Rio Pipeline 2003
Conference & Exposition

IBP317_03

STORAGE CAPACITY IN PIPELINES - A POSSIBLE WAY TO PRODUCE ELECTRIC POWER ON PEAK PERIODS.

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Abstract

The distribution of natural gas is carried out by means of long ducts and intermediate compression stations to compensate the pressure drops due to friction. Distances in the range of 150 to 200 km between compression stations and duct diameter around 500 mm are commonly recommended. Compression stations receive the natural gas at approximately 59 bar and discharge it at 102 bar. The natural gas compressors are usually driven by an electric motor or a gas turbine system, offering possibilities for energy management, one of these consisting in generating energy for use in-plant or to commercialize as independent power producer; it can be done by matching the natural gas demand at the minimum pressure allowed in the reception point and the storage capacity of the discharge duct with the maximum compressor capacity, for storing the natural gas at the maximum allowed pressure and permitting the gas turbine drives an electric generator during the time in which the decreasing pressure in duct is above the minimum acceptable by the receptor. This work analyzes an existing compression station and its actual demand curves, estimating the time period that the gas turbine system driver can operate the electric generator and the potential of costs reduction from the point of view of energy resources (natural gas and electric costs).

Introduction

The Brazilian energetic scenery has been very unexpected in the last years, characterized in 2001 by a serious deficit in electricity offer and by a surplus in 2003. The source of this energy (more than 90% from hydroelectric power stations) is strongly dependent on weather, which explains in part the fact that the relatively dry period in 2000-2001 resulted in an electric crisis. By other side, the various Brazilian regions (Northeast, Southeast, etc.) are not completely interconnected, meaning that in the crisis period the surplus eventually available in one region wasn't transported to a deficitary region. In years 2001-2002 several new hydraulic and thermoelectric plants were planned and some of them were erected or are nowadays in erecting process. In 2003 the country presents an excess of energy, and this turns the future scenery projections a difficult goal.

This work suggests one possibility to partially overcomes these uncertainties, avoiding the adoption of solutions that can be revealed erroneous if the imagined scenery result too different

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of reality. Here, the energy consumed in natural gas make-up in pipelines is disposed to be utilized in a rational form, exploiting the storage capacity of long ducts. By this way, the tendency of investments is not to increase the weather dependency but also to compensate the electricity distribution deficiencies because this proposal stimulates the distributed generation. Studies such as the one conducted by Roy-Aikins(1995) are directed in the same way for applications in pipelines in Kenya.

1 System concept

Compression plants can drive the natural gas compressors by means of electric motors or gas turbines, and maximum compressor capacity must be at least equal to the peak demand. This fact allows that, in a period of low natural gas (NG) demand, the compressor keeps sending a volume that exceeds the demand, thus increasing the pressure in the duct and storing some amount of gas (Landa et al., 2002). This storage is useful in order to diminish abrupt changes on compressor load but may also serves, in special circumstances, to permit the gas to be transported for a period that depends on the duct size and pressure, consumer demand and minimum acceptable pressure. In Figure 1, the upper horizontal line represents the maximum compressor capacity, in which the capacity is expressed as equivalent kW.

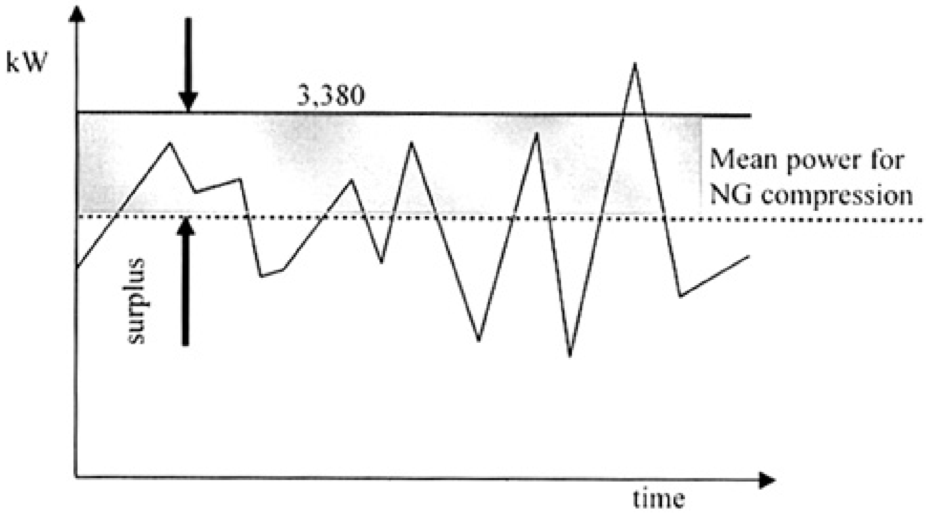

Figure 1.- Qualitative curves of mean and instantaneous demands.

Variable line represents instantaneous gas demand, also expressed as equivalent kW. The mean power demanded for NG compression is the lower dotted horizontal line. In a typical operation, the compressor fits the demand gas curve by varying its speed. The discharge pressure also varies because of pressure drops in duct. The shaded area may be associated to a quantity of energy that the compressor driver can use for other finalities (here named "dynamic" storage), such as to drive an electric generator or to maintain the compressor at its full capacity being the excess stored in the duct ("static" storage). The first alternative is operationally more complex because for producing a stable electric energy the stocked gas must be enough to supply gas when the demand is over the mean demand. The second allows, when convenient, stopping the compressor and coupling the drive to an electric generator.

