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The Isomorph Heat Engine

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State of the art heat engines are not optimized for the use in solar applications. From a discussion of their limitations we derive a new kind of hot air machine, characterized by a high internal efficiency a low pressure increase and a consequently low operating temperature. An aeolipile serves to expand the gas.

1) Introduction

In order to completely substitute fossil fuels, solar energy must meet three requirements:

1) solar thermal energy must be available at the elevated temperatures, which are needed in many industrial applications, and at a price competitive to fossil fuels.
2) The transformation of solar to electric energy must be efficient under the conditions, which characterize solar plants.
3) It must be possible to store solar energy for several months without significant energy loss.

These points are not satisfied by state of the art technology:

1) state of the art solar concentrating systems (like parabolic mirrors) are complex and expensive.
2) High quality machines, which transform heat energy to electricity do exist, for example steam turbines or Stirling engines. But those machines were not developed for solar applications - when operated together with solar concentrating systems, these machines are quite inefficient. For instance the steam turbines, which were to be used for the Desertec Project [1], had an efficiency of typically 15%, whereas the same kind of turbines when operated in a traditional power plant has efficiencies of about 40%.
3) Usually molten salt storages are proposed for storing solar heat, or batteries for storing electricity from solar plants: Storing heat with molten salt is easy in small laboratory set ups. But for storing the amounts of energy typically needed in industrial applications, huge and complex systems would be needed. Consequently such systems never have been realized in real world applications. Storing electricity in batteries is very expensive.

Recently, problem (1) has been solved with the development of the Linear Mirror technology – the Linear Mirror II provides solar energy at elevated temperatures, it has a convenient price and is very simple to operate [2], [3].
Also on problem (3) some progress has been achieved performing solar pyrolysis of cheap biomass with the Linear Mirror II system [4].
In this paper we want to discuss problem (2): why are state of the art devices so inefficient in the context of solar applications, and can one overcome the respective problems?

2) Limitations of state of the art machines in the context of solar thermal energy

Existing technology for transforming heat energy to mechanical energy is highly developed. However, this technology has been developed during the last 200 years, the era of fossil fuels, and therefore the optimization of this technology was done in this very context. When one applies solar thermal power to these technologies, several problems arise:

2.1) adiabatic compression
From a physics point of view, a reasonably efficient heat engine can operate at a moderately high temperature, for example a heat engine operating between 325 °C (600 K) and 25 °C (300 K, ambient temperature) is 50% efficient from a thermodynamic point of view. State of the art machines instead work at much higher temperatures, in order to achieve for instance a thermodynamic efficiency of 50%. In steam engines or -turbines high temperatures and pressures are needed, because the energy used to transform liquid water to vapor (during the Rankine cycle) cannot be transformed to mechanical work. Therefore one tries to operate the machine at a very high temperature and pressure, so that the energy used for evaporation is not too large compared to the energy stored in the heat and the pressure of the water vapor.
In machines working with hot gases instead (Brayton-, Diesel-, Otto-cycle), the high operational temperature is due to the adiabatic (or isentropic) compression usually applied in these machines: when adiabatically compressing a gas, temperature and pressure of the gas raise strongly. For example, if 1 liter of air at ambient temperature and pressure is compressed (for instance by means of a piston) into a volume of 0.1 liters, the gas will heat to a temperature of 750 K and it will reach a pressure of 25 bar (this is explained in more detail in [4]).[1] (While in the case of an isothermal compression from 1 liter to 0.1 liter the gas would not change its temperature and it would have a pressure of 10 bar.)
The hot pressurized gas resulting from adiabatic compression cannot yet be used for performing effective work, since its expansion back to ambient pressure will yield the same work, which had to be invested for the compression process. In order to obtain effective work from the machine, the already hot gas needs to be heated to still higher temperatures first.
As a result, machines with adiabatic compression need to work at very high temperatures, in order to reach a reasonable thermodynamic efficiency. This is not a problem when burning fossil fuel, which easily exceeds burning temperatures of 1000 K. But it is a problem for solar applications.
2.2) Adiabatic expansion
Also the adiabatic expansion, usually applied in state of the art piston engines, is a significant problem: the expansion cylinders are cooled by the expanding gas – when after the expansion process fresh gas

1 In order to make this paper understandable also to the non-expert, we quote from publicly available sources like wikipedia whenever possible. This should be possible without compromising scientific precision, since we only make use of references, which we have verified for scientific correctness.

of high temperature enters the cool cylinder, part of the gas thermal energy is lost to the cold cylinder walls and cannot be used anymore for performing mechanical work. This limits the thermal efficiency of the machine. (Historically, this problem was to be reduced by the use of multiple stage expansion machines, thereby increasing the size and complexity of the machines).

