considered in practice cycle analysis. The results obtained in this paper may provide guidance for the performance evaluation and improvement of real reciprocating heat engines. [Journal of American Science 2009;5(5):175-180]. (ISSN: 1545-1003).

Key words: Finite time thermodynamics; Dual cycle; Variable specific heat ratio; Performance analysis

1. Introduction

Traditional thermodynamics is a theory about equilibrium states and about limits on process variables for transformations from one equilibrium state to another. In order to obtain more realistic limits to the performance of real processes, thermodynamics is extended to finite-time thermodynamics to deal with processes which have explicit time or rate dependencies (Bejan 1996; Aragon-Gonzalez et al. 2006; Zhao and Chen, 2006; Parlak et al., 2008). Thus, significant achievements have ensued since finite-time thermodynamics was developed in order to analyze and optimize the performances of real heat-engines (Chen et al., 1998; Aragon-Gonzalez et al., 2000; Chen et al., 2004). Blank and Wu (1994) analyzed the effect of combustion on the performance of an endoreversible dual cycle. Lin et al. (1999) derived the relations between the net power and the efficiency for the Dual cycle with due consideration of the heat-transfer losses. Wang et al. (2002) modeled Dual cycle with friction-like term loss during a finite time and studied the effect of friction-like term loss on cycle performance. Sahin et al. (2002a, 2002b) optimized the performance of a new combined power cycle based on power density analysis of the dual cycle and made a comparative performance analysis of an endoreversible dual cycle under a maximum ecological function and maximum power conditions. Hou (2004) studied the effect of heat transfer through a cylinder wall on the performance of the dual cycle. Chen et al. (2004) determined the characteristics of net work and efficiency for Dual cycle with heat transfers and friction losses. It is found that there are optimal values of the cut-off ratio at which the net work output and efficiency attain their maxima. Parlak et al. (2004) optimized the performance of an irreversible Dual cycle: the predicted behavior was corroborated by experimental results. Ust et al. (2005) performed an ecological performance analysis for an irreversible Dual cycle by employing the new thermo-ecological criterion as the objective function. Parlak et al. (2005) optimized the performance of irreversible Dual cycle, gave the experimental results, and compared the performance of Dual and Diesel cycles under the maximum power output. Parlak and Sahin (2006) defined the internal irreversibility by using entropy production, and analyzed the effect of the internal irreversibility on the performance of irreversible Dual cycle. Zhao et al. (2007) defined the internal irreversibility by using compression and expansion efficiencies and analyzed the performance of Dual cycle. The above work was done without considering the variable specific heats of working fluid, so Ghatak and Chakraborty (2007) and Chen et al. (2006) analyzed the effect of variable specific heats and heat transfer loss on the performance of the dual cycle when variable specific heats of working fluid are linear functions of its temperature. Furthermore, Ge et al. (2009) analyzed the performance of an air standard Dual cycle with nonlinear relation between the specific heats of working fluid and its temperature, by using finite-time thermodynamics.

All of the above mentioned research, the specific heats at constant pressure and volume of working fluid are assumed to be constants or functions of temperature alone and have the linear and or the non-linear forms. But when calculating the chemical heat released in combustion at each instant of time for internal combustion engine, the specific heat ratio is generally modeled as a linear function of mean charge temperature (Gatowski et al., 1984; Ebrahimi, 2006). The model has been widely used and the phenomena that it takes into account are well knows (Klein, 2004). However, since the specific heat ratio has a great influence on the heat release peak and on the shape of the heat release curve (Brunt, 1998), many researchers have elaborated different mathematical equations to describe the dependence of specific heat ratio from temperature (Gatowski et al., 1984; Brunt, 1998; Egnell, 1998; Klein, 2004; Klein and Erikson, 2004; Ceviz and Kaymaz, 2005). It should be mentioned here that the most important thermodynamic property used in the heat release calculations for engines is the specific heat ratio (Ceviz and Kaymaz, 2005). So, Ebrahimi (2009) modeled the dual cycle with considerations the variable specific heat ratio during a finite time and only studied the effect of cut-off ratio on cycle performance. Therefore, the objective of this study is to examine the effect of variable specific heat ratio on the net work output and the thermal efficiency of air standard Dual cycle.