If the compressor drive is an electric motor, the gas storage in the off-peak tariff period and stopping the motor in the peak period tariff may be convenient. In the turbine gas drive case, advantages are the ones for the electric motor, with the eventual additional advantage that the cost of storage is natural gas based instead of electric energy based, being the first case normally cheaper. When the drive is an electric motor, the investment probably will be lower and the costs of electricity and gas have a fundamental role in the decision to adopt or not the proposal.

The scheme in the gas turbine case needs a coupling system to allow a quick and reliable change of the operation mode. Figures 2 and 3 indicate two possibilities.

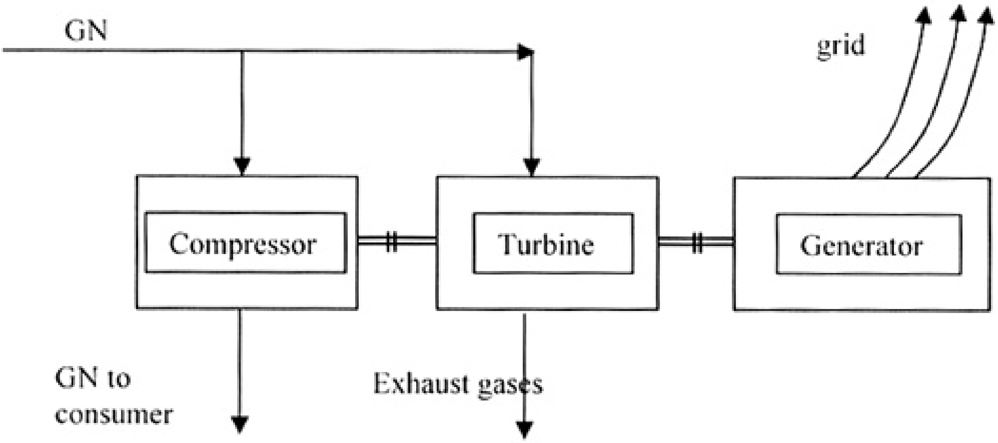

Figure 2.- Mechanical coupling

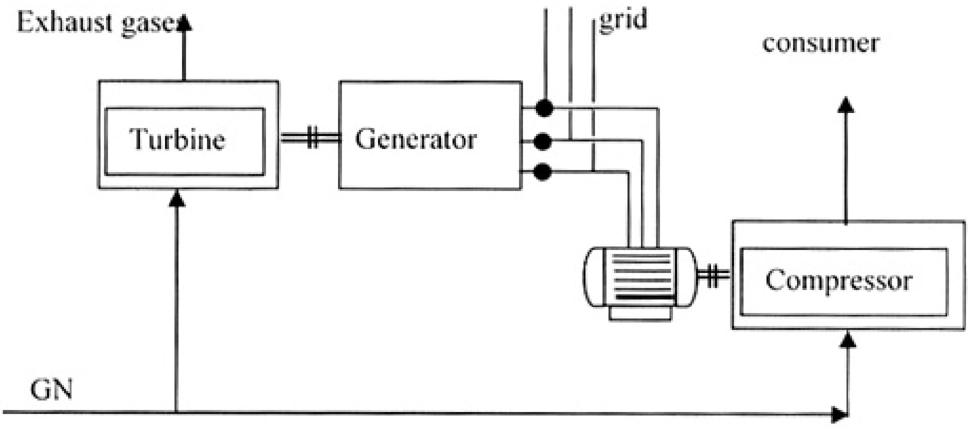

Figure 3.- Electric coupling

If the "dynamic" storage is considered, a device to control the frequency must be provided between the generator and the electric motor (i. e., a frequency converter, don't shown in Figure 3) when utilizing an "electric" coupling, and in a similar way this device must be employed in the "mechanical" coupling too. This is due to the variable speed operation of the compressor, that imposes the additional cost of the converter.

For this reason, the "static" storage concept is preferred, in which the compressor variable speed only affects the "filling" time of the duct to eventually drive an electric generator at constant speed during the storage time. This solution must be carefully implemented, considering that it implies on assuring certain logistic conditions, as described below.

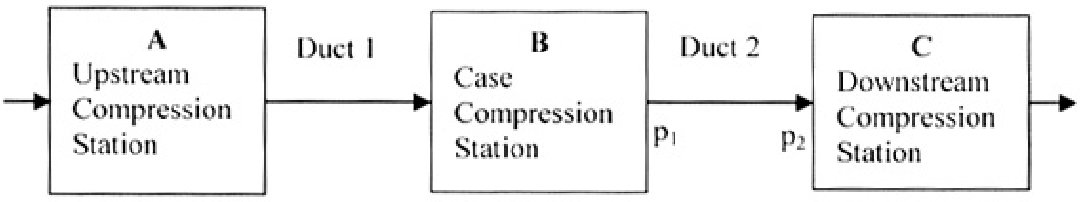

Figure 4.- Compression station network

For a compression station network (Fig. 4), when duct 2 is full filled or packed, the compressor of station B can stop and the NG is transported to station C by the potential pressure energy in duct 2. During this period, the compressor mover can drive an electric generator. A simple mass balance indicates a problem with the handling of the incoming NG from station A. To overcome that, there are two possibilities: to storage NG also in duct 1 or stopping the compressor in station A. The last will create problems to an eventual plant upstream station A.

As can be perceived, the application of the storage concept involves a strategic analysis of a network of plants and a synchronized operation. In this paper it is analyzed the "static" storage assuming that all upstream station or plant B correlated problem were solved.