2.3) Mechanical compression

Heat engines, which do not perform a Rankin cycle usually perform a mechanical compression of the working gas, be it isothermal, adiabatic or isentropic. The term “mechanical compression” meaning, that the Volume of the gas is decreased by a moving mechanical device – usually this is a piston (for instance in a Stirling engine), or a rotating compressor (for instance in a Brayton turbine). This can clearly be seen in the respective p-V diagrams, describing these cycles.

As far as piston engines are concerned, a seal is needed in order to avoid that pressurized gas escapes between the piston and the cylinder wall.

These seals create a considerable friction. One can reduce this friction with oil lubricants, but these cannot be used at high temperatures.

In machines with internal combustion the limited oil temperature is not a fundamental problem, since the cylinders are cooled by water.

If an external heat source is to drive the engine – like in solar applications -, then the hot cylinder cannot be cooled by water (for example state of the art Stirling- or Ericsson machines cannot have a cooling of the machine's hot compartment).

2.4) non-multiplicative machine efficiencies

If for example an ideal electrical motor has a power of P, and if the real version of the motor has a mechanical efficiency of α, then the real motor will provide a power of $\alpha \cdot P$ – the efficiency is multiplicative.

In heat engines instead the efficiencies multiply only in the limit of very high temperatures. Let us imagine an ideal machine, which makes use of mechanical work for compressing a gas, C, and provides work when expanding this gas, E. Then the effective mechanical work done by the machine is W=E-C, since part of the mechanical work done by the expansion stage is consumed by the mechanical compression.

A real machine instead has limited efficiencies for these processes: compared to an ideal machine, a real machine with an efficiency of $\alpha<1$ for the expansion stage will provide a reduced power $\alpha \cdot E$. And in order to provide the needed power of compression C to the machine, one needs to provide a higher power of C/β, it the compression stage has the efficiency β. The work effectively done by the machine is then $W=\alpha \cdot E-\frac{1}{\beta} \cdot C$ (I)

which means, the efficiency is not a multiplicative effect (it is not true that W(real) $=\alpha \cdot \beta$ W(ideal)). Rather, the machine will not be able to run, it will not be able to do any work at all, which amounts to saying that its effective overall efficiency is zero, as long as $\frac{E}{C}<\frac{1}{\alpha \cdot \beta}$ (II).

Only when the temperature difference becomes sufficiently large, so that $\frac{E}{C}>\frac{1}{\alpha \cdot \beta}$ (III), the machine will start running.

This amounts to saying, that the internal losses of a heat engine do not only reduce the useful work done by the machine, but they also require much higher operational temperatures, compared to what would be needed from a purely thermodynamic point of view.

For instance, a Stirling motor with its cool compartment at ambient temperature and an efficiency of 0.7 for compression and expansion, will require a temperature in the hot compartment of 600 K in order to begin operating with an overall efficiency close to 0.

3) Requirements for a solar thermal heat engine

From what was said in the previous chapter we conclude, that for solar thermal applications, heat engines should make use of isothermal compression. In reality, ideal isothermal compression cannot be achieved in a machine of practical use, since the heat transfer through the metal wall of the engines is limited, even Ericsson or Stirling engines will not show an ideal isothermal compression in practice, rather the compression will have an adiabatic component. For the use in solar thermal applications it is important, that this component is limited as much as possible. The temperature increase of the adiabatic compression can be limited by limiting the pressure increase. For example, when compressing 1 liter of gas with a temperature of 300 K and a pressure of 1 bar to a volume of 0.75 liters, the pressure of the gas increases to 1.5 bar and the temperature increases by 37 K. In the context of a solar thermal application, this temperature increase of 37 K appears acceptable. Therefore, in a machine for a solar thermal application, the gas pressure should not be increased by more than a factor of 1.5.

The machine also should not make use of mechanical compression for the reasons discussed in the derivation of expression (III). From a purely physics point of view, mechanical compression is not a necessity for creating a cyclic process, therefore one can try to avoid it.

Also the use of water vapor is not ideal for a solar thermal application: the heat needed for transforming water to vapor cannot be recovered by mechanical devices. In order to make steam engines or turbines efficient, steam pressures must be very high, this is problematic from a practical point of view.

4) The Isomorph hot air engine

4.1) Mechanism for creating pressurized gas

As pointed out before, we do not want to increase gas pressure by mechanically reducing the gas volume by means of a piston or similar. In order to increase the pressure of the gas it is sufficient to heat the gas or part of the gas, without changing the volume of the container containing the gas.
This can be achieved by a device as shown in figure 1 :
In figure 1 a cylinder filled with gas has a hot and a cold end. A piston, which is moving up and down in this cylinder is correspondingly forming a hot and a cold compartment during its movement. Since there is some space between the piston and the cylinder walls, gas can move between these two compartments.
When the piston moves from the hot to the cold compartment, cold gas begins to move from the cold to the hot compartment, its temperature increases, and therefore the pressure in the cylinder increases.
Once a certain pressure is reached, a check valve (shown in figure 1b) opens and pressurized gas leaves the cylinder.

