A Study on the Estimating the Degree of Reaction for a Turbine Using a Synchronizable Turbocharging System

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(Received April 30, 1997)

동기화 터보 챠저계를 이용한 터빈 반동도 예측에 관한 연구

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(1997년 4월 30일 접수)

요 약

터보 챠저의 반동도와 터빈 노즐유량의 변화를 행하여 엔진의 성능을 향상시킬 수 있었다. 터빈의 에너지 손실과 그영향을 미치는 반동도 및 터빈 입구의 유로의 변화, 그리고 블레이드에서 역 유동에 대한 개선 조건도 제시하였다.

SYMBOLS AND ABBREBIATIONS

c_1 : absolute nozzle velocity
c_2 : velocity ratio in inlet
c_3 : velocity ratio in outlet
c_{m_2} : wheel outlet velocity ratio
D_1 : diameter of blade wheel
d : degree of radiality
F_{1ij} : current value of the turbine nozzle area
F_1 : inlet blade wheel area
F_2 : outlet blade wheel area bar
$\overline{F_k}$: mean nozzle area
G_{tj} : current mass flow rate through turbine
l : blade of length
v_{1ij} : specific volume of the gas flow before blade wheel.
v_2 : specific volume of the gas flow after blade wheel.
x_{01} : velocity characteristic ratio, $\frac{u_1}{c_1}$
α_1 : reaction degree
φ : nozzle velocity coefficient.
ϕ : blade wheel velocity coefficient.
ξ_g : outlet gas density
ρ : outlet gas density
τ : time of gas impulse
μ_1 : viscocity in nozzle
μ_2 : viscocity in blade wheel
h_t : specific turbine inlet energy.
μ_ρ : reaction amendment.
v : relative blade velocity
ω_2 : outlet velocity in turbine
π_1 : phase in inlet of turbine
π_T : phase in outlet of turbine
π_T : isentropic number

1. INTRODUCTION

The change of the reaction of degree is considered by using both an account and experimental methods. A brief description of the experimental installation with a synchronized turbine shows the connection between gas flow parameters defined during phases of the exhaust cycle. The exhaust cycle from an internal combustion engine with a impulse turbocharging system is simulated by three periods of maximum, medium and minimum pressures corresponding to the phases of exhaust from the cylinder. With the influence of the increasing degree of reaction during all phases of the exhaust cycle in connection with the kinematic parameters in the blade assembly flow, the minimum degree of reaction is defined in the third period of synchronization.

2. THEORETICAL TREATMENTS AND DISCUSSIONS

Actual flow characteristics in the turbine blade may be shows the diagrams of the laboratory test apparatus with the air receiving pipe, air flow gauge, combustion chamber, fuel source, turbine synchronizing device and etc. The source of the simulated gas was a combustion chamber. Fig. 1 shows the experimental gas turbine installation with this sychronizing process for the analytical models. The synchronization of the geometrical and energy parameters in the exhaust part of a turbocharging system of a diesel is produced by changing the turbine nozzle area in one cycle, provided that the diesel has two strokes during one rotation or four strokes during two rotations of the crankshaft. During the preliminary and free