2 Storage capacity

The storage capacity is the mass (or Sm^3) that the duct or pipeline contains and can be used in a satisfactory form by the consumer, say a downstream station C in Figure 4. In Figure 5, the pressure profile along the duct is represented for some operational conditions.

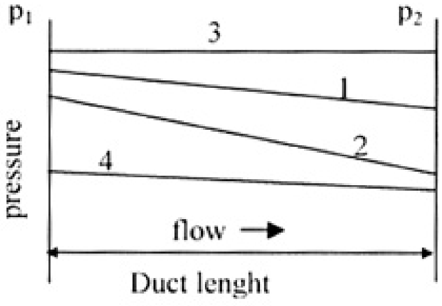

Figure 5.- Pressure profile on duct

The pressure drop p_1-p_2 (see also Figure 4) is calculated according the Weymouth formula (CRANE, 1973) and the pressure profile can be considered a right line for the mass flow and duct dimensions of this case study. Line 1 indicates a lower pressure drop relatively to line 2, that in a first instance leads to suppose that the mass flow is higher in transportation according line 2 than in line 1. This may not be always the reality, because with lower pressure the velocity must be higher for the same flow.

Line 3 represents the case of no flow, i. e., the compressor had charged the duct at the maximum permissible pressure during a period of null NG demand by station C. This situation will be denominated as "full filling case". When the duct is operating according to some profile as line 1, and the compressor is stopped, it is assumed that the duct acquired an equilibrium pressure that can be estimated by the mean value of p_1 and p_2. This will be called the "operational filling case".

The storage capacity depends on the consumer demand, that is normally variable. The assumptions for a reasonable model are:

-The possibility of establishing a minimum constant demand when using the storage capacity is real;

-It is possible to determine a minimum admissible pressure p_2 to permit operating station C;

-When using the storage capacity, the pressure is uniform along the duct;

-The NG can be considered as perfect gas with the appropriated compression factor.

The information presented in Table 1 was used to calculate the storage capacity:

Table 1.- Data used in storage capacity calculation.

<table>
<tr><th colspan="4">Duct</th></tr>
<tr><td>Length: 180 km</td><td colspan="2">Diameter: 0.5 m</td><td>Volume: 35,000 m^3</td></tr>
<tr><th colspan="4">Natural gas (NG)</th></tr>
<tr><td>R=415.1 J/kg.K</td><td>ρ_N=0.8939 kg/Nm^3</td><td>ρ_S=0.8316 kg/Sm^3</td><td>Operating temperature=27 °C</td></tr>
<tr><th colspan="4">Natural gas demand (Sm^3/h)</th></tr>
<tr><td>Maximum</td><td colspan="2">Normal</td><td>Minimum</td></tr>
<tr><td>193,400</td><td colspan="2">125,000</td><td>65,000</td></tr>
</table>

The storage capacity can be estimated for many operating conditions and minimum acceptable pressure p at the inlet of station C. It was supposed an internal operating pressure p_3 in plant C and a maximum flow coefficient K in a virtual inlet control valve, so the estimation of the minimum acceptable p_2 can be done when the minimum acceptable demand is established, i.e, it is considered that in normal operation this virtual valve operates partially closed. depending the required flow and the pressure p_2 and that when the storage is used and the pressure begin to diminish, the valve begin to open still its maximum aperture, determining the minimum useful p_2. Figure 6 shows this supposed control system.

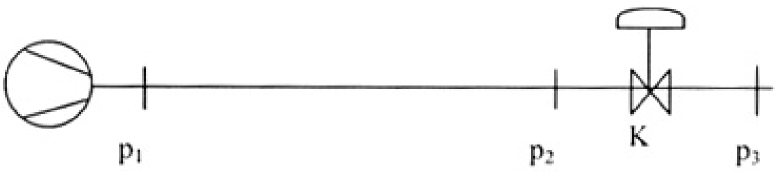

Figure 6.- Suggested Control System

The mass flow is determined by

$$\dot{m} = K\sqrt{(p_2 - p_3)\rho_2}$$

By imposing p_3 and using different actual operational conditions, such as different compressor discharge pressure and demand, it is possible to determine p_2 when calculating the pressure loss in duct, estimating values for K. Using the maximum value calculated for K it is possible to calculate the minimum necessary p_2 to provide different minimum required demand. The next section will explain this, by using the compressor curves.

3 Filling required time

Figure 7 presents the efficiency curves assumed for the natural gas compressor considered in the case-study.

