A NEW COMPACT HEAT ENGINE

by

Miodrag NOVAKOVIĆ

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The Differential Cylinder Heat Engine (DCHE) reported consists of two different size cylinders with pistons where four passages (channels) enable fluid communications between cylinders. The pistons are connected in opposition to share the work. As the channels are open and closed by movement of pistons the working fluid passing through the adequate channel is heated, cooled or let adiabaticaly flown from one cylinder to the other. The arrangement enables different thermodynamic cycles to be performed. Here the Brayton cycle is chosen by adequate choice of volume ratio and by positioning the channel apertures. During isobaric parts of the cycle the gas is adequately heated or cooled when passing through corresponding channel. During these process temperatures remain constant (and different) in each cylinder. The performance of the engine is analyzed and the parameters and efficiency determined.

Introduction

The concept of Stirling engine and Stirling cycle appears to attract the interest of researchers and inventors although it approaches to its bycentenary 1 . The Stirling engine is still further developed and succesfully applied 2 . The concept of external combustion engine is more and more attractive for developing countries as it allows free choice of inexoensive and not polluting fuels, including agricultural waste.

The proposed concept may be characterized as further development of external combustion engine at mechanical simpification.

Basic concept of DCHE

The basic DCHE engine consists of two different size cylinder where the working fluid by movement of pistons is transferred from one to the other cylinder adiabatic or with the external heat exchange during the fluid transfer. Several possible arragments of differential cylinder are possible. Differential Cylinder Heat Engine

(DCHE) with two coaxial cylinders is chosen for easy explanation of performance (Fig. 1). It can be seen that the volume of one cylinder increases while the other decreases (left large cylinder, right small cylinder). One should note that when the pistons move in such a way as to increase the volume in the large cylinder (to right) the working fluid is in expansion. The movement in opposite direction is compression.

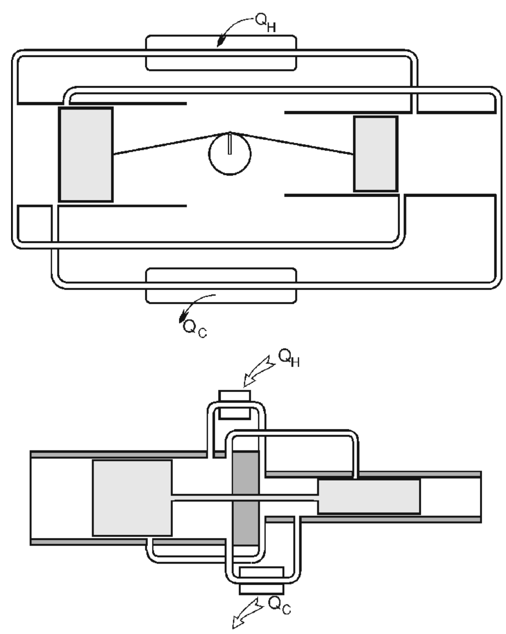

Figure 1. Variable differential cylinder arrangement

The thermodynamic system such as this one consisting of fluid (gas) in two parts of same pressure P which parts could have different temperatures is a composite one. One should have in mind that due to the linear nature of the ideal gas equation, all ideal gas laws are valid for this composit system. If M represents the total mass ($M_l + M_s$), volume V represents total volume ($V_l + V_s$) and temperature T represents average temperature ($T_l M_l/M + T_s M_s/M$)in the P, V, T, M relations. The four channels are fitted with one-way valve, permitting only one way flow of gas. It should be noted that for every position of coupled pistons and the sense of their movements there is always one channel open for passage of gas from one cylinder to the other. When the pistons moves toward right, the fluid flows from small cylinder to the large one in expansion as more space is provided in the large one in expansion as more space is provided in the large cylinder then lost in small cylinder.

Depending on the position of pistons and the sense of movements the flow is achieved through a particular channel, heated, cooled or adiabatic channel. If, during expansion it flows through non-heated channel C_2 (Fig. 2) we have an adiabatic expansion and the temperatures in cylinders and the pressure will fall. If it flows through heated channel C_1 then the joint pressure may drop, rise or remain constant depending on the temperature increase.

