Scientia et Technica Año XXV, Vol. 25, No. 02, junio de 2020. Universidad Tecnológica de Pereira. ISSN 0122-1701 y ISSN: 2344-7214
DOI: 10.22517/23447214.23481

Thermodynamic Analysis of a System to Generate Electrical Energy from the Mechanical Energy of a Natural Gas

Análisis termodinámico de un sistema para generar energía eléctrica a partir de la energía mecánica de un gas natural.

J.D. Hernández-Vásquez ; R.D. Pardo-Zapata ; B. Carrol-Gutiérrez

***Abstract*—The objective of this work is to design a system for generating electricity from the mechanical energy of a natural gas at high pressure. The main motivation for the development of the research is based on the need to detect by the natural gas distribution industry, where it is considered that the use of the mechanical energy of natural gas (flow energy and kinetic energy) can be used for the Electric power generation, through a turbo expander, and thus power the electromechanical components of a substation. In this way, energy consumption costs are reduced, which translates into unquestionable gains in energy efficiency. The methodology applied is based on the use of physical principles such as the conservation of mass and energy in a control volume. Likewise, the guidelines established in the guideline for the expression of measurement uncertainty allowed us to estimate an interval where the real value of the mechanical power generated at the output of the turboexpander is found. Based on experimental data in a natural gas distribution substation, the consolidated results allowed quantifying the average mechanical power at the inlet of a turboexpander (8155 W) and, in the typical situation where the turboexpander reduces its outlet pressure to 50% , an average mechanical power is generated at the output of the turboexpander equal to 4893 W, which translates into an efficiency of 40%. This research work allowed us to conclude that the design of a system for electric power generation is viable based on the thermodynamic and dimensional parameters associated with the natural gas distribution system, as well as the mechanical power that can be generated at the exit of a turboexpander.**

***Index Terms*— Energy efficiency, Electric power generation, Electromechanical Engineering, Mechanical energy, Natural gas.**

***Resumen*— Este trabajo tiene por objetivo diseñar un sistema de generación de energía eléctrica a partir de la energía mecánica de un gas natural a alta presión. La motivación principal para el desarrollo de la investigación se fundamenta en la necesidad detectar por la industria de distribución de gas natural, donde se considera que el aprovechamiento de la energía mecánica del gas natural (energía de flujo y energía cinética) puede ser aprovechado para la generación de energía eléctrica, a través de un turbo expansor, y así alimentar los componentes electromecánicos de una subestación. De esta forma se disminuyen costos de consumo de energía lo que se traduce en incuestionables ganancias de eficiencia energética. La metodología aplicada se basa en la utilización de principios físicos como lo son la conservación de masa y energía en un volumen de control. De igual forma, lo lineamiento establecidos en la guía para la expresión de la incertidumbre de medición, permitió estimar un intervalo donde se encuentra el valor real de la potencia mecánica generada a la salida del turbo expansor. A partir de datos experimentales en una subestación de distribución de gas natural, los resultados consolidados permitieron cuantificar la potencia mecánica promedio en la entrada de un turbo expansor (8155 W) y, en la situación típica donde el turbo expansor reduce su presión de salida al 50%, se genera una potencia mecánica promedio a la salida del turbo expansor igual a 4893 W, lo que se traduce en una eficiencia de 40%. Este trabajo de investigación permitió concluir que el diseño de un sistema para generación de energía eléctrica es viable a partir de los parámetros termodinámicos y dimensionales asociadas al sistema de distribución de gas natural, así como la potencia mecánica que puede ser generada a la salida de un turbo expansor.**

***Palabras claves*— Energía mecánica, Eficiencia energética, Gas natural, Generación de energía eléctrica, Ingeniería Electromecánica.**

***Resumo*— Este trabalho tem como objetivo projetar um sistema para gerar eletricidade a partir da energia mecânica de um gás natural em alta pressão. A principal motivação para o desenvolvimento da pesquisa baseia-se nos desafios impostos pela indústria de distribuição de gás natural, onde se considera que o uso da energia mecânica do gás natural (energia de fluxo e energia cinética) pode ser usada para a Geração de energia elétrica, através de um turbocompressor, e, assim, alimentar os**

This manuscript was sent on October 14, 2020 and accepted on March 06, 2020.
José Daniel Hernández-Vásquez is with Universidad Antonio Nariño. Faculty of Mechanical, Electronic and Biomedical Engineering (FIMEB). Mechanical Engineering Program. GIFOURIER Research Group. Puerto Colombia, Colombia (e-mail: johernandez79@uan.edu.co).

Rubén Darío Pardo Zapata is with Universidad Antonio Nariño. Faculty of Mechanical, Electronic and Biomedical Engineering (FIMEB). Mechanical Engineering Program. GIFOURIER Research Group. Puerto Colombia, Colombia (e-mail: rubpardo@uan.edu.co).

Brandon Carrol Gutiérrez is with Universidad Antonio Nariño. Faculty of Mechanical, Electronic and Biomedical Engineering (FIMEB). Mechanical Engineering Program. GIFOURIER Research Group. Puerto Colombia, Colombia (e-mail: brancarguti@uan.edu.co).

componentes eletromecânicos de uma subestação. Isso reduz os custos de consumo de energia, o que se traduz em ganhos inquestionáveis em eficiência energética. A metodologia aplicada é baseada no uso de princípios físicos, como a conservação de massa e energia em um volume de controle. Da mesma forma, as diretrizes estabelecidas no guia para a expressão da incerteza de medição permitiram estimar um intervalo em que é encontrado o valor real da potência mecânica gerada na saída do expansor turbo. Com base em dados experimentais em uma subestação de distribuição de gás natural, os resultados consolidados permitiram quantificar a potência mecânica média na entrada de um turbo expansor (8155 W) e, na situação típica em que o turbo expansor reduz sua pressão de saída em 50%, uma potência mecânica média é gerada na saída do expansor turbo igual a 4893 W, o que se traduz em uma eficiência de 40%. Este trabalho de pesquisa permitiu concluir que o projeto de um sistema para geração de eletricidade é viável com base nos parâmetros termodinâmicos e dimensionais associados ao sistema de distribuição de gás natural, bem como na potência mecânica que pode ser gerada na saída de um turbocompresor.

Palavras chaves— **Energia mecânica, Engenharia eletromecânica, Eficiência energética, Gás natural, Geração de energia elétrica.**

I. INTRODUCTION

In 2018, energy demand in Colombia expanded by 3.3% and the country has enough generating plants to supply 100% and export in small proportions of fuels that are used as a source of generation. Its main method of generation is hydraulics, this being a "friendly" way with the environment and sufficient. However, when there is a decrease in hydraulic sources caused mainly by El Niño phenomenon, it is necessary to use thermal plants (either gas, coal or ultimately liquids) to supply the deficit caused, being unfriendly to the environment. Thus, it is necessary to look for new alternatives for power generation. At present, the total mechanical energy (kinetic and potential) is not being used when the pressurized fossil fuel is extracted and in the large gas and liquid regulation stations, where the speed produced by the fall of Pressure given in the process is not being used efficiently, thus wasting a very useful opportunity for the generation of electrical energy. So, this work aims to perform a thermodynamic analysis of a system to generate electrical energy from the mechanical energy of a natural gas using real data from the measurement system of a natural gas substation on the Colombian Caribbean coast.

Natural gas is widely used as a fuel for power generation to obtain electricity, due to its low costs and high efficiency in generation systems such as the combined cycle [1].

In 2001, Amell et al. [1] describe the aspects of the combined cycle power plants in dominant mode for the generation of electric power, they emphasize that turbines and combined cycles are the dominant mode of electricity generation and that this is generates at a lower cost and with less environmental impact in its study Technological trends for the improvement of the performance of combined cycle plants.

State that natural gas is a new energy vector that will play a great role in energy production over the next decades for technological, economic, environmental and geoponic reasons, in their research on natural gas as new Energy vector highlights the factors and its participation as a fundamental component in the energy matrix [2]. Also say that the use of natural gas for electricity generation has two advantages: greater energy efficiency and less environmental impact [3].

According to [4] the growing fraction of natural gas within the generation of electric energy from fossil fuels contributes significantly to the demand of the energy sector. Already in 2007. The authors [4] implemented a system for generating electricity from biogas, which allowed the use of biogas generated from excreta of animal origin. The results were very interesting, once the authors obtained a ratio of 2 m³ of biogas for each kWh generated.

In addition, the authors affirmed that the generation of electricity from fossil fuels has been the most important generation process and will meet the needs of the energy sector. In 2009, Gonzalez [5] searched on the gasification of coal for electric power generation analysis with valuation of real options is economically convenient, obtained that the project to obtain electric energy through natural gas, the project has a High sensitivity regarding efficiency and costs.

The fact that the use of natural gas for electricity generation has great advantages compared to other fossil fuels. In that work on the economic and environmental impact of the use of natural gas in the generation of electricity in the Amazon, he demonstrated how the use of this for the generation of electricity has a positive effect supported by the reduction of costs and emissions emitted to the environment [6]. In 2016, a research realized by Pasquevich et al. [7] was based on the implementation of a natural gas generator set to reduce the costs of electricity consumption. The analysis involved ecological calculations whose results allowed it to find a reduction of 1807.65 MT / year of carbon dioxide and 100.54 MT / year of sulfur dioxide. Additionally, in economic terms the authors affirm that the useful profit of the project is $ 186331.04 / year, with an initial investment of 468620.35 U $$ and an operational return on investment of 2.5 years [8-10].

Giving continuity to the theoretical foundation, a series of basic concepts related to the research topic are described below.

II. THEORETICAL BACKGROUND

A. *Principle of energy conservation for a control volume*

A control volume, also known as an open system, is characterized by the exchange of mass between the system and its borders. They are usually used for energy analysis in the oil and gas industry for various components: valves, turbines, heat exchangers, combustion chamber, compressors among other turbomachines [11].

