A NEW APPROACH ON THE NOTION OF GENERALIZED THERMODYNAMIC CYCLE IN GAS THERMAL ENGINES

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Rezumat. *Se introduce un ciclu termodinamic în care agentul primeşte şi cedează căldură prin toate cele trei transformări termodinamice simple (v = ct., p = ct. şi T = ct.). Cele două lanţuri de câte trei transformări sunt legate prin transformări adiabatice. Căldura cedată în transformare de răcire izocoră şi izobară este recuperată parţial, fiind reintrodusă în ciclu în timpul transformărilor de încălzire izocoră şi izobară. Transformările simple din ciclu sunt definite prin rapoarte parţiale de comprimare şi de destindere sau prin rapoarte parţiale de temperatură. Se introduce randamentul recuperării căldurii. Se dau relaţiile pentru randamentul termic şi pentru lucrul mecanic produs în ciclul generalizat.*

1. INTRODUCTION

In 1955, Emil Gaiginschi has analyzed a general thermodynamic cycle of the internal combustion piston engines [1]. The thermodynamic cycle (fig. 1) refers to an ideal engine inside which the gas receives heat from a heat source in all three basic possible ways, namely through an isochoric, an isobaric and an isothermal process, and yields heat to a cold source also through all possible processes. The group of three thermodynamic processes through which the heat gets introduced is linked with the one of the three thermodynamic processes through which the heat is extracted from the cycle through an isoentropic process of compression and through an isoentropic expansion process. In internal combustion engines general cycles, the processes of adding and rejecting heat take place in the following order: the first is an isochoric process, second an isobaric process and last an isothermal process.

If the heat extracted from the cycle during the isochoric and isobaric heat rejection processes is partially reintroduced in the cycle during the isochoric and isobaric heat addition processes, then the so called Generalized Heat Regenerating Cycle for Gas Thermal Engines is obtained, notion already proposed by the authors in [2].

The paper presents a new approach concerning the property analysis of the Generalized (Universal) Heat Regenerating Cycle for Gas Thermal Engines by using partial temperature ratios.

2. GENERALIZED REGENERATIVE THERMODYNAMIC CYCLE OF GAS THERMAL ENGINES

The GHRCGTE comprises all eight thermodynamic processes present inside the Gaiginschi cycle [1], introducing as innovation heat recovery processes that retrieve some of the cycle rejected energy (fig. 2). The heat regeneration processes are characterized by the heat regeneration ratios:

$$\eta_{rv} = \frac{q_{rv}}{q_{2v}} \text{ and } \eta_{rp} = \frac{q_{rp}}{q_{2p}}, \tag{1}$$

where q_{rv} and q_{rp} are the amounts of heat regenerated in those processes and q_{2v} and q_{2p} are the amounts rejected in the respective processes.

It is to prefer expressing the total amount of regenerated heat $q_r = q_{rv} + q_{rp}$ through the overall efficiency of the heat regenerating processes, efficiency defined by the following relations:

$$\eta_r = \frac{q_r}{q_{2v} + q_{2p}} = \frac{\eta_{rv} \cdot q_{2v} + \eta_{rp} \cdot q_{2p}}{q_{2v} + q_p}. \tag{2}$$

3. ANALYSIS OF THE GENERALIZED HEAT REGENERATING CYCLE FOR GAS THERMAL ENGINES BY MEANS OF PARTIAL VOLUMETRIC RATIOS

To analyze the generalized regenerative thermodynamic cycle, 1 kg of ideal gas is employed as working fluid and the partial volumetric ratios for the isobaric compression ε_p, the isothermal compression ε_t, the adiabatic compression ε_a are defined, as well as the partial volumetric ratios for the isobaric expansion δ_p, the isothermal expansion δ_t and the adiabatic expansion δ_a:

$$\varepsilon_p = \frac{v_1}{v_2};\ \varepsilon_t = \frac{v_2}{v_3};\ \varepsilon_a = \frac{v_3}{v_4};$$
$$\delta_p = \frac{v_6}{v_5};\ \delta_t = \frac{v_7}{v_6};\ \delta_a = \frac{v_8}{v_7}, \tag{3}$$

where v_1, v_2 ... v_8 are the specific volumes of the gas at the peaks of the cycle.

The isochoric pressure ratio λ is also defined, i.e. a ratio equal to the isochoric temperature ratio:

$$\lambda = \frac{p_5}{p_4} = \frac{T_5}{T_4}. \tag{4}$$

Using Eqs. (1) and (2) and the basic thermodynamic processes equations, the temperatures at the cycle peaks are calculated and the expressions in Table 1 are obtained.

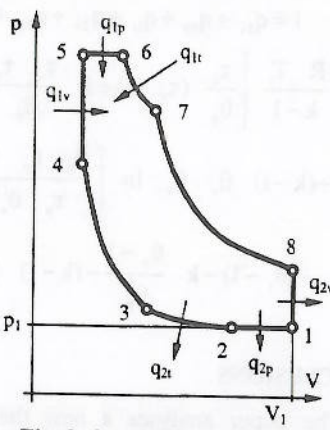

Fig. 1. General Cycle for Gas Thermal Engines [1].