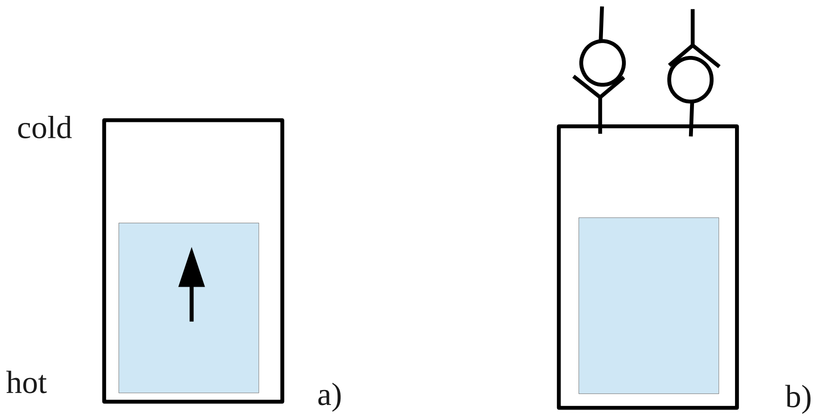

Figure 1: (a) a displacement piston moves up and down in a cylinder. At one end the cylinder is cooled, at the other end it is heated. Corresponding to the movement of the piston, the gas in the (closed) cylinder will move between the hot and the cold end, correspondingly increasing and decreasing its temperature and therefore its pressure.
(b) two check valves allow gas to enter or to leave the cylinder.

From a material point of view the device resembles a part of a beta type Stirling engine. However, its function is different from a Stirling engine: in a Stirling engine gas is first mechanically compressed, by one or several pistons, which reduce the volume of the gas. After that the already compressed gas is heated. In the device shown in figure 1, there is no mechanic compression - the gas pressure is not increased by decreasing the volume of the gas at any point.
Said differently, a Stirling engine is defined by a sequence of isothermal and isochoric constituent processes. In our device there is neither an isothermal, nor an isochoric process.
Actually, the pressure increase of the device in figure 1 cannot be described by any of the constituent processes used in the discussion of conventional thermodynamic machine cycles – it is neither adiabatic, nor isentropic, nor isothermal. Instead the “compression” in our device can be described as follows:
We consider a volume of air, V, which consists of two volumes, V1 and V2, connected by a small tube of infinite size. To describe the size of the volumes we use the parameter α with V1 = $\alpha \cdot V$ and correspondingly V2 = $(1-\alpha) \cdot V$.
The properties of the air in these volumes may be described by the general law for ideal gases [6], with the variables as defined there:

$$p \cdot V = n \cdot R \cdot T \qquad \text{(IV)}$$

As long as both volumes of gas have the same temperature, and if the total number of gas molecules is n, we have $\alpha \cdot n$ gas molecules in volume V1 and $(1-\alpha) \cdot n$ molecules in volume V2.
If we now increase the temperature in volume V1 from the initial temperature T_1 to the higher temperature T_2, a part of the gas molecules will leave volume V1 and move to volume V2, we denote this quantity of gas molecules with δ. The pressure of the gas (which is the same in V1 and V2, since they are connected by a thin tube) will increase to p_2.
This new situation of the gas in volume V1 can correspondingly be described (based on (IV)) as:

$$p_2 \cdot \alpha \cdot V = (\alpha \cdot n - \delta) \cdot R \cdot T_2 \quad \text{(V)}$$

while the gas volume V2 can be described correspondingly as

$$p_2 \cdot (1-\alpha) \cdot V = ((1-\alpha) \cdot n + \delta) \cdot R \cdot T_1 \quad \text{(VI)}$$

we can express δ by rewriting (V) as : $\delta = \frac{\alpha \cdot n \cdot R \cdot T_2 - \alpha \cdot p_2 \cdot V}{R \cdot T_2}$ (VII)

inserting (VII) into (VI) we obtain the pressure, which results when a fraction α of a volume of gas V is heated from a lower temperature T_1 to a higher temperature T_2: $p_2 = \frac{p_1}{(1-\alpha) + \alpha \cdot T_1 / T_2}$ (VIII)

A graphic representation of this expression is shown in figure 2, where a ratio of $T_2/T_1 = 2$ is assumed as an example.

