Comparison of Performances of Air-Standard Atkinson, Diesel and Otto Cycles with Constant Specific Heats

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Abstract: The current paper examines the application of finite-time thermodynamics in order to compare the performance between air-standard cycles, i.e. Atkinson, Diesel and Otto cycles with constant specific heats of working fluid. The effects of input temperature and compression ratio on the net output work and efficiency of the Atkinson cycle, Diesel cycle and Otto cycle are analyzed. It is assumed that the compression and power processes are isentropic and any convective, conductive and radiative heat transfer to cylinder wall during the heat rejection process may be ignored. The efficiency of these cycles is compared for equal maximum temperature as well. The findings may present guidance concerning performance evaluation and improvement of practical internal combustion engines.

Keywords: Atkinson Cycle, Diesel Cycle, Efficiency, Finite-Time Thermodynamics, Otto Cycle

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1 INTRODUCTION

Atkinson, Diesel and Otto cycles are three types of four-stroke engines. The Atkinson cycle was designed and built by James Atkinson in 1882. The Diesel cycle was invented by Rudolph Diesel in 1893, and the Otto cycle was developed by Nikolas August Otto in 1876 [1]. In recent years, many attentions have been paid to analyse the performance of internal combustion engines. The Comparison of performances of air-standard Atkinson and Otto cycles with heat transfer considerations has been made by Hou [2].

Performance analysis and parametric optimization of an irreversible Atkinson heat-engine are studied by Zhao [3] and Chen [4]. Optimization of Dual cycle considering the effect of combustion process on the power is studied by Chen [5]. The effect of heat transfer on the performance of an air-standard Diesel cycle is studied by Akash [6]. Effect of mean piston speed, equivalence ratio and cylinder wall temperature on performance of an Atkinson engine and Performance of an endoreversibe Atkinson cycle with variable specific heat ratio of working fluid have been examined by Ebrahimi [7], [8].

Finite-time thermodynamic modeling and analysis for an irreversible Atkinson cycle, finite-time thermodynamic modelling and analysis of an irreversible Otto-cycle and reciprocating heat-engine cycles are done by Chen [9-11]. Performance analysis of an irreversible Otto cycle using finite-time thermodynamics carried out by Mehta [12]. Influence of heat loss on the performance of an air-standard Atkinson cycle examined by Hou [13] and the effects of friction and temperature-dependent specific-heat of the working fluid on the performance of a Diesel-engine is investigated by Al-Sarkhi [14]. In this paper, a comparative study for the performance of the Atkinson, Diesel and Otto cycles are investigated. The related analysis has been done as a case study regarding the constant maximum temperature per cycle and input temperature.

Nomenclature

C_p: Constant pressure specific heat (kJ/kg.K)
C_v: Constant volume specific heat (kJ/kg.K)
k: Specific heat ratio (C_p/C_v)
q_{in}: Heat added to working fluid (kJ/kg)
r: Cut-off ratio
r_c: Compression ratio
r_p: Pressure ratio
s: Entropy (kJ/kg.K)
T_i: Temperature at state i (K)
V_i: Volume at state i (m^3)
w: Net work output (kJ/kg)
η: Efficiency

2 CYCLES MODELS

The T-s diagrams of the Atkinson, Diesel and Otto cycles are shown in Fig. 1.a, Fig. 1.b, and Fig 1.c. The adiabatic compression and expansion processes are the same in the Atkinson, Diesel and Otto cycles.

