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Theme

Optimization of turbo-expander operating parameters to enhance Liquids (LPG and Condensate) recovery.

Presented by

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Abstract

Title: **“Optimization of the operating parameters relating to the turbo-expander to enhance Liquids recovery.”**

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Among the most important facilities dedicated to gas processing are the **Joule-Thomson valve** and the **expansion turbine**, commonly known as the **Turbo-expander**. These are essential devices used to reduce the pressure of raw gas, a necessary step for separating heavier hydrocarbons. To achieve low pressure and temperature at the outlet, the proper functioning of the expander must be ensured. The study of the variation of the Turbo Expander's operating parameters enabled us to determine the optimal parameters for improving liquids recovery, especially considering that no changes to the equipment sizing will be necessary. After optimization, a gain of 19.23 tons/day of LPG and 12.216 tons/day of condensate was achieved.

Key words: Turbo-expander, Joule-Thomson valve, LPG, Condensate.

الملخص:

العنوان : تحسين معلمات التشغيل المتعلقة بالموسع التوربيني لتعزيز استعادة السوائل

المؤطر : عبد المعز أحمد الطالب: قرش إسلام

من بين أهم التجهيزات المخصصة لمعالجة الغاز صمام جول-طومسون والتوربين التمددي، المعروف عادةً باسم التوربو-إكسباندر. تُعد هذه الأجهزة ضرورية لتخفيض ضغط الغاز الخام، وهي خطوة أساسية لفصل الهيدروكربونات الثقيلة. ولتحقيق ضغط ودرجة حرارة منخفضين عند المخرج، يجب ضمان الأداء السليم للتوربين. وقد مكّنتنا دراسة تغير معلمات تشغيل التوربو-إكسباندر من تحديد المعلمات المثلى لتحسين استرجاع السوائل، خاصةً مع الأخذ في الاعتبار أنه لن تكون هناك حاجة لتعديل في أبعاد المعدات. وبعد عملية التحسين، تم تحقيق مكاسب قدرها 19.23 طن/اليوم من الغاز البترولي المسال (GPL) و12.216 طن/اليوم من المكثفات.

الكلمات المفتاحية :الموسع التوربيني، صمام جول-طومسون، الغاز البترولي المسال(GPL) ، المكثفات.

Dedication

What could be more beautiful than sharing the most precious moments of our lives with those we love?

As I reach the end of my academic journey, I am deeply pleased to dedicate this humble work:

To my dear mother, who always fills me with hope and has never ceased to pray for me.
To my beloved father, for his constant encouragement, unwavering support, and above all, for his love and sacrifices to ensure that nothing would hinder my studies.
To my brother and sisters,
To my extended family,
To my dearest friends and all those who shared the school benches with me,
Each by name, and each in their rightful place of honor.

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General Introduction

General Introduction

It is well known that the hydrocarbon sector plays an important role in our country. Today, it serves as a key pillar of economic development due to the revenues it generates. This sector is the sole source of energy supply to the market and represents approximately 97% of the country’s foreign currency income.

Due to its economic and environmental advantages, Liquefied Petroleum Gas (LPG) is one of the most in-demand fuels both locally and globally. Currently, raw gas plays an increasingly important role in the energy sector. The abundance of its reserves and its environmental benefits encourage its use, particularly in high value-added sectors such as precision industries.

Among the most important facilities dedicated to gas processing are the **Joule-Thomson valve** and the **expansion turbine**, commonly known as the **Turbo-expander**. These are essential devices used to reduce the pressure of raw gas, a necessary step for separating heavier hydrocarbons.

The turbo-expander is considered the heart of every gas or oil industry. It plays a vital role in the liquefaction process of LPG. To achieve low pressure and temperature at the outlet, the proper functioning of the expander must be ensured. Given its importance in the production process, a study has been proposed on: **“Optimization of the operating parameters relating to the turbo-expander to enhance Liquids recovery.”**

To this end, the project is divided into two parts: **Theoretical Part**, consisting of one chapter:

▪ Chapter I: General Overview of Natural Gas and Liquefied Petroleum Gas (LPG).

Practical Part, consisting of one chapter; Chapter II: Calculations, Results, and Interpretation.

The study concludes with a general conclusion summarizing the main findings of the research.

Chapter I

Overview of natural gas and Expansion Mechanisms through Turbo-expander and Joule-Thomson Valve

Chapter I: Overview of natural gas and Expansion Mechanisms through Turbo-expander and Joule-Thomson Valve

I-1) Overview of Natural Gas and LPG:

Natural gas is a non-renewable primary energy source that is well-distributed across the world. It is clean and increasingly used. Natural gas has many advantages: relative abundance, flexibility of use, ecological qualities, and competitive prices. The utilization of this energy depends on the technical mastery of the entire gas chain, which includes production, treatment, and transportation.

Natural gas undergoes processing to produce a range of consumable products.

Market requirements demand rigorous treatment to facilitate its transport and distribution. The quality of natural gas is characterized by specific standards, particularly the calorific value, the content of C5+ hydrocarbons, and the water content, in order to obtain "on spec" gas. Thus, raw gas from wells is processed in a chain to remove water, recover heavy hydrocarbon fractions (condensate), and LPG. [1]

I-1-1) Definition:

Natural gas is a fossil energy source, like oil or coal, naturally present in porous rocks in a gaseous form. It is a mixture composed of 70% to 95% methane (CH_4), a significant amount of CO_2 and H_2O, as well as traces of certain metallic elements. It is therefore mainly composed of hydrogen and carbon, hence its classification as a hydrocarbon. [1]

I-1-2) Sources:

Natural gas fills the pores and fractures of sedimentary rocks deep underground and beneath the seabed. The part of a sedimentary formation that contains natural gas is often referred to as a "reservoir," "field," or"deposit.". Natural gas exists throughout the world, either alone or associated with crude oil. It can be trapped in various types of sedimentary rocks, including sandstones, carbonates, coal seams, and layers of shale or "shales." [2]

I-1-3) Natural Gas Characteristics:

- **Density:**
  The density of a gas is the ratio of its mass per unit volume to that of air under specified conditions of temperature and pressure. It can also be obtained from its molecular weight, which can be defined using its chemical composition through the following relation:

$$\boldsymbol{Gas\ density\ =\ Molecular\ weight\ /\ 28.966}$$

- **Heating value:** It represents the amount of heat released during the combustion of a unit volume of gas, measured under reference conditions. It is expressed in [Joules/m³].

There are two types of calorific value:

  - **Higher Heating Value (HHV):** Corresponds to the heat released when all the combustion products (hydrogen or hydrogen products) are brought back to ambient temperature, with the water formed being in liquid state.
  - **Lower Heating Value (LHV):** Corresponds to combustion in which the water remains in vapor form. The LCV differs from the HCV by an amount of heat equal to the latent heat of vaporization of water.

- **Chemical composition:** It is used for vaporization studies. It also serves to calculate certain properties of the gas as a function of pressure and temperature (compressibility, density), and to define the conditions of its processing during exploration (extraction of liquid products). [3]

I-1-4) Different Types of Natural Gas:

The appearance of a liquid phase depends on the temperature and pressure conditions in the reservoir and at the surface, which leads to the distinction of the following types:

- Dry gas: does not form liquid under production conditions.
- Wet gas: forms a liquid phase during production at surface conditions, without retrograde condensation in the reservoir.

- Condensate gas: forms a liquid phase in the reservoir during production through retrograde condensation.
- Associated gas: coexists in the reservoir with an "oil" phase. Associated gas includes both gas cap gas and dissolved gas. [2]

I-1-5) Natural Gas Processing Technique

Natural gas processing consists of at least partially separating certain constituents present at the wellhead, such as water, acid gases, and heavy hydrocarbons, in order to bring the gas to transport or commercial specifications.
Gas treatment processes vary worldwide, and the choice of a particular method is based on the following criteria:

- Quality of the raw effluent
- Recovery rate of the targeted liquid hydrocarbons
- Specifications of the final products
- Total investment cost

Some components of natural gas must be extracted either due to requirements of the subsequent processing or transport steps, or to comply with commercial or regulatory specifications.
It may therefore be necessary to at least partially remove :

- Hydrogen sulfide (H_2S): toxic and corrosive
- Carbon dioxide (CO_2): corrosive
- Mercury: corrodes equipment made of aluminum
- Water: leads to the formation of hydrates
- Heavy hydrocarbons: condense in transport pipelines

The specifications to be met for treated gas are related either to transport conditions or to usage conditions (commercial gas).

In the case of pipeline transport, transport specifications aim to avoid the formation of a liquid phase, pipeline blockage due to hydrates, and excessive corrosion. In this case, a maximum value is imposed on the hydrocarbon dew point, which depends on the transport conditions and can, for example, be set at 0°C to prevent any risk of phase formation by in-line condensation.

In the case of commercial gas, the specifications are more stringent and also include a range within which the calorific value must fall. Typical specifications apply to commercial gas. Associated gas from oil is a mixture (gas + liquid hydrocarbons) containing a high proportion of formation water.

The gas treatment steps are as follows:

A. **Water Removal:** The free water contained in the feed is removed by decantation in separation vessels after cooling. The water that saturates the hydrocarbons is removed by adsorption on molecular sieves.
B. **Liquid Hydrocarbons Extraction:** This is done by progressively lowering the temperature of the associated gas using cooling processes such as:
    - **PRITCHARD Process:** It is based on cooling the gas through heat exchange and expansion, using a propane loop as the refrigerant system and a throttling valve called the Joule-Thomson valve. At the end of the cycle, the temperature approaches -23°C.
    - **HUDSON Process:** It is based on gas cooling through heat exchange and a series of expansions via a Joule-Thomson valve and a dynamic machine called a "Turbo Expander," which allows reaching a temperature level of -40°C.

I-2) Definition of LPG:

Liquefied Petroleum Gas (LPG) is a gaseous mixture composed mainly of butane and propane at ambient temperature and atmospheric pressure, but it can remain in liquid form under relatively low pressures (4–18 bar).

LPG is used as an efficient fuel for vehicles and in various fields such as petrochemicals, electricity production, and air conditioning, etc. [4]

I-2-1) Sources:

Liquefied Petroleum Gases (LPG) are mainly produced:

- In crude oil refineries, during petroleum distillation or during thermal cracking or catalytic reforming of products intended for gasoline production.
- In natural gas (NG) treatment and separation units, which aim to separate and collect condensates (propane, butane, etc...).
- Through the direct recovery of gases separated from crude oil. [4]

I-2-3) Properties of LPG:

Refined LPG is generally almost odorless and extremely flammable. Due to its high volatility, it can form explosive mixtures when in contact with air. To better detect and identify possible leaks, an odor is added using suitable substances (mercaptans). LPG is not truly toxic, although it may have a slight anesthetic effect if inhaled for a long time, potentially causing headaches and stomachaches.

When LPG escapes in liquid form from a pressurized container, it produces cold: upon contact with skin, it causes characteristic burns known as “cold burns.”

- The specific weight of LPG is about half that of water.
- Propane gas has a density 1.5 times that of air.
- LPG is neither toxic nor corrosive to steel.
- LPG does not have lubricating properties, and this must be taken into account when sizing compressors and pumps.

Commercial products vary greatly from one another. Moreover, their vapor pressure, specific weight, and anti-knock properties are highly sensitive to changes in ambient temperature. The Heating value of LPG is practically equal to that of gasoline when expressed in kilocalories per kilogram of fuel. However, these values differ significantly when expressed in kilocalories per liter of liquid fuel at 15°C, due to the difference in density between LPG and gasoline. On average, the density of LPG at 15°C is 0.555 kg/liter.[4]

I-2-4) Extraction of LPG from Natural Gas:

The processes used in LPG extraction units in Algeria are based on the condensation of heavy hydrocarbons (C3+). This condensation is achieved by cooling the raw gas using a specific refrigeration method for each process. In general, the raw gas is cooled by expansion, which results in the production of liquid. The cold gas and liquids obtained provide the necessary refrigeration for pre-cooling the feed gas of the unit before its isenthalpic expansion through the Joule-Thomson valve or isentropic expansion through the turbo-expander (expansion turbine). [4]

I-3) Expansion Mechanisms through Turbo-expander and Joule-Thomson Valve

In the oil and gas industry, gas expansion processes play a critical role in pressure reduction, energy recovery, and cryogenic gas processing. These processes are integral to natural gas liquefaction, gas conditioning, and separation operations, where the controlled reduction of pressure leads to significant thermodynamic and operational benefits. Two commonly employed technologies for gas expansion are the **turbo-expander** and the **Joule-Thomson (JT) valve**.

Turbo-expanders, also known as expansion turbines, enable isentropic expansion of high-pressure gases, converting part of the pressure energy into mechanical work, which can be harnessed for power generation or refrigeration. In contrast, Joule-Thomson valves facilitate a throttling process where gas pressure is reduced through an isenthalpic expansion, leading to a temperature drop without energy recovery.

The selection between these two technologies depends on various factors including process efficiency, capital and operational costs, thermodynamic behavior of the working gas, and the desired end-use—whether it be energy recovery, dew point control, or achieving cryogenic conditions. Understanding the mechanisms and performance characteristics of both expansion methods is essential for optimizing gas processing operations and improving the overall energy efficiency of oil and gas facilities.

I-3-1) Definitions:

- **Expansion:** A thermodynamic transformation in which a system containing a fluid transition from an initial state characterized by an initial pressure to a final state where the pressure is lower than the initial pressure.
    - Fluid expansion allows us to determine its properties.
    - Two historical expansions have played an important role in determining fluid properties and in refrigeration machines: **Joule-Lussac expansion** and **Joule-Kelvin expansion**, also known as **Joule-Thomson expansion**. [5]
- **Entropy:** Physically, entropy represents the degree of disorder in a system. It is a measure of the system's disorder, and the increase in entropy in an isolated system (second law of thermodynamics) reflects the tendency toward a more probable state.

- **Enthalpy:** Enthalpy is a thermal property of fluids that considers the physical state and the temperature and pressure conditions they are subjected to. It allows for solving thermodynamic problems in a relatively simple manner.
- **Internal Energy:** A substance possesses a certain **internal energy** due to the forces exerted between its molecules, atoms, and elementary particles, as well as their translational, rotational, and vibrational movements.
- **State Function:** A quantity whose value is determined as soon as all the state variables are known. In other words, the value of this function depends only on the state of the system at a given moment and not on its history. [6]

I-3-2) Concept of Expansion:

Expansion is the process that enables cooling in a **Liquefied Petroleum Gas (LPG) recovery** system. It can be carried out in two ways: [7]

- **Using a valve** (also known as **Joule-Thomson expansion**).
- **Using a machine** (**Turbo-Expander**).

a) Expansion without Work Production (Joule-Thomson) (J.T):

Joule-Thomson (J.T) expansion occurs through a **narrow orifice**, allowing gas to flow from an initial state **(P_1, T_1)** to a final state **(P_2, T_2)** while being thermally insulated. This process is also referred to as **gas throttling** and involves expansion **without producing external work**.

According to the **First Law of Thermodynamics**, J.T expansion takes place at **constant enthalpy**. For a real gas, this expansion is generally accompanied by a **temperature drop (cooling effect)**. The **schematic diagram** of J.T valve expansion illustrates the fluid evolution in an expansion device (Figure I.1) [8].

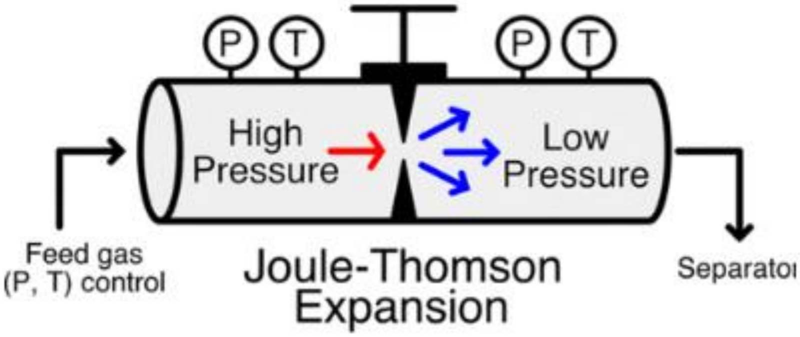

Figure I.1: Expansion through an orifice

b) Expansion with Work Production (Turbo-Expander):

Another type of expansion can occur in an expansion turbine, where the energy of the compressed gas is converted into work.

The expansion is thermally isolated, so the process is adiabatic, and we observe a cooling of the gas.

In the real process, the evolution is obviously irreversible due to friction in the turbine. However, in idealized processes, it is assumed that the evolution is reversible and may be considered as such [8].

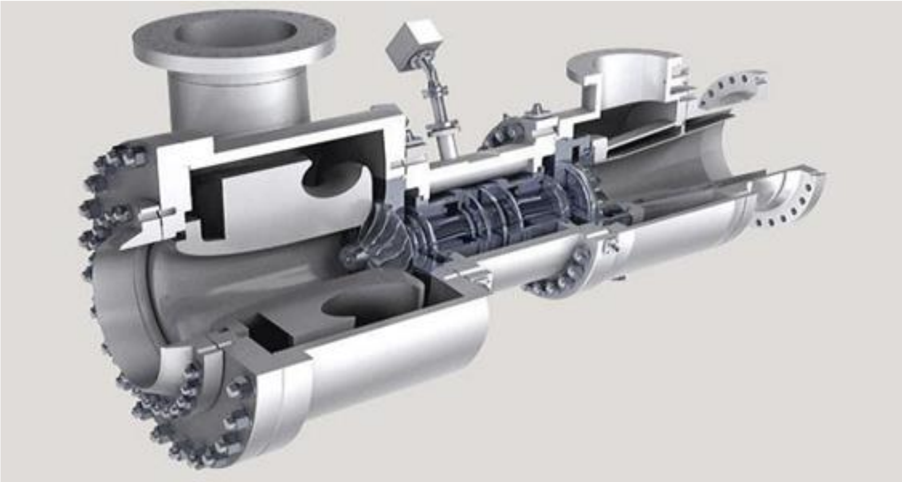

Figure I-2: Turbo expander machine

I-4) Joule-Thomson Valve:

-History:

William Thomson, later known as Lord Kelvin (Belfast, 1824 – Nether Hall, 1907), was a renowned British physicist whose contributions had a lasting influence on science. He entered Cambridge in 1841 and, after completing his studies, continued his academic journey in Paris, working with the physicist Henri Victor Regnault. At just 22 years old, Thomson was appointed as the Chair of Natural Philosophy at the University of Glasgow, where he remained for the duration of his career.

Thomson's early research demonstrated that gases could be cooled using compression-expansion cycles. In 1854, he introduced the absolute temperature scale, now known as the Kelvin scale. Alongside his work in thermodynamics, he developed several important instruments, including the mirror galvanometer, a recording device, and an electrometer—innovations that brought him widespread recognition at the time. Beyond his groundbreaking work in electricity and thermodynamics, he also made notable contributions to mechanics, hydrodynamics, magnetism, and geophysics [9].

Joule-Thomson expansion refers to a steady, laminar, and slow expansion process in which a gas flows through a porous medium—typically cotton or raw silk—within an insulated, horizontal pipeline. A pressure difference exists across the medium, driving the flow. This type of expansion is inherently isenthalpic, meaning it occurs at constant enthalpy.

If a gas undergoes Joule-Thomson expansion without any change in temperature, it is said to obey Joule's second law—a behavior characteristic of ideal gases. In contrast, real gases usually experience a temperature change during this process, a phenomenon known as the **Joule-Thomson effect** [9].

I-4-1) Joule Thomson Effect:

The Joule-Thomson effect describes the increase or decrease in the temperature of a real gas or a liquid when it is allowed to expand freely through a valve or other throttling device in an insulated area. The device was kept insulated so that no mechanical work is extracted from the liquid [10]. This Joule-Thomson effect is an example of an isenthalpic process where the enthalpy of the fluid is kept constant. This effect was named after James Prescott Joule and William Thomson during 1852. These effects sometimes referred as the Joule-Kelvin effect in engineering field. For this effect to occur there should be temperature change when gas is allowed through an insulated device but the behaviour of an ideal gas oppose the JouleThomson effect [10].

I-5) Turbo-expander :

I-5-1) Definition:

A **turboexpander** is a rotating device equipped with an expansion turbine that converts the energy of a high-pressure gas into mechanical work, similar in principle to a steam or gas turbine. In typical turbines, this mechanical work is harnessed to generate power either by driving an electric generator or operating another rotating machine such as a compressor or high-capacity pump.

However, in applications involving gas refrigeration, the primary purpose of a turboexpander is to cool the gas stream through expansion, with mechanical work produced as a secondary effect. That said, this byproduct is far from wasted—most turboexpanders are coupled with compressors or generators that utilize this energy. In such configurations, the attached device acts as a load or brake, effectively serving as an energy sink for the expander.

This type of machine is sometimes referred to as a **"compandor"**, though that term is less commonly used in the natural gas processing industry.