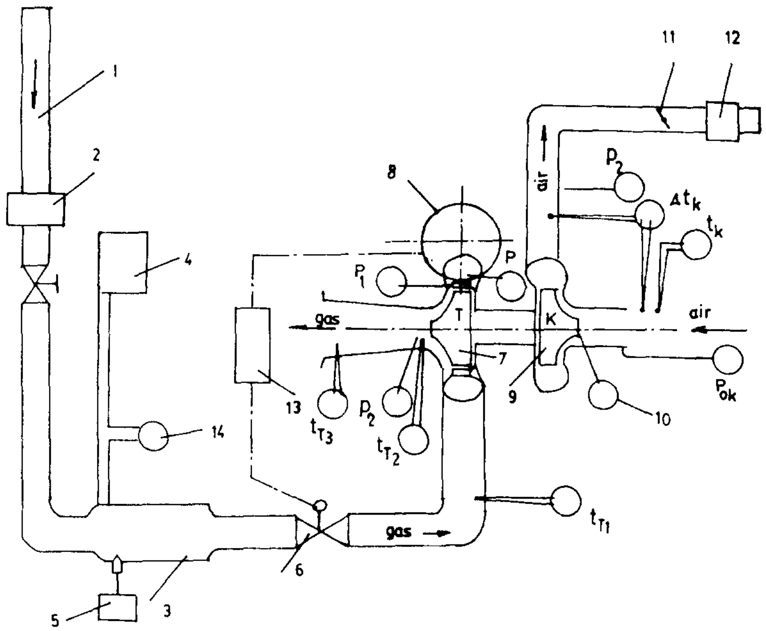

Fig. 1 **Diagram of experimental gas turbine installation with synchronized process 1 - air receiving pipe ; 2 - air flow gauge ; 3 - combustion chamber ; 4 - fuel source ; 5 - ignition device ; 6 - flow impulse simulating device ; 7 - turbine synchronizing device ; 8 - turbine outlet ; 9 - compressor ; 10 - tachometer ; 11 - flow regulating device ; 12 - air flow gauge ; 13 - controling arrangement ; 14 - fuel consumption gauge**

phase part of the exhaust, the power of the turbine is increased by enlarging the turbine nozzle and by increasing the allowable passage which increases the mass flow rate through the turbine. During the scavenging and filling phase, the turbine power is increased by reducing the allowable passage of the nozzle assembly, which increases the gas flow net power. The correlation between the turbine nozzle area and pressure in front of the turbine is defined by the regularity of the changing parameters during each phase. For three stages, pressure is regulated in the exhaust three times. In each stage, there is a unique value for the turbine nozzle area which is made by closing part of the allowable gas channel. Ordinary turbines for turbochargers have a degree of reaction near $\rho=0.45\sim0.55$. If the nozzle area is altered, the degree of reaction is changed according to the equation(1).

$$\rho=1-\frac{F_2\, v_{1ij}}{2\, F_{1ij}\, v_2} \tag{1}$$

The current efficiency of the radial - axial turbine is discovered by using the equation(2) which shows the degree reaction value.

$$\eta_{uij} = 1-[(1-\varphi)^2(1-\rho)+(\frac{1}{\varphi^2}-1)(\overline{c_{m_2}}^2\varphi^2 (1-\rho)+\sin^2\alpha_1+\overline{d_2}\, {x_{01}}^2) + \overline{c_{m_2}}^2\varphi^2(1-\rho)\sin^2\alpha_1+(\rho_g(1-\frac{c_3}{c_2})+(\frac{c_3}{c_2})^2)]_{i_j} \tag{2}$$

The gas expenditure is discovered by using the equation of mass flow through the nozzle and wheel blade channel of the one gas passage inlet.

$$G_{ti}\sum_{j=1}^{n}\frac{1}{j}\,\mu_1\mu_2F_{1i\rho}\sqrt{2h_t} = \frac{\mu_2F_2}{1-\zeta}\,\rho\overline{\omega_2}\sqrt{2h_t} \tag{3}$$

The dimensionless relative velocity(3) is found thus.

$$\overline{\omega_2} = \frac{\omega_2}{c_1} = \sqrt{1+\overline{d}^2x_{01}^2-2\phi\cos\alpha_1x_{01}^2\sqrt{(1-\rho)^3}} \tag{4}$$

The current reaction amendment is ;

$$\mu_{pi} = (\frac{\pi_t^{\frac{1}{k_T}}\sqrt{1-\pi_1^{-\rho}}}{\pi_t^{\frac{1}{k_T}}\sqrt{1-\pi_1^{-\rho}}})i \tag{5}$$

The current degree of the gas expansion in the nozzle assembly in subsonic and supersonic stream is ;

$$\pi_{1i} = \frac{\pi_1}{[1+\rho(\pi_T^{\rho}-1)]^{\frac{1}{\rho_{ij}}}} = [\frac{(k_T+1)}{2}]^{\frac{1}{\rho}} \tag{6}$$

And the current amendment of reaction degree is ;

$$\mu_{pij} = \sqrt{1-\rho_{ij}}[1+\rho_{ij}(\pi_{Tij}^{\rho}-1)]^{\frac{1}{k_T-1}} \tag{7}$$

An estimation of the current mass flow rate through a synchronized turbine may be discovered by defining the characteristics of the changing reaction degree during each phase of the exhaust and during every change of the turbine nozzle area. Equation (1) arranges the links between thermodynamical parameters, nozzle and blade wheel areas, and indirectly shows the connection with the kinematic parameters of the stage by specific volumes v_{1ij}, v_{2ij}. By selecting the regularity of the nozzle value, we can see the variable reactions of degree inside every range in three ranges. Every value of the nozzle corresponds to the defined flow rate. The initial analysis is produced for the same period of 4 times for every phase. Inside every period, the gas pressure is changed according to a different regularity. In the phase of high pressure and mass flow rate (first period), the variable parameters are changed insignitcantly. In the phase of medium pressure and mass flow rate (second period), the variable parameters are changed significantly. Fig. 2 describes the three - stage syn-