2. Thermodynamic analysis

The temperature entropy diagram of a Dual heat engine is shown in figure 1. The compression process is an isentropic process ($1 \rightarrow 2$); the heat additions are an isochoric process ($2 \rightarrow 3$) and an isobaric process ($3 \rightarrow 4$); the expansion process is an isentropic process ($4 \rightarrow 5$) and the heat rejection is an isochoric process ($5 \rightarrow 1$).

As mentioned above, it can be supposed that the specific heat ratio of the working fluid is function of temperature alone and has the following linear form:

$$\gamma = \gamma_o - k_1 T \tag{1}$$

where γ is the specific heat ratio and T is the absolute temperature. γ_o and k_1 are constants.

The heat added to the working fluid, during processes ($2 \rightarrow 3$) and ($3 \rightarrow 4$) is

$$Q_{in} = \int_{T_2}^{T_3} c_v dT + \int_{T_3}^{T_4} c_p dT = \int_{T_2}^{T_3} \left(\frac{R_{air}}{\gamma_o - k_1 T - 1} \right) dT + \int_{T_3}^{T_4} \left(\frac{R_{air}\left(\gamma_o - k_1 T\right)}{\gamma_o - k_1 T - 1} \right) dT = \frac{R_{air}}{k_1} \ln\left(\frac{\gamma_o - k_1 T_2 - 1}{\gamma_o - k_1 T_4 - 1} \right) + R_{air}\left(T_4 - T_3\right) \tag{2}$$

where M is the molar number of the working fluid which is function of engine speed. R_{air} and c_p are molar gas constant and molar specific heat at constant pressure for the working fluid, respectively.

The heat rejected by the working fluid during the process ($5 \rightarrow 1$) is

$$Q_{out} = \int_{T_1}^{T_5} c_v dT = \int_{T_1}^{T_5} \left(\frac{R_{air}}{\gamma_o - k_1 T - 1} \right) dT = \frac{R_{air}}{k_1} \ln\left(\frac{\gamma_o - k_1 T_1 - 1}{\gamma_o - k_1 T_5 - 1} \right) \tag{3}$$

where c_v is the molar specific heat at constant volume for the working fluid.

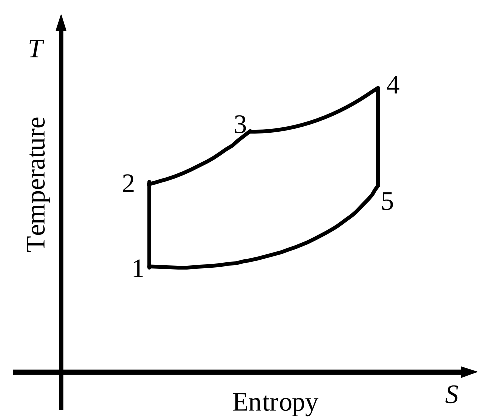

Figure 1. Diagram for the air standard Dual cycle

According to references (Ge et al., 2008a; Al-Sarkhi, 2007), the equation for a reversible adiabatic process with variable specific heat ratio can be written as follows:

$$TV^{\gamma-1} = \left(T + \mathrm{d}T\right)\left(V + \mathrm{d}V\right)^{\gamma-1} \tag{4}$$

From Eq. (4), we get the following equation

$$T_i\left(\gamma_o - k_1 T_j - 1\right) = T_j\left(\gamma_o - k_1 T_i - 1\right)\left(V_j / V_i\right)^{\gamma_o - 1} \tag{5}$$

The compression, r_c, and cut-off, β, ratios are defined as

$$r_c = V_1/V_2 \tag{6}$$

and

$$\beta = V_4/V_3 = T_4/T_3 \tag{7}$$

Therefore, the equations for processes ($1 \rightarrow 2$) and ($4 \rightarrow 5$) are shown, respectively, by the following:

$$T_1(\gamma_o - k_1T_2 - 1)(r_c)^{\gamma_o - 1} = T_2(\gamma_o - k_1T_1 - 1) \tag{8}$$

$$T_4(\gamma_o - k_1T_5 - 1) = T_5(\gamma_o - k_1T_4 - 1)\left(\frac{T_3}{T_4}r_c\right)^{\gamma_o - 1} \tag{9}$$

