A NOVEL DESIGN OF THE COMBUSTION ENGINE FOR IMPROVEMENT OF THE EFFICIENCY AND DURABILITY

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Abstract

For the purpose of the improvement of the efficiency of the combustion engine, the new solution which links in the advantage of the engine with the spark-ignition and the diesel engine is proposes. The creature of the solution consists in the realization the process of the combustion at the constant of the volume combustion chambers. It is realized with a piston stand during the period of combustion process. This permits on maximum pressure increasing and average indicated pressure. Advantages of this solution are self-evident. The enlargement of the efficiency is obtained, and finally - decrease of fuel consumption. Whereas at such itself average indicated pressure, the of maximum decrease of appears. This maximum pressure decrease causes decrease of mechanical loads of most essential engine parts, for which the pistons belong. The novel design of the engine is

In order to reduce the thermal loads on the piston and the negative effects of thermal shocks, the novel construction based design was proposed, where during the time when the thermal loads are the most severe, the mechanical loads are isolated from the inertial loads and the inertial loads are non existent. Besides the reduction of the thermal loads additional gains in overall efficiency were obtained as the result of the combustion process with the piston stopped. That system forms the part of United States Patent No. 6,481.393 B1.

Thermal shocks are reasons for high temperature gradients occurring in materials of engine components and sets, what in turn makes for high total stresses, even at lack of mechanical loads that accelerate damage of the engine components. With reference to heterogeneous elements like bimetals and from materials with covers, temperature gradients will be considerably greater and will represent what is due to different material properties. Experimental test results of thermal shocks for heavy-duty pistons of combustion engines are presented in the paper. Temperature measurement results on the crown and the skirt of the piston during the Diesel engine operating under different conditions are presented in the paper. Temperatures on the piston surface in the area of combustion chamber change in an every working cycle and these changes grow less with frequency (engine speed) increasing.

Keywords: *transport, combustion engine, piston composite alloys, thermal shocks, thermal fatigue damage, piston with cold centre*

1. Introduction

The thermal loads reduction will be realized when the Compound Engine with piston stop is powered back to produce the same power from given displacement as the conventional engine, requiring less fuel, hence inducing lower thermal loads on the engine components. That method forms the part of the Patent No US 6,481.393 B1. The leading concept of that method conducts combustion in the fixed volume chamber through the piston stoppage during combustion. That system is known as Compound Engine System. The Compound Engine System allowing for superior heat dissipation from the piston due to the design feature allowing for cold piston centre as it is not in contact with hot gasses from the combustion process, and also due to the dual heat dissipation path, one the conventional through the piston skirt to the cylinder wall and the second one conducting the heat through the central portion of the piston to intake cylinder. Especially disadvantageous situation takes place, when along with thermal loads there is influence of the mechanical loads, e.g. compressive forces and inertias in combustion chamber. The influence of mechanical loads additionally increases the influence of thermal shocks. The synergy influence of both sorts of loads - thermal and mechanical - essentially increases the probability of the piston's damage.

2. Thermal loads

When a piston is exposed to temperature gradients or when a complex piston folding of two or more materials having different coefficients of linear thermal expansion is heated in a way homogenous or a not uniform that will produce stresses because of a different expansibility of each fragment. A conservation of continuity occurs here rather than its loss, what causes an occurrence of strains. If some element does not handle that stress, then a deprivation of continuity taking place will result in part damage.

Thermal shocks are at the bottom of high temperature gradients occurring in material, and that makes for high strains causing mechanical loads, that will accelerate the part damage. With reference to parts and heterogeneous pistons, namely bimetal, and e.g. in case of ceramic coats, temperature gradients will be greater than what is due to different properties of materials. So the problem of thermal shocks with reference to such pistons will be more considerable, especially when the influence of thermal shocks with reference to composite materials is considered. Thus thermal shocks refer to both heterogeneous warming or the cooling of homogeneous parts, and homogeneous heating or cooling of heterogeneous (bimetal or with coatings) materials. In consideration of different coefficients of thermal expansion of materials it is possible to state that heating up of group of two materials with different coefficients of the thermal linear expansion makes for excessive stress and possible damage to the structural member, also by heating and subsequent reheating the fatigue damage may appear. It is necessary to underline that even with reference to homogeneous material and homogeneous heating or cooling, the thermal stresses can appear because of complex shape of the parts working in conditions of high temperatures.