I-5-2) Main Characteristics of a Turbo Expander

The main characteristics of a Turbo-Expander are [11]:

- Reaction turbine (radial admission, axial exhaust);

- Energy recovery typically achieved in a single expansion stage;
- Wide power range for oil industry applications from 50 to 8000 kW;
- Good isentropic efficiency: 80 to 86%;
- Maintenance of efficiency under variable load through the use of adjustable guide blades at the intake (possibility of load variation from 50 to 120% of nominal flow rate);
- Good tolerance to the presence of condensate and solid particles;
- Energy recovery favored by low intake temperatures. [12]

I-5-3) Role of a turbo-expander:

Natural gas treatment processes are often classified based on the refrigeration techniques they employ. Key methods include:

- The Joule-Thomson (J-T) valve
- The propane refrigeration loop
- The turboexpander system

Among these, the **turbo-expander** is widely used due to its high efficiency in achieving the extremely low temperatures required for the effective recovery of heavier hydrocarbons.

The turbo-expander operates by extracting energy from high-pressure gas as it undergoes **isentropic expansion** through a turbine, resulting in a significant pressure and temperature drop. This temperature reduction is more substantial than that achieved through the Joule-Thomson effect, enabling greater condensation and liquid recovery (PRCV 108).

The mechanical energy produced during expansion is typically used to drive a compressor, which increases the pressure of the processed gas before it is delivered as saleable product [11].

I-5-4) Description of main parts and their functions:

The **Turbo-Expander**, developed by **MAFI-TRENCH Corporation**, is mounted on a chassis and equipped with its own dedicated lubrication system and sealing gas supply. The gas to be processed flows through the expander and compressor casing, whose precisely engineered geometry governs the gas flow regime, ensuring efficient, pressure-loss-free circulation toward the turbine blades.

The system is designed with ease of operation and maintenance in mind, with its components organized into three main sections:

- The **turbine section**, featuring intake and exhaust flanges
- 18The **central section**, housing the rotor
- The **compressor section**, also with intake and exhaust flanges

The design of this assembly demands extremely tight operating tolerances and the use of high-quality materials to withstand the rigorous service conditions, including high rotational speeds and elevated temperatures [11].

a) Expansion Wheel (Expander)

The **expander wheels** are precision-machined from solid, heat-treated billets of aluminum, titanium, or stainless steel, utilizing advanced five-axis computer-aided manufacturing (CAM) technology to ensure high accuracy and performance.

This high-speed expansion turbine operates at a rotational speed of **10,000 rpm**. Its blades feature a distinctive **V-shaped mechanical design**, optimized to disrupt the gas flow, effectively reducing both pressure and temperature during expansion.

The turbine operates under the following input conditions: **pressure = 95 kg/cm²** and **temperature = –11°C**, while the output conditions are **pressure = 67.3 kg/cm²** and **temperature = –31°C**, resulting in a pressure drop of approximately **32 kg/cm²** [11].

Figure I-3: Expansion Wheel

b) Compressor Wheel:

The **compressor wheel** captures the kinetic energy generated by the expander wheel and converts it into mechanical energy to drive a **single-stage centrifugal compressor**. This process compresses the remaining light hydrocarbons (primarily methane and ethane, C_1 and C_2) from **67 to 72.1 kg/cm²**, preparing the gas for further processing—either **reinjection into the reservoir** or **delivery to the sales network**.

Known for their broad operating range and exceptional efficiency, compressor wheels are fabricated from high-strength materials such as **aluminum, titanium, or stainless steel**. Each wheel undergoes rigorous testing to ensure **vibration resistance**, particularly at the **blade and disk resonance frequencies**, ensuring reliable operation under demanding conditions[11].

Figure I-4: Compressor Wheel

c) Rotation Transmission System (Shaft):

The **shaft** serves as the central structural component, supporting all mechanical elements, including the **expander and compressor wheels**, **lubrication bearings**, and **mechanical seals** (such as labyrinth seals). It also acts as the critical link between both ends of the machine.

Constructed as a **single-piece rigid shaft**, it employs a proprietary wheel attachment system that guarantees a secure fit, precise balance, and efficient torque transmission across the full spectrum of **operating speeds, power levels, pressures, and temperatures**.

Figure I-5: Rotation Transmission System

d) Bearings:

To support the drive shaft and manage axial thrust, the **MTC turbo-expander** is equipped with two specialized types of bearings:

- **Radial Bearings:** The machine uses **oscillating pad radial bearings**, specifically five-pad, load-on-pad, non-adjustable designs. These are well-suited for the high rotational speeds required in this application, providing stable and efficient shaft support.
- **Thrust Bearings:** These bearings are essential for maintaining the **axial alignment** of the turbine rotor within precise tolerances. The MTC design features **threaded heel-type thrust bearings**, which are integrally machined into each journal bearing. They are engineered to handle axial loads in both directions with equal capacity.

Axial thrust is continuously monitored using pressure detection probes positioned beside each bearing. The data collected from these sensors is sent to an **automatic thrust equalizer**, which dynamically adjusts the axial load to maintain system stability.

Figure I-6: Bearings

e) Variable Inlet Guide Vanes (IGVs):

IGVs function by converting gas pressure into velocity, aligning the gas flow with the peripheral speed of the expander wheel. This design allows the overall pressure drop to be distributed between the IGVs and the expander wheel, optimizing both **temperature reduction** and **power recovery**.

The adjustable geometry of the IGVs, controlled externally, enables them to act as a **control valve**, allowing the system to adapt to varying flow rates and inlet conditions. By eliminating the need for an upstream throttle valve, the turboexpander can fully utilize the available pressure to generate **maximum power output** and achieve **the lowest possible temperatures**.

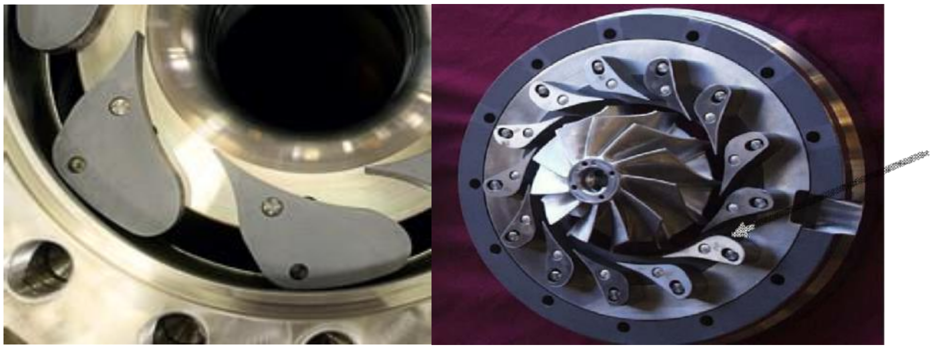

Figure I-7: Inlet Guide Vanes (IGVs)

f) Sealing Options:

Expander compressors are typically **hermetically sealed** and utilize **labyrinth seals**, as their design eliminates shaft ends extending through the pressure boundary, effectively preventing gas leakage.

In contrast, **expander generators** often require **mechanical seals** to prevent process gas from entering the bearing housing. Without these seals, the gas could contaminate the **lubricating oil** or interfere with **magnetic bearing systems**, potentially compromising performance and reliability.

Figure I-8: Sealing system

g) Sealing Gas System

The Turbo-Expander receives sealing gas primarily from the compressor's discharge gas during normal machine operation. Alternatively, sealing gas can be supplied from the dry gas available in the shared network of the three trains. This secondary source is intended to maintain the required sealing gas pressure within the system and is particularly useful during startup.

During startup, sealing gas surrounds the shaft, which is isolated by a labyrinth seal positioned between the bearings, the thrust bearing, and the rear sides of the compressor and turbine wheels. Since the turbine exhaust pressure is higher than the compressor inlet pressure, the pressure behind the turbine wheel is utilized to regulate the sealing gas injection pressure.

Sealing gas is introduced at the labyrinth seals, where it diffuses toward both the backs of the compressor and turbine wheels and the bearings, serving two key functions [7]:

- Acting as a thermal barrier to protect the bearings
- Preventing oil from migrating into the colder sections of the machine

h) Lubrication System

Bearings and thrust bearings require a continuous and adequate supply of oil to operate efficiently. The oil flow must be sufficient to dissipate the heat generated by friction within the oil films, as well as the heat conducted from the gas through the shaft to the bearings and thrust bearings. An acceptable temperature increase in the oil as it passes through these components typically ranges between 10°C and 20°C.

If the temperature rise becomes excessive, the oil's viscosity decreases, compromising its mechanical properties and preventing the formation of effective oil films [13].

Before any work on the Turbo Expander, the following steps must be taken [11]:

- Isolate the energy source,
- Close the inlet valves,
- Completely drain the Turbo Expander and its auxiliaries,
- Isolate the inlet and outlet of the Turbo Expander using blanking joints,
- Seal the openings leading to the inside of the machine and pipes to prevent sand from entering.

I-5- 5) Turbo-expander compression trains:

Turbo-expander compression trains are commonly used in petrochemical processes for extracting the heavier hydrocarbons from natural gas. These heavier hydrocarbon gases include but are not limited to ethane, propane, butane and pentane and are commonly called natural gas liquids or NGL. Figure I-1 below shows a typical gas processing plant design. In this example, the expander is used to cool the process gas stream before entering a Separator drum where it is used as inlet for the compressor. Gas from the top of the separator drum is routed through a cold box before being compressed by the compressor portion of the turbo-expander compression train.

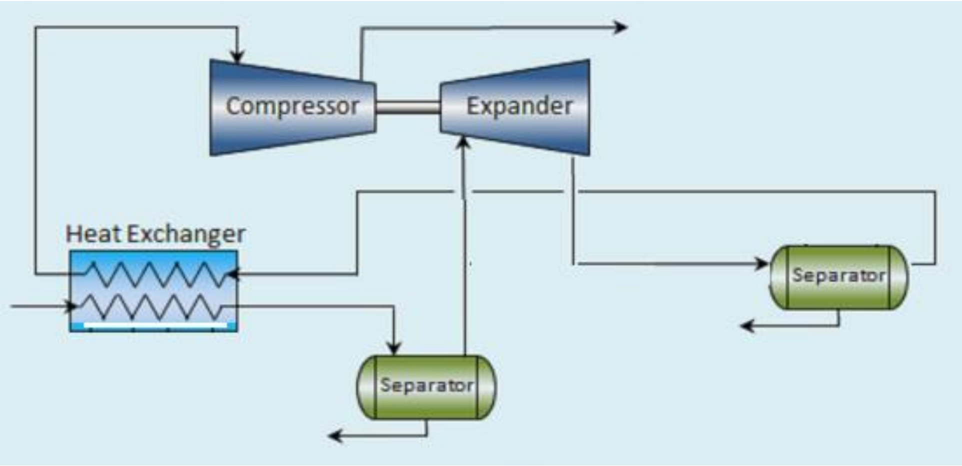

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Figure I-9: Typical gas processing plant design

The turbo-expander and recompressor parts of the unit operate on the same shaft. A J-T (Joule-Thompson) valve is used to bypass flow around the turbo-expander when the expander is offline or is unable to meet the flow demands of the process. The J-T valve is also used for startup of the train. The recompressor uses a recycle valve for anti-surge protection as well as startup and shutdown of the unit. There is a bypass line around the recompressor to divert flow when the turbo-expander train is offline and the process is operating in J-T mode. See Figure I-2 below.

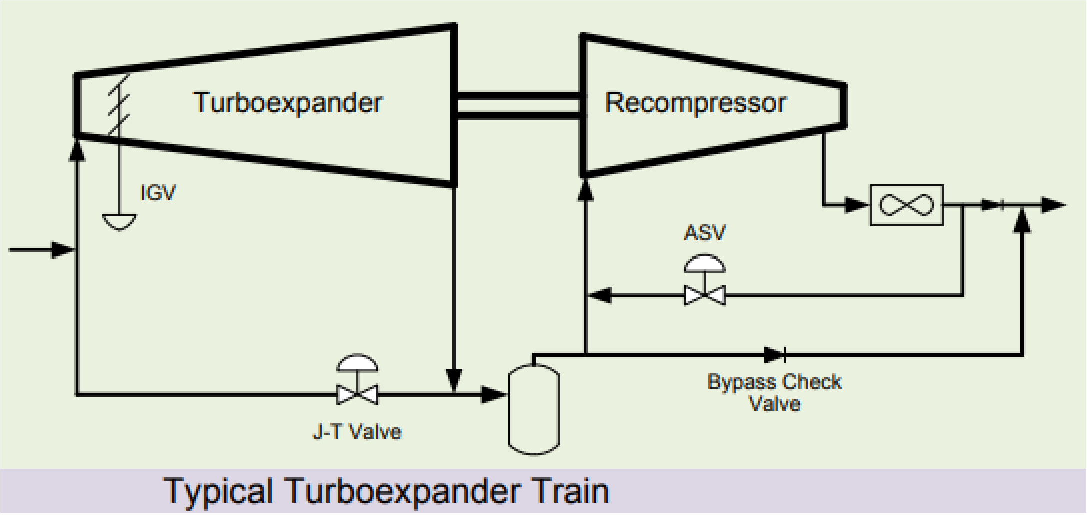


Figure I-10: Typical Turbo-expander train

Production is controlled by manipulating the expander guide vanes. Typically this is done by maintaining a constant pressure at the separator drum, however, other parts of the process such as the inlet separator pressure or recompressor discharge pressure may be controlled as well.

I-5-6) Comparative Analysis of Expander and J-T Valve in liquids Production:

By partially closing the expander's guide vanes, the torque output from the expander is reduced. In contrast, the compressor maintains a relatively constant torque. For most compressors, an increase in flow rate corresponds to a higher power demand. Since opening the recycle valve increases the flow through the compressor, it can be used to adjust the rotational speed of the turbo-expander-compressor train.

Initially, the speed of the train can be reduced by opening the recompressor's recycle valve. This increases the compressor's torque while the expander's torque remains unchanged, resulting in a net deceleration of the train. Using the recompressor recycle valve as the first control point allows the expander guide vanes to remain more open, which enhances condensate recovery.

The increase in condensate production is attributed to the isentropic expansion of gas in the expander, a work-producing process, in contrast to the isenthalpic expansion across a Joule-Thomson (J-T) valve. Isentropic expansion results in a greater drop in both pressure and temperature compared to the J-T valve, leading to more efficient gas cooling and increased condensate formation.

Figure I-3 illustrates the difference: the expander follows an isentropic path from point 1 to point 2, while the J-T valve expansion follows a nearly vertical, constant-enthalpy path from point 1 to point 3.

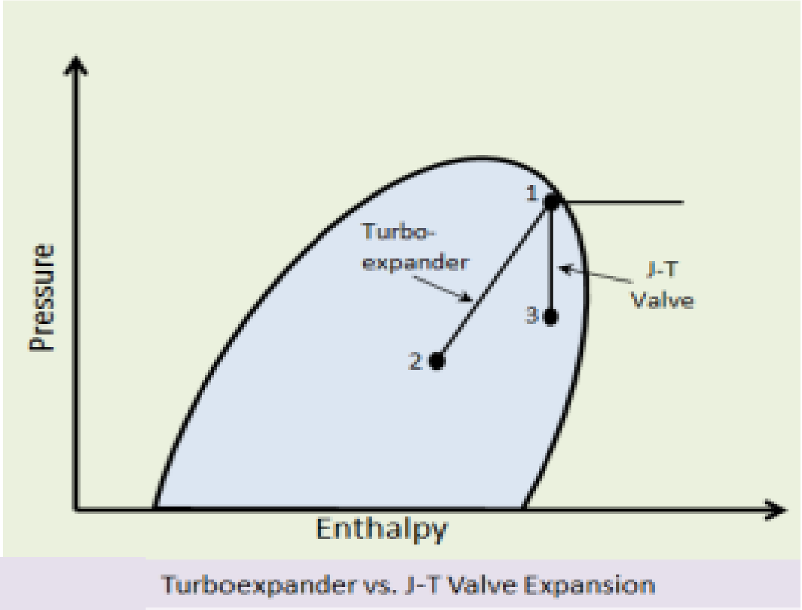


Figure I-11: Turbo-expander versus Joule Thomson expansion

I-6) Enthalpy of a Mixture of Vapor or Liquid:

The enthalpy of a mixture of vapor or liquid at a given temperature and pressure is determined using the following formula:

$$Hm = Hm^0 - (Hm^0 - Hm)$$

With $H_m^0 = \sum y_i H_i^0$

And $(H_m^0 - H_m) = RT_c[(\frac{(H^0-H)}{RT_c})^0 + W_m(\frac{(H^0-H)}{RT_c})^1]$

H_i^0: The enthalpy of a pure component *i* depends on temperature.

Y_i : Molar function of each component *i* in the mixture.

R: gas constant.

W_m: acentric factor of a mixture: $W_m = \sum y_i W_i$

W_i: acentric factor of a pure component *i.*

$(\frac{(H^0-H)}{RT_c})^0$: The effect of pressure on the enthalpy of a simple fluid.

$(\frac{(H^0-H)}{RT_c})^1$: The effect of pressure on the enthalpy of a real fluid.

These last two parameters are determined graphically as a function of the reduced pressure Pr and the reduced temperature Tr of the mixture.
With: Pc and Tc are the critical pressure and temperature of the mixture. W_m is the acentric factor of the mixture.

$$W_m = \sum y_i W_i$$

W_i: the acentric factor of a pure component i

Pr: reduced pressure of the mixture. $Pr = P/P_c$

Pc: critical pressure of the mixture.

Tr: critical temperature of the mixture. $Tr = T/T_c$

Tc: reduced temperature of the mixture.

I-7) Entropy of a Mixture of Vapor or Liquid

The entropy of a mixture of vapor or liquid at a given temperature and pressure is given by the following formula:

$$S_{mix} = S_{mix}^0 - (S^0 - S)_{mix}$$

With:

$$(S^0 - S)_{mix} = R\left(\frac{(S^0 - S)}{R}\right)^0 + W_{mix} + R\left(\frac{(S^0 - S)}{R}\right)^1 + \ln P$$

And $S_m^0 = \sum y_i S_i^0 - R \sum Y_i \ln y_i$

With:

S_i^0: The enthalpy of a pure component i depends on temperature.

y_i: mole fraction of each component i in the mixture.

P: service's pressure

$\left(\frac{(S^0-S)}{R}\right)^0$: the effect of pressure on the enthalpy of a simple fluid.

$\left(\frac{(S^0-S)}{R}\right)^1$: the effect of pressure on the enthalpy of a real fluid.

These last two parameters are determined graphically as a function of the reduced pressure Pr and the reduced temperature Tr of the mixture.

The volumetric and thermodynamic properties of non-polar substances are listed in tables, where the reduced temperature ranges from 0.8 to 4, and the reduced pressure ranges from 0 to 9. This correlation cannot be used in the critical region, for low-temperature liquids.
Lee and Kesler [9] modified the Curl - Pitzer equation to extend the temperature range to $0.3 \leq Tr \leq 0.4$ and the pressure range to $0 \leq Pr \leq 10$. This correlation is more efficient and useful compared to the Curl - Pitzer law for calculations close to the critical region or at low temperatures.

I-8) Enthalpy of a Total Vapor or Liquid:

The enthalpy of a mixture of vapor or liquid at a given temperature and pressure is determined using the following formula:

$$H_{mt} = Lh_l + Vh_v$$

With:

L: liquid phase in the mixture.

V: vapor phase in the mixture.

h_l: liquid enthalpy.

h_v: Vapor enthalpy.

H_{mt}: Total enthalpy of the mixture.

I-9) Entropy of a Total Vapor or Liquid

Similarly, the total entropy of a mixture is given by the following formula:

$$\mathrm{S_{mt} = LS_l + VS_v}$$

With:

L: liquid phase in the mixture.

V: vapor phase in the mixture.

S_v: Vapor entropy.

S_l: Liquid entropy.

S_{mt}: Total entropy of the mixture.

Conclusion

In a throttling process (control valve, nozzle, or orifice), the overall process is isenthalpic. However, the isentropic process occurs over a short period of time. Nevertheless, even though the isentropic process takes place over a short period, it should not be ignored. The isentropic process leads to a decrease in the temperature of the fluid.

