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INVESTIGATING ROOT CAUSES OF CATU COMPRESSOR STATION SHUT-DOWN DUE TO HIGH DISCHARGE TEMPERATURE

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ABSTRACT

One of the most important compressor stations operated by Petrobras Transporte S.A. – TRANSPETRO – is called Catu Compressor Station, which operates for the GASENE gas pipeline, usually compressing gas in order to attend Brazilian Northeastern region demand.

Catu Compressor Station has often presented outlet gas temperatures very close to its upper limit of 50ºC, with some sporadic events of automatic station shutdown when surpassing this limit. Since they began, gas temperature profiles along the

Catu compression process have been monitored and investigated. Depending on the pipeline flow direction and demand, this marginal operation could impact directly on the station's compression versatility.

Possible causes for this high outlet gas temperature problem are presented through a "fishbone" analysis, leading to a master action plan. This plan mainly comprehended the analysis and check of design data and operational parameters of the centrifugal compressors and its downstream process heat exchangers, culminating in field tests to submit this equipment to the highest possible range of operational conditions.

Despite the difficulties, mainly for field test accomplishment, the master plan revealed an incompatibility between the current operating profile of Catu compressors and the design thermal capacity of its heat exchangers. To better support this find and predict the possible operational limits, a compression process modelling effort was conducted utilizing dynamic process simulation. The simulation results showed the limitation extension imposed on the compressor's operational envelope by its heat exchanger capacity, for a variety of operational conditions, such as different environmental and process gas temperatures.

Finally, options for mitigating and solving the presented operational limitation are proposed and discussed.

INTRODUCTION

Petrobras Transporte S.A. - TRANSPETRO is the wholly-owned PETROBRAS subsidiary responsible for operation and maintenance (O&M) services of a 7300 km gas pipeline network, including 11 (eleven) compressor stations, distributed along 12 (twelve) different States of Brazil and fully remotely controlled and operated by CNCO (TRANSPETRO's Control and Dispatch Room, located at the company headquarters in Rio de Janeiro).

The Catu Compressor Station is located in the northeastern portion of TRANSPETRO gas pipeline network (see Figure 1) and began operations in February 2011, having been designed for an operational flow of 16.1 million Nm³/d and nominal flow of 21 million Nm³/d (7 million Nm³/d per machine for a compression ratio of 1.67). It is important to note that "Nm³/d" refers to a volumetric flow unit normalized to the condition of 20ºC and 1 atm. (Petrobras condition).

Figure 1 – Catu Compressor Station location

Since the beginning of operations in this station, the current natural gas transport scenario proved to be different from that predicted during the design stage, so that the demand for gas flows from this station rarely exceeds 5 million Nm³/d. Its operation is destined to complement the demand for natural gas from the Northeast Region, through the GASENE gas pipeline and the excess production from the State of Bahia. To meet these conditions it is necessary to operate only one of the three compressors that comprise the nominal capacity of the compressor station.

Considering the scenario above, the occurrence of high temperatures in the compression station outlet is frequently observed, at levels very close to or above the design set-point to trip the turbo-compressors, defined at 50ºC. There have already been some occurrences of tripping the station, especially as from 2013, when the compressor station began to have greater demand.

Since then, the operational team has been monitoring continuously the natural gas temperature throughout the entire compression process for this station, in addition to the variations in environmental temperature, given that the later shows wide variations during the day, with this effect more intense on hot and sunny days when the temperature reaches values very close to 40ºC.

Depending on the demand for the gas pipeline system, in terms of flow and the compression ratio (or head) required, and the environmental temperature, it was perceived that the capacity of the Catu Compression Station could be compromised due to the limitation of the compressed natural gas air coolers for a specific given operating condition.

ROOT CAUSE ANALYSIS

To analyze the frequent occurrence of high temperatures in the gas flow downstream of the heat exchangers, a multidisciplinary technical study was held involving the operational and maintenance teams. The potential causes were organized in a diagram of root causes or “fishbone” (Ishikawa), as in the figure below:

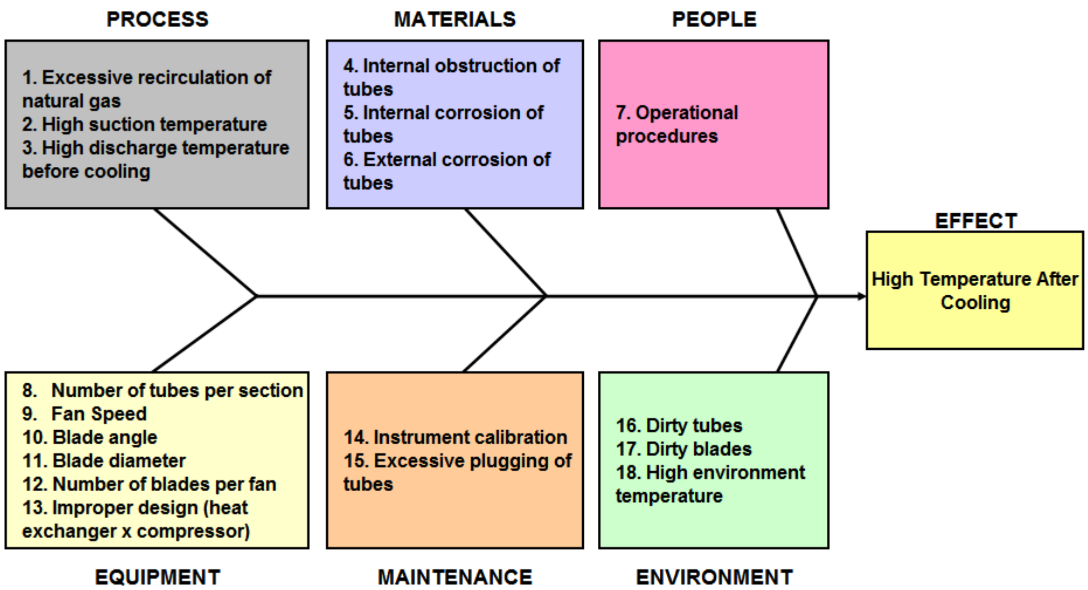

Figure 2 – Initial “fishbone” diagram

Starting with the possible causes surveyed in the diagram above, an action plan was prepared for their verification. At first all of the verification actions were carried out in the field and were independent of the equipment operation. A large number of the possible causes were discarded by this process, as illustrated by the following diagram.