For the analysis of a control volume, once there is mass flow in motion, a flow work, known as enthalpy, is performed by the molecules of the fluid in order to produce such movement. This work of flow (enthalpy, h) is given by thermodynamic properties, known as a state function. These properties correspond to the product of pressure and volume, added to the internal energy, as shown in the following expression:

$$h = u + pv \tag{1}$$

Thus, the principle of energy conservation for a control volume is shows in (2), with the following simplifying assumptions: (i) the control volume is in a stationary state (there is no relative movement in relation to the coordinate axis); (ii) the state of the substance within the control volume does not change over time; (iii) the heat transferred to the control volume and the work produced are constant:

$$\dot{Q}_{VC} - \dot{W}_{VC} + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) - \sum \dot{m}_s \left(h_s + \frac{V_s^2}{2} + gz_s \right) = 0 \quad (2)$$

The previous expression, the term $\dot{m}\left(\frac{V^2}{2} + gz\right)$ is known as the mechanical energy of the analyzed open system. This mechanical energy is the sum of the kinetic energy of the substance (due to its velocity) and the potential energy (due to the difference in height in relation to the coordinate axis).

The expression in (2) is of great interest and application in this paper, once the analyzed natural gas flow, as well as the electromechanical components that the fluid passes through, correspond to a control volume in which the thermodynamic fundamentals described in this section are fully applicable.

B. Analysis of physical variables in a natural gas

The analysis of physical variables in a natural gas is performed using the classical theory enshrined in thermodynamics [2]. For this analysis the equation of an ideal gas was applied considering a compressibility factor (Z) different from one. This Z factor represents an indicator of the behavior of the proximity of a real gas to an ideal gas, which is closer to one, the real gas is much closer to the properties of an ideal gas.

For the specific case of this paper, the analyzed natural gas is, in its chemical composition, 99.14% methane ($CH4$) 0.86% other gases. Thus, applying (6) was used to determine the mass of the gas:

$$PV = ZmR_gT \quad (3)$$

Since it is a real gas, to determine the compressibility factor it is necessary to determine the pseudo-critical pressures and temperatures, based on Kay's rule [11]. Applying (4) and (5) are used to determine these two properties:

$$P_{cr} = \sum_{i=1}^{k} y_i P_{cr_i} \quad (4)$$

$$T_{cr} = \sum_{i=1}^{k} y_i T_{cr_i} \quad (5)$$

For the specific case of this investigation, since it is a natural gas whose chemical composition is essentially methane, the partial pressures and temperatures (experimentally measured) correspond to the critical pressures and temperatures set forth in the equations above.

Following the analysis of the physical variables for a natural gas system, once the critical pressures and temperatures have been determined, the reduced pressure (P_r) and reduced temperature (T_r), must be calculated, applying (6) and 7 respectively.

$$P_r = \frac{P}{P_{cr}} \quad (6)$$

$$T_r = \frac{T}{T_{cr}} \quad (7)$$

In this investigation $P_r = 1\ and\ T_r = 1$. This is because the pressures measured by the pressure transmitter is equivalent to that calculated by (7). Similarly, the temperature measured by the resistance thermometer is equivalent to that calculated using (8).

Knowing the values of the pressure and reduced temperature, the Generalized Compressibility Graph of Nelson-Obert [11] was used to determine the compressibility factor for natural gas. Annex A contains the graph proposed by Nelson-Obert. Thus, knowing the Z factor, and from the other properties (pressure, temperature, volume, constant gas) it is possible to determine the mass of natural gas by means of (8), which is a mathematical clearance of (3):

$$m = \frac{P \cdot V}{Z(P_r, T_r) \cdot R_g \cdot T} \quad (8)$$

Once the mass of the natural gas has been determined, it is necessary to apply the Gibbs ratios to obtain the enthalpy, that is, the flow energy of the natural gas. Applying (9) was possible to find this thermodynamic property. For the analysis in this investigation a reversible and isentropic process is assumed

$$dh = Tds + vdP \quad (9)$$

Finally, once the enthalpy of natural gas has been determined, it will be possible to perform an energy balance in a control volume (turboexpander). The energy balance is generalized in (10). This expression allows determining the mechanical power generated by the turboexpander (E_g), from the mechanical input energy (E_{in}) and the mechanical output energy (E_{in}) of the control volume:

$$E_g = E_{in} - E_{out} \quad (10)$$

The mechanical energy of natural gas in the inlet section is determined by the inlet mass (m_{in}), the enthalpy (h_{in}) and the velocity of the fluid at the inlet (Vel_{in}), applying (11):

$$E_{in} = m_{in} \cdot h_{in} + \frac{1}{2} m_{in} \cdot (Vel_{in})^2 \quad (11)$$

The fluid velocity at the inlet can be determined by (12), from the flow measurement (Q) and the area of the duct (A):

$$E_{in} = m_{in} \cdot h_{in} + \frac{1}{2} m_{in} \cdot \left(\frac{Q}{A}\right)^2 \quad (12)$$

The input mass and input enthalpy can be determined by applying (8) and (9) respectively. However, (13) and (14) represent, in a specific way, the calculation of the input mass and the enthalpy of input using the respective sub-indices that allow their identification:

$$m_{in} = \frac{P_{in} \cdot V}{Z_{in}(P_r, T_r) \cdot R_g \cdot T_{in}} \quad (13)$$

$$h_{in} = v_{in} \cdot P_{in} = \frac{V}{m_i} \cdot P_{in} \quad (14)$$

Thus, substituting (13) and (14) in (12) and, subsequently, replacing that result in (10) (for energy input and output), expression (13) presents the general way to determine the energy generated by the turboexpander in The natural gas distribution system:

$$E_g = \left[\left(\frac{P_{in} \cdot V}{Z_{in}(P_r, T_r) \cdot R_g \cdot T_{in}}\right) \cdot \left(\frac{V}{m_i} \cdot P_{in}\right) + \left(\frac{1}{2} m_{in} \cdot \left(\frac{Q}{A}\right)^2\right)\right] - \left[\left(\frac{P_{out} \cdot V}{Z_{out}(P_r, T_r) \cdot R_g \cdot T_{out}}\right) \cdot \left(\frac{V}{m_{out}} \cdot P_{out}\right) + \left(\frac{1}{2} m_{out} \cdot \left(\frac{Q}{A}\right)^2\right)\right] \quad (15)$$

III. METHODOLOGY

The process of obtaining natural gas from the time it is extracted from the subsoil until it reaches the end user, whether at the urban or industrial level, goes through a series of physical-chemical processes that condition it, transport and distribute it to the end user.

The natural gas extraction process begins with the exploration of the deposits by means of geological studies and analyzes raised at the site where the extraction is projected to discover and quantify possible gas wells. After identifying the gas well and if the reserve is declared approved, after determining the quantity, quality and estimated duration of the same, an exploitation plan is developed, which is nothing more than the activities necessary to extract the gas safely from the subsoil and its separation from heavy hydrocarbons. Usually, this gas is pressurized between 3000 psig and 5000 psig at the wellhead. The drilling is done and the extracted natural gas is taken to a plant to perform dehydration, sweetening, dew point adjustment, mercury removal unit, nitrogen rejection, paraffin handling and pressure reduction (1200 psig maximum). Once brought to standardized standard conditions, the transport system is delivered. The transport system consists of the transfer of this gas through gas pipelines, which are usually buried and with sectioning valves strategically located along it to section it by sections when necessary, from the extraction zone to the cities or industries that require it. When the transport system conducts the gas to the city or industry, it is passed through a regulation and distribution station (Fig. 1), in which the gas is received at 1200 psig, it passes through a filtration system to prevent particles solid or liquid enter the equipment found below, then it reaches the regulation system that is responsible for reducing the pressure from 1200 psig to 300 psig.

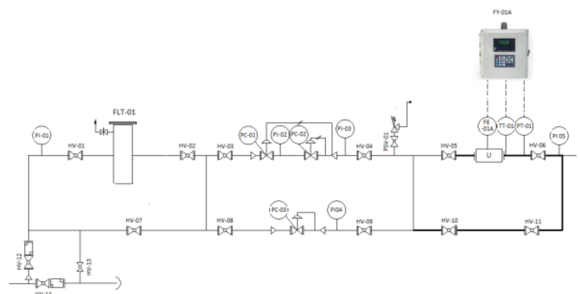

Fig. 1. Current design of a regulation station

IV. RESULTS AND DISCUSSION

A. Instrumentation associated with the generation of electricity in a natural gas substation

For the use of the mechanical energy of the natural gas that flows through the regulation station to obtain electrical energy, it is essential to include a turboexpander in the process, because this is the one who will receive and convert that mechanical energy of the natural gas and transmit it to the electric power generator. Currently, the regulation station has a solar energy system that feeds its electrical and electronic equipment, however, when the cloudy days exceed their autonomy, the process is affected by running out of equipment. Installing the turboexpander with the other elements will allow a continuous flow of energy since natural gas is flowing at the station 24 hours a day throughout the year. The turboexpander must be installed downstream of the ultrasonic meter and the pressure and temperature transmitters (Fig. 2), this in order to be certain that the measured values of the variables used in the calculations are the current ones that are entering the turboexpander and thus have greater certainty in the results following adequate traceability.

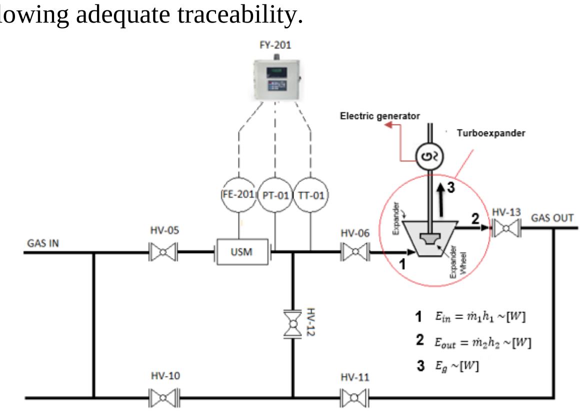

Fig. 2. Design with turbo expander of a regulation station

The following describes the mechanical and electromechanical components that make up the natural gas distribution system and are encoded in Fig. 2:

- FE-201: Ultrasonic meter signals.
- USM: Ultrasonic gas meter.
- PT-01: Pressure transmitter signal.
- FY-201: Flow computer.
- TT-01: Temperature transmitter.
- HV-05-13: Hands valves.

Similarly, the addition of a bypass line with its respective blocking valve to give continuity to the gas flow in case a preventive maintenance (out of line) to the turboexpander is needed. The system is locked by opening the HV-11 / HV-12 valves and closing the HV-06 / HV-13 valves. In this way, a constant and continuous operation of the operation is guaranteed. Additionally, the inclusion of the turboexpander would not generate lost profits to the system.

According to the original research approach, which is based on the study of a natural gas regulation station of a transport and distribution company in which the installation of a turboexpander is planned at the station's exit line The measurement of process variables is extremely necessary, as well as the identification of the associated instrumentation and quantification of mechanical power.