A problem of heat stresses has a capital importance with reference to high load combustion engines. Present designs of combustion engines involve bigger resistance to high temperatures and application of materials resistant to the influence of the high temperatures but one fundamental feature of these materials is plasticity absence. For that reason, thermal stress is one of the most essential criteria making allowance for the usage of these materials. However the thermal stresses have also essential importance with reference to plastic materials and damages occurring in these materials are influenced by the thermal shocks.

Thermal stresses should be distinguished from thermal shocks. With reference to thermal shocks stresses are caused by high-frequency temperature gradients, usually they are instant (shock) activities. For example, if a part is initially exposed to the constant temperature and then it is suddenly dipped in environment of other temperature, the effect of the thermal shock is brought out. In facultative moment the stress is defined by a field of the temperature. However the temperature gradients, which appear in the temporary condition, are generally much higher than those, which appear in steady-state, therefore the thermal shocks stresses are usually higher than thermal stresses. Other factor discriminating thermal stresses from thermal shocks is a speed of stress growth, which is very high with reference to the thermal shocks, and many materials, which are exposed to this high-speed initiation stresses, cannot absorb these stresses. Therefore some fragile materials during fast initiation stresses cannot absorb them without the damage. In consequence of the thermal shocks occurrence realized at high speed which could be absorbed if they would be introduced gradually. There is also vital distinction of the single cycle of the thermal shock of the causing thermal stresses from the thermal fatigue. When the damage is caused by the realization of several similar cycles of thermal stresses, and not by the single cycle, that process has reference to the thermal fatigue.

The novel method of dealing with the thermal stresses occurring in an engine piston is presented as the Compound Engine System. In the Compound Engine System the piston is configured in such a way that the central portion of the piston is not exposed to the high temperature gasses, therefore the temperature gradient is altered in the positive manner, lowering the thermal shock and the stresses induced. Furthermore, the dual heat dissipation path effectively lowers the overall piston temperatures.

Value of thermal stresses depends, beside temperatures, on volume of heat flux and of running time of the heat flux on parts, whereat the occurring moment of maximum stresses appears earlier the heat flux is bigger. Furthermore, the different influence of the single thermal shock and periodic influence of repeated thermal shocks are observed. exemplary maximum undimensional stresses in the function of the undimensional heat flux are represented in Fig. 1, whereat the maximum undimensional tension is a relation of the thermal stress occurring in a part subjected to operate of the temperature to the stresses, when the thermal expansibility of the given element is blocked.

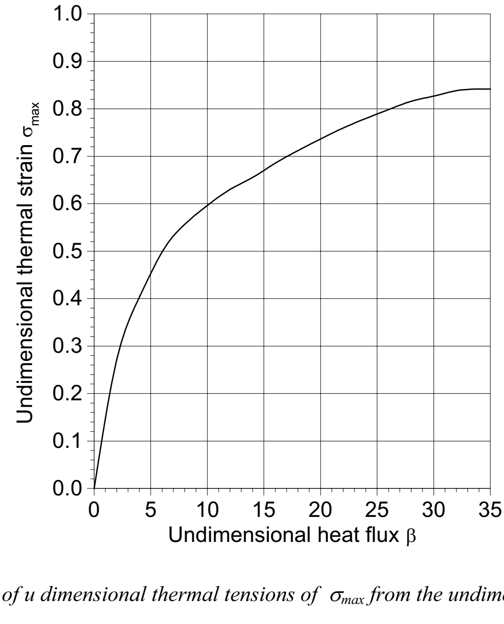


Fig. 1. The dependence of u dimensional thermal tensions of σ_{max} from the undimensional heat stream of β

From the plot presented in Fig. 1 it follows that the change of the maximum stresses is almost linear with reference to small values of the heat flux and asymptotically tends to unite with reference to big values of the stream flux.

The thermal shock resistance can be theoretically calculated by the thermal stress parameters:

$$R_1 = \frac{\sigma_b(1-\mu)}{\alpha E}, \tag{1}$$

$$R_2 = R_1 * \lambda, \tag{2}$$

where:
R_1 and R_2 - material constant,
σ_b - bend strength,
E - Young's modulus,
μ - Poisson's Number,
α - thermal linear coefficient,
λ - thermal conductivity.

The generally undimensional thermal stress σ can be expressed by the dependence:

$$\sigma = \frac{\sigma_o(1-\mu)}{E\alpha(T-T_o)}, \tag{3}$$

where:
σ_o - initial stress,
μ - Poisson's Number,
E - Young's modulus,
α - thermal linear coefficient,
T - temperature in stress place,
T_o - reference temperature.

3. Test equipment

Procedures of research are based on unique research devices, measuring equipment allowing to measure strains in the area of high temperatures, and the advanced computer simulation of the method of element finite (MEF) and the ANSYS software. The views of the devices employed for the realization of research of thermal shocks are presented in Fig. 2.

