Guest Forum

Pragmatic Efficiency Limits for Internal Combustion Engines

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This article gives an overview of the thermodynamic principles demonstrating that the maximum efficiency theoretically possible with a hydrocarbon fueled internal combustion engine is one hundred percent. From this basis the focus turns to articulating irreversibilities that naturally occur within the processes of converting the chemical energy in the fuel into shaft work. These losses are classified as losses that cannot be eliminated when using the current embodiment of internal combustion engines, and losses that in principle could be reduced through application of advanced technologies. Because power is obtained from the engine via unrestrained chemical reaction, i.e. combustion, we must accept a loss of work potential of between 20 and 25 percent of the fuel's energy. Other losses, such as friction, heat loss and exhaust energy account for the balance of the useable energy that is not converted directly into shaft work. The interplay between combustion temperature, the ratio of specific heats of the combustion chamber gases, heat transfer and exhaust availability is presented as support for a postulate that the maximum pragmatic efficiency is most readily achieved through efforts to keep combustion temperatures low, which in turn maximizes the direct conversion of the fuel's chemical energy into shaft work while minimizing the available energy lost to heat transfer and exhaust flow.

炭化水素を燃料とする内燃機関において，理論上実現可能な最大効率が100%であることを裏付ける熱力学の原理について概説する。次に，それに基づき，燃料のもつ化学エネルギーを軸仕事に変換するプロセスにおいて，必然的に発生する不可逆性について明らかにする。このようなエネルギー損失は，現在の内燃機関の構造を用いる限り避けられないものと，原理的には先進技術の応用により低減の可能性があるものとに分類できる。内燃機関の出力が制御不可能な化学反応，すなわち燃焼によって得られるという性質上，燃料エネルギーの20%から25%にあたる潜在的仕事量の損失は避けられない。摩擦や熱損失，排気エネルギーなどその他の損失は，直接軸仕事には変換されないものの，利用可能なエネルギーの一部である。最大のエネルギー効率を得るには低い燃焼温度を維持するのが最も容易，という仮説を立証するため，燃焼温度，燃焼室内のガスの比熱比，熱伝達，排気の利用可能性の相互関係について示す。低温燃焼においては，燃料の化学エネルギーが直接軸仕事に変換される量が最大になると同時に，利用可能なエネルギーのうち熱伝達や排気の形で失われる分が最小になる。

Introduction

Internal combustion engines using liquid hydrocarbon fuels are an extremely effective combination of energy converter and energy carrier for mobility applications. The high energy density and specific energy of liquid hydrocarbons are well matched for applications in which the fuel must be carried onboard the vehicle; and the engine is a convenient and effective device for converting the stored energy in the fuel into mobile power. Together the IC Engine and HC fuel are a robust and economically viable power propulsion system and will remain so for decades to come[1]

However, the principle source of fuel-petroleum, is a limited resource which is in high demand and with the global development currently underway the demand is likely to increase. Furthermore the impact of carbon emissions from our mobility systems is a concern relative to its impact on the global climate. Consequently, it is of utmost importance that our mobility systems achieve the maximum possible efficiency with minimal environmental impact, while still preserving utility to the user. In the author's opinion this is one of the grand challenges facing the propulsion technical community today.

Two reasonable questions arise when considering the powertrains of our propulsion systems. What is the maximum efficiency that is theoretically possible and how does the efficiency of our current powertrains compare to this maximum? And, what are practical limits to the efficiency when pragmatic engineering constraints are imposed on to the system? This latter question is very important in that it yields realistic stretch targets to which we direct our development efforts, and it allows us to identify the important phenomena that should be addressed to make our mobility systems consume less fuel, emit little to no emissions and still provide the desired utility.

The purpose of this article is to identifying the pragmatic limits of engine efficiency achievable using engine embodiments likely to be present for the next several decades, namely a piston cylinder configuration in which the high pressure and temperature gases from combustion are expanded to extract work. To do this I will first review the maximum theoretical efficiency for an internal combustion engine and then identify the losses which occur in a typical engine. From this perspective I will then offer discussion as to which losses are unavoidable and comment on how other losses can be minimized within the scope of practical technologies.

