Vjekoslav Brkić, Osijek:

# STIRLING ENGINE

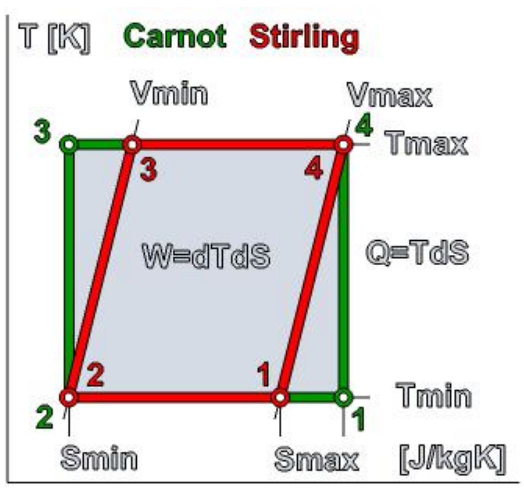
(The Challenge for Engineers All Over the World!)

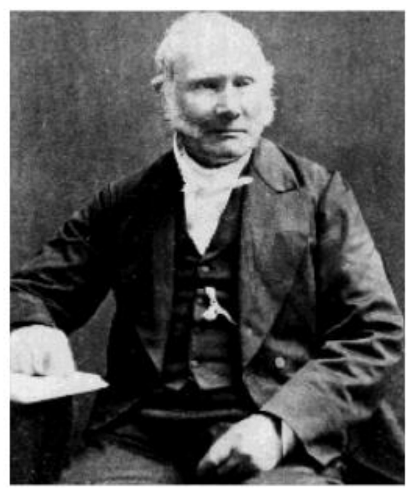
The sad faces of Sadi Carnot and Robert Stirling testify to us that people in their time did not understand (with honorable exceptions) the significance and essence of their work. And the most saddest of all this is that this essence is not yet understood by those who would have all this in their "little finger" – our professors of physics.

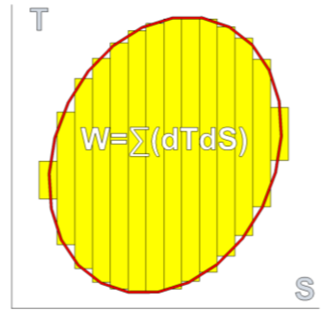
## THERMODYNAMIC THEORY OF HEAT ENGINES: CARNOT, STIRLING

Sadi Carnot (1796 - 1832) first realized that heat is a form of kinetic energy that can be transformed into useful work but only under the condition that this energy flows. He immediately found a comparison with an aquatic turbine that converts the kinetic (potential) energy of the water into useful work. Namely, if the flow of water through the turbine is stopped, the energy conversion will also stop. In order for the water turbine to give "useful work" it is necessary that the water flow through it. We can never turn all the energy of water into work. Complete analogy is valid for every heat engine. This is a natural fact (**natural law**) discovered by Carnot.

Heat is the form of kinetic energy of molecules of some mass: gas, liquid or solid. The amount of energy that may be contained in a mass is determined by the mass (**m**) and the temperature (**T**) and by the heat capacity ($C_p$ or $C_v$) of that substance (mass). $Q = m \cdot T \cdot C_p$ or $Q = m \cdot T \cdot C_v$
Some **mass** can exchange energy with its environment by changing its **state**. ($p \cdot V = n \cdot R \cdot T$)
**Changing the state** of a mass is an **indicator of energy exchange** of this mass with its environment.
**The total internal energy** of some mass is called **enthalpy**.
**Energy** flowing in or out of a mass can make that **mass change the enthalpy and spend or produce some work** (compression-expansion, heating-cooling).
**ENERGY** that a mass can potentially exchange with the environment is called **ENTROPY**.
When some mass **does not exchange energy** with the environment, we say that its **ENTROPY is CONSTANT**.
When some mass **does not have energy to exchange** with the environment, its **ENTROPY is ZERO** (0°K).
Whenever a mass changes its state **at constant temperature** it means that by doing so, the same amount of energy is received from the environment and delivered to the environment. If the mass receives the work - it transmits heat (entropy), and if the mass receives the heat (entropy) the mass gives work, this is the **PROCESS OF MAXIMUM CHANGE OF ENTROPY – MAXIMUM ENERGY FLOW!**