Fig. 2. The views of devices employed for the realization of thermal shocks with the thermo vision device

That will allow keeping equal and repeatable temperature necessary for research realization. The temperature in the chamber is obtained with combustion of fuel. Samples of the research pistons are heated in the stream of combustion gases, and then cooled with a compressed air also by given period. The temperature of samples is checked with a thermo vision camera and kept with the high accuracy. Stand operation is controlled with a computer control system which keeps the established temperature of samples and the rotational speed of the system of samples fastening and also controls terms of heating and cooling. In the conducted research the temperature measurements are performed in different places, samples and strains are investigated by means of special strain gauges, enabling conduct of measurement in conditions of high temperatures. Data obtained from measurement constitute starting point for the advanced analysis with the method of elements finite (MEF) at the utilization computer system ANSYS.

The view of automatic computer controlled device employed for the realization of heating and cooling, on the right - the air-compressor is shown in the Fig. 3.

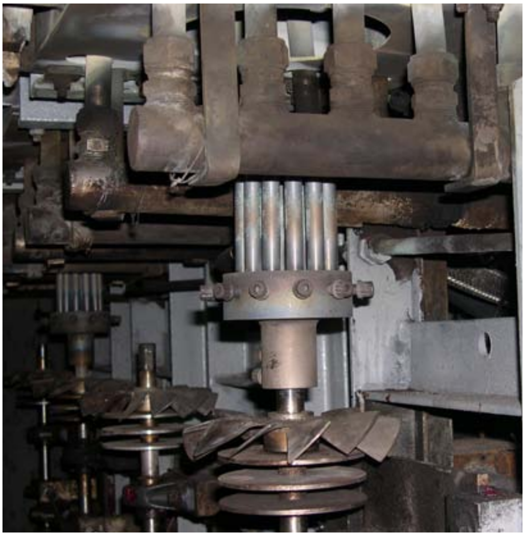


Fig. 3. The view of automatic computer controlled device employed for the realization of heating and cooling.

The views of the measuring-card set and the recording of the temperature controlled with the computer during research are presented in Fig. 4.

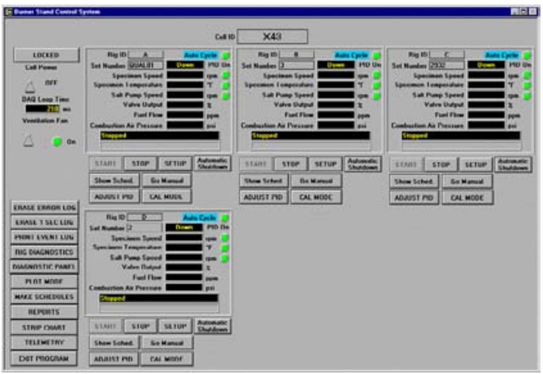


Fig. 4. The views of the measuring-card set and the recording of the temperature controlled with the computer during research

The research stand is entirely automated and controlled with technical computer program.

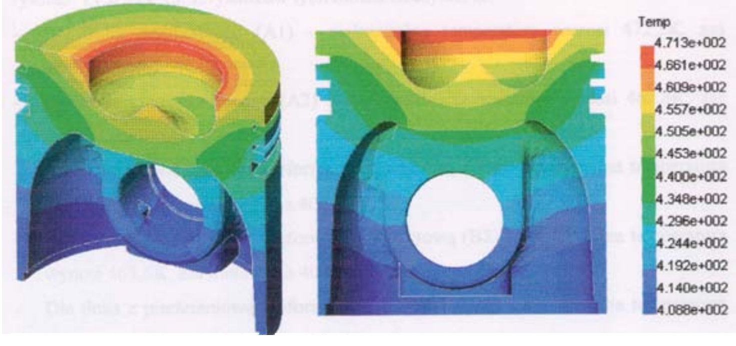
3. Tested materials and test results

Composite materials are substances made up of two materials of different physical and mechanical proprieties. As metal matrix of composite materials, iron and its alloys and many metals and non iron alloys–such as–aluminum, magnesium, copper, tin, lead, and titanium are applied. The reinforcing phase composes of particles–and short and long fibres–on the basis of graphite, carbon, boron, and oxides: Al2O3, SiO2, ZrO3, TiO2, carbides: Sic, TiC, B4C, nitrides: Si3N4, TiN. Furthermore additives increasing wet ability are introduced, which in general modify the character of the oxide coat on the metal surface. The reinforcing phase is oxidized, copper-plated, nickel-plated or chromium-plated.
Basic parameters of the composite and standard material are presented in the Table 1.