Maximum Possible Work

One of the most important concepts to realize when asking what is the maximum possible work that can be obtained from an internal combustion engine is that the engine we use in our propulsion systems is not a thermodynamic cycle. It is a chemical process. In a thermodynamic cycle the working fluid undergoes a cycle. This does not happen in an internal combustion engine. The air fuel mixture is brought into the engine, allowed to react to products, expanded, and then is exhausted. The next engine cycle uses a different air fuel mixture, that is, the working fluid is thrown away and not brought back to its initial condition. Consequently, using classic thermodynamic heat-engine cycle analysis is not appropriate to answer the question we are addressing in this paper.

A thermodynamic analysis addressing the maximum useful work that can be obtained from a chemical process, such as the combustion process in an internal combustion engine, shows that the maximum useful work obtainable is the negative of the change in Gibbs Free energy of the chemical reaction[2]:

$$W_{\mathrm{max,\,useful}} = -(\Delta G)_{T_0,\,P_0}$$

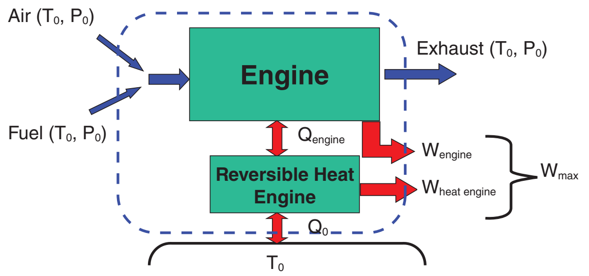
It is worth noting here that this is also the equation for the maximum theoretical useful work that can be obtained from a fuel cell. When describing a fuel cell it is usual to write:

$$(\Delta G)_{\mathrm{rxn}} = -nFE$$

where:
n = number of moles of electrons transferred
F = Faraday's constant
E = Electrical potential difference

When the change in Gibbs Free energy is written in terms of the electrochemical potentials the above equation is called the Nernst Equation[3].

It is instructive to conceptualize what an engine would look like if it could be made to achieve this ideal result. Figure 1 is such a conceptualization. The embodiment of the ideal engine shown in Figure 1 appears to be similar to what is actually in development today. However, there are distinct pedagogical differences. In the conceptualization shown in Figure 1, it is assumed that everything is reversible in the engine. Namely the air and fuel enter the engine at atmospheric temperature and pressure, undergo reversible processes throughout the engine, including the chemical reaction, and then leave the engine as equilibrium products at atmospheric conditions. These reversible processes will dictate specific state histories so it may be necessary to invoke a heat transfer to get the products to atmospheric temperature. As depicted in the figure, any such heat transfer would be done through a reversible heat-engine which has its heat rejection at atmospheric conditions. The work obtained from this reversible heat-engine is then added to the work output of the engine shaft to give the maximum possible work.



$$W_{max} = -\left(H_{prod} - H_{react}\right) + T_0{}^*\left(S_{prod} - S_{react}\right) = Q_{HV} + T_0{}^*(S_{prod} - S_{react})$$

$$W_{max} = -\,(\Delta G)_{T_0,\,P_0}$$

Figure 1 Conceptualization of an Engine to Achieve the Maximum Possible Work from a Charge of Air and Fuel Reacting to Products

Shown on the bottom of Figure 1 is the energy balance for determining the work from this reversible engine. It is worth noting that the maximum work theoretically obtainable is equal to the heating value of the fuel, Q_{HV}, adjusted by the unusable heat which is rejected at atmospheric temperature, $T_0{}^*(S_{prod} - S_{react})$. The combination of these two terms is equal to the negative of the change in the Gibbs Free energy of the chemical reaction.

The Relationship between the Fuels Heating Value and Gibbs Free Energy

One interesting subtlety of this result is the realization that the maximum theoretical work obtainable from an internal combustion engine, or fuel cell, is given by the change in Gibbs Free energy as opposed to the fuel's Heating Value. A table comparing the Heating Value and the negative of the Gibbs Free energy for several fuels when oxidized with air at atmospheric conditions is shown below.