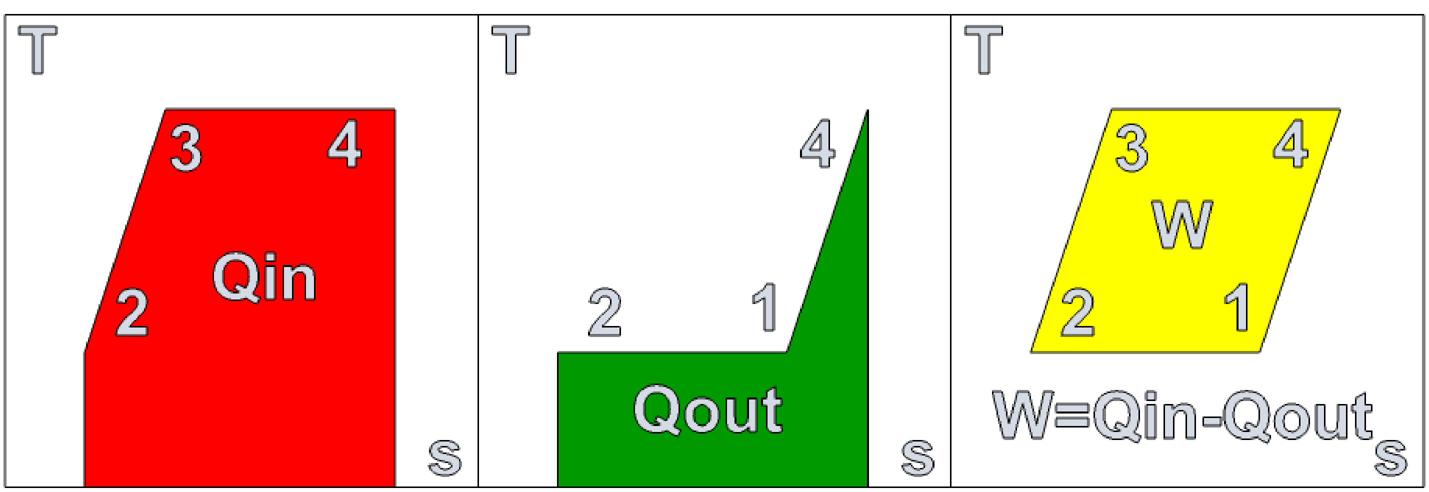



The quantity of energy thus exchanged (**Q**) is proportional to temperature (**T**) and entropy change (**$s_{max}$ - $s_{min}$**): **$Q = T \cdot ds$** or **$Q = T(s_{max} - s_{min})$**. Therefore, the most obvious, the processes of converting heat into work can and must be monitored and displayed in the so-called **T,s-diagram** (temperature-entropy-diagram).
**Each working medium** (air, hydrogen, helium, water, etc.) **has its own T,s-diagram!** If two reciprocal adiabatic changes are linked by two reciprocal isothermal changes in the cycle, we get **Carnot's circular process**. Since this is a process that adiabatically connects two isotherms (with identical and maximum entropy change), it will therefore **make the maximum possible conversion of heat-to-work or work-to-heat** between two temperatures. Heat and work are just different forms of the same energy of mass. This is also a natural fact (**natural law**) discovered by Carnot.

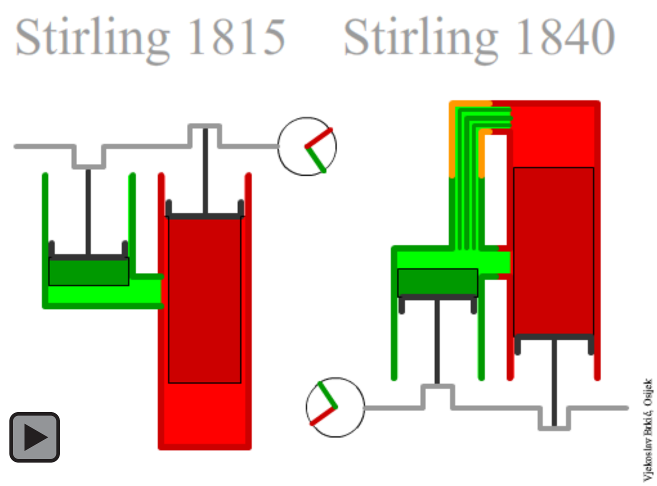
The difference between the input and output of heat to some mass is the work that this mass performs. The difference between the work taken and the work carried out by a mass is called useful work (**$W_u$**). The quotient between the output and the input of the heat in a work cycle is called the efficiency ($e$) of the working cycle (engine?). This quotient (out/in) shows us how much (theoretically) **the heat can convert into work or work into the heat**.
**$W_u = W_{out} - W_{in} = Q_{in} - Q_{out}$ , $e = Q_{out}/Q_{in} = T_{min}ds/T_{max}ds = T_{min}/T_{max}$ , if $Q_{in} = 1$, then $1 - e = Q_{out}$ = LOST!**
As each energy conversion process has its own efficiency, the overall efficiency of the heat engine will be: $e_{heat\ engine} = e_{carnot} \cdot e_{stirling} \cdot e_{mechanic}$ . Why is the Carnot cycle important? Is the Carnot cycle an imaginary, unattainable cycle? It is not! Why? Because every realistic working cycle can be represented as a sum of many small (infitezimal) Carnot cycles. **The comparison of any real cycle with the Carnot cycle serves as an objective measure of the efficiency of each thermodynamic process** (heat engine).