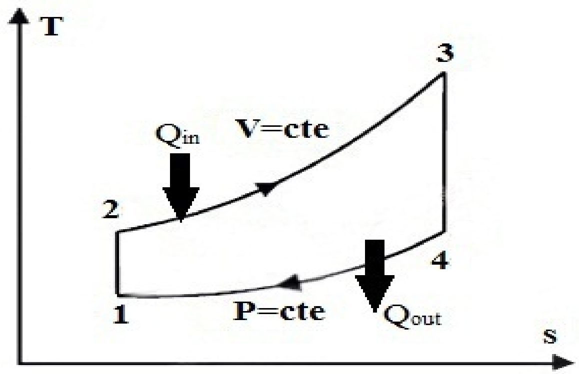

Fig. 1 a) T-s diagram for Atkinson cycle

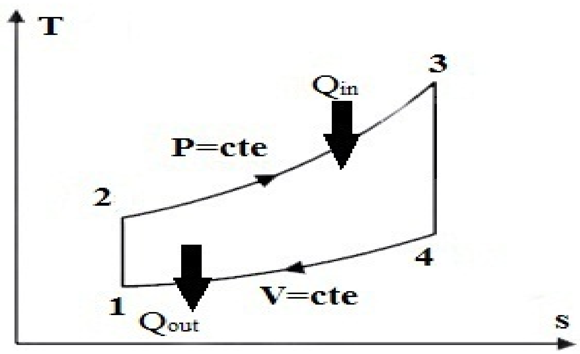

Fig. 1 b) T-s diagram for Diesel cycle

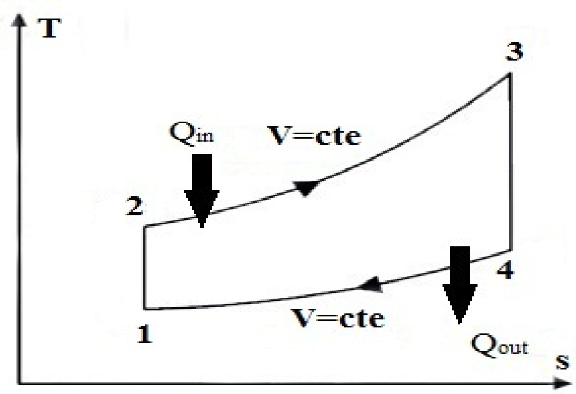

Fig. 1 c) T-s diagram for Otto cycle

In the Atkinson cycle the heat is added to the isochoric process ($2 \rightarrow 3$) and the heat is rejected in the isobaric process ($4 \rightarrow 1$). In the Diesel cycle the heat is added to the isobaric process ($2 \rightarrow 3$) and the heat rejected in the isochoric process ($4 \rightarrow 1$) and finally in the Otto cycle the heat addition and rejection processes occur in the isochoric state $(2 \rightarrow 3)$, $(4 \rightarrow 1)$.

2.1. Thermodynamic analysis of the air-standard Atkinson cycle

Following the assumption described above, process $(1 \rightarrow 2)$ is an isentropic compression from bottom dead center (BDC) to top dead center (TDC). The heat addition takes place during the process $(2 \rightarrow 3)$ which is isochoric. The isentropic expansion process $(3 \rightarrow 4)$ is the power or expansion stroke. The cycle is completed by an isobaric heat rejection process $(4 \rightarrow 1)$. The heat added to the working fluid per unit mass is due to combustion. Assuming constant specific heats, the net work output per unit mass of the working fluid is given by the following equation:

$$w = C_v (T_3 - T_2) - C_p (T_4 - T_1), \quad (1)$$

Where C_p and C_v are the constant pressure and constant volume specific heat, respectively; and T_1, T_2, T_3 and T_4 are absolute temperatures at states of 1, 2, 3 and 4. For the isentropic process $(1 \rightarrow 2)$ and $(3 \rightarrow 4)$, we have:

$$T_2 = T_1 r_c^{k-1}, \quad (2)$$

$$\frac{T_4}{T_3} = (\frac{V_3}{V_4})^{k-1} = (\frac{V_3}{V_1})^{k-1} (\frac{V_1}{V_4})^{k-1}$$
$$= (\frac{V_2}{V_1})^{k-1} (\frac{V_1}{V_4})^{k-1} = r_c^{1-k} (\frac{V_1}{V_4})^{k-1}, \quad (3)$$

Where r_c is the compression ratio (V_1/V_2) and k is the specific heat ratio (C_p/C_v). Additionally, since process $(4 \rightarrow 1)$ is isobaric, thus:

$$\frac{V_1}{V_4} = \frac{T_1}{T_4}. \quad (4)$$

Substitution of Eqs. (2) and (4) into Eq. (3) yields:

$$T_4 = T_1 (\frac{T_3}{T_2})^{\frac{1}{k}}. \quad (5)$$

The heat added per unit mass of the working fluid during the constant volume process $(2 \rightarrow 3)$ per cycle is represented by the following equation:

$$q_{in} = C_v (T_3 - T_2), \quad (6)$$

and finally:

