# Heat Engines

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**Abstract**

By adjusting thermodynamic parameters associated with heat engines in a simulated environment a better understanding of engine cycles and applied thermodynamics was reached. The Carnot engine cycle had the greatest reversible efficiency. Engine efficiency decreased with increasing heat loss. Different gases had no effect on the engine efficiency. An efficient heat engine was necessarily a poor refrigerator.

## 1 Introduction

A heat engine is a mechanical device which operates in a cycle absorbing heat from a high temperature source and expelling heat to a low temperature sink, and in doing so, does useful work on its surroundings.

An engine's cycle consists of a number of processes, which can be either reversible or irreversible. A reversible process occurs when the thermodynamic properties of the system are well defined at all times. Thus the engine is always in thermal equilibrium. The thermodynamic properties may not be well defined during an irreversible process. An engine whose processes are irreversible is called an irreversible engine; all real engines are irreversible. In such a case approximations must be made to describe the cycles in term of thermodynamic processes, such as representing an irreversible process by a reversible one.

The *efficiency* of an engine is defined as the ratio of the amount of net work done by the engine, to the amount of heat that is absorbed from a heat source. Utilizing the first law of thermodynamics the efficiency may be written as

$$\mu = 1 - \frac{|Q_c|}{Q_h} \tag{1}$$

where $\mu$ is the efficiency, $Q_c$ is the heat discharged from the engine, $Q_h$ is the heat absorbed by the engine. Carnot proved that, for a reversible engine, the amount of work produced and the efficiency of the engine depend only on the temperature of the source and sink. Thus the efficiency of the Carnot engine may be written as;

$$\mu = 1 - \frac{T_c}{T_h} \tag{2}$$

A refrigerator is the reverse of a heat engine. Work is done to the refrigerator which extracts heat from a low temperature source and expels heat to a source at a higher temperature. The measure of performance of a refrigerator is its *Coefficient of performance*, $w$;

$$w = \frac{Q_c}{W} \tag{3}$$

where $Q_c$ is the heat extracted from the cold source, and $W$ is the work done to the refrigerator.

Engines may be divided into two main categories: internal and external combustion. The gasoline and diesel engines are two examples of internal combustion engines, where heat is supplied by an internal source. An external combustion engine has heat supplied by an external source. For example, the Stirling and steam engine. [1]

## 1.1 Engine cycles

The thermodynamic processes for an ideal gas are

- adiabatic - constant entropy
- isobaric - constant pressure
- isochoric - constant volume
- isothermal - constant temperature

The following are the ideal (utilizing an ideal gas) thermodynamic cycles associated with engines which were studied.

Carnot Cycle

1. Isothermal compression
2. Adiabatic compression
3. Isothermal expansion
4. Adiabatic expansion back to initial conditions

Diesel Cycle

1. Adiabatic compression
2. Isobaric expansion
3. Adiabatic expansion

4. Isochoric process back to initial conditions

Lenoir Cycle

1. Isobaric compression
2. Isochoric process (increasing temp.)
3. Adiabatic expansion back to initial conditions

Otto Cycle

1. Isochoric process (increasing temp.)
2. Adiabatic expansion
3. Isochoric process (decreasing temp.) back to initial conditions.

Stirling Cycle

1. Isothermal compression
2. Isochoric process (increasing temp.)
3. Isothermal expansion
4. Isochoric process (decreasing temp.) back to initial conditions

## 2 Experimental procedure

The experiments were performed in a computer simulated environment using the CUPS Thermal and Statistical Physics simulation software, which numerically models the thermodynamical processes associated with heat engines[1]. This software allowed the parameters of the engines, gases, and temperatures to be readily adjusted with a fair range of variability.

## 3 Results and discussion

Six experiments were performed to gain an understanding of the thermodynamic process associated with heat engines.

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[1] CUPS also models many other physical processes

### 3.1 Reversible engines operating between the same upper and lower temperatures

Investigated the efficiency of the Diesel, Otto, and Wankel engines operating between the same upper and lower temperatures, and in a reversible sense. The compression ratio was systematically adjusted for each engine until the maximum efficiency was found. For all engines, the maximum efficiency, $\mu_{max}$ coincided with the maximum allowable (by software) compression ratio. The same upper and lower temperatures were used for all three cycles; $1500K$ and $1000K$ respectfully.

