PROSPECTS FOR IMPROVING THE THERMODYNAMIC EFFICIENCY OF A HEAT ENGINE

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The efficiency of the Carnot cycle of a heat engine is the highest possible theoretical efficiency. Real heat engines, despite the great efforts of design teams, barely achieve half of the theoretical thermal efficiency. This significant difference is generally attributed to imperfect heat exchange and frictional resistances of the machine. One can only agree with this opinion to a certain extent. The difference in efficiency is so significant that fundamental reasons can be assumed. The article describes the direction of solving the efficiency problem by regulating the load of the working piston and the direction of solving it by thermally regulating the working piston stroke process. A new method of analyzing thermal processes brings new possibilities and perspectives for improving machine efficiency.

KEYWORDS

Carnot cycle, efficiency, equivalence of transformations, isotherm, adiabatic spring

1 INTRODUCTION

The thermodynamic equilibrium is determined by the equation of state, which is valid throughout the P-V diagram (Figure 1). The P-V diagram is essentially a map of the energy balance of a heat engine In a given P-V diagram, different thermodynamic states can be achieved by regulating work and heat into the working piston system. In order to achieve the highest efficiency, the working point A is used, from which the effective work of the piston can be achieved along the isotherm to the working point C. Point A is represented by high pressure and small volume. Point C is at a higher than atmospheric pressure of the gas and a large volume. Point A can be reached from point C by various thermodynamic changes. During these changes, different work can be done on the gas. The difference in thermal transformations was first pointed out by Clausius in 1862 in the theorem on the equivalence of transformations [Clausius 1862]: *"In general, when a body changes its state, work is performed externally and internally at the same time, - the external work having reference to the forces which extraneous bodies exert upon the body under consideration, and the internal work to the forces exerted by the constituent molecules of the body in question upon each other."*

After establishing the equivalence theorem between heat and work, Clausius realized that there are two types of transformations, i.e., the transformation of work into heat and the transformation of heat at high temperatures into low temperatures in reversible thermodynamic cycles [Clausius 1867, Clausius 1879]. Clausius considered that Carnot's theorem expressed an equivalent relation between these two kinds of transformations. He called it the theorem of equivalence of transformations (TET) [Xue 2024].

Although the theorem is focused on transformation equivalences of reverse processes, it is also possible to assume transformation equivalence of direct processes. Nowadays, this topic is receiving increased attention again [Xue 2019].

2 ANALYSIS OF PISTON WORK

A heat engine works on the principle of changing the temperature and the amount of heat supplied or removed from the system. It is still possible to change the load during the stroke of the machine's piston. A gaseous substance, unlike a liquid and a solid, has a special property, which consists in redistributing energy into mechanical work and changing the internal energy of the gas. This redistribution depends on the external load and on the supply and removal of heat in the piston in closed system. In the following text, we will present an analysis that at first glance will resemble a well-known textbook text on thermodynamic states. However, a difference in the explanation of the phenomena will also be shown, which is a key incentive for finding a new direction in the design of heat engines.

Let the initial point of the description of the work of the piston be thermodynamic state A (Figure 1). If the load on the piston does not change throughout the entire stroke, then the pressure will be constant. A change in stroke can only be achieved by adding heat to the gas volume. The change is only possible after the isobar, which results in an increase in the gas temperature and a displacement of the piston to point D. It is worth remembering that if heat is not added to the piston system, the piston will be stationary, and no change will occur.