$$\eta = \frac{w}{q_{in}}. \quad (7)$$

2.2. Thermodynamic analysis of the air-standard Diesel cycle

The process $(1 \rightarrow 2)$ in the Diesel cycle is an isentropic compression from bottom dead center (BDC) to top dead center (TDC). The heat addition takes place during the process $(2 \rightarrow 3)$ which is isobaric by nature. The isentropic expansion process $(3 \rightarrow 4)$ is the power or expansion stroke. The cycle is completed by an isochoric heat rejection process $(4 \rightarrow 1)$. The heat added to the working fluid per unit mass is due to combustion. Assuming constant specific heats, the net work output per unit mass of the working fluid is given by the following equation:

$$w = C_p (T_3 - T_2) - C_v (T_4 - T_1), \quad (8)$$

$$T_2 = T_1 r_c^{k-1}, \quad (9)$$

$$T_4 = T_1 (r)^k, \quad (10)$$

Where 'r' stands for cut-off ratio (T_3/T_2). The heat added per unit mass of the working fluid during the constant pressure process $(2 \rightarrow 3)$ per cycle is represented by the following equation:

$$q_{in} = C_p (T_3 - T_2), \quad (11)$$

and finally:

$$\eta = \frac{w}{q_{in}}. \quad (12)$$

2.3. Thermodynamic analysis of the air-standard Otto cycle

The air-standard Otto cycle incorporates an isentropic compression $(1 \rightarrow 2)$, an isochoric heat addition $(2 \rightarrow 3)$, an isentropic expansion $(3 \rightarrow 4)$, and an isochoric heat rejection processes $(4 \rightarrow 1)$. The heat added to the working fluid per unit mass is due to combustion. Assuming constant specific heats, the net work output per unit mass of the working fluid is given by the following equation:

$$w = C_v (T_3 - T_2) - C_v (T_4 - T_1), \quad (13)$$

$$T_2 = T_1 r_c^{k-1}, \tag{14}$$

$$T_4 = T_1 (r). \tag{15}$$

The heat added per unit mass of the working fluid during the constant volume process ($2 \rightarrow 3$) per cycle is represented by the following equation:

$$q_{in} = C_v (T_3 - T_2), \tag{16}$$

and finally

$$\eta = \frac{w}{q_{in}}. \tag{17}$$

3 NUMERICAL VALUES

The following parameters are used in the present paper: $T_1 = 280 \rightarrow 320$ K, $T_3 = 2000$ K, $C_p = 1.003$ kJ/kg.K, $C_v = 0.716$ kJ/kg.K and $k = C_p/C_v = 1.4$. The compression ratio (r_c) for Atkinson cycle is between $8 \rightarrow 16$, for Diesel cycle is between $12 \rightarrow 24$ and for Otto cycle is between $8 \rightarrow 12$. T_2 and T_4 for Atkinson cycle obtain by Eqs. (2) and (5), for Diesel cycle obtain by Eqs. (9) and (10) and for Otto cycle obtain by Eqs. (14) and (15). Then, by substituting T_2 and T_4 in the input heat and net work equations, the efficiency may be obtained in terms of other factors.

4 RESULTS AND DISCUSSION

This section presents the analysis of the paper's findings. Figures 2, 3, and 4 display the comparison among the air-standard cycles (Atkinson, Diesel and Otto) net work output versus efficiency characteristics for the constant specific heat and constant maximum temperature (T_3) with different input temperature (T_1). For the specific efficiency of all cycles, the net work output is maximum in such a way that this maximum value enjoys the greatest value for the Diesel cycle and the lowest value for the Otto cycle.
Figures 5, 6, and 7 display the comparison of the efficiency among air-standard cycles. As these figures represent, the maximum efficiency between the air-cycles is related to the Atkinson cycle in the range of compression ratio which is studied in this paper and the minimum one is related to the Diesel cycle.