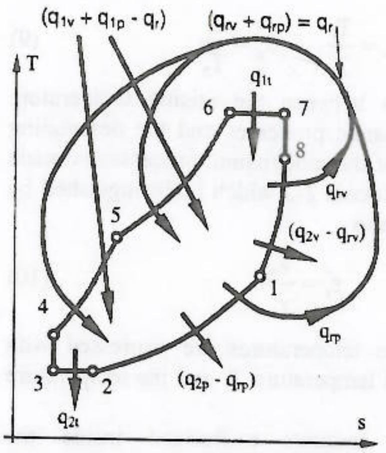

Fig. 2. Generalized Heat Regenerating Cycle for Gas Thermal Engines [2].

Table 1. *Temperature expressions at cycle peaks*

Peak	1	2	3	4	5	6	7	8
Temperature	T_1	$\frac{T_1}{\varepsilon_p}$	$\frac{T_1}{\varepsilon_p}$	$\frac{\varepsilon_a^{k-1}}{\varepsilon_p} T_1$	$\lambda \frac{\varepsilon_a^{k-1}}{\varepsilon_p} T_1$	$\delta_p \lambda \frac{\varepsilon_a^{k-1}}{\varepsilon_p} T_1$	$\delta_p \lambda \frac{\varepsilon_a^{k-1}}{\varepsilon_p} T_1$	$\lambda \frac{\delta_p}{\varepsilon_p} \frac{\varepsilon_a^{k-1}}{\delta_a^{k-1}} T_1$

Table 2. *Heat amounts exchanged*

Process	heat added to the cycle	heat rejected from the cycle
isochoric processes 4-5 and 8-1	$q_{1v} = \frac{R\ T_1}{k-1} \frac{\varepsilon_a^{k-1}}{\varepsilon_p} (\lambda - 1)$	$q_{2v} = -\frac{R\ T_1}{k-1}\left(\lambda\ \delta_p\ \frac{\varepsilon_a^{k-1}}{\varepsilon_p}\ \frac{1}{\delta_a^{k-1}} - 1\right)$
isobaric processes 5-6 and 1-2	$q_{1p} = \frac{k\ R\ T_1}{k-1} \frac{\varepsilon_a^{k-1}}{\varepsilon_p}\ \lambda\ (\delta_p - 1)$	$q_{2p} = -\frac{k\ R\ T_1}{k-1} \frac{\varepsilon_p - 1}{\varepsilon_p}$
isothermal processes 6-7 and 2-3	$q_{1t} = R\ T_1\ \lambda\ \delta_p\ \frac{\varepsilon_a^{k-1}}{\varepsilon_p}\ \ln(\delta_t)$	$q_{2t} = -\ R\ T_1\ \frac{1}{\varepsilon_p}\ \ln\ (\varepsilon_t)$

The expressions of the heat amounts exchanged during each process are acquired by employing the expressions of peak temperatures in the cycle (table 2).

The thermal efficiency for the GRCGTE has the following expression:

$$\eta_{tr} = 1 - \frac{|q_{2v}| + |q_{2t}| + |q_{2p}| - q_r}{q_{1v} + q_{1t} + q_{1p} - q_r} = 1 - \frac{q_{\text{rejected}}}{q_{\text{added}}}, \quad (5)$$

where

$$q_{\text{rejected}} = \frac{R\ T_1}{k-1}\frac{1}{\varepsilon_p}\left\{(1-\eta_r)\left[\left(\lambda\ \frac{\delta_p\ \varepsilon_a^{k-1}}{\delta_a^{k-1}} - \varepsilon_p\right) + k(\varepsilon_p - 1)\right] + +(k-1)\ \delta_p\ \ln\ (\varepsilon_t)\right\}; \quad (6)$$

$$q_{\text{added}} = \frac{R\ T_1}{k-1}\ \frac{\varepsilon_a^{k-1}}{\varepsilon_p}\left\{(\lambda - 1) + k\ \lambda\ (\delta_p - 1) + +(k-1)\lambda\delta_p \ln(\delta_t) - \eta_r\left[\left(\frac{\lambda\ \delta_p}{\delta_a^{k-1}} - \frac{\varepsilon_p}{\varepsilon_a^{k-1}}\right) + k\frac{\varepsilon_p - 1}{\varepsilon_a^{k-1}}\right]\right\}. \quad (7)$$

For the work yielded in the cycle the following expression was obtained

$$l = l_{1p} + l_{1t} + l_{1a} + l_{2p} + l_{2t} + l_{2a} =$$
$$= \frac{R\ T_1}{k-1}\frac{1}{\varepsilon_p}\left\{\lambda\varepsilon_a^{k-1}\left[k(\delta_p - 1) + (k-1)\delta_p \ln(\delta_t) + \frac{\lambda - 1}{\lambda}\right] - \left[k(\varepsilon_p - 1) + (k-1)\ln(\varepsilon_t) + \lambda\delta_p\frac{\varepsilon_a^{k-1}}{\delta_a^{k-1}} - \varepsilon_p\right]\right\} \quad (8)$$