Of the three engine cycles studied the Diesel engine had the highest efficiency of $\mu_{max} = 0.670$, both the Otto and Wankel engines had an efficiency of $\mu_{max} = 0.630$, see table 1.

| Engine Type | $\mu_{max}$ |
|---|---|
| Diesel | 0.670 |
| Otto | 0.630 |
| Wankel | 0.630 |

Table 1: Engine maximum efficiencies

Substituting the operating temperatures used in the experiment ($T_h = 1500K$ and $T_c = 1000K$) into equation 2 we obtain the efficiency for the Carnot cycle; $\mu$=0.33. This is defined as the efficiency obtainable for any reversible thermodynamic cycle and clearly contradicts our results outlined in table 1.

### 3.2 Relationships between the efficiencies, heat absorbed and work done

The relationships between the efficiencies, heat absorbed and work done by an Otto engine was investigated. The experiment was performed in a reversible environment with Nitrogen gas.

Two data series were obtained to form a *picture* of how the efficiency, heat absorbed and work done by the engine are related to its operating temperatures;

1. $T2$ was fixed at $700K$ and $T3$ systematically varied between $1500K$ and $2000K$, the efficiency, heat absorbed and work done was recorded for one cycle of the engine.
2. $T3$ was fixed at $1700K$ and $T2$ systematically varied between $650K$ and $825K$[2], again the efficiency, heat absorbed and work done was recorded for one cycle of the engine.

The work done was plotted against the efficiency and the heat absorbed for the two data series, see figures 1 and 2 respectively. From the graphs it can be seen that an increasing $T3$ resulted in an increase of work done and heat absorbed by the engine with an associated constant value of efficiency. It can also be seen that an increasing $T2$ resulted in a relatively constant amount of work performed by the engine associated with an increase in engine efficiency and therefore a decrease in the amount of heat absorbed. This demonstrated a clear relationship between these three variables.

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[2] Software error (pressure out of range) when set $T3 = 850K$

There was a trade-off between the heat absorbed by the engine and the work it performed. By adjusting the operating temperatures of the engine cycle either of these two conflicting properties could be maximized, minimized, or set appropriately. For example if only a limited supply of heat was available to the engine then the work done could be maximized by selecting the largest available value of $T3$ (determined by the amount of heat available) and a large value of $T2$. However if an unlimited supply of heat was available then both the work done and the efficiency could be maximized by selecting the largest possible value for $T3$ (determined by the physical constraints of the engine) and a small value $T2$.

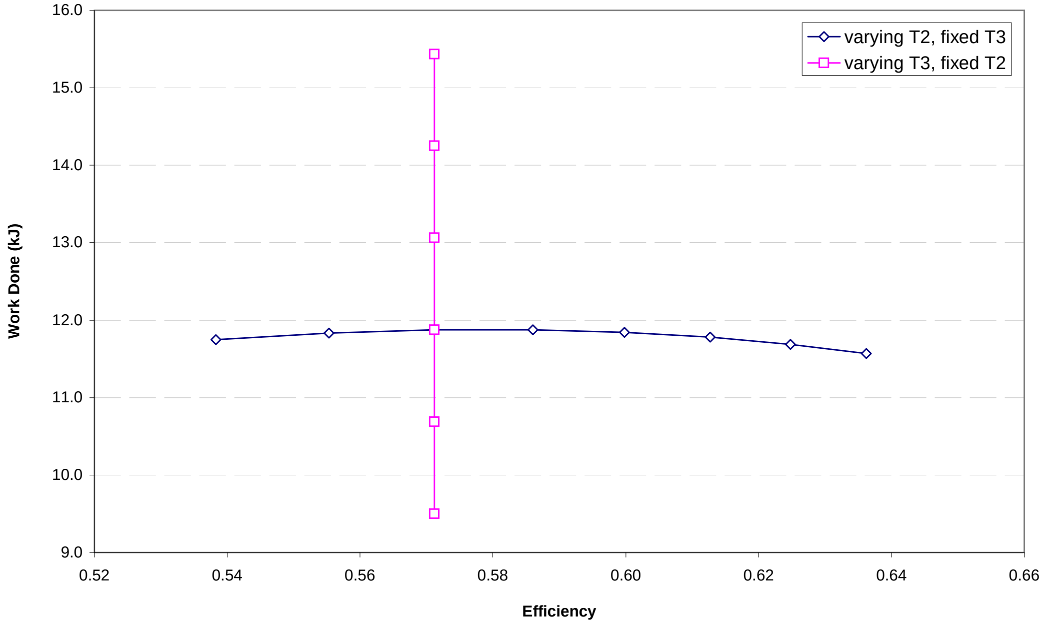

Figure 1: Relationship between the work done and the efficiency for a reversible Otto engine.