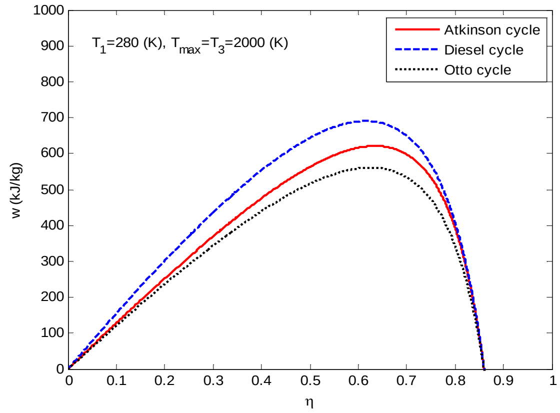

Fig. 2 The comparison between the air-standard cycles net work output versus efficiency characteristic

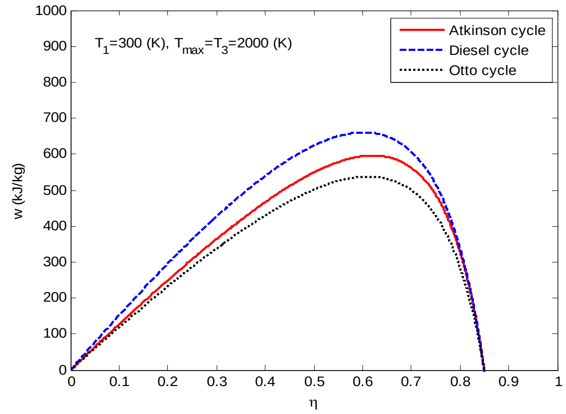

Fig. 3 The comparison between the air-standard cycles net work output versus efficiency characteristic

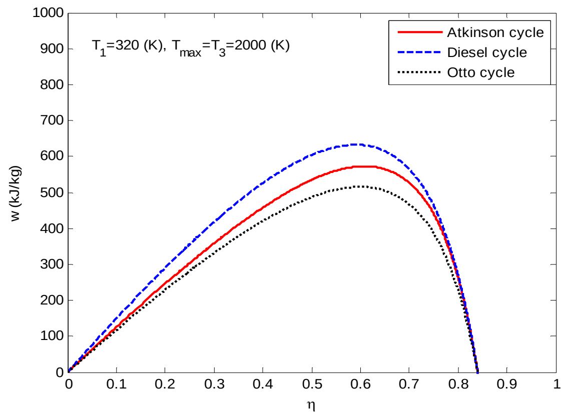

Fig. 4 The comparison between the air-standard cycles net work output versus efficiency characteristic

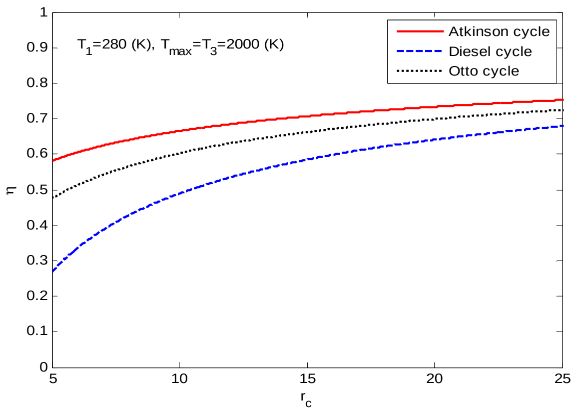

Fig. 5 The comparison between the air-standard cycles efficiency versus compression ratio

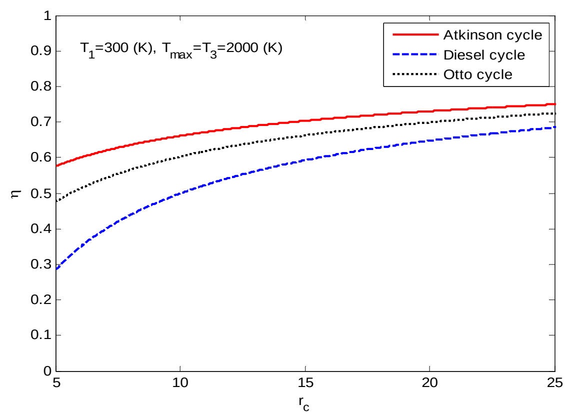

Fig. 6 The comparison between the air-standard cycles efficiency versus compression ratio