The energy transferred to the working fluid during combustion is given by the following linear relation (Zhao and Chen, 2007; Chen et al., 2008).

$$Q_{in} = A - B(T_2 + T_4) \tag{10}$$

where A and B are two constants related to combustion and heat transfer which are function of engine speed. From equation (10), it can be seen that Q_{in} contained two parts: the first part is A, the released heat by combustion per second, and the second part is the heat leak loss per second, $Q_{leak} = B(T_2 + T_4)$.

Thus, the net work output of the Dual cycle engine can be written as

$$W_{out} = \frac{R_{air}}{k_1}\ln\left(\frac{(\gamma_o - k_1T_2 - 1)(\gamma_o - k_1T_5 - 1)}{(\gamma_o - k_1T_4 - 1)(\gamma_o - k_1T_1 - 1)}\right) + R_{air}(T_4 - T_3) \tag{11}$$

The thermal efficiency of the Dual cycle engine is expressed by

$$\eta_{th} = \frac{\frac{1}{k_1}\ln\left(\frac{(\gamma_o - k_1T_2 - 1)(\gamma_o - k_1T_5 - 1)}{(\gamma_o - k_1T_4 - 1)(\gamma_o - k_1T_1 - 1)}\right) + T_4 - T_3}{\frac{1}{k_1}\ln\left(\frac{\gamma_o - k_1T_2 - 1}{\gamma_o - k_1T_4 - 1}\right) + T_4 - T_3} \tag{12}$$

When the values of r_c, β and T_1 are given, T_2 can be obtained from Eq. (8) and T_3 can be found from Eq. (7), then, substituting Eq. (2) into Eq. (10) yields T_4, and the last, T_5 can be worked out using Eq. (9). Substituting T_1, T_2, T_3, T_4 and T_5 into Eqs. (11) and (12), respectively, the net work output and thermal efficiency of the Dual cycle engine can be obtained. Therefore, the relations between the net work output, the thermal efficiency and the compression ratio can be derived.

3. Results and discussion

The following constants and parameter values have been used in this exercise: $T_1 = 300\,K$, $k_1 = 0.00003 - 0.00009\,K^{-1}$, $\gamma_o = 1.31 - 1.41$, $A = 60000\,J.mol^{-1}$, $\beta = 1.1$ and $B = 28\,J.mol^{-1}K^{-1}$ (Chen et al., 2006; Ghatak and Chakraborty, 2007; Ge et al., 2007; Ebrahimi, 2009). Using the above constants and range of parameters, the characteristic curves of the net work output and efficiency, varying with the pressure ratio, and the net work output versus efficiency can be plotted.

The variations in the temperatures T_2, T_3, T_4 and T_5 with the compression ratio are shown in figure 2. It is found that T_2, T_3 and T_4 increase with the increase of compression ratio, and T_5 decreases with the increase of compression ratio. In figure 2, there are two special states: one is the state with $T_5 \geq T_4$, the another is the state with $T_2 \geq T_3$. In the two special states, the cycle cannot work.