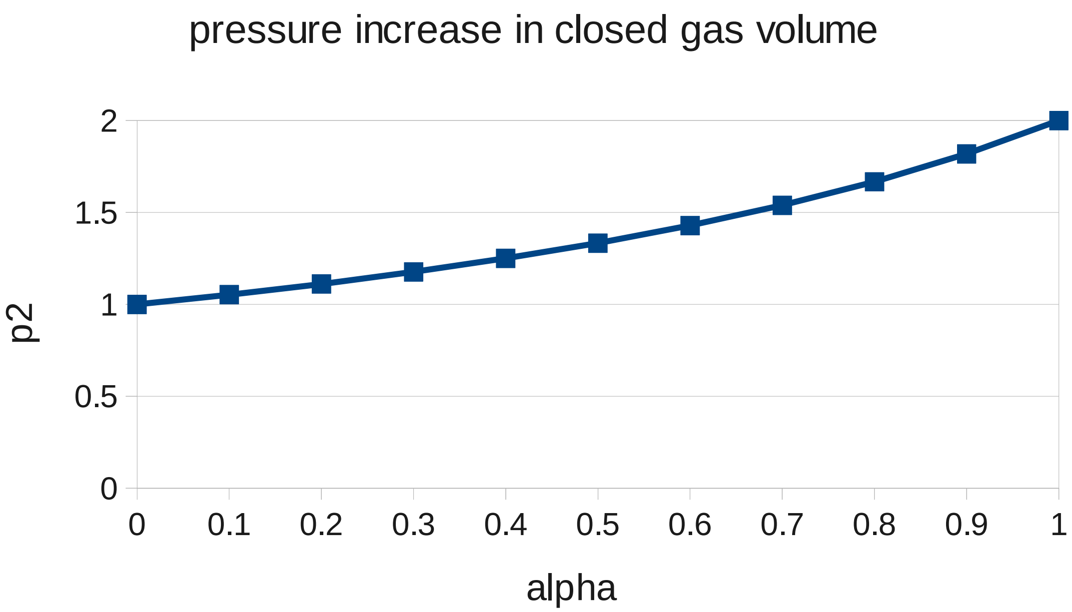

Figure 2: pressure in the cylinder of figure 1, p_2, as a function of the fraction of the hot gas, α, assuming for this example $T_2/T_1 = 2$.

For example, in order to increase the pressure by 1/3, half of the gas volume must be heated from T_1 to $2 \cdot T_1$. Once the piston has moved to a position where the pressure is sufficient to open the outflow check valve and to keep it open, a process of isobaric expansion starts[2], and it is this isobaric expansion, which provides the work, which is delivered by the machine.

2 in the naming conventions used by engineering in the discussions of state of the art machines, the term “isobaric expansion” usually is not being used, rather what we refer to as “isobaric expansion” there is called “isobaric heating”. If we would follow this convention, if we referred to the isobaric expansion not as expansion, then we seemingly would propose a hot air machine without expansion stage – and therefore an impossible machine -., since the adiabatic expansion discussed later in the article is not fundamental for the functioning of the machine.

In figure 1, the valves for the inflowing and the outflowing gas are both at the cold side of the cylinder. In this case the pressurized gas leaving through the check valve, does not undergo adiabatic expansion. Alternatively, the outflow of the pressurized gas can be placed in the hot part of the machine, in which case all of the gas will undergo isobaric expansion, increasing the power of the machine correspondingly.

The device as described up to now does not perform work. A separate mechanism is needed for extracting mechanical work from the flow of pressurized air, which is provided by the cylinder.
In principle, any turbine or expansion piston could be used. In practice, turbines tend to be inefficient when they are of small size, and furthermore we did not find an existing turbine optimized for operation at a pressure difference of 0.3 bar. Piston devices suffer from the problems described above (adiabatic expansion, internal temperature losses).
A good choice for extracting work from the isobaric expansion is the aeolipile.

4.2) Aeolipile mechanism

>> An **aeolipile** (or **aeolipyle**, or **eolipile**), also known as a **Hero engine**, is a simple bladeless radial steam turbine which spins when the central water container is heated. Torque is produced by steam jets exiting the turbine, much like a tip jet or rocket engine. In the 1st century AD, Hero of Alexandria described the device, and many sources give him the credit for its invention.

The aeolipile Hero described is considered to be the first recorded steam engine or reaction steam turbine. The name – derived from the Greek word Αἴολος and Latin word *pila* – translates to "the ball of Aolus", Aeolus being the Greek god of the air and wind.

Pre-dating Hero's writings, a device called an aeolipile was described in the 1st century BC by Vitruvius in his treatise De architectura; however, it is unclear whether it is the same device or a predecessor, as there is no mention of any rotating parts << [7]

Figure 3: An illustration of Hero's aeolipile

An aeolipile does not necessarily have to be operated with steam. It can instead be operated by the pressurized air, provided by the device described in the previous chapter.

In approximation the velocity of the gas exiting the aeolipile is given by the equation of Bernoulli

$$\Delta p = \frac{1}{2} \cdot \rho \cdot v^2 \quad \text{(IX)}$$

where v is the velocity of the gas, ρ its the density, and Δp is the pressure difference between the pressure in the aeolipile and ambient pressure. For $\rho = 1.2\ kg/m^3$ and for example Δp = 0.3 bar we obtain v = 224 m/s.

