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**THERMODYNAMIC ANALYSIS OF AN ATKINSON CYCLE UNDER EFFICIENT  
POWER DENSITY CONDITION**

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**ABSTRACT**

Thermodynamic analysis of an ideal air standard Atkinson cycle under Efficient Power Density is presented in this paper. Three past known criteria in the context of Finite time thermodynamics or Entropy Generation Minimization i.e Power, Power density & efficient power are re-casted in terms of Work Criteria Function which is relatively a new approach to analyze the performance & maximize the power output of any heat engines. The formulation of this concept gives rise to new performance criteria i.e Efficient power density (EPD) which is defined as the efficient power divided by maximum volume of working fluid & its maximum value gives Maximum Efficient Power Density (MEPD). This theory has been implemented to calculate the Power output & efficiency of an Atkinson cycle. Finally a comparative study of different criteria has been made to draw the inference & thus result is obtained. The result obtained from this analysis showed that engine designed at MEPD condition are more efficient than those designed at MP, MPD & MEP conditions. This work has been carried out by incorporating relative air fuel ratio, fuel mass flow rate & residual fraction such that these parameters are the function of variable specific heat & it is observed that the efficiency increases with the increase of relative air fuel ratio & residual fraction. This result can be helpful in the thermodynamic modeling & design of practical Atkinson engine.

**KEYWORDS:** Atkinson cycle, Finite time thermodynamics, power density, efficient power, efficient power density, Work criteria Function (WCF), relative air fuel ratio, mass flow rate of fuel & residual gases.

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**INTRODUCTION**

Atkinson cycle is a type of internal combustion engine which was named after its inventor a British Engineer James Atkinson in 1882 [1]. FTT concept has been used as diagnostic tool in wide range of application & research areas in the fields of quantum thermodynamics [2-13]. It has been used to optimize & analyze the performance of real thermodynamic process, systems, engines & cycles. Leoff determined the thermal efficiency of a reversible Atkinson cycle at maximum work output. Ge et al studied the performance of endo-reversible & irreversible Atkinson cycle. Wang & Hou compared the performance of air standard Atkinson cycle & Otto cycles [14-19]. Chen et al & Sahin et al evaluate the performance characteristics of reciprocating Diesel, Otto, Atkinson, Brayton, Carnot, dual & Miller cycles & made a comparative performance analysis &

optimization of irreversible Atkinson cycle under maximum power density & maximum power conditions [20-25]. From detailed study it is found that under MPD condition it is more advantageous in the point of view of engine size & thermal efficiency. Liu & Chen investigated the influence of variable heat capacities of the working fluid, heat leak losses, compression & expansion efficiencies & other parameters of Atkinson cycle & Joule Brayton cycle [26-30]. Recently it was found that temperature dependent specific heats gives better approximation to actual cycles than using constant temperature specific heats. [31-39]

Maheshwari.G & Patodi.K analyzed the Atkinson cycle with variable specific heat of the working fluid under MEP conditions [40-42]. They conclude that

MEP conditions had an advantage of smaller size & are more efficient than those designed at MP & MPD conditions beside engines designed at MEP conditions require lesser pressure ratio than those designed at MPD conditions[43-46]. The optimal design parameters have been derived analytically & the effect of irreversibilities on general & optimal performances was evaluated. Maximizing the efficient power gave a compromise between power & efficiency. The different performance criteria were employed to optimize the performance of Atkinson cycle using FTT concept & taking account endoreversible & internally irreversible conditions. The inclusion of the engine size in the evaluation of its performance is very important factor from an economical point of view. Huleihil.M formulate a more generalized approach combining the known criteria in literature ( maximum power, maximum power density & maximum efficient power) are reviewed & recast in terms of Work Criteria Function (WCF)[47]. This WCF allows the definition of a new criterion, the efficient power density (EPD) which is defined as efficient power divided by maximum volume of working fluid & its maximum is Maximum efficient power density (MEPD).

$$WCF = \eta^a \cdot Q_h / V_{max}^b \quad (1)$$

In this equation a & b are integers to represent the criterion considered in the study. The study uses a=0, b=0 to give the expression of the heat input to the system & the power extracted by the engines is given when a=1 & b=0. The power density criterion is defined when a=1 & b=1. The efficient power criterion is defined when a=2 & b=0. The efficient power density is defined when a=2 & b=1.