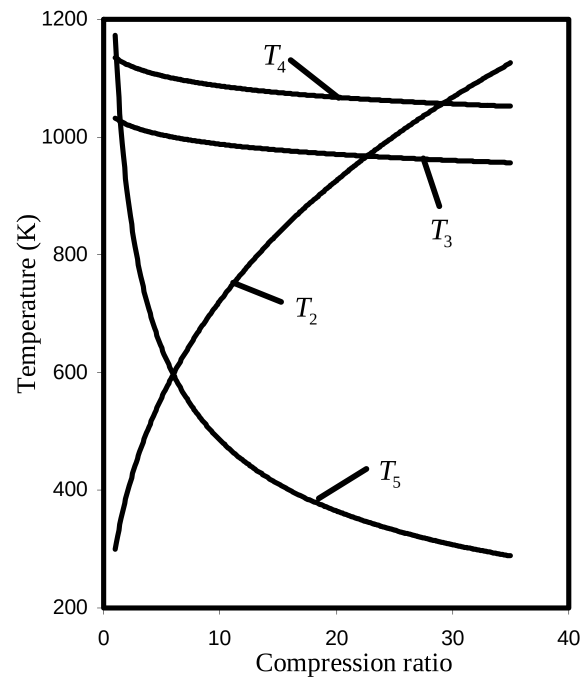

Figure 2. The temperature versus compression ratio for $\beta = 1.1$

Figures. 3-6 display the influence of the parameters γ_o and k_1 related to the variable specific heat ratio of the working fluid on the Dual cycle performance with considerations of heat transfer. From these figures, it can be found that γ_o and k_1 play a key role on the work output and the thermal efficiency. It should be noted that the heat added and the heat rejected by the working fluid decrease with increases of γ_o, while increase with increasing k_1. (see Eqs. (2) and (3)). It can be seen that the effect of γ_o is more than that of k_1 on the net work output and thermal efficiency. It should be mentioned here that for a fixed k_1, a larger γ_o

corresponds to a greater value of the specific heat ratio and for a given γ_o, a larger k_1 corresponds to a lower value of the specific heat ratio. It can also be found from these figures that the net work output versus compression ratio characteristic is approximately parabolic like curves. In other words, the net work output increases with increasing compression ratio, reach their maximum values and then decreases with further increase in compression ratio. But, the thermal efficiency increases with increasing compression ratio. It is also clearly seen that the effects of γ_o and k_1 on the work output and thermal efficiency are related to compression ratio. They reflect the performance characteristics of an endoreversible Dual cycle engine.

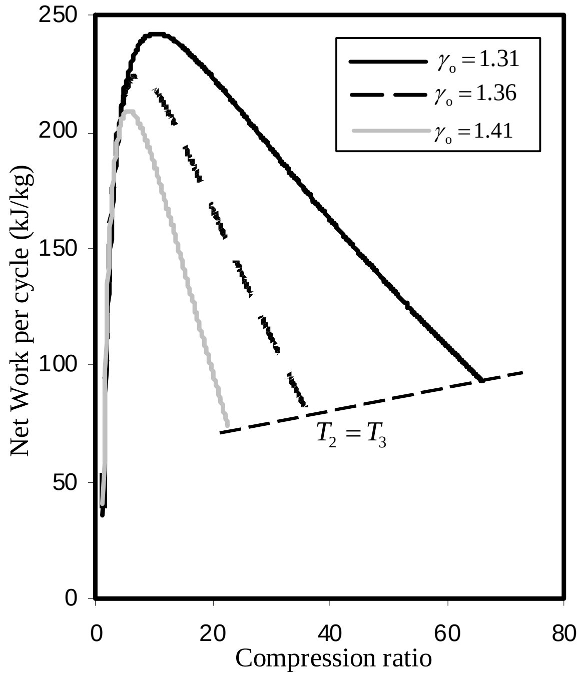

Figure 3. Effect of γ_o on the variation of the net work per cycle (per unit mass of gas) with compression ratio $\left(k_1 = 0.00006\,K^{-1}\right)$

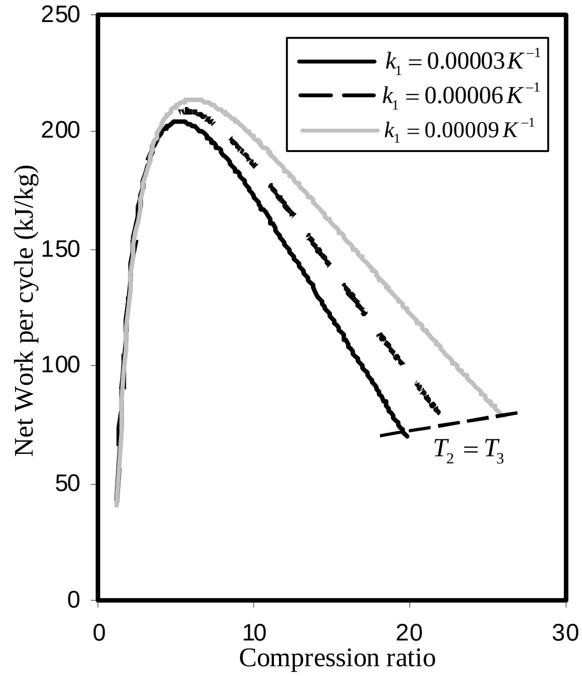

Figure 4. Effect of k_1 on the variation of the net work per cycle (per unit mass of gas) with compression ratio $\left(\gamma_o = 1.41\right)$

