# Entransy Analysis of an Irreversible Diesel Cycle

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**Abstract:** The purpose of this paper is to research an irreversible Diesel cycle by using entransy approach. Entransy may be expressed as heat transfer potential of a subject and it has begun to investigate as a new thermodynamic assessment parameter. Optimization of heat transfer processes is very important, because of their extensity. Result of optimizing heat transfer is to use energy efficiently and decrease $CO_2$ emission that is main reason of the global warming. Because of the these reasons, entransy analysis of a Diesel cycle is investigated and result are presented. Some obtained results for entransy analysis are: entransy efficiency has minimum (0.191) at x = 19.296, $\dot{G}_D$ has a maximum ($1.538\times10^6$ kW K) at x = 8.316 for $\eta_E = \eta_C = 1$. cycle and has a maximum point at x = 6.959 and it value is $1.341\times10^6$ kW K for $\eta_E = \eta_C = 0.8$.

**Keywords:** Entransy, irreversibility, Diesel cycle, exergy.

## 1. INTRODUCTION

Heat transfer is energy flow resulting from temperature difference and it is the most convenient energy transfer mechanism at the energy conversion systems. More than 80 % of the energy system is predicted that it consists of heat transfer process. Improved heat transfer processes have potential to decrease $CO_2$ emission that is the most important reason of the global warming [1-3]. Because of the results referred above, a method was developed for optimizing heat transfer processes called as entransy. Entransy may be defined as heat transfer ability of a system. Thermodynamically, heat transfer is an irreversible process and there are always entransy dissipation result of heat transfer. This phenomena is similar to exergy destruction that is irreversible work resulting from irreversibilities in a system. Entransy concept is very similar to electrical capacitor and is defined as following [4]:

$$G = \frac{1}{2} QT \quad (1)$$

where, $G$ (kJK) is entransy; $Q$ (kJ) is stored heat energy in the subject and $T$ (K) is the temperature of the subject Similar to energy and exergy balance equation, entransy dissipation is: [5]:

$$\dot{G}_H - \dot{G}_L - \dot{G}_d - \dot{G}_w = 0 \quad (2)$$

where, $\dot{G}_H$ is entransy rate of added heat, $\dot{G}_L$ is entransy rate of the rejected heat, $\dot{G}_d$ is entransy dissipation rate and $\dot{G}_w$ entransy rate to environment *via* work.

In literature, although there are studies about entransy [3-35], a small part of these are about thermodynamic cycles [4-8]. In this paper, irreversible Diesel cycle is investigated by using entransy approach first time and results are compared with classical thermodynamic parameters.

## 2. SYSTEM DESCRIPTION AND THERMODYNAMIC ANALYSIS

In this study, an irreversible Diesel cycle is analyzed according to entransy approach and classical thermodynamic evaluation parameters. In the thermodynamic analysis assumptions listed following are applied:

- System is in steady state conditions

- All processes are irreversible.

- Environmental conditions are $T_o$ 298.15 (K) and $P_o$ 100 (kPa).

- Specific heats are independent from the temperature. Specific heat at constant pressure is, $C_P$ 1.005 (kJ/kg) and isentropic coefficient is k 1.04.

- Fluid used in the system is air and it is assumed as ideal gas.

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- $\frac{P_2}{P_1} = \frac{P_3}{P_4}$.

Heat transfer rate is ($\dot{Q}$):

$$\dot{Q} = \dot{m}c_p dT \quad (3)$$

Temperature- entropy diagram (T-S) of the system can be seen in Figure **1**.