**THERMODYNAMIC ANALYSEIS**

The PV & TS diagram of air standard Atkinson cycle is shown in figure 1. All four processes are reversible. process 1-2 is an adiabatic (isentropic) compression; process 2-3 is a heat addition at constant volume; process 3-4 is adiabatic expansion process; process 4-1 heat rejection at constant pressure. In actual practical cycles the specific heats of working fluid are variable & these variations will have great influence on the performance of cycle[32-37]. The variable specific heat model incorporates residual fraction mass flow rate of fuel & air, relative air fuel ratio.

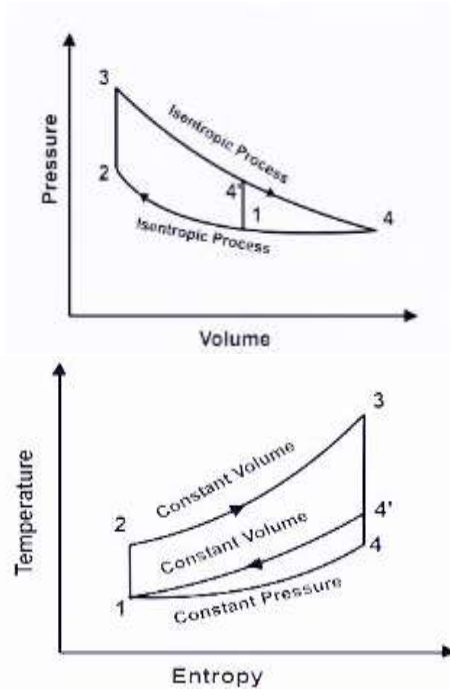


Figure 1: P-V and T-S diagram of air standard Atkinson cycle

The relations between the mass flow rate of the fuel (m<sub>f</sub>), mass flow rate of air (m<sub>a</sub>), mass flow rate of mixture (m<sub>x</sub>), mass flow rate of residual gas (m<sub>r</sub>), relative air fuel ratio (λ) & residual fraction (X<sub>r</sub>) are given in Eq (2)-Eq(12)[37]. The subscripts f, a, x, r represents fuel, air, mixture, residue respectively. The variations of specific heats with respect to following are given below:

$$C = \frac{(m_a c_a + m_f c_f + m_r c_r)}{(m_a + m_f + m_r)} \quad (2)$$

$$x_r = \frac{m_r}{(m_a + m_f + m_r)} \quad (3)$$

$$1 - x_r = \frac{m_a + m_f}{(m_a + m_f + m_r)} \quad (4)$$

$$\lambda = \frac{(m_a / m_f)_{actual}}{(m_a / m_f)_{ideal}} \quad (5)$$

$$Z = \frac{(1 - x_r)}{\{1 + \lambda(m_a / m_f)_{ideal}\}} = \frac{m_f}{(m_a + m_f + m_r)} \quad (6)$$

$$z \cdot \lambda \left(\frac{m_a}{m_f}\right)_{ideal} = \frac{m_a}{(m_a + m_f + m_r)} = \frac{\text{mass of air}}{\text{total mass of mixture}} \quad (7)$$

$$\left\{ \frac{m_a}{(m_a + m_f + m_r)} \right\} = \frac{(1 - x_r) \lambda (m_a / m_f)_{ideal}}{\{1 + \lambda(m_a / m_f)_{ideal}\}} \quad (8)$$

$$\left\{ \frac{mf}{(ma+mf+mr)} \right\} = \frac{(1-xr)}{\{1+\lambda(\frac{ma}{mf})_{ideal}\}} \quad - (9)$$

$$\left\{ \frac{mr}{(ma+mf+mr)} \right\} = \frac{(xr)\{1+\lambda(\frac{ma}{mf})_{ideal}\}}{\{1+\lambda(\frac{ma}{mf})_{ideal}\}} \quad - (10)$$

$$C_{vx} = \frac{[(1-xr)\{\lambda(\frac{ma}{mf})_{ideal}c_{va}+c_{vf}\}+xrc_{vr}\{1+\lambda(\frac{ma}{mf})_{ideal}\}]}{\{1+\lambda(\frac{ma}{mf})_{ideal}\}} \quad - (11)$$

$$C_{px} = \frac{[(1-xr)\{\lambda(\frac{ma}{mf})_{ideal}c_{pa}+c_{pf}\}+xrc_{pr}\{1+\lambda(\frac{ma}{mf})_{ideal}\}]}{\{1+\lambda(\frac{ma}{mf})_{ideal}\}} \quad - (12)$$