Table 1 Enthalpies and Free Energy Changes of Several Fuels when reacted with air at atmospheric conditions (adapted from Heywood[2])

Fuel	Heating Value (MJ/kmol)	- Gibbs Free Energy (MJ/kmol)
Methane	802.3	800.6
Methanol	638.59	685.35
Propane	2044.0	2074.1
Octane	5074.6	5219.9

Two observations are apparent in examining the values given in Table 1. First the heating values and changes in Gibbs Free energy of reactions for typical hydrocarbon fuels are very close to the same value. That is the maximum theoretical efficiency of an internal combustion engine is effectively one hundred percent. The second observation is that some of the changes in Gibbs Free energy are larger than the Heating Value. This indicates that theoretically it is possible to extract more work from the engine than the heating value of the fuel, which is typically referred to as the energy input. This circumstance is a result of expansion of the products of combustion all the way to atmospheric pressure as part of maximizing the work output. In some cases, this expansion to atmospheric pressure would result in a temperature below atmospheric, which means that the heat transfer between the engine and the environment is from the environment to the engine. Thus work is obtained from the auxiliary heat-engine through a heat transfer from the environment into the engine to bring the engine back up to the atmospheric temperature.

Identifying Irreversibilities within the Engine

There are two underlying precepts in understanding the maximum theoretical work that could be obtained from an internal combustion engine. The first is that all processes are conceptualized to be reversible, that is, there are no losses. This means that all of the energy within the fuel that could have been converted into useful work, actually is converted into useful work. This recognizes the second precept underlying the development, namely that energy has quality, called exergy or availability, and that irreversible processes degrade useable energy into unusable energy; namely exergy or availability can be destroyed. Evaluating the availability destruction that occurs in the processes of a real engine is an instructive exercise for quantifying losses relative to the ideal engine described above. Furthermore it is possible to assess whether technological development can make inroads into reducing those losses and thus improve the efficiency of the engine. An analysis of the losses is brought about by performing an availability, or exergy, balance. Such a balance is shown in Figure 2.

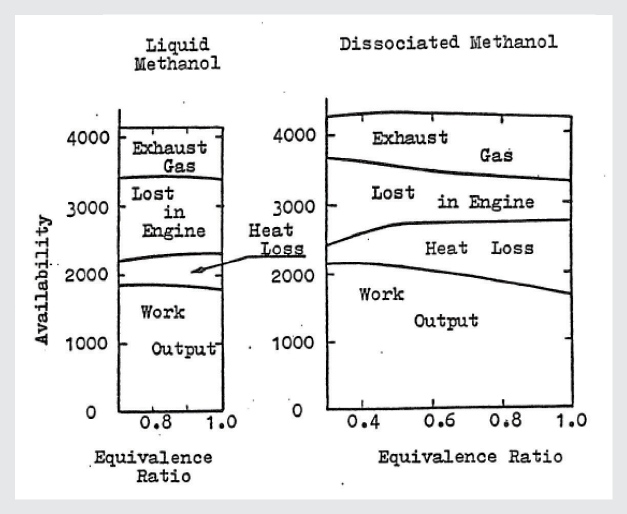


Figure 2 Availability Accounting per Mass of Fuel for Engine Operation for Different Equivalence Ratios for Methanol and Dissociated Methanol[4]. The units of the availability are kcal/liter of Methanol.

From the discussion above recall that for an internal combustion engine, the usable energy in the fuel is equal to the change in the Gibbs Free energy between the reactants and the products. The graphs given in Figure 2 are displayed in terms of availability, and are plotted on a kcal per liter of methanol basis, in recognition that in a real engine, some of the Gibbs Free energy is degraded into non useable forms, i.e. an availability destruction or “loss”. The energy is conserved but its usability has been degraded.

Figure 2 is the equivalent of a stack chart of what happens to the useable energy for each operating condition. The work output represents energy leaving the engine as shaft work, the desired outcome for the engine. The heat loss represents useable energy that left the engine as a heat transfer as opposed to shaft work. The term “lost in engine” is a measure of the irreversibilities of the combustion process itself. It is not an inefficiency of combustion. It is a degradation of useable energy because of the unconstrained chemical reactions taking place within the combustion chamber, even though the combustion has gone to completion. Finally, the exhaust gas availability is the useable energy leaving the engine in the exhaust. Realize, the available energy contained within the heat transfer and exhaust gases leaving the engine represent that portion of the energy in the heat transfer and exhaust flow that is useable, as opposed to the amount of energy within those respective energy flows.

