A Comparative Analysis of the Final Phases of the Expansion Process in Diesel Power Cycles with Non - synchronized and Synchronized Turbochargers

V. A. Shouripa and Si - Young Kim*

Far Eastern Technical Institute of Fish Industry and Economy
*Pukyong National University

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동기 및 비동기화된 디젤엔진 싸이클에서 팽창 최종단계의 비교 분석

V. A. Shouripa · 김 시 영

극동수산대학교, 부경대학교

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요 약

터빈 노즐 면적을 최적화함과 동시에 동기화 시킴으로서 기관의 싸이클 특성의 변화를 시도하였다. 그 결과 동력 추출을 위한 가스 유동이 제한을 받게 되고 최종의 팽창비 δ에 의하여 싸이클의 변화가 이루어졌으며 동력의 이득은 싸이클 효율이 증가됨으로써 성취되었다.

SYMBOLS AND ABBREBIATIONS

G_{ij} : gas flow rate

H_{ij} : specific gas power front of the turbine

H_{ij_n} : specific available turbine power

K : isentropic number

p_t : the gas pressure front of the turbine [kg/cm²]

p_{t_n} : the gas pressure after the turbine [kg/cm²]

R : gas constant number.

$T_{t_{ij}}$: the gas temperature front of the turbine [° K]

η_{ij} : internal efficiency of the turbine

i : index of the current crank shaft angle

j : undex turbine gas inlet

$\phi_i - \phi_1$: angle range, determinning exhaust phase.

p_k : supercharging pressure [kg/cm²]

p_o : atmosphere pressure [kg/cm²]

η_{ij} : turbine efficiency.

ε : compression ratio$(=\frac{v_0}{v_c})$

λ : pressure ratio$(=\frac{p_z}{p_c})$

n_1 : polytropic number of the compression process

n_2 : polytropic number of the expansion process.

ρ : preliminary expansion ratio

ε : cut - off ratio$(=\frac{V_a}{V_c}, =\frac{V_b}{V_c})$

ρ : preliminary expansion ratio.$(=\frac{V_z}{V_c})$

1. INTRODUCTION

The synchronization of the mass flow rate by of gas variation of the turbocharger nozzle area according to the crank angle during the exhaust stroke from every cylinder gives engineers an opportunity to decrease power losses that a turbocharger usually caused. The decrease of the exhaust gas power expended for the turbocharger has exerted by observed positive effect on internal combustion. The difference between power synchronized and non - synchronized turbocharging may be exploited for the internal efficiency of the cylinder - piston section of the turbocharged diesel engine and may be passed on to the crankshaft.

2. THEORETICAL ANALYSIS

The main pre - condition of effective comparison must be constant pressure at the terminal part of the combustion stage p_z and constant turbocharging pressure. According to the generally accepted expression of Orlin(1983), the mean indicated pressure is

$$p_{it} = \frac{p_c}{\varepsilon - 1}[\lambda(\rho - 1) + \lambda\rho(1 - \frac{1}{\delta^{n_2-1}})\frac{1}{n_2 - 1} - (1 - \frac{1}{\varepsilon^{n_1-1}})\frac{1}{n_1 - 1}] \quad (1)$$

The average indicated pressure determines the indicated power N_i and indicated efficiency η_i.

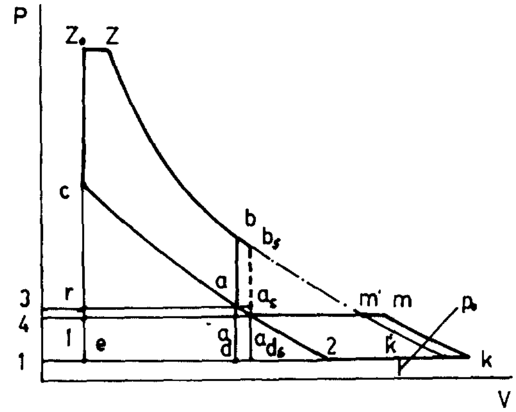

Fig. 1 Superposed theoretical p - V diagram of a diesel, turbine and compressor four - stroke engine

Usually there are two distinct areas in Figure 1 representing energy available from the exhaust gas the blow - down (area b - k - d) and work done by the piston (area a' - d - e - i). The maximum potential energy available to drive a turbocharger turbine has already been established as the sum of these two areas. Although the energy associated with one area is easier to harness than the other, it is difficult to device a system that will harness all the energy. To achieve that, the inlet pressure must rise instantaneously to p_e when the exhaust valve opens, followed by isentropic expansion of the exhaust gas through p_e to the ambient pressure $p_k = p_o$ which must be held at p_m, such a series of processes is impracticable. But there is the possibility to harness part of the lost energy by increase of area $b_s - a_s - a - b$(Fig. 1).