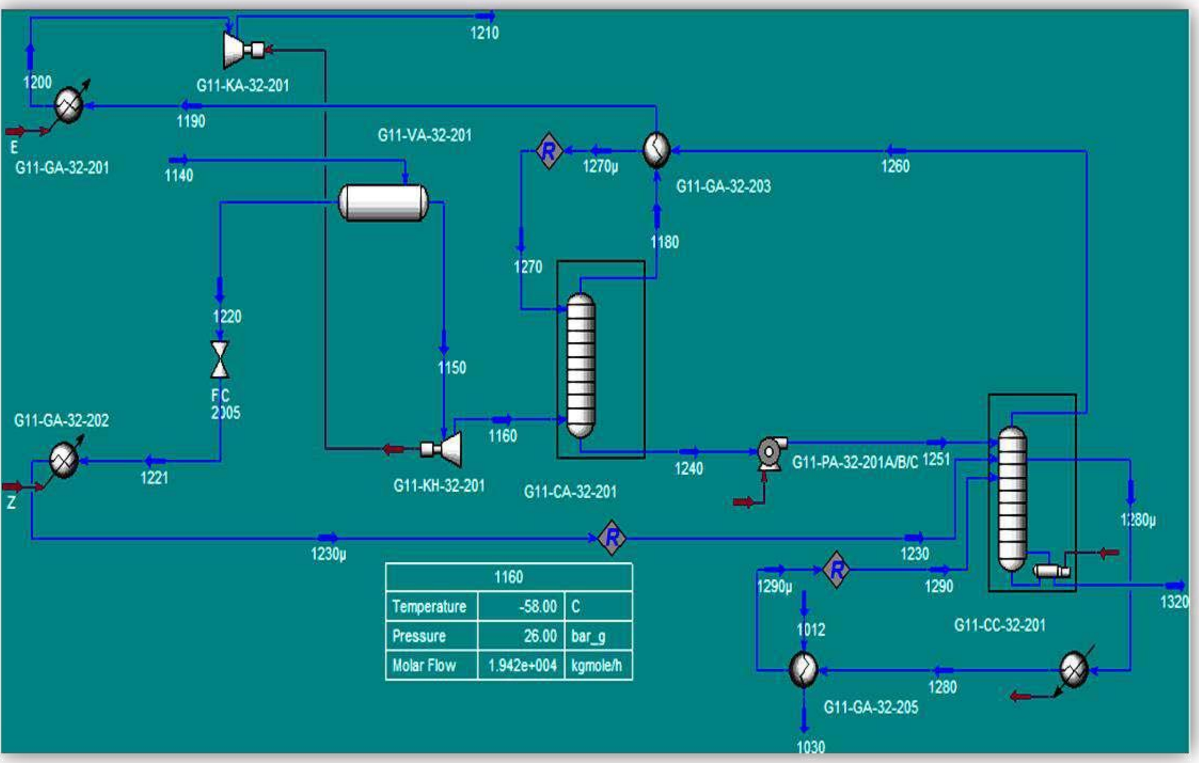
Chapter II

Calculations, Results, and Interpretation

II. Calculations, Results, and Interpretation

This chapter presents an application of the efficiency study of turbo-expender, with the objective of estimating the optimal recovery of LPG and condensate. To achieve this, we based our analysis on the operating conditions (feed flow rate, variation in inlet temperature and pressure) provided by the manufacturer ATLAS COPCO.

in (CPF) unit G11 (Raw gas processing and LPG recovery zone) of gassi touil.



1160		
Temperature	-58.00	C
Pressure	26.00	bar_g
Molar Flow	1.942e+004	kgmole/h

Figure II-1 shows the convergence of the simulation of a Turbo-Expander (Unit G11).

II.1 Operating Data

To perform our calculations, we gathered the operating data and established a few assumptions, as indicated below (see Table II-1):

- The plant operates under **steady-state conditions**.
- The gas exiting the separator vessel is **expanded isentropically** through the **Turbo-Expander**.

As for the operating data, they are specified as follows:

Table II-1 Operating Data

	Parameters	Values
Turbo-expander in duty	Inlet Pressure G11-CA-32-201 (bars)	26
	Efficiency (%)	83
	Inlet Pressure TE (bars)	65,7
	Inlet Temperature TE (°C)	-19,7
Turbo-expander off	Inlet Pressure G11-CA-32-201 (bars)	32

The chromatographic analysis of the gas leaving separator vessel G11-VA-32-201 provided the following composition:

Table II-2: Molar Composition of the Gas Mixture at the Inlet of the Turbo-Expander (TE)

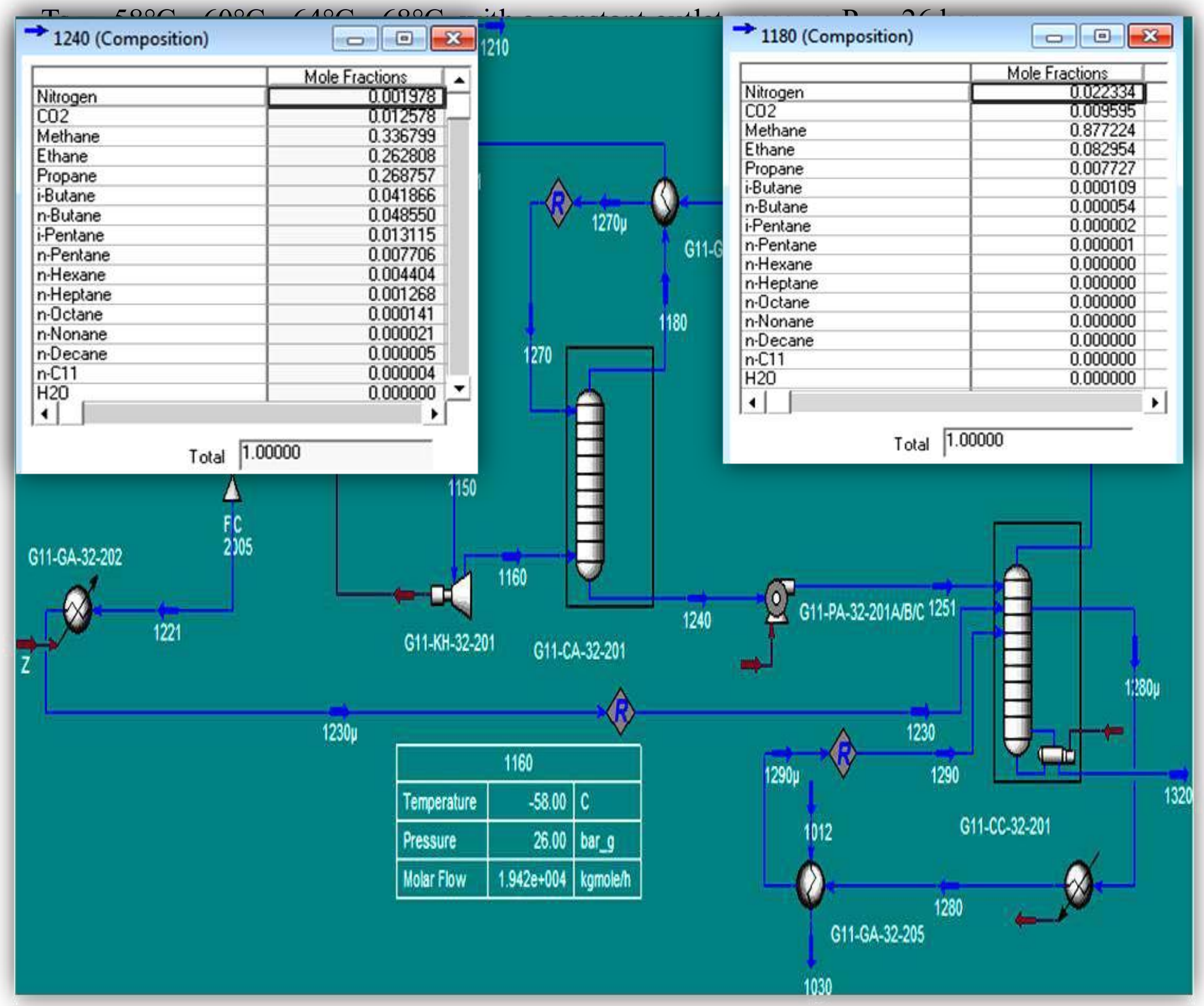
Components	**Molar fraction**
N_2	**0,0225**
CO_2	**0,0090**
CH_4	**0,8630**
C_2H_6	**0,0730**
C_3H_8	**0,0222**
iC_4H_{10}	**0,0036**
nC_4H_{10}	**0,0042**
iC_5H_{12}	**0,0012**
nC_5H_{12}	**0,0007**
nC_6H_{14}	**0,0004**
nC_7^+	**0,0001**
TOTAL	**1**

II.2 Turbo-Expander

II.2.1 Composition at the Turbo-Expander Outlet

Given the high number of iterations required to perform a single flash calculation—and considering the multiple flash calculations needed—we used the **HYSIM/HYSYS** software by **Hyprotech** to carry out flash calculations at various outlet temperatures:

T 58°C 60°C 64°C 68°C with a constant outlet pressure P 26 bar



1240 (Composition)

	Mole Fractions
Nitrogen	0.001978
CO2	0.012578
Methane	0.336799
Ethane	0.262808
Propane	0.268757
i-Butane	0.041866
n-Butane	0.048550
i-Pentane	0.013115
n-Pentane	0.007706
n-Hexane	0.004404
n-Heptane	0.001268
n-Octane	0.000141
n-Nonane	0.000021
n-Decane	0.000005
n-C11	0.000004
H2O	0.000000

Total 1.00000

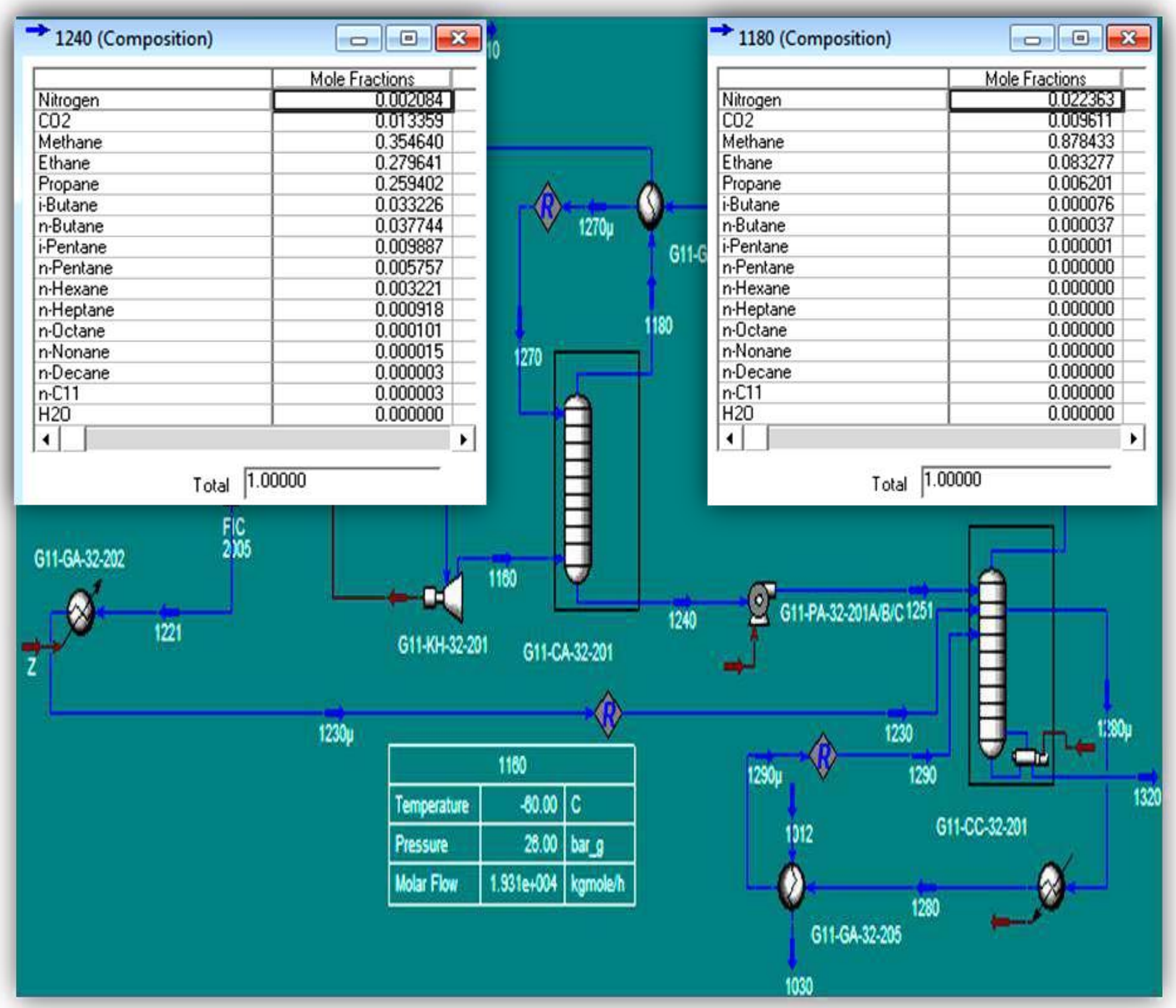
1180 (Composition)

	Mole Fractions
Nitrogen	0.022334
CO2	0.009595
Methane	0.877224
Ethane	0.082954
Propane	0.007727
i-Butane	0.000109
n-Butane	0.000054
i-Pentane	0.000002
n-Pentane	0.000001
n-Hexane	0.000000
n-Heptane	0.000000
n-Octane	0.000000
n-Nonane	0.000000
n-Decane	0.000000
n-C11	0.000000
H2O	0.000000

Total 1.00000

1160		
Temperature	-58.00	C
Pressure	26.00	bar_g
Molar Flow	1.942e+004	kgmole/h

Figure II-2 The convergence of the Turbo-Expander simulation used to calculate the outlet composition at **T_0 = -58 °C**.



1240 (Composition)

	Mole Fractions
Nitrogen	0.002084
CO2	0.013359
Methane	0.354640
Ethane	0.279641
Propane	0.259402
i-Butane	0.033226
n-Butane	0.037744
i-Pentane	0.009887
n-Pentane	0.005757
n-Hexane	0.003221
n-Heptane	0.000918
n-Octane	0.000101
n-Nonane	0.000015
n-Decane	0.000003
n-C11	0.000003
H2O	0.000000

Total 1.00000

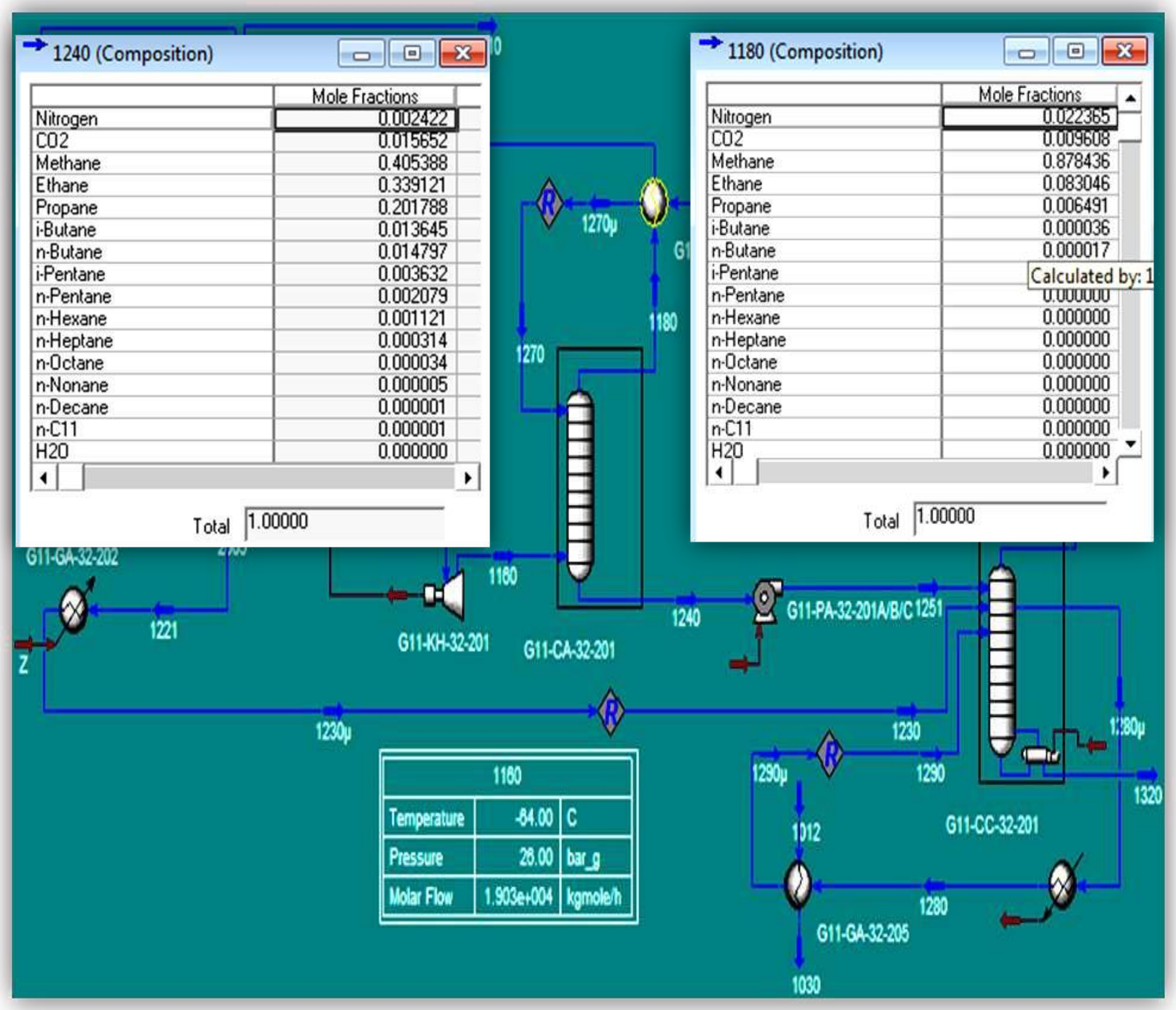
1180 (Composition)

	Mole Fractions
Nitrogen	0.022363
CO2	0.009611
Methane	0.878433
Ethane	0.083277
Propane	0.006201
i-Butane	0.000076
n-Butane	0.000037
i-Pentane	0.000001
n-Pentane	0.000000
n-Hexane	0.000000
n-Heptane	0.000000
n-Octane	0.000000
n-Nonane	0.000000
n-Decane	0.000000
n-C11	0.000000
H2O	0.000000

Total 1.00000

1160		
Temperature	-60.00	C
Pressure	28.00	bar_g
Molar Flow	1.931e+004	kgmole/h

Figure II-3 shows the convergence of the Turbo-Expander simulation used to calculate the outlet composition at **T_o = -60 °C**.



1240 (Composition)

	Mole Fractions
Nitrogen	0.002422
CO2	0.015652
Methane	0.405388
Ethane	0.339121
Propane	0.201788
i-Butane	0.013645
n-Butane	0.014797
i-Pentane	0.003632
n-Pentane	0.002079
n-Hexane	0.001121
n-Heptane	0.000314
n-Octane	0.000034
n-Nonane	0.000005
n-Decane	0.000001
n-C11	0.000001
H2O	0.000000

Total 1.00000

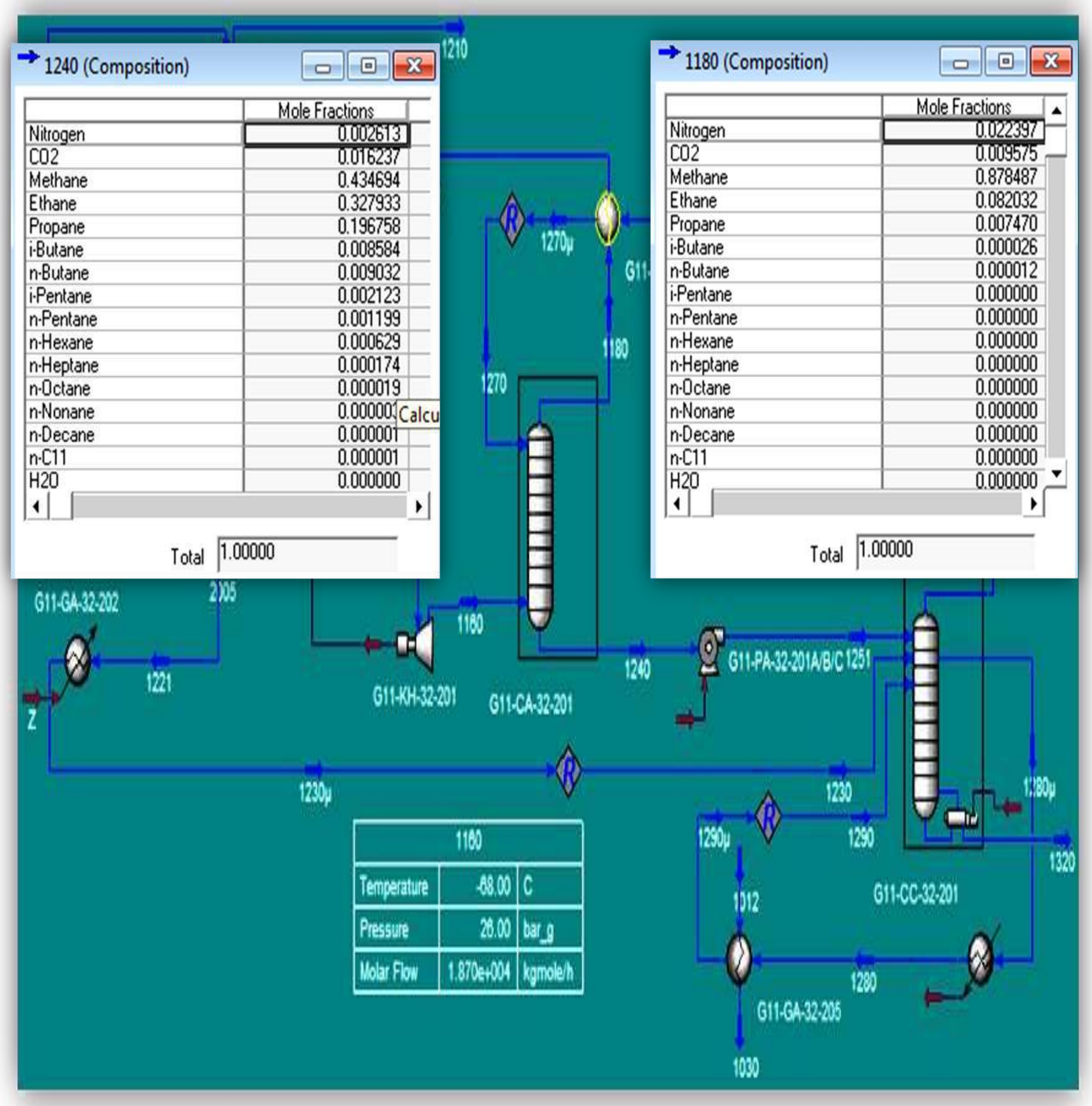
1180 (Composition)

	Mole Fractions
Nitrogen	0.022365
CO2	0.009608
Methane	0.878436
Ethane	0.083046
Propane	0.006491
i-Butane	0.000036
n-Butane	0.000017
i-Pentane	Calculated by: 1
n-Pentane	0.000000
n-Hexane	0.000000
n-Heptane	0.000000
n-Octane	0.000000
n-Nonane	0.000000
n-Decane	0.000000
n-C11	0.000000
H2O	0.000000

Total 1.00000

1180		
Temperature	-64.00	C
Pressure	26.00	bar_g
Molar Flow	1.903e+004	kgmole/h

Figure II-4 shows the convergence of the Turbo-Expander simulation used to calculate the outlet composition at **T_0 = -64 °C**.