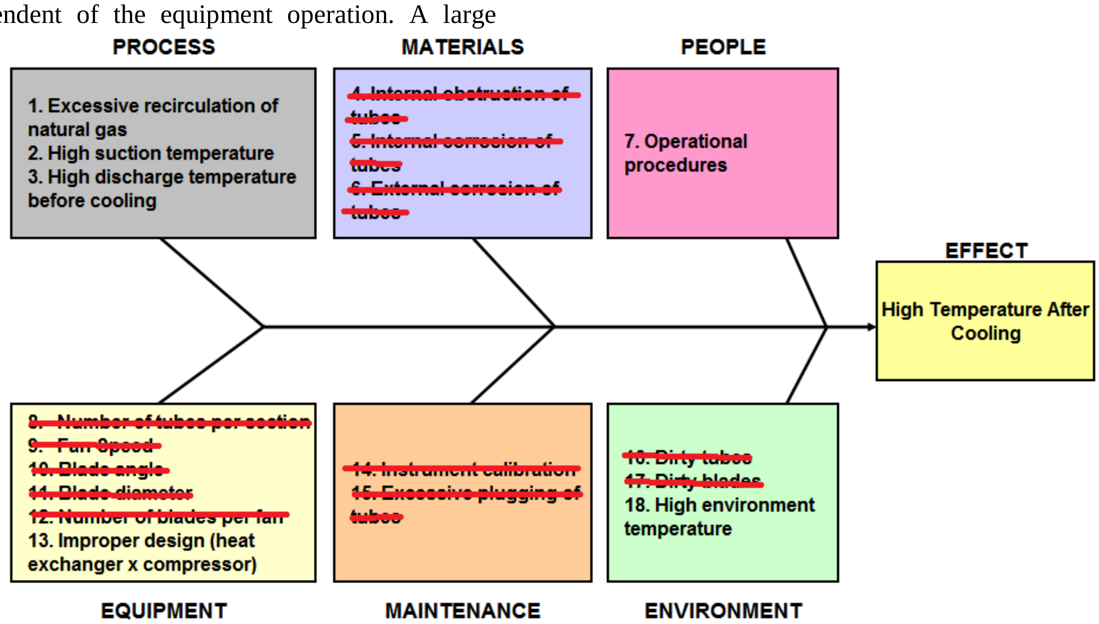

Figure 3 – “Fishbone” diagram after field inspection

The other causes were verified through data analysis of the principal equipment design (compressor and heat exchanger) and operational tests in the field.

DESIGN DATA ANALYSIS

The Catu Compressor Station consists of four parallel trains, in a 3+1 configuration (one as spare unit). Each train comprises a mechanical pair formed by a gas turbine (driver) and a centrifugal compressor (process or driven equipment). This mechanical pair is denominated in this work as turbo-compressor set, or simply turbo-compressor. In addition, downstream of each turbo-compressor are the process heat exchangers.

Catu heat exchangers are air-cooler gas-cooled type and used only to control the temperature of the compressed gas to be injected into the pipeline. From the design specifications, there are two for each of the four centrifugal compressors and should attend the rated operational point of each compressor.

Continuing with the action plan, the design data for the centrifugal compressors and their heat exchangers were analyzed. A simplified comparative chart was drawn up and is presented in the Table in Figure 4, where the process data adopted in the design of the compressor station and the equipment analyzed are shown.

DESIGN VARIABLE	COMPRESSOR STATION OVERALL SPECIFICATION	COMPRESSOR SPECIFICATION	HEAT EXCHANGER SPECIFICATION
Inlet Pressure	60 kgf/cm²	62.5 kgf/cm²	100 kgf/cm²
Outlet Pressure	100 kgf/cm²	100.9 kgf/cm²	-
Inlet Temperature	20.0 ºC	20-30 ºC	82.7 ºC
Outlet Temperature	45.0 ºC	68.2 ºC	51.7 ºC
Nominal Vol. Flow @ 20 °C 1 atm	$7.0\text{x}10^6$ Nm³/day	$6.67\text{x}10^6$ Nm³/day	$7.1\text{x}10^6$ Nm³/day
Environment Temperature	-	-	36.1 °C

Figure 4 – Process data comparison

It may be verified that there is a variation in the values of the temperatures considered in the design. In particular we highlight the outlet temperature considered in the design of the heat exchangers (51.7ºC), whose value is above the set-point of the design to trip the turbo-compressors, defined at 50ºC. Further, the outlet temperatures from the compressors and those entering the heat exchangers considered in the design differ substantially.

As for the flows considered in the design, it may be perceived that there is congruence in the values. However, as already mentioned, the normal operational flows for Catu rarely exceed 5 million Nm³/d, demanding the operation of only one machine with partial opening of the anti-surge valve. It is important to emphasize that operation with some of the flow in recirculation through the compressor contributes to an increase in the temperature of the compressor suction. It is observed on the operation screens that the temperature of the compressor suction at Catu varies between 20 and 30ºC during a normal day, as may be seen in graph in Figure 5. It is a fact that this increase in the temperature of compressor suction contributes to the incidence of the problem studied in this work.

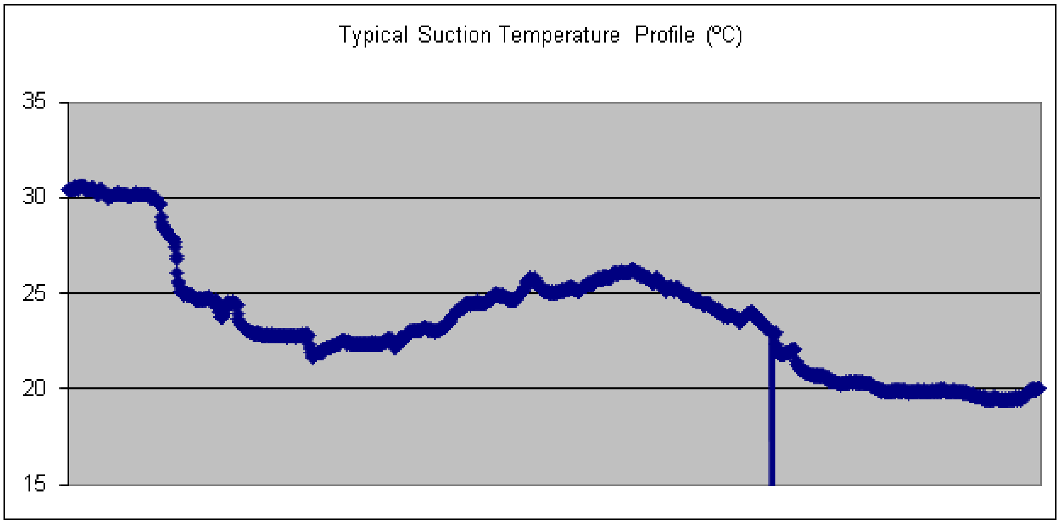

Figure 5 – Suction temperature variation during a typical day at Catu

Finally, it is believed that the environmental temperature considered in the design for the heat exchangers (36.1°C) is appropriate and complies with the criteria in API 661 [2]. As an illustration, there follows in Figure 6 a chart from the National Institute of Metrology in Brazil (INMET) for the month of January 2013 (the Alagoinhas Station – a place very close to Catu). The orange dots represent the maximum environmental temperatures per day.

