

DETERMINATION OF HYDROELECTRIC GENERATOR EFFICIENCY BY MEANS OF THE RETARDATION METHOD

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Abstract - The efficiency of the great power generators is determined either by the calibrated generator method if the tests are made on the manufacturer stand (especially in the case of the turbo-generators), or by the calorimetric method, if the tests are carried out in the power plant (especially in the case of the hydro-generators). In Romania, the efficiency of a hydro-generator in a power plant was for the first time tested by means of the retardation method in 2010. The method consists in the electrical coupling of two generators, one functioning in motor operating conditions, the other in generator operating conditions. After the generator reaches 110% of the rated rotational speed, it is disconnected and allowed to retard (brake) freely until it gets to about 80% of the rated rotational speed. Retardation tests are performed under no load with the generator excited, unexcited and short-circuited. The decrease with time of the rotational speed (deceleration) and the electrical quantities are registered. The rated moment of inertia J_n is determined and, according to it, the losses in the bearings, the air-friction losses (by means of Reinhadt formula) and the supplementary losses in the stator copper winding, by means of a relation of the $p = n_n J_n (dn/dt)$ type, where n_n is the rated rotational speed, J_n the rated inertia moment and dn/dt is the rotational speed derivative corresponding to the rated rotational speed. One more characteristic is indicated, namely the absorbed power – no-load voltage, under excited, no load operating conditions with constant rotational speed by means of which the losses under no load P_o , mechanical losses P_{mec} and the iron losses P_{fe} are determined.

The method is simpler, more accurate and takes less time. Finally, an application for a 14.5 MW hydro generator is presented.

Key words: hydroelectric generator, efficiency, retardation method

1. INTRODUCTION

Efficiency of great electric power generators is determined either by means of the calibrated generator method if the tests are performed on the manufacturer stand, especially in the case of the turbo generators, by the calorimetric method if the tests are performed in the power station, especially in the case of the hydro generators, or by the retardation method only for hydro

generators if the turbine chamber can be sealed and the water can be entirely taken out from it.

The calibrated motor method consists in utilizing an electrical driving motor at the rated rotational speed of the tested generator. The losses of the calibrated motor are known with great accuracy which enables the determination of the mechanical power supplied to the shaft based on the power absorbed from the grid. The losses of the generator to be tested are determined by separating the losses during no load unexcited operation, no load excited operation and permanent three –phase short circuit operation.

The calorimetric method consists in determining heat losses transmitted to the cooling agent through conduction, convection and radiation and their separation according to the no load unexcited operation, no load excited operation, permanent three phase short circuit and rated load operation.

The retardation method consists in the free retardation of the tested generator between 110% and 80% of the rated rotational speed and the determination of the rated moment of inertia and deceleration (derivative of the rotational speed decrease) and, according to these, of the air friction losses. The losses of the tested generator are determined by separating the losses registered during operation under no load unexcited operating conditions, no load excited conditions and permanent three phase short circuit.

The last method was never been used in Romania until 2010, when efficiency of the reversible hydro bulb type hydro generators from the Ipotesti – Slatina hydro power station was tested for the first time by means of the retardation method, after their rehabilitation. Utilization of this method was also facilitated by the presence of a diagram with two hydro generators coupled to a power transformer, with circuit breaker at each hydro generator terminals, with common voltage bus bar and circuit breaker between the common bar and the power transformer.

The tests were carried out by a team of specialists from VatechHidro Company, Weitz, Austria and ICEMENERG Bucharest, Romania.

2. DESCRIPTION OF THE RETARDATION METHOD

Essentially, the method consists in recording the time and the rotational speed decrease during retardation of the tested generator from 110% to 80 % of the rated

rotational speed and determining the deceleration (the derivative of the rotational speed decrease). By means of these values the rated inertia moment is determined and then the losses by means of a relation of the type:

$$P_t = \left(\frac{\pi}{30}\right)^2 J_n n \frac{dn}{dt} \quad (1)$$

where:

P_t - the total losses during the retardation test (kW)

J_n - the rated inertia moment (kg m²)

n - the motor rotational speed (rot/min)

dn/dt - the deceleration during the deceleration test

The tested generator operates in motor operating conditions with the directing apparatus closed and without water in the turbine chamber under different working conditions (regimes), supplied by another generator electrically connected to it. The two generators are disconnected from the system and separated from the power transformer. They are coupled between themselves through the common bus bar. The excitations of the two generators should be supplied from an independent source. The two generators are started and brought to the rated rotational speed and excited until the rated voltage is obtained and they function under steady state regime up to the temperature stabilization in the shafts of the tested generator. Afterwards the tested generator is brought to different operating conditions and the supplying generator is disconnected and left to retard freely. The values of time and rotational speed are registered (at a recording speed of 0.2 s), as well as the other electrical quantities.