1240 (Composition)

	Mole Fractions
Nitrogen	0.002613
CO2	0.016237
Methane	0.434694
Ethane	0.327933
Propane	0.196758
i-Butane	0.008584
n-Butane	0.009032
i-Pentane	0.002123
n-Pentane	0.001199
n-Hexane	0.000629
n-Heptane	0.000174
n-Octane	0.000019
n-Nonane	0.00000
n-Decane	0.000001
n-C11	0.000001
H2O	0.000000

Total 1.00000

1180 (Composition)

	Mole Fractions
Nitrogen	0.022397
CO2	0.009575
Methane	0.878487
Ethane	0.082032
Propane	0.007470
i-Butane	0.000026
n-Butane	0.000012
i-Pentane	0.000000
n-Pentane	0.000000
n-Hexane	0.000000
n-Heptane	0.000000
n-Octane	0.000000
n-Nonane	0.000000
n-Decane	0.000000
n-C11	0.000000
H2O	0.000000

Total 1.00000

1160		
Temperature	-68.00	C
Pressure	26.00	bar_g
Molar Flow	1.870e+004	kgmole/h

Figure II-5 shows the convergence of the Turbo-Expander simulation used to calculate the outlet composition at **T_o= -68 °C**.

The liquid and vapor compositions obtained are presented in the following table.

Table II-3: Calculated Composition of the Vapor-Liquid Mixture.

Compon-ents	Gas inlet Xi G11-VA-32-201	T= -58°C Xi		T= -60°C Xi		T= -64°C Xi		T= -68°C Xi	
		Vap	Liq	Vap	Liq	Vap	Liq	Vap	Liq
N	0,0225	0,0223	0,0020	0,0223	0,0020	0,0223	0,0024	0,0223	0,0026
CO2	0,0090	0,0096	0,0126	0,0096	0,0133	0,0096	0,0156	0,0095	0,0162
CH4	0,8630	0,8772	0,3368	0,8784	0,3546	0 ,8785	0,40538	0 ,8784	0,43469
C2H6	0,0730	0,0829	0,2628	0,0832	0,2796	0,0830	0,3391	0,0820	0,3279
C3H8	0,0222	0,0077	0,2687	0,0062	0,2594	0,0064	0,20188	0,0074	0,1967
iC4H10	0,0036	0,0001	0,0418	0,0000	0,0332	0,0000	0,01364	0,0000	0,0085
nC4H10	0,0042	0,0000	0,04850	0,0000	0,03774	0,0000	0,01479	0,0000	0,0090
iC5H12	0,0012	0,0000	0,0131	0,0000	0,0179	0,0000	0,0036	0,0000	0,0021
nC5H12	0,0007	0,0000	0,0070	0,0000	0,0098	0,0000	0,02000	0,0000	0,0011
nC6H14	0,0004	0,0000	0,0044	0,0000	0,0057	0,0000	0,0011	0,0000	0,0006
$nC7^{+}$	0,0001	0,0000	0,0012	0,0000	0,0032	0,0000	0,0003	0,0000	0,0001
Mw	18.70	17 ,97	33 ,05	17 ,93	31 ,82	17.93	28,55	17,94	27,64

II.3 Entropy and Enthalpy Calculation at the Turbo-Expander Inlet at T = -19.7°C

II.3.1 Example of Entropy Calculation at the Turbo-Expander Inlet

The data in the following table represent the necessary values for the calculation of the mixture entropy (at T = -19.7 °C, P = 65.7 bar) at the inlet of the Turbo-Expander. These were determined from charts (see annex).

Table II-4: Entropies at the Inlet of the Turbo-Expander (T = -19.7°C, P = 65.7 bar).

Compon-ents.	Mw	Xi mol	Entropy S° at – 19.7°c		Critical Temp (K)	Critical Pressure Pc (atm)	Acentric factor (ω)
			kj/kg K	kj/kmole K			
N_2	28.00	0.0225	2.95	82.6	126.2	33.5	0.0400
CO_2	44.01	0.009	0.30	13.20	304.2	72.9	0.2667
CH_4	16.04	0.8630	4.33	69.45	191.1	45.8	0.0108
C_2H_6	30.07	0.0730	2.50	75.18	305.5	48.2	0.0972
C_3H_8	44.09	0.0222	2.20	97.00	370	42	0.1515
iC_4H_{10}	58.12	0.0036	1.55	90.09	408.1	36	0.1852
nC_4H_10	58.12	0.0042	1.30	75.56	425.2	37.5	0.1981
iC_5H_{12}	72.15	0.0012	1.63	117.60	461	32.9	0.2286
nC_5H_{12}	72.15	0.0007	1.03	74.31	469.8	33.3	0.2510
nC_6H_14	86.18	0.0004	1.23	106	507.9	29.9	0.298
nC_7^+	100.2	0.0001	1.52	152.3	540.2	27	0.349

II.3.1 Entropy of Mixture at (P_1, T_1)

The entropy of the mixture at (P_1, T_1) is given by the following relation [14]:

$$S_{1_{mix}}(P_1, T_1) = S^o_{mix} - (S^o - S)_{mix}$$

Where:

- S: Entropy of the mixture at the given conditions.

The following equation allows the calculation of:

$$S^o_{mix} = \sum X_i S^o_i - R \sum X_i ln X_i$$

Where:

- R: Ideal gas constant = 8.314566 kJ/K·kmol
- X_i: Mole fraction of component i
- S^o_i: Standard entropy of component i

Pitzer's equation is used to calculate:

$$(S^o - S)_{mix} = R[(S^o - S / R)^o + \omega_{mix}(S^o - S / R)^1 + lnP]$$

Where:

- $\omega_{mix} = \sum X_i \omega_i$

ω_i: Acentric (Pitzer) factor of each component (from Table II.4)

The quantities $(S^o - S / R)^o$and $(S^o - S / R)^1$ are obtained graphically from entropy charts as a function of the reduced pressure P_r and reduced temperature T_r (see annex).

The pseudo-critical temperature T_{pc} , from Kay's rule, is given by:

$$T_r = T / T_{pc} \ , \ T_{pc} = \Sigma X_i T_{ci}$$

Where:

- T: Operating temperature in K

- T_{ci}: Critical temperature of component i in K
- T_r : Reduced temperature

Similarly, the reduced pressure is:

$$P_r \;=\; P \,/\, P_{pc} \;\;,\;\; P_{pc} = \Sigma X_i \, P_{ci}$$

Where:

- P: Operating pressure in atm
- P_{ci}: Critical pressure of component i in atm
- P_r: Reduced pressure

For equation (2), the following values must first be calculated:

$\Sigma X_i \, S_i \;=\; 70.44 \, Kj/Kmol.°K$ and $\Sigma \, X_i ln X_i \;=\; -0.5909$

Hence, (2)

$$S^o_{mix} \;=\; 70.44 - [(-0.5909) \,*\, 8.314566] \;=\; 75.35 \, kJ/Kmol \cdot K$$

To determine $(S° \,-\, S)mix$, it is necessary to calculate:

$$T_{pc} \;=\; \Sigma Xi.Tci \text{ and } P_{pc} = \Sigma X_i.P_{ci}$$

The calculation gives:

For $T_{pc} \;=\; 205.374 \, K$ and $P_{pc} = \; 45.75 \, atm$

Given the values:

$$P1 = \; 65.7 \, bar \;=\; 64.85 \, atm$$

$$T1 \;=\; -19.7 \, °C \;=\; 253.45 \, °K$$

$$Mw \;=\; 18.68 \, Kg/Kmol$$

We can determine:

$$T_r = \; 253.45/205.374 \;= 1.234$$

$$P_r \;= 64.85/45.75 \;= 1.425$$

So for:

$T_r = 1.21$ and $P_r = 1.435$

We can determine the quantities:

$(S^o - S / R)^o$ and $(S^o - S / R)^1$

From the charts (see appendix), we therefore find:

$(S^o - S / R)^o = 1.47$

$(S^o - S / R)^1 = 0.28$

The calculation of the acentric factor ω_{mix} gives:

$\omega_{\mathrm{mix}} = \Sigma Xi\ \omega i = 0.02518.$

Hence:

$$(\mathrm{S}° - \mathrm{S})_{\mathrm{mix}} = 8.314566\ [1.47 + (0.28 * 0.02518) + \ln 64.85] = 46.97\ \mathrm{Kj/Kmol.°K}$$

Finally, (1):

$$\mathrm{S}^1_{\mathrm{mix}}(\mathrm{P}_1,\ \mathrm{T}_1) = \mathrm{S}^{\mathrm{o}}_{\mathrm{mix}} - (\mathrm{S}^{\mathrm{o}} - \mathrm{S})_{\mathrm{mix}} = 75.35 - 46.97 = 28.38\ \mathrm{Kj/Kmol.°K}$$

$\mathrm{S}^1_{\mathrm{mix}}$ (P = 65.7 bar, T= -19.7 °C) = 28.3801 Kj/Kmol. °K

II.3.2 Example of Enthalpy Calculation at the Turbo-Expander Inlet

The data in the following table represent the necessary data for calculating the enthalpy of the mixture H1 at the Turbo-Expander inlet (determined from the charts [see appendix]):

Table II-5 Enthalpies at the Turbo-Expander Inlet (P = 65.7 bar, T = -19.7 °C).

Comp	Mw(kg/kmol)	Xi Mol	Entropy H° à T= -19.7°C		TC (°K)	Pc (atm)	Acentric Factor (w)
			(Kj/Kg)	(Kj/Kmol)			
N_2	28.00	0.0225	517.90	14501.12	126.2	33.5	0.0400
CO_2	44.01	0.009	380.00	16723.80	304.2	72.9	0.2667
CH_4	16.04	0.8630	864.00	13858.56	191.1	45.8	0.0108
C_2H_6	30.07	0.0730	520.00	15636.40	305.5	48.2	0.0972
C_3H_8	44.09	0.0222	465.00	20501.85	370	42	0.1515
iC_4H_{10}	58.12	0.0036	392.00	22783.04	408.1	36	0.1852
nC_4H_{10}	58.12	0.0042	364.00	21155.68	425.2	37.5	0.1981
iC_5H_{12}	72.15	0.0012	410.00	29581.50	461	32.9	0.2286
nC_5H_{12}	72.15	0.0007	313.63	22628.40	469.8	33.3	0.2510
nC_6H_{14}	86.18	0.0004	342.17	29488.2	507.9	29.9	0.298
nC_{7+}	100.2	0.0001	382.5	38326.5	540.2	27	0.349

The enthalpy of the mixture at (P_1, T_1) is given by the following equations [14]:

$$\mathrm{H}^{1}_{\mathrm{mix}}(P_1 1, \mathrm{T}_1 1) \;=\; \mathrm{H}^{\mathrm{o}}_{\mathrm{mix}} - (\mathrm{H}^{\mathrm{o}} \;-\; \mathrm{H})_{\mathrm{mix}}$$

With

H: The enthalpy of the mixture.

The following equation is used to calculate:

$\mathrm{H}^{\mathrm{o}}_{\mathrm{mix}} = \Sigma\ \mathrm{X_i H^o_i}$

Pitzer's equation is given to calculate:

$(\mathrm{H}^{\mathrm{o}} \;-\; \mathrm{H})_{\mathrm{mix}} = \;\mathrm{R\,Tc}\,[\left(\frac{\mathrm{H^o-H}}{\mathrm{RT}_c}\right)^{o} + \mathrm{W_{mix}}\;\left(\frac{\mathrm{H^o-H}}{\mathrm{RT}_c}\right)^{1}]$

$\omega_{\mathrm{mix}} \;=\; \Sigma\,\mathrm{X_i}\omega_{\mathrm{i}}$

With

ω_{i}: the acentric or expansion factor of each component, determined from Table II.5.

$\mathrm{X_i}$: mole fraction of each component in the mixture.

The quantities $\left(\frac{\mathrm{H^o-H}}{\mathrm{RT}_c}\right)^{o}$ and $\left(\frac{\mathrm{H^o-H}}{\mathrm{RT}_c}\right)^{1}$ are determined graphically from the entropy diagrams as functions of reduced pressures and reduced temperatures (See appendix).

The pseudo-critical coordinates – Kay's rules – are given by the following relations:

$T_{\mathrm{r}} \;= \mathrm{T/T_{pc}}$

With

T: operating temperature in K,

$\mathrm{T_{pc}}$: Pseudo-critical temperature in K,

T_{r}: reduced temperature.

The value of T_{pc} is calculated by the following formula:

$$T_{pc} = \sum X_i\, T_{ci}$$

With

T_{ci}: critical temperature of each component in K, determined from Table II.5.
X_i: mole fraction of each component in the mixture.

Similarly, to determine:

$$P_r = P/P_{pc}$$

With

P: operating pressure in atm,

P_{pc} : pseudo-critical pressure in atm,

P_r: reduced pressure.

The value of P_{pc} is calculated using the following formula:

$$P_{pc} = \sum X_i\, P_{ci}$$

With

P_{ci} : critical pressure of each component in atm, determined from Table V.5.

X_i : molar fraction of each component in the mixture.

it is first necessary to calculate the values of:

$$H_{mix}^{o} = \Sigma\, X_i H_i^{o} = 14271.17\ Kj/Kmol.$$

Hence,

$$H_{mix}^{o} = 14271.17\ Kj/Kmol$$

necessary to calculate:

$$P_{pc} = \sum X_i P_{ci} \text{ And } T_{pc} = \sum X_i T_{ci}$$

$$T_{pc} = 205.40\ °K \text{ And } P_{pc} = 45.75 \text{ atm}$$

Given

$$P_1 = 65.7 \text{ bar} = 64.85 \text{ atm}$$

$$T_1 = -19.7°C = 253.45\ °K$$

$$Mw = 18.68 \text{ Kg/Kmol}$$

We can determine:

$$T_r = 253.45/205.4 = 1.23$$

$$P_r = 64.85/45.75 = 1.42$$

So, for: $T_r = 1.23$ and $P_r = 1.42$, we can determine the following quantities:

$\left(\frac{H^o - H}{RT_c}\right)^o$ and $\left(\frac{H^o - H}{RT_c}\right)^1$ From the charts (see appendix), we find the following values:

$$\left(\frac{H^o - H}{RT_c}\right)^o = 1.467$$

$$\left(\frac{H^o - H}{RT_c}\right)^1 = 0.280$$

The calculation of the acentric factor W_{mix} gives:

$$W_{mix} = \Sigma X_i W_i = 0.025184$$

Thus:

$$(H^o - H)_{mix} = 8.314566 \times 205.4 \times [1.466 + (0.025182 \times 0.28)] = 2515.69\ Kj/Kmol$$

Finally:

$$H^1_{mix}(P1, T1) = H^o_{mix} - (H^o - H)_{mix} = 14271.17 - 2515.69 = 11755.48\ Kj/Kmol$$

$$H^1_{mix}\ (P = 65.7\ bar, T = -19.7\ °C) = 11755.48\ Kj/Kmol.$$

II.3.3 Calculation of Entropies and Enthalpies at the Outlet of the Turbo-Expander

In the same manner mentioned above, the entropies **S_2** and the enthalpies **H_2** are calculated at different temperatures $\boldsymbol{T_o}$ and at **P2 = 26 bar**.

$S_{2_{mix}}\ (P\ =\ 26\,bar, T\ =\ Ts)$ and $H_{2_{mix}}\ (P\ =\ 26\,bar, T\ =\ Ts)$

Knowing that the $\boldsymbol{T_o}$ are respectively: -58, -60, -64, -68°C.
The results obtained are presented in the following table:

Table II-6: Values of Entropies and Enthalpies at the Inlet and Outlet of the

	T (°C)	P (bar)	H (Kj/Kmol)	ΔH (Kj/Kmol)	S (Kj/Kmol°K)
inlet TE	-19.7	65.7	11755.48	0	28.38
outlet TE	-58	26	11606.48	149	36.51
	-60	26	11409.75	345.73	34.89
	-64	26	11228.08	527.4	33.89
	-68	26	10987.88	767.6	33.47

II.4 Determination of the Actual Outlet Temperature of the Turbo-Expander (T_o Actual)

An isentropic expansion corresponds to $S_2 = S_1 = 28.38\ kJ/Kmol \cdot K$, i.e., $\Delta S = 0$. We plot the curves $S = f(T)$ and $\Delta H = f(T)$; the results are given in Table II.6.

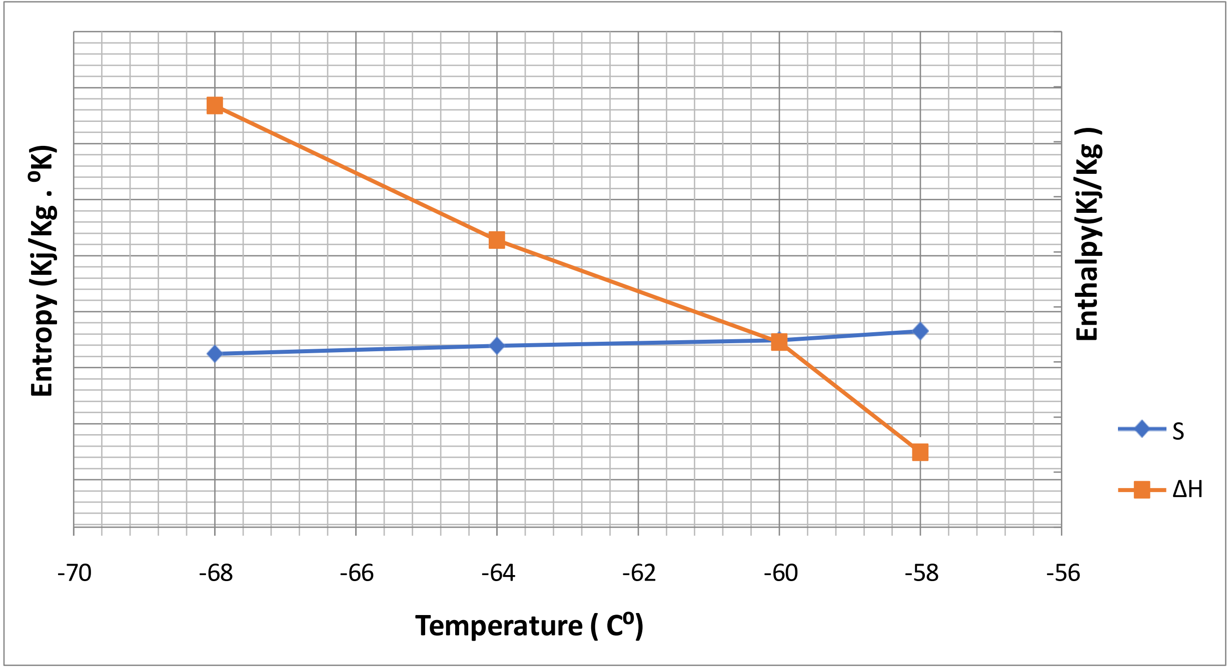


Figure II-6: Variation of S = f(T) and ΔH = f(T).

And after extrapolation on the graph, the theoretical outlet temperature of the Turbo-Expander is found to be: $T_{o_{\text{⍰⍰eo}}} = -65.5\ °C$, which corresponds to $\Delta S = 0$ and $\Delta H_{\text{⍰⍰eo}} = 980.5\ kJ/kmol$.

For a Turbo-Expander efficiency of 83%, the enthalpy variation will be:

$\Delta H_{real} = \Delta H_{theo} * 0,83$ So : $\Delta H_{real} = 813.86\ kJ/kmole$

And the real temperature found at the Turbo-Expander outlet will be:

$T_{s_{real}} = -63.4°C$.

At this temperature $T_{o_{real}} = -63.4°C$, we have $S_1 = S_2 = 28.58\ kJ/kmol \cdot K$.

Thus, the expansion hypothesis is verified by the equation:

$\Delta S = S2 - S1 = 28.58 - 28.38 = 0.2\ \mathrm{kj/kmol.K}$, which is a result very close to zero.

The calculated results of the temperatures T_o are presented in the following table.