The heat supplied or heat addition in the isochoric process may be written as

$$Q_s = m_x c_{vx} (T_3 - T_2) \quad - (13)$$

Mass flow rate of air fuel mixture is given as

$$m_x = \frac{mf\{1+\lambda(\frac{ma}{mf})_{ideal}\}}{(1-xr)} \quad - (14)$$

The heat rejected during isobaric heat rejection process is given as

$$Q_r = m_x c_{px} (T_4 - T_1) \quad - (15)$$

From Equation (11), (12), (13), (14) & (15) we get following equations

$$Q_s = m_x \left[ (1-xr) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{va} + c_{vf} \right\} + x_r c_{vr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \frac{(T_3 - T_2)}{(1-xr)} \right] \quad - (16)$$

$$Q_r = m_x \left[ (1-xr) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{pa} + c_{pf} \right\} + x_r c_{pr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \frac{(T_4 - T_1)}{(1-xr)} \right] \quad - (17)$$

**Power output & MP output**

The power output (W) of the cycle can be written as  $W = Q_s - Q_r$  - (18)

Substituting the value of  $Q_s$  &  $Q_r$  from equation (16) & (17), it can be written as

$$W = \left[ \frac{mf}{(1-xr)} \right] \left[ (1-xr) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{va} + c_{vf} \right\} + x_r c_{vr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ T_3 - T_2 \right] - \left[ \frac{mf}{(1-xr)} \right] \left[ (1-xr) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{pa} + c_{pf} \right\} + x_r c_{pr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ T_4 - T_1 \right] \quad - (19)$$

Multiplying & dividing by  $T_1$  in eq<sup>n</sup> (19), we will get

$$W = \left[ \frac{mf}{(1-xr)} \right] \left[ T_1 \right] \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{va} + c_{vf} \right\} + x_r c_{vr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \left( \frac{T_3}{T_1} \right) - \left( \frac{T_2}{T_1} \right) \right] - \left[ \frac{mf}{(1-xr)} \right] \left[ T_1 \right] \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{pa} + c_{pf} \right\} + x_r c_{pr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \left( \frac{T_4}{T_1} \right) - \left( \frac{T_1}{T_1} \right) \right] \quad - (20)$$

Defining the maximum cycle temp. ratio ( $\tau$ )

$$\tau = \left( \frac{T_3}{T_1} \right) \quad - (21)$$

& Isentropic temp. ratio ( $\theta$ )

$$\theta = \left( \frac{T_2}{T_1} \right) \quad - (22)$$

The total change in entropy change in cycle must be zero, therefore

$$T_2 T_4^\gamma = T_3 T_1^\gamma \quad - (23)$$

From Equation (21), (22) & (23)

$$\frac{T_4}{T_1} = \left( \frac{\tau}{\theta} \right)^{1/\gamma} \quad - (24)$$

Using equation (21)- (24), we get Net Work done

$$W = \left[ \frac{mf}{(1-xr)} T_1 \right] \left[ \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{va} + c_{vf} \right\} + x_r c_{vr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \tau - \theta \right] - \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{pa} + c_{pf} \right\} + x_r c_{pr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \right] \quad - (25)$$

Assuming:

$$K_1 = \left[ \frac{mf}{(1-xr)} \right] \left[ T_1 \right] \quad - (26)$$

$$K_2 = \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{va} \right\} \right] \quad - (27)$$

$$K_3 = \left[ x_r c_{vr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \quad - (28)$$

$$K_4 = \left[ (1-x_r) \left\{ \lambda \left( \frac{ma}{mf} \right)_{ideal} c_{pa} + c_{pf} \right\} \right] \quad - (29)$$

$$K_5 = \left[ x_r c_{pr} \left\{ 1 + \lambda \left( \frac{ma}{mf} \right)_{ideal} \right\} \right] \quad - (30)$$

$$K_6 = [K_2 + K_3] \quad - (31)$$

$$K_7 = [K_4 + K_5] \quad - (32)$$

$$K_8 = [K_6 / K_7] \quad - (33)$$

$$Q_s = [K_1][K_6][\tau - \theta] \quad - (34)$$

$$Q_r = [K_1][K_7] \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \quad - (35)$$