To every smart engineer who wants to design a heat engine it is now clear that the efficiency of heat conversion into work is determined by the **maximum and minimum temperature** in the operating cycle of his engine, and the power of the engine is determined by the surface through which heat flows through its engine. And what other engine parameter is it possible (easy?) to mechanically control?

**Robert Stirling** (1790 - 1878) replied, "**VOLUME**! I will design a engine that will work between two isochora (**at constant volume**). But how? After compression of the working medium in the cold space, the same volume of media (**$V_1$**) needs to be displaced by a special piston (displacer) along the wall of the working cylinder in a hot space where the working medium will expand to a larger volume (**$V_2$**) and give useful work, then the working medium must be displaced again at the same volume into a cold space to compression to a smaller volume (**$V_1$**)". Cunningly! But how to simultaneously control two pistons in two different volumes? **Well, I did not devise that yet**!



And so began a story about the **Stirling engine**, which has not yet ended. **Stirling's cycle** exists but its realization and use is still waiting for its engineer! Numerous "inventors of the Stirling engine" have "invented" their engine versions (α, β, γ) but they, actually, did not move beyond those solutions that Stirling himself presented to the world. (Palm, LTD, etc.). Especially, it is funny to follow for what purpose some inventors have constructed their engine: for a bicycle drive, to drive a car! Ha, ha, ha – another new and additional waste of energy! The serious purpose of this engine would be to **exploit waste heat** from high temperature technological and energetic processes (nuclear?), and the **exploitation of heat** from geothermal sources, from the energy of the sun, and also as an efficient cooling engine, a **heat pump**. (The Stirling engine could cool and pre-charge internal combustion engines – for free!).