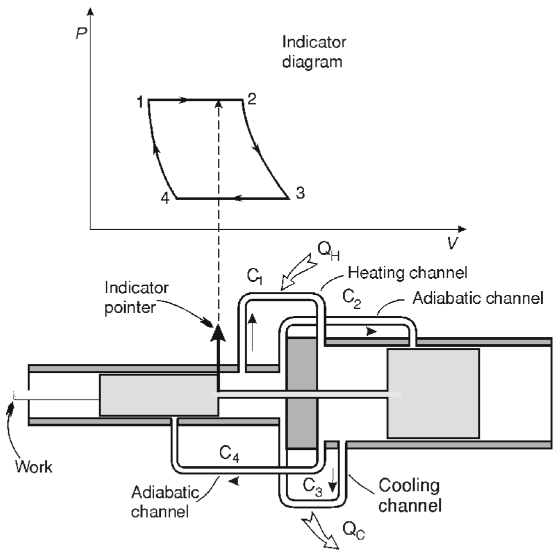

Figure 2. The heat engine with differential cylinder

The heating can be adjusted that the pressure does not change nor the temperatures in the cylinders. During such heating process temperatures in both cylinders remain constant but the average temperature rises as amount of hot gas in the large cylinder is increasing. The pressure of both parts is practically the same, as the pressure drop due flowing fluid may be very small.

Transferring all the gas from small cylinder to the large one increases its volume *r* times (the volume ratio). Increasing its temperature in heated passage at same ratio *r* times the ideal gas pressure remains same being proportional to temperature. Similar reasoning applies for flow in cooled channel.

It should be noted that the DCHE processes of fluid passing the each four channels, correspond to four processes in a Brayton cycle energy plant components (Fig. 3) 3, 4 .

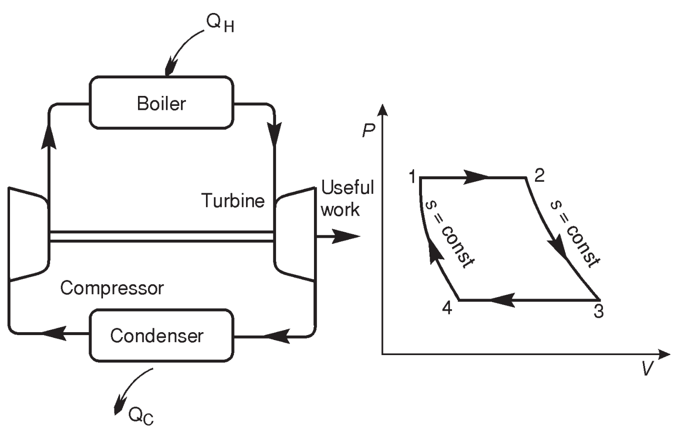

Figure 3. The Brayton cycle
(1) Flow in heated channel C_1 (see Fig. 2) – Expansion in the boiler; (2) Flow in adiabatic channel C_2 (see Fig. 2) – Expansion in the turbine; (3) Flow in cooled channel C_3 (see Fig. 2) – Compression in the condenser; (4) Flow in adiabatic channel C_4 (see Fig. 2) – Compression in the compressor

Thermodynamic properties of the DCHE

The performance of the DCHE is represented on *P-V* diagram in Fig. 4 5 . The hihghest temperature required for process T_{HS} is the heat source (reservoir) temperature. It can be deduced from a compeat isobaric process P_1 = const, assuming that whole gas is heated to T_{HS}. The T_{CS} is the heat sink temperature and can be found from isobaric process P_3 = const, assuming that the whole gas is cooled to T_{CS}. In analysis of the DCHE's performance it is useful to use the following dimensionless parameters:

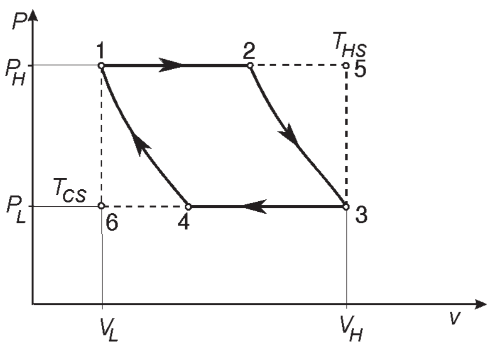

Figure 4. The DCHE on *P-V* diagram

$$\tau \quad \frac{T_{HS}}{T_{CS}} \qquad \pi \quad \frac{P_H}{P_L} \qquad r \quad \frac{V_H}{V_L} \qquad (1)$$

Substituting the expressions for V_H (V_3) and V_L (V_1) in deffinition of the dimensionless parameter *r* we have

$$\frac{D}{d} \quad \sqrt{r} \qquad (2)$$

where *D* and *d* are the diameters of the large and the small cylinder respectively.