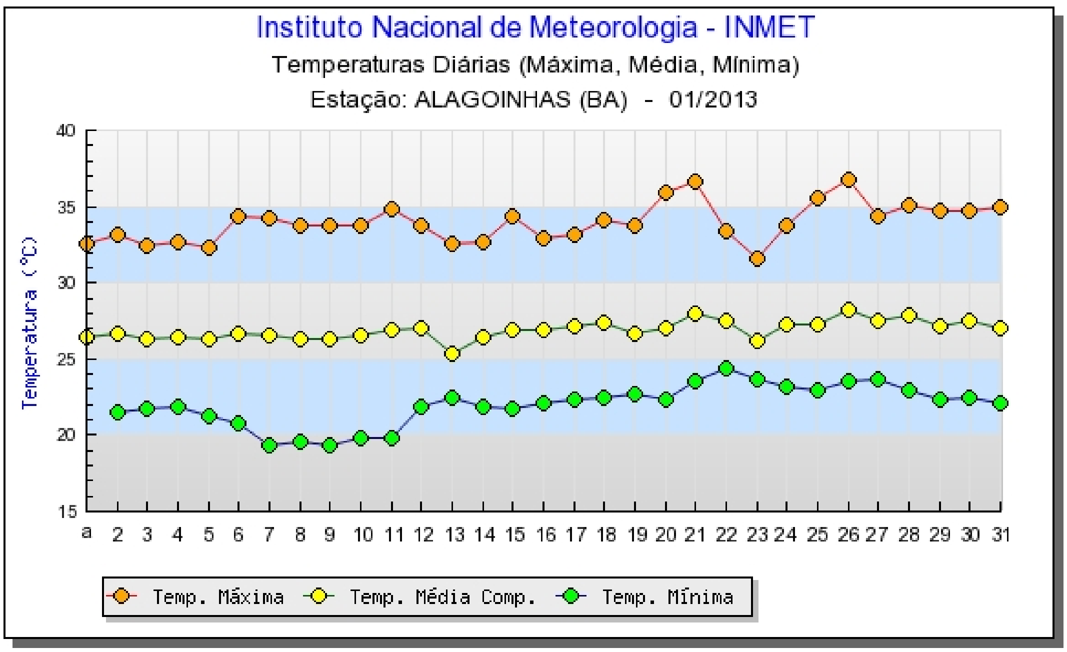

Figure 6 – Maximum environmental temperatures per day during January, 2013

As demonstrated, items 1, 2, 13 and 18 from the fishbone diagram in Figure 3 may be considered as analyzed, and it is believed that they act as contributors to the occurrence of the high temperatures of the outlet gas. Item 7 (training) is going to be analyzed in the next section.

FIELD TESTS

With a view to corroborate the analysis of items 1, 2, 3, 13 and 18 from the fishbone diagram, in addition to verifying the possible cause related to the operational procedure (item 7), in May 2013, effective operational tests were carried out on two of the four turbo-compressors. These tests had the objective of analyzing the performance of the coolers and evidencing any possible operational restriction imposed by them on the operational envelope of the compressors. The holding of the tests had the following premises:

- To submit the compressors to the diverse possible operational conditions within its envelope of compression including the nominal design condition, so as to observe the cooling capacity of the equipment under these operational conditions;
- To coincide the moment of highest pressure differential between the suction and the outlet during the hottest

part of the day (approximately 2 p.m.);

- To maintain the anti-surge valve totally closed so as to preclude the recirculation of hot gases in the suction of the compressors, thereby eliminating any possibility of compressor suction temperatures rising due to the recirculation of gas.

In order to analyze the behavior of the coolers better during the tests, three points that represent the most critical situations were considered:

- Point 01: the instant when the highest temperature of the compression station outlet was recorded;
- Point 02: the instant when the highest environmental temperature was recorded;
- Point 03: the instant when the greatest pressure differential between compression suction and outlet was recorded.

The results obtained were organized in tables in the Figures below.

TEST RESULTS - TURBO-COMPRESSOR C			
Variable	Point 01 (highest temperature after cooling)	Point 02 (highest environment temperature)	Point 03 (highest differential pressure)
Time	14:20h	14:20h	16:00h
Environment Temperature	31.3 °C	31.3 °C	29.4 °C
Temperature Before Cooling	67.3 °C	67.3 °C	70.0 °C
Temperature After Cooling	49.6 °C	49.6 °C	49.3 °C
Volume Flow @ 20 °C 1 atm	8.8 x 10^6 Nm^3/day	8.8 x 10^6 Nm^3/day	8.3 x 10^6 Nm^3/day
Differential Pressure	28.0 kgf/cm²	28.0 kgf/cm²	32.0 kgf/cm²

Figure 7 – Test results for turbo-compressor C

TEST RESULTS - TURBO-COMPRESSOR D			
Variable	Point 01 (highest temperature after cooling)	Point 02 (highest environment temperature)	Point 03 (highest differential pressure)
Time	15:00h	13:50h	15:20h
Environment Temperature	29.4 °C	31.4 °C	27.6 °C
Temperature Before Cooling	66.0 °C	64.3 °C	66.2 °C
Temperature After Cooling	49.8 °C	48.0 °C	48.2 °C
Volume Flow @ 20 °C 1 atm	9.1 x 10^6 Nm^3/day	9.2 x 10^6 Nm^3/day	9.1 x 10^6 Nm^3/day
Differential Pressure	30.0 kgf/cm²	28.0 kgf/cm²	31.2 kgf/cm²

Figure 8 – Test results for turbo-compressor D

From the Tables above, it was possible to observe the low capacity in cooling the compressed natural gas when the compressors are operating in points different from their rated operational points and, therefore, outside the only condition foreseen in the specification and design of the heat exchangers. It is important to note that the temperature of the station's outlet maintained itself very close to the set-point for the trip for the operational points highlighted in Figures 7 and 8. Also, the flows at these points were all above those considered in the design; on the other hand, the environmental temperature always remained below that considered in the design.

It should be considered here, that for reasons of adverse conditions imposed by the system of gas pipelines, the condition of the compressor design (design point) could not be reproduced, nor the more extreme operating conditions of the centrifugal compressor, which combine higher flows with greater pressure differentials (head). In addition to this, it is known that the environmental temperature could attain levels higher than those experienced during the tests.

Due to the impossibility of controlling several of the variables involved, or to analyze the performance of the heat exchanger better, it was necessary to use a minimally rigorous simulation model which considered the characteristics and data of the design of the entire Catu Compressor Station. Such an analysis would point out the limitations imposed on the compressor's envelope of operation. Additionally, this study should point out graphically the possible bands of operation for Catu, considering the seasonal variations in environmental temperature.