B. Application of the principles of conservation of mass and energy in a control volume

This section presents the quantification of the mechanical energy of natural gas at the inlet of a turboexpander and simulates the differences in pressure and temperature to quantify the power generated at the outlet of a turboexpander. The projected turboexpander is analyzed with an open system, once there is mass transfer across its borders. That is, it is analyzed as a control volume.

For this analysis, experimentally obtained data was used in a natural gas distribution substation. These data were collected for 6 continuous days, in which it was possible to perform a time-hour measurement 24 hours a day. Thus, it was possible to total 435 experimental pressure, flow and temperature data, which corresponds to 145 points for each magnitude evaluated. In order to make the reading of this document friendly and not lose the sequence of the analysis, the experimentally obtained data are consolidated in Table I.

TABLE I
EXPERIMENTAL RESEARCH DATA (ENTRANCE TO THE CONTROL VOLUME)

Date/hour DD/MM/AAAA h:min	Volumetric flow Qin (m^3/h)	Pressure Pin (kPa)	Temperature Tin (K)
30/04/2019 0:00	9.27	1752.7	300.29
30/04/2019 1:00	9.68	1748.4	300.20
30/04/2019 2:00	9.84	1752.2	300.13
30/04/2019 3:00	9.34	1752.1	300.09
30/04/2019 4:00	9.61	1748.6	300.04
30/04/2019 5:00	14.62	1742.5	300.11
30/04/2019 6:00	24.47	1740.4	300.47
30/04/2019 7:00	24.37	1741.3	300.70
30/04/2019 8:00	24.93	1738.8	300.78
30/04/2019 9:00	24.41	1738.8	300.89
30/04/2019 10:00	26.84	1737.2	301.04
30/04/2019 11:00	36.70	1732.6	301.58
30/04/2019 12:00	39.35	1729.4	302.09
30/04/2019 13:00	29.46	1739.7	301.88
30/04/2019 14:00	17.37	1746.7	301.32
30/04/2019 15:00	13.15	1748.6	301.11
30/04/2019 16:00	15.23	1740.7	301.02
30/04/2019 17:00	18.79	1739.4	301.11
30/04/2019 18:00	22.66	1738.3	301.13
30/04/2019 19:00	23.29	1740.4	301.15
30/04/2019 20:00	17.04	1748.1	301.04
30/04/2019 21:00	12.20	1750.6	300.79
30/04/2019 22:00	10.44	1751.0	300.69
30/04/2019 23:00	9.36	1751.9	300.56
1/05/2019 0:00	9.02	1752.8	300.49
1/05/2019 1:00	9.23	1750.7	300.38
1/05/2019 2:00	7.26	1753.0	300.36
1/05/2019 3:00	6.24	1752.3	300.21
1/05/2019 4:00	7.86	1745.6	300.09
1/05/2019 5:00	9.20	1744.8	300.05
1/05/2019 6:00	14.13	1743.6	300.13
1/05/2019 7:00	19.38	1741.0	300.33
1/05/2019 8:00	25.33	1739.7	300.64
1/05/2019 9:00	25.92	1741.0	300.87
1/05/2019 10:00	24.41	1740.8	300.97
1/05/2019 11:00	31.80	1734.9	301.29
1/05/2019 12:00	38.99	1731.2	301.87
1/05/2019 13:00	32.26	1738.9	301.97
1/05/2019 14:00	20.21	1744.7	301.58
1/05/2019 15:00	15.03	1746.6	301.41
1/05/2019 16:00	15.42	1746.1	301.43
1/05/2019 17:00	17.35	1745.4	301.29
1/05/2019 18:00	19.82	1740.5	301.15
1/05/2019 19:00	20.71	1741.7	301.09
1/05/2019 20:00	15.97	1748.4	301.02
1/05/2019 21:00	12.40	1749.9	300.85
1/05/2019 22:00	11.08	1751.2	300.73
1/05/2019 23:00	9.73	1751.4	300.65
2/05/2019 0:00	9.06	1752.8	300.58
2/05/2019 1:00	8.89	1752.4	300.48
2/05/2019 2:00	8.56	1752.7	300.41
2/05/2019 3:00	8.89	1749.7	300.32
2/05/2019 4:00	9.00	1749.0	300.24
2/05/2019 5:00	14.73	1742.4	300.25
2/05/2019 6:00	23.14	1740.1	300.52
2/05/2019 7:00	22.61	1741.2	300.72
2/05/2019 8:00	24.32	1739.8	300.67
2/05/2019 9:00	24.01	1740.3	300.73
2/05/2019 10:00	25.83	1738.7	300.88
2/05/2019 11:00	32.89	1735.4	301.25
2/05/2019 12:00	38.80	1732.4	301.88
2/05/2019 13:00	28.95	1742.0	301.66
2/05/2019 14:00	18.05	1747.6	301.24
2/05/2019 15:00	14.98	1748.1	301.29
2/05/2019 16:00	15.77	1745.7	301.29
2/05/2019 17:00	19.25	1739.5	301.21
2/05/2019 18:00	21.70	1739.0	301.19
2/05/2019 19:00	22.95	1741.2	301.15
2/05/2019 20:00	16.85	1748.6	301.01
2/05/2019 21:00	12.48	1751.3	300.82
2/05/2019 22:00	10.23	1752.5	300.72
2/05/2019 23:00	9.00	1752.8	300.65
3/05/2019 0:00	7.81	1753.5	300.58
3/05/2019 1:00	7.85	1753.4	300.49
3/05/2019 2:00	7.87	1754.1	300.41
3/05/2019 3:00	7.72	1748.9	300.33
3/05/2019 4:00	8.13	1745.3	300.25
3/05/2019 5:00	13.96	1743.2	300.24
3/05/2019 6:00	22.67	1740.8	300.45
3/05/2019 7:00	23.36	1744.9	300.58
3/05/2019 8:00	23.94	1740.6	300.64
3/05/2019 9:00	23.12	1744.9	300.73
3/05/2019 10:00	23.59	1739.7	300.83
3/05/2019 11:00	34.56	1735.9	301.29
3/05/2019 12:00	38.98	1732.4	301.89
3/05/2019 13:00	30.03	1741.8	301.74
3/05/2019 14:00	18.46	1747.7	301.37
3/05/2019 15:00	15.30	1747.6	301.34
3/05/2019 16:00	15.88	1745.9	301.37
3/05/2019 17:00	19.51	1740.2	301.21
3/05/2019 18:00	23.06	1739.3	301.19
3/05/2019 19:00	22.37	1745.2	301.19
3/05/2019 20:00	16.81	1749.1	301.09
3/05/2019 21:00	12.87	1749.8	300.97
3/05/2019 22:00	11.41	1750.7	300.96

3/05/2019 23:00	10.38	1751.8	300.81
4/05/2019 0:00	9.20	1752.9	300.72
4/05/2019 1:00	8.89	1753.4	300.63
4/05/2019 2:00	8.68	1751.1	300.56
4/05/2019 3:00	9.30	1747.2	300.44
4/05/2019 4:00	9.89	1744.9	300.40
4/05/2019 5:00	12.48	1743.2	300.38
4/05/2019 6:00	17.40	1742.1	300.46
4/05/2019 7:00	21.09	1740.3	300.67
4/05/2019 8:00	24.83	1739.1	300.93
4/05/2019 9:00	25.10	1741.6	301.09
4/05/2019 10:00	23.58	1743.5	301.15
4/05/2019 11:00	29.85	1736.0	301.41
4/05/2019 12:00	37.83	1731.7	301.95
4/05/2019 13:00	32.78	1738.3	302.10
4/05/2019 14:00	20.72	1744.8	301.65
4/05/2019 15:00	13.89	1747.3	301.45
4/05/2019 16:00	11.22	1748.2	301.53
4/05/2019 17:00	13.42	1738.7	301.55
4/05/2019 18:00	15.82	1736.5	301.71
4/05/2019 19:00	16.57	1736.7	301.68
4/05/2019 20:00	10.69	1746.5	301.61
4/05/2019 21:00	8.50	1748.8	301.47
4/05/2019 22:00	5.74	1749.3	301.37
4/05/2019 23:00	5.17	1752.2	301.25
5/05/2019 0:00	4.30	1751.6	301.17
5/05/2019 1:00	4.18	1752.8	301.05
5/05/2019 2:00	4.20	1752.9	300.87
5/05/2019 3:00	3.25	1751.9	300.85
5/05/2019 4:00	3.27	1744.7	300.68
5/05/2019 5:00	5.79	1743.9	300.49
5/05/2019 6:00	9.61	1741.5	300.47
5/05/2019 7:00	16.18	1741.8	300.57
5/05/2019 8:00	21.47	1739.8	300.76
5/05/2019 9:00	21.28	1744.9	300.96
5/05/2019 10:00	20.21	1744.2	301.05
5/05/2019 11:00	23.05	1738.2	301.19
5/05/2019 12:00	26.54	1736.7	301.52
5/05/2019 13:00	25.70	1742.8	301.70
5/05/2019 14:00	13.77	1748.5	301.63
5/05/2019 15:00	10.80	1749.2	301.54
5/05/2019 16:00	12.94	1743.4	301.23
5/05/2019 17:00	13.72	1745.0	301.06
5/05/2019 18:00	11.77	1745.6	301.06
5/05/2019 19:00	14.31	1742.7	300.97
5/05/2019 20:00	11.34	1751.5	300.95
5/05/2019 21:00	5.38	1754.9	300.93
5/05/2019 22:00	6.39	1747.0	300.73
5/05/2019 23:00	4.96	1754.8	300.65
6/05/2019 0:00	4.40	1754.9	300.63

The measurements were taken from a pressure transmitter, a resistance thermometer Pt100 type and a volumetric flow meter. It is worth noting that the original data for pressure, flow and temperature are indicated by the flow computer in English units. That is, for flow: kpc (kilo cubic foot); for pressure: psi (pound per square inch); for temperature ºF (degrees Fahrenheit). To facilitate the engineering treatment performed on the data, these units were converted to the International System (SI), using the different conversion factors. In this way, it has to be for flow: m^3/h; for pressure: kPa; for temperature K. Two fundamental blocks for research are described below: quantification of mechanical energy at the input and output of the control volume.