The Bernoulli equation is precise only for incompressible fluids, and it assumes that there are no frictions, turbulences or similar kinds of energy loss.
The fact, that air is a compressible gas and the unavoidable energy losses in the exhaust nozzle of the aeolipile must be subject of a further fluid dynamic simulation, they are beyond the scope of this paper.
In the context of our discussion two things are relevant: first, there is no fundamental limitation to the efficiency of the aeolipile which is specific for the aeolipile from a physics point of view. Second, the compressibility of the gas is not fundamental to aeolipile operation (while instead it is of fundamental importance for the operation of all conventional heat engines) – an aeolipile can also be operated with water, in which case the equation (IX) will be precise (apart from friction losses).

Since the aeolipile is so simple, and since it should have a good efficiency from a physics point of view, one might ask, why aeolipiles are not used in practical applications?
In literature as well as in all internet references known to us, it is stated that the aeolipile is only a toy and not a useful tool, for example: >>Diese frühe Dampfturbine war Spielerei und wurde nie einer weiteren Nutzung zugeführt<< [8].
or >> … Sein Dampfrad musste bei dem mangelhaften, in den Kinderschuhen der Entwicklung stehenden Zustand des Maschinenbaus spurlos verschwinden..<< [9]. These points of view are however not explained, as if they were self evident. The only reference known to us, which tries to explain why the aeolipile is supposed to be inefficient, is from J.G.Landels:
>> Could this form of steam engine ever have been used as a practical power source? The answer is, almost certainly not. It operates best at a high speed, and would have to be geared down in a high ratio. Hero could have managed that, since the worm gear was familiar to him, but not without friction loss. Inadequate heat transfer from the burning fuel to the cauldron would keep the efficiency low, but the worst problem of all is the “sleeve joint”, where the pipe (…) enters the sphere. When making a working reconstruction of this device, I had the greatest difficulty in reaching a compromise between a loose joint which leaks steam and lowers the pressure, and a tight one which wastes energy in friction. << [10].
But even if it were true, that the mentioned problem of the sleeve joint cannot be solved by engineering, it can be solved by physics. According to equation (IX) the pressure in a gas can be lowered by increasing the gas velocity:
Figure 4 (a) shows a fixed tube, connected to a rotating tube through a joint (the joint is indicated by a dotted line). If instead (as shown in figure 4 b) the flow section is reduced in the joint, the pressure in the joint will correspondingly decrease.

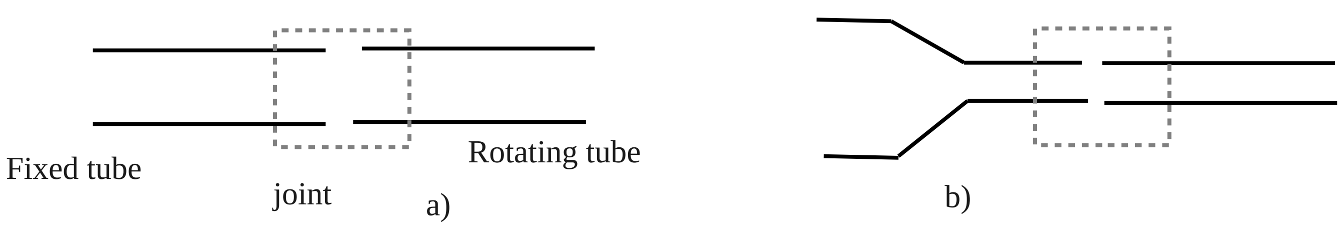

Figure 4: (a) gas under a high pressure flows at a low velocity from a fixed tube into a rotating tube. A joint is needed between the tubes, so that the gas does not exit.
(b) by reducing the cross section of the flow its velocity is increased and its pressure is decreased.
If the cross section of the flow between the two tubes is equal to the cross section of the exhaust nozzle of the aeolipile, then the pressure in the joint between the tubes will be approximately equal to ambient pressure. In this case a joint may not be needed between the tubes.

4.3) Closed cycle operation

The aeolipile can be operated within a closed container, which can be connected to the inflow of the pressure cylinder, so that a closed cycle operation results. In this case, the entire gas volume can be set under high pressure, so that a large absolute pressure increase Δp results. The power of the device will increase correspondingly.
A closed cycle operation also permits the use of hydrogen or helium as a working gas. This will also increase the power of the device, since the increased heat conductivity will allow the pressure cylinder to run at higher speeds of rotation.

4.4) Optimization of exhaust nozzle

Usually and usually in an implicit way aeolipiles are assumed to have a simple hole as an exhaust nozzle [7]. Instead the exhaust nozzle may have the shape of a De Laval nozzle, or it may act on blade surfaces similar to a conventional tubines, as indicated in figure 5.
The optimum design of the exhaust nozzle in any case needs to be determined from a fluid dynamic simulation, in function of the particular working conditions in a given application.
Figure 5 shows, that an aeolipile can be understood as being a turbine with only one blade or one pair of blades. From a practical point of view, a turbine of a given power can be realised either as a relatively small and fast spinning conventional turbine with many blades or as an aeolipile kind of turbine with one “blade”, with a respectively larger diameter and a slower speed of rotation.