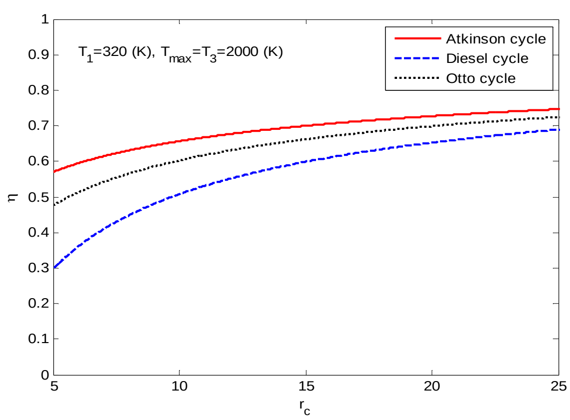

Fig. 7 The comparison between the air-standard cycles efficiency versus compression ratio

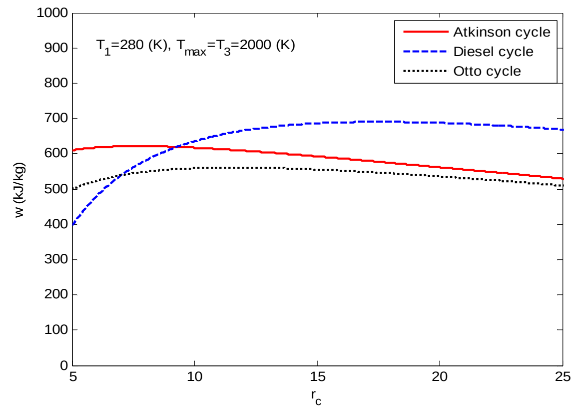

Fig. 8 The comparison between the air-standard cycles net work output versus compression ratio

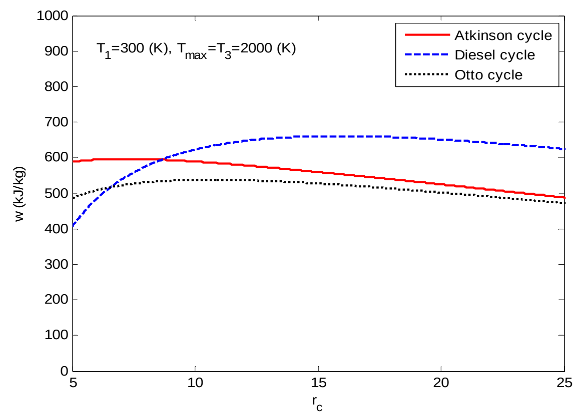

Fig. 9 The comparison between the air-standard cycles net work output versus compression ratio

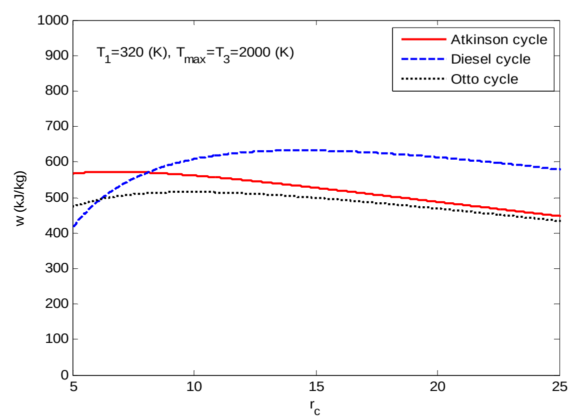

Fig. 10 The comparison between the air-standard cycles net work output versus compression ratio

Figures 8, 9, and 10 display the comparison of net work output among the air-standard cycles. The results show that considering the low compression ratio, the maximum net work output is related to the Atkinson cycle and the minimum net work output is relevant to the Diesel cycle. By increase of the compression ratio, the net work output of the Diesel cycle exceeds that of the Otto cycle. For the large value of compression ratio, the net work output of the Diesel cycle has the greatest value compared with the other air cycles.

5 CONCLUSION

In this paper, a thermodynamic analysis of the three air-standard cycles, i.e. Atkinson, Diesel and Otto is presented. Moreover, the effects of various factors such as maximum and minimum temperature, and compression ratio on the performance of these cycles are investigated. The performance of the air-standard cycles is also compared. The obtained results show that the highest efficiency belongs to the Atkinson cycle, while the lowest one is related to the Diesel cycle, and the efficiency of Otto cycle rests between Atkinson and Diesel cycles. The present study examined the effects of input temperature variation on the performance of cycles as well.

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