Several interesting observations can be made from Figure 2. First, there is a significant irreversibility associated with the combustion process and this loss gets bigger when the engine is operated under lean conditions. This loss represents approximately 20 percent of the fuel’s useable energy. Second, there are significant available energy flows leaving the engine in the forms of heat transfer and exhaust flow. And finally, the work out of the engine per unit mass of fuel increases for lean mixtures, even though the irreversibilities of combustion increase. This is so because the available energy thrown away in the exhaust and with the heat transfer decreases as the engine is operated with progressively lean air-fuel ratios. These decreases more than compensate for the increased losses that occur within the lean combustion.

Detailed Analysis of the Individual Losses

A more detailed assessment of the individual losses is insightful as to where potential for improving the efficiency of real engines lie. As a prelude to this discussion I point out that the analysis of the losses presented in Figure 2 did not include engine friction. Indeed, reduction in engine friction is an important component of improving efficiency. Friction represents work that was leaving the engine as shaft work but got diverted. Any reduction in friction manifests itself immediately as a one-to-one increase in shaft work. The discussion here is focused on the thermodynamic phenomena associated with the losses.

Availability Destruction from Combustion

A loss for approximately 20 percent of the fuel’s useable energy in combustion is discouraging and would seem to represent an opportunity for improvement. This has been the subject of much discussion and analysis[5, 6, 7, 8]. However, the combustion irreversibility is a result of allowing the gradient between chemical potentials of the reactants and products, the affinity, to relax unconstrained. Thermodynamics teaches us that when any large gradient is allowed to relax unconstrained there will be large losses, viz. heat transfer across a large temperature gradient, or the irreversibilities associated with fluid flow associated with a large pressure gradient. Even if it were possible to extract work from the cylinder at the same rate at which the chemical reaction were occurring-constant temperature combustion, the irreversibilities of combustion would not be reduced[9]. The only way to reduce the irreversibilities of combustion is to raise the temperature at which the chemical reactions occur. This is why the losses of combustion increase with lean operation, the combustion temperatures are lower. Within the practical combustion temperatures for internal combustion engines the irreversibilities of combustion will range from 20 to 25 percent[9].

Consequently using unconstrained chemical reactions as part of the process of converting the chemical energy of the fuel into work means we will have to accept a loss of approximately 20 to 25 percent of the work potential of the fuel. We will not be able to engineer our way around this. It is worth noting that this same analysis is also true for fuel cells.

The paradox of increased combustion irreversibilities and increased work output per unit mass of fuel with lean combustion is resolved through a more detailed assessment of the availability transfers occurring during the expansion process, which impacts the availability leaving the engine in the exhaust gas and as heat transfer.

Work Extraction via Cylinder Gas Expansion and Useable Exhaust Energy

The work obtained from the gases being expanded within the cylinder is given by the expression:

$$w = \int P dv$$

The pressure and the volume are related via the expression:

$$Pv^{\gamma}$$

where:
w = work per unit mass
P = cylinder pressure
v = Specific volume of the gases in the cylinder
γ = ratio of specific heats

The ratio of specific heats, which is a function of gas composition and temperature, plays an important role in determining the work output from the engine.

Figure 3 is a simple plot showing the effect of composition and temperature on the ratio of specific heats, γ, and the impact of the value of γ on the engine efficiency. One can see from Figure 3 that as the temperature increases, γ decreases. It is also apparent that at a given temperature γ is lower for a mixture of combustion products than it is for air, and similarly a mixture of air and fuel. The right hand plot shows the efficiency of an engine at different compression ratios for different values of γ. For ease of presentation the calculation of the efficiency shown here was done using a simplified ideal gas analysis. From the two graphs in Figure 3 it is evident that if γ is larger there is more work extraction per unit of volume expansion in the engine. Furthermore it is apparent that small changes in γ can have measurable impact on the efficiency.