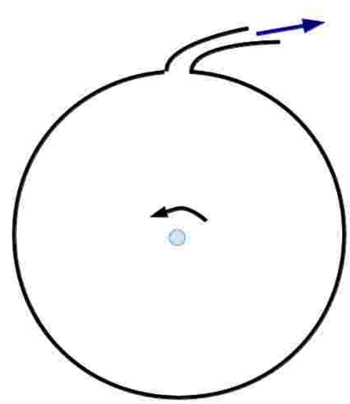

Figure 5: an aeolipile with an exhaust nozzle shaped like the space between two conventional turbine blades. Covering the outer perimeter of the aeolipile with these nozzles, a design similar to a conventional turbine results.

5) First experimental results

5.1) experimental setup

In order to verify the theoretical arguments made in the previous chapters, Isomorph srl has constructed a very simple prototype hot air engine, based on those arguments. The engine is not optimized in any sense, its purpose is only the detection of possible unforeseen practical problems in the construction of such a machine. A photograph is shown as figure 6:

The pressure cylinder has a diameter of 20 cm and is 40 cm high. The piston is 30 cm high, so that the effective gas volume is 3.1 liters. The space between cylinder wall and piston is 2 mm. Both the cylinder and the piston are made from a standard steel tubes, without the use of a lathe.

Usually, pistons oscillating in a cylinder are moved by means of crank mechanisms. Instead we have suspended the piston on an industrial spring, so that it can oscillate up and down within the cylinder. Spring and piston form a pendulum, its velocity of oscillation is given by the mass of the piston and the spring constant. The oscillation is initiated, and damping losses are compensated by means of a home made linear motor. The whole ensemble is sealed.

Each check valve consists of a hole and a metal ball fitting this hole. The valves are mounted on the top of the cylinder, in the cold compartment. The motor is equipped with a pressure sensor and with a distance sensor, which reads the distance of the piston from the upper wall of the cylinder.

The bottom of the cylinder is heated by a gas flame, its temperature is monitored.

The outflow check valve is connected to an eolipile. The aeolipile consists of a tube of 4 mm diameter, mounted on a ball bearing. At a distance of 25 cm from the axis of rotation the tube has a hole of 3 mm diameter in its wall, which serves as a simple exhaust nozzle. The hole is oriented to make the air leave the tube at an angle normal to the tube axis and normal to the axis of rotation.

Also the tubes at the transition to the rotating aeolipile have a diameter of 3 mm, so that the pressure in this transition is approximately equal to ambient pressure. Neither this transition nor the hole serving as an exhaust nozzle are optimized in any way, they are just simple holes drilled into a metal tube.

The speed of rotation of the aeolipile can be measured with an infrared sensor. The temperature, position and pressure sensors are read by a micro controller.

Figure 6: the experimental Isomorph heat machine. The heating is provided by a gas flame under the cylinder.

Gas between the piston and the cylinder walls, and gas in the tube containing the spring does not contribute to the pressure variation caused by temperature changes – these “dead spaces” are about 15% of the working volume. Figure 2 shows that for instance for T_1=300 K and T_2=600 K the pressure increase from heating the working gas would be a factor of two without the presence of dead spaces, while with 15% dead spaces it is only about a factor of 1.7 – the pressure in our device can at maximum increase from 1 bar to 1.7 bar, due to the dead spaces.

The heat exchange occurs only in the space between piston and cylinder walls, there is no dedicated heat exchanger or recuperator. Therefore the pressure changes during the operation of the device are expected to be smaller than the maximum value.

5.2) Measurement results

The piston performed 1.3 oscillations per second, for the measurements described here the temperature of the hot compartment was brought to 410 °C. Figure 7 shows the pressure in the cylinder as a function of the position of the cylinder, the valves were closed for this measurement.
Figure 7 shows how the pressure increases to 0.29 bar when the piston is entirely in the cold compartment. When instead the cylinder is in the hot compartment, so that the air is in the cold compartment, the pressure falls 0.08 bar below ambient pressure.