The possible cause "Operational Procedures" (item 7 in the fishbone diagram) would reference the increase in temperature of the outlet when the gas turbine (driver) was accelerated quickly and when the anti-surge valve was maintained open and in manual mode for meeting the compression demand for natural gas, allowing already compressed hot gas into the suction of the compressor. Accordingly, there was the suspicion that the operational procedure practiced by the operating team, as defined by the company's standards of execution, was contributing, and resulting in an increase in the outlet temperature. So, during the carrying out of the tests, even while maintaining the anti-surge valve closed and with lower rates of acceleration practiced, it was possible to observe the occurrence of high temperatures in the outlet of the compressors at the critical points in their operating envelopes. Therefore, item 7 from the fishbone diagram was discarded as a possible cause, as may be seen in the updated fishbone diagram in the following figure.

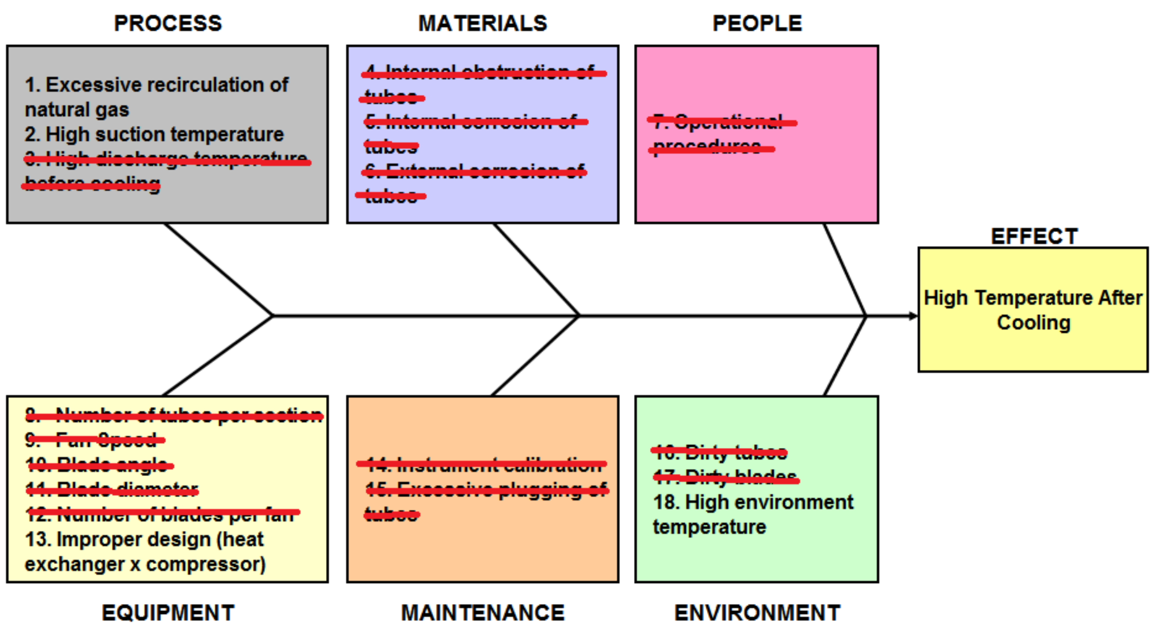

Figure 9 – "Fishbone" diagram after field tests

PROCESS SIMULATION

To analyze the behavior and performance of the heat exchangers better, it would be necessary to utilize a set of simulation resources, which would allow the identification of several parameters that influence the thermal capacity of the heat exchangers under study, in addition to enabling the mapping of operational limitations imposed on the station's compressors by them.

In the modeling of the Catu's compression process, only one of the four compression trains was considered. The modelling of the entire arrangement with the four compression trains in parallel is not justified, given that each of them has dedicated heat exchangers that are aligned, as shown in the Figure 10.

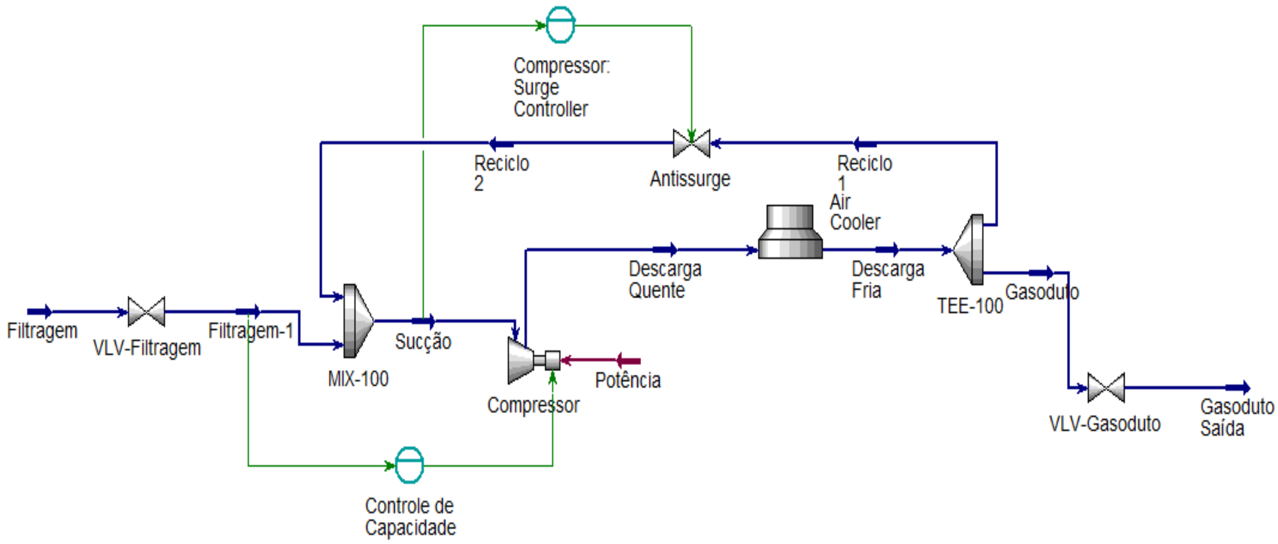

Figure 10 – Catu compression model

It is important to emphasize that the following premises were assumed in the development of the Catu model:

- The characteristic curves of the centrifugal compressors utilized in the model are those obtained during acceptance tests from the manufacturer of this equipment in new and clean conditions; that is, the curves utilized do not consider the effects of possible loss of performance arising from their time of operation;
- The composition of natural gas specified in the current entering the model follows a typical composition, according to records of chromatographic measurement;
- The modelling of the heat exchanger was simplified and the value of its global coefficient of heat transfer was estimated at 1.166484x106 kJ/C-h (heat exchangers considered clean);
- The variation in the environmental temperature was considered as being from 30 to 40°C, aiming at representing the climatic seasonality;
- The variation in suction temperature of the gas was between 20 and 30°C, in accordance with that observed on the real operational screens, and with the intention of reproducing the effect of the compressor's operation with the anti-surge valve partially open;
- The minimum suction pressure of the compressor was considered as being 50 kgf/cm²;
- The maximum outlet pressure of the compressor was 100 kgf/cm², in accordance with the limitation of the gas pipeline design.

