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A New Approach to Piston Engines

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Preface

The main aim of the book is to present development in heat air engines. We attempt to apply an idea of external heating to the piston engine manufactured with well known technology for internal combustion engines. External heating, i.e., delivery of energy from outside in order to create mechanical energy inside the engine, is an extensively developed range of engineering applications, especially in the light of a possibility to use a much wider scope of potential "fuels" than those which can only be burnt inside the engine cylinder. In fact, we intend to use any kind of heat from solar, through burning different fuels to heat generated in the nuclear process. On the other hand, externally heated engines still developing since 1800s exhibit a very complicated and difficult mechanical construction in exploitation, with many wear problems. We propose to employ the standard internal combustion piston engine design which is fed with heat from an external heater to warm up the working fluid which, in turn, employs simple thermodynamic laws interchanging its potential energy into the mechanical one. As in internal combustion piston engines, the working fluid expanding over the moving piston triggers mechanical rotations with torque in the rotating crankshaft, providing thus drive for any machinery.

The idea of air engine which originates from the original Stirling design is entirely different from it. It combines the proven technology of internal combustion engines together with their lubrication system and can be an effective solution not only in the future when most mineral fuels run out but even nowadays as it eliminates problems with lubrication of the mechanism, the main disadvantage of present solutions. Additionally, it can use the cheapest working fluid, the atmospheric air, instead of costly helium or hydrogen. Stability of the heat generation process outside the engine is another advantage of the proposed engine. The work is generated by expansion of hot and compressed air in a cylinder located between two heat exchangers, having extreme temperature and pressure values. A compression ratio considered is about 1:10 although higher values can be reached.

The idea comes back to 1995 and was invented by Lech Brzeski and Zbyszko Kazimierski. An engine, in both 2-stroke and 4-stroke cycles, working in a closed heat cycle is in some way equivalent to internal combustion engines as energy is generated in similar working loops although heat cycles are different. The idea was confirmed by an experimental model in early 2000s when further development of another prototype stopped due to a lack of financial support. Thus, all our efforts were directed to increase theoretically the heat exchange level which was the main problem detected during tests. We present some ideas which can increase dramatically an amount of heat delivered to the working fluid in the work cycle. In parallel, we have also developed new versions of the engine which have yielded even higher performance characteristics in our simulations and remain within feasible engineering solutions even if some devices are added.

The 4-stroke version of the engine appears to be a very attractive proposition as it applies only a single cylinder. Even such a solution is able to realize a complete thermodynamic cycle. When expanded to a multicylinder design, the advantages are obvious. All proposed 2-stroke versions apply either 2 separate cylinders or a design with double-action pistons. The simulation results show impressive numbers of the power and efficiency generated by the engine – it can reach 50 kW per 1 liter of the working volume at the efficiency equal to about 40 %.

Therefore, we compare these numbers with those available for other, effectively working externally heated engines, where a choice of installations of modern Stirling devices is obvious. The results are promising, especially if air and not helium is applied.

We can expect many possible applications of such a source of mechanical energy worldwide and not only, as space applications are possible as well. In the future, when availability of mineral fuels is limited, such engines can replace internal combustion solutions.

Lodz
November 2015

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Professor Lech Brzeski who passed away in 2006 was one of the main inventors of the EHVE. The authors of this book are immensely grateful for His contribution.