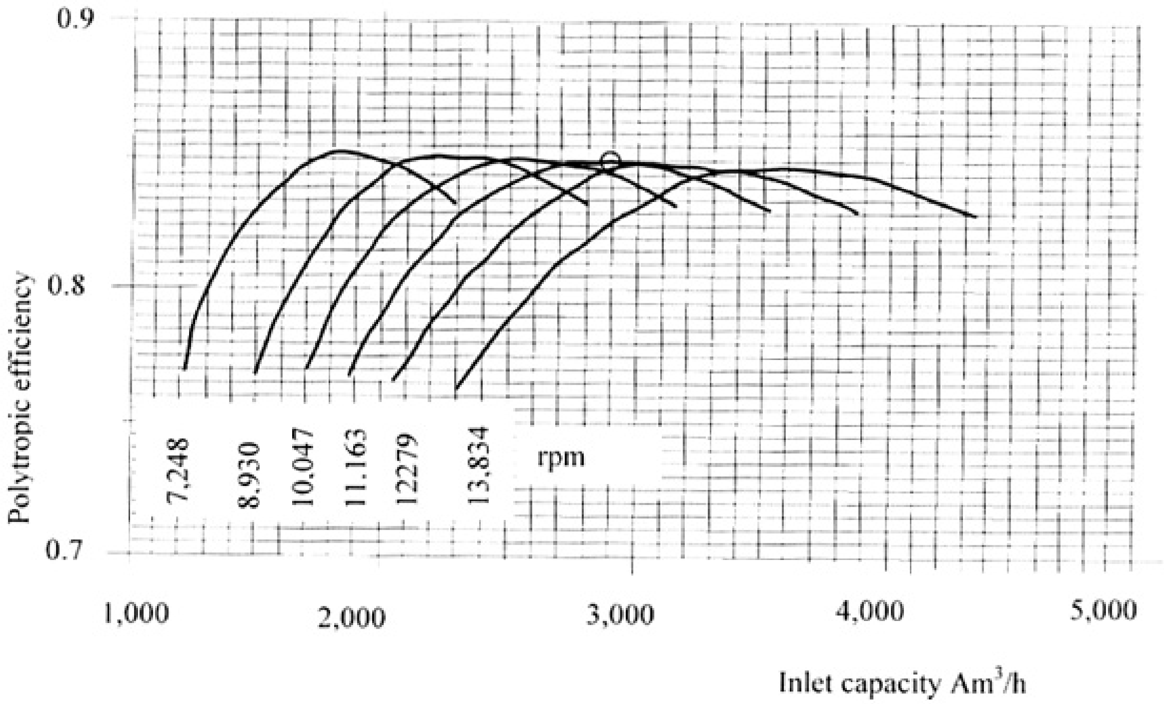

Figure 7.- Compressor performance curves -Efficiency

The compressor curves of Figure 8 show that it is possible to provide the same demand by using different discharge pressures and compressor speed. The dotted line is the preferred mode of operation for the required flow (160,800 kg/h or 193,362 Sm^3/h) and the actual suction pressure of 58 kgf/cm^2, for which the efficiency is the maximum, according Figure 7.

The unit Am^3 means actual m^3, i.e., the volume corresponding to a fixed quantity of mass at actual suction temperature and pressure, adopted to be 30 °C and 58 kgf/cm^2 in this case-study. The unit Sm^3 is the volume in standards conditions, calculated for a fixed quantity of mass with temperature of 20 °C and a pressure of 1 atmosphere.

In Figure 8, point 1 indicates the flow reduction process by means of pressure augmentation and constant speed. Point 2 shows the process when the discharge pressure is maintained and the speed is reduced. The power consumption in case 2 is lower than case 1, confirming that the efficiency is better in case 2. In practice, the flow reduction is obtained by a combination of speed reduction and a variation of discharge pressure.