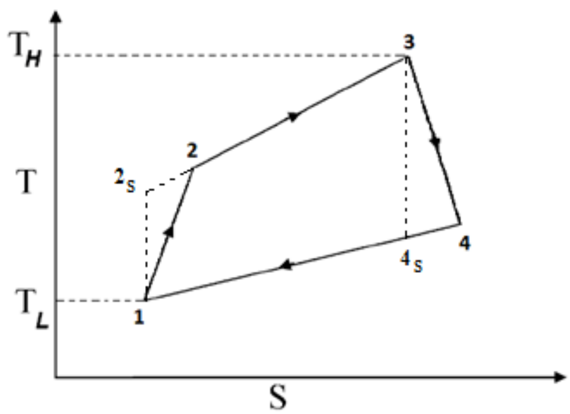


**Figure 1:** T-s diagram of the irreversible Diesel cycle [36,37].

Added heat and rejected heat from the irreversible Diesel cycle is described as following respectively:

$$\dot{Q}_H = \dot{m}c_p \int_2^3 dT = \dot{m}c_p (T_3 - T_2) \quad (4)$$

$$\dot{Q}_L = \dot{m}c_v \int_1^4 dT = \dot{m}c_v (T_4 - T_1) \quad (5)$$

where, $\dot{m}$ mass rate at the system (kg/s). Entransy rate is:

$$\dot{G} = \dot{m}cTdT \quad (6)$$

Added heat, rejected heat entransy and entransy rate by means of work to environment are defined as following respectively:

$$\dot{G}_H = \dot{m}c_p \int_2^3 TdT = \frac{\dot{m}c_p (T_3^2 - T_2^2)}{2} \quad (7)$$

$$\dot{G}_L = \dot{m}c_v \int_1^4 TdT = \frac{\dot{m}c_v (T_4^2 - T_1^2)}{2} \quad (8)$$

$$\dot{G}_W = \dot{W}T_o \quad (9)$$

Relations between reversible and irreversible cycles can be obtained by using compression and expansion efficiencies [37-43]:

$$\eta_C = \frac{T_{2S} - T_1}{T_2 - T_1}, \ \eta_E = \frac{T_4 - T_3}{T_{4S} - T_3} \quad (10)$$

Work output, exergy output, energy efficiency, exergy efficiency, entropy generation, equations are described as following respectively:

$$\dot{W} = \dot{Q}_H - \dot{Q}_L \quad (11)$$

$$Ex = \dot{Q}_H \left(1 - \frac{T_o}{T_H}\right) \quad (12)$$

$$\eta = \frac{\dot{W}}{\dot{Q}_H} \quad (13)$$

$$\varphi = \frac{\dot{W}}{Ex} \quad (14)$$

$$S_{gen} = \left(\frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H}\right) \quad (15)$$

Second law of the thermodynamics can be expressed by using Clausius equation.

$$\frac{\dot{Q}_H}{T_H} - \frac{\dot{Q}_L}{T_L} \le 0 \quad (16)$$

This inequality can be converted to equality by means of defining an internal irreversibility parameter (*I*):

$$I \frac{\dot{Q}_H}{T_H} = \frac{\dot{Q}_L}{T_L} \quad (17)$$

Using equation (17), equation (18) can be obtained:

$$I = \frac{\dot{Q}_L T_H}{\dot{Q}_H T_L} \quad (18)$$

For the reversible Diesel cycle $T_2$ and $T_4$ are:

$$T_{2S} = x^{k-1}.T_1 \quad (19)$$

$$T_{4S} = \frac{T_3}{x^{k-1}} \quad (20)$$

where x $\left(\frac{V_1}{V_2}\right)$ is compression ratio,. $T_2$ and $T_4$ can be defined again by using equations (10), (19) ve (20):

$$T_2 = \frac{\left(T_{2S} - T_1\right)}{\eta_C} + T_1 \tag{21}$$

$$T_4 = T_4 + \left(T_{4S} - T_3\right)\eta_E \tag{22}$$

using equations (2-20), all parameters are defined again following.