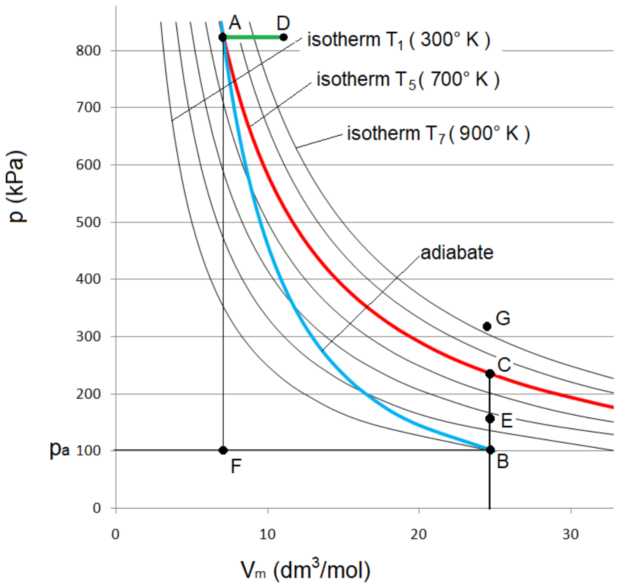

Figure 1. P-V diagram of selected thermodynamic states for a monatomic gas, p_a is atmospheric pressure

Without adding heat, piston movement can be achieved by removing the load, while the intensity of the load reduction can have an approximately decreasing exponential curve. However, the movement stops at a certain point because the gas pressure cannot overcome the external load resistance given by the load curve. The only exception is the load reduction corresponding to the adiabatic shape. Theoretically, the piston will not stop, but it is an extremely slow process. It is a gradual change of state along the A-B curve. This change does external work. However, this is useless work, because in a cyclic process it is necessary to return this work to the system in order to reach the initial state A.

One might ask, what happens if the load in state A is immediately removed? Here it is also true that the change will occur adiabatically, but extremely quickly. The change cannot occur along another curve because it neither adds nor removes heat from the system. This change, unlike the previous case, does not do external work.

Based on the above considerations, by some combination of heat supply and load change, a reasonably fast process of change after adiabatic can be achieved. The load can be lower than in the adiabatic state and by adding additional heat the process will change at a non-zero rate after the adiabatic state. This is a special combination of heat and load.

A load that is decreasing but its course is above the adiabatic curve will stop at some point. Theoretically, the piston should not move from point A. However, some movement can be assumed in the case when there is a small difference between the load curve and the adiabatic curve. For further piston movement, heat must be added to the system. If only a small amount of heat is supplied, the piston will stop before the end of the stroke. With a suitable amount of heat supply, the piston will reach the end of its stroke along the load curve. If more heat is supplied, the piston will reach the end of its stroke at a higher speed. Then at the end of the stroke, the excess heat supplied is converted isochorically to state G. This is a useless heat conversion that additionally loads the piston with shock. It can therefore be stated that the piston always moves along a given load curve and the speed of movement is determined by the amount of heat supplied. The resulting state at the end of the stroke depends on the total volume of heat supplied.

The previous considerations are important for answering the question, at which load curve is the heat to mechanical work conversion ratio best? From point A, the piston can be moved along different load curves. The theory suggests that movement along an isotherm does not change the internal energy of the gas. This statement may evoke the misconception that all the heat supplied was converted into mechanical work. This would only be true if the volume of gas in the cylinder did not change. But then the work couldn't be done. In fact, the heat supplied has been converted into a change in the volume of the gas, which corresponds to a multiplication of the internal energy in the ratio of the relative change in the volume size. Although the internal energy of the gas relative to its volume did not change, only a relatively small portion of the heat supplied was converted into useful mechanical work. This statement follows from Clasius's theorem on the equivalence of transformations.

If the load curve lies above the isotherm, the ratio of the conversion of supplied heat and useful mechanical work will be even worse, because even with a change in volume, the internal energy of the gas will increase.

If the load curve lies below the isotherm but above the adiabatic, the ratio of heat input to mechanical work will be better, but efficiency will deteriorate due to the smaller working area of useful work between the adiabatic and the given load curve. The efficiency of the isothermal process is given by the ratio of the area section A-C-B-A to the area section A-B-F-A. The area section A-E-B-A naturally has a worse efficiency.