2.1. Test at no load, excited operation

The test aims at determining the losses P_o under no load as a sum of the mechanical losses P_{mech} and the iron losses P_{Fe} .

The test consists in increasing the absorbed active power– no load voltage characteristic, namely decreasing the voltage at the tested generator terminals in steps from 1.1 U_n up to about 0,3 U_n in 10% steps, by reducing the excitation current and measuring the active power absorbed. The voltage, active power, power factor and the rotational speed of the tested generator are measured. The curve $P_{abs} = f(U)$ is drawn and extrapolated up to $U=0$.

The value of the power for $U = U_n$ represents the value of the no load losses P_o . The value of the power at $U = 0$ represents the value of the mechanical losses P_{mech} . The iron losses P_{Fe} are obtained by subtracting the mechanical losses from the value of the no load losses

$$P_{Fe} = P_o - P_{mech} \quad (2)$$

If necessary, the correction of the iron losses at the rated voltage and frequency is made:

$$P_{Fe n} = P_o (U_n / U_{meas})^2 (f_n / f_{meas})^2 \quad (3)$$

where:

U_{meas}, f_{meas} –measured value

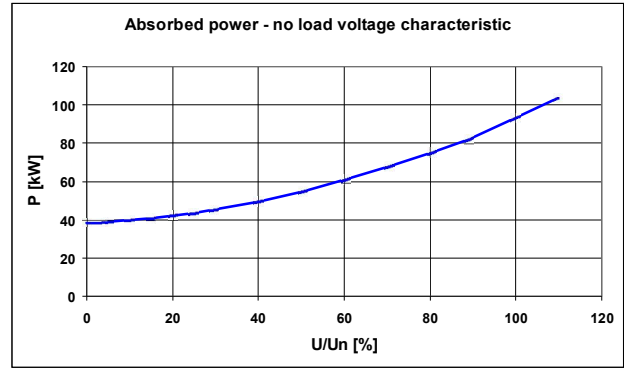


Fig.1. The absorbed power versus no load voltage characteristic

2.2. Retardation test at no load , excited

The test aims at determining the rated inertia moment corresponding to the rated speed.

The tests consists in bringing the tested generator to a speed of about 120-130 % of the rated speed and a voltage of about 120 % of the rated voltage, disconnecting the supplying generator and retarding it between 115 % and 80% of the rated speed under constant excitation.

The rated inertia moment J_n is determined as follows: from the measured values the variation of the rotational speed derivative with time is determined as the variation of the tangent to the curve $n = f(t)$ in each point $n(t)$:

$$\frac{dn}{dt} = \frac{\Delta n}{\Delta t} = \frac{n_i - 0,95 n_i}{t_{0,95 n_i} - t_{n_i}} \quad (4)$$

where:

n_i - rotational speed in the current point

t_i - time corresponding to rotational speed n_i

$t_{0,95 n_i}$ - time corresponding to rotational speed 0.95 n_i

and the retardation characteristics under excited no load conditions, rotational speed - time and the derivative rotational speed – time are drawn on the same diagram in relative units (fig.2)

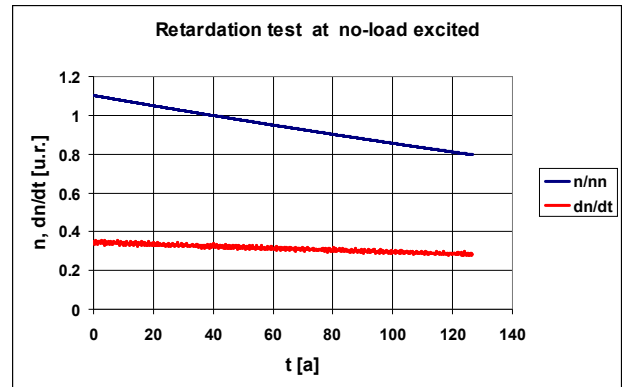


Fig.2. Curves $n = f(t)$ and $dn/dt = f(t)$ during the retardation test at no-load excited