C. Quantification of the mechanical energy of natural gas at the control volume input

Considering the chemical composition of natural gas (essentially methane), critical pressures and temperatures were calculated from (4) and (5), respectively. Then and, using the experimental data (input to the control volume) of pressure and temperature it was possible to apply (6) and (7) to determine the pressure and reduced temperature, respectively.

The compressibility factor for a real gas was determined using the Nelson-Obert Generalized Compressibility Graph. The value found was equal to 0.22 (kPa · m^3 · kmol / kJ · kg). Using the molar mass of methane (16 kg / kmol) it was possible to transform the compressibility factor into units as a function of mass (kg). In this sense, the calculated compressibility factor was equal to 3.52 (kPa · m^3 · kg / kJ · kg). The universal constant for methane is equal to 0.5182 (kJ / kg · K) [2].

In relation to the dimensions of the pipeline through which natural gas is transported, it has an internal diameter of 4 inches and a length of 20 meters. In this way, the total calculated volume was equal to 0.16 m^3.

With the data of the open system inlet pressure, the total calculated volume, the compressibility factor, the natural gas constant (methane) and the natural gas temperature, (8) was applied to determine the mass of the gas that system entry Once the mass (kg) was calculated and the total volume (m^3) was determined, the specific volume (m^3/kg) of natural gas was determined. This value is around 0.32 m^3 / kg.

Once the mass of the natural gas was determined, it was possible to calculate the enthalpy of it based on the specific volume and pressure of the gas, applying (9). Knowing the volumetric flow of natural gas and the internal area of the pipeline. Finally, the average mechanical power of natural gas that enters the control volume was quantified by applying (12) and is equal to 8154.85 W. Table II summarizes the results obtained. The calculations were made for each of the 145 experimental points obtained through the 6 days of measurement in the natural gas substation.

Scientia et Technica Año XXV, Vol. 25, No. 02, junio de 2020. Universidad Tecnológica de Pereira. ISSN 0122-1701 y ISSN: 2344-7214
DOI: 10.22517/23447214.23481

TABLE II
CALCULATION OF THERMODYNAMIC PROPERTIES, DIMENSIONAL PARAMETERS AND QUANTIFICATION OF THE MECHANICAL POWER OF NATURAL GAS AT THE ENTRANCE OF A TURBOEXPANDER

Critical pressure	**Critical Temp.**	**Reduced pressure**	**Reduced Temp.**	**Compressibility factor**		**Compressibility factor (Methane)**	**Pipeline Area**	**Pipeline Lengh**	**Pipeline Volume**	**Mass flow**	**Specific Volume**	**Enthalpy**	**Flow rate**	**Kinetic energy**	**Flow Energy**	**Mechanical energy**
Pcr (kPa)	**Tcr (K)**	**Pr -**	**Tr -**	**Z (kPa m^3 kmol / kJ kg)**	**Z (kPa m^3 kg / kJ kg)**	**m (kJ/kg·K)**	**A m^2**	**L m**	**V m^3**	**m (kg/s)**	***v* (m^3/kg)**	**h (kJ/kg)**	**Vel m/s**	**ECin kJ/s**	**EFin kJ/s**	**Ein W**
1752.7	300.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0082	0.31	547.7	0.3176	4.E-04	4513.5	4513.5
1748.4	300.20	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0086	0.31	547.6	0.3317	5.E-04	4702.4	4702.4
1752.2	300.13	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0087	0.31	547.5	0.3372	5.E-04	4789.6	4789.6
1752.1	300.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0083	0.31	547.4	0.3202	4.E-04	4547.7	4547.7
1748.6	300.04	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0085	0.31	547.3	0.3294	5.E-04	4669.5	4669.5
1742.5	300.11	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0129	0.31	547.4	0.5008	2.E-03	7074.5	7074.5
1740.4	300.47	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0216	0.31	548.1	0.8385	8.E-03	11830.5	11830.5
1741.3	300.70	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0215	0.31	548.5	0.8350	7.E-03	11787.9	11787.9
1738.8	300.78	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0219	0.32	548.6	0.8543	8.E-03	12042.2	12042.2
1738.8	300.89	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0215	0.32	548.8	0.8365	8.E-03	11792.3	11792.3
1737.2	301.04	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0236	0.32	549.1	0.9196	1.E-02	12951.5	12951.5
1732.6	301.58	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0321	0.32	550.1	1.2574	3.E-02	17662.6	17662.6
1729.4	302.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0343	0.32	551.0	1.3484	3.E-02	18905.8	18905.9
1739.7	301.88	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0259	0.32	550.6	1.0093	1.E-02	14235.4	14235.4
1746.7	301.32	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0153	0.31	549.6	0.5952	3.E-03	8428.0	8428.0
1748.6	301.11	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0116	0.31	549.2	0.4505	1.E-03	6386.8	6386.8
1740.7	301.02	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0134	0.32	549.1	0.5219	2.E-03	7365.0	7365.0
1739.4	301.11	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0165	0.32	549.2	0.6439	3.E-03	9079.8	9079.8
1738.3	301.13	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0199	0.32	549.3	0.7763	6.E-03	10940.9	10940.9
1740.4	301.15	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0205	0.32	549.3	0.7979	7.E-03	11258.1	11258.1
1748.1	301.04	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0151	0.31	549.1	0.5839	3.E-03	8275.1	8275.1
1750.6	300.79	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0108	0.31	548.7	0.4181	9.E-04	5933.7	5933.7
1751.0	300.69	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0093	0.31	548.5	0.3579	6.E-04	5080.1	5080.1
1751.9	300.56	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0083	0.31	548.2	0.3206	4.E-04	4553.3	4553.3
1752.8	300.49	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0080	0.31	548.1	0.3090	4.E-04	4391.4	4391.4
1750.7	300.38	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0082	0.31	547.9	0.3163	4.E-04	4488.9	4488.9
1753.0	300.36	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0065	0.31	547.9	0.2488	2.E-04	3535.6	3535.6
1752.3	300.21	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0056	0.31	547.6	0.2140	1.E-04	3039.6	3039.6
1745.6	300.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0070	0.31	547.4	0.2692	3.E-04	3809.5	3809.5
1744.8	300.05	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0081	0.31	547.3	0.3152	4.E-04	4458.7	4458.7
1743.6	300.13	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0125	0.31	547.4	0.4842	1.E-03	6844.9	6844.9
1741.0	300.33	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0171	0.31	547.8	0.6640	4.E-03	9372.0	9372.0
1739.7	300.64	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0223	0.32	548.4	0.8678	8.E-03	12240.5	12240.5
1741.0	300.87	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0228	0.32	548.8	0.8880	9.E-03	12533.8	12533.8
1740.8	300.97	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0215	0.32	549.0	0.8364	8.E-03	11805.2	11805.2
1734.9	301.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0279	0.32	549.6	1.0896	2.E-02	15326.2	15326.2
1731.2	301.87	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0341	0.32	550.6	1.3360	3.E-02	18751.6	18751.6
1738.9	301.97	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0283	0.32	550.8	1.1053	2.E-02	15581.8	15581.8
1744.7	301.58	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0178	0.32	550.1	0.6923	4.E-03	9792.9	9793.0
1746.6	301.41	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0133	0.31	549.8	0.5149	2.E-03	7291.0	7291.0
1746.1	301.43	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0136	0.31	549.8	0.5284	2.E-03	7480.2	7480.2
1745.4	301.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0153	0.31	549.6	0.5946	3.E-03	8413.4	8413.4
1740.5	301.15	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0174	0.32	549.3	0.6789	4.E-03	9580.3	9580.3
1741.7	301.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0182	0.32	549.2	0.7097	5.E-03	10021.8	10021.8
1748.4	301.02	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0141	0.31	549.1	0.5471	2.E-03	7754.8	7754.8
1749.9	300.85	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0110	0.31	548.8	0.4248	1.E-03	6027.0	6027.0
1751.2	300.73	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0098	0.31	548.6	0.3796	7.E-04	5389.1	5389.1
1751.4	300.65	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0086	0.31	548.4	0.3333	5.E-04	4732.8	4732.8
1752.8	300.58	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0080	0.31	548.3	0.3105	4.E-04	4412.2	4412.2
1752.4	300.48	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0079	0.31	548.1	0.3046	4.E-04	4327.1	4327.1