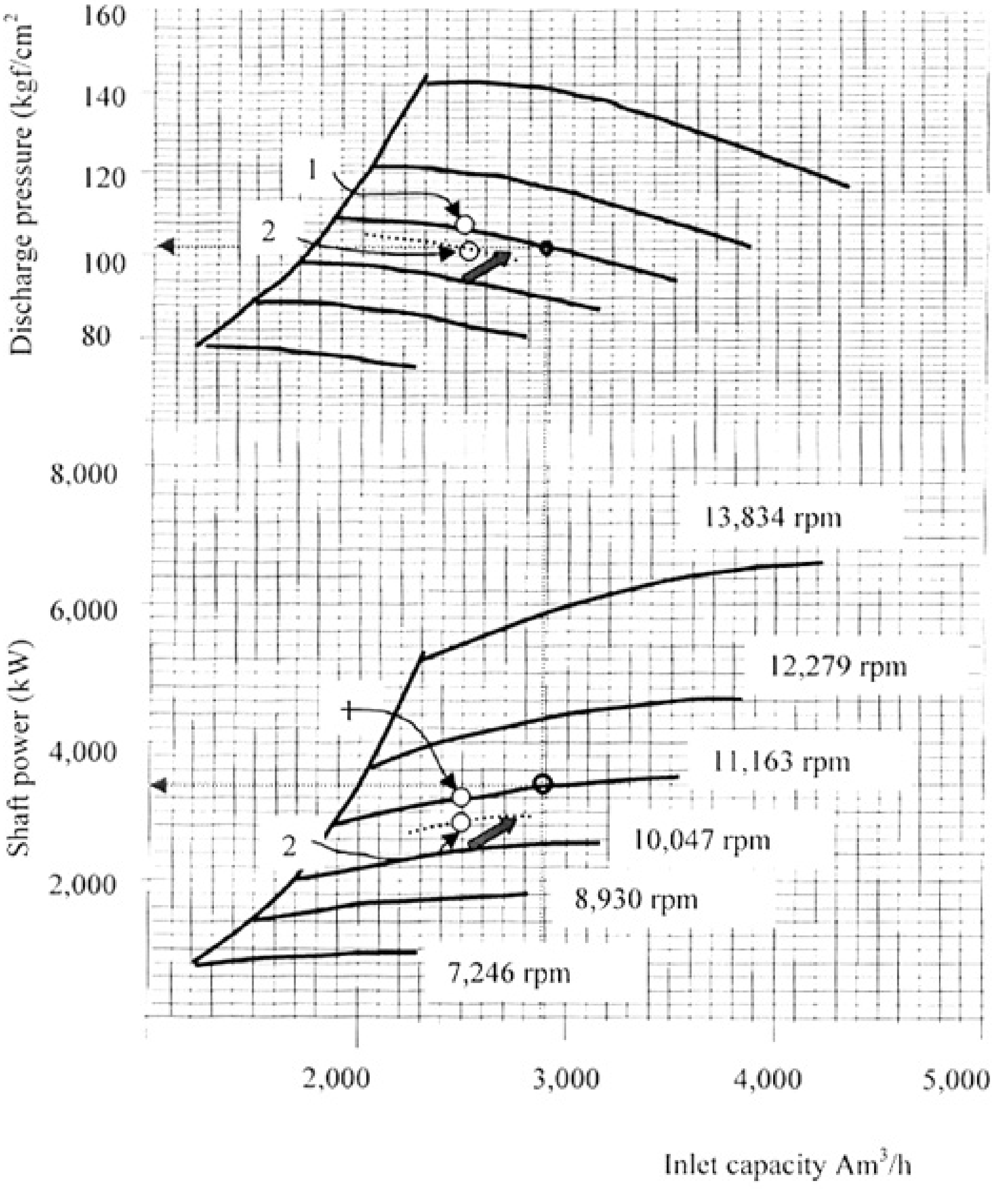

Figure 8.- Compressor performance curves-Power end pressure

The filling process during operation is only possible if the demand is lower than the compressor capacity, then, the speed compressor is raised, in a possible process such as indicated by the wide arrow in Figure 8. The filling time can be calculated by using this new capacity minus the demand, and the initial and final mass in the duct, maintaining the initial pressure drop because it is mainly dependent on demand. That is illustrated in Figure 9, in which line 1 is the initial condition and lines 2 to 4 indicate the rise of pressure in the duct, maintaining the pressure drop due to demand. Line 4 represents the profile for maximum filling, limited to the maximum compressor discharge pressure p_1 or the maximum duct admissible pressure.

Line 5 is the idealized profile in which the pressure is homogeneous and equal to the mean value between p_1 and p_2. in the first moment. During the duct discharge it is supposed that the pressure duct is gradually reduced, which means that the horizontal profile is maintained.

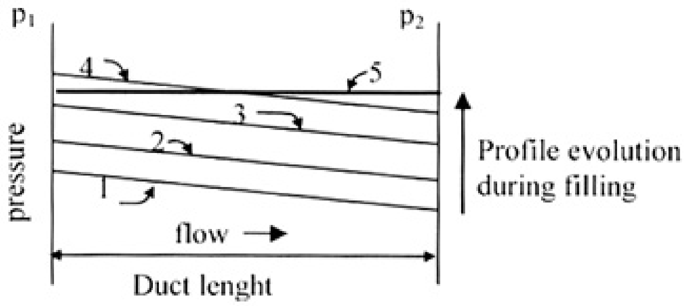

Figure 9.- Pressure profile during filling

4 Economic evaluation

Economic evaluation here presented is based in the different electricity and natural gas cost. comparing the present cost of electricity with the cost of the alternative. This work consider two possibilities for the compressor driver, an electric motor and a natural gas turbine, and it is necessary to study each case in a different form.

4.1 Electric motor drive

Considering a constant relationship between electric power and natural gas delivery the evaluation is simple. As shown in Figure 8 by the wide arrows, the consideration above is reasonable.

By this way, if the NG demand permits, each day would be possible to storage NG in the duct in an enough quantity to permit stopping the electric motor in the peak period tariff. There is no advantage to maintain the compressor (and motor) in standby out of the peak period because the electricity economy will be cancelled in the next duct filling process. So. in this case it is only necessary to storage NG for the hours of the peak period tariff. The present annual cost of electricity is

$$\text{Present cost} = \{(24 - TP)OP + TP \cdot IP\}261 + 104 \cdot 24 \cdot OP$$

and the cost of the alternative (storage of NG) is

$$\text{Alternative cost}=365\cdot 24\cdot \text{OP}$$

The ratio F between the present cost and alternative is

$$F = 0.0298\left\{(24 - TP) + \frac{TP}{R}\right\} + 0.2849$$

where OP and IP are the electricity cost in US$/MWh for the off-peak period and peak period respectively. TP is the hours per day of peak period (3 hours in Brazil) and the numbers 261 and 104 correspond to the days per year with and without peak period respectively. R is equal to the ratio between OP and IP. Figure 10 presents this economy ratio for different values of R (in Brazil between 0.5-0.8).

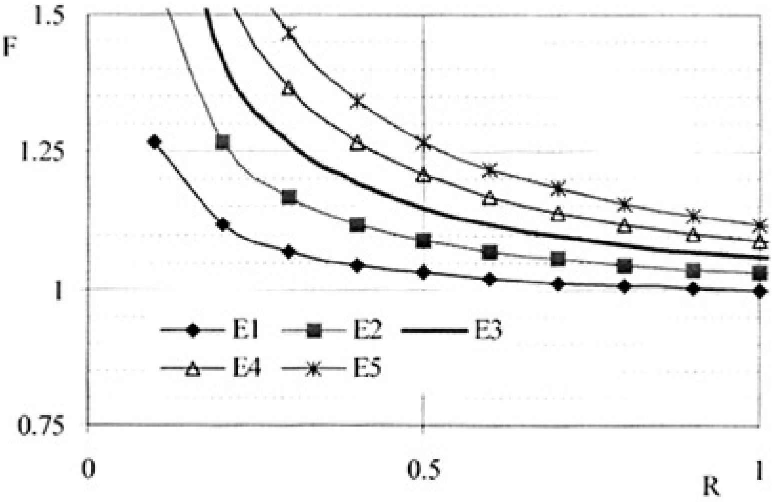

Figure 10.- Economy ratio for electric motor drive

The curves E1 to E5 correspond to TP equal to one to five hours, respectively. The shape of the curves are coherent with R, meaning that the higher the difference in cost. the higher the economy. The calculus has considered that storage is possible all the day of the year. Table 2 indicates estimated values for different operation condition and it is possible to conclude that if the normal demand is around 125,000 Sm^3/h. as indicated in Table 1,. this assumption is appropriate, specially because for three operation hours (TP) it is not necessary to fulfill the duct. Factor F may be used to calculate the percentage of annual economy relative to the present cost with the expression