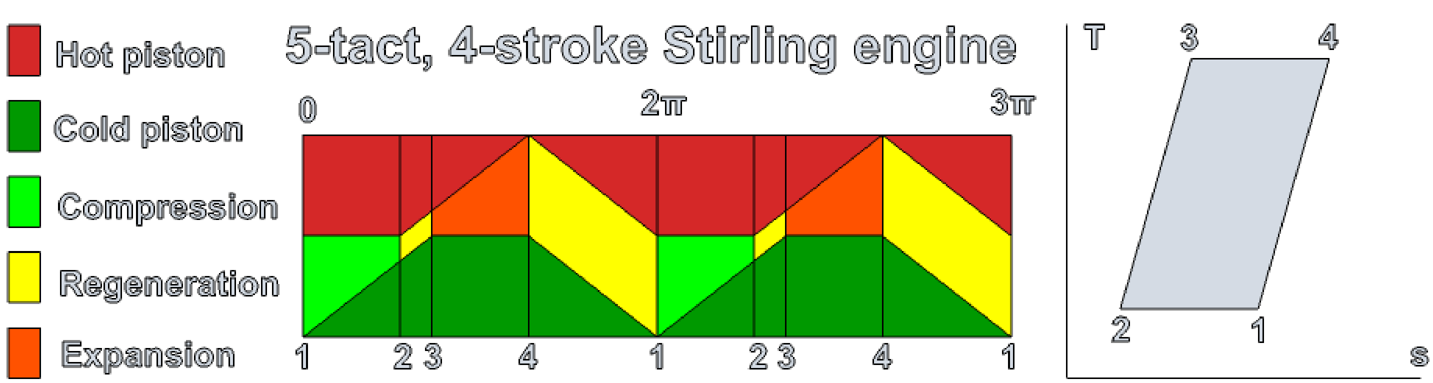

**THEORETICAL STIRLING MOTOR**

Let's consider the theory of the Stirling cycle and engine first. The engine must consist of a warm and cold space. The working cycle of the working medium must consist of isothermal compression, isohoric heating, isothermal expansion and isohoric cooling. Isothermal compression must be performed in cold space to volume $\mathbf{V_1}$, and isothermal expansion in the hot space to volume $\mathbf{V_2}$. And where will be done isohoric processes of heating and cooling? Stirling solved this problem by trick: **by displacer**, while later designers suggested: **regenerator**; a special part of the engine that would exchange heat during the adiabatic process: isohoric heating or cooling of the working medium. So what parts, then, must have our engine, and which operations should be performed? The Stirling engine's essential elements are:

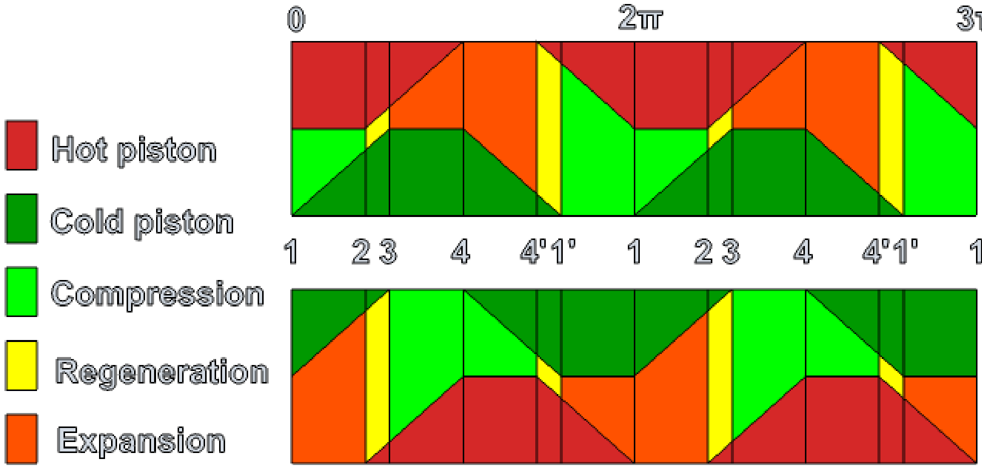
1. **Cold space with a piston** – serves for isothermal compression of medium with intense cooling,
2. **Regenerator for heat exchange** – serves to change the temperature of the working medium before the isothermal expansion or isothermal compression,
3. **Hot Space with a piston** – It serves for isothermal expansion of the working medium with intense heating.

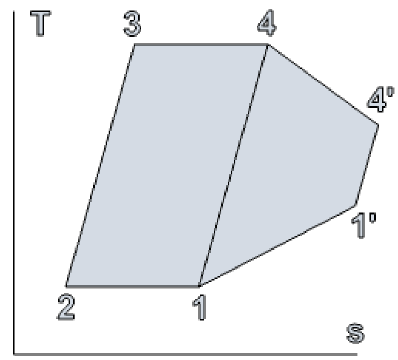
Which operations (tacts) must perform all three elements in each working cycle (cycle time) of the engine?:

1. **Compression** (cold space + cold piston),
2. **Regeneration** (cold piston + regenerator + warm piston),
3. **Expansion** (warm space + warm piston),
4. **Regeneration** (warm piston + regenerator + cold piston),
5. **Waiting** (Each engine element has a tact of waiting while the previous element in the cycle does not perform its function.).