Applying adequate equations T/V = = const, and PV^k = const for isobaric and adiabatic processes of the cycle respectively, all the *P*, *V*, *T* data for points 1, 2, 3 are expressed as function P_L, V_L, T_l and dimensionless parameters π and r (see Table 1). The temperature of cold and hot source, T_{CS}, T_{HS} are also determined (points 6 and 5 respectively in Fig. 4)

$$T_{CS} \quad T_l \pi^{\frac{1}{k}} \qquad (3)$$

$$T_{HS} \quad T_l r \pi^{\frac{k \ 1}{k}} \qquad (4)$$

It should be noted that there is no fluid with temperature T_2 and T_4, these temperatures correspond to mixed temperature of the fluid in large and small cylinder (V_l and V_s).

Using the eq. (3) the temperatures of points 1, 2, 3, 4 are also expressed by T_{CS} (see Table 1).

It is useful to find the relation between the parameters. Combining the eq. (1a) with the expressions for T_{HS} and T_{CS} one can get the following relation

$$\tau = r\pi \qquad (5)$$

Thermal efficiency of the Brayton cycle is 6, 7

$$\eta = 1 - \pi^{-\frac{k-1}{k}} \tag{6}$$

from eq. (6) it is clear that the thermal efficiency of the Brayton cycle increases with the cycle's pressure ratio π. The DCHE has limitation that depends on the temperature ratio T_{HS}/T_{CS}. T_{HS} is the temperature of the heat reservoir and depends on the used fuel. T_{CS} is the lowest available temperature, *i. e.* The temperature of the surrounding. So, for the given temperature ration τ the DCHE has a maximum heat efficiency when the pressure ratio π has a maximum value.

Table 1. The DCHE's state properties

	P	V	T	T
1	$P_L\pi$	V_L	$T_l\pi^{(k-1)/k}$	$T_{CS}\pi$
2	$P_L\pi$	$V_L r\pi^{-1/k}$	$T_l r\pi^{(k-2)/k}$	$T_{CS} r\pi^{(k-1)/k}$
3	P_L	$V_L r$	$T_l r\pi^{-1/k}$	$T_{CS} r$
4	P_L	$V_L\pi^{1/k}$	T_l	$T_{CS}\pi^{1/k}$
5	$P_L\pi$	$V_L r$	$T_l\pi^{-1/k}$	T_{CS}
6	P_L	V_L	$T_l r\pi^{-(k-1)/k}$	T_{CS}

It is obvious that the lowest possible volume ratio $r_{\min}$ will be when $V_2 \rightarrow V_1$ and $V_3 \rightarrow V_4$, whence

$$r_{\min} = \frac{V_1}{V_3} = \frac{P_1}{P_4} = \pi^{\frac{1}{k}}$$

combining with eq. (5) one can get

$$\pi_{\max} = \tau^{\frac{k}{k-1}} \tag{7}$$

The DCHE's maximum useful work of a cycle per unit mass

The useful work per unit mass in a cycle is

$$W = q_{\exp} - q_{compr}$$

having in mind

$$q_{\exp} = C_p(T_2 - T_3) \qquad \text{and} \qquad q_{compr} = C_p(T_1 - T_4)$$

substituting for T_1, T_2, T_3 and T_4 from Table 1 (last column):

$$W_m^* = \frac{W}{C_p T_{CS}} = (\pi^{\frac{1}{k}} + r\pi^{\frac{k-1}{k}} - r - \pi) \tag{8}$$

whence, with eq. (5) and $k_1 = 1/k$, we have

$$W_m^* \quad \frac{W}{C_p T_{CS}} \quad r^{\ k_1} \tau^{k_1} \quad r^{k_1} \tau^{1\ \ k_1} \quad r \quad r^{\ 1} \tau \tag{9}$$

Where W_m^* is a the dimensionless useful work per unit mass. The maximum value of W_m^* at given the π occures when the first derivative with respect to r is zero:

$$\frac{\partial}{\partial r}(W_m^*)_{\tau \ \ const} \quad k_1 r^{\ k_1 \ \ 1} \tau^{k_1} \quad k_1 r^{k_1 \ \ 1} \tau^{1 \ \ k_1} \quad 1 \quad r^{\ 2} \tau \quad 0 \tag{10}$$

The nonlinear eq. (10) is solved by Newton-Rhapson iteration technique.

Results and discussion

Figure 5 shows a plot of thermal efficiency of the DCHE *vs*. temperature ratio τ.