Table 1. Characteristics of tested materials

Parameter	Composite material	Standard
Material	AK12+20% Al_2O_3	AK12
Specific density	1560 kg/m^3	2700 kg/m^3
Specific heat at 250 ^{o}C	1010 J/kgK	990 J/kgK
Thermal diffusivity at 250 ^{o}C	0.45 cm^2/s	0.69 cm^2/s
Coefficient of lineal expansion at 250 ^{o}C	15*10^{-6} K^{-1}	21*10^{-6} K^{-1}
Thermal conductivity	98 W/m K	155 W/m K
R_m	3.28*10^8 N/m^2	2.45*10^8 N/m^2
R_p	2.89*10^8 N/m^2	2.25*10^8 N/m^2
As	0.35 %	0.5-1.5 %
Young's Modulus	98 GPa	80 GPa
Poisson Number	0.22	0.28

Example of the temperature field in the composite piston is presented in Fig. 6 for two different manufacturing of pistons.



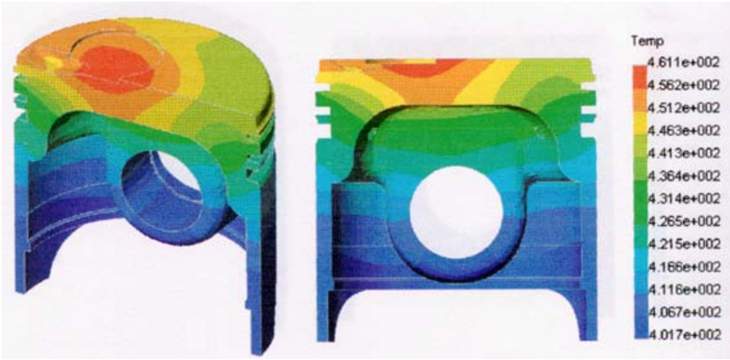


Fig. 6. Temperature (K) field in the composite piston for two different manufacturing of pistons

Values of stresses due to the temperature field in piston are presented in Fig. 7 for two different manufacturing of pistons.
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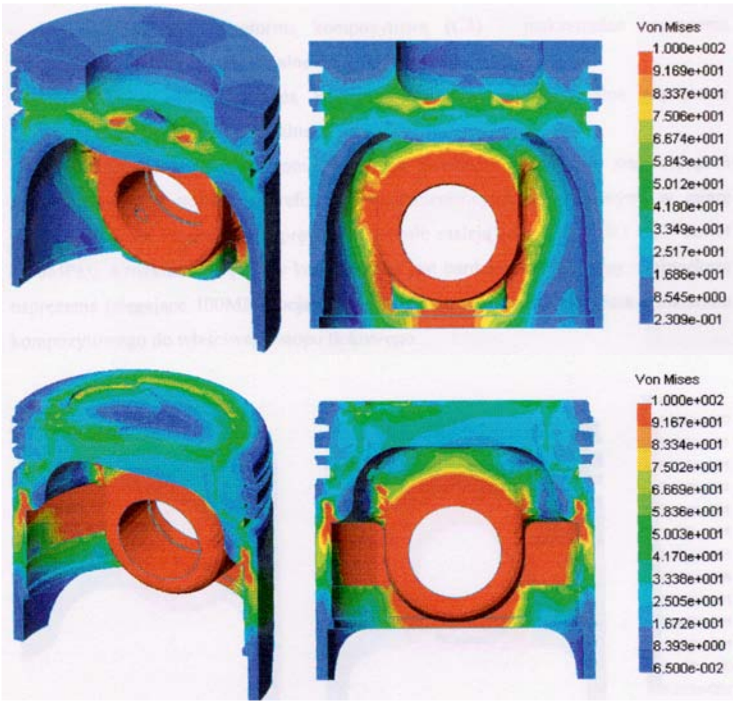

Fig. 7. Values of stresses (MPa) due to the temperature field in piston for two different manufacturing of pistons

Values of strains in the composite piston due to the temperature field are presented in Fig. 8. for two different manufacturing of pistons.

The example of the influence of the thermal shocks number on the strain of the piston sample is presented Fig. 9. The piston is made of the composite material of proprieties presented in Table

1 on the basis of the silumin close to eutectic mixture and Al_2O_3. The research conditions, due their laboratory realization, differ from the real condition with reference to the sample residence time in the high temperature of 360 ^oC. It should be underlined that conditions occurring in the combustion engine are not drastically extreme, as in conducted research of samples. The very essential influence has a thermal conductivity to the resistance on thermal shocks with reference to fragile materials.