Superimposed theoretical $p - V$ diagrams of a diesel, turbine and compressor four - stroke engine are suggested. Along line 2 - a the air is compressed from atmospheric pressure $p_o = p_2$ to the turbocharging pressure. Line 1 - 2 and a - 3 show the state of the air before and after its compression in the air compressor.

Lines r - a and a - c represent respectively air delivery to the engine cylinder and compression. Line $c - z_0 - z$ represent combustion, line $z - b$ the expansion of gases without synchronization, and line $b - a - a' - i - r$ outflow and discharge of gases from the cylinder (without synchronization). The gas pressure in the cylinder during the exhaust stroke will be lower than the turbocharging pressure within the entire piston stroke. Upon leaving the cylinder, the products of combustion expand in the exhaust manifold to a pressure of $p_{\exp}=p_{ep}$ and their temperature is reduced to the value of *Tep'*. The parameters of the gas (pep, *T'ep*) before the turbine blades is characterized by point m'. Expansion of the gases in the turbocharger blades takes place along line m' - k' down to pressure p_{epo} which theoretically will be equal to the atmospheric pressure $p_{epo}=p_{ep}$.

Lines 4 - m' and k' - 1 represent the condition of gases before the gas turbocharger and after it.

Area 1 - 2 - a - 3 shows the potential energy of air compression in the air blower and area 4 - m' - k' - 1 illustrates the potential energy of the gas turbocharger. The difference of these areas expresses the loss of energy in the transformation of energy in the turbine and compressor sections of the turbocharger. Areas r - a - a' - i and $a - c - z_0 - z - b$ characterize work of the engine.

Area b - m' - a represents the work expended by the gas, under the throttling effects when passing through the engine exhaust valves and turbine nozzle assembly, and when expanding through the exhaust pipe. This energy is not lost completely since it raises the gas temperature (*to* T_{ep}) and specific volume (to v_m) before the turbine blades. Therefore, the actual state of the gas before the turbine is represented by point m, while area m' - m - k - k' indicates the increase of the work performed by the gas in the turbine.

The depth of the expansik on process is estimated by the ratio of subsequent expansion $\delta = V_b/V_z$. The value of δ is interrelated with the values of ε and ρ by the following equation

$$\delta = \frac{V_b}{V_z} = \frac{V_b V_e}{V_c V_z} = \frac{\varepsilon}{\rho} \tag{2}$$

For turbocharger turbine operation, exploitation is necessary of a specific useful part of the power stroke on which turbocharger turbine efficiency depends. The power and efficiency gain from this turbine enables later opening of exhaust valves in synchronized conditions than in non - synchronized conditions.

The increase of the turbine power and the turbine efficiency in the free flowing as well as forced exhaust periods, as well as the whole of the scavenging period, allow p_{tij} before turbine pressure decreases while maintaining the turbocharging operating and efficiency parameters, from Orlin(1983)

$$N_{til} = \frac{K}{K-1} R T_{til} \left[1 - \left(\frac{p_{t_o}}{p_{tij}} \right)^{\frac{K-1}{K}} \right] \eta_{tij} G_{tij} \tag{3}$$

The temperature of the gas at the terminal part of expansion

$$T_b = \frac{T_z}{\delta^{n_2 - 1}} \tag{4}$$

where there are equal combustion parameters, is decreased, thereby limiting the raising of turbine power. With a equal piston displacement without any change in *L/D* and with little increase in the range of the power generating stroke L_u of the synchronized cycle exponent number η_2 is decreased insignificantly, because the cooling area per unit of the expanding gases becomes greater, L - the value of power generating piston stroke movement, D - the

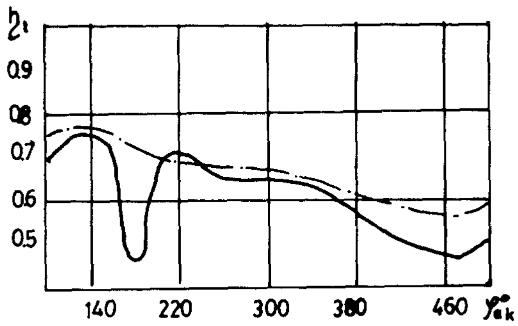

Fig. 2 Turbine officiency durin one cycle of the exhaust
—— **nonsynchronic turbine**
– · – **synchronic turbine**

value of piston diameter. Fig. 2 Turbocharging efficiency during one exhaust cycle from each cylinder (six cylinders, four - strokes, two gas inlets in the turbine).