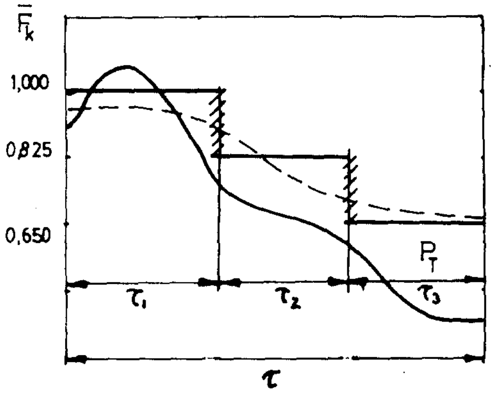

Fig. 2 Three - stage synchronization of the turbine nozzle area (— : nonsynchronic, - - - : synchronic)

chronization of the turbine nozzle area.

In the phase of low pressure and mass flow rate (third period), the variable parameters are changed insignificantly. The process of change of the variable parameters has been described on the basis of an investigation of the six - cylinder internal combustion engine with two branch exhaust pipes. According to equation (1), the degree of reaction is changed depending on the turbine nozzle area and the specific volume of the gas before and after the blade wheel. The specific volume after hardly changes and corresponds to the thermodynamic conditions after the turbine, if we take into account the hydraulic resistance of the exhaust pipe. Fig 1. shows that the shaded parts are nondefined periods of the operating process of a closed nozzle. It is possible to suppose that these nondefined periods are not essential and equal, which is approximately 15% of the time of one cycle with synchronization T. The degree of reaction can be used for estimating the dimensionless speed coefficient during each period of the nozzle area change(4),

$$n_s = x_{01}\sqrt{\frac{l}{D_1}}\sin\alpha_1 \sqrt[4]{1-\rho} \tag{8}$$

During every stage of synchronization, the dimensionless speed coefficient is changed, and the quality of energy transformation in the turbine is decreased. In a nonsynchronized turbine with conditions of a changing mass flow rate, the degree of reaction is changed during all phases of exhaust, and the characteristics of the operating process are greatly changed. There is even a compression effect which decreases the turbine efficiency. The degree of reaction becomes negative in the compressor operation of the turbine, although the geometric parameters F_2 and F_1 of a nonsynchronized turbine are essential to the change of the thermodynamic parameters because of the variable degree reaction. In the conditions of staged synchronization, the geometric parameter F_1 is decreased, while F_2 is constant; but the increasing relationship of F_2/F_1 becomes smaller than v_{1ij}/v_{2ij}, which causes the degree reaction rho not to become negative. A compressor effect is not created during the phase of very low mass flow rate. The changing process of the degree reaction, during the nondefined (transitional) subperiod, maybe ignored because its part is very small in the whole cycle. During the operating process of the synchronized turbine, the relative velocity w1, absolute velocity c, and velocity ratio x_{01} become smaller than in an ordinary impulse turbine. And it also shows that the nonsynchronized turbine demonstrates very variable velocity triangles, which define the change of reaction degree.

Each velocity triangle is composed of absolute, relative and blade velocities. The axial and tangential velocity componenents are also drawned. The absolute flow angle are designated relative angles. Velocity - vector relations for each phase at the inlet and exit for the turbine blade are shown in Fig. 3. The inlet is determined by the nozzle while the exit condi-

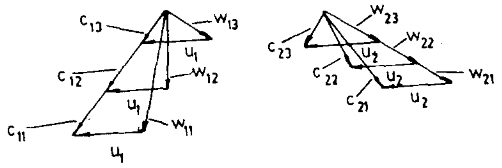

Fig. 3 **The inlet and outlet velocity triangles of the nonsynchronic turbine during three phases**

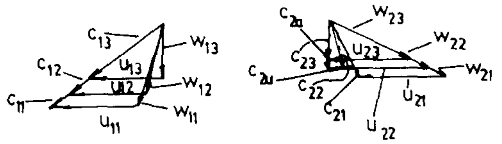

Fig. 4 **The inlet and the outlet velocity triangles of the synchronizing turbine during three phases(τ of sub-indexes 1, 2, 3 are corresponds to the first, second and stages)**

tion are calculated by the turbine blade-flow approximations. The flow is assumed that the turbine blade geometry is fixed and nozzle angle is adjusted for the speed of the turbine rotor. And the velocity-vector triangles of the nonsynchronized turbine during three phases by velocity components analysis is carried out by the equation (4).