In the case of a load curve matching the adiabatic, theoretically no useful work will be performed, as was mentioned above.

From the above considerations it follows that the most efficient conversion of the supplied heat into mechanical useful work is with a load curve in the shape of an isotherm. This is an important observation also because it applies to all cases of thermodynamic changes. This also applies if the gas conversion cycle is not closed. The conversion of supplied heat into mechanical useful work should occur along an isotherm in all heat engines. There is no other more advantageous conversion. In this simplified process of transformation, theoretically neither the time nor the speed of heat supply to the piston matters. The thermodynamic changes will theoretically always occur along load curves. The shape of the load curves determines the mechanism that is driven by the piston. The curves depend on the kinematic and dynamic properties of the connected mechanisms.

Moreover, the entire consideration is valid only for an ideal monoatomic gas. In a monatomic gas, the kinetic energy of the molecules is directly converted into pressure energy. The single-stroke action itself is not cyclical and has high efficiency. The efficiency of the cyclic process is significantly worse because the piston must return to state A in order for the isothermal transformation to be repeated. The piston can most efficiently return to state A adiabatically, which requires additional work to be done on the gas.

3 MODELING THE WORK OF A PISTON WITH AN IDEAL GAS

The thermodynamic point A is the state in which useful work can be done by the piston in different ways. The optimal process is to perform work following the isotherm. Maintaining the piston stroke process on the theoretical isotherm curve requires certain operating conditions to be met [Rimar 2022]. Little attention is paid in theory to the influence of these conditions. It is the analysis of the influence of working conditions that leads to a new concept of a heat engine. The following models analyze various thermodynamic processes.

3.1 First model

Consider a piston without the mass of a body that does not offer any friction during its stroke. No heat will be added to the system. Theoretically, the piston should move from state A adiabatically to state B. This is an unrealistic process, because in reality there is always friction of the kinematic components, force resistance of the inertial mass of the moving parts, and loss from the performance of useful work. Without force resistance to the piston's movement, one can consider a very rapid change that ends in state B.

3.2 Second model

Let's consider a mass piston with an adjustable load against the movement. In this case, the piston naturally performs mechanical work during the stroke. Let us require a load curve under an adiabatic process, at the same time no heat will be supplied to or removed from the system. This requirement is necessary due to the occurrence of piston movement. In this case, the change of state is maintained adiabatically, but at the same time no useful work is done. From a technical point of view, such a system can be imagined as a pneumatic spring. This is a regressive spring, the technical implementation of which leads to design problems. Such an adiabatic spring initially has a large force resistance, which decreases during the stroke, and in addition, the spring must also conserve the accumulated energy through mechanical work.

The described requirement for a spring is to some extent satisfied by the behavior of inertial mass. The optimal load for given thermodynamic conditions can be set on the flywheel using a shaped cam. Figure 2 shows a diagram of a dual system. The work energy is first transferred from the first piston in state A to the flywheel. After a half-turn of the flywheel, the energy from the flywheel is transferred to the second piston, while the piston is compressed to state A. After a full revolution, the direction of rotation of the flywheel changes and the cycle repeats in the reverse order of the elements. The movement of the pistons is performed sequentially with the indicated directions. The disadvantage is that such a system must have stable operating conditions in order to achieve the highest possible spring efficiency. In this model, the piston's lift energy is converted into the flywheel's inertial energy and vice versa. In theoretical terms, this mutual conversion of energies could proceed indefinitely. But no useful work is done. Entropy does not change in an adiabatic state. A real adiabatic spring must be excited by cyclic heat supply to the piston. This way, losses are covered, and the process can be kept running.