From Equation (18), (34) & (35) it can be written as

$$W = [K_1] \left\{ [K_6][\tau - \theta] - [K_7] \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \right\} \quad - (36)$$

For a given  $\tau$  taking the derivative of W with respect to  $\theta$  & setting it equal to zero  $\left[ \frac{dW}{d\theta} = 0 \right]$  will give the optimum value of  $\theta$  as  $\theta_{mp}$ . Substituting the value of  $\theta_{mp}$  in Equation (36)  $[\theta \approx \theta_{mp}]$  will give the MP output ( $W_{mp}$ ) as:

$$W_{mp} = [K_1] \left\{ [K_6][\tau - \theta_{mp}] - [K_7] \left[ \left( \frac{\tau}{\theta_{mp}} \right)^{1/\gamma} - 1 \right] \right\} \quad - (37)$$

The efficiency ( $\eta$ ) of cycle can be expressed as

$$\text{Efficiency}(\eta) = \frac{\text{Net work done}}{\text{Heat supplied}} = \frac{W}{Q_s} \quad - (38)$$

Substituting the value of W &  $Q_s$  from Equation (34) & (36), We get

$$\eta = 1 - \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_7}{(\tau - \theta) \cdot K_6} \right] \quad - (39)$$

On using Equation (33)&(36) we get efficiency at the MP condition as function of  $\tau$

$$\eta_{mp}(\tau) = 1 - \left[ \left\{ \frac{\tau}{\theta_{mp}(\tau)} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_7}{(\tau - \theta_{mp}(\tau)) \cdot K_6} \right]$$

$$\eta_{mp}(\tau) = 1 - \left[ \left\{ \frac{\tau}{\theta_{mp}(\tau)} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mp}(\tau))} \right] \quad (40)$$

**Power density & MPD condition**

The power density ( $W_{pd}$ ) of the cycle is defined as the ratio of the output power (W) to the maximum specific volume ( $v_4$ ).

Power Density is termed as

$$W_{pd} = \frac{W}{v_4} \quad (41)$$

$$\text{For closed cycle } v_4 = \left( \frac{\tau}{\theta} \right)^{1/\gamma} \times v_1 \quad (42)$$

Combining equation (36) & (42)

$$W_{pd} = \left[ \frac{mf}{(1-xr)} \right] \left[ \frac{T_1}{\left( \frac{\tau}{\theta} \right)^{1/\gamma}} \right] \left[ \frac{1}{v_1} \right] \{ [K_6][\tau - \theta] - [K_7] \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \} \quad (43)$$

For a given  $\tau$ , taking the derivative with respect to  $\theta$  and setting it equal to zero ( $\frac{dW_{pd}}{d\theta} = 0$ ) will give the optimum value of  $\theta$  as  $\theta_{mpd}$ . Substituting the value of  $\theta_{mpd}$  in Equation (43) [ $\theta \approx \theta_{mpd}$ ] it can be written  $\theta_{mpd}$ ,  $W_{mpd}$  &  $\eta_{mpd}$  as

$$W_{mpd} = [K_1] \left[ \frac{1}{\left( \frac{\tau}{\theta_{mpd}} \right)^{1/\gamma}} \right] \left[ \frac{1}{v_1} \right] \{ [K_6][\tau - \theta_{mpd}] - [K_7] \left[ \left( \frac{\tau}{\theta_{mpd}} \right)^{1/\gamma} - 1 \right] \} \quad (44)$$

$$\eta_{mpd}(\tau) = 1 - \left[ \left\{ \frac{\tau}{\theta_{mpd}(\tau)} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mpd}(\tau))} \right] \quad (45)$$

**Efficient power & MEP**

The efficient power of the cycle is defined as the product of power (W) & efficiency ( $\eta$ ).