Effects of radial-velocity components and radial variation of the velocity-vector triangles are shown in Fig. 4. And the inlet and outlet velocity-vector triangles of the synchronized turbine during three phases in second indexes u_1, u_2, u_3 correspond to the first, second and third stages are also included by calcualtions with the equation (4). The velocity triangles of the synchronized turbine in all stages are not essentially different. The nonessential change of velocity in the synchronized turbine can be explained by the decreasing pressure change in front of the inlet gas passage channel. During the phase of maximum mass flow rate, the nozzle area is biggest; during the phase of minimum mass flow rate, the nozzle area is smallest. The first nozzle area corresponding to the mass flow rate decreases the absolute velocity c_1, while the second nozzle area corresponding to the mass flow rate increases the absolute velocity c_1 in the turbine. As a result, the difference between the absolute velocity during the three phases of the change mass flow rate of maximum, medium, minimum is not significant. The kinematics of the gas flow in the turbine defines the degree of reaction(5).

$$\rho = 1 - \left[\frac{1}{1-\psi_1^2} \left(\sqrt{(\psi_1 \cos\alpha_1 x_{01})^2 + (1-\psi_1^2)(1-d_2^2 x_{01} - \overline{w}_2^2} - \psi_1 \cos\alpha_1 x_{01} \right) \right]_{ij}^2 \qquad (9)$$

It is possible to see from the triangles in Fig. 3. and Fig. 4. that in the nonsynchronized turbine the velocity ratio $x_{01}=u_1/c_1$ is changed significantly because the blade velocity u_1 is constant, but the absolute velocity c_1 is variable in a wide range during one cycle of the exhaust. In the syncronized turbine, the velocity ratio $x_{01}=u_1/e_1$ is not significantly changed; because the blade velocity u_1 is constant, while the absolute velocity c_1 is varable in a narrow range during one cycle of the exhaust. During the phase of minimum mass flow rate, the degree of reaction does not become negative nor equal to zero, and the difference of the gas pressure before and after the blade wheel is kept positive. This maintains the thermodynanic characteristics of the turbine operating process. The losses of gas flow energy are thus redistributed. From equation (9) we can see the narrow range degree of reaction will be changed by a stage mode. With the account mass flow coefficient of the turbine $\mu=c_1/c_2$, the better value degree of the reaction inside each stage is defined by energy and the Euler turbine equations.

$$\rho_{bv} = 1 - \left[\frac{-b + \sqrt{b^2 - 4ac}}{2a} \right]^2 \quad (10)$$

where;

$$a = \frac{1-\psi^2}{\psi_2 \cos^2 \alpha_1} [d_2^2 \psi^2 (1-\psi)^2 + \psi^2 \cos^2 \alpha_1]_j,$$

$$b = \frac{2}{\psi \cos \alpha_1} [d_2^2 \psi^2 (1-\psi)^2 + \psi^2 \cos^2 \alpha_1]_j,$$

$$c = \frac{\mu^2}{\psi^2} - \overline{d_2^2}(1-\psi^2) - 1$$

Fig 5. shows the best value of reaction ρbv for a synchronized turbine and the current value of the reaction for an ordinary turbine during one exhaust cycle. During the third stage of the changed parameters and nozzle, the degree of reaction in conditions of minimal mass flow rate in a synchronized radial - axial turbine is kept positive and is defined by the equation(4)

$$\rho = 1 - \left[\frac{-\psi v \cos \alpha_1 + \sqrt{\psi^2 v^2 \cos^2 \alpha_1 + (d^2 + 1 - \psi)(1 - d^2 v^2)}}{F_2 + 1 - \psi^2} \right]^2 \quad (11)$$