Herein lies one of the reasons for the higher efficiency of lean burn engines. Lean burn engines have lower combustion temperatures than stoichiometric engines.

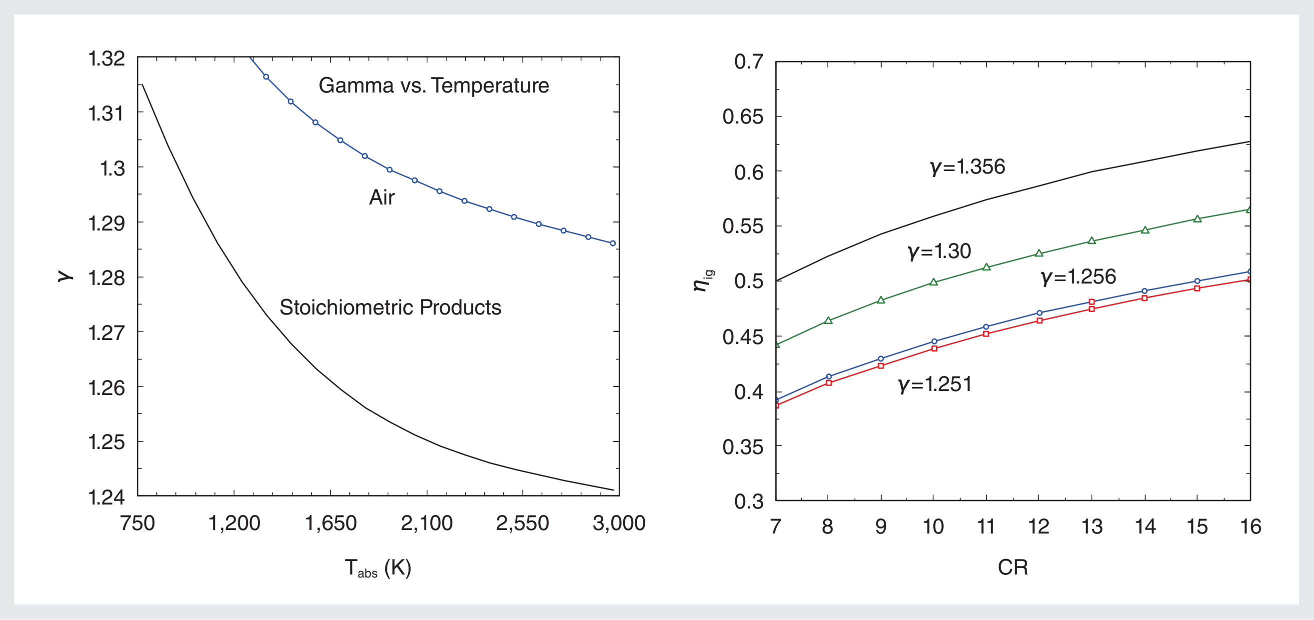


Figure 3 The Effect of Mixture Composition and Temperature on, and the Effect of γ on the Efficiency of an Internal Combustion Engine-Plotted vs. Compression Ratio (CR)

Even though there is a decrease in γ because of the composition change and the increase in temperature from combustion, the lower temperature of the lean combustion results in a γ that is larger than that for the stoichiometric combustion products. The larger relative γ of lean combustion results in a larger work extraction per increment of volume expansion than occurs with stoichiometric combustion products. Because of this there is less useable energy thrown away in the exhaust for lean combustion. This is what is shown in the availability balance given in Figure 2.

Useable Energy in the Heat Transfer

The available energy in heat transfer depends on the temperature at which the heat transfer takes place. Heat transfer occurring at higher temperatures has the ability to do more useful work than lower temperature heat transfer.

Figure 4 shows the portion of the heat transfer that could theoretically be converted to work as a function of the temperature at which the heat transfer takes place. The range of temperatures shown in the Figure was chosen to represent temperatures that might typically be experienced during combustion.