To obtain the results, it was necessary to establish several simulated operational scenarios capable of submitting the compression model to the highest possible number of operational points in the centrifugal compressor envelope. To achieve this, some of the interesting variables in the model had variations controlled according to pre-defined intervals.

The results of the simulation study that follow are in the form of operational envelope charts, or characteristic curve charts, from the compressor at the Catu Compression Station, with their respective regions of operation where the heat exchangers do not meet the maximum temperature of outlet gas permitted (50°C). The points outside the envelope should be ignored.

The operational envelope charts are presented per environmental temperature (40, 35 and 30°C), given that for each temperature there are three charts, one for each temperature of suction gas (30, 25 and 20°C). The motive for which the results must be presented in this form is due to the necessity to correct the compressor's operational envelope for each suction temperature of gas considered. The characteristic curves, which form the operational envelope, are the polynomial curves represented in the charts for each value of rotation corrected, represented in the legend to the chart by isolated numerical values in rotations per minute (RPM).

We can also see the compressor's design point represented as a green dot in each chart, as corrected for the condition considered (corrected design point).

1. Results for an environmental temperature of 40°C

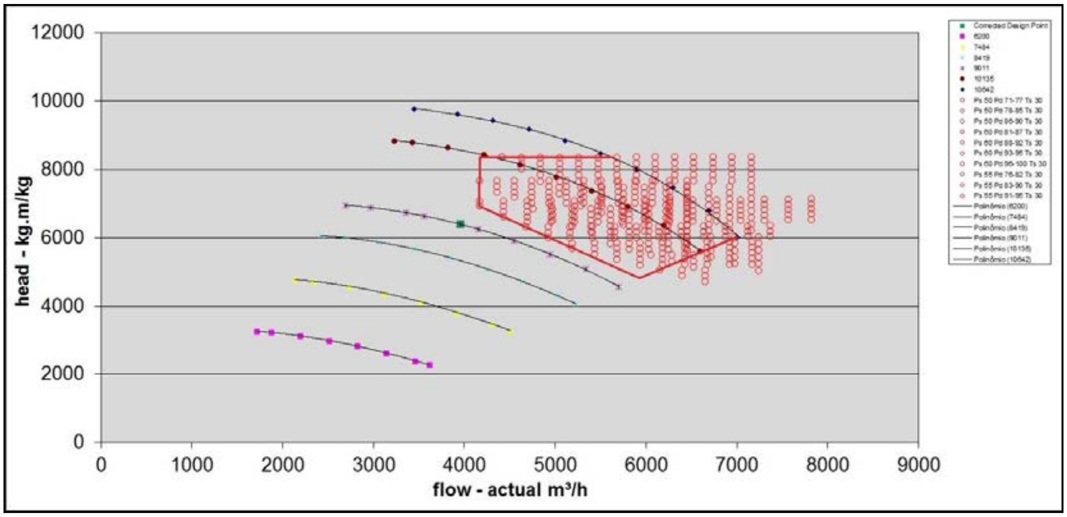

Figure 11 – Suction temperature of 30ºC

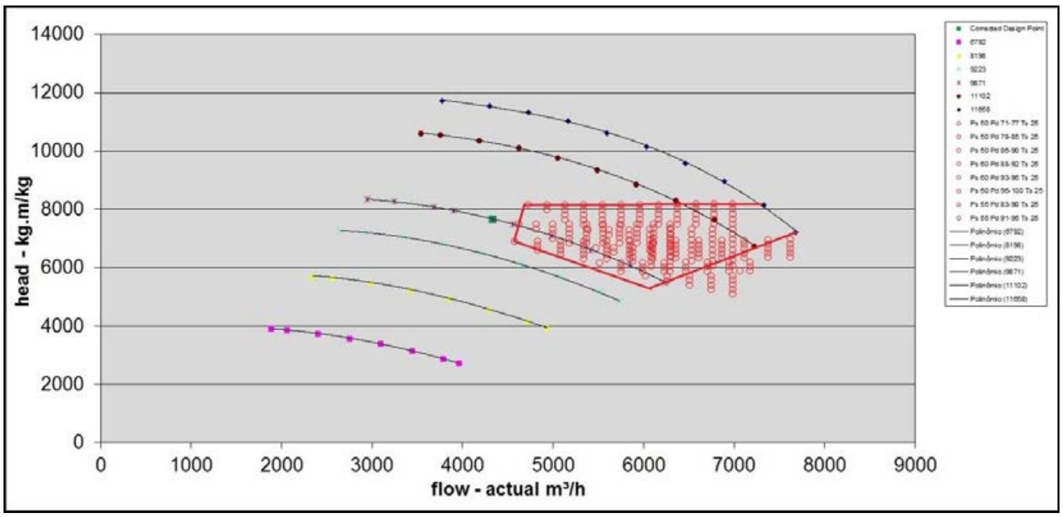

Figure 12 – Suction temperature of 25ºC

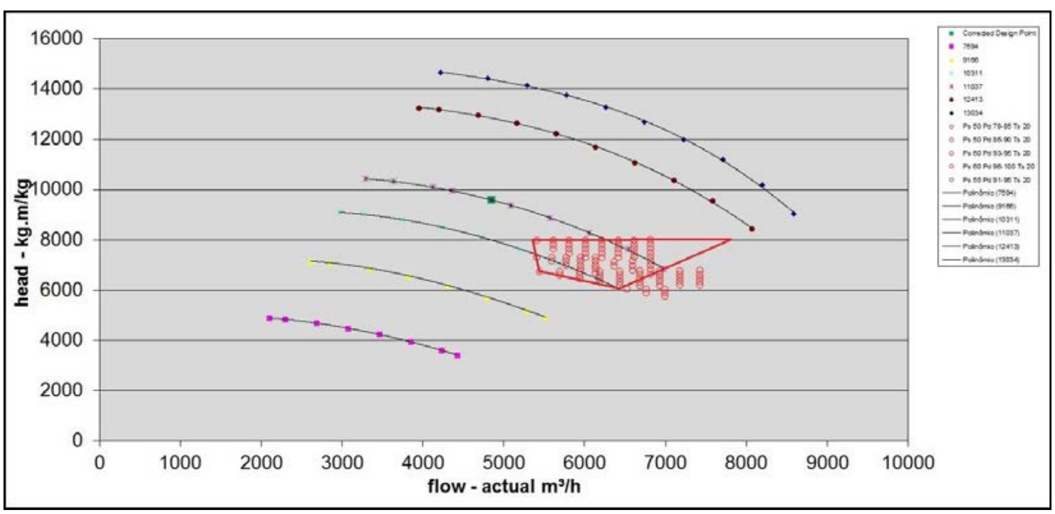

Figure 13 – Suction temperature of 20ºC