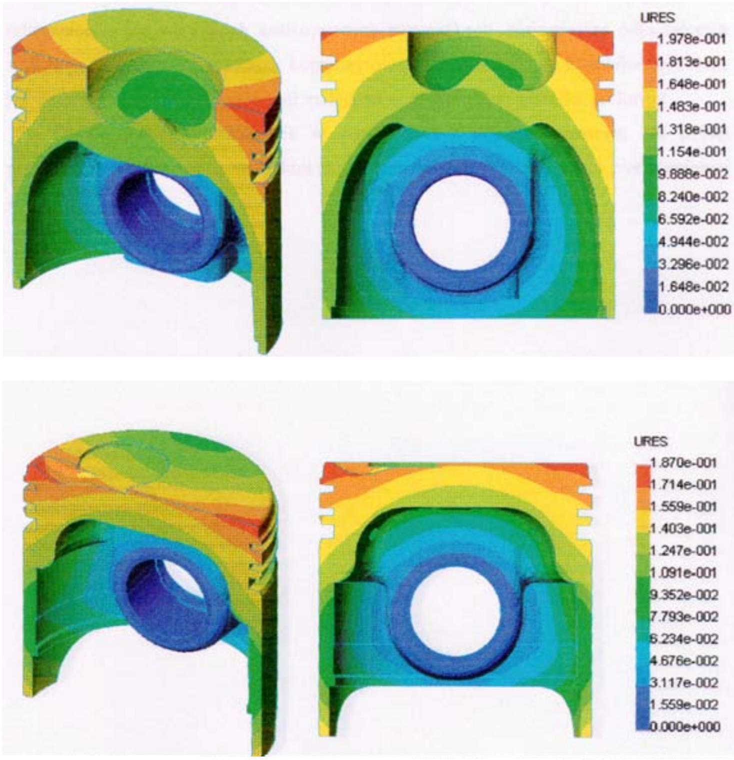

Fig. 8. Values of strains (mm) in the composite piston due to the temperature field for two different manufacturing of pistons

The dependence (4) represents the influence of basic parameters on the resistance on thermal shocks:

$$\Theta = \frac{kt}{\rho\ c\ h^2}, \tag{4}$$

where:

θ - undimensional time,
k - coefficient of thermal conductivity
t - time,
ρ - density,
c - specific heat,
h - half of slab thickness.

In fragile materials the stress concentration is usually governing and leads to damages. So the stress concentration has decisively the greatest importance in research of thermal shocks with reference to fragile materials. With reference to those materials, the stress concentration does not have such essential meaning for the single loads, but has the essential meaning, when load is applied cyclically. The thermal damage in plastic materials occurs in general after many thermal shocks. Therefore the stress concentration has capital meaning with reference to plastic materials. It is especially well visible with reference to such materials in which the metallurgical composition of the material is compactly dependent from the local plastic deformation.

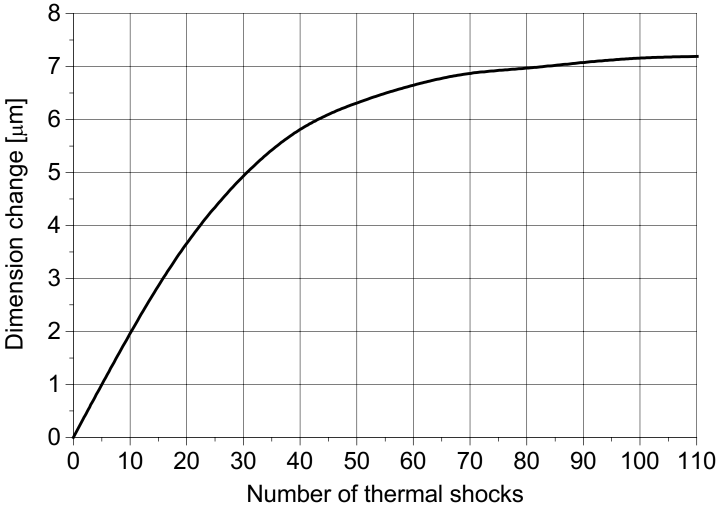

Fig. 9. The example of the influence of the thermal shocks number on the deformation of the piston sample

From other parameters affecting the resistance on thermal shocks the coefficient of linear thermal expansion should be obviously mentioned. With reference to fragile materials this resistance is inversely proportional to the coefficient of linear thermal expansion. The same also refers to plastic materials. Thus every decreasing of the coefficient of linear thermal expansion improves the resistance of the material on thermal shocks. Therefore novel materials research makes allowance for decreasing of this coefficient. Certain alloys of materials can show even negative values of this coefficient. Thus materials of the zero-coefficient of expansion will be ideal thermal materials from the point view of the resistance of parts on thermal shocks with reference to fragile materials. Other parameter influencing the resistance on thermal shocks is Young's modulus. Thus materials with small values of this modulus are more resistant to the thermal shocks. With reference to plastic materials the influence of Young's modulus is not so essential as with reference to fragile materials.