It can also be found from the figures 3 and 4 that if compression ratio is less than certain value, the increase (decrease) of γ_o (k_1) will make the net work output bigger, due to the increase in the ratio of the heat added to the heat rejected. In contrast, if compression ratio exceeds certain value, the increase (decrease) of γ_o (k_1) will make the net work output less, because of decrease in the ratio of the heat added to the heat rejected. One can see that the maximum net work output, the working range of the cycle and the optimal compression ratio corresponding to maximum net work output decrease (increase) about 13.7% (4.5%) and 67% (33%), 50.5% (21.4%) when γ_o (k_1) increases (increases) 7.6% (200%). This is due to the fact that the ratio of heat added to heat rejected increases (decreases) with increasing γ_o (k_1) in this case. It should be noted here that both the heat added and the heat rejected by the working fluid decrease with increasing γ_o (see Eq. (4)), and increase with increase of k_1 (see Eq. (5)). Referring to Figures 5 and 6, it can be seen that the efficiency increases with the increase of γ_o and the decrease of k_1 throughout the compression ratio range. On average, the thermal efficiency increases (decreases) by about 23% (6.2%) when γ_o (k_1) increases (increases) 7.6% (200%) over a range of compression ratios from 1.1 to 19.8.

4. Conclusion

In this paper, the effects of specific heat ratio of the working fluid on the performance of an endoreversible Dual cycle during the finite time are investigated. The analytical formulas of work output versus compression ratio and thermal efficiency versus compression ratio of the cycle are derived. The effects of variable specific heat ratio of working fluid on the performance of the cycle are analyzed. The results obtained herein show that the effects of variable specific heat ratio of working fluid on the work output and thermal efficiency of the cycle are significant and should be considered in the design of practical Diesel engines. The detailed effect analyses are shown by one numerical example. The results can provide significant guidance for the performance evaluation and improvement of real Dual engines.

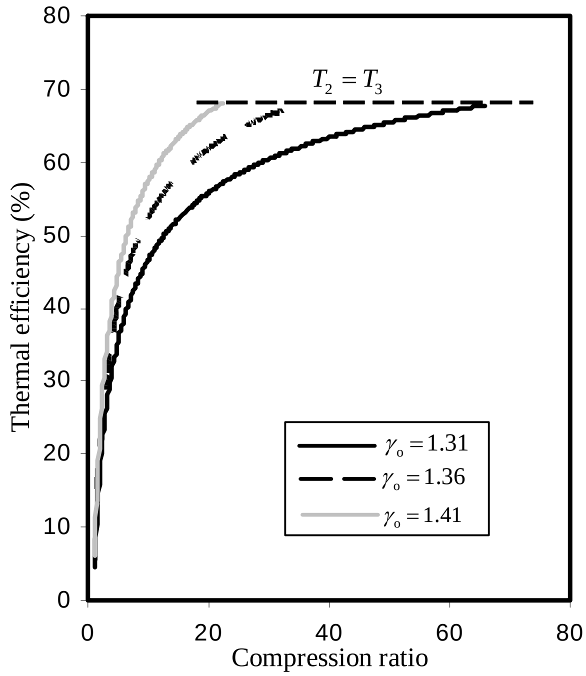

Figure 5. Effect of γ_o on the variation of the thermal efficiency with compression ratio $\left(k_1 = 0.00006\,K^{-1}\right)$