$$\text{Economy}\,(\%) = \left(1 - \frac{1}{F}\right)\cdot 100$$

Table 2.- Storage capacity of duct, required filling time and cycle duration(all in hours)

Flow (Sm^3/h)	Compressor pressure 80 kgf/cm^2			Compressor pressure 90 kgf/cm^2		
	Storage capacity	Required filling time	Cycle duration	Storage capacity	Required filling time	Cycle duration
80,000	18.88	6.79	25.67	24.73	3.39	28.12
90,000	18.64	7.47	26.11	24.52	3.73	28.25
100,000	18.36	8.30	26.66	24.28	4.15	28.43
110,000	18.05	9.34	27.39	24.01	4.67	28.68
120,000	17.71	10.68	28.39	23.71	5.34	29.05
130,000	17.33	12.46	29.79	23.38	6.23	29.61
140,000	16.92	14.95	31.87	23.02	7.47	30.49
150,000	16.46	18.69	35.15	22.63	9.34	31.97
160,000	15.96	24.92	40.88	22.2	12.46	34.66
170,000	15.41	37.39	52.8	21.74	18.69	40.43

4.2 Gas Turbine Drive

As in the preceding item, a constant ratio between natural gas consumption by the turbine and natural gas delivered by the compressor is here accepted. The alternative in to use the gas turbine (GT) to produce electricity will be of interest if this electricity is cheaper than the electricity acquired from grid.

4.2.1 Gas Turbine Electricity cost

The GT data sheet indicates that for a shaft power of 3,380 kW, 2,944 kcal/s of fuel are needed. Considering that during the storage time the GT operates at full load, its operational cost may be estimated as

$$\text{Hourly cost} = 41.9 \cdot 10^6\, MM \left[\frac{US\$}{h}\right]$$ and the cost of the kWh produced as

$$CMWh = \frac{41.9 \cdot 10^6}{3{,}380 \cdot 1{,}000} MM \left[\frac{US\$}{MWh}\right]$$

where MM is the NG cost in US$ per million BTU, which is estimated to be 3 US$/MMBTU in Brazil.

Because the uncertainly and variability of energy cost. it is possible to imagine three sceneries: **CMWh**>IP>OP; OP<**CMWh**<IP and **CMWh**<OP<IP. The first scenery is not of interest.

4.2.2 OP<CMWh<IP

In this scenery the storage is only of interest when the focus is in the peak period.

The annual economy is calculated as Economy=TP(IP-CMWh)·261 assuming to be possible to storage all the days with peak load tariff.

A factor such as of section 4.1 may be calculated as

$$F = \frac{\{(24-TP)OP + TP \cdot IP\}261 + 104 \cdot 24 \cdot OP}{\langle\{(24-TP)OP + TP \cdot IP\}261 + 104 \cdot 24 \cdot OP\rangle - TP \cdot (IP - CMWh) \cdot 261}$$

or

$$F = \frac{\{(24-TP)R + TP\}261 + 104 \cdot 24 \cdot R}{\langle\{(24-TP)R + TP\}261 + 104 \cdot 24 \cdot R\rangle - TP \cdot (IP - R \cdot RR) \cdot 261}$$

in which RR is CMWh/OP. If the NG prize is 3 US$ per million BTU, CMWh is 37 US$/kWh. a cost higher than the peak period. In this case the alternative must be discarded.

Figure 11 presents factor F for sceneries in which RR is in the range between 1 to 9 and is performed with TP=3 hours. Curve EE10 means RR=1, EE30 means RR=3, and so on.

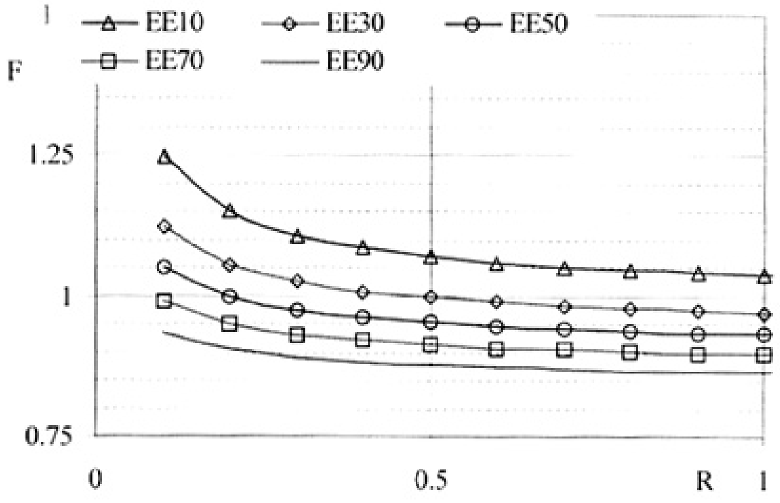

Figure 11.- Economy ratio for OP<CMWh<IP

Note that. for a reference R value of 0.5, the F factor is lower than the case of electrical drive in Figure 10, for RR=1. If OP is in the order of 28 US$/MWh, the prize of NG might be 2.26 US$/million BTU.