1752.7	300.41	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0076	0.31	548.0	0.2931	3.E-04	4165.2	4165.2
1749.7	300.32	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0079	0.31	547.8	0.3045	4.E-04	4319.7	4319.7
1749.0	300.24	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0080	0.31	547.7	0.3084	4.E-04	4372.2	4372.2
1742.4	300.25	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0130	0.31	547.7	0.5046	2.E-03	7127.5	7127.5
1740.1	300.52	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0204	0.32	548.2	0.7930	6.E-03	11187.0	11187.1
1741.2	300.72	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0199	0.32	548.5	0.7747	6.E-03	10936.6	10936.6
1739.8	300.67	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0214	0.32	548.4	0.8333	7.E-03	11754.0	11754.0
1740.3	300.73	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0212	0.32	548.5	0.8226	7.E-03	11606.8	11606.8
1738.7	300.88	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0227	0.32	548.8	0.8852	9.E-03	12477.5	12477.5
1735.4	301.25	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0289	0.32	549.5	1.1270	2.E-02	15855.6	15855.6
1732.4	301.88	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0339	0.32	550.6	1.3295	3.E-02	18672.5	18672.5
1742.0	301.66	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0255	0.32	550.3	0.9919	1.E-02	14009.0	14009.0
1747.6	301.24	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0159	0.31	549.5	0.6184	3.E-03	8761.8	8761.8
1748.1	301.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0132	0.31	549.6	0.5132	2.E-03	7273.4	7273.5
1745.7	301.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0139	0.31	549.6	0.5402	2.E-03	7646.0	7646.0
1739.5	301.21	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0169	0.32	549.4	0.6597	4.E-03	9303.5	9303.5
1739.0	301.19	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0191	0.32	549.4	0.7434	5.E-03	10480.1	10480.1
1741.2	301.15	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0202	0.32	549.3	0.7864	6.E-03	11101.3	11101.3
1748.6	301.01	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0149	0.31	549.1	0.5772	2.E-03	8183.4	8183.4
1751.3	300.82	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0111	0.31	548.7	0.4276	1.E-03	6071.8	6071.8
1752.5	300.72	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0091	0.31	548.5	0.3505	6.E-04	4980.3	4980.3
1752.8	300.65	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0080	0.31	548.4	0.3083	4.E-04	4381.4	4381.4
1753.5	300.58	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0069	0.31	548.3	0.2674	2.E-04	3802.0	3802.0
1753.4	300.49	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0070	0.31	548.1	0.2690	3.E-04	3824.7	3824.7
1754.1	300.41	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0070	0.31	548.0	0.2695	3.E-04	3832.4	3832.4
1748.9	300.33	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0068	0.31	547.8	0.2645	2.E-04	3750.6	3750.6
1745.3	300.25	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0072	0.31	547.7	0.2787	3.E-04	3943.6	3943.6
1743.2	300.24	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0123	0.31	547.7	0.4785	1.E-03	6762.0	6762.0
1740.8	300.45	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0200	0.31	548.0	0.7767	6.E-03	10961.9	10961.9
1744.9	300.58	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0207	0.31	548.3	0.8005	7.E-03	11325.0	11325.0
1740.6	300.64	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0211	0.32	548.4	0.8203	7.E-03	11575.2	11575.2
1744.9	300.73	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0204	0.31	548.6	0.7923	6.E-03	11208.0	11208.0
1739.7	300.83	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0208	0.32	548.7	0.8083	7.E-03	11400.4	11400.4
1735.9	301.29	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0303	0.32	549.6	1.1842	2.E-02	16666.3	16666.4
1732.4	301.89	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0341	0.32	550.7	1.3355	3.E-02	18756.6	18756.7
1741.8	301.74	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0264	0.32	550.4	1.0288	1.E-02	14527.7	14527.7
1747.7	301.37	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0163	0.31	549.7	0.6325	3.E-03	8962.2	8962.2
1747.6	301.34	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0135	0.31	549.7	0.5241	2.E-03	7425.4	7425.4
1745.9	301.37	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0140	0.31	549.7	0.5440	2.E-03	7700.1	7700.1
1740.2	301.21	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0172	0.32	549.4	0.6686	4.E-03	9432.5	9432.5
1739.3	301.19	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0203	0.32	549.4	0.7902	6.E-03	11142.9	11142.9
1745.2	301.19	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0197	0.31	549.4	0.7665	6.E-03	10845.3	10845.3
1749.1	301.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0149	0.31	549.2	0.5761	2.E-03	8169.0	8169.0
1749.8	300.97	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0114	0.31	549.0	0.4408	1.E-03	6253.6	6253.6
1750.7	300.96	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0101	0.31	549.0	0.3910	8.E-04	5549.9	5549.9
1751.8	300.81	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0092	0.31	548.7	0.3557	6.E-04	5051.1	5051.1
1752.9	300.72	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0082	0.31	548.5	0.3152	4.E-04	4480.2	4480.2
1753.4	300.63	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0079	0.31	548.4	0.3045	4.E-04	4328.0	4328.0
1751.1	300.56	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0077	0.31	548.2	0.2972	3.E-04	4219.6	4219.6
1747.2	300.44	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0082	0.31	548.0	0.3185	4.E-04	4511.3	4511.3
1744.9	300.40	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0088	0.31	547.9	0.3390	5.E-04	4795.2	4795.2
1743.2	300.38	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0110	0.31	547.9	0.4277	1.E-03	6044.8	6044.8
1742.1	300.46	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0154	0.31	548.1	0.5963	3.E-03	8421.7	8421.7
1740.3	300.67	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0186	0.32	548.4	0.7226	5.E-03	10194.8	10194.8
1739.1	300.93	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0219	0.32	548.9	0.8508	8.E-03	11996.7	11996.7
1741.6	301.09	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0221	0.32	549.2	0.8601	8.E-03	12144.4	12144.4
1743.5	301.15	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0208	0.32	549.3	0.8080	7.E-03	11420.5	11420.5
1736.0	301.41	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0262	0.32	549.8	1.0228	1.E-02	14394.6	14394.7
1731.7	301.95	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0330	0.32	550.8	1.2963	3.E-02	18198.6	18198.7
1738.3	302.10	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0287	0.32	551.1	1.1232	2.E-02	15829.1	15829.1
1744.8	301.65	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0183	0.32	550.2	0.7100	5.E-03	10043.9	10043.9
1747.3	301.45	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0123	0.31	549.9	0.4759	1.E-03	6741.6	6741.6
1748.2	301.53	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0099	0.31	550.0	0.3845	7.E-04	5449.7	5449.7
1738.7	301.55	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0118	0.32	550.0	0.4598	1.E-03	6480.9	6480.9

1736.5	301.71	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0139	0.32	550.3	0.5420	2.E-03	7630.6	7630.6
1736.7	301.68	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0145	0.32	550.3	0.5679	2.E-03	7995.2	7995.2
1746.5	301.61	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0094	0.32	550.2	0.3663	6.E-04	5186.6	5186.6
1748.8	301.47	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0075	0.31	549.9	0.2912	3.E-04	4128.8	4128.8
1749.3	301.37	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0051	0.31	549.7	0.1965	1.E-04	2787.4	2787.4
1752.2	301.25	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0046	0.31	549.5	0.1772	7.E-05	2516.8	2516.8
1751.6	301.17	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0038	0.31	549.4	0.1474	4.E-05	2093.7	2093.7
1752.8	301.05	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0037	0.31	549.1	0.1431	4.E-05	2033.5	2033.5
1752.9	300.87	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0037	0.31	548.8	0.1437	4.E-05	2042.7	2042.7
1751.9	300.85	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0029	0.31	548.8	0.1112	2.E-05	1579.1	1579.2
1744.7	300.68	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0029	0.31	548.5	0.1121	2.E-05	1585.5	1585.5
1743.9	300.49	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0051	0.31	548.1	0.1985	1.E-04	2806.5	2806.5
1741.5	300.47	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0085	0.31	548.1	0.3291	5.E-04	4646.7	4646.7
1741.8	300.57	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0143	0.31	548.3	0.5543	2.E-03	7827.0	7827.0
1739.8	300.76	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0189	0.32	548.6	0.7355	5.E-03	10374.4	10374.4
1744.9	300.96	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0188	0.31	549.0	0.7291	5.E-03	10313.9	10313.9
1744.2	301.05	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0178	0.31	549.1	0.6925	4.E-03	9792.3	9792.3
1738.2	301.19	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0203	0.32	549.4	0.7898	6.E-03	11130.7	11130.7
1736.7	301.52	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0233	0.32	550.0	0.9094	1.E-02	12804.2	12804.2
1742.8	301.70	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0226	0.32	550.3	0.8807	9.E-03	12443.8	12443.8
1748.5	301.63	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0122	0.31	550.2	0.4717	1.E-03	6686.0	6686.1
1749.2	301.54	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0095	0.31	550.0	0.3701	7.E-04	5248.9	5248.9
1743.4	301.23	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0114	0.32	549.5	0.4433	1.E-03	6266.2	6266.2
1745.0	301.06	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0121	0.31	549.2	0.4701	1.E-03	6650.4	6650.4
1745.6	301.06	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0104	0.31	549.2	0.4034	8.E-04	5709.3	5709.3
1742.7	300.97	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0126	0.32	549.0	0.4902	2.E-03	6926.0	6926.0
1751.5	300.95	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0101	0.31	549.0	0.3886	8.E-04	5517.4	5517.4
1754.9	300.93	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0048	0.31	548.9	0.1843	8.E-05	2621.6	2621.6
1747.0	300.73	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0057	0.31	548.5	0.2191	1.E-04	3102.8	3102.8
1754.8	300.65	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0044	0.31	548.4	0.1700	6.E-05	2419.0	2419.0
1754.9	300.63	1	1	0.22	3.52	0.5182	0.0081	20	0.16	0.0039	0.31	548.4	0.1509	4.E-05	2146.3	2146.3

D. Quantification of the mechanical energy of natural gas at the exit of the control volume

For the analysis of the mechanical energy of natural gas at the exit of the control volume the procedure for the calculation of thermodynamic parameters. In line with the objectives pursued in the investigation, once the start-up of a turboexpander is projected, there are no experimental data on the pressure and temperature at the exit of the analyzed open system. Thus, taking into account the electromechanical operation of a turboexpander, where its main function is the generation of energy through the movement of a rotor and the use of the mechanical energy of a gas that allows said movement, it is known that the pressure and the temperature of the fluid decreases at the outlet of the turboexpander. In this way, to simulate the mechanical energy at the outlet of the turboexpander, a simulation of the decrease in pressure and temperature at the outlet was performed based on the input conditions. That is, 9 data sheets were made, which simulate a decrease in pressure and temperature from 10% to 90% of the values measured experimentally at the input. Thus, applying (12), the mechanical energy of natural gas at the outlet of the turboexpander could be quantified. This, simulating decreases in pressure and temperature from 10% to 90%. In this order, it was possible to obtain a value of the mechanical power generated by the turboexpander by applying the principle of energy conservation through (15).

From the quantification of the mechanical power of natural gas at the inlet and outlet of the turboexpander, applying (15), the mechanical power that would be generated by the turboexpander was quantified based on the different pressure and temperature drops that may be obtain.

Table III consolidates the results obtained in relation to the generated mechanical power. This result becomes fundamental in the selection of an electric generator for the natural gas transport substation.