2. Results for an environmental temperature of 35ºC

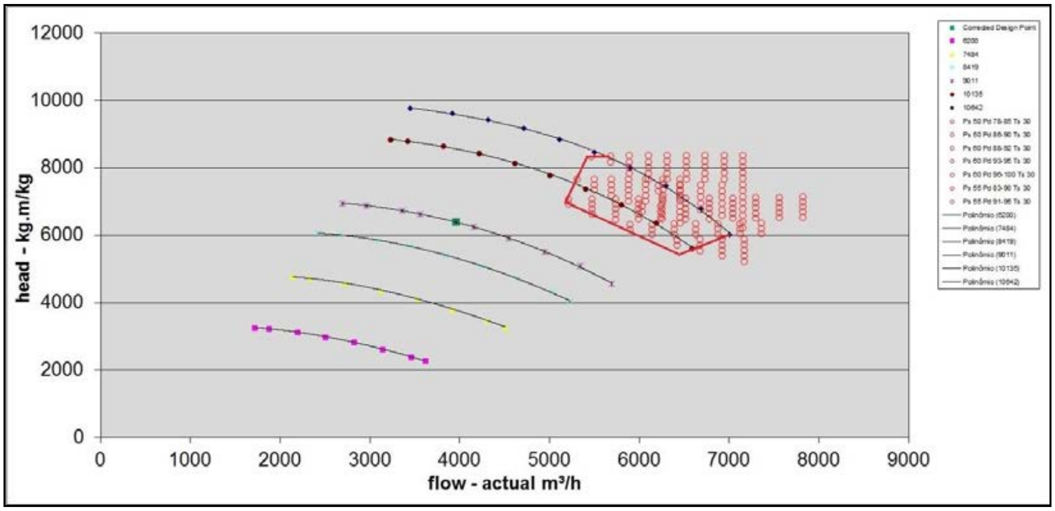

Figure 14 – Suction temperature of 30ºC

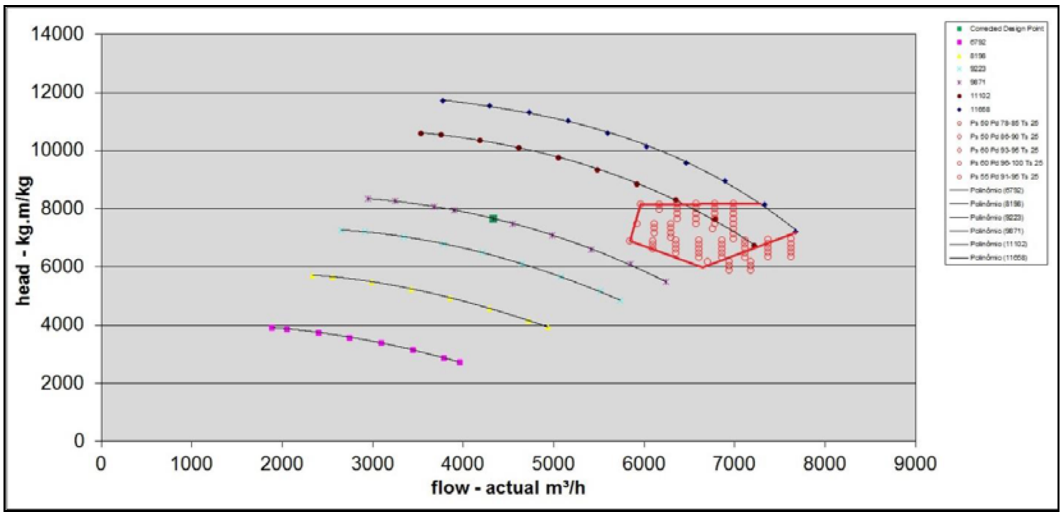

Figure 15 – Suction temperature of 25ºC

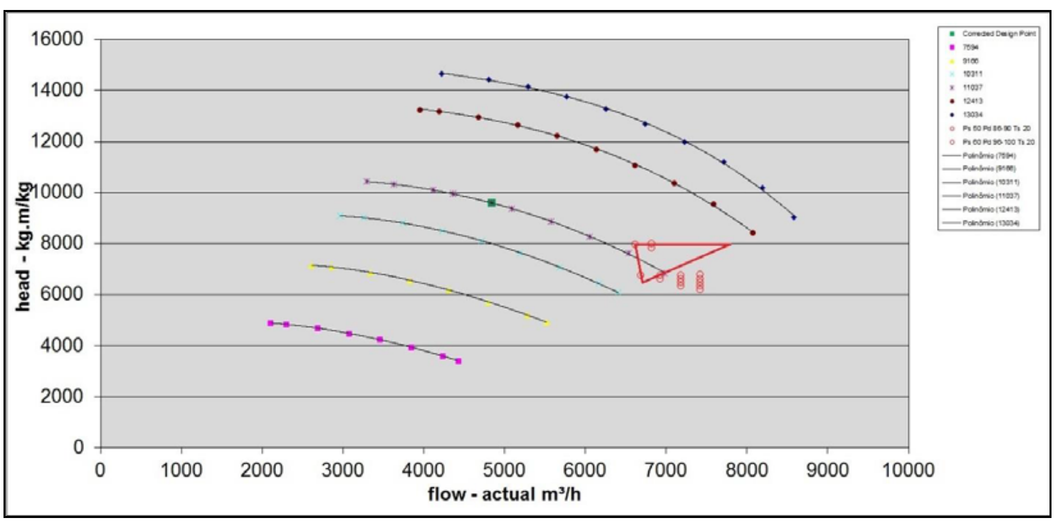

Figure 16 – Suction temperature of 20ºC

3. Results for an environmental temperature of 30ºC

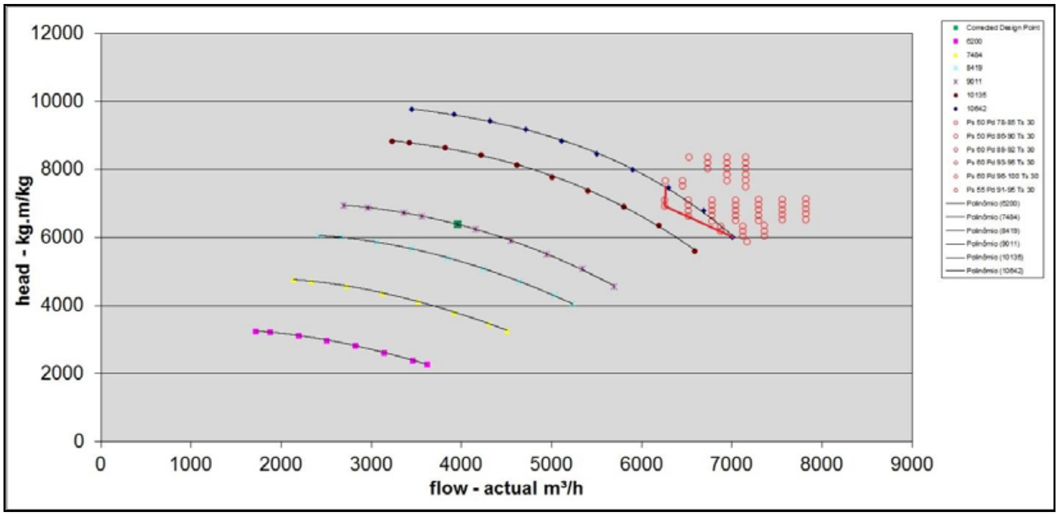

Figure 17 – Suction temperature of 30ºC

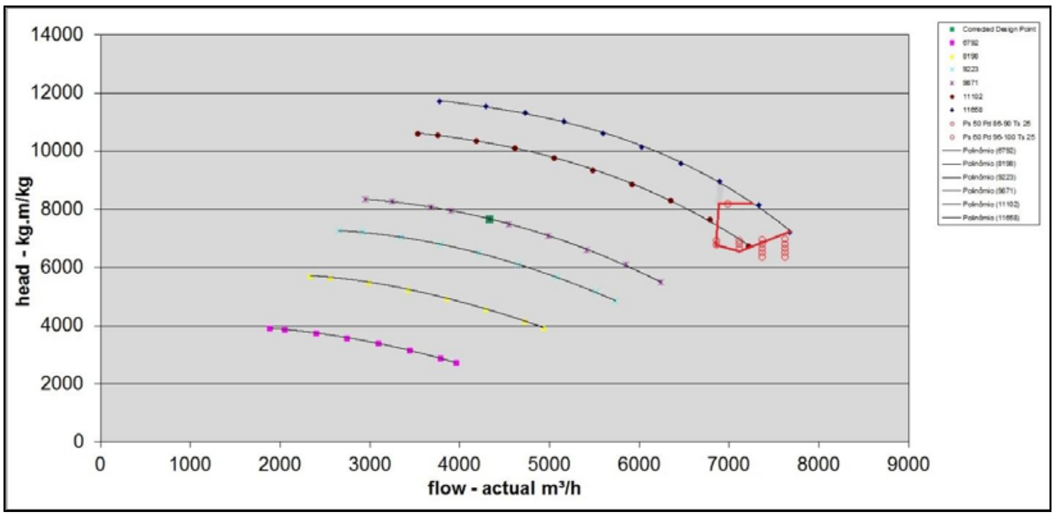

Figure 18 – Suction temperature of 25ºC

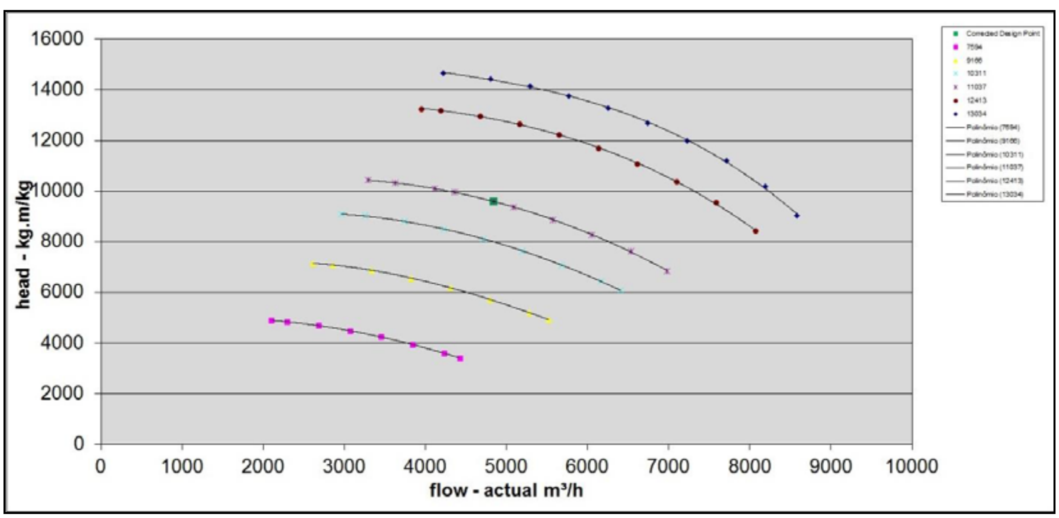

Figure 19 – Suction temperature of 20ºC (no operational restrictions)

CONCLUDING REMARKS

From the charts, the influence of the environmental temperature on the performance of the heat exchangers in Catu for values above 30°C is evident. The charts of Figures 14, 15 and 16 for environmental temperature of 35°C, the value closest to that considered in the design of the heat exchangers (36.1ºC), indicate a region of restricted operation considered acceptable. With an increase in this temperature, there is a proportional increase in the region of operational restriction, as can be seen for example in the charts in Figures 11, 12 and 13 for environmental temperature of 40°C.

Other evidence is in respect of the compressor suction temperature, whose influence on the performance of the heat exchangers is shown to be analogous to the environmental temperature, according to the results of the simulation. Here it is important to emphasize that, with the variation in the value of the suction temperature during the simulations; it became obligatory to correct the operational envelope of the compressors, which was duly considered in the preparation of the charts in Figures 11 to 19. It must be noted that, relative to the gas suction