ENERGY RECOVERING DURING GAS PRESSURE LETDOWN PROCESS IN NATURAL GAS PIPELINE TRANSMISSION

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***Abstract**. Based on a 120 million natural gas cubic meters daily estimated consumption in 2011 on the Brazilian market this paper evaluates the Vortex tube energy recovering potential during the gas pressure letdown in natural gas pipelines transmission. The Vortex tube is a simple, no moving components, small and lightweight, low cost, easy-to-operate and maintenance free device for gas expansion to simultaneously produce heating and cooling. A quantitative evaluation of the heating and cooling potential is presented when the Vortex tube technology is employed to recycle the natural gas pressure drops throughout the local distribution system in the state of Parana, the southern part of Brazil. Assuming steady state functioning of the natural gas pipelines and Vortex tubes, the energy analysis is performed based on a thermodynamically reversible model for the natural gas expansion between the initial gas pressure, when the natural gas enters the local distribution system, and the final gas pressure when the gas is delivered to the end consumers.*

***Keywords**: energy recovery, Vortex tube, NG pipeline transmission, Brazilian market, heating and cooling potential*

1. INTRODUCTION

In connection with an estimated NG consumption of 120×10^6 m^3/day in 2011 on the Brazilian market ("PETROBRAS" Review, July 2007), the aim of this paper is to evaluate the Vortex tube energy recovering potential during the gas pressure letdown in natural gas (NG) pipelines transmission. To accurately develop a quantitative evaluation for the Vortex tube potential to improve energy efficiency it is presented an approach based on the NG market experience in the southern part of Brazil into the state of Parana.

Virtually any process using high-temperature or high-pressure gas may be a resource for energy recovery. Some 10% of the NG transported through transmission pipelines is burnt in order to drive compressors and to pump the remaining NG into transcontinental pipes. Then, at each city gate, typically wasting the potential energy of the pressure drop, the NG pressure is reduced by valves instead of using gas expanders to recycle the pressure drop at the points of gas flow into the local distribution system.

The Vortex tube represents such a non-moving components and easy-to-operate device for gas expansion to simultaneously produce heating and cooling. It has been described first in 1933 and then patented in 1934 by Georges Ranque a French scientist (Ranque, 1933, Ranque, 1934). Later, in 1946, a larger interest in this non-conventional method for producing cooling has been generated by a widely read article of Rudolph Hilsch (Hilsch, 1946).

The Vortex tube is built by two concentric pipes of different diameters joined at one end. The two cylindrical chambers into the pipes are separated by a disk with a central orifice. The other end of the larger pipe is equipped with an outlet valve to control the gas stream discharge, while the gas stream flowing through the smaller pipe discharges freely. Next to the junction and equally spaced around the larger pipe periphery are nozzles arranged to discharge tangentially into the cylinder. The core of the forced vortex, created into the tube when supplying compressed gas to the nozzles, is cold and is extracted from the end of smaller chamber. The periphery of the vortex is hot and is extracted from the end of the larger chamber, controlled by the valve.

During the last two decades, the need for more efficient, less polluting technologies and more ecological technical solutions, generated a careful examination of the Vortex tube as an attractive alternative for new developments in lasers cooling, air conditioning for transportation, small refrigerators, solid state fermentation (Stanescu *et al.*, 1997), hot air for ignition of oil, carburetors, and borer cooling (R433 Vortex Tube Refrigerator Technical Specification, P. A. Hilton Ltd.). Tunkel *et al.* (1996) also patented a method to reduce the NG pressure at the City Gate stations by employing Vortex tubes to eliminate the stations' energy consumption for gas flow heating and to create a cooling duty for further utilization.

Though used in industry the Vortex tube remained partly misunderstood until now. A number of theories have been developed to understand and explain the processes within the Vortex tube (Rocha *et al.*, 1997). The theory of D. C. Fulton (R433 Vortex Tube Refrigerator Technical Specification, P. A. Hilton Ltd.) considers the conservation of angular momentum to explain the separation of the compressed gas entering the Vortex tube, into a cold gas stream and a hot one. Based on the First and Second Laws of Thermodynamics, Petrescu *et al.* (1995) studied comparatively the Hilsch-Ranque Vortex tube expansion processes and the adiabatic reversible expansion performances. A comprehensive study of various aspects of Vortex tube's design also made Radcenco (1990) by employing the exergy method.