Defining efficient power as

$$W_{ep} = w \times \eta \quad (46)$$

Substituting the value of W &  $\eta$  from Equation (36) & (39) we get

$$W_{ep} = [K_1] \{ [K_6][\tau - \theta] - [K_7] \left[ \left( \frac{\tau}{\theta} \right)^{1/\gamma} - 1 \right] \} \cdot \left\{ 1 - \left[ \left\{ \frac{\tau}{\theta} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta)} \right] \right\} \quad (47)$$

For a given  $\tau$ , taking the derivative with respect to  $\theta$  and setting it equal to zero ( $\frac{dW_{ep}}{d\theta} = 0$ ) will give the optimum value of  $\theta$  as  $\theta_{mep}$ . Substituting the value of  $\theta_{mep}$  in Equation (47) [ $\theta \approx \theta_{mep}$ ] it can be written  $W_{mep}$  &  $\eta_{mep}$  as

$$\text{For maximum efficient power, } \frac{dW_{ep}}{d\theta} = 0 \quad (48)$$

$$W_{mep} = [K_1] \{ [K_6][\tau - \theta_{mep}] - [K_7] \left[ \left( \frac{\tau}{\theta_{mep}} \right)^{1/\gamma} - 1 \right] \} \cdot \left\{ 1 - \left[ \left\{ \frac{\tau}{\theta_{mep}} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mep})} \right] \right\} \quad (49)$$

$$\eta_{mep} = 1 - \left[ \left\{ \frac{\tau}{\theta_{mep}(\tau)} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mep}(\tau))} \right] \quad (50)$$

**Efficient power density & MEPD**

Efficient power density (EPD) which is defined as the efficient power divided by maximum volume of working fluid.

For efficient power density

$$W_{epd} = \frac{W_{ep}}{v_4} \quad (51)$$

From equation (42) & (49)

$$W_{epd} = [K_1] \left[ \frac{1}{\left( \frac{\tau}{\theta_{ep}} \right)^{1/\gamma}} \right] \left[ \frac{1}{v_1} \right] \{ [K_6][\tau - \theta_{ep}] - [K_7] \left[ \left( \frac{\tau}{\theta_{ep}} \right)^{1/\gamma} - 1 \right] \} \cdot \left\{ 1 - \left[ \left\{ \frac{\tau}{\theta_{ep}} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{ep})} \right] \right\} \quad (52)$$

For a given  $\tau$ , taking the derivative with respect to  $\theta$  and setting it equal to zero ( $\frac{dW_{epd}}{d\theta} = 0$ ) will give the optimum value of  $\theta$  as  $\theta_{mepd}$ .

Substituting the value of  $\theta_{mepd}$  in Equation (52) [ $\theta \approx \theta_{mepd}$ ] it can be written  $W_{mepd}$  &  $\eta_{mepd}$  as

For maximum efficient power density

$$\frac{dW_{epd}}{d\theta} = 0 \quad (53)$$

$$W_{mep} = [K_1] \left[ \frac{1}{\left( \frac{\tau}{\theta_{mepd}} \right)^{1/\gamma}} \right] \left[ \frac{1}{v_1} \right] \{ [K_6][\tau - \theta_{mepd}] - [K_7] \left[ \left( \frac{\tau}{\theta_{mepd}} \right)^{1/\gamma} - 1 \right] \} \cdot \left\{ 1 - \left[ \left\{ \frac{\tau}{\theta_{mepd}} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mepd})} \right] \right\} \quad (54)$$

$$\eta_{mepd} = 1 - \left[ \left\{ \frac{\tau}{\theta_{mepd}(\tau)} \right\}^{1/\gamma} - 1 \right] \cdot \left[ \frac{K_8}{(\tau - \theta_{mepd}(\tau))} \right] \quad (55)$$

**RESULTS AND DISCUSSION**

The derived expressions are used & plotted in order to compare the performance of the Atkinson cycle with variable specific heat of the working fluid. The following constants & range of parameters are selected  $\gamma = 1.4$ ,  $\tau = 1-20$ ,  $\lambda = 0.9-1.2$ ,  $C_{va} = 0.717 \text{ kJ/kgK}$ ,  $C_{vf} = 1.638 \text{ kJ/kgK}$ ,  $C_{vr} = 0.8268 \text{ kJ/kgK}$ ,  $C_{pa} = 1.004 \text{ kJ/kgK}$ ,  $C_{pr} = 1.711 \text{ kJ/kgK}$ ,  $C_{pr} = 1.133 \text{ kJ/kgK}$ ,  $K_1 = 0.6623$ ,  $K_2 = 11.1587$ ,  $K_3 = 1.3228$ ,  $K_4 = 15.0939$ ,  $K_5 = 1.8128$ ,  $K_6 = 12.4765$ ,  $K_7 = 16.9067$ ,  $K_8 = 1.36$   $X_r = 5\% - 20\%$   $m_f = 0.0015 - 0.003 \text{ kg/s}$ ,  $T_1 = 298 \text{ K}$ ,  $(m_a/m_f)_s = 15.1 [33]$