# Double acting 6-tact, 4-stroke Stirling engine



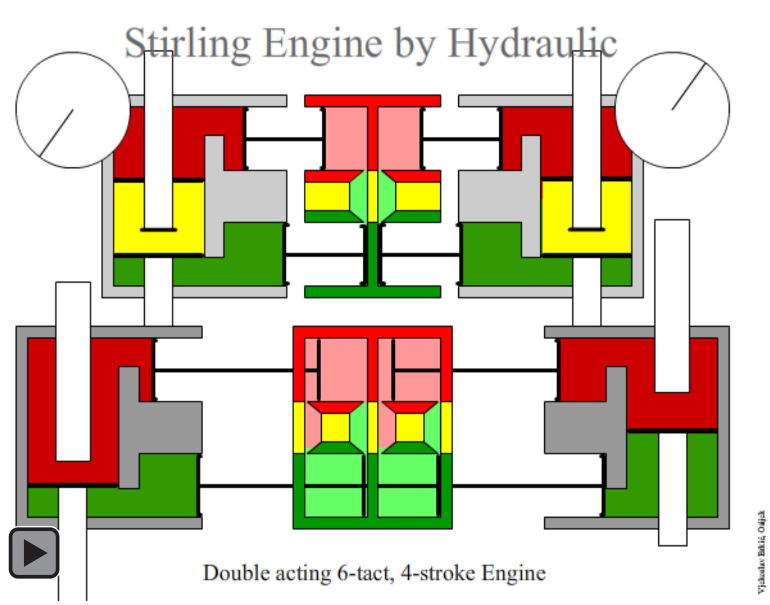




So theoretically Stirling's engine is a machine that has a **5-tact cycle**! If we show a working cycle of the engine in working time (**2π = 360°**) then we get a diagram that schematically shows the operation of this engine. From the diagram of the motion of the cold and hot piston it is evident that in the proportional 5-tact operating cycle, significant changes in velocity, acceleration and direction of the motion of the pistons at the transition of expansion to regeneration and from regeneration to compression have to be made. In order to reduce these big changes in speed and acceleration, it is quite logical that the Stirling engine should work in a **6-tact operating cycle** – with two tact of waiting. In this design the engine would work at the same speed and change of acceleration in all phases of operation.

In the 6-tact version of the theoretical Stirling engine, it is immediately apparent that the cold and hot pistons are driven by two same curves that are displaced in time for one tact (stroke). Furthermore, it is noticeable that the spaces on the opposite side of the pistons change according to Stirling's principle by creating an additional new volume $\mathbf{V_3 = V_1 + V_2}$ in the engine. If we now let the "Theoretically Stirling Engine" work in the double acting cycle, its work process can be shown in the T,s-diagram in the image above. From the diagram it is apparent that such a engine could theoretically additionally give another 50% more useful work than a single acting engine.

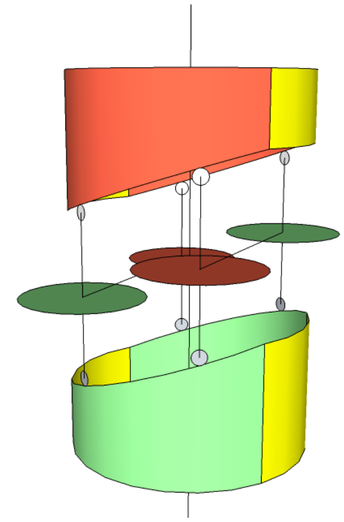
**THE THEORETIC STIRLING ENGINE DRIVE**

Neither Robert Stirling nor any of the later Stirling engines builders have solved the problem of the drive of the engine elements, but they were trying to solve them **by improvisations**: by shifting the cylinder or crankshaft by 90°, by joke mechanism, by hexagonal mechanism, and so on. Any improvisation is actually not a solution to the main Stirling's problem, and the working cycles of these engines should not be even called Stirling's.
That delusion was most influenced by the overwhelming **deception** – that the heat engine of usable power should be a high-speed engine, and that is **NOT** true!




Double acting 6-tact, 4-stroke Engine

Modern Engineering teaches us that the precise movements of a machine parts can be done only by means of hydraulics or by using appropriate curve follower – cam (in recent times and using stepper motors). Therefore, the first idea of the Stirling problem solution should be a hydraulic mechanism that could satisfy all five tacts of the Stirling engine.



The second solution, which would have to be simpler with its design, is the design of an appropriate, circular-cylindrical curve follower by which the connecting rod of the pistons of the engine should be moved.
If we consider the theoretical scheme of the motion of both the pistons of the engine, and if this motion curve is mapped to the cylinder mantle, we will get a curve follower – cam – to precisely move the pistons of the Stirling engine if their followers are spaced for two tacts (120°).