The aim of this paper is to present a quantitative evaluation of the heating and cooling potential when the Vortex tube technology is employed to recycle the NG pressure drops throughout the local distribution system in the state of Parana, the southern part of Brazil. Assuming steady state functioning of the NG pipelines and Vortex tubes, the energy analysis is performed based on a thermodynamically reversible model for the NG expansion between the NG pressure when entering the local distribution system and the final pressure when the NG is delivered to the end consumers.

Figure 1. NG transmission system in the southern part of Brazil and the local distribution system in Parana - inside the blue circle. (Reproduction with the permission of the COMPAGAS Company).

2. CONFIGURATION OF THE LOCAL DISTRIBUTION SYSTEM IN THE STATE OF PARANA, BRAZIL

Many natural gas pipeline systems are configured principally for the long-distance transmission of natural gas from production regions to market areas. Providing interstate transportation across various states and operating at pressures higher than distribution pipeline systems, these long-distance systems are often referred to as the transmission system.

Distribution system represents the mainlines, service lines, measurement stations, and other plant assets used by the Local Distribution Company to deliver and control the flow of natural gas to the end consumers' facility. City-gates are the location, usually near a city limit, where gas ownership transfers from a gas supplier to a Local Distribution Company at a measuring and regulating station. NG to be distributed is firstly depressurized at the City-gates, as well as scrubbed and filtered to ensure low moisture and particulate content. To make the detection of leaks much easier, Mercaptan is also added prior to distribution.

Local distribution systems deliver smaller volumes of gas, at pressures lower than the transmission pressure, over shorter distances to a great number of individual end consumers. Thus, small-diameter pipes are used for NG transportation from the City-gates to each individual end customer's location of use. At Local Measuring and Regulating Station (LMRS) NG to be distributed throughout the local distribution system is typically depressurized from the initial gas pressure - when NG enters the local distribution system - and the final gas pressure when the gas is delivered to each one of the end consumers. Table 1 shows the depressurization level and the NG volume delivered across each LMRS along the local distribution system in Parana, Brazil.

Table 1. LMRSs technical characteristics of the NG local distribution system in Parana, Brazil.

Local Measuring and Regulating Station (LMRS)	Depressurization level	Natural Gas delivered
000 - Araucária City-Gate	1.00	100.0%
01 - LMRS	0.14	1.4%
02 - LMRS	0.14	0.6%
03 - LMRS	0.22	2.2%
04 - LMRS	0.22	0.3%
05 - LMRS	0.22	0.7%
06 - LMRS	0.14	0.2%
07 - LMRS	0.72	6.8%
08 - LMRS	0.22	0.3%
09 - LMRS	0.22	0.6%
10 - LMRS	0.22	0.2%
11 - LMRS	0.14	0.3%
12 - LMRS	0.22	3.4%
13 - LMRS	0.14	0.9%
14 - LMRS	0.22	2.1%
15 - LMRS	0.22	2.8%
16 - LMRS	0.22	7.3%
17 - LMRS	0.22	4.3%
18 - LMRS	0.72	8.4%
19 - LMRS	0.14	2.4%
20 - LMRS	0.22	2.4%
21 - LMRS	0.50	0.7%
22 - LMRS	0.50	13.0%
23 - LMRS	0.50	8.5%
24 - LMRS	0.50	1.1%
25 - LMRS	0.50	2.9%
26 - LMRS	0.22	0.6%
27 - LMRS	0.50	1.6%
28 - LMRS	0.14	0.0%
29 - LMRS	0.50	4.7%
30 - LMRS	0.14	1.4%
31 - LMRS	0.22	4.4%
32 - LMRS	0.14	0.4%
33 - LMRS	0.50	3.2%
34 - LMRS	0.50	6.6%
35 - LMRS	0.50	3.2%

3. VORTEX TUBE FUNDAMENTALS

The Vortex tube is modeled in here as a thermodynamic open system as shown in Fig. 2. The control volume consists of the two cylindrical chambers within pipes, contained between the inlet ports into nozzles, and the outlet ports of pipes open to the surroundings. The outlet area of the larger pipe (the "hot end") is controlled by a valve, while the outlet from the smaller pipe (the "cold end") is free.