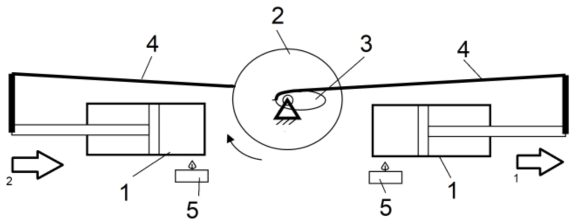

Figure 2. Scheme of Adiabatic spring: 1-pneumatic piston, 2-flywheel, 3-cam, 4-traction rope, 5-heat supply

3.3 *Third model*

The third model follows on from the second model, as it is a piston with adjustable load in the shape of an isotherm. It is necessary to supply heat to the cylinder system and at the same time regulate the output load with a load curve in the shape of an isotherm. From the point of view of converting heat into useful work, this is the most advantageous process.

Theoretically, an appropriate inertial mass derived from the rectilinear reciprocating motion of the piston is sufficient for adiabatic movement. A load mechanism with isothermal characteristics must be added to this mechanism. The additional mechanism acts similarly to the loss in model two. The only difference is that useful work is performed. At the same time, losses resulting from friction and imperfect heat transfer in the system are compensated. The stroke ends at point C. So, in the piston, it is necessary to reduce the internal energy of the gas by removing heat along the isochore. This will bring the system to point B and the cycle can be repeated. This process requires some time. The technical solution to this problem can be diverse. One direction of the solution can focus on replaceable pistons. By replacing a warm piston with a cooled one, the cycle can be closed immediately at point A. Another direction of the solution can be focused on replacing the working medium, similar to what is done in internal combustion engines. A third solution may be based on a slow process where there is enough time to remove excess heat from the system.

The steepness of the adiabatic curve is given by the heat capacity of the gas.

$$pV^{\kappa} = const\,, \tag{1}$$

where the exponent κ is a function of the heat capacity at constant volume and constant pressure.

$$\kappa = \frac{c_p}{c_V} > 1\,, \tag{2}$$

For a monatomic gas, $\kappa = \frac{5}{3} = 1.67$, for a diatomic gas, the exponent is smaller $\kappa = \frac{7}{5} = 1.4$.

The schematically designed mechanism has a heated piston part, an inertial mass, a return mechanism and a nonlinear transmission to perform useful work (Figure 3).

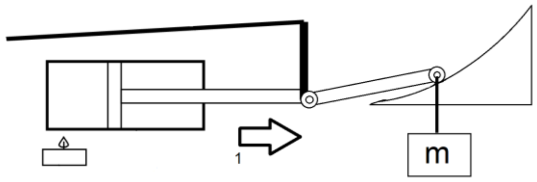

Figure 3. Scheme of the additional load mechanism for an isothermal process, m is the load

The heat supply must be synchronized with the regulated load in the form of a load curve. The heat supplied increases the gas pressure, while the volume increases, which in turn reduces the gas pressure. If more heat is supplied at the beginning of the process, the pressure increases disproportionately to the volume and the state shifts outside the isotherm. If too little heat is supplied, the process slows down and stops.

The load characteristic similar to the isotherm is also commonly used in modern drives. The load characteristic of the crank mechanism is only similar to the required load characteristic according to the isotherm. In this direction, there are still unexplored reserves for creating a special mechanism with better characteristics.

Improving the efficiency of internal combustion engines did not go in the direction of regulating the load characteristic. In the study [Erol 2019], the analysis found that different mechanisms used in the beta-type Stirling engine show different working efficiencies. The classic crank mechanism is still used in engines. Savings were obtained by regulating the injection of the ignition mixture. Correct injection timing ensures indirect regulation of heat supply to the system. Under different working modes, the injection time and size value are optimized. Thus, the efficiency of internal combustion engines increased rapidly in the nineties of the last century in the automotive industry. Overall, however, this improvement still has a significant margin of efficiency compared to the ideal Carnot cycle.

4 CAUSES OF LOW EFFICIENCY OF HEAT MACHINES

Using two isotherms and two adiabats, it is possible to create a cyclical process known as the Carnot cycle. The efficiency is determined only by the difference in thermodynamic temperatures of the heater and cooler

$$\eta = 1 - \frac{T_C}{T_H}\,, \tag{3}$$

where T_H is the heater temperature and T_C is the cooler temperature.