$$\dot{W} = c_v.\dot{m}.\left((T_1 + T_3)(\eta_E - 1 - \eta_E.x^{1-k})\right) + \frac{c_p.\dot{m}.\left(\eta_C.T_3.x - T_1\left((\eta_C - 1)\right)x + x^k\right)}{\eta_C x} \tag{23}$$

$$Ex = c_p\dot{m}\left(1 - \frac{T_o}{T_3}\right)\left(T_3 + T_1\left(\frac{1 - x^{-1+k}}{\eta_C} - 1\right)\right) \tag{24}$$

$$\eta = \frac{x^{-k}.\begin{pmatrix} c_v.\eta_C.x\left(T_3 - T_1\right)x^k - \eta_E.T_3\left(x^k - x\right) \\ +c_p.x^k\left(T_1.\left(x^k + \left(\eta_C - 1\right)\right) - \eta_C.T_3.x\right)\end{pmatrix}}{c_p\left(T_1.((\eta_C - 1).x + x^k) - \eta_C.T_3.x\right)} \tag{25}$$

$$\varphi = \frac{\begin{matrix} T_3.x^{-k}.\left(c_v.\eta_C.x\left(T_1 - T_3\right).x^k + \eta_E.T_3(x^k - x)\right) \\ -c_p.x^k.(T_1.\left(\eta_C - 1\right).x + x^k - \eta_C.T_3.x)\end{matrix}}{c_p(T_1 - T_3)(T_1.((\eta_C - 1).x + x^k) - \eta_C.T_3.x)} \tag{26}$$

$$ExD = T_o.\dot{m}.\left(\left(\begin{matrix} \dfrac{c_p.\left(T_1.((\eta_C - 1).x + x^k - \eta_C.T_3.x)\right)}{\eta_C.T_3.x} + \\ \dfrac{c_v\left(T_3.(1 + \eta_E.(x^{1-k} - 1)) - T_1\right)}{T_1}\end{matrix}\right)\right) \tag{27}$$

$$I = \frac{c_v.T_3.\left(T_3.\left(1 + \eta_E.\left(x^{1-k} - 1\right)\right) - T_1\right)}{c_p.T_1\left(T_3 + T_1.\left(\frac{\left(1 - x^{1-k}\right)}{\eta_C} - 1\right)\right)} \tag{28}$$

$$\dot{G}_H = \frac{c_p.\dot{m}.\left(T_3^2 - \left(T_1 + \frac{T_1.(x^{(-1+k)} - 1)}{\eta_C}\right)^2\right)}{2} \tag{29}$$

$$\dot{G}_L = \frac{c_v.\dot{m}.((T_3 - \eta_E T_3 + \eta_E T_3 x^{(1-k)})^2 - T_1^2)}{2} \tag{30}$$

$$\dot{G}_W = T_o\left(\begin{matrix} c_v.\dot{m}.\left(T_1 + T_3\left(\eta_E - 1 - \eta_E.x^{1-k}\right)\right) \\ + \dfrac{c_p.\dot{m}.\left(\eta_{C.}T_3.x - T_1.\left(\eta_{C.} - 1\right).x + x^k\right)}{\eta_C.x}\end{matrix}\right) \tag{31}$$

$$\dot{G}_d = \frac{c_p.\dot{m}.\left(T_3^2 - \left(T_1 + \frac{T_1.(x^{(-1+k)} - 1)}{\eta_C}\right)^2\right)}{2} - T_o\left(\begin{matrix} c_v.\dot{m}.\left(T_1 + T_3\left(\eta_E - 1 - \eta_E.x^{1-k}\right)\right) + \\ \dfrac{c_p.\dot{m}.\left(\eta_{C.}T_3.x - T_1.\left(\eta_{C.} - 1\right).x + x^k\right)}{\eta_C.x}\end{matrix}\right) - \frac{c_v.\dot{m}.((T_3 - \eta_E T_3 + \eta_E T_3 x^{(1-k)})^2 - T_1^2)}{2} \tag{32}$$

where ExD represents exergy destruction and it is obtained by multiplying environmental temperature with entropy generation. In addition, it is physical meaning is that a measurement of the lost work based on entropy generation. Entransy efficiency is:

$$\gamma = \frac{\dot{G}_L}{\dot{G}_H} \tag{33}$$

using the above equations it can be described as:

$$\gamma = \frac{c_v.((T_3 - \eta_E T_3 + \eta_E T_3 x^{(1-k)})^2 - T_1^2)}{c_p.\left(T_3^2 - \left(T_1 + \frac{T_1.(x^{(-1+k)} - 1)}{\eta_C}\right)^2\right)} \tag{34}$$