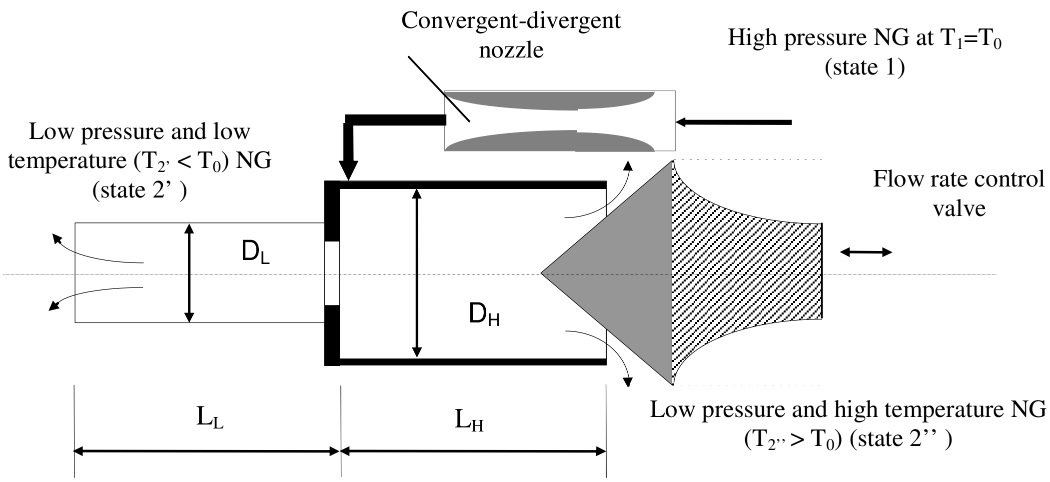

Figure 2. Schematic lateral view of the Vortex Tube (L_H and D_H represent respectively the length and diameter of the hot side of the Vortex tube, while L_L and D_L indicate the length and diameter of the cold side).

A forced vortex is created when supplying compressed gas to the nozzles. Jets discharge into the chamber at very high velocity and the vortex rotates at very high angular speed. Due to the viscous forces, the vortex rotates at constant angular velocity and its tangential velocity is proportional to the radius. Based on the conservation of the angular momentum of the gas leaving the nozzles, the angular momentum of the vortex core must have decreased by exactly the same amount as the angular momentum of the periphery has increased. The redistribution of angular momentum along radius is accompanied by the redistribution of the gas mass along the radius. Simultaneously, the rotational and translational kinetic energies are redistributed into the gas mass.

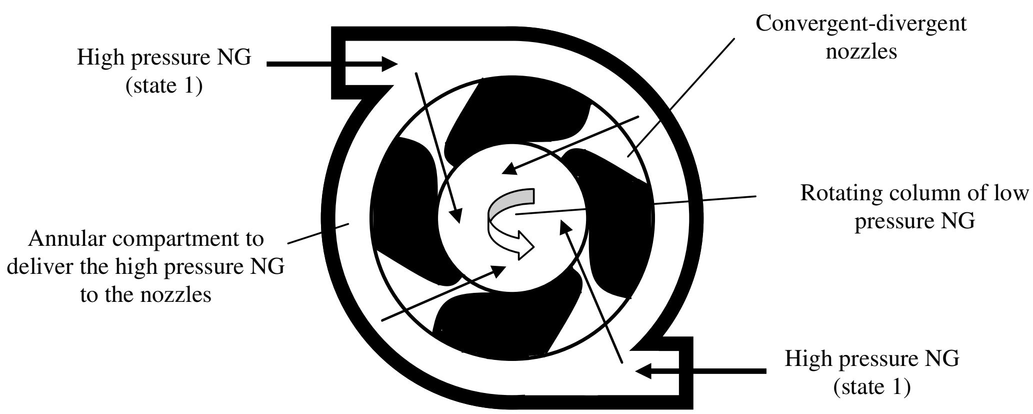

Figure 3. Schematic view of the Vortex Tube (transversal view)

The two gas streams within the Vortex tube are throttled when passing through the orifice into the disk that separates the two chambers, or through the hot end area controlled by the valve. These throttling occur such that the kinetic energies differently reenter the gas masses. This means that the two gas streams, each one a fraction of the total gas entering the Vortex tube, both at different temperatures smaller than the initial temperature of the compressed gas, will not regain exactly the energy they lost during redistribution.

This makes possible that the average temperature of one gas stream (extracted from the "cold end") is smaller than the initial temperature of the compressed gas, since the gas stream regains less energy than it lost. Obviously, the other gas stream (extracted from the "hot end") is hotter than the compressed gas supplied to the Vortex tube, since now the gas regains more energy that it lost. The valve fitted in the "hot end" controls the proportions of the total gas flow which passes from the "hot end" and "cold end".