4.2.3 CMWh<OP< IP

This scenery is more complex because that both the total storage capacity (TE) and the filling time (FT) in hours must be considered, composing a cycle. Filling and storage time are not cost dependent, but are functions of the physical characteristics of the process, such as pressure drop in duct, pressure p_1, demand and compressor capacity. According to sections 2 and 3, TE and FT are determined for several operational conditions. As shown in Table 2, the cycles durations (CD) are higher than one day, being necessary to calculate the number of cycles per year. separately for the days with and without peak load tariff.

The numbers of cycles in days with peak tariff (N_{cp}) are

$$N_{cp} = \frac{261 \cdot 24}{CD} \text{ and for days without peak tariff } N_{sp} = \frac{104 \cdot 24}{CD}$$

The economy per cycle for the period with peak E_{cp} tariff is

$$E_{cp} = (OP - CMWh)(TE - TP) + (IP - CMWh) \cdot TP$$

and for the period without peak tariff (E_{sp})

$$E_{sp} = (OP - CMWh) \cdot TE$$

where is considering that TE<24 in every case and that the use of storage is planned to include the peak tariff period. The economy factor becomes in this case

$$F = 1 - \frac{\{(24 - TP)OP + TP \cdot IP\}261 + 104 \cdot 24 \cdot OP}{N_{cp}\{(OP - CMWh)(TE - TP) + (IP - CMWh) \cdot TP\} + N_{sp}(OP - CMWh) \cdot TE}$$

or

$$F = 1 - \frac{\{(24 - TP)R + TP\}261 + 104 \cdot 24 \cdot R}{N_{cp}\{(R - R \cdot RR)(TE - TP) + (1 - R \cdot RR) \cdot TP\} + N_{sp}(R - R \cdot RR) \cdot TE}$$

Figures 12 to 14 present the economy factor F for three NG flow and two outlet compressor pressure p_1.