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Contents

Nomenclature

α	Crankshaft angle (rad, deg)
α_A	Heat transfer coefficient (W/m^{2}K)
A	Surface of heat exchange area (m^2)
A_{CE}	Surface of the expander piston (m^2)
A_{CC}	Surface of the compressor piston (m^2)
A_j	Cross-section area of the governed valves (m^2)
c_j	Damping at the j-th valve (Ns/m)
c_p	Specific heat at constant pressure (J/kg K)
c_v	Specific heat at constant volume (J/kg K)
δ_{ME}	Overlapping angle of the valves (rad)
$\Delta\alpha_j$	Increase in the valve angle (rad)
d	Diameter (m)
D	Cylinder diameter (m)
d_j	Diameter of the j-th valve (m)
e_T	Total internal energy (J/kg)
η	Efficiency (%)
η_C	Cycle efficiency (%)
η_{PH}	Efficiency with the pre-heater present (%)
h_B	Enthalpy in the blower (J/kg)
h_{C0}	Clearance under the piston at its lowest position (m)
h_{E0}	Clearance over the position of the expander piston at its upper point (m)
$h_{j,max}$	Maximum lift of the j-th valve (m)
h_{SBi}	Enthalpy isentropic increase of blowers (J/kg)
i_T	Total enthalpy (J/kg)
κ	Isentropic expansion index
k_j	Spring stiffness of the j-th valve (N/m)
L	Mechanical work (J)
l	Length of tubes (m)
λ	Heat conductivity coefficient (W/m K)
$\dot{m}_i$	Mass flow rate (kg/s)
M_v	Mass transported through a valve (kg)

$\dot{m}_{g,i}$	Mass stream of the working fluid in the i-th cell (kg/s)
$\dot{m}_T$	Mixing air streams (kg/s)
m_j	Mass of the j-th valve (kg)
μ	Dynamic viscosity (kg/m s)
n	Number of heat exchanger tubes (–)
n_H	Number of heater tubes (–)
n	Rotational speed (rpm)
Nu	Nusselt number (–)
$\mathbf{n}$	Unit normal vector
ω	Angular velocity of the crankshaft (rad/s)
Π_B	Output to input pressure ratio for a blower (–)
p	Pressure (Pa)
P	Power (W, kW)
Pr	Prandtl number (–)
$\dot{q}_A$	Surface heat flux density (J/sm^2)
$\dot{q}_V$	Volume heat flux density (J/sm^2)
Q	Heat (J)
$\dot{Q}_A$	Heat stream through the surface area (W)
$\dot{Q}_V$	Heat stream through the volume (W)
ρ	Density (kg/m^3)
R	Specific gas constant (J/kg K)
Re	Reynolds number (–)
s	Stroke (m)
s	Specific entropy (J/kg K)
SC	Settling chambers
S	Entropy (J/K)
t	Time (s)
u	Velocity of the surface (m/s)
T	Temperature (K)
t_{pe}	Period of the engine work (s)
V	Volume (m^3)
v	Absolute velocity (m/s)
w	Relative velocity (m/s)
ζ	Coefficient of losses for the mass flow (–)
$\mathrm{B_s}$	Blowers – $\mathrm{B_1}$, $\mathrm{B_2}$, B_{H1}, B_{H3}, B_{Cl2}, B_{Cl4}
$\mathrm{Cl_j}$	Collectors of the cooler – $\mathrm{Cl_2}$, $\mathrm{Cl_4}$
$\mathrm{H_j}$	Collectors of the heater – $\mathrm{H_1}$, $\mathrm{H_4}$

Subscripts

B	Blower
c	Valve closing
C	Compressor
Cl	Cooler

CS	Averaged compressor mass flow rate
Cs	Crank shaft
E	Expander
ES	Averaged expander mass flow rate
f	Friction
FW	Flywheel
G	Heater radiators
H	Heater
iso	Isochoric
o	Valve opening
PH	Pre-heater
PR	Piston rod
RV	Rotary valve
wCL	Cooler wall
wH	Heater wall

Chapter 1
Introduction

The Externally Heated Valve Engine, further on referred to as the EHVE, and its continuous development are described here. External heating, i.e., when heat energy is delivered from outside, was an important task in designing machines able to generate mechanical energy in different applications. The idea of the EHVE aims at a possible use of any kind of heat coming from, e.g., burning fuels or wastes through solar to nuclear energy. Additionally, as most of historical and present devices applying external heating are technologically complicated, we have decided to apply a typical, well developed piston engine with internal combustion in the EHVE design, which may result in easier implementation of the EHVE. Such a technology involving a piston-cylinder set in connection with a standard crankshaft does not need to resign from typical oil lubrication, which is the main disadvantage of other machines using external heating.

Historically, the very first engine employing external heating was built by Robert Stirling in 1816. He was a Scottish minister who invented the first working closed-cycle air engine. It gave the beginning to a class of engines using hot air, further on developed by other designers. Later, in 1884 Fleeming Jenkin proposed that all such engines should therefore generically be referred to as Stirling engines. The idea has been developed till now with many successful applications [1, 2].