MP Criterion:

$\tau$	$\theta_{mp}$	$\eta_{mp}$
1	0.983	0.018
5	1.923	0.569
10	2.566	0.701
15	3.039	0.759
20	3.426	0.793

**Table 1 MP criterion**

MPd Criterion:

$\tau$	$\theta_{mpd}$	$\eta_{mpd}$
1	0.981	0.019
5	2.648	0.669
10	4.731	0.818
15	6.815	0.875
20	8.898	0.904

**Table 2 MPD criterion**

MEP Criterion:

$\tau$	$\theta_{mep}$	$\eta_{mep}$
1	0.989	0.0227
5	3.4	0.7168
10	5.4	0.8615
15	14.96	0.9353
20	19.96	0.9515

**Table 3 MEP criterion**

MEPD Criterion:

$\tau$	$\theta_{mepd}$	$\eta_{mepd}$
1	2.1	0.4931
5	7.06	0.8563
10	12.45	0.9198
15	17.62	0.9438
20	22.5	0.9592

**Table 4 MEPD criterion**

**Comparative study:**

$\tau$	$\lambda$	$m_f$	$X_r$	$\eta_{mp}$	$\eta_{mpd}$	$\eta_{mep}$	$\eta_{mepd}$
1	0.90	1.5	0.05	0.018	0.019	0.0227	0.4931
5	1	1.9	0.09	0.569	0.669	0.7168	0.8563
10	1.10	2.4	0.14	0.701	0.818	0.8615	0.9198
15	1.15	2.8	0.19	0.759	0.875	0.9353	0.9438
20	1.20	3.0	0.20	0.793	0.904	0.9515	0.9592

Table 5 Comparative analysis of different efficiencies with respect to Max. cycle temp.ratio( $\tau$ ),Relative air fuel ratio( $\lambda$ ), Mass flow rate( $m_f$ ) &Residual fraction( $X_r$ )

Variations of efficiency of the Atkinson cycle with respect to the isentropic temperature ratio is shown in Table 1,2,3 &4..It is inferred that the efficiency increases with increase in isentropic temperature ratio( $\theta$ ),i.e

( $\eta_{mepd} > \eta_{mep} > \eta_{mpd} > \eta_{mp}$ ). The comparative study can be analyzed from Table 5. The Variations of efficiency of the cycle with respect to the maximum cycle temperature ratio ( $\tau$ ) is shown in Table 5. It is investigated that with the increase of maximum cycle temperature ratio ( $\tau$ ) efficiency increases &is maximum value yields for maximum value of ( $\tau$ ).If we analyze the table carefully it can be observed that increasing the value of  $\tau$  the gap between efficiency reduces drastically & particularly in case of  $\eta_{mep}$  &  $\eta_{mepd}$  is almost same for maximum limit of  $\tau$ . From above Table 5 it can be examined efficiency increases with increase in Relative air fuel ratio( $\lambda$ ),Residual fraction( $X_r$ ) & Mass flow rate of fuel( $m_f$ ).It is found that the relative air fuel ratio, the fuel mass flow rate & the residual gases effects the performance of the engine in terms of power output & efficiency & thus they are important parameters during the design of the engine.

**CONCLUSION**

A new criterion i.e MEPD criterion which has been introduced for analyzing the performance of an air standard Atkinson cycle with considerations of variable specific heats of working fluid incorporating the effect of relative air fuel ratio, the fuel mass flow rate & the residual gas is investigated.

The conclusion drawn from the above results are as follows:

The increase in relative air fuel ratio increases the maximum power output & the maximum thermal efficiency.

The maximum power output, the maximum thermal efficiency, the working range of cycle, the power output for maximum thermal efficiency & the thermal efficiency at maximum power output increases as the fuel mass flow rate increases.

The engines designed at MEPD conditions are much more efficient than all other conditions, it requires smaller size which reduces investment cost & has high pressure ratio which is required to run engine efficiently.

The analysis helps us to understand the strong effects of relative air fuel ratio, fuel mass flow rate & residual gases on the performance of an Atkinson cycle.

The results obtained in this paper will help for designing &improvement of the practical internal combustion engine in the future.