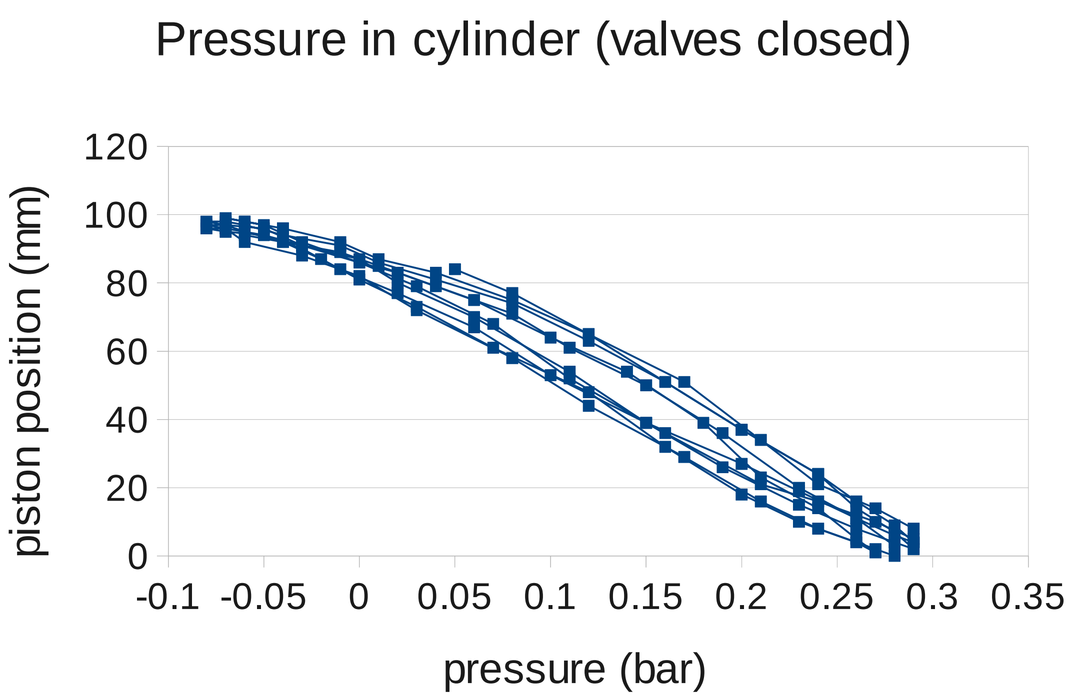

Figure 7: pressure increase in the cylinder of the Isomorph hot air engine (x axis) versus distance of piston from upper cylinder surface (0 mm means, that the piston is entirely in the upper cold compartment of the cylinder). Several subsequent oscillations are shown. The check valves are closed.

During normal operation the valves are not blocked, but close and open according to the pressure differences. The resulting function of pressure versus piston position is shown in figure 8.

The aeolipile connected to the outflow rotated at 300 rpm.

Because neither the narrow section delivering air to the aeolipile, nor the hole serving as exhaust nozzle have been optimized, significant pressure losses are to be expected. This pressure loss was estimated by connecting the aeolipile to a constant pressure reservoir at 2 bar (1 bar over atmospheric pressure). Keeping the arm of the aeolipile fixed, this arm developed a force of 0.37 N, due to the air exciting from the hole of 3 mm diameter.
The force exercised by a medium of 1 bar of excess pressure on a circular area of 3 mm diameter would result in a force of 0.7 N instead. In this sense we can roughly estimate, that this very simple aeolipile has already an efficiency of 50%.

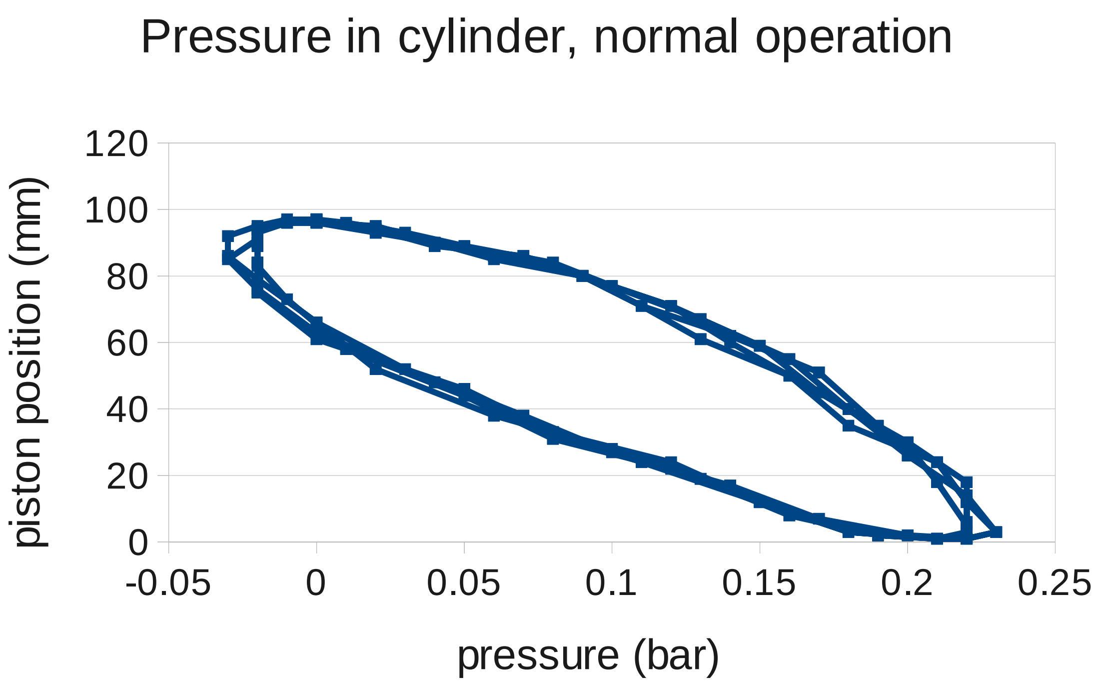

Figure 8: pressure in the cylinder when check valves are not blocked (normal operation).