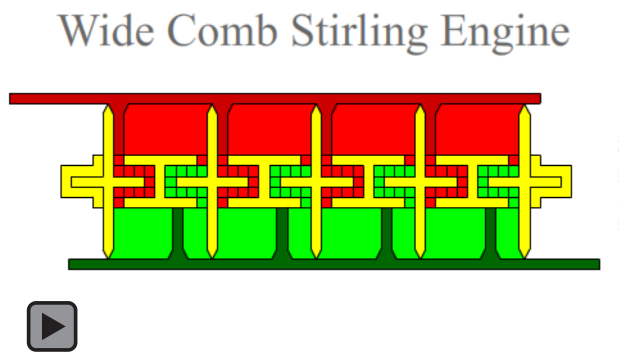
## HEAT TRANSFER AND HEAT FLOW

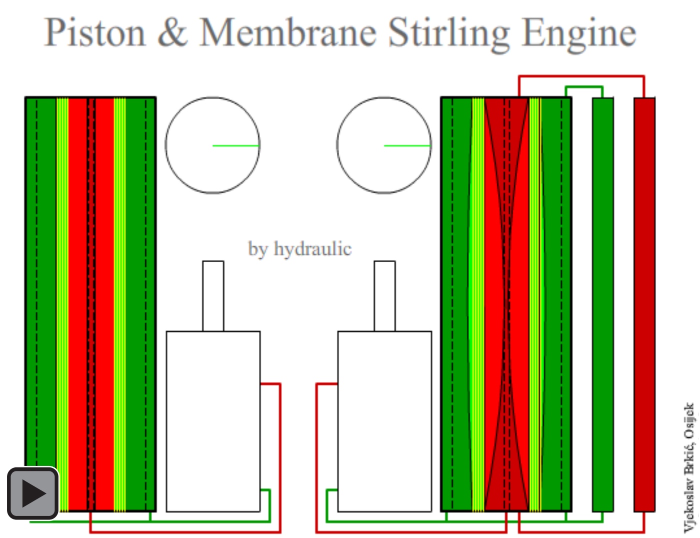
**The first and not the last concern of the engineer designing the heat engine are the efficient transition and passage of heat on the engine, in the engine and from the engine**. Hence, the design of a heat engine with the larger surfaces for the transition and the passage of heat are imperative in their construction. Hence, and so much the popularity of Palm and LTD versions of the Stirling engine, though they have only demonstrable use value. Many illiterate designers have completely neglected this key fact because they have assumed that heat flows from itself, into an infinite amount, from a warm place to the cold. That would not be! The power of the engine is directly and proportionally dependent on the flow of heat through the engine. The heat flow (**Q**) is proportional to the flow surface (**A**), the flow temperatures difference (**dT**) and the total heat transfer coefficient (**U**) [$W/m^2K$] and will be: $\mathbf{Q = A \cdot U \cdot dT}$.
Every heat engine should always be calculated first as if it were Carnot's! And then the calculation should be corrected for the real factors of thermodynamic and mechanical efficiency of the engine, in fact, it is the safest, the result obtained is multiplied by 2 ($e_{stirling} \cdot e_{mechanic} \approx 0.5$). For this it is necessary to know the total difference of temperature (**dT**) and total difference of the entropy (**ds**) of the assumed cycle that the engine should work with:
$T(1,2) = T_{min}$, $T(3,4) = T_{max}$, $s(1) = s_{max}$, $s(2) = s_{min}$, $dT = T_{max} – T_{min}$, $ds = s_{max} – s_{min}$, $Q_{carnot} = dT \cdot ds$
$\mathbf{Q_{carnot} = W_{real}\ (T_{max}/T_{min}) = A_{carnot}\ (U \cdot dT)}$, $\mathbf{A_{carnot} = W_{real}\ (T_{max}/T_{min})/\ (U \cdot dT)}$, $\mathbf{A_{real} \approx 2 \cdot A_{carnot}}$
Example (fictitious): If we intend to build a engine of material (steel + air) whose total heat transfer coefficient $U = 30\ W/m^2K$, which would work at a temperature difference of 350 K to 600 K, the heat exchange surface at a temperature gradient of dT = 50° C, for each kW the power of the engine should be:
$A_{carnot} = 1000\cdot(600/350)/(15\cdot50) = 1{,}14\ m^2$, $A_{real} = A_{carnot} /(e_{\mathbf{stirling}} \cdot e_{\mathbf{mechanic}}) \approx 2\cdot A_{carnot} = 2{,}28\ m^2$.
**The second concern of the engineers should be the mechanical efficiency of the engine: the shorter the working shifts of the engine elements!**

## NEW HIPOTETICAL STIRLING HEAT ENGINES

After discussing the theoretical issues of Stirling's engine, now we can devote ourselves to the engine's performance issue. The hypothetical Stirling engine actually had to be a step further than what Stirling presented to the world, that is, the new engine would have to work, **indeed, in the Stirling cycle**.
The engine design has to solve the problem of a very large heat exchange surface when heating, cooling and regenerating with very small movements the moving parts of the engine according to Stirling's thermodynamic cycle. So what are the possible solutions to our problem?