## 3. RESULTS AND DISCUSSION

In this study, entransy analysis is performed for the irreversible Diesel cycle and relations with other thermodynamic parameters are investigated. Diesel cycle is already external irreversible and an internal irreversibility parameter is defined to obtain a total irreversible cycle. Analyses are performed for the cases that $\eta_E = \eta_C$ are 1 and 0.8. Results of analyses can be shown in Figures **2-7**. In Figures **2-4**, represent endoreversible or internal irreversible ($\eta_E = \eta_C = 1$) Diesel cycle. According to entransy analysis results obtained these figures show result: $\dot{G}_H$ decreases linearly according to x and $\dot{G}_L$ and $\dot{G}_D$ changes logarithmically with x. $\dot{G}_L$ decrease logarithmically while $\dot{G}_D$ increases until a maximum point (1.538x$10^6$ kW K), which can be called as critical point, at x = 8.316 and then it starts to decrease logarithmically according to x. Conventional thermodynamic parameters is illustrated in Figure **3**. It can be seen that *ExD* and *I* decrease logarithmically with x. However, $\dot{W}$ increase until a maximum point, which is called as optimum point, (984.001 kW) at x = 6.333, after this point it begins to decrease. In Figure **4**, energy, exergy and entransy efficiencies are investigated as well as entransy loss ratio.*η* and *φ* increases with x while *ε* decreases. *γ* increases according to x too, however, increasing rate of it is faster than *η* and *φ.*