Table II-7 Turbo Expander T_o

T (°C)	T_o (°C) Theoretically calculated (100%)	T_o (°C) Calculated real (83%)	T_o (°C) Actually
outlet Turbo-Expander	- 65.5	- 63.4	- 61

The analysis of the values in Table II.7 shows that:

- The obtained temperatures are close to the actual process temperatures, which confirms the validity of the thermodynamic model used in determining the operating parameters.
- The actual outlet temperature differs from the current temperature by 2.4°C. This minimal difference explains the reliability and the accuracy of obtained results.
- The actual outlet temperature obtained at the exit of the Turbo-Expander is higher than the theoretically predicted one, which is due to the friction of gas molecules against the wheel of the Turbo-Expander.

II.5 Determination of Recovered LPG and Condensate Quantities

The flow rate of gas exiting G11-VA-32-201 is $19285\ kmol/hr$ (equivalent to **12 million Sm³/day**).

A flash calculation is performed at the outlet of the Turbo-Expander with the following conditions:
T_o (real) $= -63.4\ °C$ and $P = 23\ bar$.
The obtained results are presented in **Table II- 8**.

Table II-8: Flash Calculation

	Turbo-Expander Inlet	Turbo-Expander Vap Outlet	Turbo-Expander Liq Outlet
N_2	0.0225	0.0238	0.0017
CO_2	0.009	0.0088	0.0129
CH_4	0.8630	0.8981	0.3184
C_2H_6	0.0730	0.0601	0.2739
C_3H_8	0.0222	0.0082	0.2397
iC_4	0.0036	0.0005	0.0519
nC_4	0.0042	0.0004	0.0640
iC_5	0.0012	0.0000	0.0194
nC_5	0.0007	0.0000	0.0114
C_6	0.0004	0.0000	0.0066
C_7^+	0.0001	0.0000	0.0001
M_W	18.68	17.69	34.06
Fraction mol	1	0.905	0.095

The quantity of LPG recovered in the liquid phase of G11-CA-32-201 is:

The molar mass of the LPG is:

$$\mathrm{M_W\ LPG = M_W C3 \times \%\ molC3 + M_W\ iC4 \times \%mol\ iC4 + \ M_W nC4 \times \%\ mol\ nC4}$$

$$\mathrm{M_W\ LPG\ =\ 44.09 \times 23.97\ +\ 58.12 \times 5.19\ +\ 58.12 \times 6.4}$$

$$\mathrm{M_W\ LPG}\ = 17.3 kg/kmole.$$

The quantity of condensate recovered in the liquid phase of G11-CA-32-201 is:

The molar mass of condensate is

$$\mathrm{M_W cond\ =\ M_W iC_5 \times\ \%\ mol\ iC_5\ +\ M_W nC_5 \times \%\ mol\ nC_5\ +\ M_W C_6 \times \%\ mol\ C_6\ +\ M_W C_{7_+} \times \%\ mol\ C_{7_+}}$$

$$\mathrm{M_W cond =\ 72.15 \times 1.94\ +\ 72.15 \times 1.14\ +\ 86.15 \times 0.66\ + 100.2 \times 0.01}$$

$$\mathrm{M_W cond =\ 2.8}\ kg\ /kmol$$

Therefore, the quantity of LPG recovered in G11-CA-32-201 is:

$$Q_{\mathrm{LPG}} = \mathrm{M_W\ LPG} \times mole\ fraction\ of\ liquid \times\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet$$

$$Q_{\mathrm{LPG}}\ =\ (17.3 \times 0.095 \times 19285 \times 24)/1000$$

$$Q_{\mathrm{LPG}}\ =\ 765.213\ tons/day$$

And the amount of condensate recovered in G11-CA-32-201 is:

$$\mathrm{Qcond\ =\ M_W\ cond \times mole\ fraction\ of\ liquid\ *\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet}$$

$$\mathrm{Qcond\ =\ (2.8\ * 0.095\ * 19285\ *\ 24)\ /1000}$$

$$\mathrm{Qcond\ =\ 123.849}\ tons/day$$

The calculated quantities of LPG and condensate are presented in the following table:

Table II-9: Quantities of LPG and Condensate Produced in the T.E.

	LPG t/Day	Cond t/Day
Turbo-Expander	765.213	123.849

Based on the results, we can say that:

- The use of the Turbo-Expander has a great advantage for the recovery of liquid hydrocarbons (condensate and especially LPG).
- These results highlight the importance of proper maintenance of the Turbo-Expander in order to avoid prolonged shutdowns of this machine.

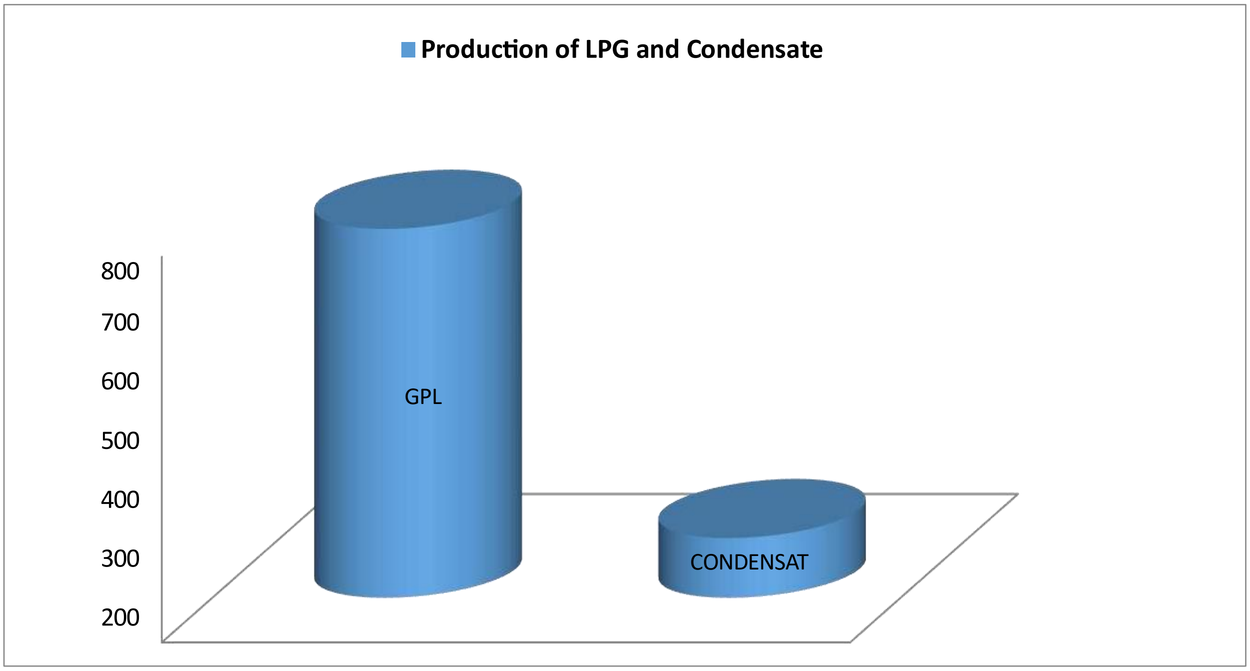


Figure II-7: Daily Quantities of LPG and Condensate Produced (Turbo-Expander

II.6 Optimization of the Operating Parameters of the Turbo-Expander

The operating parameters that determine the proper functioning of the Turbo-Expander at inlet pressure and temperature of T.E.

The goal of this study is to find the best operating parameters of the Turbo-Expander in order to maximize the recovery of liquid hydrocarbons.
The influential parameters on the recovery of LPG and condensate are the inlet pressure and temperature of the Turbo-Expander.

II.6.1 Methodology

The adopted optimization procedure is based on two steps:

- Variation of the pressure at the T.E inlet for a given constant temperature.
- Variation of the temperature at the T.E inlet, for an optimized T.E inlet pressure.
- Recall that the optimization process is based on using the HYSYS simulator.

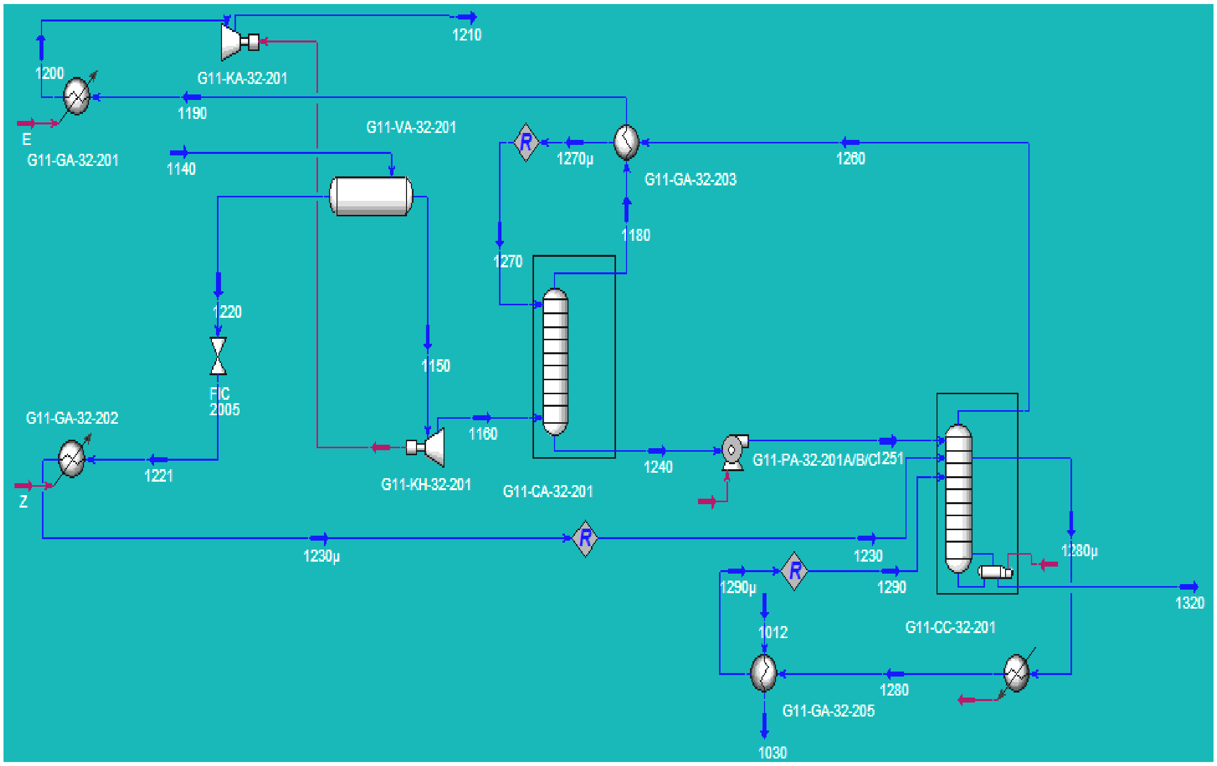


Figure II-8 shows the convergence of the Turbo-Expander simulation.

II.6.2 Optimization of Turbo-Expander Inlet Pressure

The Turbo-Expander manufacturer (ATLAS COPCO) recommends operating at an inlet pressure between 60 bar and 68 bar. Additionally, the Turbo-Expander trip pressure is set at P = 70 bar.

The optimization procedure first consists of varying the Turbo-Expander inlet pressure from 63 bar to 66.5 bar while keeping the inlet temperature fixed (current Te_1 = -17.9 °C).

At each pressure, the Turbo-Expander outlet temperature Ts is determined using the HYSYS simulator.

The results obtained using HYSYS are presented in the following Table (II.10):

Table II-10 Simulation Results (1)

inlet Pressure (bar)	63	63.5	64	64.5	65	65.5	66	66.5
inlet Temp T.E (°C)	-17.9	-17.9	-17.9	-17.9	-17.9	-17.9	-17.9	-17.9
Outlet Temp T.E (°C)	-59.16	-59.47	-59.78	-60.08	-60.38	-60.68	-61.00	-61.27

The results from the above table are represented in the following figure:

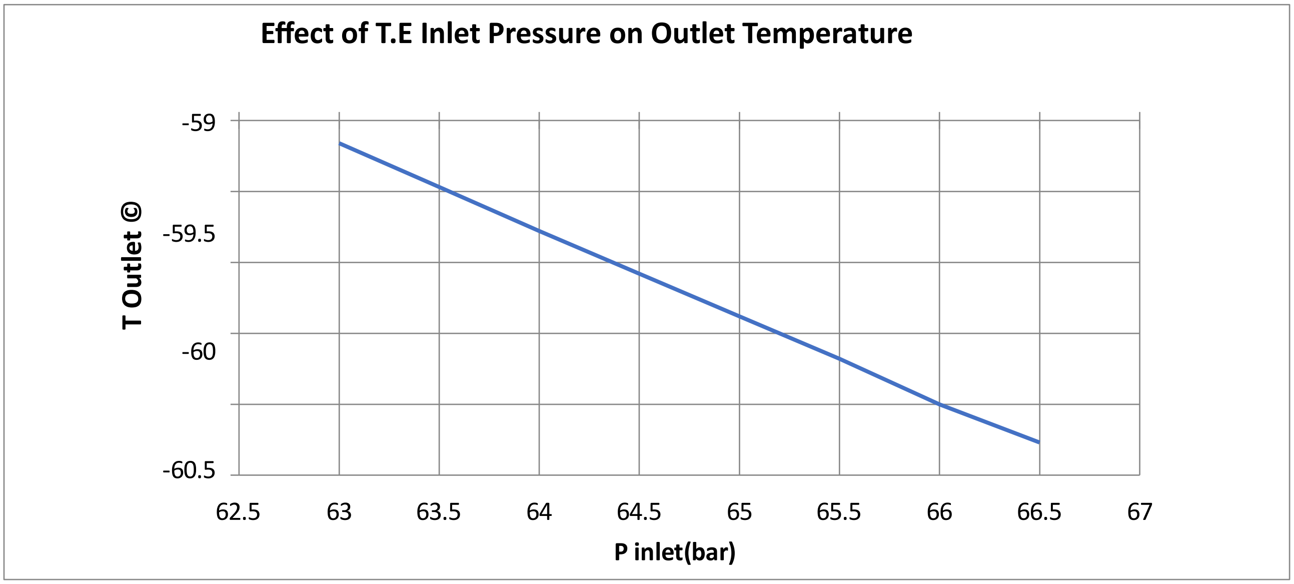


Figure II-9 Effect of T.E Inlet Pressure on Outlet Temperature

Based on the graph (Fig. **II-9**), we can conclude the following:

- As the inlet pressure of the Turbo-Expander increases, the outlet temperature Ts decreases.
- Therefore, the optimized operating pressure for the Turbo-Expander is **66.5 bar**, which remains safely below the trip (shutdown) pressure of the Turbo-Expander.

II.6.3 Optimization of the Turbo-Expander Inlet Temperature

The optimization procedure consists of varying the inlet temperature of the Turbo-Expander from **-17°C to -19°C**, while keeping the **optimized inlet pressure fixed at 66.5 bar**. For each inlet temperature, the corresponding Turbo-Expander outlet temperature (**To**) is determined using the **HYSYS simulator**.

The results obtained from HYSYS are presented in **Table II.11** below:

Table II-11 Simulation Results (2)

inlet Pressure (bar)	66,5	66,5	66,5	66,5	66,5
inlet Temp T.E (°C)	-17	-17,5	-18	-18,5	-19
Outlet Temp T.E (°C)	-60,47	-60,92	-61,36	-61,80	-62,24

The results of Table (II.11) are shown in the following figure:

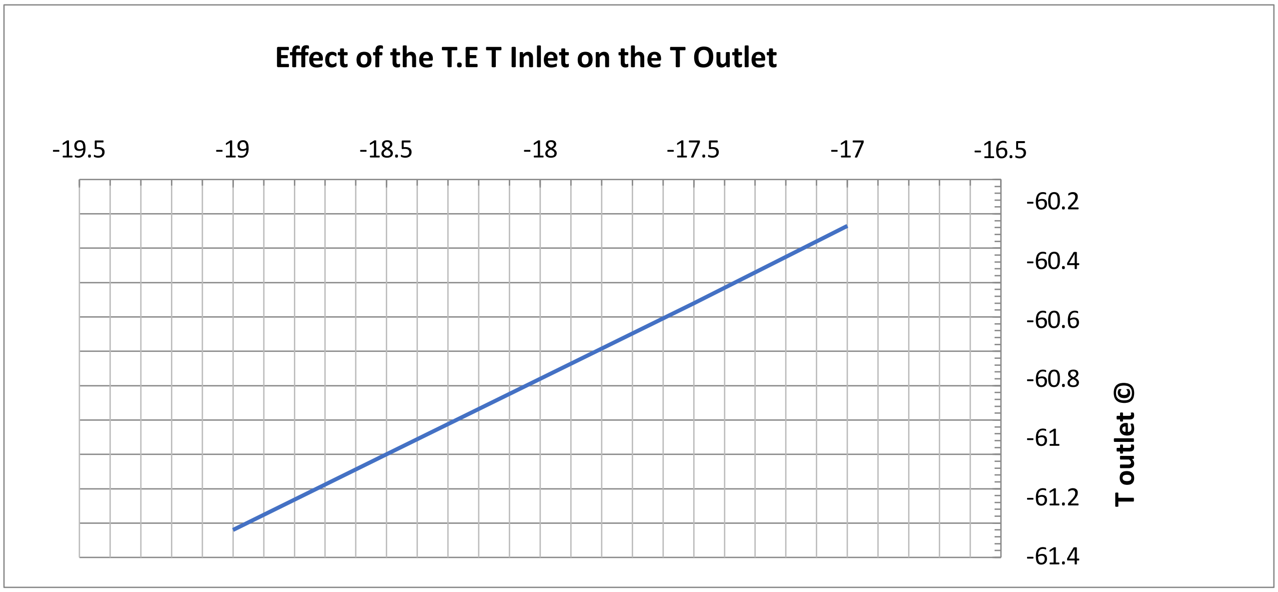


Figure II-10: Effect of Turbo-Expander Inlet Temperature on Outlet Temperature

According to the graph (Fig. II.9), we observe that:

- The lower the inlet temperature, the lower the Turbo-Expander outlet temperature.

Remark:

The gas temperature at the Turbo-Expander outlet must not fall below -61.80 °C under current operating conditions, as this temperature drop would create a closed loop between the absorber and the deethanizer. In such a scenario, an increase in liquid level is observed in the absorber, which in turn leads to a high liquid level in the deethanizer, eventually recirculating back into the absorber.

Therefore, the optimal inlet temperature for the Turbo-Expander is: -18.5 °C.

To achieve better recovery of LPG and condensate, we recommend operating the Turbo-Expander with the optimized parameters of pressure and temperature, which are:

$P = 66.5\ bar$ and $T = -18.5\ °C$.

II.7 Determination of the Quantities of LPG and Condensate Recovered Before Optimization

This section aims to determine the flash at the Turbo-Expander outlet using the current operating parameters, namely:

- $Actual\ T = -17.95\ °C$
- $Actual\ P = 66\ bar$

The obtained results are presented in Table (II.12):

Table II-12 Results of the flash at actually T and P

	Inlet Turbo-Expander	**Vap outlet Turbo-Expander**	**Liq outlet Turbo-Expander**
N_2	0.0225	0.0238	0.0019
CO_2	0.009	0.0087	0.0130
CH_4	0.8630	0.8975	0.3373
C_2H_6	0.0730	0.0602	0.2667
C_3H_8	0.0222	0.0085	0.2298
iC_4	0.0036	0.0005	0.0500
nC_4	0.0042	0.0004	0.0633
iC_5	0.0012	0.0000	0.0141
nC_5	0.0007	0.0000	0.0119
C_6	0.0004	0.0000	0.0067
C_7^+	0.0001	0.0000	0.0019
M_W	18.68	17.69	34.06
Mole Fraction	1	0.909	0.091

The amount of LPG recovered in the liquid phase of G11-CA-32-201 is:

The molar mass of LPG is:

$$\mathrm{M_W\ LPG = M_W C3 \times \%\ molC3 + M_W\ iC4 \times \%mol\ iC4 + \ M_W nC4 \times \%\ mol\ nC4}$$

$$\mathrm{M_W\ LPG\ =\ 44.09 \times 22.98 +\ 58.12 \times 5.00\ +\ 58.12 \times 6.33}$$

$$\mathrm{M_W\ LPG}\ = 16.71 kg/kmole.$$

The molar mass of condensate is:

$$\mathrm{M_W cond\ =\ M_W iC_5 \times\ \%\ mol\ iC_5\ +\ M_W nC_5 \times \%\ mol\ nC_5\ +\ M_W C_6 \times \%\ mol\ C_6\ +\ M_W C_{7_+} \times \%\ mol\ C_{7_+}}$$

$$\mathrm{M_W cond = \ 72.15 \times 1.41\ +\ 72.15 \times 1.19\ +\ 86.15 \times 0.67\ + 100.2 \times 0.19}$$

$$\mathrm{M_W cond} = \ 2.47\ kg\ /kmol$$

Therefore, the quantity of LPG recovered in G11-CA-32-201 is:

$$Q_{\mathrm{LPG}} = \mathrm{M_W\ LPG} \times mole\ fraction\ of\ liquid \times\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet$$

$$Q_{\mathrm{LPG}}\ =\ (16.71 \times 0.091 \times 19285 \times 24)/1000$$

$$Q_{\mathrm{LPG}}\ =\ 703.8\ tons/day$$

And the quantity of condensate recovered in G11-CA-32-201 is:

$$\mathrm{Qcond\ =\ M_W\ cond \times mole\ fraction\ of\ liquid\ *\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet}$$

$$\mathrm{Qcond\ =\ (2.47\ * 0.091\ * 19285\ *\ 24)\ /1000}$$

$$\mathrm{Qcond}\ =\ 104.03\ tons/day$$

The calculated quantities of LPG and condensate are presented in the following table:

Table II-13 Quantities of LPG and condensate produced in the Turbo-Expander before optimization.