temperature considered in the compressor design (25°C), the characteristic curves of the compressor "move up" for simulated suction temperatures below 25°C. This was expected given that the compressor needs to operate with higher rotations to meet the compression demands of a denser gas. On the contrary, the characteristic curves of the compressor "move down" for simulated suction temperatures higher than 25°C, presenting lower rotation values. As already mentioned, the variation of the suction temperature sought to reproduce the operational effect of the compressor with the anti-surge valve partially open.

It is important to note in the regions of operational restrictions in the charts in Figures 11 to 18, the presence of the compression process limitation, indicated by the higher horizontal line in some of the charts. As can be seen in the charts, this horizontal line is always around the values of the polytrophic head of 8,000 kg·m/kg.

The results of the simulation show that the heat exchangers in Catu are meeting the specifications of service for which they were designed. Seasonal increases in the environmental temperature could impact the compression process, depending on the degree of the increase and the combination of other variables, such as the suction temperature of the gas. An increase in this latter variable, whether due to the normal variation of gas temperature originating from the gas pipeline, or the operation of a partially open anti-surge valve, could equally impact the compression.

Otherwise, it is clear that the sizing of the Catu's heat exchangers could have considered a larger number of operating points, as provided in the datasheet of the compressor (see figure below), which would better represent higher compressor flows and their corresponding cooling demands.