### 3.3 Efficiencies of different cycles

The efficiencies of the Carnot, Diesel, Lenoir, Otto, and Stirling engines were rated. The idealized engine cycles described in section 1.1 were entered step by step into the reversible simulation software. The same upper ($2000K$) and lower ($800K$) temperatures was used for all six engines.

Calculations were initially used in an attempt to determine the thermodynamic properties required to close the Carnot cycle, but after consideration it was determined to be easier to use an iterative trial-

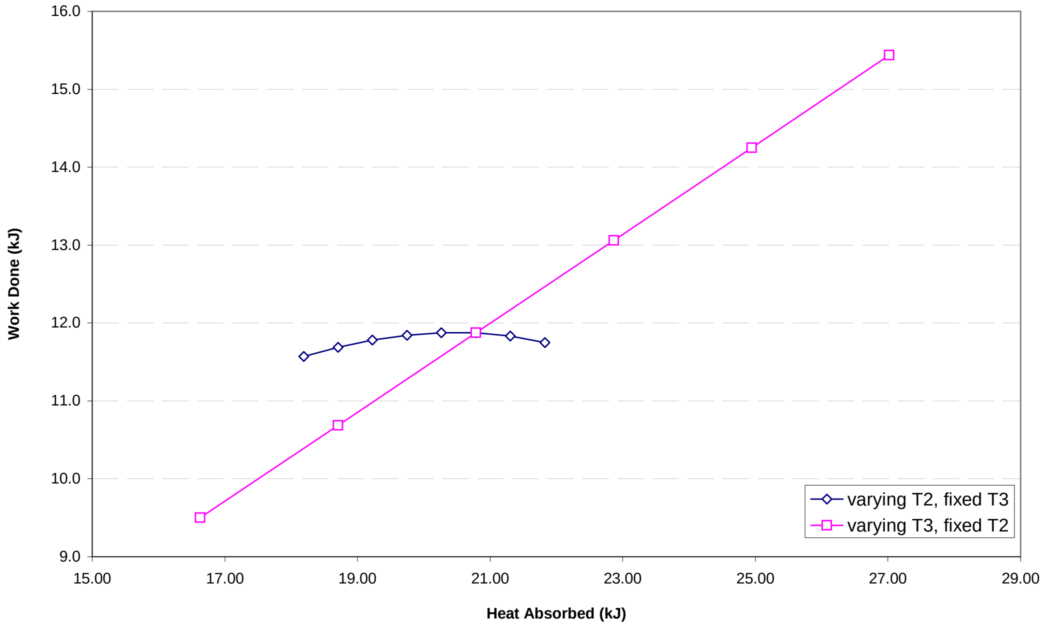

Figure 2: Relationship between the work done and the heat absorbed for a reversible Otto engine.

and-error method.

The Carnot engine had the highest efficiency, $\mu = 0.594$, which was significantly greater than the other engines, see table 2.

Comparing table 2 with table 1, we see that the ordering of the Otto and Diesel engines has reversed; the Otto engine has a higher efficiency than the Diesel engine in this case. This is most likely due to the different upper and lower temperatures used in the two experiments.

## 3.4 Irreversible Engines

The effect of heat loss on the efficiency of an Otto engine (see section 1.1 description of cycle) was investigated. Including a heat loss factor in each cycle step of an ideal reversible cycle is a reasonable way to approximate an irreversible engine. The operating temperatures of the cycle were as follows; $T1 = 300K$, $T2 = 700K$, $T3 = 1700K$.

| Engine Type | $\mu$ |
|---|---|
| Carnot | 0.594 |
| Otto | 0.361 |
| Diesel | 0.301 |
| Stirling | 0.263 |
| Lenoir | 0.125 |

Table 2: *Design-your-own* engine efficiencies

The simulation software had an option to select the percentage of heat loss in the system. This parameter was systematically varied from 0% - 100% and the engine efficiency plotted against it. As expected the efficiency decreases with increasing heat loss, see figure 3.