Then, the speed derivative in point $n = n_n$ is determined as the tangent to the retardation curve $n = f(t)$ in that point:

$$\left(\frac{dn}{dt}\right)_n = \left(\frac{\Delta n}{\Delta t}\right)_n = \frac{n_{1,05 n_n} - n_{0,95 n_n}}{t_{0,95 n_n} - t_{1,05 n_n}} \quad (5)$$

where:

$(\Delta n)_n$ - the difference between $1.05 n_n$ and $0.95 n_n$

$(\Delta t)_n$ - the corresponding time interval

The value of the rated inertia moment is calculated by means of the relation:

$$J = \left(\frac{30}{\pi}\right)^2 \frac{P_o}{n_n \left(\frac{dn}{dt}\right)_n} \quad (\text{kgm}^2) \quad (6)$$

where:

P_o - the losses under no load are determined at # 2.1
 n_n - rated rotational speed

$\left(\frac{dn}{dt}\right)_n$ - derivative of the rotational speed in point $n=n_n$

2.3. The retardation test at no-load unexcited

The test aims at separating the mechanical losses in the bearings and the losses due to air friction by means of the Reinhardt method.

The test consists in bringing the tested generator at a speed of about 120-130 % of the rated speed and disconnecting the supplying generator simultaneously with the disconnection of excitation and its free retardation between 115 % and 80% of the rated speed.

The separation of the mechanical losses by means of the Reinhardt method is performed as follows:

From the measured values the derivative of the speed in the point $n = n_n$ is determined in the same way as at point 2.2 (relation 4).

The value of the mechanical losses at the rated speed is calculated by means of the relationship:

$$P_{\text{mec } n_n} = \frac{n_n \left(\frac{dn}{dt}\right)_n J_n}{\left(\frac{30}{\pi}\right)^2} \quad (\text{kW}) \quad (7)$$

where the quantities have the same meaning as above.

The variation of the speed derivative with time is determined as the variation of the tangent to the curve $n = f(t)$ in each point $n(t)$ in the same way as in # 2.2. (relation 4)

The function $P_{\text{mec}} = f(t)$ is calculated

$$P_{\text{mec}}(t) = \frac{n(t) \frac{dn}{dt}(t) J_n}{\left(\frac{30}{\pi}\right)^2} \quad (\text{kW}) \quad (8)$$

The curve is calculated and drawn:

$$\frac{P_{\text{mec}}(t)}{\sqrt{(n(t))^3}} = f\left(\sqrt{(n(t))^3}\right) \quad (9)$$

for each point of the retardation curve $n=f(t)$, where $P_{\text{mec}}(t)$ are the mechanical losses with time, determined by means of the relation 8.

The regression curve is determined as a straight line and the free term of the equation of the straight line represents the separation coefficient of the losses in the bearing k_{bearing} from the mechanical losses at the rated speed (Reinhardt method)

$$P_{\text{bearing}} = k_{\text{bearing}} P_{\text{mec } n_n} \quad (10)$$

$$P_{\text{air total}} = P_{\text{mec } n_n} - P_{\text{bearing}} \quad (11)$$

The total losses due to air are made up of the turbine friction losses and the generator rotor friction losses. They are separated in the following way:

The Kaplan turbine losses by air friction:

$$P_{\text{air turbine}} = 6.5(60 n)^3 D^5 10^{-7} = 0.14 n^3 D^5 \quad (12)$$

The generator rotor losses by air friction

$$P_{\text{air rotor gen}} = P_{\text{air total}} - P_{\text{air turbine}} \quad (13)$$

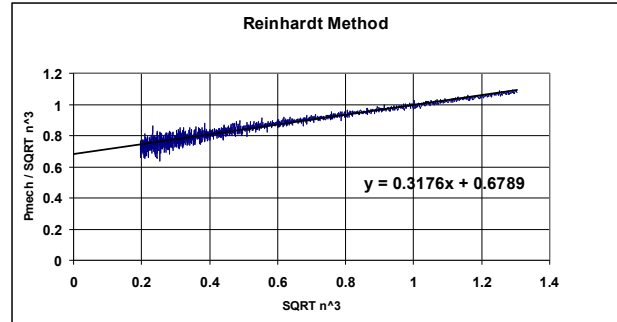


Fig.3. Reinhardt characteristic $P_{\text{mec}} / \sqrt{n^3} = f(\sqrt{n^3})$,
 $\text{SQRT } n^3 \rightarrow \sqrt{n^3}$