In general, the theoretical efficiency of the Carnot cycle cannot be surpassed. Considerable reserves are hidden, for example, in the imperfection of the course of thermodynamic cycles, which was explained in the previous text.

Another source of low efficiency is the structure of the real gas. An ideal gas has a monatomic structure. In that case, all the energy of the collisions of the molecules is converted into pressure. Real gases are polyatomic and the impact energy is converted partly into rotational energy and partly into vibrational energy of molecular bonds. This happens according to the equipartition theorem, with the working temperature of the gas playing a significant role. These additional energies are losses and do not contribute to the creation of the working pressure or useful work.

The theory shows that the internal energy of one mole of gas U_m for i-degrees of freedom of the gas will be

$$U_m = \frac{i}{2}\, R_m T, \tag{4}$$

where R_m is the molar gas constant and T is the absolute temperature of the gas.

According to the equipartition theorem, the energy distribution in a gas molecule is uniform according to the heat capacity of diatomic gases as a function of the gas temperature (Figure 4). This issue is discussed in more detail in [Li 2023].

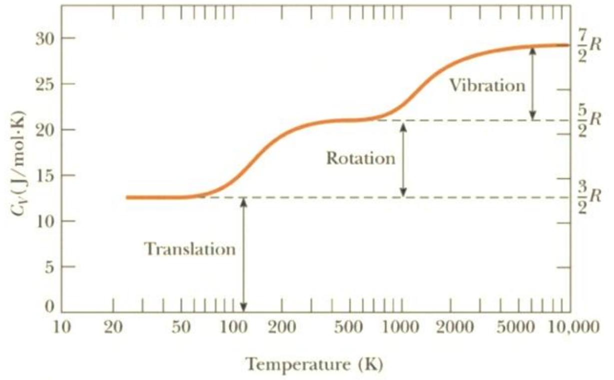

Figure 4. Molar Specific Heat of Hydrogen vs. Temperature [Serway 2012]

The gas below the rotation temperature behaves more or less like a monatomic gas. The worst-case energy distribution is above the vibration temperature. Under unsuitable working conditions, it can be roughly estimated that 2/3 of the internal energy of the gas will not be used to create the working pressure. Then the real efficiency of the Carnot cycle can be estimated by comparing the internal energies with different degrees of freedom. A much worse case is if the individual types of energy in the gas are divided equally into 1/3 rotational energy, 1/3 vibrational energy, and 1/3 translational energy of the molecule. Only translational energy is involved in creating the working pressure. The degradation of theoretical efficiency can then be calculated as follows

$$\eta_1 = \frac{\frac{3}{2}R_mT}{\frac{5}{2}R_mT+\frac{7}{2}R_mT} = \frac{3}{12} = 0.25\,, \tag{5}$$

where η_1 is the rate of reduction in the efficiency of the Carnot cycle. The real efficiency of the Carnot cycle for polyatomic gases can be reduced by up to 25 percent due to the above mechanism.

5 CONCLUSIONS

The article points out the possibilities of increasing the efficiency of heat engines through a special design of an adiabatic return spring. Although no useful work is done in this process, there is no theoretical loss of energy as in the crank mechanism. This is an unexplored direction of possible development of machines. This direction of development can also be supported by appropriate dosing of heat into the process, which affects the resulting efficiency. As for the heat balance, it is possible to use the form of monoatomic gases to increase the efficiency of the cyclic work of machines. Another approach is to use polyatomic gases, whose mechanical useful work will take place below the rotation temperature. All the indicated directions of development require new design solutions. The task of the article is to invite scientific capacities to examine possible directions of development, since the issue of reducing emissions and increasing the efficiency of heat engines is still extremely topical

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