Reduction of thermal loads

The novel method of reduction of thermal loads on pistons was proposed that would subsequently result in reduction of possibilities for fatigue borne failures of the pistons. That method can be realized through the usage of new conduct of combustion process in the constant volume combustion chamber as shown on the following graph in Fig 10. The constant volume combustion chamber is obtained with swashplate. Compound Engine with piston stop configuration with swashplate is presented in Fig. 11.

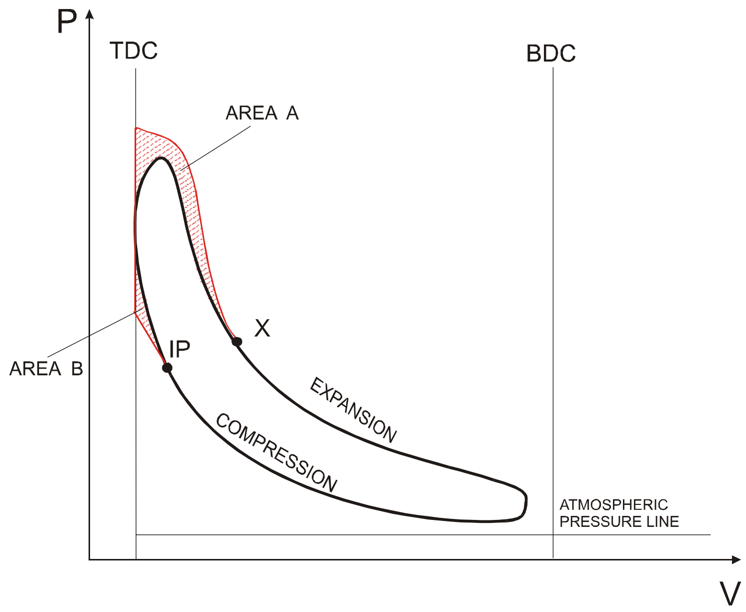

Fig. 10. Pressure changes in the piston stop cycle, Compound Engine System

The graph depicts typical cylinder pressure change P with a change of volume V in a Diesel engine. The shaded area A depicts the additional gain realized by pressure build up during the piston stop that extends to the point of piston travel X where the combustion would be completed. The area B depicts the gain realized where advance in injection and pressure build up before the TDC is eliminated.

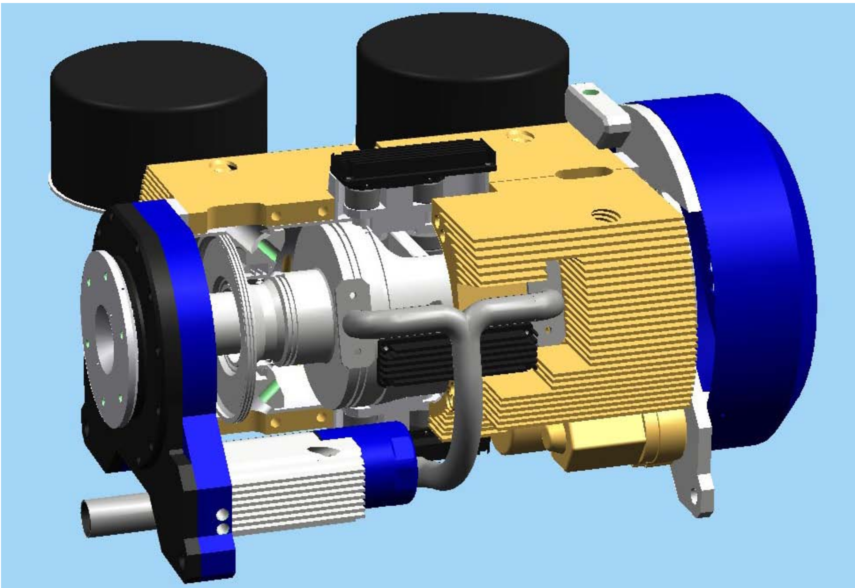

Fig .11. Compound Engine with piston stop configuration (swashplate)