The curve ETHAMAX represent the case of the theoretical maximum possible η for the given τ. The other curve (WMMAX) represents the values of η for the given τ when the maximum useful work is achieved per unit mass. The following Fig. 6 gives us the value of D/d *vs*. τ. Finally in Fig. 7 the values of dimensionless useful work per unit mass (eq. 9) *vs*. τ is given, with parameters of WMMAX (eq. 10) and with T_{CS} = 300 K.

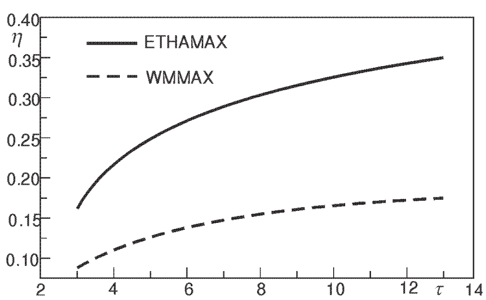

Figure 5. Thermal efficiency of the DCHE *vs.*τ

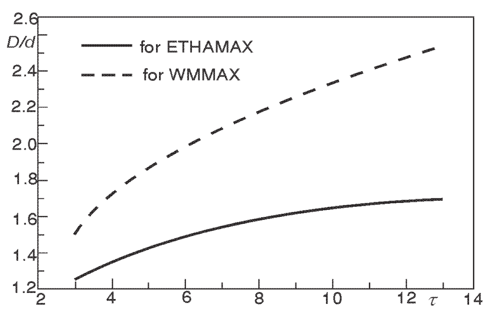

Figure 6. The DCHE's cylinders ratio *vs.*τ

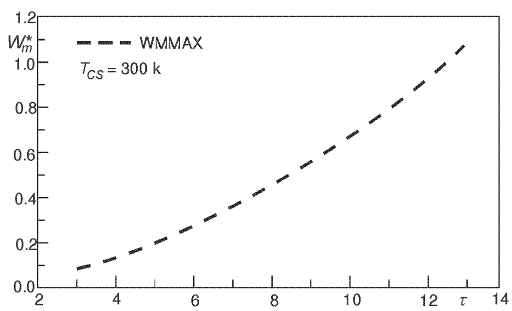

Figure 7. Dimensionless work of the DCHE *vs.* τ

Nomenclature

C_p J/kgK – specific heat capacity at constant pressure
C_v [J/kgK] – specific heat capacity of constant volume
D m – diameter of the large cylinder
d m – diameter of the small cylinder
k – specific heat ratio $k = C_p/C_V$
M [kg] – total mass of working fluid
M_l [kg] – mass of working fluid in large cylinder
M_s [kg] – mass of working fluid in small cylinder
P Pa – pressure
P_H [Pa] – high pressure
P_L [Pa] – low pressure
Q_H J – total heat given to the cycle at high temperature
Q_C J – total heat extracted from the cycle in condenser
q J/kg – heat exchanged per 1 kg of working fluid
r – volume ratio
$r_{\min}$ – theoretical minimal volume ratio of DCHE
s J/kg – Enthropy
T K – absolute temperature
T_{CS} K – temperature of cold source sink
T_{HS} K – temperature of hot source
Te [K] – temperature of working fluid in large cylinder
V_L [m^3] – volume of working fluid after compresion
V_H [m^3] – volume of working fluid after expansion
V_l m^3 – volume of large cylinder
V_s – volume of small cylinder
W J/kg – useful work
W_m^* – dimensionless useful work

Greek symbols

π – Pressure ratio
τ – Temperature ratio
η – Thermal efficiency

References

1 Organ, A. J., Analysis of the Gas Turbine Rotary Regenerator, *Proc. Instn. Mech. Engs., Vol. 211* (1977), Part D, pp. 97–102
2 SIGMA Elektroteknisk A.S. N-1550 Helen, Norway
3 Chicurel, R., A Modified Otto Engine for Fuel Economy, *Applied Energy*, *38* (1988), pp. 105–107
4 Aly, S. E., Diesel Engine Waste Heat Power Cycle, *Applied Energy, 29* (1988), pp. 179–182
5 Šarenac, R. Z., MSc thesis, Department of Mechanical Engineering, University of Novi Sad, Novi Sad, Yugoslavia (1980)
6 Van Wylen, G. J., Thermodynamics, John Wiley and Sons, New York, 1959
7 Novaković, M., Djurić, M., Technical Thermodynamics, Faculty of Technology, University of Novi Sad, Novi Sad, Yugoslavia, 1998

Author's address:

M. Novaković
Faculty of Technology, University of Novi Sad
Bul. Cara Lazara 1, 21000 Novi Sad, Yugoslavia

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