01	APPLICABLE TO: O PROPOSAL ⊗ PURCHASE O AS BUILT		ITEM TAG N^er^ C-4100.1201A/B/C/D						
02	⊗ SERVICES: NATURAL GAS PIPELINE COMPRRESSION		N° OF UNITS REQUIRED: 3 + 1 STD BY (parallel)						
03	☐		☐ MODEL:						
04	⊗ DRIVER COMBUSTION GAS TURBINE (TS- C-4100.1201A/B/C/D)								
05	FOR: GAS NATURAL Catu compression Station								
06	NOTE: INFO. TO BE O BY PURCHASER ☐ BY MANUFACTURER ☐ BY MANUFACTURER OR PURCHASER								
07	OPERATING CONDITIONS *(look for end sheets notes)*								
08		NORMAL	OTHER CONDITIONS						
09	ALL DATA ON PER UNIT BASIS / production year	Year:	2007	2008	2009	2010	2011	2012	RATED
10	STAGE								
11	GAS HANDLED: Natural gas (NG)	NG	NG	NG	NG	NG	NG	NG	NG
12	CORROSIVE COMPOUNDS: *(see gas analysis)*	NA							NA
13	STARTING GAS:	NG							NG
14	STD FLOW Rate;10^6 Nm3/d (1.013 bar; 20C):	pipeline	6.94	9.33	11.70	16.28	18.98	20.95	20.00
15	MASS FLOW, WET, kg/h:								~= 191,247
16	Qty. of Compressors rqd.:	Compr.	01 compr	01	02	02	02	03	03
17	Volume flow / compr. (std): (Nm^3/day)		6.94	9.33	5.85	8.14	9.49	6.98	6.67

Figure 20 – Extract from Catu's compressor datasheet

From the extract above, it is possible to verify that the highest predicted flow per compressor is of 9.49 million Nm^3/d. This value exceeds the nominal flow considered in the heat exchangers' design, as shown in the table of Figure 4.

From the above-mentioned, and returning to the "fishbone" diagram of Figure 9, items 1, 2, 13 and 18 can be finally confirmed as main actors for the occurrence of high temperatures at the station outlet.

As first measure to mitigate the limitation of heat exchangers for meeting the present compression demands, the simulation model utilized in this work was adapted as a forecasting tool and released to the operational technicians at Control and Dispatch Room (CNCO). This tool enables them to predict if the heat exchangers meet the necessities of heat exchange in a determined operational condition.

In addition, and related to the Catu design, the flexibility analysis and temperature limitation for station's downstream piping were revisited, in order to consider the possibility of increasing the set point for the outlet temperature in the station to trip the turbo-compressors, presently defined at 50ºC. Thus, a change management process is in progress and the set point will be increased to 55ºC with the expectation of minimizing the incidence of the problem, as illustrated by simulation results in the chart of Figure 21. This chart represents the worst case scenario simulated in the present work: environmental temperature of 40°C and compressor's suction temperature of 30°C.

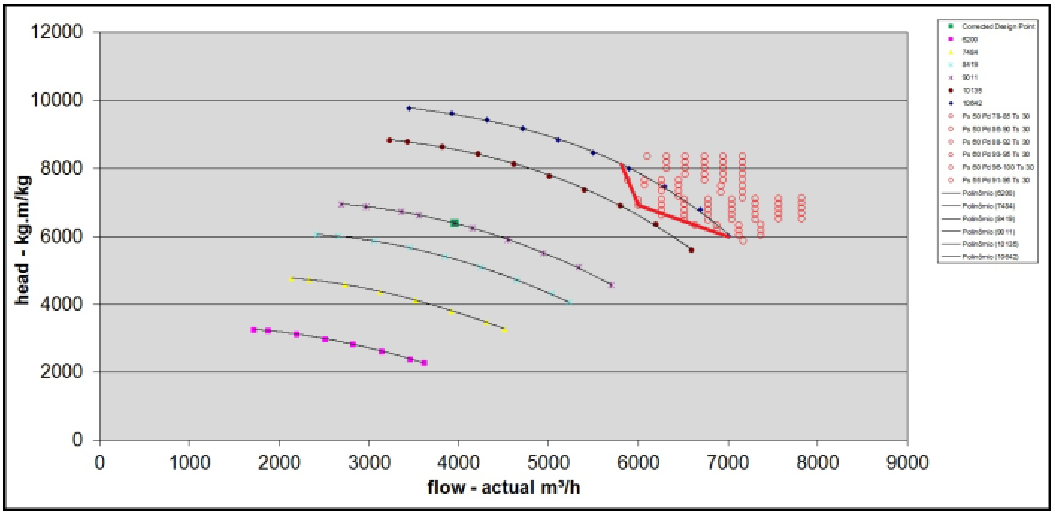

Figure 21 – Restricted operational area for the new set point level (a new display of results for previous Figure 11)

Finally, the way to solve the problem would be to increase the heat exchanger capacity. Some technical solutions may be adopted in this direction, with different degrees of cost, effectiveness and facility of implementation, according to Giammaruti [4]. However, it is important to underline that the decision on this line of action would depend heavily on the scenarios for the future transport of gas in the system of gas pipelines that includes the Catu station. This is because it would make no sense to spend time and money on increasing the heat exchangers' capacity, if these future scenarios indicate operating conditions closer to that for which this equipment was designed.

LESSONS LEARNED

The investigation presented herein represents a good example on how the heat exchangers' sizing underestimated the compressor's operational envelope.

In industry, mainly on recognizably stable processes, it is not economic feasible to have a heat exchanger designed for covering the whole compressor envelope. It can be an unnecessary budget consuming for the project.

But the reality experienced in gas compressor stations operated by TRANSPETRO has been quite different. The constant changes on availability and operational profiles among the various gas injection points in the pipeline network cause the compressor stations do not have a continuous pattern of operation.

Thus, for TRANSPETRO it is true that the dimensioning of a compression plant as a whole, and especially for the heat exchangers, must foresee the serving of a higher number of operational points (or operational scenarios), expanding the operational possibilities for more critical regions in the operational envelopes of the compressors, and consequently, increasing the operational versatility of the plant. Its cooling capacity should be compatible with that required by the compression process, minimizing the impacts and operational restrictions.

Additionally, it is important to take into consideration more thoroughly the maximum admissible temperature for natural gas in pipelines for each new design process, especially for compressor stations, which can result in lower acquisition and operating costs.

From the point of view of project management, the operational teams should participate more effectively since the beginning of any undertaking involving the transport of natural gas, as in the case of this work. This culture of involving the final users since the conceptual design phase is always highly beneficial, because it enables the designers to have a better evaluation of the present and future scenarios of natural gas transport, in addition to an operational vision closer to reality.

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