	LPG T/Day	**Condensate T/Day**
Turbo-Expander	703.8	104.03

II.8 Determination of the quantities of LPG and condensate recovered after optimization:

This involves determining the flash at the Turbo-Expander outlet for the optimized inlet parameters, namely:

$T\ optim\ =\ -18.5\,°C$

$P\ optim\ =\ 66.5\ bar$

The results obtained are presented in Table (II.14):

Table II-14: Results of the flash at optimized temperature and pressure.

	Inlet Turbo-Expander	Outlet Vap Turbo-Expander	Outlet Liq Turbo-Expander
N_2	0.0225	0.0237	0.0018
CO_2	0.009	0.0088	0.0128
CH_4	0.8630	0.8963	0.3316
C_2H_6	0.0730	0.0610	0.2637
C_3H_8	0.0222	0.0089	0.2312
iC_4	0.0036	0.0005	0.0516
nC_4	0.0042	0.0004	0.0656
iC_5	0.0012	0.0000	0.0159
nC_5	0.0007	0.0000	0.0109
C_6	0.0004	0.0000	0.0070
C_7^+	0.0001	0.0000	0.0020
M_W	18.68	17.69	34.06
Mole Fraction	1	0.908	0.092

The amount of LPG recovered in the liquid phase of G11-CA-32-201 is:

The molar mass of LPG is:

$$\mathrm{M_W\ LPG = M_W C3 \times \%\ molC3 + M_W\ iC4 \times \%mol\ iC4 + \ M_W nC4 \times \%\ mol\ nC4}$$

$$\mathrm{M_W\ LPG}\ =\ 44.09 \times 23.12 +\ 58.12 \times 5.16\ +\ 58.12 \times 6.56$$

$$\mathrm{M_W\ LPG}\ = 16.98 kg/kmole.$$

The molar mass of condensate is:

$$\mathrm{M_W cond\ =\ M_W iC_5 \times\ \%\ mol\ iC_5\ +\ M_W nC_5 \times \%\ mol\ nC_5\ +\ M_W C_6 \times \%\ mol\ C_6\ +\ M_W C_{7_+} \times \%\ mol\ C_{7_+}}$$

$$\mathrm{M_W cond} =\ 72.15 \times 1.59\ +\ 72.15 \times 1.09\ +\ 86.15 \times 0.7\ + 100.2 \times 0.2$$

$$\mathrm{M_W cond} =\ 2.73\ kg\ /kmol$$

Therefore, the quantity of LPG recovered in G11-CA-32-201 is:

$$Q_{\mathrm{LPG}} = \mathrm{M_W\ LPG} \times mole\ fraction\ of\ liquid \times\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet$$

$$Q_{\mathrm{LPG}}\ =\ (16.98 \times 0.092 \times 19285 \times 24)/1000$$

$$Q_{\mathrm{LPG}}\ =\ 723.03\ tons/day$$

And the quantity of condensate recovered in G11-CA-32-201 is:

$$\mathrm{Qcond\ =\ M_W\ cond \times mole\ fraction\ of\ liquid\ *\ Daily\ molar\ flow\ rate\ of\ gas\ at\ the\ Turbo - Expander\ inlet}$$

$$\mathrm{Qcond}\ =\ (2.73\ * 0.092\ * 19285\ *\ 24)\ /1000$$

$$\mathrm{Qcond}\ =\ 116.24\ tons/day$$

The calculated quantities of LPG and condensate are presented in the following table:

Table II-15: Quantities of LPG and Condensate Produced in the Turbo-Expander After Optimization

	LPG T/Day	Condensate T/Day
Turbo-Expander	723.03	116.246

The quantities of LPG and condensate calculated before and after optimization are presented in the following Table (II.16):

Table II-16: Quantity of LPG and Condensate Recovered Before and After Optimization

	QGPL (T/Day)	**Q condensate (T/Day)**
Before optimization	**703,8**	**104,03**
After optimization	**723,03**	**116,246**
Production gain	**19,23**	**12,216**

Based on the results obtained in Table (II.16), we observe that:

- A production gain of 19.23 tons per day of LPG and 12.216 tons per day of condensate was achieved after optimizing the operating parameters of the Turbo-Expander.
- The amount of LPG gained is significantly higher compared to the amount of condensate recovered.

The results from Table (II.16) are shown in the following figure:

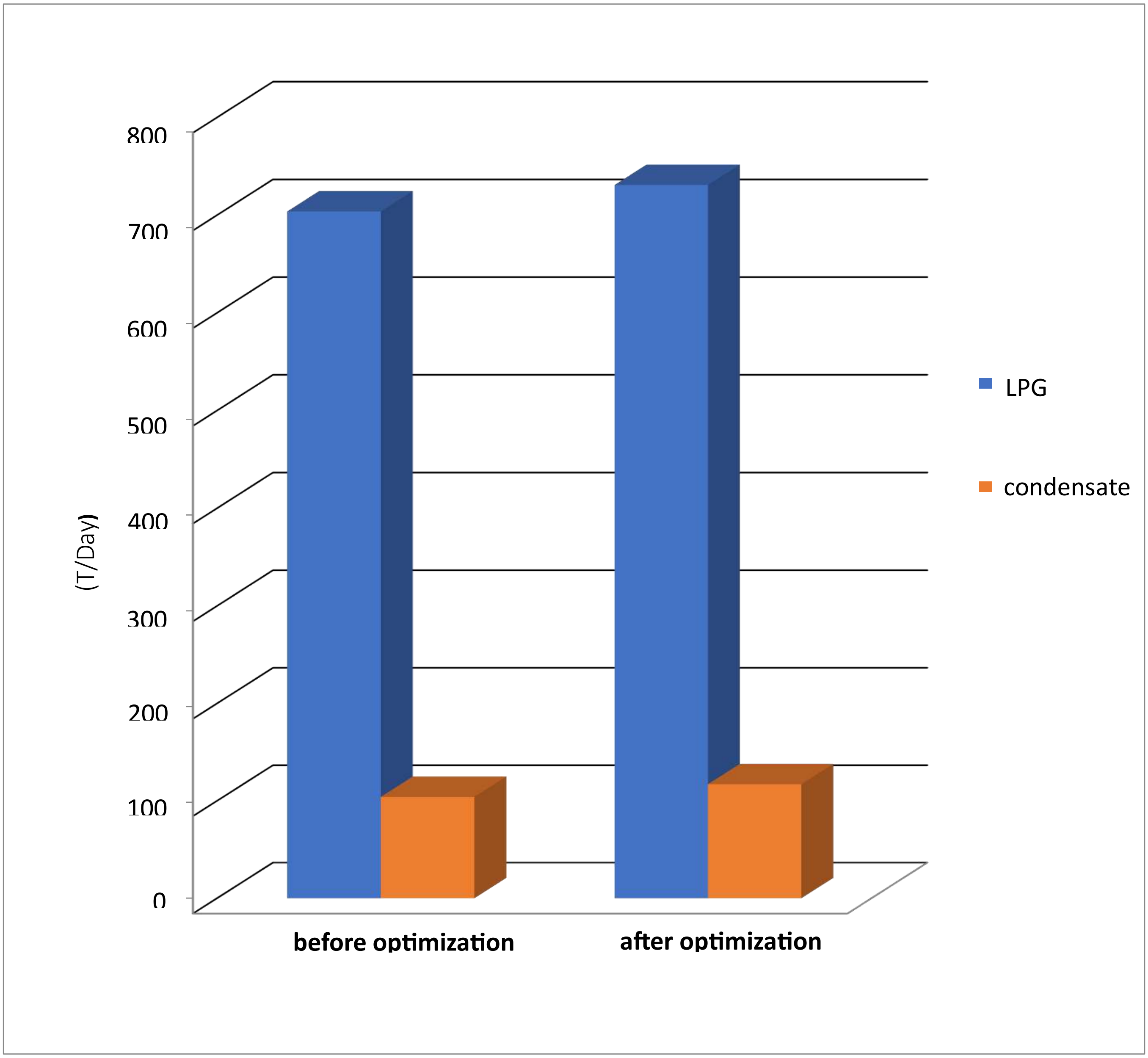


Figure II-11: Comparison of the quantities of LPG and condensate recovered before and after optimization.

General Conclusion

General Conclusion

Through this thesis, we have attempted to optimize the operating parameters of the cryogenic section at the CPF-GTL unit using the available energy, with the objective of improving LPG recovery. To achieve this, we aimed to thoroughly understand the process and become familiar with the various pieces of equipment within this section.

The simulation of this section using the HYSYS simulator, with design case data that closely reflects the current operating conditions, allowed us to establish a model representing this section, which will serve for studying other current operating cases. The study of the variation of the Turbo Expander's operating parameters enabled us to determine the optimal parameters for improving liquids recovery, especially considering that no changes to the equipment sizing will be necessary.

Based on the results obtained, and in comparison, with the current performance of our unit, we concluded that:

- The optimal inlet temperature for the Turbo Expander is -18.5°C.
- The optimal inlet pressure for the Turbo Expander is 66.5 bar.
- After optimization, a gain of 19.23 tons/day of LPG was achieved.
- After optimization, a gain of 12.216 tons/day of condensate was achieved.

Following the various results obtained, we can deduce that:
The variation in the raw gas composition, as well as the inlet pressure and temperature to the plant, directly affects the operating parameters and the recovery of finished products.