4. MATHEMATICAL MODEL

To evaluate the Vortex tube energy recovering potential we consider the steady state operation of the pipeline system and the Vortex tubes installed to recycle the pressure drops throughout the local distribution system. We are mainly interested in energy recovery during the gas pressure letdown from pressure p_1, when the NG enters the local distribution system, and the end consumer final pressure $p_{2'} = p_{2''}$.

Figure 4 schematically shows the compression process 0 – 1' to increase the NG pressure to the p_1 level in order to pump it along the pipeline. Line 1' – 1 represents the cooling process occurring at constant pressure while the NG flows along the pipeline. "Cold" and "hot" gas expansions occur along the lines 1 – 2' e 1 – 2'' and lines 2' – 3 e 2'' - 3 represent the energy recovery processes.

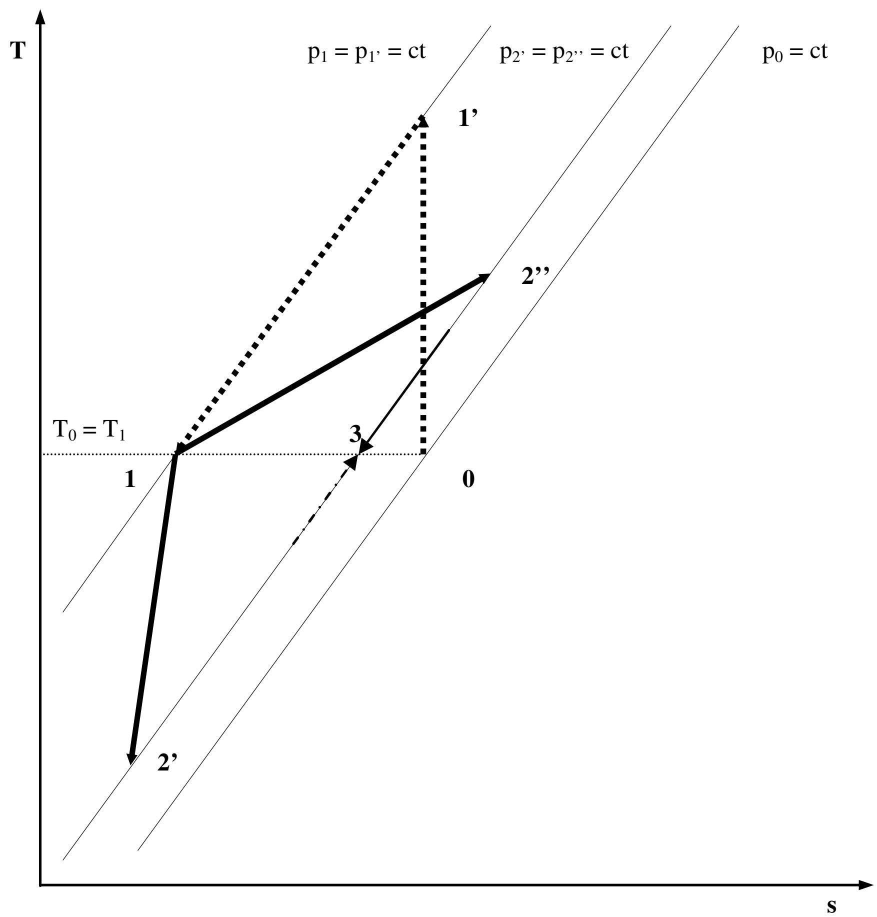

Figure 4. T - s diagram for thermodynamic evaluation of the processes inside the Vortex tube. "Cold" and "hot" gas expansions occur along lines 1 – 2' e 1 – 2'' while lines 2' – 3 e 2'' - 3 represent the energy recovery processes.