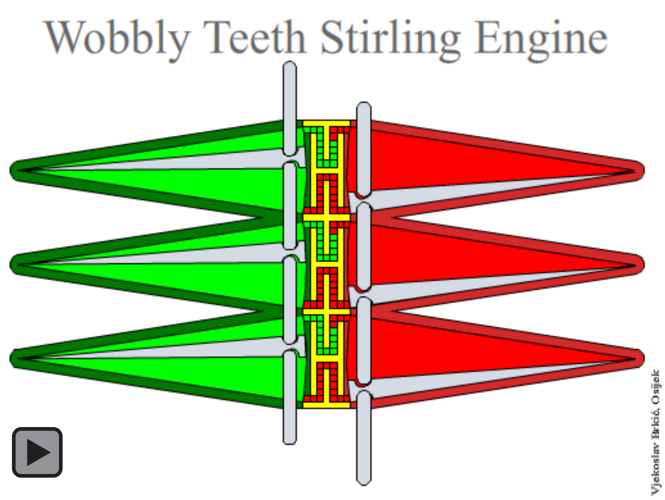
**Wide Comb Heat Engine** (linear / roto). This type of Stirling machine provides a very large surface of heat exchange in the direction perpendicular to the direction of movement of the machine elements, and the drive could be over the curve, either hydraulically. From the accompanying animations it is apparent that such a engine could work in the following way: fixed cold piston, fixed hot piston, fixed regenerator (animation). It is also very easy to imagine this version of the engine except in the flat, circular, and cylindrical versions, and also in a circular design with hot and cold work pistons in the form of a star.

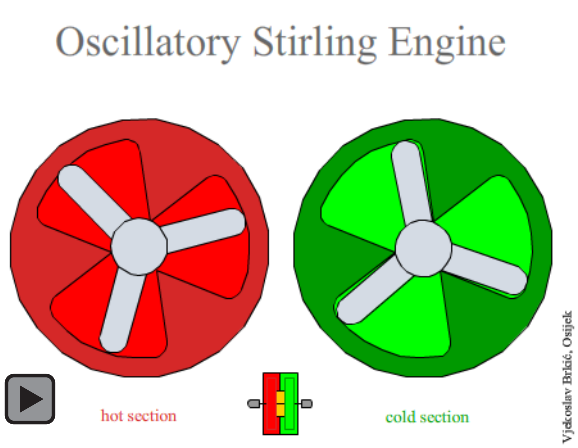



**Piston / Membrane Heat Engine**. This type of machine as the previous one provides a very large heat exchange surface, but this time in the direction of motion of the engine elements. The feature of this design is that it can be operated modularly if the drive is hydraulic and circular if it is mechanically driven over the curve. The main feature of the membrane design is "no moving parts". In the hydraulic design of the engine the hydraulic fluid could simultaneously be both a heating and cooling engine medium. The membrane version also provides the best possible control of the pressure of the working medium in the engine.

**Wobbly Teeth Heat Engine**. This version of the engine as well as the previous one provides a very large surface for heat exchange, but this time the greatest possible in the direction perpendicular to the moving elements of the machine. This design is quite similar to the membrane design, especially in terms of pressure control of the working medium, and is suitable for modular connection of multiple units with different stages of operation.




**Hypothetical Oscillatory Heat Engine**. The previous analysis of the work of Stirling's engine, its working cycle, and working parts leads us to the conclusion that a hypothetical (theoretical) version of a heat engine can be used in which the moving parts of the engine itself (by inertia) oscillated in some natural working tact if the static motor parts (casing and regenerator) are brought to the oscillatory state. This should be a completely new field of research in the development of heat engines. Good Luck!

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P. S.

To see the animations in this document, you must have installed all three versions of Flash Player on your computer:

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| ActiveX Version: | 32.0.0.192 (for IE) [install_flash_player_ax.exe   20.301 KB] |
| NPAPI Plug-in Version: | 32.0.0.192 (for Firefox, Acrobat) [flashplayer_32_plugin_debug.exe   20.558 KB] |
| PPAPI Plug-in Version: | 32.0.0.192 (for Chrome) [install_flash_player_ppapi.exe   20.623 KB] |