2.4. Retardation test at short-circuit

The test aims at determining the losses under load conditions and the supplementary losses in the stator winding copper. The test consists in bringing the tested generator to a rotational speed of about 120-130 % of the rated rotational speed, supplying generator disconnection from the common bus bar, sudden short-of the stator winding, excitation at the rated current and its free retardation between 115 % and 80% of the rated rotational speed.

The determination of the supplementary losses in the stator winding copper is performed as follows:

From the measured values the variation with time of the rotational speed derivative as a tangent to the curve $n = f(t)$ in each point $n(t)$ is determined in the same way as in # 2.2. (relation 4)

The rotational speed and rotational speed – time characteristics are drawn on the same diagram in relative units (fig.4).

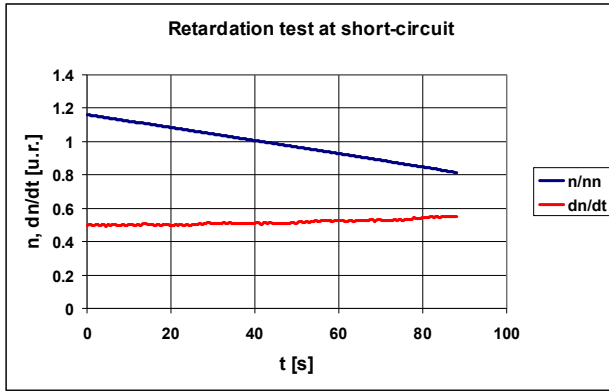


Fig.4. Curves $n = f(t)$ and $dn/dt = f(t)$ for the retardation test at short-circuit

Then, the speed derivative in the point $n = n_n$ is determined in the same way as in point 2.2 (relation 4).

The value of the short-circuit losses is calculated at the rated speed:

$$P_{sc} = \frac{n_n \left(\frac{dn}{dt} \right)_n J_n}{\left(\frac{30}{\pi} \right)^2} \quad (\text{kW}) \quad (14)$$

The losses under load are obtained by subtracting the rated mechanical losses from the short-circuit losses

$$P_{load} = P_{sc} - P_{mech\ n} \quad (15)$$

The corrected losses under load are obtained by subtracting the joule losses in the electrical circuit up to the short-circuiting breaker P_{bar} and multiplying by the square ratio of the short-circuit current and the rated current

$$P_{load\ cor} = \frac{(P_{load} - P_{bar})(I_{sc}/I_n)^2}{P_{bar} = R_{bar} I_{sc}^2} \quad (16)$$

The supplementary losses are obtained by subtracting the joule losses in the stator copper from the losses under load

$$P_{supl} = P_{load} - P_{Cu\ st} \quad (17)$$

$$P_{Cu\ st} = R_{stat} I_{sc}^2$$

3. DETERMINATION OF EFFICIENCY

Determination of efficiency still requires certain under load tests for determining the rated excitation current, the losses in the excitation system outside the rotor and the fan losses, if such losses occur. These tests are similar to those that are made for the calorimetric method. Efficiency is determined in the same way as in the case of all methods.

The losses are divided into two categories:

- Constant losses that are the same for any regime: the sum made up of the mechanical losses in the bearings, ventilation losses (air friction), losses in the iron, other constant losses – losses in fans:

$$P_{const} = P_{bearing} + P_{air\ rot\ gen} + P_{Fe} + P_{vent} \quad (18)$$

- Variable losses that vary with the load, the sum of the losses that vary with the load: the losses in the rotor winding copper, losses in the excitation system outside the rotor, main and supplementary losses in the stator winding copper:

$$P_{ex} = R_{rot\ 75^\circ C} I_{ex2} \quad P_{sist\ exc} = P_{sist\ exc\ n} (I_{ex}/I_{exn})^2 \quad (19)$$

$$P_{Cu\ st} = R_{st\ 75^\circ C} \quad P_{supl} = P_{supl\ n} (I_{st}/I_{st\ n})^2$$

Usually, the losses that vary with the load are determined for: 1.0 – 0.75 – 0.5 – 0.25 of the rated active power P_n for $\cos\varphi = \cos\varphi_n$ and from the rated apparent power S_n for $\cos\varphi = 1$.