TABLE III
MECHANICAL POWER GENERATION AT THE OUTLET OF THE TURBOEXPANDER FROM THE MECHANICAL POWER OF NATURAL GAS

Mechanical power generated from percentage decrease of Pressure and Temperature at the outlet of the turboexpander								
10% Eg (W)	20% Eg (W)	30% Eg (W)	40% Eg (W)	50% Eg (W)	60% Eg (W)	70% Eg (W)	80% Eg (W)	90% Eg (W)
451.4	902.7	1354.1	1805.4	1805.4	2708.1	3159.5	3610.8	4062.2
470.2	940.5	1410.7	1881.0	1881.0	2821.5	3291.7	3762.0	4232.2
479.0	957.9	1436.9	1915.8	1915.8	2873.8	3352.7	3831.7	4310.6
454.8	909.5	1364.3	1819.1	1819.1	2728.6	3183.4	3638.2	4092.9
466.9	933.9	1400.8	1867.8	1867.8	2801.7	3268.6	3735.6	4202.5
707.4	1414.9	2122.3	2829.8	2829.8	4244.7	4952.1	5659.6	6367.0
1183.0	2366.1	3549.1	4732.2	4732.2	7098.3	8281.3	9464.4	10647.4
1178.8	2357.6	3536.4	4715.2	4715.2	7072.7	8251.5	9430.3	10609.1
1204.2	2408.4	3612.7	4816.9	4816.9	7225.3	8429.5	9633.8	10838.0
1179.2	2358.5	3537.7	4716.9	4716.9	7075.4	8254.6	9433.8	10613.1
1295.1	2590.3	3885.4	5180.6	5180.6	7770.9	9066.0	10361.2	11656.3
1766.3	3532.5	5298.8	7065.0	7065.0	10597.5	12363.8	14130.0	15896.3
1890.6	3781.2	5671.7	7562.3	7562.3	11343.5	13234.1	15124.7	17015.2
1423.5	2847.1	4270.6	5694.2	5694.2	8541.3	9964.8	11388.3	12811.9
842.8	1685.6	2528.4	3371.2	3371.2	5056.8	5899.6	6742.4	7585.2
638.7	1277.4	1916.0	2554.7	2554.7	3832.1	4470.7	5109.4	5748.1
736.5	1473.0	2209.5	2946.0	2946.0	4419.0	5155.5	5892.0	6628.5
908.0	1816.0	2723.9	3631.9	3631.9	5447.9	6355.8	7263.8	8171.8
1094.1	2188.2	3282.3	4376.4	4376.4	6564.5	7658.6	8752.7	9846.8
1125.8	2251.6	3377.4	4503.3	4503.3	6754.9	7880.7	9006.5	10132.3
827.5	1655.0	2482.5	3310.0	3310.0	4965.1	5792.6	6620.1	7447.6
593.4	1186.7	1780.1	2373.5	2373.5	3560.2	4153.6	4746.9	5340.3
508.0	1016.0	1524.0	2032.0	2032.0	3048.1	3556.1	4064.1	4572.1
455.3	910.7	1366.0	1821.3	1821.3	2732.0	3187.3	3642.6	4098.0
439.1	878.3	1317.4	1756.6	1756.6	2634.9	3074.0	3513.1	3952.3
448.9	897.8	1346.7	1795.6	1795.6	2693.4	3142.3	3591.1	4040.0
353.6	707.1	1060.7	1414.2	1414.2	2121.4	2474.9	2828.5	3182.0
304.0	607.9	911.9	1215.8	1215.8	1823.8	2127.7	2431.7	2735.7
381.0	761.9	1142.9	1523.8	1523.8	2285.7	2666.7	3047.6	3428.6
445.9	891.7	1337.6	1783.5	1783.5	2675.2	3121.1	3566.9	4012.8
684.5	1369.0	2053.5	2738.0	2738.0	4107.0	4791.4	5475.9	6160.4
937.2	1874.4	2811.6	3748.8	3748.8	5623.2	6560.4	7497.6	8434.8
1224.0	2448.1	3672.1	4896.2	4896.2	7344.3	8568.3	9792.4	11016.4
1253.4	2506.8	3760.1	5013.5	5013.5	7520.3	8773.6	10027.0	11280.4
1180.5	2361.0	3541.6	4722.1	4722.1	7083.1	8263.7	9444.2	10624.7
1532.6	3065.2	4597.9	6130.5	6130.5	9195.7	10728.3	12261.0	13793.6
1875.2	3750.3	5625.5	7500.6	7500.6	11250.9	13126.1	15001.2	16876.4
1558.2	3116.4	4674.5	6232.7	6232.7	9349.1	10907.3	12465.4	14023.6
979.3	1958.6	2937.9	3917.2	3917.2	5875.8	6855.1	7834.4	8813.7
729.1	1458.2	2187.3	2916.4	2916.4	4374.6	5103.7	5832.8	6561.9
748.0	1496.0	2244.0	2992.1	2992.1	4488.1	5236.1	5984.1	6732.1
841.3	1682.7	2524.0	3365.4	3365.4	5048.1	5889.4	6730.7	7572.1
958.0	1916.1	2874.1	3832.1	3832.1	5748.2	6706.2	7664.3	8622.3
1002.2	2004.4	3006.5	4008.7	4008.7	6013.1	7015.3	8017.4	9019.6
775.5	1551.0	2326.4	3101.9	3101.9	4652.9	5428.4	6203.8	6979.3
602.7	1205.4	1808.1	2410.8	2410.8	3616.2	4218.9	4821.6	5424.3
538.9	1077.8	1616.7	2155.6	2155.6	3233.4	3772.4	4311.3	4850.2
473.3	946.6	1419.8	1893.1	1893.1	2839.7	3313.0	3786.3	4259.5
441.2	882.4	1323.7	1764.9	1764.9	2647.3	3088.5	3529.7	3971.0
432.7	865.4	1298.1	1730.8	1730.8	2596.2	3029.0	3461.7	3894.4
416.5	833.0	1249.6	1666.1	1666.1	2499.1	2915.7	3332.2	3748.7
432.0	863.9	1295.9	1727.9	1727.9	2591.8	3023.8	3455.8	3887.8
437.2	874.4	1311.7	1748.9	1748.9	2623.3	3060.6	3497.8	3935.0
712.8	1425.5	2138.3	2851.0	2851.0	4276.5	4989.3	5702.0	6414.8
1118.7	2237.4	3356.1	4474.8	4474.8	6712.2	7830.9	8949.6	10068.3
1093.7	2187.3	3281.0	4374.6	4374.6	6562.0	7655.6	8749.3	9842.9
1175.4	2350.8	3526.2	4701.6	4701.6	7052.4	8227.8	9403.2	10578.6
1160.7	2321.4	3482.0	4642.7	4642.7	6964.1	8124.7	9285.4	10446.1
1247.7	2495.5	3743.2	4991.0	4991.0	7486.5	8734.2	9982.0	11229.7
1585.6	3171.1	4756.7	6342.2	6342.2	9513.3	11098.9	12684.4	14270.0
1867.2	3734.5	5601.7	7469.0	7469.0	11203.5	13070.7	14938.0	16805.2
1400.9	2801.8	4202.7	5603.6	5603.6	8405.4	9806.3	11207.2	12608.1
876.2	1752.4	2628.5	3504.7	3504.7	5257.1	6133.3	7009.5	7885.6
727.3	1454.7	2182.0	2909.4	2909.4	4364.1	5091.4	5818.8	6546.1
764.6	1529.2	2293.8	3058.4	3058.4	4587.6	5352.2	6116.8	6881.4
930.4	1860.7	2791.1	3721.4	3721.4	5582.1	6512.5	7442.8	8373.2
1048.0	2096.0	3144.0	4192.0	4192.0	6288.0	7336.1	8384.1	9432.1
1110.1	2220.3	3330.4	4440.5	4440.5	6660.8	7770.9	8881.0	9991.2
818.3	1636.7	2455.0	3273.4	3273.4	4910.0	5728.4	6546.7	7365.1
607.2	1214.4	1821.5	2428.7	2428.7	3643.1	4250.2	4857.4	5464.6
498.0	996.1	1494.1	1992.1	1992.1	2988.2	3486.2	3984.2	4482.2
438.1	876.3	1314.4	1752.6	1752.6	2628.9	3067.0	3505.2	3943.3
380.2	760.4	1140.6	1520.8	1520.8	2281.2	2661.4	3041.6	3421.8
382.5	764.9	1147.4	1529.9	1529.9	2294.8	2677.3	3059.8	3442.2
383.2	766.5	1149.7	1533.0	1533.0	2299.5	2682.7	3066.0	3449.2
375.1	750.1	1125.2	1500.2	1500.2	2250.4	2625.4	3000.5	3375.5
394.4	788.7	1183.1	1577.4	1577.4	2366.2	2760.5	3154.9	3549.2
676.2	1352.4	2028.6	2704.8	2704.8	4057.2	4733.4	5409.6	6085.8
1096.2	2192.4	3288.6	4384.8	4384.8	6577.2	7673.4	8769.5	9865.7
1132.5	2265.0	3397.5	4530.0	4530.0	6795.0	7927.5	9060.0	10192.5
1157.5	2315.0	3472.6	4630.1	4630.1	6945.1	8102.6	9260.1	10417.7
1120.8	2241.6	3362.4	4483.2	4483.2	6724.8	7845.6	8966.4	10087.2
1140.0	2280.1	3420.1	4560.2	4560.2	6840.2	7980.3	9120.3	10260.4
1666.6	3333.3	4999.9	6666.5	6666.5	9999.8	11666.4	13333.1	14999.7
1875.7	3751.3	5627.0	7502.7	7502.7	11254.0	13129.6	15005.3	16881.0
1452.8	2905.5	4358.3	5811.1	5811.1	8716.6	10169.4	11622.2	13074.9
896.2	1792.4	2688.7	3584.9	3584.9	5377.3	6273.6	7169.8	8066.0
742.5	1485.1	2227.6	2970.2	2970.2	4455.2	5197.8	5940.3	6682.9
770.0	1540.0	2310.0	3080.0	3080.0	4620.1	5390.1	6160.1	6930.1
943.2	1886.5	2829.7	3773.0	3773.0	5659.5	6602.7	7546.0	8489.2
1114.3	2228.6	3342.9	4457.1	4457.1	6685.7	7800.0	8914.3	10028.6
1084.5	2169.1	3253.6	4338.1	4338.1	6507.2	7591.7	8676.2	9760.8
816.9	1633.8	2450.7	3267.6	3267.6	4901.4	5718.3	6535.2	7352.1
625.4	1250.7	1876.1	2501.4	2501.4	3752.2	4377.5	5002.9	5628.3
555.0	1110.0	1665.0	2219.9	2219.9	3329.9	3884.9	4439.9	4994.9
505.1	1010.2	1515.3	2020.5	2020.5	3030.7	3535.8	4040.9	4546.0
448.0	896.0	1344.1	1792.1	1792.1	2688.1	3136.1	3584.1	4032.2
432.8	865.6	1298.4	1731.2	1731.2	2596.8	3029.6	3462.4	3895.2
422.0	843.9	1265.9	1687.9	1687.9	2531.8	2953.8	3375.7	3797.7
451.1	902.3	1353.4	1804.5	1804.5	2706.8	3157.9	3609.1	4060.2
479.5	959.0	1438.5	1918.1	1918.1	2877.1	3356.6	3836.1	4315.6
604.5	1209.0	1813.4	2417.9	2417.9	3626.9	4231.4	4835.9	5440.3
842.2	1684.3	2526.5	3368.7	3368.7	5053.0	5895.2	6737.3	7579.5
1019.5	2039.0	3058.4	4077.9	4077.9	6116.9	7136.4	8155.8	9175.3
1199.7	2399.3	3599.0	4798.7	4798.7	7198.0	8397.7	9597.3	10797.0
1214.4	2428.9	3643.3	4857.8	4857.8	7286.6	8501.1	9715.5	10929.9
1142.0	2284.1	3426.1	4568.2	4568.2	6852.3	7994.3	9136.4	10278.4
1439.5	2878.9	4318.4	5757.9	5757.9	8636.8	10076.3	11515.7	12955.2