The thermal loads reduction will be realized when the Compound Engine with piston stop is powered back to produce the same power from given displacement as the conventional engine, requiring less fuel, hence inducing lower thermal loads on the engine components. That method forms the part of the Patent No US 6,481.393 B1. The leading concept of that method conducts combustion in the fixed volume chamber through the piston stoppage during combustion. That system is known as Compound Engine System. The Compound Engine System allowing for superior heat dissipation from the piston due to the design feature allowing for cold piston centre as it is not in contact with hot gasses from the combustion process, and also due to the dual heat dissipation path, one the conventional through the piston skirt to the cylinder wall and the second one conducting the heat through the central portion of the piston to intake cylinder. This engine is utilizing the two-diameter piston providing the working surface as the larger piston surface area minus the surface area of the smaller piston. The larger piston bore is opening the exhaust windows at the bottom of its stroke and the smaller piston is opening the intake windows at the same time providing the through flow through the cylinder area for efficient exhaust of the burned gases and the fresh mixture or air induction into the cylinder.

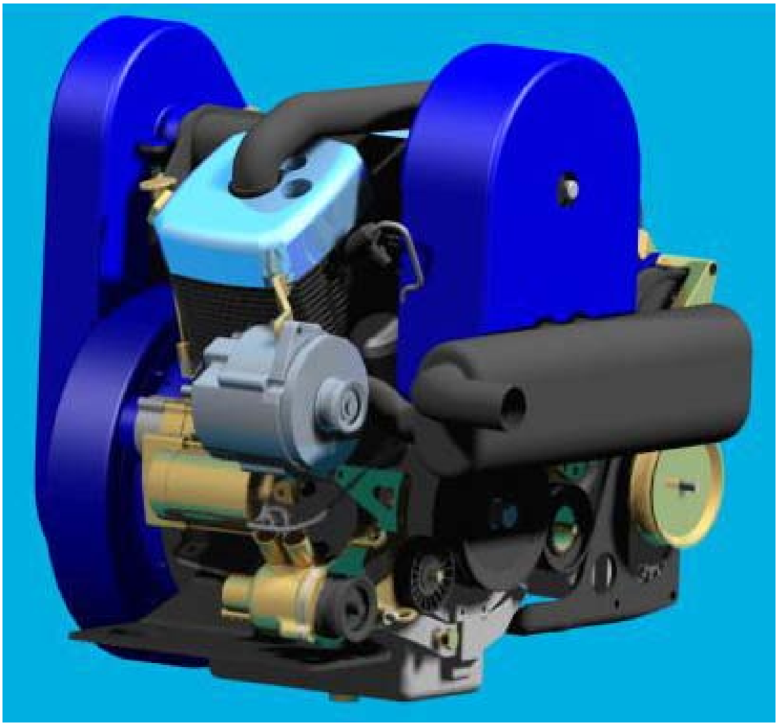

Fig. 12. Compound Engine 999cc V Twin and conventional crankshaft

The low-pressure blower is required to introduce the fresh mixture or air into the intake windows and cylinders. No valves or valve train is used and the piston cylinder lubrication is accomplished in the same manner as the conventional 4 strokes. Higher Volumetric efficiency than the conventional 2-stroke engine is expected with the basic simplicity of the design that does not have the valves and the valve drive mechanism. The above-mentioned patents addressed also the piston stop issue allowing for most of the combustion to take place in the locked constant volume combustion chamber for the greater fuel efficiency. The novel system will increase the

displacement utilization about 30% in comparison with the four-stroke engines (Fig. 14) and about Compound Engine 999cc V Twin and conventional crankshaft are presented in Fig. 12.
The conventional four-stroke engine with the hot piston centre is presented in Fig. 13.

Conclusions

The proposed new solution allows the lowering of thermal loads while in addition increasing the overall efficiency of the engine as the result of realization of combustion process while the piston is stopped. The key result of the novel design is also the complete elimination of inertial loads and isolation of mechanical loads while the piston is under the highest thermal loads (Fig. 10).

The effective design based solution for the suppression of thermal stresses in piston sections outside of the realm of material technology lies in the Compound Engine System Configuration, where the whole central section of the piston is exposed to the cold air as it is forming the part of the intake device, also the said intake device provides for the second heat path for conductive cooling of the piston. The Compound Engine Configuration virtually rewrites the rules for cooling of pistons in the internal combustion engines by creating the dual path for heat evacuation.
Young's modulus influences more essential on the resistance of thermal shocks of fragile materials, with the decrease favourably influencing the resistance. Thermal shocks occur during heterogeneous heating or cooling with reference to homogeneous materials, or homogeneous heating or cooling of heterogeneous materials. They appear also during homogeneous heating of homogeneous materials of complicated configuration.