The total losses are equal to the sum of the losses that vary with the load and the constant losses.

The output power is equal to the active power of the generator at $\cos\varphi = \cos\varphi_n$ and the apparent power at $\cos\varphi = 1$ (when the reactive power is zero). The input losses are equal to the sum of the output power and the total losses. Efficiency is equal to the ratio between the input power and the output power:

$$\eta = \frac{P}{P + \sum P_i} 100 \quad (\%) \quad (20)$$

where:

P – generator active power
 P_i – different losses considered

4. APPLICATION TO A 14.5 MVA BULB TYPE REVERSIBLE HYDRO GENERATOR

The main electrical parameters of the tested hydro generator are:

- rated active power $P = 14,21$ MW
- rated voltage $U_n = 6.3$ kV,
- rated stator current $I_{st\ n} = 1329$ A,
- $\cos\varphi_n = 0,98$,
- rated speed $n_n = 130,0$ rot/min

As a result of the tests the following results have been obtained:

From the no load excited operation test (# 2.1.) the absorbed power – voltage under no load characteristic in fig.1 and the values of the speed and rated voltage: no load losses: $P_o = 93.44$ kW (when $U = U_n$), the mechanical losses $P_{mech\ n} = 40,27$ kW (through extrapolation when $U = 0$), and the iron losses by subtracting $P_{Fe} = 53.17$ kW (relations 2, 3).

By means of the values registered during the retardation test at no load excited, (# 2.2) the retardation and the deceleration curves at no load excited have been drawn in fig. 2 and by means of the losses no load excited P_o the value of the rated moment of inertia $J_n = 202\ 263$ Kgm² has been calculated (by means of relation 5).

Afterwards, the retardation test under no load unexcited operating conditions has been performed and the Reinhardt curve in fig. 3 has been drawn there resulting the coefficient of bearing loss separation $k_{bearing} = 0,6799$ (the free member of the regression curve). By means of relations 10-13 the friction bearing losses $P_{bearing} = 27.38$ kW and the friction losses due to the air of the generator rotor $P_{air\ rotor\ gen} = 10.25$ kW have been calculated.

Based on the short circuit retardation test (#2.3.) the retardation and deceleration curves under short circuit in fig.4 have been drawn and by means of relations 14 -17 the short circuit losses $P_{sc}=148,49$ kW and the supplementary rated losses in the stator winding copper $P_{supl\ n}=16,31$ kW, respectively, have been calculated.

During the on load tests the regulation graph (fig.5) from which there resulted the rated excitation current at $\cos\phi$ for the rated stator current, the rated excitation current at $\cos\phi_n$ $I_{ex\ n} = 950.2$ A and $\cos\phi = 1$ $I_{ex} = 836,8$ A has been drawn.

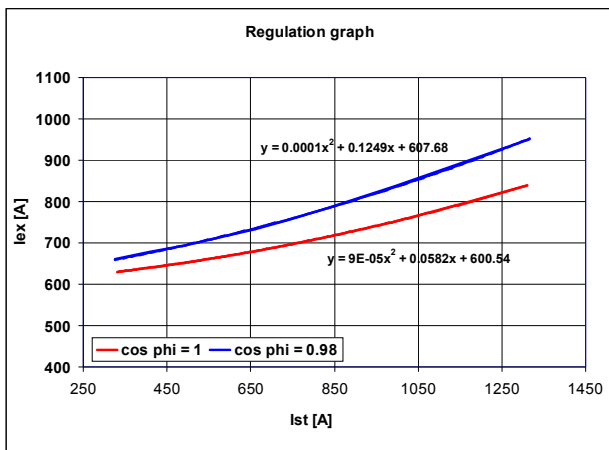


Fig.5. Regulation graph

The losses in the excitation system outside the rotor, excitation transformer respectively, rectifying bridge, etc, $P_{sist\ exc\ n} = 12,49$ kW and the losses in the two auxiliary fans $P_{vent} = 7.38$ kW have also been determined.