The maximum pressure developed by the pressure cylinder of 0.3 bar is about 1/3 of what would be possible in an ideal machine with perfect heat transmission to the working gas. One would expect, that this difference is for the most part due to the poor heat transmission in this very simple prototype. To test this hypothesis qualitatively we operated the device with a mixture of helium and air. The maximum pressure increased from 0.3 bar to 0.6 bar, and the velocity of the aeolipile increased from 300 rpm to 420 rpm.

We conclude from these results, that the theoretical discussions, which lead to the design of Isomorph hot air engine are essentially correct and reasonably complete.

5.4) Economics

The raw materials for our experimental device had a value of 300 €. The workshops providing the flanges for the cylinder and the piston and the axis of the aeolipile charged us 450 €. Making an additional enclosure for the aeolipile in order to create a closed circuit device and adding some heat exchanger would add some relatively small additional cost.
Assuming that with an improved heat exchanger and possibly operating with helium the device can operate at 10 oscillations per second and assuming a closed circuit at a pressure of 10 bar, with an pressure increase in the cylinder of average 3 bar, and placing the outflow valve at the hot compartment, the device would develop a power of about 9 kW.
These numbers show that the Isomorph hot air engine has indeed the potential to become a simple and economic device for transforming thermal energy – in particular solar thermal energy – to mechanical energy, again confirming the theoretical considerations presented in this paper.

6) Outlook

The pressurized air for the aeolipile does not necessarily need to be provided by a device as described in this article. The aeolipile can be operated with any source of pressurized gas, including steam. Therefore the aeolipile can substitute turbines not only in solar applications – as discussed in this article – but also in in many conventional applications. For instance, in conventional coal driven power plants equipped with steam turbines, the turbines can be substituted with or supported by eolipiles.
This would resolve a major problem with conventional renewable energy sources: wind energy and photovoltaic energy have large fluctuations. Conventional power plants cannot cope with these fluctuations, because conventional turbines need a long heating up time, and once they are running, their power cannot be modified by much.
These problems can be solved with eolipile technology: eolipiles can start within seconds. Since they are cheap, several eolipiles of different sizes can be kept available, and combinations of these eolipiles can be operated to match actual power demands. Alternatively, the flow section delivering steam to the aeolipile can be made variable, as well as the size of the exit nozzles, in order to modify the power of the eolipile. Instead of modifying the size of the exit nozzle, several nozzles of different sizes can be mounted on one aeolipile, and a mechanism can activate those, which are needed in order to provide the power needed.
As a result conventional power plants, equipped with eolipiles, would be able to react fast to fluctuating renewable energy sources. This would remove one of the major obstacles to the further increase of renewable energies.

7) Looking back

The aeolipile dates back to the same period, in which Archimedes most likely had used the Linear Mirror for the first time [11]. The question of why these technologies have never again been used until the present day is relevant, it cannot be answered by physics alone, and must be discussed with the other humanities (we assume, that physics makes, or should make part of the humanities). As a first contribution to this discussion and in the context of this article we note:
It is sometimes assumed, that in the ancient world mechanical machines for doing work were not developed, because there were slaves providing cheap labor, therefore investing in the development of

a machine would not have made economic sense.
In modern times instead, science is entirely organized by public administration. In organized science young scientists have no freedom, they are kept as intellectual slaves, and cannot develop new ideas.
In order to remember the annihilated scientific culture of ancient Alexandria, and in order to remember those thousands of young minds destroyed each year in our times, we would like to propose to our peers to refer to the Isomorph Machine as “memory machine” in the future.

8) Conclusion

Based on general physics arguments we have derived a new kind of motor – the Isomorph hot air machine. The device is able to operate at lower temperatures compared to state of the art devices, and is therefore well suited for the use in solar power plants. It is characterized by a very low internal friction without making use of lubricants. The compression of the working gas is not done mechanically, as in conventional hot air machines, but exclusively by heating the gas. The isobaric expansion created by the device is used by an aeolipile. The aeolipile operates without any joint, since the gas flowing into the aeolipile is dynamically reduced in pressure.
A first and not optimized machine worked well, suggesting that the theoretical consideration made in this paper are correct and indicating that they are essentially complete.
An aeolipile, as described in this paper can also be used together with other sources of pressurized gas or steam. For instance eolipiles could substitute steam turbines in conventional power plants. This would enable conventional power plants to react much faster to changing power demands and it would therefore remove one of the major obstacles to the diffusion of renewable energies in general.

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