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**REFERENCES**

1. Pulkrabek WW. Engineering Fundamentals of the Internal Combustion Engines, 2nd edn. Prentice-Hall, 2004.
2. Voir H.B.Rietlinger(1930) L'utilisation de la chaleur les machines a feu( On the use of

- heat in steam engines)Valliant-Carmann.Paris.pp 13
3. F. L. Curzon and B. Ahlborn, "Efficiency of a carnot engine at maximum power output," *American Journal of Physics*, vol. 43,pp. 22–24, 1975.
  4. I. I. Novikov, "The efficiency of atomic power stations," *Atomnaya Energiya*, vol. 3, p. 409, 1957, English translation in *Journal of Nuclear Energy*, vol. 7, p. 125 , 1958.
  5. P. Chambadal. *Thermodynamique de la Turbine Gaz* (Thermodynamics of the Gas Turbine",in French). Hermann & Cie, 1949.
  6. B. Andresen, "Current trends in finite-time thermodynamics,"*Angewandte Chemie-International Edition*, vol. 50, no. 12, pp.2690–2704, 2011.
  7. M. Moreau, B. Gaveau, and L. S. Schulman. Stochastic dynamics, efficiency and sustainable power production. *The European Physical Journal D-Atomic, Molecular, Optical and Plasma Physics*, 62(1):67{71, 2011.
  8. T. Yilmaz and Y. Durmus, "Efficient power analysis for an irreversible Carnot heat engine," *International Journal of Energy Research*, vol. 32, no. 7, pp. 623–628, 2008.
  9. J. Yvon. *The Saclay Reactor : Two years experience on heat transfer by means of compressed gas*. In *Proceedings of the International Conference on Peaceful Uses of Atomic Energy*, page387, Geneva, Switzerland, 1955. United Nations.
  10. R. S. Berry. *Finite-Time Thermodynamics*, pages 131{146. Springer series in chemical physics,2008.
  11. A. Bejan. *Engineering Advances on Finite-Time Thermodynamics*. *American Journal of Physics*, 62(1):11{12, 1994.
  12. A. Bejan. Entropy generation minimization : The new thermodynamics of finite-size devices and finite-time processes. *Journal of Applied Physics*,79(3):1191{1218, 1996.
  13. S. Ozkaynak, S. Goktun, and H. Yavuz, "Finite-time thermodynamic analysis of a radiative heat engine with internal irreversibility," *Journal of PhysicsD: Applied Physics*, vol. 27, no.6, pp. 1139–1143, 1994.
  14. Ge Y, Chen L, Sun F, et al. Reciprocating heat-engine cycles. *Appl Energy* 2005;81:180–6.
  15. Ge Y, Chen L, Sun F, et al. Performance of an endoreversible Atkinson cycle. *J Energy Inst* 2007;80:52–4.
  16. Lin JC, Hou SS. Influence of heat loss on the performance of an air standard Atkinson cycle. *Appl Energy* 2007;84:904–20.
  17. Ge Y, Chen L, Sun F. Finite time thermodynamic modeling and analysis for an irreversible Atkinson cycle. *Therm Sci* 2010;14:887–96.
  18. Wang P, Hou SS. Performance analysis and comparison of an Atkinson cycle coupled to variable temperature heat reservoirs under maximum power and maximum power density conditions. *Energy Convers Manage* 2005;46:2637–55
  19. Hou SS. Comparison of performances of air standard Atkinson and Otto cycles with heat transfer considerations. *Energy Convers Manage* 2007;48:1683–90.
  20. L. Chen, W. Zhang, and F. Sun, "Power, efficiency, entropy generation rate and ecological optimization for a class of generalized irreversible universal heat-engine cycles," *AppliedEnergy*, vol. 84, no. 5, pp. 512–525, 2007.
  21. Chen L, Sun F, Wu C. Performance analysis of an irreversible Brayton heat engine. *J Inst. Energy* 1997;70:2.
  22. Chen J. The maximum power output and maximum efficiency of an irreversible Carnot heat engine. *J Phys D Appl Phys* 1994;27:1144.
  23. Chen L, Ni N, Cheng G, et al. Performance analysis for a real closed regenerated Brayton cycle via methods of finite time thermodynamics. *Int J Ambient Energy* 1999;20:95.
  24. Chen L, Sun F, Wu C. Effect of heat resistance on the performance of closed gas turbine regenerative cycles. *Int J Power Energy Syst* 1999;19:141.
  25. Chen L, Lin J, Sun F. Efficiency of an Atkinson engine at maximum power density. *Energy Convers Manag* 1998;9:337.
  26. Chen L, Zheng J, Sun F, et al. Performance comparison of an endoreversible closed variable temperature heat reservoir Brayton cycle under maximum power density and maximum power conditions. *Energy Convers Manag* 2001;42:337.
  27. Qin X, Chen L, Sun F. The universal power and efficiency characteristics for irreversible reciprocating heat engine cycles. *Eur J Phys* 2003;24:359–66.