Further, the constant losses have been calculated by means of relation 18: $P_{const} = 70,68$ kW and the rated variable losses by means of relation 19 $P_{var} = 181.7$ kW. The rated efficiency, calculated by means of relation 20, was $\eta = 98,251$ % (on load and rated $\cos\phi$).

The efficiency has also been determined by means of the same relation considering the values of the stator currents and excitation (from the regulation graph) and for other loads resulting from the values in tables 1 and 2 and the curves in fig. 6.

Table 1 Efficiency for $\cos\phi = 0,98$

Load	u.r.	1	0.75	0.5	0.25
I_{st}	A	1328.8	996.6	664.4	332.2
I_{ex}	A	950.2	831.5	734.8	660.2
P_{const}	kW	70.68	70.68	70.68	70.68
$P_{cu\ rot}$	kW	66.84	51.18	39.97	32.26
$P_{sist\ ex}$	kW	12.45	10.19	8.45	7.19

$P_{cu\ st}$	kW	86.10	48.43	21.53	5.38
P_{supl}	kW	16.31	9.17	4.08	1.02
P_{tot}	kW	252.39	189.67	144.71	116.54
$P_{iesire} = P$	kW	14210.0	10657.5	7105.0	3552.5
$P_{intrare}$	kW	14462.9	10847.7	7250.2	3669.6
Efficiency	%	98.255	98.251	98.004	96.824

Table 2 Efficiency for $\cos\phi = 1$

Load	u.r.	1	0.75	0.5	0.25
I_{st}	A	1328.8	996.6	664.4	332.2
I_{ex}	A	836.8	747.9	678.9	629.8
P_{const}	kW	70.68	71.20	71.20	71.20
$P_{cu\ rot}$	kW	51.84	41.41	34.12	29.36
$P_{sist\ ex}$	kW	10.29	8.68	7.50	6.70
$P_{cu\ st}$	kW	86.10	48.43	21.53	5.38
P_{supl}	kW	16.31	9.71	4.32	1.08
P_{tot}	kW	235.22	179.43	138.66	113.73
$P_{iesire} = P$	kW	14500.0	10875.0	7250.0	3625.0
$P_{intrare}$	kW	14735.7	11054.4	7388.7	3738.7
Eff.	%	98.404	98.377	98.123	96.958

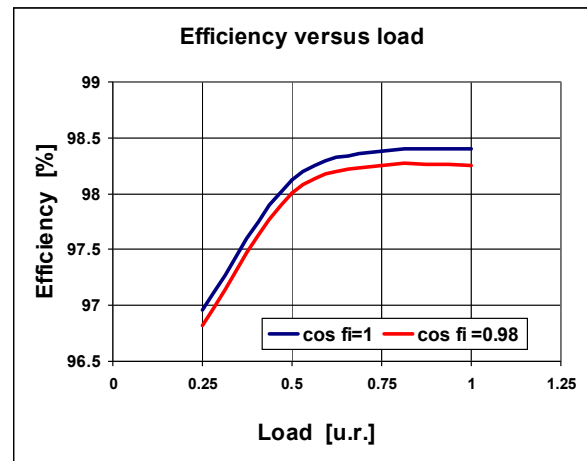


Fig 6 Variation of efficiency with load

5. CONCLUSIONS

The method is simpler, takes less time and is more accurate.

When the calorimetric method is used, thermal resistances and sections with diaphragms should be mounted on the three cooling circuits: air, hydrogen or water coolers (for the windings directly cooled with water), coolers for the oil lubricating the two generator bearings. At the same time, when using this method the thermal regimes stabilization for the 4 tests takes between 4 and 8 hours for each according to the generator size.

When the calibrated motor method is used the presence of a test stand and of a driving motor whose power should cover the losses of the tested generator (about 500 - 800 kW) are required. With this method a test takes about 2-3hours.

The retardation method does not require supplementary mountings, besides the rotational speed and electrical quantity measurement transducers, as in the case of the other methods. The test takes about 1 hour.

The calorimetric and the calibrated motor methods provide results whose accuracy varies between 2.5 and 5 %, while the retardation method provides 2 % accurate results.

The only conditions required for applying the retardation method are: the possibility to connect, disconnect respectively, two generators from the same power plant and to empty the turbine chamber (so that to operate in compensation regime).

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