There are numerous works in which experimental results on Stirling or similar externally heated engines using different fuels or even alternative sources of energy are published, e.g., [3–20]. Depending on the particular design, they were intended to reach very different performance levels. The presented applications include some demonstration devices [14], waste heat recovery [21–25], general purpose installations [7, 26], solar heated engines [27], marine applicable [5, 28] and even projects potentially possible to work in the outer space like [29]. Examples of reviews of many published elsewhere solutions can be found in [27, 30, 31]. An interesting summary of the performance of some existing machines is presented in [32]. There are also some experimental results, e.g., [33], which provide a foundation for comparisons to other engines with external heating.

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Air-powered engines like the EHVE, which works in a modified Joule cycle, are still developed theoretically, see [34], or practically, e.g., [35].

The working fluid in most modern Stirling engines is helium due to their heat transfer properties, although they are usually very expensive both in manufacturing and maintenance. Their crankshafts have very complex designs and heat regenerators have to be used. Application of internal heat exchangers makes lubrication inside the engine practically impossible. Typical Stirling engines use the pressure ratio of the value approximately equal to 2, whereas the maximal pressure is higher than in the EHVE as it does not need any regenerator.

An early design of the EHVE comes from 1995 and is described in [36], with its later developments reported in [37] and [38]. The working fluid in the EHVE is the cheapest gas available – atmospheric air. All of the EHVE designs allow the ratio of applied pressures, i.e., maximal to minimal values, to be approximately 10, like for internal combustion engines. The maximal pressure designed for the EHVE is approximately 100 bar but along with improvement in the sealing system, it can become higher. Any exchange or replenishment of such a fluid is easy.

Heat energy is delivered to the engine through its heaters, the mechanical energy is produced when the hot fluid expands under high pressure in a cylinder called an expander. Then, it is transferred to the engine cooler for cooling at low pressure. In very early versions of the EHVE, two small heaters were applied, later versions used a larger, single heater with blowers forcing the flow through it. Both the heater and the cooler are heat exchangers that are the outside parts of the EHVE. Taking into account this fact, we assume that the latter are counter-current devices. A simple calculation method where all unknown values are time-dependent only is presented later in this book.

The engines discussed in [36, 37] are similar to that described by Kovacs [39]. The similarity arose by chance, in fact both ideas were developed independently with no knowledge on the other work. However, there are no data or even a type of applied heaters in [39]. For this reason, this engine has not been considered here.

The valve control and the flow of the working fluid inside the EHVE use the well-known technology of internal combustion engines. The first design involving a piston located in a single cylinder is presented in Chap. 2. The engine is composed of four essential parts: an expander, a compressor, a heater and a cooler. The heater in this version consists of two small devices, the cooler uses water as a cooling fluid. This is a 2-stroke engine. The expander is placed over the piston, whereas the compressor – below it. Two of four engine valves are of self-acting type.

Let us remind the main advantage of the EHVE which is the fact that it uses air as the working fluid, a conventional crankshaft and a standard oil lubrication system. The method of general calculations is explained in detail in Chap. 2. The experiments were performed on this version of the EHVE, but its construction was changed slightly. A compact, but difficult to manufacture engine cylinder was altered to a 2-cylinder design given in Chap. 3. The main conclusion that followed from the experimental results was a low level of heat amount delivered to the prototype. Theoretically, the heat transfer coefficient can be calculated for the main assumption of continuous work of the engine. As appeared in the experiment, it was not fully achieved. Then, the majority of our efforts has been directed to increase a level of heat exchange which is critical for successful operation of the engine. Such a requirement can be fulfilled if some additional devices are applied in the early version of the EHVE. These are a blower and distributors [40]. Another solution to this problem is given in Chap. 4. This is the first step to improve the EHVE.