28. Chen L, Lin J, Sun F, et al. Efficiency of an Atkinson engine at maximum power-density. *Energy Convers Manage* 1998;39:337–41.
29. Zhao Y, Chen J. Performance analysis and parametric optimum criteria of an irreversible Atkinson heat-engine. *Appl Energy* 2006;83:789–800.
30. Zheng T, Chen L, Sun F, et al. Power, power density and efficiency optimization of an endoreversible, Braysson cycle. *Exergy* 2002;2:380–6.
31. Sahin B, Kodal A, Yavuz H. Efficiency of a Joule Brayton engine at maximum power density. *J Phys D Appl Phys* 1995;28:1309
32. Ebrahimi R. Effects of mean piston speed, equivalence ratio and cylinder wall temperature on performance of an Atkinson engine. *Math Comput Model* 2011;53:1289–97.
33. Ebrahimi R. Performance analysis of irreversible Atkinson cycle with consideration of stroke length and volumetric efficiency. *J Energy Inst* 2011;84:38–43.
34. Sarkhi A, Abu-Nada E, Al-Hinti I, et al. Performance evaluation of a miller engine under various specific heat models. *Int Commun Heat Mass Transf* 2007;34:897–906.
35. Abu-Nada E, Al-Hinti I, Al-Sarkhi A, et al. Thermodynamic modeling of spark-ignition engine: effect of temperature dependent specific heats. *Int Commun Heat Mass Transf* 2006;33:1264–72.
36. Ebrahimi R. Performance of an endoreversible Atkinson cycle with variable specific heat ratio of working fluid. *J Am Sci* 2010;6:12–7.
37. Ebrahimi R. Thermodynamic modeling of an Atkinson cycle with respect to relative air fuel ratio, fuel mass flow rate & residual gases. *ACTA physica polonica A*, 2013;124:29
38. Ust Y. A comparative performance analysis and optimization of irreversible Atkinson cycle under maximum power density and maximum power conditions. *Int J Thermophys* 2009;30:1001–13
39. Sarkhi A, Akash B, Abu-Nada E, et al. Efficiency of Atkinson engine at maximum power density using temperature dependent specific heats. *Jordan J Mech Ind Eng* 2008;2:71–5.
40. Maheshwari G, Chaudhary S, Somani SK. Performance analysis of a generalized radiative heat engine based on new maximum efficient power approach. *Int J Low Carbon Tech* 2009;4:9–15.
41. Maheshwari G, Chaudhary S, Somani SK. Performance analysis of endoreversible combined Carnot cycles based on new maximum efficient power(MEP) approach. *Int J Low Carbon Tech* 2010;5:1–6.
42. Maheshwari G, Patodi K. Performance analysis of an Atkinson cycle with variable specific heats of the working fluid under maximum efficient power conditions(MEP) approach. *Int J Low Carbon Tech* 2012;6:1–6.
43. Yimaz T. A new performance criterion for heat engines: efficient power. *J Energy Inst* 2006;79:38.
44. Maheshwari G, Khandwawala AI, Kaushik SC. Maximum power density analysis for an irreversible radiative heat engine. *Int J Ambient Energy* 2005;26:71
45. Maheshwari G, Khandwawala AI, Kaushik SC. A comparative performance analysis of an endoreversible heat engine with thermal reservoir of finite heat capacitance under maximum power density and maximum power conditions. *Int J Ambient Energy* 2005;26:147.
46. Maheshwari G, Chaudhary S, Somani SK. Optimum criteria on the performance of a generalized irreversible Carnot heat engine based on thermos economic approach. *Int J Ambient Energy* 2007;28:197–204.
47. Work criteria function of Irreversible Heat engines. *Physics research International* 2014;pp1-7

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