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ENERGY BALANCE AND SIZING OF REFRIGERATION CASCADE SYSTEM OF 4 STAGES OF APPLIED TO LIQUEFACTION OF PETROCHEMICAL INPUTS USING CARBON DIOXIDE (CO_2) IN ONE OF STAGES.

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Abstract. *This article aims to demonstrate a computer simulation that describes the operation of a system geared to liquefaction of inputs processed in the petrochemical industry through a cooling system that operates in cascade with one of the cryogenic circuits loaded with carbon dioxide (CO2) The idea of carrying one of the cryogenic circuits with CO 2 was motivated by the large potential availability of this gas in Brazil in the coming years, due to the discovery of large oil reserves located in the pre-salt layer. In this layer, CO 2 is combined with natural gas, also quite abundant, which led us to choose the gas itself for the liquefying process. The concept of energy balance in thermodynamic cycles was adopted, applying the 1st Law of Thermodynamics for Control Volumes to obtain performance results that can meet the operating conditions imposed and enable the operation of the equipment modeled in this article. The modeling and dimensioning of the system were made by using the software EES (Engineering Equation Solver), while the COP circuit was emphasized for evaluation of the system performance emphasize.*

Keywords: *Industrial Refrigeration, Carbon Dioxide, Cascade Refrigeration, Energy Balance.*

1. INTRODUCTION

DA SILVA (2009) addresses that, the growing need for the design of cooling systems that use chlorine-free refrigerant with low rate of global warming, called "natural fluids", the design of an industrial system geared to liquefy gases processed in the petrochemical industry (petrochemical inputs) would somehow fill the gap in the industrial segment. The fluids used in this modeling are methane (R-50) ethylene (R-1150), propylene (R-1270) and, particularly, carbon dioxide or CO_2 (R-744). The discovery of pre-salt increases abundantly the amount of CO_2 which gives rise to the need of alternative sinks, as well as reinjection in oil wells. Their application in industrial refrigeration consolidated as one such alternative, which will result in reducing the amount of CO_2 to be reinjected into the reservoir extraction, following the global trend of using increasingly natural refrigerants in industrial refrigeration systems. After careful analysis of the features of some refrigerants called "natural fluids", we concluded that R-744 or carbon dioxide (CO_2) should be used not only because it meets the above requirements, but also because of the great expectation of availability in the coming years. This article describes the development of an equipment aimed at the liquefaction of inputs processed in the petrochemical industry through a cooling system that operates in cascade, comprised of four (4) stages, one of them loaded with carbon dioxide (CO_2) .

STOEKER (1994). The arrangement of circuits in cascade is ideal for systems that have low (or extra low) evaporation temperature. Under such evaporation temperature, the refrigerant fluid used in a single stage would present a high specific volume in the suction, which causes low volumetric efficiency to the compressors. In some cases the compression ratio (CR) in these circuits is high, resulting in high discharge temperatures and the need for greater amounts of compression power. This type of system is

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presented as a solution where there is a risk of a cooling circuit operate with negative pressure (below atmospheric), which might allow the admission of air and humidity, two extremely harmful elements to the integrity of a refrigerant circuit. The operating conditions, particularly pressure and temperature, delimit the application of each type of refrigerant fluid in their respective stage of the cascade circuit. Therefore, the evaporator of a high temperature circuit, connected to the capacitor circuit, provides the establishment of an "artificial environment" for the feasibility of the condensation.

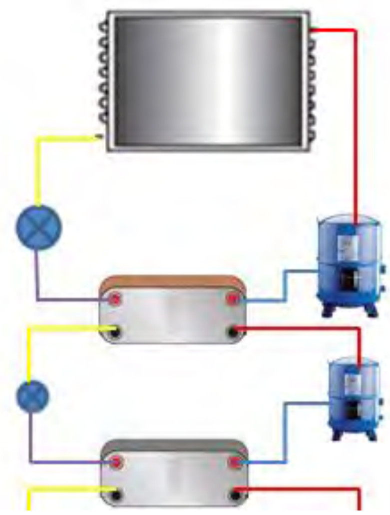

Figure 01 - Example of cascade refrigeration circuit.

2. DESCRIPTION OF THE SYSTEM AND METHODOLOGY.

The refrigerator of the system consists of four (04) vapor compression refrigeration circuit arranged in cascades as specifications in the information table.

Table 1. Values of temperature and condensation pressure as well as of evaporation adopted for modeling the system.

Circuit	Refrigerant Fluid	Condensation Temperature (° C)	Condensation Pressure (kPa)	Evaporation Temperature (° C)	Evaporation Pressure (kPa)
1	Methane (R-50)	-100.0	2604.0	-161.5	101.3
2	Ethylene (R-1150)	- 40.0	1453.0	-105.0	94.36
3	Carbon dioxide (R-744)	-10.0	2649.0	-50.0	682.3
4	Propylene (R-1270)	40.0	1652.0	-20.0	306.7

Figure 02 shows 1) the schematic diagram of the liquefaction system modeled and 2) the indication of each refrigerant fluid adopted in the circuit.