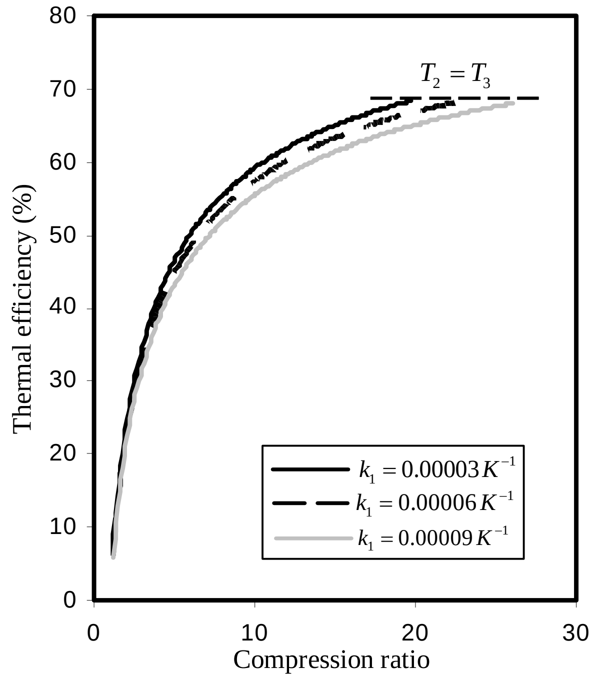

Figure 6. Effect of k_1 on the variation of the thermal efficiency with compression ratio $(\gamma_o = 1.41)$

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Reference

[1] Al-Sarkhi, A., Al-Hinti, I., Abu-Nada, E. and Akash, B., 2007. Performance evaluation of irreversible Miller engine under various specific heat models, International Communications in Heat and Mass Transfer. 34, 897–906.

[2] Aragon-Gonzalez, G., Ganales-Palma, A. and Leon-Galicia, A., 2000. Maximum irreversible work and efficiency in power cycles. Journal of Physics D: Applied Physics. 33(11), 1403–1409.

[3] Aragon-Gonzalez, G., Canales-Palma, A., Leon-Galicia, A. and Morales-Gomez, J.R., 2006. Optimization of an irreversible Carnot engine in finite time and finite size. Revista Mexicana de Fisica. 52 (4), 309–314

[4] Bejan, A., 1996. Entropy-generation minimization: the new thermodynamics of finite-size device and finite-time processes. Journal of Applied Physics. 79(3), 1191–218.

[5] Blank, D.A. and Wu, C., 1994. The effects of combustion on a power optimized endoreversible dual cycle. Energy Conversion and Management. 14(3), 98–103.

[6] Brunt, M.F.J., Rai, H. and Emtage, A. L., 1998. The calculation of heat release energy from engine cylinder pressure data. SAE Paper No. 981052.

[7] Ceviz, M.A. and Kaymaz, I., 2005. Temperature and air–fuel ratio dependent specific heat ratio functions for lean burned and unburned mixture. Energy Conversion and Management. 46, 2387–404.

[8] Chen, L. Ge, Y. and Sun, F., 2008. Unified thermodynamic description and optimization for a class of irreversible reciprocating heat engine cycles. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 222, 1489-1500.

[9] Chen, L., Ge, Y., Sun, F. and Wu, C., 2006. Effects of heat transfer, friction and variable specific-heats of a working fluid on performance of an irreversible Dual cycle. Energy Conversion and Management. 47(18/19), 3224–3234.

[10] Chen, L., Sun, F. and Wu, C., 2004. Optimal performance of

an irreversible Dual cycle, Applied Energy. 79 (1), 3-14.

[11] Chen, L., Wu, C., Sun F. and Cao, S. 1998. Heat transfer effects on the net work output and efficiency characteristics for an airstandard Otto cycle. Energy Conversion and Management. 39, 643–648.

[12] Ebrahimi, R., 2006. Experimental study on the auto ignition in HCCI engine. Ph.D. Thesis, Valenciennes et du Hainaut-Cambrésis, France, (In French).

[13] Ebrahimi, R., 2009. Effects of cut-off ratio on performance of an irreversible Dual cycle. Journal of American Science, 5, (3), 83-90.

[14] Egnell, R., 1998. Combustion diagnostics by means of multizone heat release analysis and NO calculation. SAE Paper No. 981424.

[15] Klein, M., 2004. A Specific Heat Ratio Model and Compression Ratio Estimation. Department of Electrical Engineering, Ph.D. Thesis, Linköping University. Sweden.