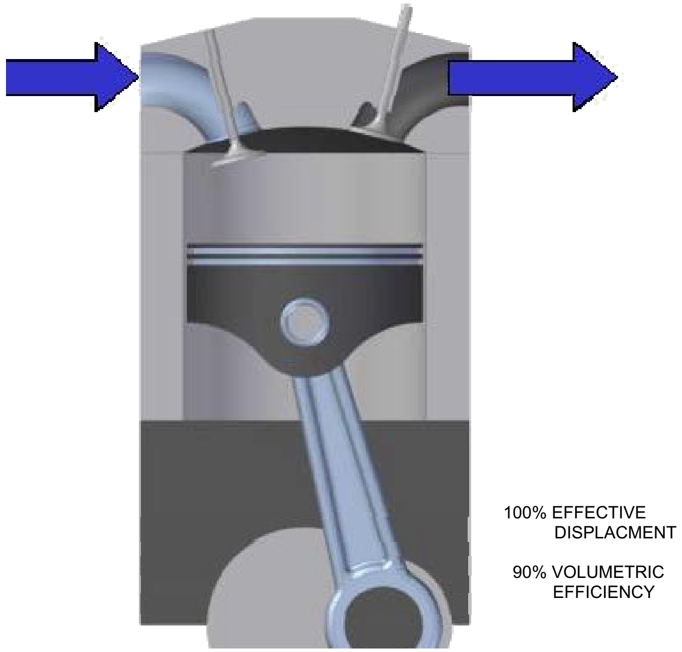

Fig. 13. Conventional four-stroke engine with the hot piston centre

The criterion of the resistance to thermal shocks with reference to fragile materials is the temperature difference at which the destruction of the material during one cycle occurs. The second criterion can be the terminal number of thermal cycles within the range settled, defining the differences of the temperature for fatigue destruction.
Compound Engine System with the cold piston centre section is shown in Fig. 14.

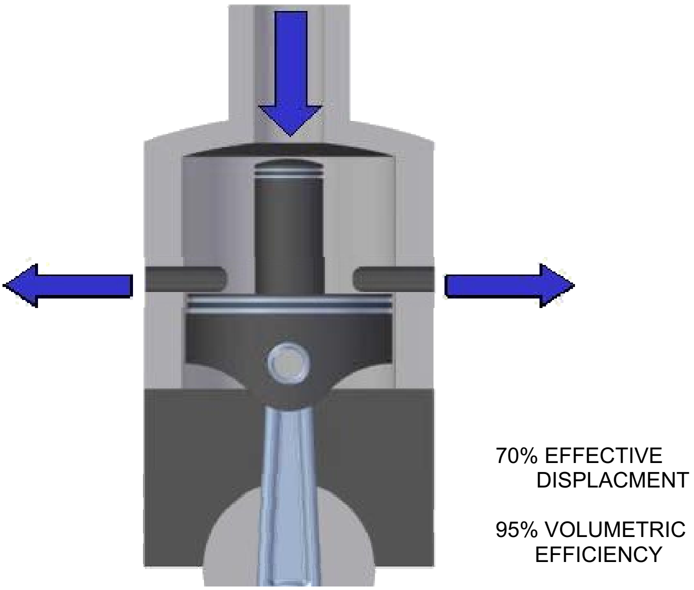

Fig. 14. Compound Engine System with the cold piston centre section

In the most cases the thermal shock resistance can be improved by increase of thermal conductivity. This should also be underlined that equations can be applied only to the infinite flat plate, but similar equations would be deduced for the same method for other cases concerning the one-dimensional heat transfer. Similarly, this should be underlined that equations are adequate only, when the duration shock appears long enough, so that the maximum stress is obtained. When the shock duration is short, the criteria do not have application. With reference to the pistons of combustion engines, the duration of thermal shock is short and from different consideration the better resistance to thermal shocks exists in the materials made on the basis of aluminum alloys than alloys of the cast iron.

A number of essential parameters were presented which can influence the improvement of the resistance to thermal shocks. Realizing this the researchers should be concentrating on decreasing of the stress concentration and minimalizing of limitations in free elongation of the part, and also, what is excessively essential, on the introduction of profitable initial stresses, as well as of protective coatings.

Observed phase transformations during research of the thermal expansibility, which occurs within the range of operating temperatures, the piston of the combustion engine modify conditions of the resistance on thermal shocks.

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