The next step in developing the EHVE is described in Chaps. 5 and 7. The changes introduced in the engine design were as follows:

- inlet and outlet collectors were added to the numerical model of both heat exchangers and two blowers were introduced,
- a new kind of valve was designed,
- a new, more detailed calculation method was developed as the basis for computer simulations,
- numerical calculations according to the new method were performed for 2- and 4-stroke versions of the EHVE.

The heater was also changed, i.e., a typical design, easy for manufacturing, was applied. All versions of the engine worked in a closed thermodynamic cycle.

A 2-stroke version, which has two blowers, is presented in Chap. 5. It consists of a single heater and a single cooler. Again, this is a typical piston-crankshaft engine. Both the heater and the cooler have some additional volumes, considered here as collectors, which are taken into account. The collector design can be complicated as each of them does not have to influence the flow coming from both the engine and the blowers. This version uses a standard oil lubrication system. The working fluid is air and the cooling fluid is water. The engine was investigated numerically.

The algorithm based on standard numerical integration procedures was applied to a set of differential equations describing the behaviour of individual parts of the engine model. It was supplied with the conditions controlling flows between them. Most of the simulations started from a set of the assumed initial conditions representing initially loaded volumes and constant rotational speed and continued until a stable solution was achieved. More realistic versions of the software covered dynamical behaviour of the numerical model from the start from the zero rotation and an application of a starter. Those calculations continued after reaching the steady rotational speed and all thermodynamic variables stabilization. All equations were written for averaged conditions in particular model elements, treating the problem as time-dependent only.

The type of heat exchangers was simulated as counter-current devices, where the temperature drops remain almost constant along their lengths. The exchangers are treated as time-dependent only, assuming that all important changes are the same and considering each of them in a single plane only. It is situated at the outlet of the exchanger tubes, in both the heater and the cooler, respectively. This approximate approach allows for applying maximal and minimal temperatures of the exchanger walls in the discussed case. The heat volume delivered to and subtracted from the EHVE in the heater and the cooler are estimated accordingly.

Some attempts were made to conduct a more detailed analysis of the heat exchange process taking place inside the exchangers, dividing them into a number of subvolumes, which was a time-space dependence modelling.

There were attempts aimed at stabilization of the flow inside the exchangers. This included separate settling chambers. A corresponding design of the EHVE is presented in Chap. 6. The way the separated settling chambers are built up is an engineering task, not considered in this book. The main results of the simulations conducted for this design are the values of power and efficiency which are not less than those obtained in the non-steady solution, see Chap. 5.

A 4-stroke version is described in Chap. 7. The experiment involving such a structure of the EHVE is foreseen. Two counter-current heat exchangers, a cooler and a heater, are applied in the engine. Blowers are used in order to increase the volume of heat exchange when the EHVE valves are closed. A disadvantage of this variant of the EHVE is a short period of full opening of the valves from the heater to the expander and from the compressor to the heater.

The valves should have possibilities to fulfil their tasks thanks to some new engineering solutions like rotary valves. The 4-stroke EHVE is an attractive proposition because it applies only one cylinder cover completely the full thermodynamic cycle, similar to internal combustion engines. This fact may be attractive in building multicylinder devices.

In order to provide the Reader with a view locating the idea of the EHVE among other modern externally heated engines, a comparison of its expected performance to similar, in terms of volume, Stirling engines, is presented in Chap. 8. As a measure of similarity, maximal pressures of the cycle are assumed and power and efficiency of both types of engines are presented. All data for Stirling installations have been taken from the experimental results.

The EHVE applications can vary broadly, i.e., they can be used at any places located close to sources of heat like dumps of garbage, cooling systems of nuclear reactors in submarines, on ships or yachts, even in the outer space when solar heat is employed. The externally heated engine is an invention to be employed when the existing sources of mineral fuels are exhausted. Prognostics when it happens are different but these fuels have to run out one day. Simultaneously, the amount of wastes is still growing and growing. Garbage will be burnt and, thus, some additional heat energy will be produced. The heat coming from bio-fuels received from plants can also be employed as a fuel. This energy, even not clean enough, can be used in the EHVE. Also, solar or nuclear heat can be employed.

Any party interested in the ideas presented here is invited to further cooperation in developing a working device, which can become a solution to the future problems of effective generation of mechanical energy.