[16] Klein, M. and Erikson, L., 2004. A specific heat ratio model for single-zone heat release models. SAE Paper No. 2004-01-1464.

[17] Lin, J., Chen, L., Wu, C. and Sun, F., 1999. Finite-time thermodynamic performance of Dual cycle. International Journal of Energy Research. 23 (9), 765-772.

[18] Gatowski, J.A., Balles, E.N., Chun, K.M., Nelson, F., Ekchian J.A. and Heywood, F.B., 1984. A heat release analysis of engine pressure data. SAE Paper No. 841359.

[19] Ge, Y., Chen, L. and Sun, F., 2008a. Finite time thermodynamic modeling and analysis of an irreversible Otto cycle. Applied Energy, 85(7), 618-624.

[20] Ge, Y., Chen, L. and Sun, F., 2008b. Finite time thermodynamic modeling and analysis for an irreversible Diesel cycle. Proceedings IMechE, Part D: Journal of Automobile Engineering. 222(D5), 887-894.

[21] Ge, Y., Chen, L. and Sun, F. 2009. Finite time thermodynamic modeling and analysis for an irreversible Dual cycle. Mathematical and Computer Modeling. 50(1/2), 101-108.

[22] Ge, Y., Chen, L., Sun, F. and Wu, C., 2007. Performance of Diesel cycle with heat transfer, friction and variable specific heats of working fluid. Journal of the Energy Institute. 80(4), 239–242.

[23] Ghatak, A. and Chakraborty, S., 2007. Effect of external irreversibilities and variable thermal properties of working fluid on thermal performance of a Dual internal combustion engine cycle. Strojnicky Casopis (Journal Mechanical Energy). 58, 1–12.

[24] Hou, S.S., 2004. Heat transfer effects on the performance of an air standard Dual cycle. Energy Conversion and Management. 45(18/19), 3003-3015.

[25] Parlak, A., 2005. Comparative performance analysis of irreversible dual and diesel cycles under maximum power conditions. Energy Conversion and Management. 46(3), 351–359.

[26] Parlak, A. and Sahin, B., 2006. Performance optimization of reciprocating heat engine cycles with internal irreversibility. Journal of the Energy Institute. 79(4), 241-245.

[27] Parlak, A. Sahin, B. and Yasar, H., 2004. Performance optimization of an irreversible Dual cycle with respect to pressure ratio and temperature ratio experimental results of a ceramic coated IDI Diesel engine, Energy Conversion and Management. 45(7/8), 1219-1232.

[28] Parlak, A., Yasar, H., Soyhan, H.S. and Deniz, C., 2008. Optimization of an irreversible Diesel cycle: experimental results of a ceramic coated indirect-injection supercharged Diesel engine. Energy & Fuels. 22, 1930–1935.

[29] Sahin, B., Kesgin, U., Kodal, A. and Vardar, N., 2002a. Performance optimization of a new combined power cycle based on power density analysis of the Dual cycle. Energy Conversion and Management. 43(15), 2019-2031.

[30] Sahin, B., Ozsoysal, O.A. and Sogut, O.S., 2002b. A comparative performance analysis of endoreversible Dual cycle under maximum ecological function and maximum power conditions. Journal of the Energy Institute. 27 (2), 173-185.

[31] Ust, Y., Sahin, B. and Sogut, O.S., 2005. Performance analysis and optimization of an irreversible Dual cycle based on an ecological coefficient of performance criterion. Applied Energy. 82 (1), 23-39.

[32] Wang, W. Chen, L. Sun, F. and Wu, C., 2002. The effects of friction on the performance of an air stand Dual cycle. . Journal of the Energy Institute. 2(4), 340-344.

[33] Zhao, Y. and Chen, J., 2006. Performance analysis and parametric optimum criteria of an irreversible Atkinson heat-engine. Applied Energy. 83, 789–800.

[34] Zhao, Y. and Chen, J., 2007. An irreversible heat engine model including three typical thermodynamic cycles and the optimum performance analysis. International Journal of Thermal Sciences. 46(6), 605–613.