3. DISCUSSION AND RESULTS

Average internal power of the synchronized turbine was estimated during one exhaust stroke, but it was influenced by the expansion process in the final part of the cycle which was analyzed because the power of the turbocharging was increased significantly during all phases of the exhaust process.

$$N_{T_s} = \frac{1}{\phi_i - \phi_1} \sum_{1}^{i=\phi} \sum_{1}^{j=m} G_{ij} H_{ij} \eta_{ij} \qquad (5)$$

The power increase of 9%, allow the decreasing of pressure p_t of 6.1%.

The determination of the gas temperature and pressure, the line of expansion in conditions of synchronization was expressed as a polytropic curve represented by the equation $pv^{n_2}=const$ with a constant mean exponent n_2, this curve had the same values of pressure and temperature at the end of the expansion phase as the polytropic curve, with varying exponents, in order to compare the two types of cycle, The mean exponents of the polytropic expansion curve were affected by how even the afterburning and cooling of the gases were as well as by the loss of gases through loose piston rings during the expansion stroke. So that dividing of the exhaust did not influence the basic part of the expansion, when the quantity of afterburning fuel increased, which led to reduction of the heat utilization coefficient, the exponent n_2 decreased also. In so far as synchronization may be used on the variable speed of the engine, the value of n_2 was also influenced by these conditions. An increase of the mean piston speed reduced the duration of expansion and, consequently, the period of heat exchange between the gases and the cylinder walls and gas losses through the piston rings. However, a rise of engine speed increased afterburning of the fuel during expansion because the higher speed reduced the time available for combustion along the line c - zo - z.

Correlation between point b and bs was determined by the polytropic equation

$$p_b \cdot v_b^{n2} = p_{bs} \cdot v_{bs}^{n2} \qquad (6)$$

The volume of the gas before the opening of the valve was determined from this equation

$$v_{bs} = \left(\frac{p_b}{p_{bs}}\right)^{1/n_2} v_b \qquad (7)$$

The difference of the volume or cylinder which was necessary for useful work of the engine, maintaining power output and decreasing power losses from air induction may be determined as

$$\Delta v_{bs} = \left(\frac{p_b}{\Delta p_{bs}}\right)^{1/n_2} \cdot v_b \qquad (8)$$

The change of the pressure p_{bs} of 6.4% increased the specific volume of the gas in the final part of the exhaust stroke and diesel

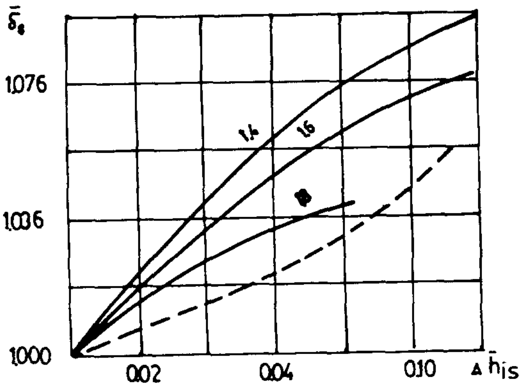

Fig. 3 The incrise relative degree of subsiquent expansion $\bar{\delta}_s = \delta_s/\delta$ depended from increase specific turbin power Δh_{is} —— change pk — · — Limit Line

cycle.

The volume for exploiting piston force was increased on condition that there was equality of gas flow mass b_g in the comparative cycles.

$$\frac{V_{bs} - V_b}{V_b} = \Delta \bar{V}_{bs} \tag{9}$$

The turbine nozzle area in synchronized conditions was increased to a greater extent than in ordinary pulse turbocharging systems by 20 - 25%. The intensity of the pressure wave arriving at the turbine was partially reflected by the increased nozzle area of the turbine. The reduced reflected pressure wave returned along the pipe and the flow impedance at the exhaust valve was reduced. In this case, the influence of pipe length on the intensity of the pressure wave was smaller, under variable operating conditions, and had the least influence on the scavenging process and on the performance of a four - stroke engine.

The increase of the internal turbocharging efficiency grew when turbocharging pressure was decreased, because the relative pressure fluctuation at the front of the turbine grew. Comparisons of synchronized and non - synchronized cycles were made for six - cylinder engines with two - inlet turbines, exhaust pipes from three cylinders were joined to each of the two turbocharger inlets. Degree of exchange of subsequent exhaust gas expansion δ was determined for different turbocharging ratios $\pi_k = \frac{p_k}{p_o}$, and for different increases specific turbine power $\Delta \bar{h}_{is} = \frac{H_{ijs}\eta_{ijs} - H_{ijn}\eta_{ijn}}{H_{ijn}\eta_{ijn}}$

4. CONCLUSIONS

1. The growth of the coefficient(degree) with subsequent expansion δ was changed by increasing of pressure as average indicated pressure and indicated power during every exhaust phase.

2. The increase of the coefficient of subsequent expansion gives significant benefits for internal combustion engines, working under variable load conditions.

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