As shown in the Figure, as the temperature at which the heat transfer takes place increases a larger portion of the heat transfer energy has the capacity to be converted into work. The two illustration lines on the Figure show the portion of the heat transfer energy that could be converted into useful work for heat transfer occurring at temperatures of 2600 K and 1900 K respectively. These temperatures could be considered representative of those occurring during stoichiometric and lean combustion. It is noted that each unit of energy lost as heat transfer at 2600 K has approximately a 3 percent larger proportion that could be converted into useful work than a similar quantity of heat transfer at 1900 K. That is each unit of energy lost to heat transfer at 2600 K represents a 3 percent greater loss of work potential than the same quantity of heat transfer lost at 1900 K.

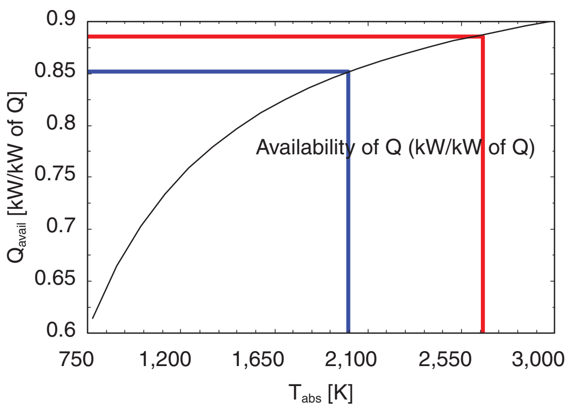


Figure 4 Proportion of the Heat Transfer that Could be Converted into Useful Work vs. Temperature at which the Heat Transfer Takes Place.

There is an added subtlety to this analysis. The rate of heat transfer is proportional to the temperature difference driving it. The lower in-cylinder temperatures associated with lean or low temperature combustion results in a lower driving potential for heat transfer. So, with lower in-cylinder temperatures both the quantity of the heat transfer and the work potential of each unit of energy lost is reduced.

Summary

Through the discussion presented in this article it has been shown that for purposes of assessing the maximum theoretical efficiency of an internal combustion engine running on hydrocarbon fuels, one can essentially consider all of the energy in the fuel to be available to do work. That is the maximum theoretical efficiency of an internal combustion engine is 100 percent.

However, because we use an unconstrained chemical reaction as part of the energy conversion process approximately 20 to 25 percent of the fuels available energy is destroyed. As long as unrestrained chemical reaction is used in our propulsion systems with current combustion temperature ranges, this loss is unavoidable.

Reducing the loss of work potential associated with heat transfer and exhaust gas leaving the engines is tenable. To this end, efforts which minimize the reduction in γ from combustion help to maximize the work extraction per unit of volume expansion, which increases efficiency and results in less usable energy being thrown away in the exhaust. Minimizing the reduction in γ can be achieved by keeping in-cylinder combustion temperatures as low as possible, even though this results in slightly larger combustion irreversibilities.

In addition lower in-cylinder temperatures also have a beneficial effect on heat transfer losses. Not only does the magnitude of heat loss decrease with lower in-cylinder temperatures, but the proportion of that energy that has the capacity to be converted into work is also reduced.

It is interesting to observe that much of the work taking place within engine combustion development laboratories is directed at reducing in-cylinder temperatures. Many approaches are being pursued, which can be described generically as low temperature combustion (LTC). The original motivation for activities in LTC was to minimize emissions of nitrogen oxides and particulates. However a side benefit is emerging. Successful control of low temperature combustion processes is also yielding benefits of improved efficiency.

Finally, one is tempted to opine as to whether there is a maximum pragmatic efficiency that can be achieved with the internal combustion engine. We must accept a loss of approximately 20 to 25 percent because of combustion, so an upper limit to the maximum pragmatic efficiency becomes 75 to 80 percent. From this basis, the question becomes how effective can we manage the thermal energy and exhaust energy flows from the engine. It is unlikely that these losses can ever be completely eliminated, however good progress is being made at reducing the losses associated with these energy flows. Engine efficiencies in excess of 50 percent have been achieved in very large slow RPM diesel engines. The Future Truck Program of the US DOE is supporting programs to demonstrate 50 percent brake thermal efficiency in heavy duty truck engines, along with identification of technical pathways to achieve 55 percent efficiency. And, a recent DOE workshop suggested that a stretch goal of approximately 60 percent might be an ultimate pragmatic limit[8].

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