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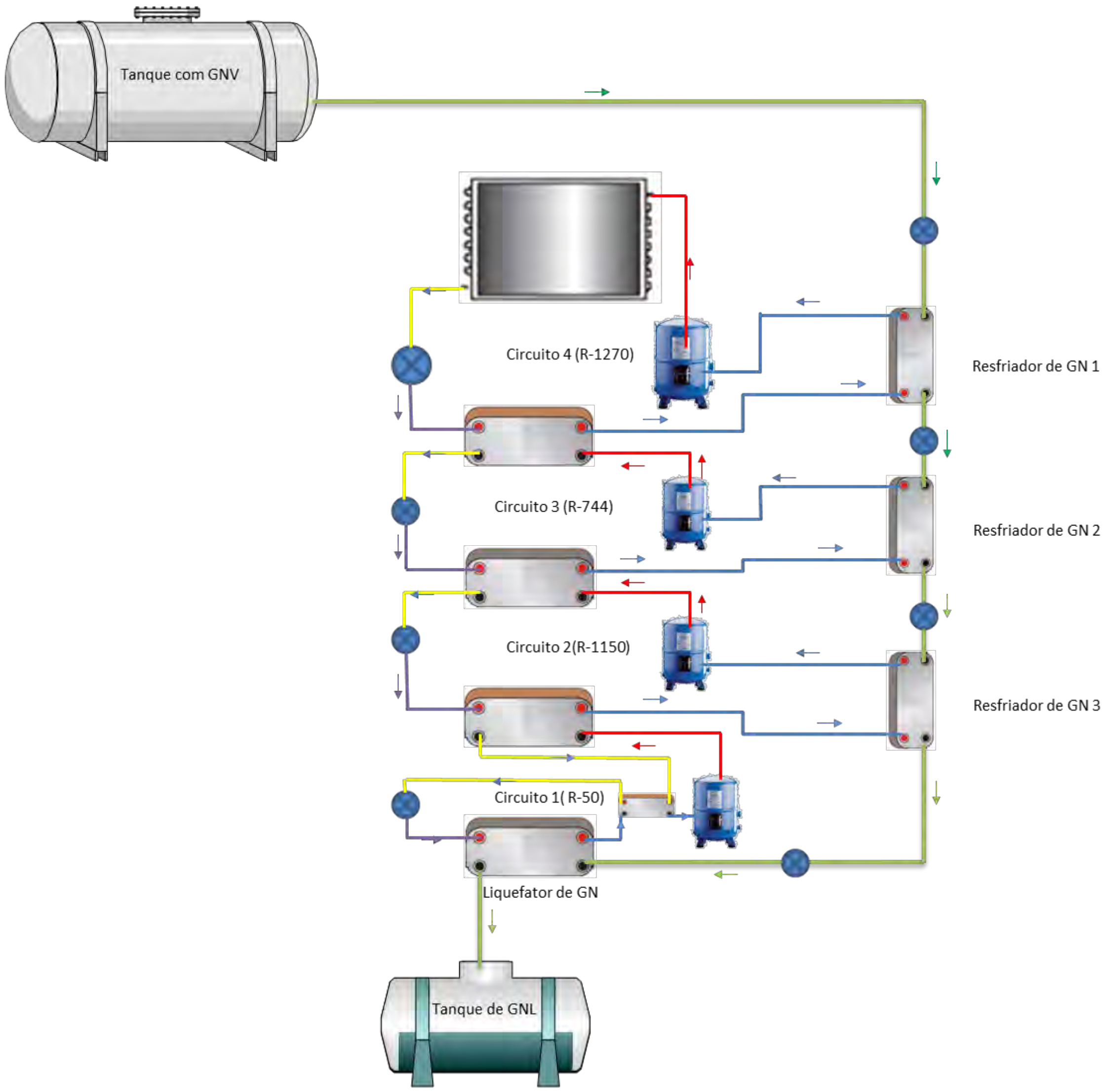

Figure 02 - the schematic diagram of the liquefaction system modeled.

In the present study, it was adopted the concept of energy balance in thermodynamic cycles, applying the 1st Law of Thermodynamics for Control Volumes to obtain performance results that can meet the operating conditions imposed and enable the design of the equipment according to equation (1).

$$\dot{Q}_{V.C.} + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right) = \frac{dE_{V.C.}}{dt} + \sum \dot{m}_s \left(h_s + \frac{V_s^2}{2} + gZ_s \right) + \dot{W}_{V.C.} \tag{1}$$

The design of the system and its modeling were done by using the EES software (Engineering Equation Solver) and the COP of the circuits as evaluator of the modeling.