Assuming the Vortex tube to be a adiabatic control volume with one compressed NG entry at state 1 and to low pressure NG exits at states 2' and 2'', the mass and energy conservation equations and the second law of thermodynamics for steady state functioning are written:

$$\dot{m}_1 - \dot{m}_{2'} - \dot{m}_{2''} = 0 \tag{1}$$

$$\dot{m}_1 h_1 - \dot{m}_{2'} h_{2'} - \dot{m}_{2''} h_{2''} = 0 \tag{2}$$

$$\dot{m}_1 s_1 - \dot{m}_{2'} s_{2'} - \dot{m}_{2''} s_{2''} + \dot{S}_{ger} = 0 \tag{3}$$

As shown in Table 1, the depressurization level and the NG flow rate are known at each local measuring and regulating station (LMRS) based on measured values. Recognizing $T_0 = T_1 = T_3$ in Fig. 4 and $\dot{S}_{ger} = 0$ based on the assumption of reversible NG expansion inside the Vortex tube, Eqs. (1) – (3) become an algebraic system of two equations with the unknowns $T_{2'}$ and $T_{2''}$:

$$h_1(T_1, p_1) - x h_{2'}(T_{2'}, p_2) - (1-x) h_{2''}(T_{2''}, p_2) = 0 \tag{4}$$

$$1 - x s_{2'}(T_{2'}, p_2) / s_1(T_1, p_1) - (1-x) s_{2''}(T_{2''}, p_2) / s_1(T_1, p_1) = 0 \tag{5}$$

where $x = \dot{m}_{2'} / \dot{m}_1$, labeled the cold fraction, is the percent of total NG input released through the cold exhaust.

Table 2. Waste energy recovery potential of Vortex tubes and turbo-expanders.

	$\lvert Q_H \rvert = Q_L$	$\dot{W}$
	(kW)	(kW)
01 - LMRS	45.19	16.89
02 - LMRS	20.18	7.54
03 - LMRS	65.41	21.38
04 - LMRS	7.93	2.59
05 - LMRS	21.82	7.13
06 - LMRS	5.14	1.92
07 - LMRS	105.30	15.13
08 - LMRS	9.92	3.25
09 - LMRS	18.08	5.92
10 - LMRS	5.16	1.69
11 - LMRS	8.16	3.05
12 - LMRS	100.30	32.81
13 - LMRS	30.14	11.31
14 - LMRS	63.69	20.94
15 - LMRS	83.59	27.51
16 - LMRS	215.80	71.00
17 - LMRS	126.60	41.66
18 - LMRS	114.30	14.33
19 - LMRS	75.39	28.23
20 - LMRS	66.16	20.04
21 - LMRS	16.43	3.63
22 - LMRS	295.40	66.56
23 - LMRS	192.50	43.38
24 - LMRS	25.73	6.15
25 - LMRS	67.10	15.64
26 - LMRS	15.96	4.80
27 - LMRS	37.67	8.96
28 - LMRS	0.90	0.34
29 - LMRS	104.20	22.82
30 - LMRS	45.28	16.90
31 - LMRS	130.80	42.61
32 - LMRS	12.81	4.81
33 - LMRS	76.48	18.18
34 - LMRS	154.10	36.36
35 - LMRS	75.83	17.87

The Vortex tube energy recovering potential is calculated as follows:

$$\dot{Q}_L = x\dot{m}_1 [\, h_3(T_3, p_2) - h_{2'}(T_{2'}, p_2)\,] \tag{6}$$

$$\dot{Q}_H = (1-x)\dot{m}_1 [\, h_3(T_3, p_2) - h_{2''}(T_{2''}, p_2)\,] \tag{7}$$

5. NUMERICAL RESULTS

To deliver the NG adequately to each individual end customer, the COMPAGAS Company - which is the local NG distribution company in Parana, Brazil - typically depressurizes the NG from 34.3 bars, the NG pressure when entering the local distribution system, to four different pressure levels: 24.5 bars, 16.7 bars, 6.9 bars and 3.9 bars.

The inlet pressure (p_1) and the cold fraction (x) settings are important factors in Vortex Tube performance. They are controlled by the valve at the hot NG exhaust. Since a cold fraction less than 50% of the input NG exiting through the cold NG exhaust would produce lowest temperatures, but would also reduce the NG flow rate, in this study, to evaluate the Vortex tube heating and cooling energy recovering potential during the gas pressure letdown it is assumed that the cold fraction is 50%.