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annex

Annexe

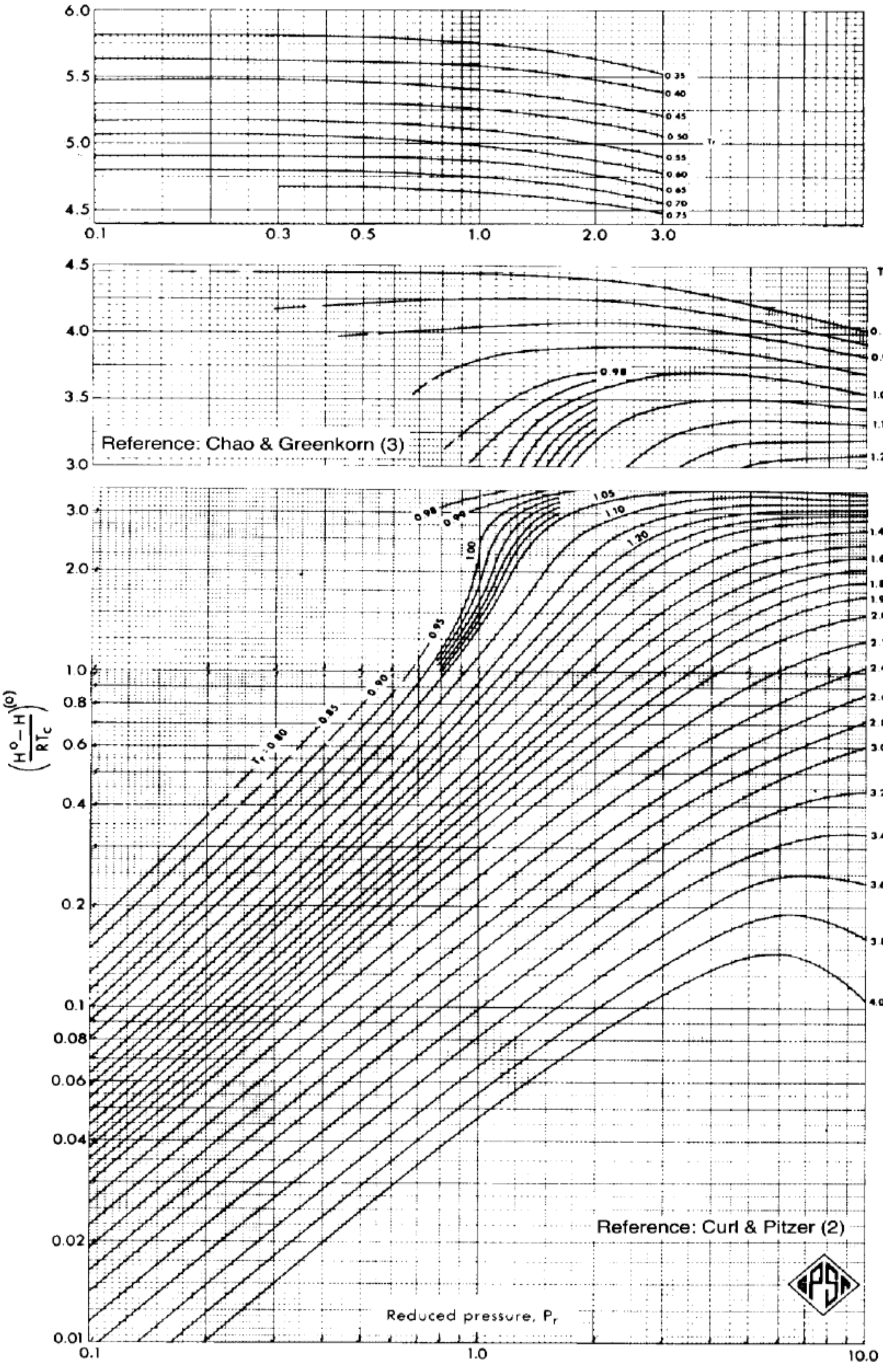

Figure 1: plot of Enthalpy Departure Chart

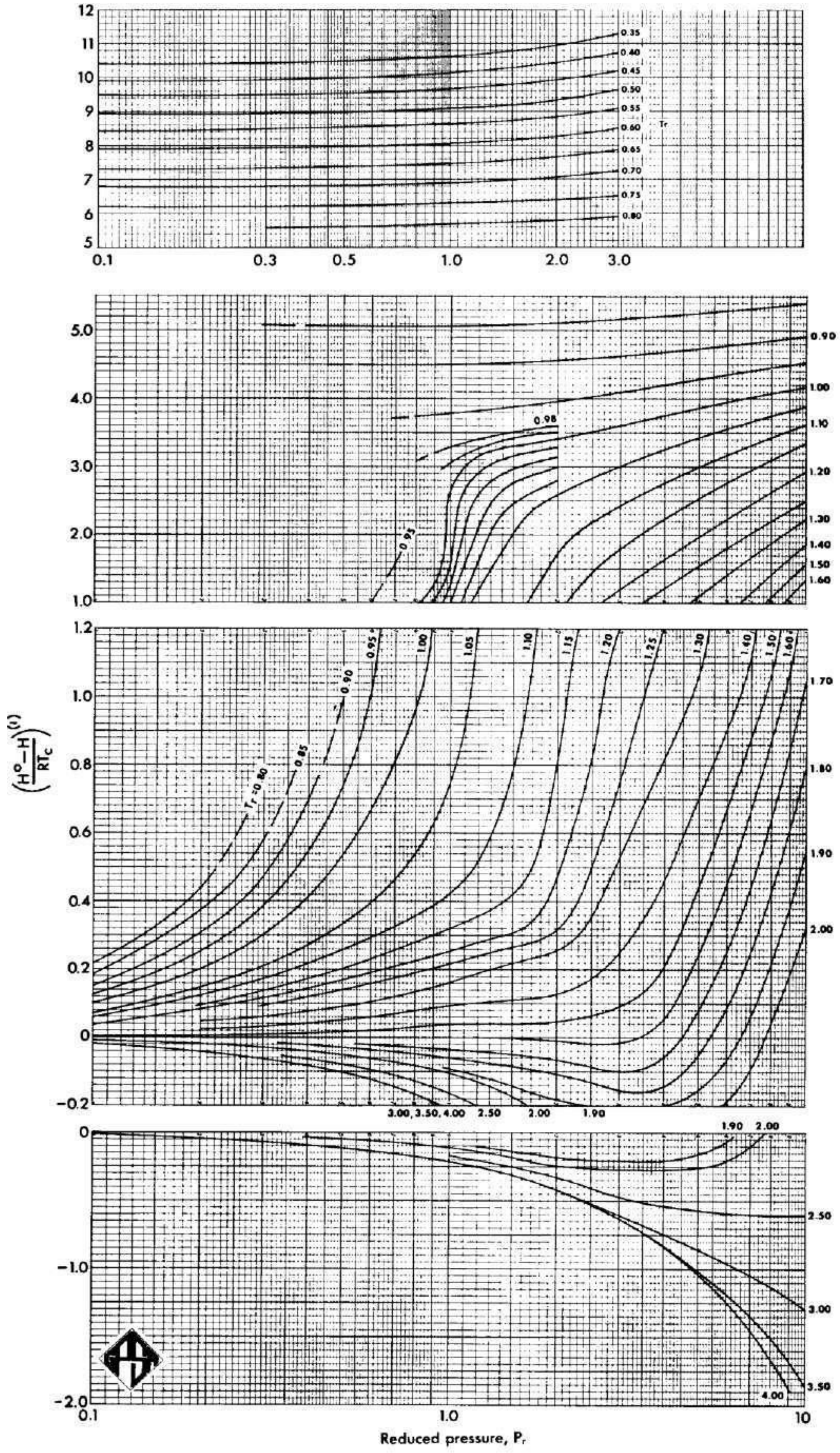

Figure 2: plot of Enthalpy Departure Chart

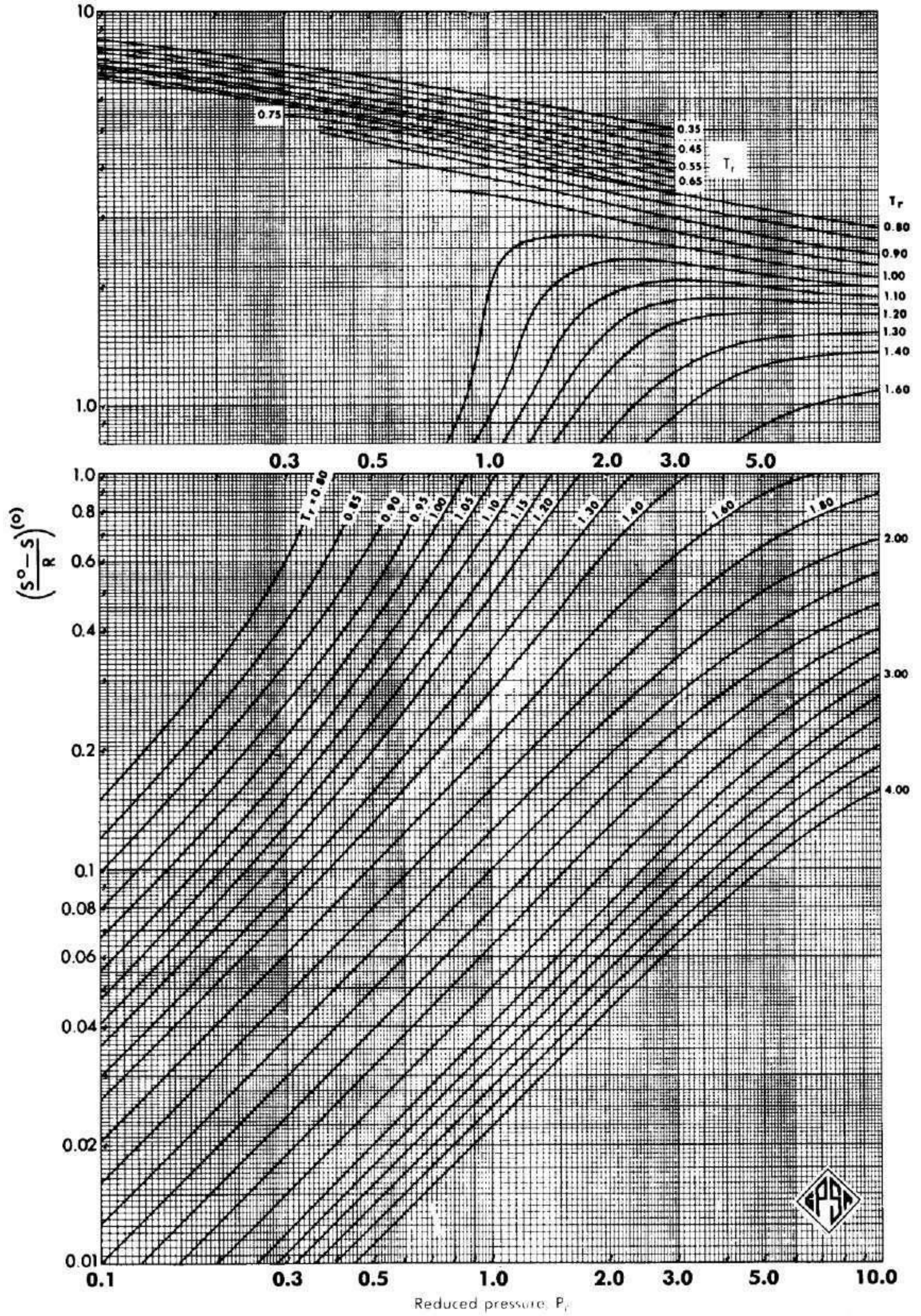

Figure 3: plot of Entropy Departure Chart

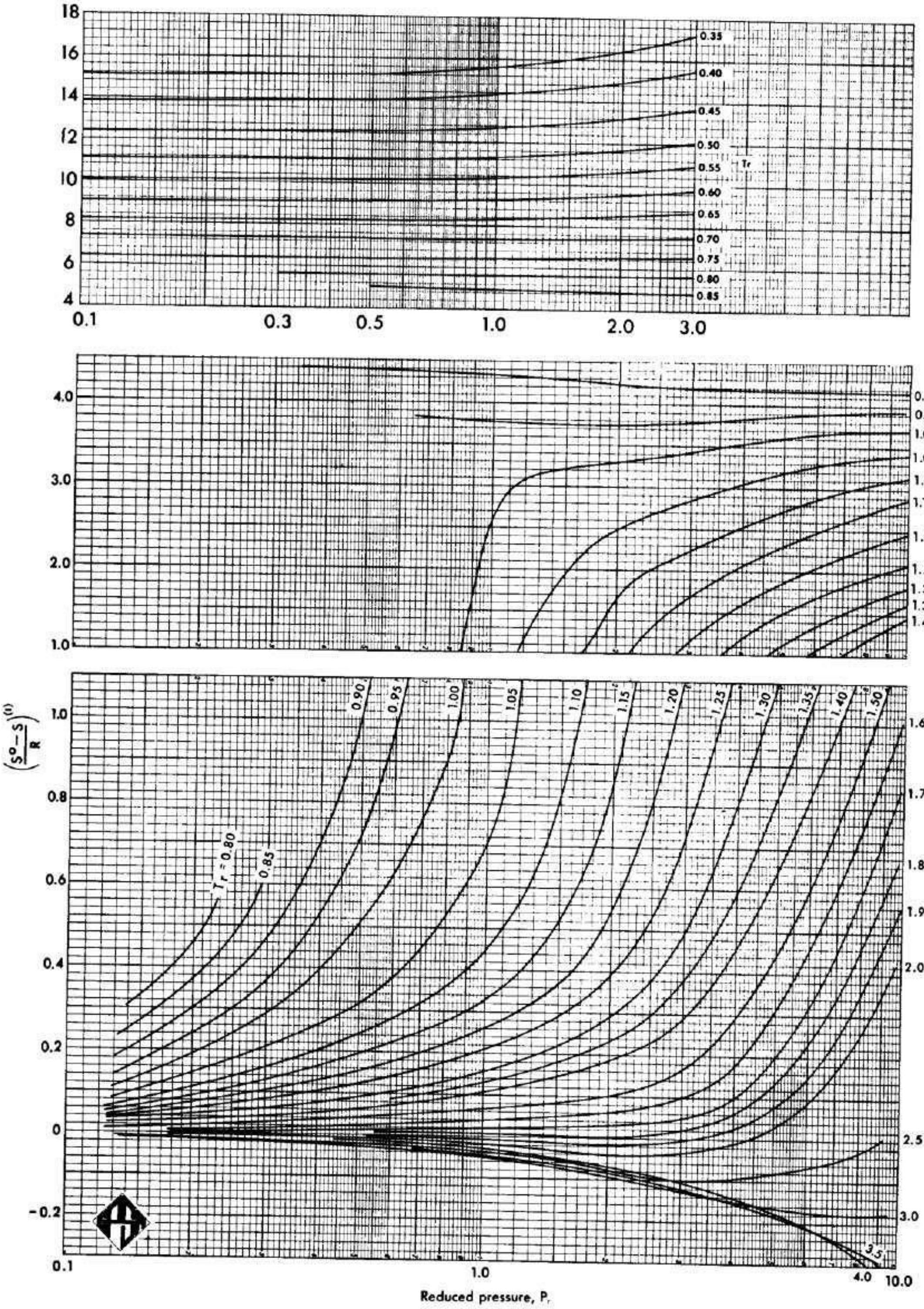

Figure 4: plot of Entropy Departure Chart

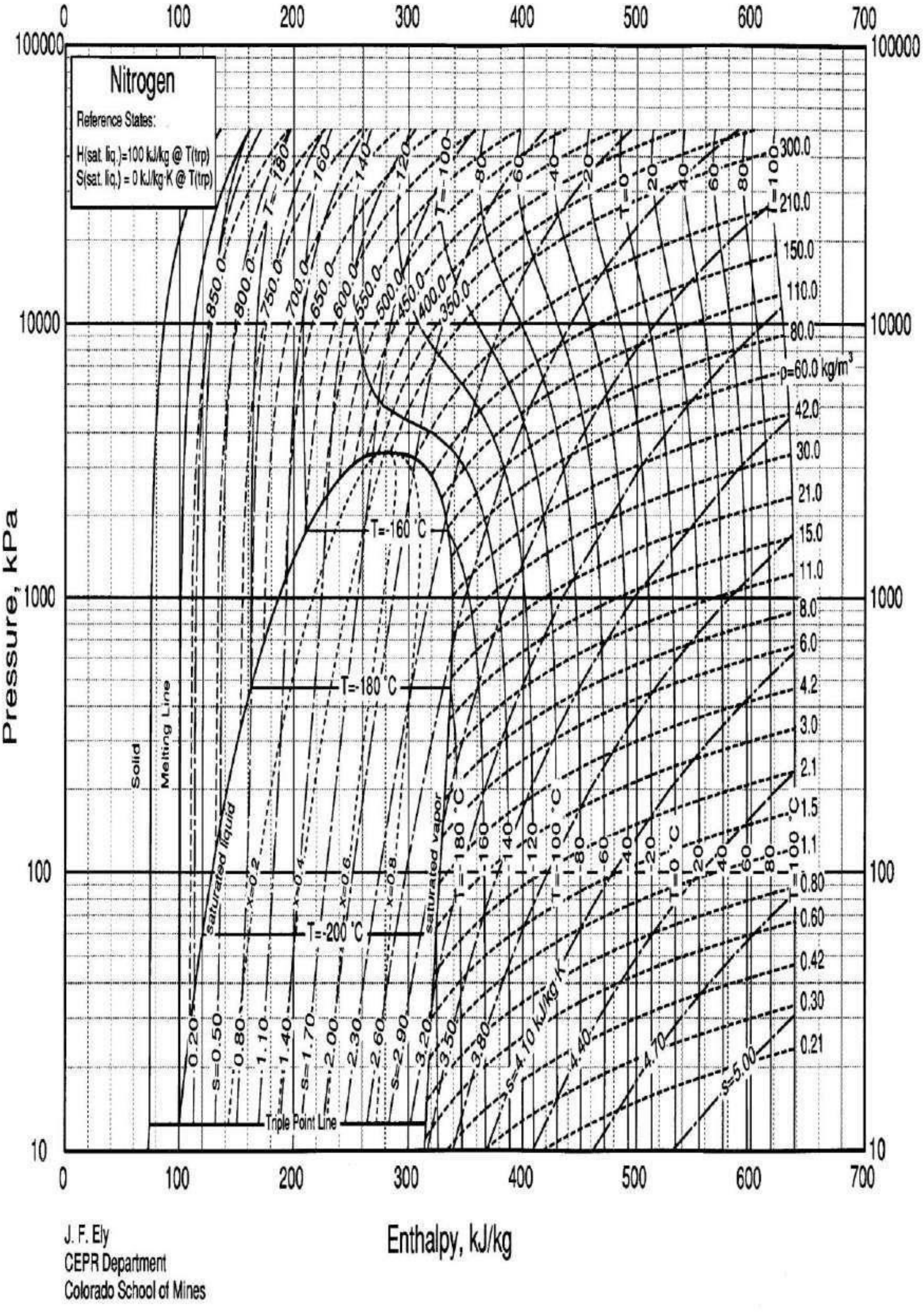

Figure 5: plot of pressure vs enthalpy

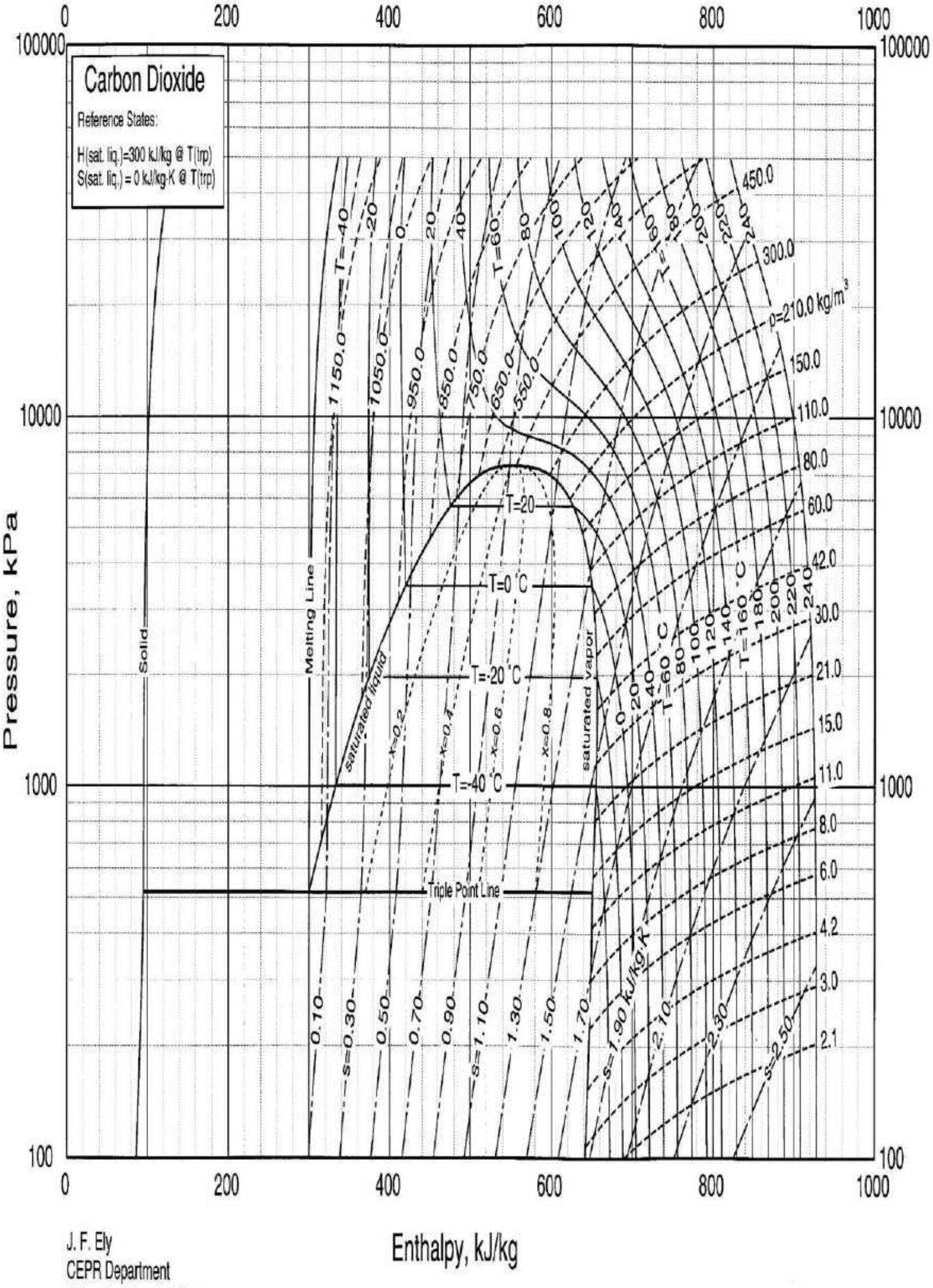

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Figure 6: plot of pressure vs enthalpy

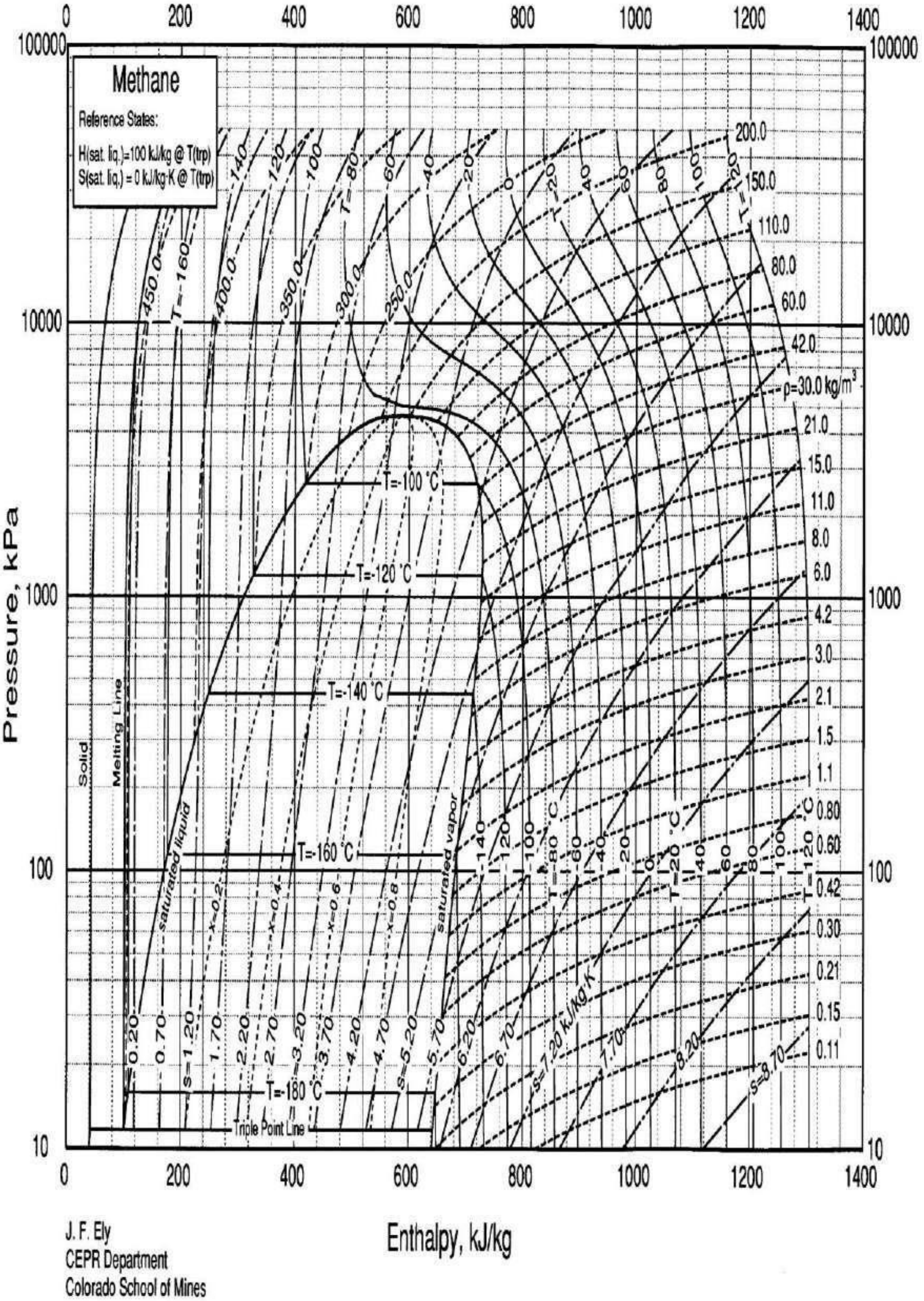

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Figure 7: plot of pressure vs enthalpy