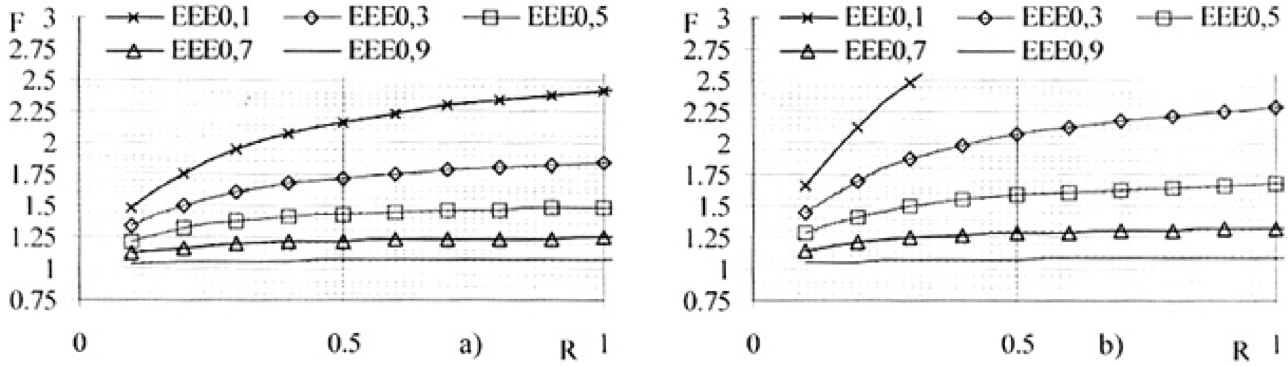

Figure 12.- Economy factor-80,000 Sm^3/h a) 80 kgf/cm^2 b) 90 kgf/cm^2

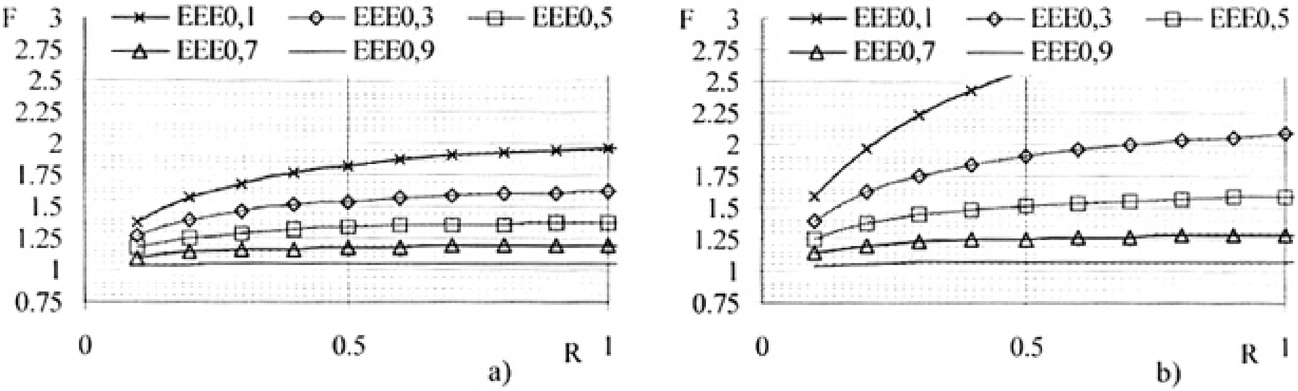

Figure 13.- Economy factor-120,000 Sm^3/h a) 80 kgf/cm^2 b) 90 kgf/cm^2

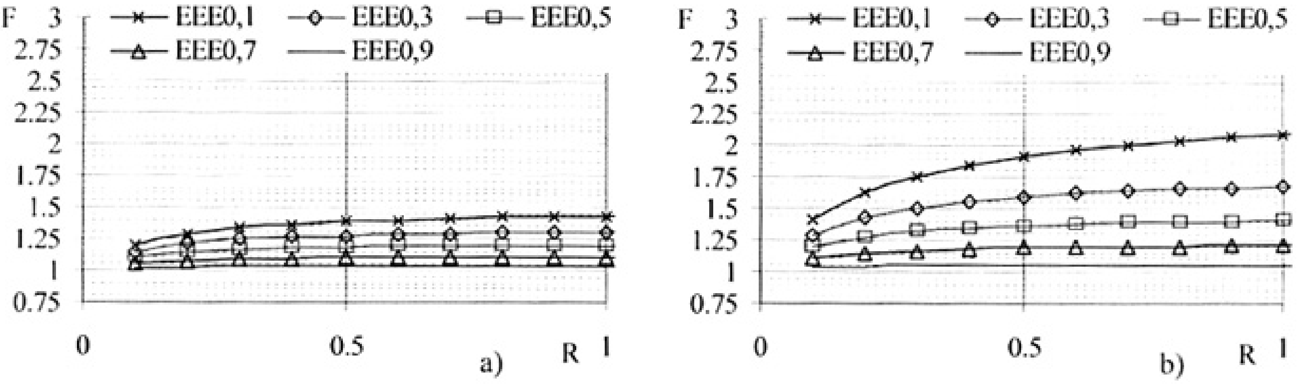

Figure 14.- Economy factor-160,000 Sm^3/h a) 80 kgf/cm^2 b) 90 kgf/cm^2

As was expected, for the same level pressure the factor F decrease with the NG flow, due to a higher pressure drop that conduce to a lower mean pressure in duct. For the same NG flow the factor F increase with the pressure, because the mean pressure increase too, meaning a more quantity of NG in duct.

In Figure 15 are drawn one curve for each of the items 4.1, 4.2.2 and 4.2.3, using TP=3 hours, RR=5 and RR=1 (curves EE50 and EE10) for item 4.2.2 and RR=0.5 for item 4.2.3. (curve EEE0.5) For item 4.2.3 are used a NG flow of 120,000 Sm^3/h and a compressor pressure of 90 kgf/cm^2.

When the cost of electricity from natural gas is between OP and IP (curves EE50 and EE10) the advantages appears only when OP<<<IP (R<<<1) and the same consideration is applicable in the case of electric motor drive (curve E3). Curve EEE0.5 was build in an unrealistic basis. because when using a cost of US$ 3 per million BTU and the actual turbine efficiency CMWh>IP and the alternative has any advantage.

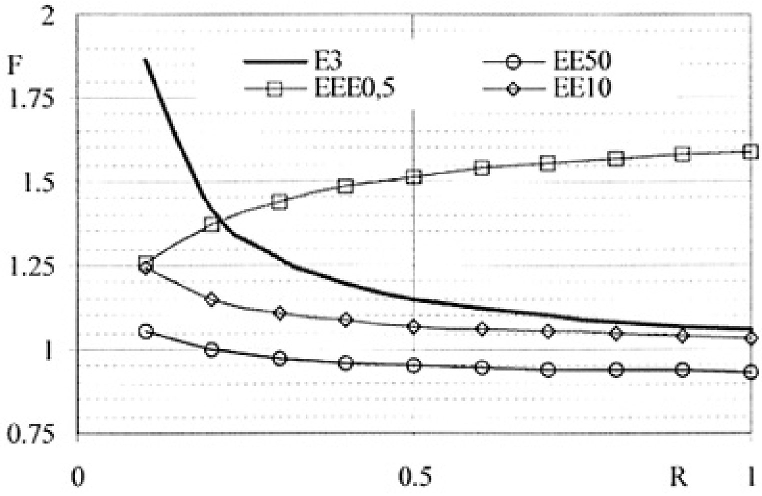

Figure 15.-Comparison of alternatives

5 Conclusions

The economy factor is better in the electrical drive case than the case the turbine electric cost is between OP and IP, and normally a decision adopted with focus in the first case is sustain by a more reliable scenery, because today, in Brazil the relation between OP and IP is known, contrary, the cost of GN are not so previsible.

According to the Figure 15 the percentual of economy is around 5% when the compressor driver is a gas turbine and the cost of electricity produced by the turbine lies between OP and IP, for a factor R=0.5. In the case of an electric motor compressor driver the economy is around 13% and in an "idealized" case in which the cost of the electricity produced by the gas turbine is lower OP, this economy is 33 % if the cost is one half of OP (EEE0.5⇒RR=0.5)

This storage suggestion may be applicable only after a verification of electricity and NG cost increased by the eventually additional operating and capital costs, and a practice that seems to be the simplest way to be adopted is when the drive is an electric motor.

The storage concept implantation claim a strategic planning together the other correlated plants or stations.

The possibility to use a HRSG (Heat Recovery Steam Boiler) for cogeneration purposes in the case of gas turbine drive is not affected when employing the storage potential, but in the case of combined cycle application the electrical output of this cycle will be variable being necessary to analyze if that fact can be carry some inconvenient.

As the duct will begin to work in a different form than the habitual, studies on the mechanical effects in the duct and compressor must be carried out.

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