Table 2 presents the numerical values, calculated based on the algebraic system (4) – (7), of the Vortex tube energy recovery potential when the Vortex tube technology is employed to recycle the natural gas pressure drops throughout the local distribution system in the state of Parana. Calculated values for the heating $\dot{Q}_H$ and cooling $\dot{Q}_L$ potential for x=0.5 are equal $|\dot{Q}_H| = \dot{Q}_L$. $\dot{Q}_H$ represents the amount of energy that would be possible to remove from the hot NG flow leaving the Vortex tube by cooling down to $T_0 = T_3$ at constant pressure this flow (line 2'' – 3 in Fig. 4). $\dot{Q}_L$ represents the amount of energy that would be necessary in order to heat up to $T_0 = T_3$ at constant pressure the cold NG flow leaving the Vortex tube (line 2' – 3 in Fig. 4).

Since turbo-expanders may also help to recover the NG pressure letdown wasted energy to generate mechanical power and increase the overall efficiency, Table 2 comparatively shows an estimate of the mechanical energy recovery potential for each LMTS. Numerical values of the mechanical power $\dot{W}$ are determined by assuming a reversible adiabatic expansion of the NG from pressure p_1 to the end consumer pressure $p_2 = p_{2'} = p_{2''}$:

$$\dot{W} = \frac{\dot{m}_1 R_{CH_4} T_1}{(k-1)} \left[1 - \left(\frac{p_{2'}}{p_1} \right)^{\frac{k-1}{k}} \right] \tag{8}$$

Numerical values in Table 2 indicate a 2.4 MW of heating and 2.4 MW of cooling energy recovery potential, theoretically available when employing the Vortex tube technology to recycle the steady state operation pressure drops throughout the local distribution system in Parana, Brazil. There is also a 0.6 MW energy recovering potential theoretically available when using turbo-expanders to generate mechanical power by recovering the NG pressure letdown wasted energy.

Table 3. Energy recovery potential at each LMRSs located along the two pipeline extensions in Curitiba.

South-North Extension No. 1		
	$\lvert\dot{Q}_H\rvert = \dot{Q}_L$	$\dot{W}$
	(kW)	(kW)
23 - LMRS	192.50	43.38
20 - LMRS	66.16	20.04
24 - LMRS	25.73	6.15
27 - LMRS	37.67	8.96
25 - LMRS	67.10	15.64
26 - LMRS	15.96	4.80
∑	405.00	99.00

South-North Extension No. 2		
	$\lvert\dot{Q}_H\rvert = \dot{Q}_L$	$\dot{W}$
	(kW)	(kW)
22 - LMRS	295.40	66.56
33 - LMRS	76.48	18.18
34 - LMRS	154.10	36.36
35 - LMRS	75.83	17.87
∑	602.00	139.00

Since the 2.4 MW of heating and 2.4 MW of cooling represents the energy recovering potential of all the NG local distribution system in Parana irrespective of its location along the piping lines, in order to determine the practically available potential it would be necessary to evaluate, according to the local distribution system existing configuration, the energy recovering potential based on the LMRSs actual locations.

Based on the actual physical configuration of the NG local distribution system, we indentified two South-North pipeline extensions providing NG to the end consumers in Curitiba, the capital of the Parana state. Table 3 indicates the energy recovering potential at each LMRS located along each of the two pipeline extensions.

Numbers in Table 3 show that, along the 1 km long South - North Extension No 2, it is available 25% of all Vortex tube heating and cooling energy recovery potential, of the whole NG distribution system in Parana. Both, the South - North Extensions No 1 and No 2 distributing NG inside the Curitiba City are responsible for more then 41% of the whole Vortex tube heating and cooling energy recovering potential during the gas pressure letdown.

6. CONCLUSIONS

The aim of this work is to evaluate the Vortex tube technology maximum potential to recover the NG pressure letdown wasted energy throughout the local NG distribution system in Parana, Brazil. It is found that 2.4 MW of heating and 2.4 MW of cooling energy are theoretically available when using the Vortex tubes. Turbo-expanders technology to generate mechanical power would theoretically recover 0.6 MW.

Since the effective energy recovery would practically occur at each LMRS, its feasibility depends on the local distribution system configuration and the LMRSs number and their actual locations. NG pressure letdown wasted energy recovery then depends on the amount to be paid in order to provide one Vortex tube or turbo-expander for each functioning LMRS. The simple, no moving components, small and lightweight, easy-to-operate, maintenance free and low cost Vortex tube technology seems to be the perfect candidate while the more complex and more expensive turbo-expander technology doesn't match very well.

It is highly desirable that future expansion of the existent NG distribution system in Parana would be implemented based on carefully designed projects to improve the interaction with the industrial surroundings by providing the heating and cooling energy to industries that use such utilities.

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