1819.9	3639.7	5459.6	7279.5	7279.5	10919.2	12739.0	14558.9	16378.8
1582.9	3165.8	4748.7	6331.6	6331.6	9497.4	11080.3	12663.2	14246.1
1004.4	2008.8	3013.2	4017.6	4017.6	6026.4	7030.7	8035.1	9039.5
674.2	1348.3	2022.5	2696.7	2696.7	4045.0	4719.2	5393.3	6067.5
545.0	1089.9	1634.9	2179.9	2179.9	3269.8	3814.8	4359.7	4904.7
648.1	1296.2	1944.3	2592.3	2592.3	3888.5	4536.6	5184.7	5832.8
763.1	1526.1	2289.2	3052.2	3052.2	4578.3	5341.4	6104.5	6867.5
799.5	1599.0	2398.6	3198.1	3198.1	4797.1	5596.6	6396.2	7195.7
518.7	1037.3	1556.0	2074.7	2074.7	3112.0	3630.6	4149.3	4668.0
412.9	825.8	1238.6	1651.5	1651.5	2477.3	2890.1	3303.0	3715.9
278.7	557.5	836.2	1115.0	1115.0	1672.4	1951.2	2229.9	2508.7
251.7	503.4	755.0	1006.7	1006.7	1510.1	1761.7	2013.4	2265.1
209.4	418.7	628.1	837.5	837.5	1256.2	1465.6	1674.9	1884.3
203.4	406.7	610.1	813.4	813.4	1220.1	1423.5	1626.8	1830.2
204.3	408.5	612.8	817.1	817.1	1225.6	1429.9	1634.1	1838.4
157.9	315.8	473.7	631.7	631.7	947.5	1105.4	1263.3	1421.2
158.6	317.1	475.7	634.2	634.2	951.3	1109.9	1268.4	1427.0
280.7	561.3	842.0	1122.6	1122.6	1683.9	1964.6	2245.2	2525.9
464.7	929.3	1394.0	1858.7	1858.7	2788.0	3252.7	3717.3	4182.0
782.7	1565.4	2348.1	3130.8	3130.8	4696.2	5478.9	6261.6	7044.3
1037.4	2074.9	3112.3	4149.8	4149.8	6224.6	7262.1	8299.5	9337.0
1031.4	2062.8	3094.2	4125.6	4125.6	6188.4	7219.7	8251.1	9282.5
979.2	1958.5	2937.7	3916.9	3916.9	5875.4	6854.6	7833.8	8813.1
1113.1	2226.1	3339.2	4452.3	4452.3	6678.4	7791.5	8904.5	10017.6
1280.4	2560.8	3841.3	5121.7	5121.7	7682.5	8963.0	10243.4	11523.8
1244.4	2488.8	3733.1	4977.5	4977.5	7466.3	8710.6	9955.0	11199.4
668.6	1337.2	2005.8	2674.4	2674.4	4011.6	4680.2	5348.8	6017.4
524.9	1049.8	1574.7	2099.5	2099.5	3149.3	3674.2	4199.1	4724.0
626.6	1253.2	1879.9	2506.5	2506.5	3759.7	4386.3	5012.9	5639.6
665.0	1330.1	1995.1	2660.2	2660.2	3990.2	4655.3	5320.3	5985.3
570.9	1141.9	1712.8	2283.7	2283.7	3425.6	3996.5	4567.5	5138.4
692.6	1385.2	2077.8	2770.4	2770.4	4155.6	4848.2	5540.8	6233.4
551.7	1103.5	1655.2	2207.0	2207.0	3310.5	3862.2	4413.9	4965.7
262.2	524.3	786.5	1048.6	1048.6	1573.0	1835.1	2097.3	2359.5
310.3	620.6	930.8	1241.1	1241.1	1861.7	2172.0	2482.3	2792.5
241.9	483.8	725.7	967.6	967.6	1451.4	1693.3	1935.2	2177.1
214.6	429.3	643.9	858.5	858.5	1287.8	1502.4	1717.0	1931.7

The previous table highlights the column corresponding to the 50% decrease in pressure and temperature, a typical value in the operation of a commercial turboexpander. This, because a high decrease in the output pressure results in a low temperature at the exit of the system. As a rule of operation, the transport of natural gas at very low temperatures (around 45 ºF) is not allowed. Thus, with a decrease in pressure and temperature of the turboexpander, in relation to the input parameters, an average mechanical power of 3261.9 W. would be obtained.

Fig. 3 illustrates the profile of the generation of mechanical power as a function of the mechanical energy of natural gas.

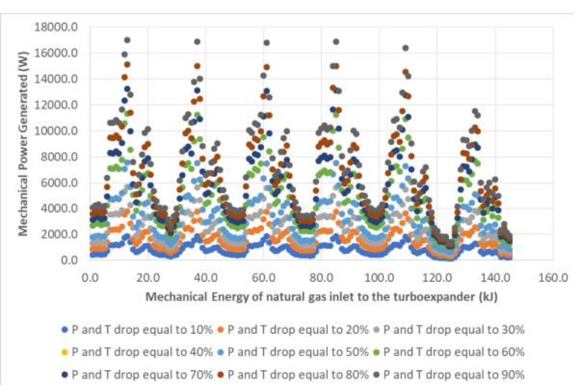

Fig. 3. Mechanical power generated from the mechanical energy of natural gas

In this figure .it can be seen that the mechanical power generated increases depending on the decrease in pressure and temperature at the outlet of the turboexpander. This result was expected, once the physical principle of operation of the turboexpander is, exactly, to perform an expansion of the working fluid, taking full advantage of the mechanical energy it contains. This results in a pressure and temperature change at the output of the equipment.

Comparing the average value of the kinetic energy (in watt) of natural gas equal to 5 x 10-3 W with the flow energy, due to enthalpy (Pv), 8155 W, it was possible to observe that the parameter that most influences Mechanical energy is the pressure of natural gas. In addition, it was possible to determine that the mechanical power generated depends strongly on the pressure difference in the system. In this sense, an analysis of the mechanical power generated as a function of the pressure difference (outlet pressure - inlet pressure) of the natural gas distribution system was performed (Fig.4).

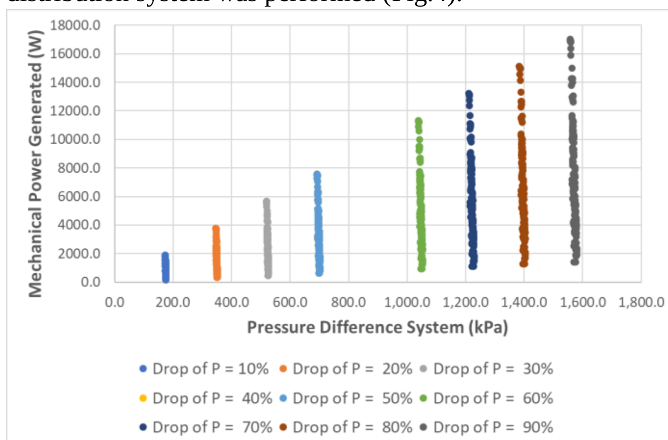

Fig. 4. Mechanical power generated from the pressure difference

The Fig. 4 confirms the increase in the mechanical power generated as the pressure difference of the system increases. That is, a further expansion of the turboexpander will produce a greater generation of mechanical power. In addition, a higher operating pressure of natural gas results in an increase in flow energy (enthalpy) and, consequently, an increase in mechanical energy.

To complete the analysis pursued by this second specific objective, Fig. 5 to Fig. 13 illustrate the generation of mechanical power as a function of the pressure difference, considering that the turboexpander output pressure varies from 10% to 90%.

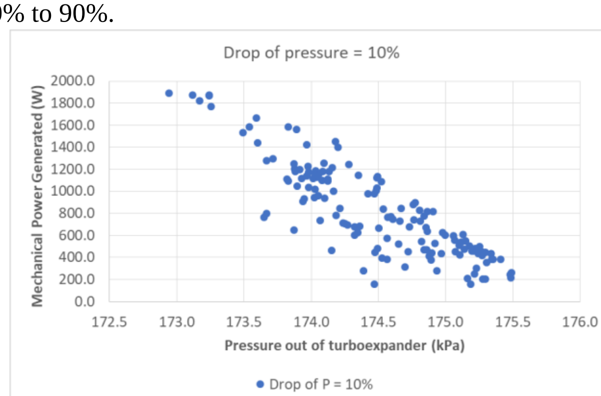

Fig. 5. Mechanical power generated from the pressure difference: output pressure drop equal to 10%.

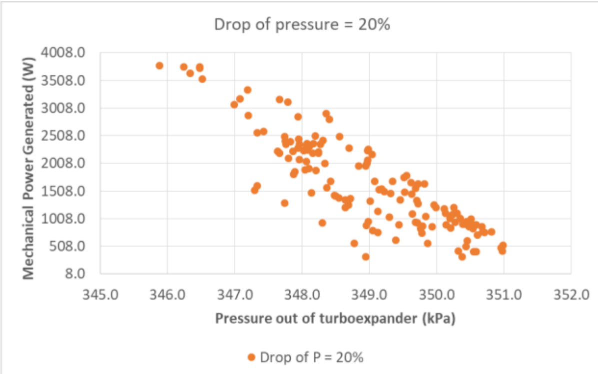

Fig. 6. Mechanical power generated from the pressure difference: output pressure drop equal to 20%.

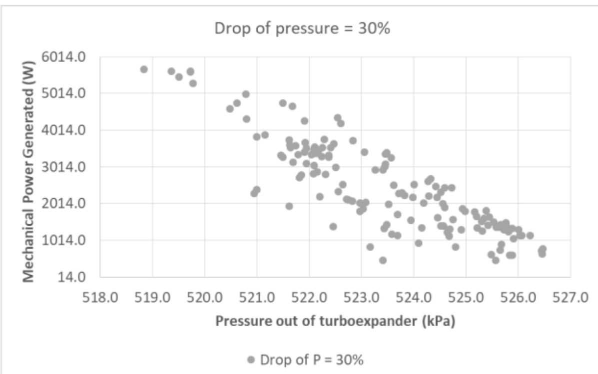

Fig. 7. Mechanical power generated from the pressure difference: output pressure drop equal to 30%.