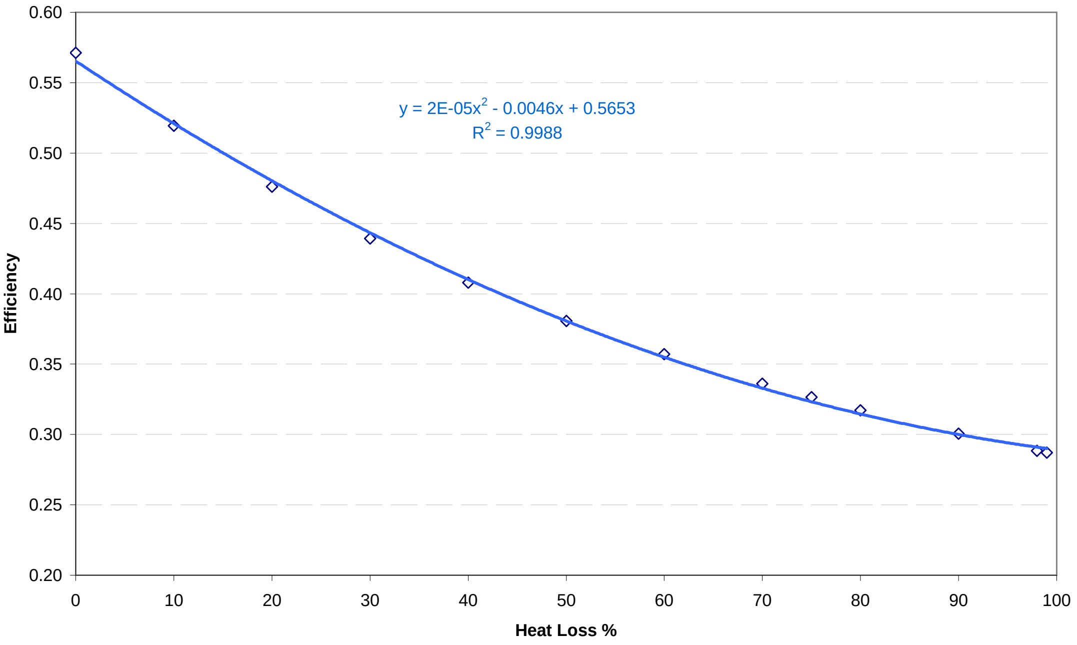

Figure 3: Effect of heat loss (to simulate an irreversible engine) on the efficiency of an Otto Engine

### 3.5 Effects of different gasses

The effect of the type of gas used within a reversible Otto engine ($T1 = 300K$, $T2 = 700K$, $T3 = 1700K$). on the efficiency of the engine was investigated. No relationship between the type of gas used and the efficiency was found, see table 4. However inert gases, such as Argon and Helium, worked at the same efficiency even though absorbing only half as much heat as non-inert gases, such as Nitrogen and Steam.

| Gas | $\mu$ |
|---|---|
| Nitrogen | 0.571 |
| Helium | 0.571 |
| Argon | 0.571 |
| $H_2O$ | 0.571 |

Table 3: Efficiency of reversible Otto engine with different gasses

### 3.6 Refrigerators

The Stirling and Carnot cycles described in section 1.1 and simulated in section 3.3 were reversed, heat was liberated from the system, and thus the engines behaved as refrigerators.

The same initial conditions as used in section 3.3 were used in this experiment, including the same upper and lower temperatures. The cycles were reversed, again using a using an iterative trial-and-error method to determine the thermodynamic parameters, however the parameter values determined in section 3.3 for each step of the engine cycles proved invaluable in closing the reversed cycles.

The Stirling refrigerator had a high coefficient of performance, whereas the Carnot refrigerator had a low value, see table 4. Comparing with the results in table 2, we observe that the Carnot engine has a high efficiency yet a low coefficient of performance, and the Stirling engine has a low efficiency yet a high coefficient of performance. This suggests that a good heat engine does not make a good refrigerator.

| Cycle | $w$ |
|---|---|
| Stirling | 2.749 |
| Carnot | 0.653 |

Table 4: Coefficient of performance ($w$) of refrigerators

## 4 Conclusion

The results may be summarized with the following,

- The heat engine based upon the Carnot cycle had a significantly higher efficiency than any other engine.

- There is a trade off between the work done by an engine and the amount of heat that it absorbs, however, either one of these conflicting properties may be easily maximized, minimized, or set appropriately, by adjusting the operating temperatures of the engine (cycle).
- More realistic, irreversible engines were simulated by a percentage heat loss in the reversible processes, as expected the engine efficiency decreased with increasing heat loss.
- Different combustion gases had no effect on the engine efficiencies.
- The coefficient of performance of a refrigerator was inversely proportional to the efficiency of the heat engine based upon the same cycle.

Thus by adjusting thermodynamic parameters associated with heat engines in a simulated environment a better understanding of engine cycles and applied thermodynamics was reached.

## References

[1] L.B. Spornick. *CUPS Manual.* Chapter 3 - Engines.