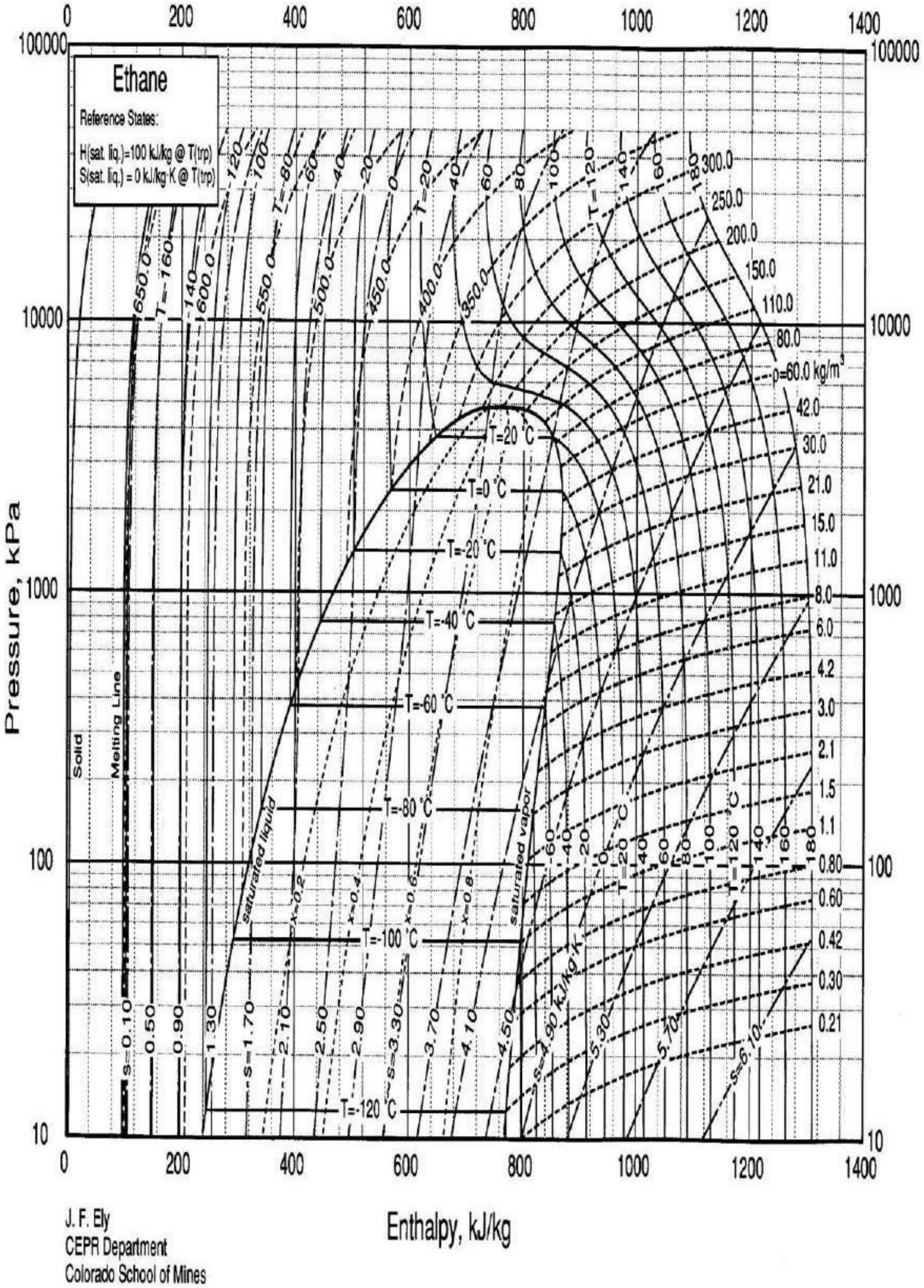

Figure 8: plot of pressure vs enthalpy

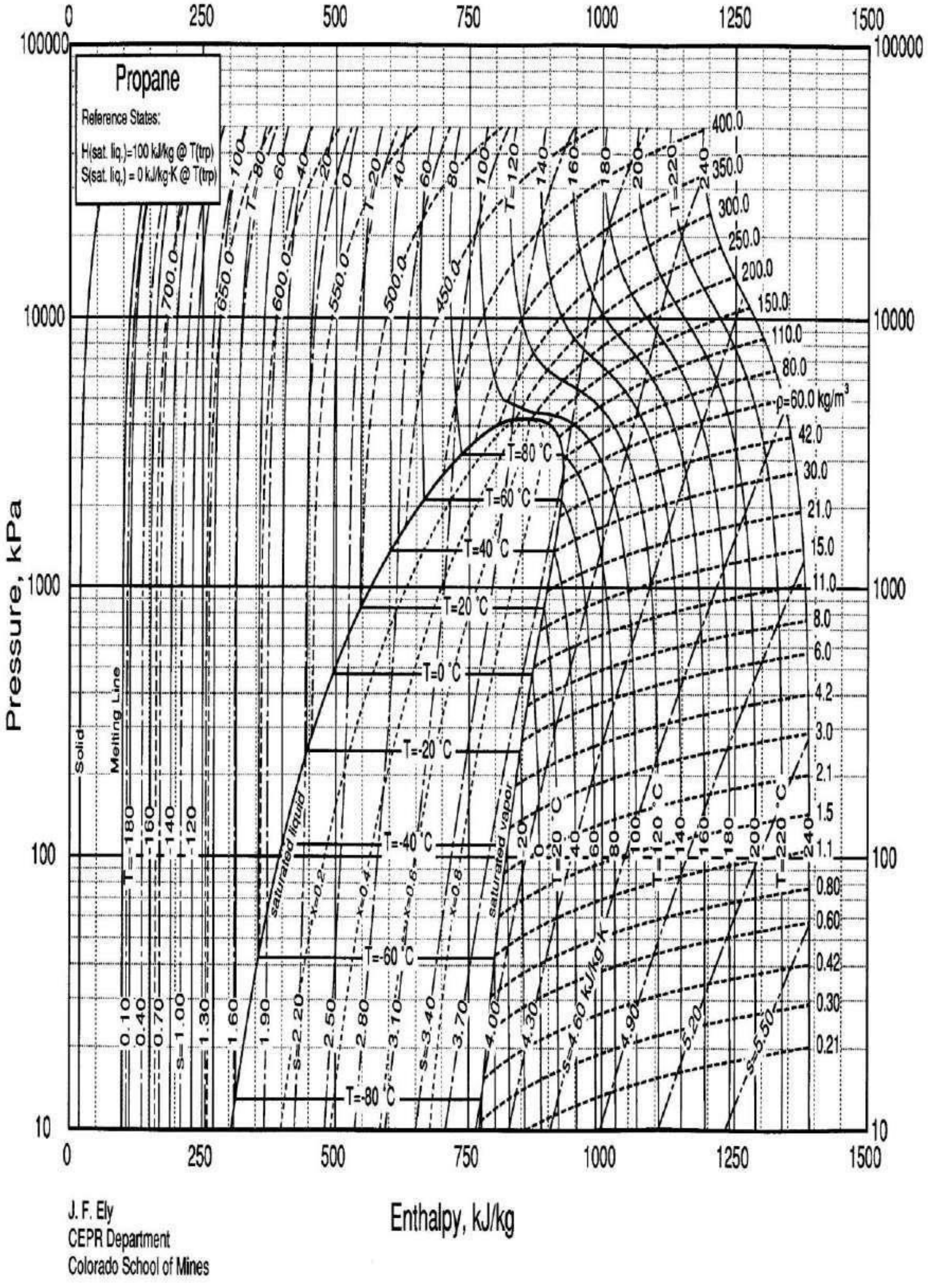

Figure 9: plot of pressure vs enthalpy

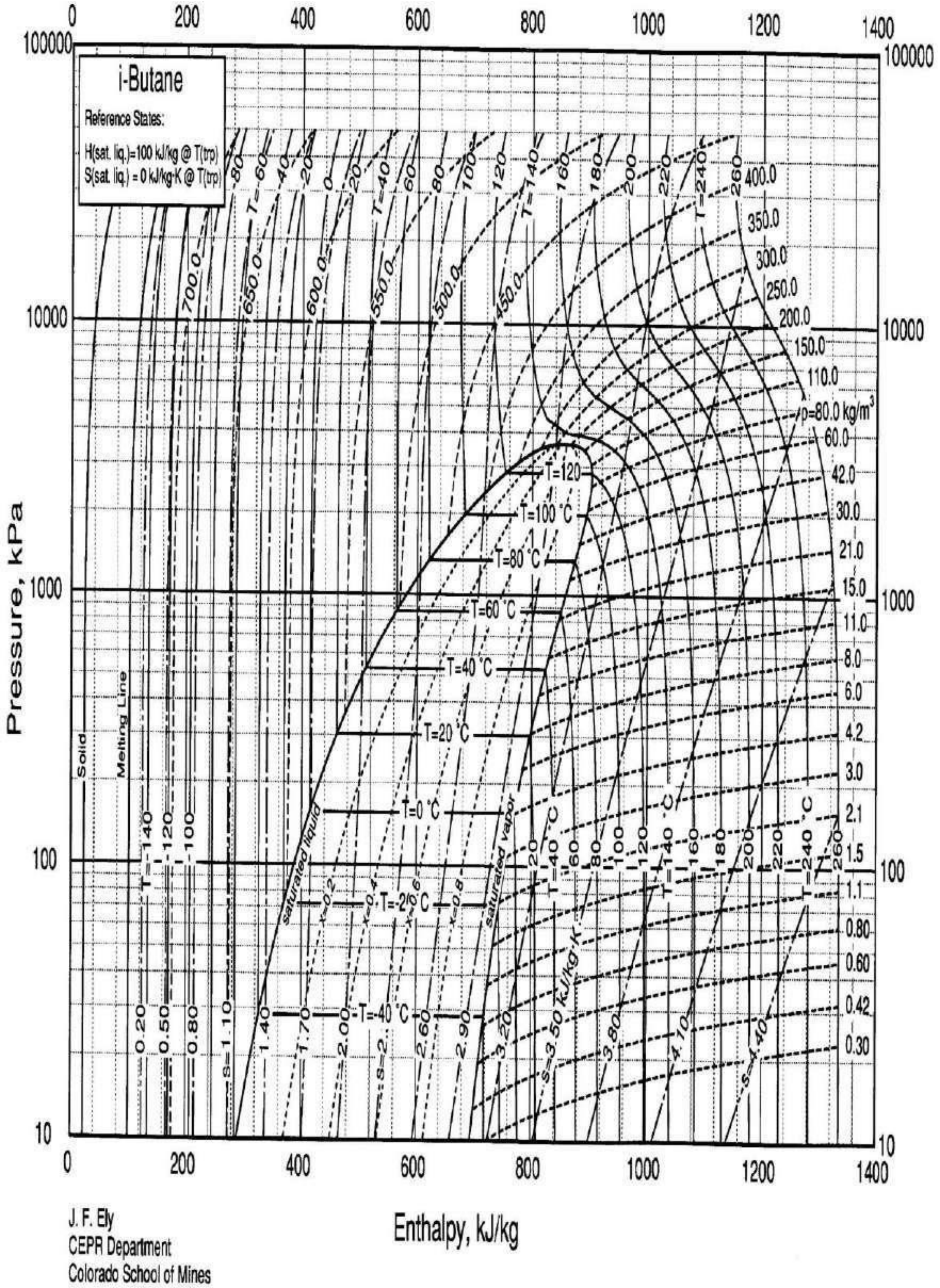

Figure 10: plot of pressure vs enthalpy

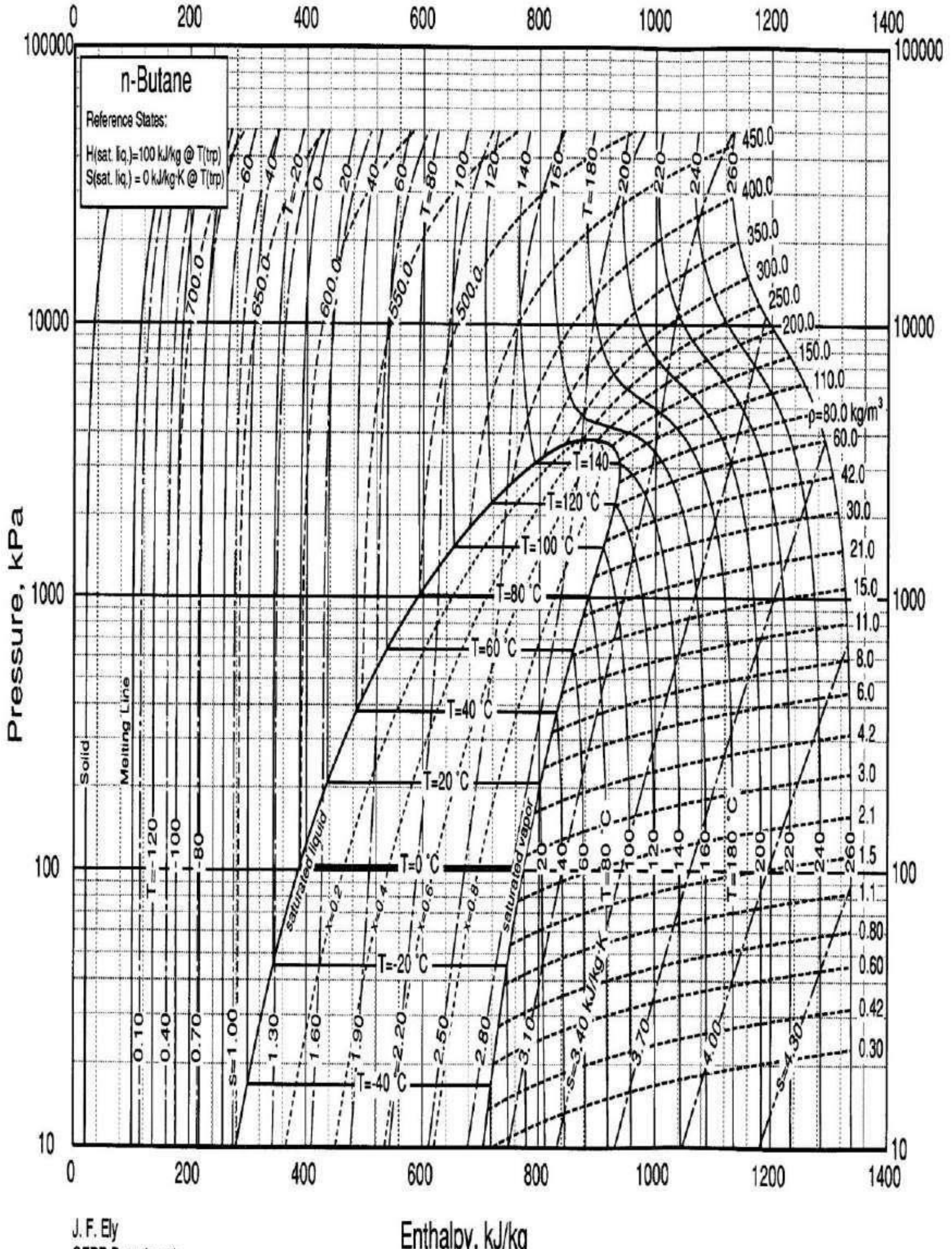

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Figure 11: plot of pressure vs enthalpy

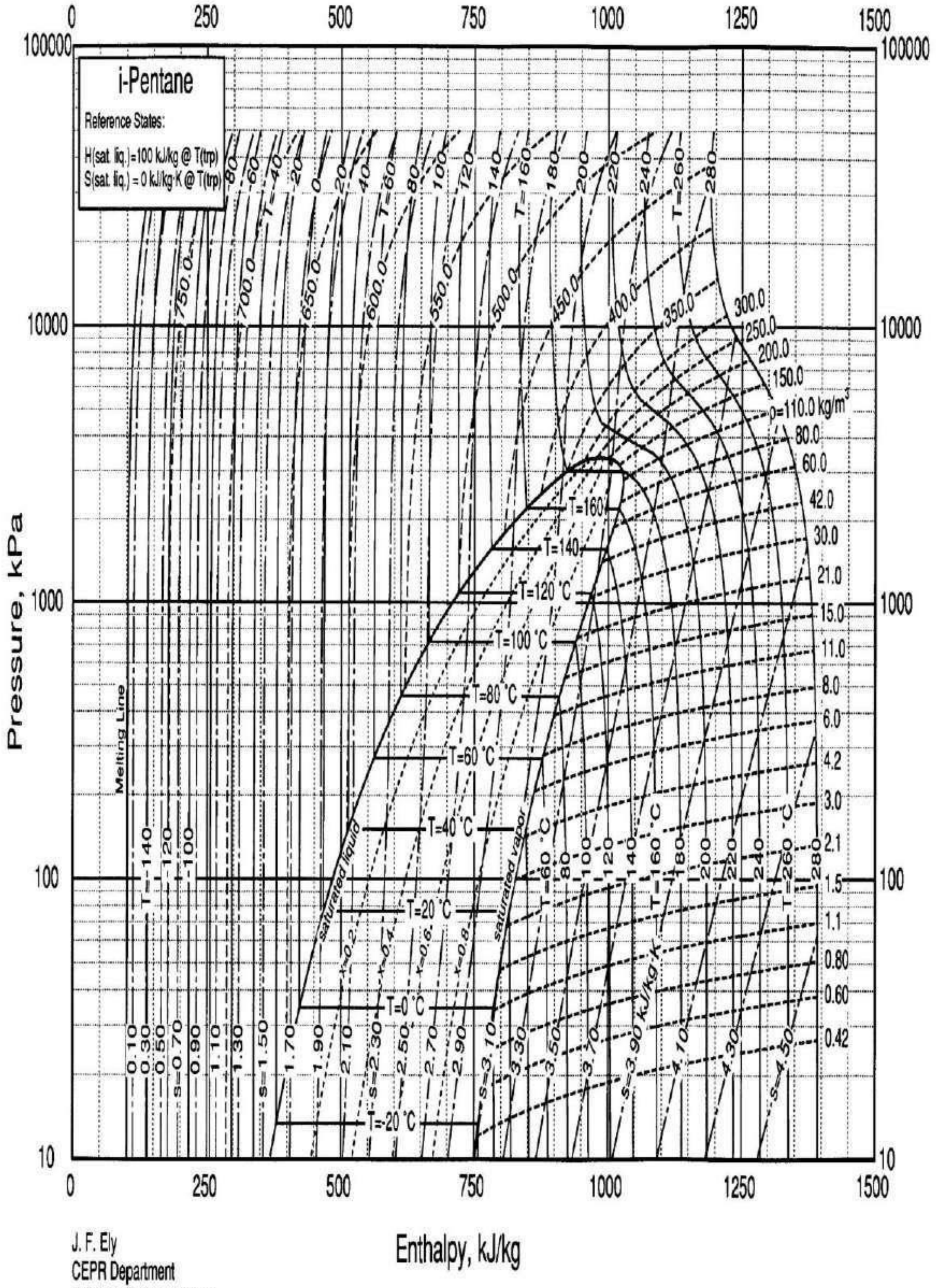

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Figure 12: plot of pressure vs enthalpy

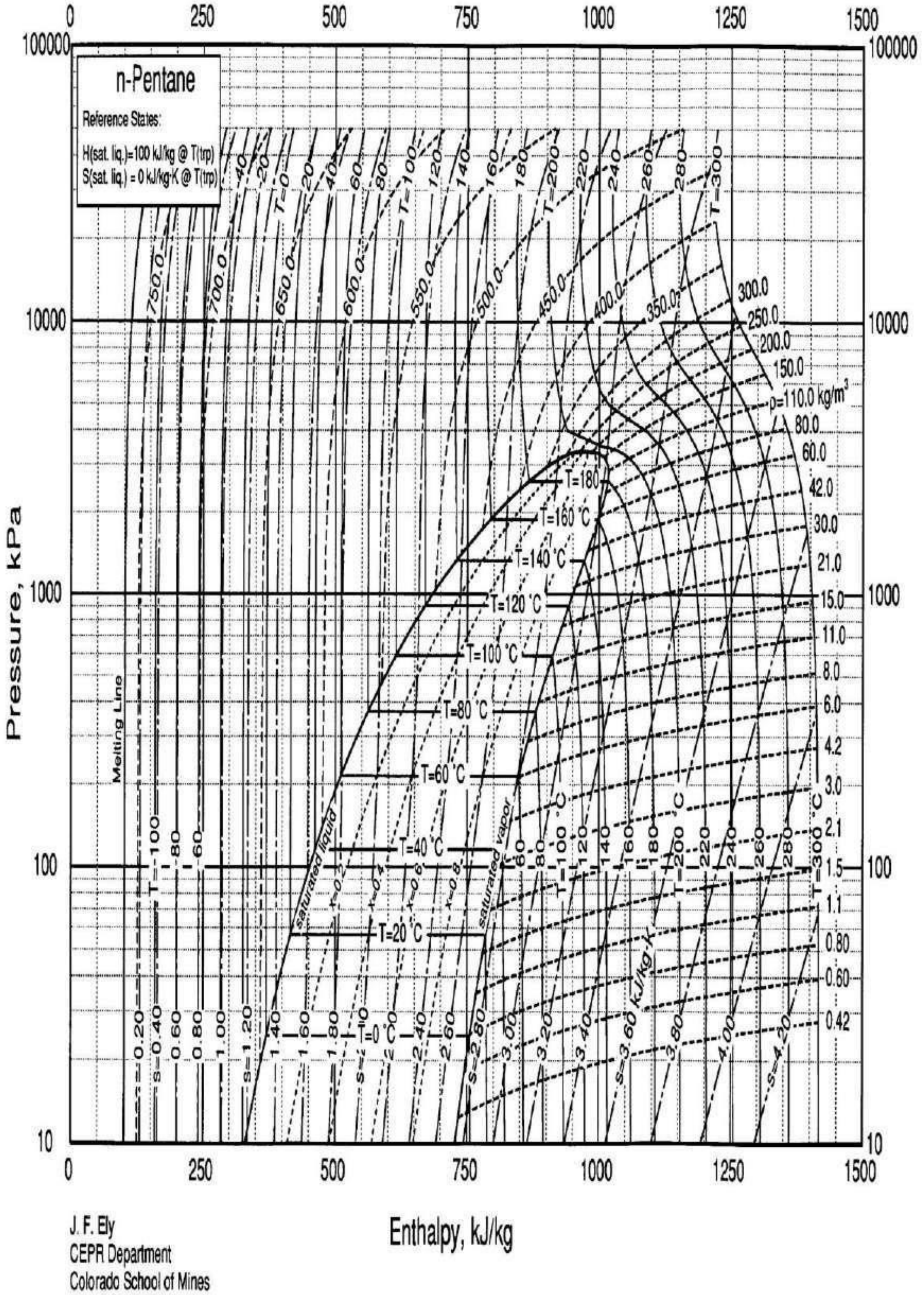

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Figure 13: plot of pressure vs enthalpy

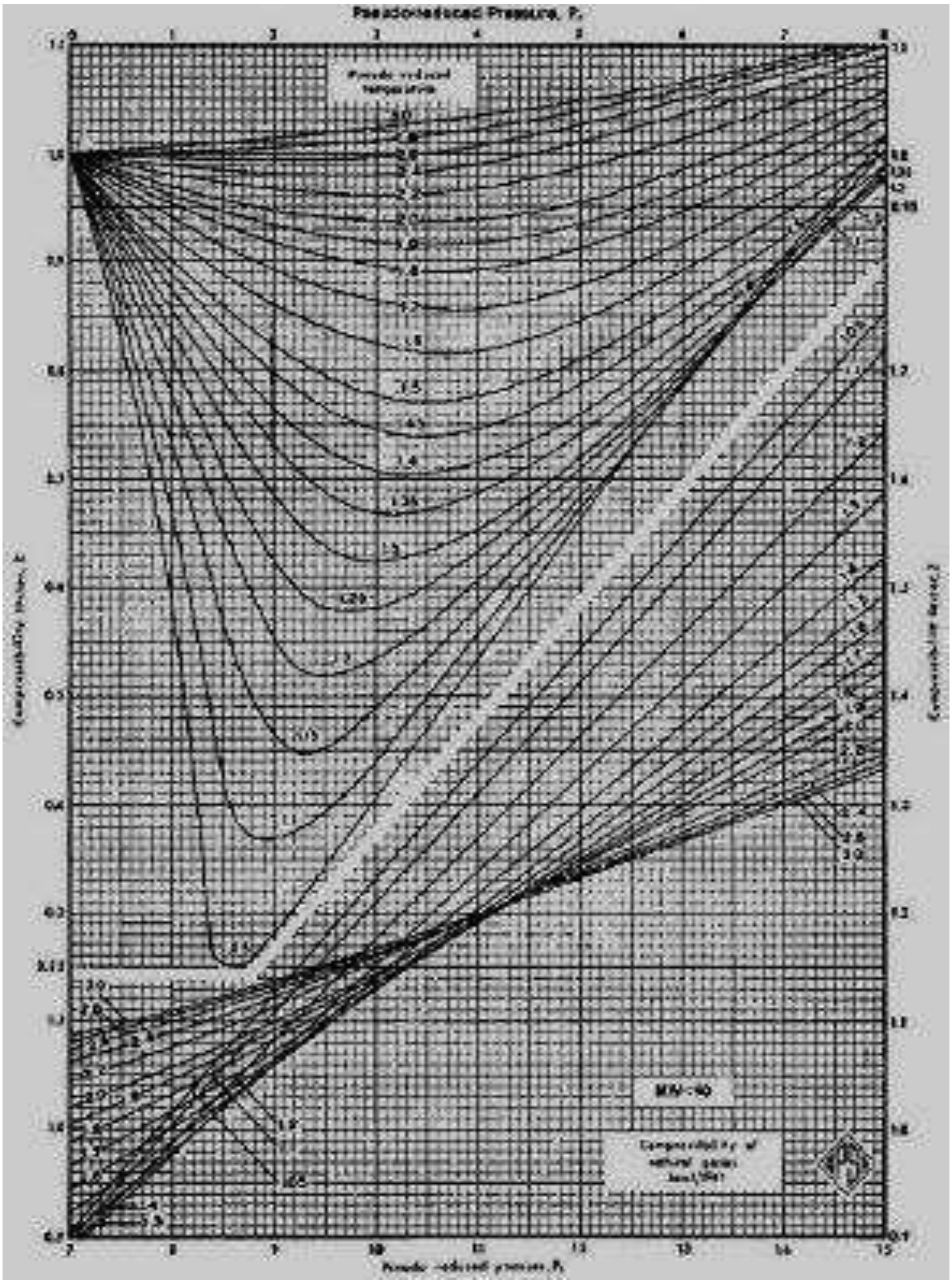

Figure 14: plot of Compressibility Chart