2.1 Removal of natural gas heat required for liquefaction

In this system of liquefaction, the natural gas passed through different stages of pressure, since the exit from the CNG cylinder until the entry in the liquefier. This resulted in 05 levels of pressure and gradual reductions in gas temperature until its arrival at the liquefier. In this path three (03) coolers were inserted,

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to establish heat exchange with the cascade circuit in order to promote the overheating of the refrigerant fluid of each circuit connected to them. The following section displays a table with the operating conditions of the liquefaction process. The thermodynamic equation adopted for determining the amount of heat to be removed from the natural gas in each stage was:

(2) $$\dot{Q}_{GN} = \dot{m}_{GN} \times \Delta h \quad (2)$$

2.2 Operating conditions of the integrating cascade circuits

2.2.1 Natural Gas Circuit

For the purpose of calculation, a flow value of 2.0 m³ / h (25 ° C and 450 kPa) was adopted for natural gas off the cylinder CNG flow of 2.0 m³ / h (25 ° C and 450 kPa). The refrigeration potencies needed to the stages of pre-cooling of the gas and to its liquefaction are outlined in the following table:

2.2.2 Cooling circuits

The cooling circuits described below require chlorine-free refrigerant fluid and low index of global warming when dispersed into the atmosphere, the so-called "natural fluids". Therefore this system is designed to meet current environmental laws, as well as the future legislation which will take effect in the medium/long term, as predict the Montreal and Kyoto Protocols.

Table 2. Refrigeration potencies needed to the stages of pre-cooling of the gas and to its liquefaction

Item	Circuit interconnection	Heat removed from natural gas (kW)	Pressure natural gas in the heat exchanger (kPa)	Inlet temperature natural gas (°C)	Temperature got out of natural gas (°C)
Cooler GN 1	4 - propylene (R-1270)	0.145 0	350.0	-5.0	-15.0
Cooler GN 2	3 - Carbon dioxide (R-744)	0.1020	200.0	-30.0	-45.0
Cooler GN 3	2 - Ethylene (R-1150)	0.1714	150.0	-80.0	-95.0
Liquefier GN	1 - Methane (R-50)	0.8329	101.3	-161.5	-161.5
Total heat removed from NG to its liquefaction (kW)		1.2513			

The equations used to obtain the energy balance in each circuit were:

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Heat absorbed in the evaporator

$$\dot{Q}_{ev} = \dot{m}(h_1 - h_4) \tag{3}$$

Heat Rejected condenser

$$\dot{Q}_{cd} = \dot{m}(h_2 - h_3) \tag{4}$$

Theoretical power of the compressor

$$\dot{W}_c = \dot{m}(h_2 - h_1) \tag{5}$$

Coefficient of Performance (COP)

$$COP = \frac{\dot{Q}_{ev}}{\dot{W}_c} \tag{6}$$

Table 3. Results of the energy balance and in particular, the COP of each circuit:

Circuit	Refrigerant	Heat absorbed in the evaporator (kW)	Heat rejected in the condenser (kW)	Theoretical power of the compressor (kW)	COP
1	Methane (R-50)	0.8329	1.603	0.7699	* 1.499
2	Ethylene (R-1150)	1.744	2.494	0.7194	2.424
3	Carbon dioxide (R-744)	2.596	3.417	0.8217	3.159
4	Propylene (R-1270)	3.560	4.398	0.8383	4.246

* Considering the efficiency gained by the heat exchanger (Economizer), which enables improved subcooling of the liquid line and improved suction superheat of the compressor circuit 1 of the Methane (R-50).

3. RESULTS AND DISCUSSION

For this simulation we adopted for natural gas to CNG cylinder output a flow of 2.0 m³ / h (25 ° C and 450 kPa), extremely small value if we consider the flow of a liquefaction plant as the one from Paulinia, in the state of São Paulo, which processes approximately 16 000 m³ / h of natural gas. Even though, it was still possible to analyze the operation, the performance and the productivity of the liquefied natural gas. Under the conditions referred above, the value reached 13.9 liters/hour.

The circuit 1, loaded with methane (R-50), presented the worst performance: its evaporator works as liquefier of the natural gas. The COP value achieved was 1.499, which can be explained by the fact that this circuit demand a considerable amount of energy for the compression, given the high specific volume

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in the suction and also because of the high compression ratio (Cr = 25.7). For the analysis, an isentropic compression was considered, namely, under real conditions there may be a decrease in the COP value in comparison to the value informed as the result of the simulation.

The circuit 2, loaded with ethylene (R-1150), had a COP value of 2.424, which is an acceptable number for the evaluation of the performance of the vapor compression refrigeration circuit.

Considering that the COP value for the circuit 3 was 3.159, the application of CO_2 (R-744) as refrigerant fluid was satisfactory.
The better results were achieved by circuit 4, loaded with propylene (R-1270): The COP value reached 4.246.

4. ACKNOWLEDGEMENTS

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