4. ANALYSIS OF THE GENERALIZED HEAT REGENERATING CYCLE FOR GAS THERMAL ENGINES BY MEANS OF PARTIAL TEMPERATURE RATIOS

Partial temperature ratios were introduced in order to individuate the processes that make up the cycle submitted to analysis:

$$\tau_a = \frac{T_4}{T_3}, \quad \tau_v = \frac{T_5}{T_4}, \quad \tau_p = \frac{T_6}{T_5}$$

and $\theta_a = \frac{T_7}{T_8}$, $\theta_v = \frac{T_8}{T_1}$, $\theta_p = \frac{T_1}{T_2}$. (9)

The connection between the raising temperature chain of thermodynamic processes and the descending temperature chain of thermodynamic processes is made by the isothermal process 2-3 which is distinguished by the partial volume ratio

$$\varepsilon_t = \frac{v_2}{v_3}. \quad (10)$$

The peak cycle temperatures are expressed with respect to the initial temperature T_1 and the temperature ratios (table 3).

Specific heat amounts exchanged inside the GRCGTE processes are described in table 4.

The efficiency of GRCGTE is shaped by the expression (5), where

$$q_{rejected} = \frac{R\ T_1}{k-1}\left\{(1-\eta_r)\left[(\theta_v - 1) + k\frac{\theta_p - 1}{\theta_p}\right] + (k-1)\ \ln\ (\varepsilon_t)\right\} \quad (11)$$

$$q_{added} = \frac{R\ T_1}{k-1}\left\{\frac{\tau_a}{\theta_p}\ (\tau_v - 1) + k\ \frac{\tau_a\ \tau_v}{\theta_p}\ (\tau_p - 1) + (k-1)\ \theta_a\ \theta_v\ \ln\left(\frac{\theta_p\ \varepsilon_p\ \tau_a^{1/(k-1)}}{\tau_p\ \theta_a^{1/(k-1)}}\right) - \eta_r\left[(\theta_v - 1) + k\ \frac{\theta_p - 1}{\theta_p}\right]\right\}. \quad (12)$$

The work performed by the cycle is obtained by:

$$l = q_{1v} + q_{1p} + q_{1t} + q_{2v} + q_{2p} + q_{2t} = \frac{R\ T_1}{k-1}\left[\frac{\tau_a}{\theta_p}\ (\tau_v - 1) + k\ \frac{\tau_a\ \tau_v}{\theta_p}\ (\tau_p - 1) + (k-1)\ \theta_a\ \theta_v\ \ln\left(\frac{\theta_p\ \varepsilon_p\ \tau_a^{1/(k-1)}}{\tau_p\ \theta_a^{1/(k-1)}}\right) - (\theta_v - 1) - k\ \frac{\theta_p - 1}{\theta_p} - (k-1)\ \ln\ (\varepsilon_t)\right]. \quad (13)$$

CONCLUSIONS

The paper analyses a new thermodynamic cycle with heat regeneration, cycle that has a generalized (universal) character for all gas thermal engines and establishes computation expressions for the thermal efficiency and the work yielded inside it.

By individuating the generalized cycle, all previously known cycles corresponding to piston or blade engines, with or without heat regeneration, are obtained (Stirling, Ericsson, Brighton, Rallis, Gaiginschi [1], Diesel, Otto, Carnot).

Employing partial volumetric ratios, the GRCGTE's expressions of the thermal efficiency and of the work per cycle are easier to be individuated in the case of cycles comprising adiabatic processes. Employing partial temperature ratios, the same expressions are also to be preferred when cycles comprising isothermal processes are involved.

Table 3. Expressions of peak cycle temperature

Peak	1	2, 3	4	5	6	7	8
Temperature	T_1	$\frac{T_1}{\theta_p}$	$\frac{\tau_a}{\theta_p}\ T_1$	$\frac{\tau_a\ \tau_v}{\theta_p}\ T_1$	$\frac{\tau_a\ \tau_v\ \tau_p}{\theta_p}\ T_1$	$\theta_a\ \theta_v\ T_1$	$\theta_v\ T_1$

Table 4. Expressions for specific heat amounts

Processes	Specific heat amounts	
	added to the cycle	rejected from the cycle
isochoric: 4-5 and 8-1	$q_{1v} = \frac{R\ T_1}{k-1}\ \frac{\tau_a}{\theta_p}\ (\tau_v - 1)$	$q_{2v} = -\ \frac{R\ T_1}{k-1}\ (\theta_v - 1)$
isobaric: 5-6 and 1-2	$q_{1p} = \frac{k\ R\ T_1}{k-1}\ \frac{\tau_a\ \tau_v}{\theta_p}\ (\tau_p - 1)$	$q_{2p} = -\frac{k\ R\ T_1}{k-1}\ \frac{\theta_p - 1}{\theta_p}$
isothermal: 6-7 and 2-3	$q_{1t} = R\ T_1\ \theta_a\ \theta_v\ \ln\left(\frac{\theta_p\ \varepsilon_p\ \tau_a^{1/(k-1)}}{\tau_p\ \theta_a^{1/(k-1)}}\right)$	$q_{2t} = -\ R\ T_1\ \ln\ (\varepsilon_t)$

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