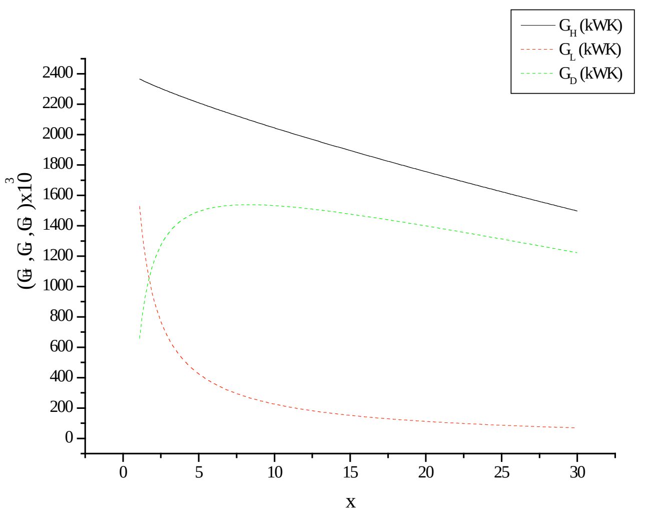


**Figure 2:** Variation of $\dot{G}_H$, $\dot{G}_L$ and $\dot{G}_D$, according to x ($\eta_E = \eta_C = 1$).

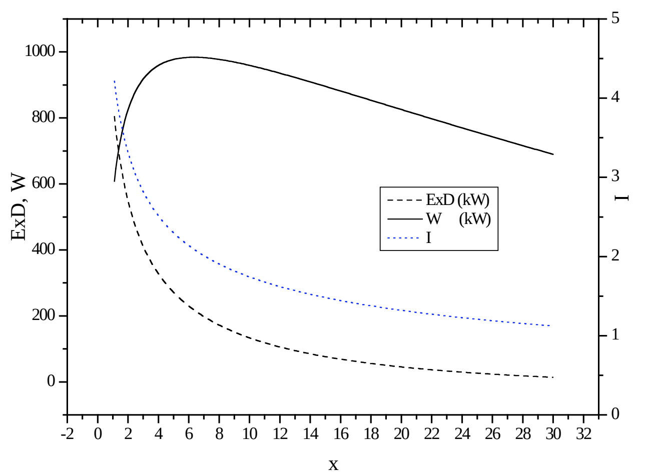


**Figure 3:** Variation of $ExD$, $\dot{W}$ and $I$, according to x ($\eta_E = \eta_C = 1$).

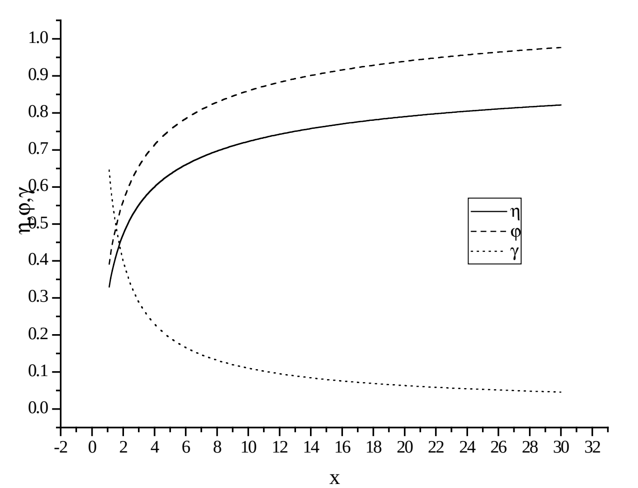


**Figure 4:** Variation of $\eta$, $\varphi$, $\lambda$ and $\varepsilon$, according to x ($\eta_E = \eta_C = 1$).

Results for the system with $\eta_E = \eta_C = 0.8$ can be found in Figures **5-7**. In Figure **5**, entransy tendency of the system is equal to previous one except that $\dot{G}_D$ has different critical point. This point is at x = 6.959 and it value is (1.341x10$^6$ kW K). As it can be seen Figure **6**. *I* and $\dot{W}$ has optimum points (a maximum point for $\dot{W}$ and a minimum point for *I*). $\dot{W}$ and *I* change logarithmically. $\dot{W}$ increases its optimum point (763.939 kW) at x =3.625, after this points it starts to decrease. *I* decreases until its optimum point (2.911) x =9.488 and then it begins to raise. Similar to pervious system, *ExD* decreases logarithmically. Energy, exergy, entransy efficiencies and entransy loss ratio. All of these parameters have maximum or minimum points. Energy and exergy efficiencies has a maximum (or optimum point). These efficiencies increases their optimum and then they start to diminish. Optimum points for energy and exergy efficiencies are 0.537 and