where $F = \dfrac{F_1 \psi \sin \alpha_1}{\psi \sin \beta_2 (1+\zeta)}$

In the one sector of two ordinary ones, in the turbine inlet, the pressure is changed in a wide range in front of the nozzle and blade wheel, while the second and third phases of the change, the degree of reaction is significantly lower than that of a synchronized turbine. For a short time, the degree of reaction for an ordinary turbine is more than that for a synchronized turbine. It is expanded by the redistributed thermodynamic parameters in front of the blade wheel because the pressure in front of the turbine is more, as soon as the gas density in the outlet from the wheel is more than from the nozzle assembly. If value f is more, the initial degree of reaction is more and it intensifies. But in conditions of operation, as concerns the engine exhaust pipe, if value f is smaller, the initial degree of reaction inside the period tau_3 is increased because during this phase the gas pressure in front of the blade wheel is increased. The difference of the regularity of the degree of reaction in conditions of synchronization causes a redistributes between the nozzle assembly and blade wheel of the parameters of gas by creating critical and supercritical regimes. During the three phases, the subcritical zone in the nozzle and blade wheel are more significant than in the nonsynchronized conditions. This is because during the first phase, the pressure in front of the turbine is decreased when the value of the nozzle area is increased. The critical form of the gas flow in the blade wheel depends on a centrifugal force. The critical form of the flow in the blade wheel occurs during the first phase, when the mass flow rate is maximum and the degree of reaction is maximum too. The critical section coincides with the outlet section. When the speed of rotation in an ordinary turbine is increased, the pressure difference before and after the blade wheel may be smaller than the resistance

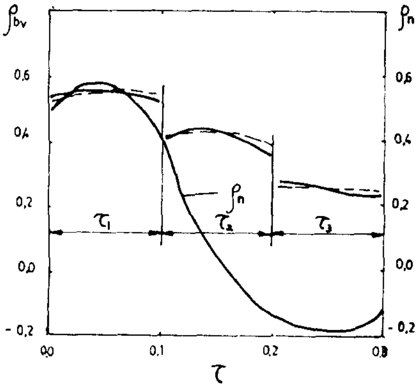

Fig. 5 **The best value degree of reaction ρ_{bv} for a synchronic turbine and current value degree of reaction for ordinary turbine during one exhaust cycle(--- : calculations, - - - : experiments)**

of the centrifugal force during the third period τ_3 when a gas stream estrangement is created. In the synchronized turbine, this phenomenon does not occur because the positive degree of reaction provides a positive difference in the two pressures. During all periods of synchronization, the degree of reaction is more than the value, when the reverse flow begins. The following equation explains it(5).

$$\rho + \psi^2(1-\rho) - \overline{d_2^2}\nu^2 - 2\psi\nu\sqrt{1-\rho} - \cos\alpha_1 = 0 \quad (12)$$

In Fig. 6., line $\mu = 0$ is the boundary of the reverse flow in the wheel, while line ρmin shows an area of slow gas motion through the wheel. Synchronization during the degree of reaction keeps the conditions for the operating process of the turbine without a reverse flow in the blade wheel. The thermodynamic parameters in the turbine provide a stable operation process during all phases of the exhaust cycle. As a result, the degree of reaction changes. The energy losses in the turbine are redistirbuted between the turbine chamber and blade assembly. The blade losses decrease, but the energy losses in the clearence between the blade wheel and the chamber walls increases. The total energy losses in the synchronized turbine are smaller than that in the nonsynchronized positive degree of reaction during the third phase of the exhaust cycle.

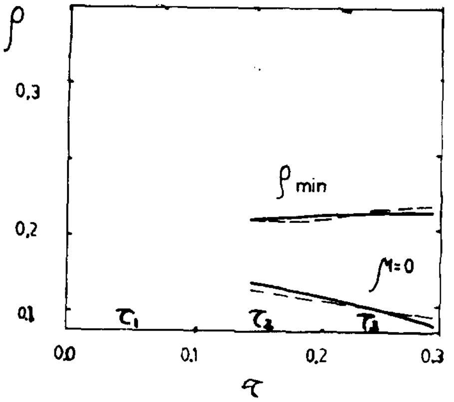

Fig.6 Area of reverse stream in the turbine and slow motion
(— : calculations, - - - : experiments)

3. CONCLUSIONS

1. During all preiods of the exhaust cycle in the synchronized turbine, a positive degree of reaction was ensured.
2. A constrasting degree of reaction can be selected at 8 - 10%, which is smaller than the degree usually used in an ordinary impluse turbine with a turbocharger. The decreasing degree of reaction is obtained by the redistribution of the thermodynamic parameters of the gas flow rate during all periods of the exhaust cycle.
3. An increase of the degree of reaction, during the third period of the synchronization, redistributes the energy losses in the blade assembly and turbine chamber. The degree of reaction by synchronization is necessary for the prevention of a reverse flow in the blade wheel.

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