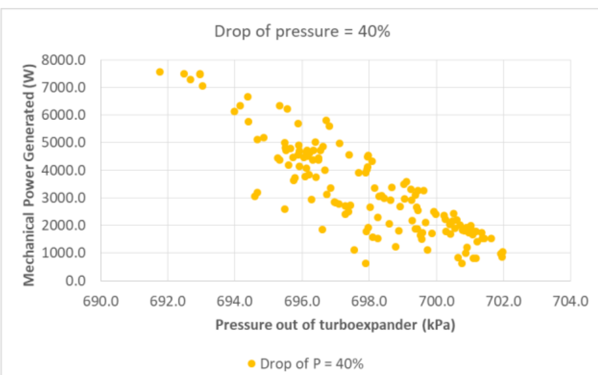

Fig. 8. Mechanical power generated from the pressure difference: output pressure drop equal to 40%.

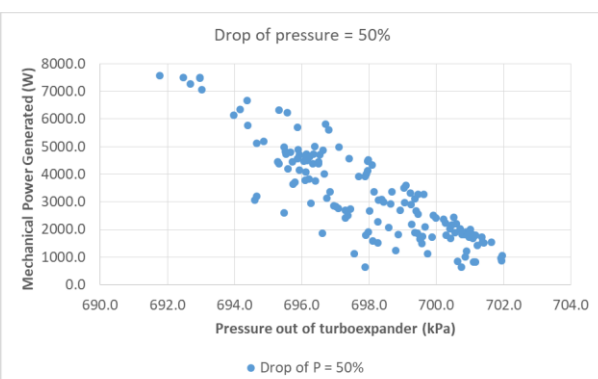

Fig. 9. Mechanical power generated from the pressure difference: output pressure drop equal to 50%.

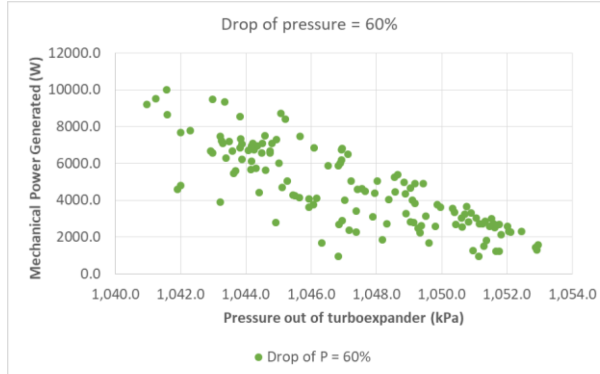

Fig. 10. Mechanical power generated from the pressure difference: output pressure drop equal to 60%.

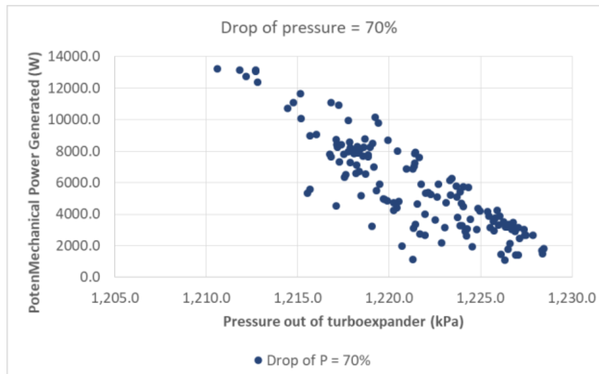

Fig.11. Mechanical power generated from the pressure difference: output pressure drop equal to 70%.

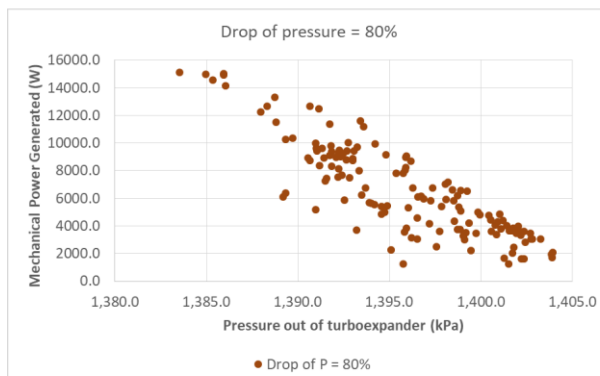

Fig. 12. Mechanical power generated from the pressure difference: output pressure drop equal to 80%.

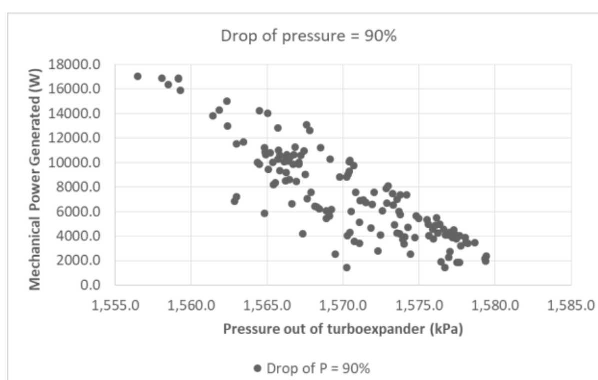

Fig. 13. Mechanical power generated from the pressure difference: output pressure drop equal to 90%.

It can be seen in the previous figures that there is a quasi-linear relationship between the pressure difference of the system and the generation of mechanical power.

V. CONCLUSION

This work allowed quantifying the mechanical power generation at the exit of a turboexpander in a natural gas transport substation, based on its mechanical input energy (flow energy and kinetic energy). By means of a thermodynamic analysis, the physical variables that significantly impact the natural gas distribution process were identified. These variables are mainly associated with thermodynamic properties and dimensional parameters of the distribution system. Among the properties, the pressure and temperature of natural gas stand out. Volumetric flow is an important factor in the distribution system once, together with dimensional parameters of the system (pipe diameter), it is essential to determine the velocity of the fluid and subsequently quantify the kinetic energy of natural gas. In relation to instrumentation, the use of pressure transmitters, resistance thermometers and computerized flow meters was considered pertinent, with the purpose of guaranteeing high metrological reliability to the measurement system, that is, obtaining lower uncertainties.

In addition, the work confirmed that it is necessary in the system, the implementation of a turboexpander connected to an electric generator in order to take advantage of the mechanical energy of natural gas and transform it for the generation of electrical energy. Applying the physical principles of mass and energy conservation, it was possible to quantify the mechanical energy of natural gas at the entrance of the turboexpander (considered a control volume). The experimental measurements of pressure, temperature and volumetric flow allowed us to estimate this mechanical energy. In relation to the mechanical energy at the outlet of the turboexpander, a simulation was necessary based on the input parameters. A drop in pressure and temperature was simulated, making variations of 10% up to 90% of the initial value at the entrance. From this, it was found that the natural gas pressure at the inlet is the most important parameter for the generation of mechanical energy. This can be explained because from this pressure measurement the enthalpy (flow energy) of natural gas is determined and, this type of energy, represents the majority of the mechanical energy of the fluid, due to the low velocity of the same. That is, the flow energy is much greater, when compared to the kinetic energy of natural gas. As recommendations, it is suggested that this work be used as a starting point for a thermodynamic analysis of the natural gas distribution system, based on the principles enshrined in the second law of thermodynamics. This will allow quantifying the entropy of the system and the exergy generated.

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José Daniel Hernández Vásquez. Doctor in Mechanical Engineering, formed by the Pontifical Catholic University of Rio de Janeiro (PUC-Rio, 2018). Master in Metrology (PUC-Rio, 2014). Mechanical Engineer (Universidad del Atlántico, 2011). During his postgraduate training he was awarded a scholarship by institutions of the Brazilian Government for the development of science and technology: CAPES, FAPERJ and CNPq. He has teaching experience at undergraduate and graduate level, ministering disciplines at the Department of Electrical Engineering and the Graduate Program in Metrology of the PUC-Rio and Faculty of Engineering of the Universidad del Atlántico. He has experience as a researcher and consultant of the Brazilian industry, acting in projects financed by the Brazilian Regulatory Body of the Electric System (Aneel) and the National Agency of Petroleum, Natural Gas and Biofuels (ANP / PETROBRAS). Focused projects, specifically to: (i) evaluate the measurement uncertainty of heat transfer systems and (ii) develop a methodology for calibration and metrological evaluation of liquid and natural gas ultrasonic meters. He has experience in the technical and administrative management of Metrology Laboratories. He is recognized by the Red Colombiana de Metrología (RCM, Sub-Network: Academia, Industry), as an expert in Metrology for the Colombian market. Currently, he works as a Full Time Professor with Exclusive Dedication in the Faculty of Mechanical, Electronic and Biomedical Engineering (FIMEB), Mechanical Engineering Program of the Universidad Antonio Nariño.
ORCID: https://orcid.org/0000-0002-0028-2912

Rubén Darío Pardo Zapata. Electromechanical Engineer from Universidad Antonio Nariño, with experience in the oil and gas sector. He has ability to identify and solve problems related to machines and processes of transformation and uses of heat and energy, through research, management or technological innovation. Design, assembly and operation of electromechanical and industrial control systems; thermal and hydraulic generation systems, transportation, storage, industrial and home distribution of electrical energy, mechanical, thermal

and flow systems and equipment, as well as in the implementation and execution of industrial maintenance systems, as well as in the implementation of Total quality systems, management and business consulting in transformation and service companies, especially in small and medium-sized industries
ORCID: https://orcid.org/0000-0001-5195-3213

Brandon Eduardo Carroll Gutierrez. Electromechanical Engineer from Universidad Antonio Nariño, with experience in the area of port logistics, performing the role of Operations Supervisor, especially in the attention of tankers and distribution through tanker trucks and others. He has extensive knowledge in the design of mechanical systems, as well as their respective maintenance. In the same way in topics related to the thermal area, as well as in control and automation systems. In addition, with powers to perform maintenance and repair of industrial machinery and equipment and power generation, in quality and safety conditions and with the required deadlines.
ORCID: https://orcid.org/0000-0003-2055-0432