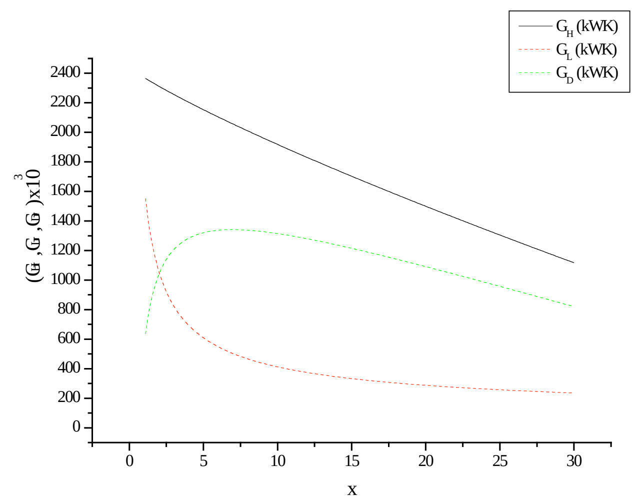


**Figure 5:** Variation of $\dot{G}_H$, $\dot{G}_L$ and $\dot{G}_D$, according to x ($\eta_E = \eta_C = 0.8$).

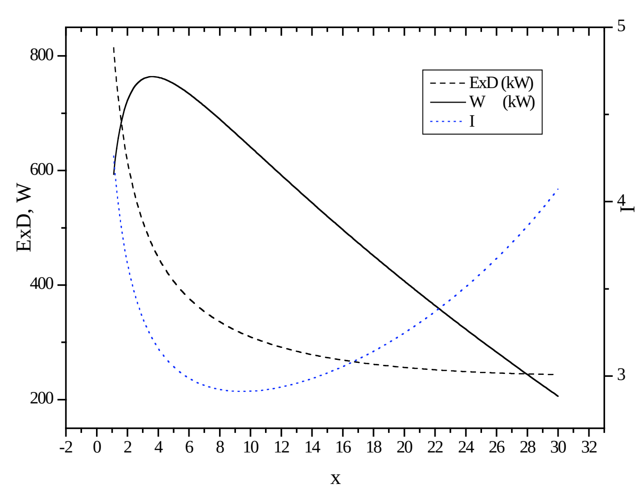


**Figure 6:** Variation of $ExD$, $\dot{W}$ and $I$, according to x ($\eta_E = \eta_C = 0.8$).

0.638 respectively at same point x= 9.488. Entransy efficiency has minimum or it can be called critical point (0.191) at x = 19.296. This parameter decrease until this point after it shows a little raising.

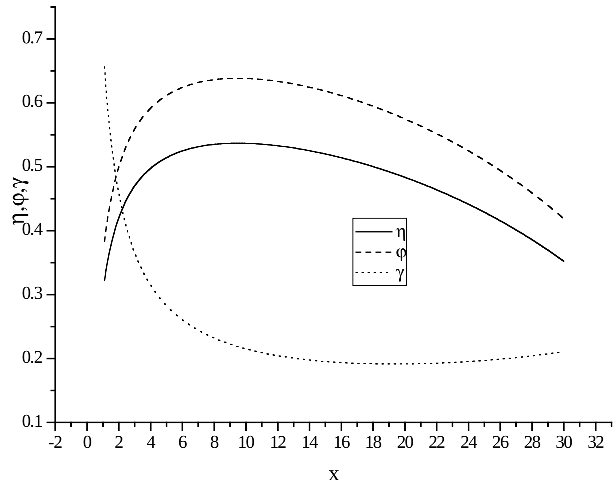


**Figure 7:** Variation of $\eta$, $\varphi$, $\lambda$ and $\varepsilon$, according to x ($\eta_E = \eta_C = 0.8$).

## 4. CONCLUSIONS

In this paper, irreversible Diesel cycle are investigated according to entransy approach and results are compared with thermodynamic performance parameters. In the previous section results are searched detail and this section these are interpreted following:

- Decreasing $\eta_E$ and $\eta_C$ causes decreasing at $\dot{G}_H$ and $\dot{G}_D$, however, it causes raising at $\dot{G}_L$ according to x .
- Decreasing $\eta_E$ and $\eta_C$ causes increasing at *ExD* and *I.* However, while $\eta_E = \eta_C = 0.8$, *I* has a minimum. After the minimum point, it increases. It can be said that $\eta_E$ and $\eta_C$ has maximum or minimum, if they are smaller than 1. Similarly, Decreasing $\eta_E$ and $\eta_C$ causes smaller work values and for smaller $\eta_E$ and $\eta_C$ decreasing rate of it is faster.
- For $\eta_E = \eta_C = 1$ any optimum or critical point does not exist for $\eta$, $\varphi$, $\varepsilon$ and $\gamma$. In contrast to this, all of these parameters have maximum or minimum points, when $\eta_E = \eta_C = 0.8$. Maximum points for energy and exergy efficiencies are 0.537 and 0.638 respectively at x= 9.488. Entransy efficiency has minimum point (0.191) at x = 19.296.
- $\dot{G}_D$ has a maximum ($1.538\text{x}10^6$ kW K) at x = 8.316 for endoreversible cycle and has a maximum point at x = 6.959 and it value is $1.341\text{x}10^6$ kW K for $\eta_E = \eta_C = 0.8$. It

It is recommended that entransy should investigated among basic thermodynamic parameters while analyzing a thermal system.

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