

EXPERIMENTAL EVALUATION OF CONVERGENT–DIVERGENT GEOMETRIES APPLIED TO NATURAL GAS TREATMENT IN THE OIL INDUSTRY

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ABSTRACT

Natural gas processing involves challenges associated with the presence of moisture and condensable components in gas streams released during drilling and production operations. The control of these phases is crucial to ensure operational safety, equipment integrity, and efficiency in separation systems. In this context, compact devices based on compressible flows have been investigated as alternatives for intensifying natural gas treatment processes. This work presents the operational evaluation of an experimental bench designed to study flows in convergent-divergent geometries with potential application in the treatment of natural gas streams. Two configurations were developed: a convergent-divergent nozzle, with the throat identified as the point of smallest diameter, and a second version containing a section of constant area of 6 cm between the convergent and divergent regions, maintaining the characteristic diameters. The experiments were carried out using dry air as the working fluid, with inlet pressures between 3 and 6 bar. The instrumented test bench provided continuous monitoring of pressure, temperature, and humidity, with data acquisition at one-second intervals, enabling the construction of profiles along the position and time. Analysis of the pressure profiles demonstrated differences in recovery dynamics in different geometries, indicating that design modifications influence the behavior of compressible flow. The results provide relevant experimental data for the development of devices applicable to the treatment and conditioning of natural gas in the oil industry, especially in applications that require compact and robust solutions.

KEYWORDS:

natural gas; compressible flow; fluid processing; separation; purification.

INTRODUCTION

The rising need for high-quality natural gas has driven the development of advanced technologies to remove contaminants, such as water and condensable components, at early stages of production. Compared with conventional technologies, supersonic separators have gained popularity due to their ability to physically separate the contaminants through rapid cooling of the gas, without requiring chemical additives or large-scale equipment (Yang et al., 2024).

The operating principle of the supersonic separator is based on compressible flow inside convergent-divergent nozzles, in which the acceleration of the fluid to supersonic velocities results in sharp drops in temperature and pressure, enabling the condensation of undesirable components (Haghighi et al., 2015). However, the separation efficiency is strongly dependent on the flow regime and on the pressure recovery at the nozzle outlet. The supersonic flow inside a convergent-divergent nozzle usually generates a shock wave, which represents a significant operational challenge when carrying out the experimental tests, because it can induce the reheat of the fluid and re-evaporation of condensed droplets, thereby compromising the separation performance (Niknam et al., 2017).

The geometry of the nozzle represents a crucial role in the formation, intensity and position of the shock waves, and also in the distribution of the thermodynamics parameters along the flow. Modifications in the divergent section or the inclusion of a constant area sections can significantly change the pressure gradients and the pressure recovery, acting as a flow stabilization and influencing the overall performance of the supersonic separator (Majidi and Farhadi, 2020; Ding et al., 2023).

In this context, this study initially focused on subsonic flow conditions since this regime allows a more controlled comprehension of the geometric effects of the nozzle on the flow and the influence of a constant area section on pressure recovery. This strategy enables a detailed analysis of pressure profiles along the constant section, reducing the complexity associated with intense compressible effects, such as the shock waves and nonlinear interactions. Thus, fundamental insights are obtained for improving the design and efficiency of the supersonic separator, which can later be used to support analyses under supersonic flow regimes.

MATERIALS AND METHODS

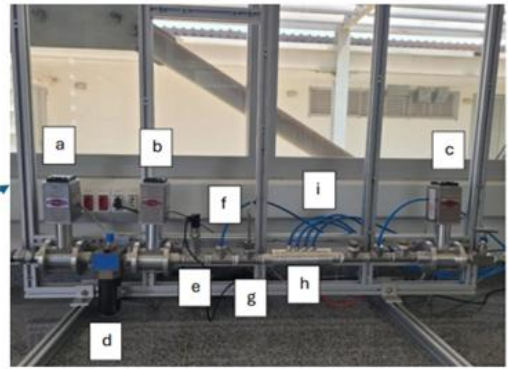
The experimental unit used in the tests is shown in Figure 1. Figure 1(a) shows the system where the compressed air is generated. The separation unit, which includes flow meter, humidifier, humidity and temperature sensors, the convergent-divergent nozzle and the measurement points along the line, is shown in Figure 1(b).

Figure 1 - Compressed air generation system (a) and separation unit (b).
(Authors, 2026).

(a)



(b)



*flow meters (a,b,c), humidifier (d), humidity, pressure and temperature sensors (e,f,g), nozzle (h), pressure sensors in the nozzle (i)

The compressed air is generated by a system consisting of a compressor with maximum pressure of 13 bar, followed by an air dryer and a storage tank with an approximate capacity of 500 L. The air is then conveyed to the separation unit through pipes suitable for the pressure range used in the experimental tests.

In the separation unit, the flow can be subjected to a humidification system to generate an air-water vapor mixture. However, in this study, the tests were carried out with dry air. The humidity was monitored only to validate this experimental condition.

The goal of the experimental tests was to evaluate the influence of inserting a constant area section on the pressure profile along the nozzle, observing the supersonic flow or not. In order to accomplish this, two geometric configurations were analyzed: a convergent-divergent nozzle (Figure 2(a)) with no addition section and including a constant area portion of 6 cm long (Figure 2(b)), with the same throat diameter and same linetypes of the convergent and divergent regions. An Arina profile (Arina, 2004) was used to create the geometries of the convergent and divergent sections, following the equations shown in Table 1.

Figure 2 – Convergent-divergent nozzle and separator (Authors, 2026).



Table 1 - Equations for convergent and divergent sections (Authors, 2026).

Section	Equation
Convergent	$A(x) = 2,5 + 3 \left(\frac{x}{x_{th}} - 1,5 \right) \left(\frac{x}{x_{th}} \right)^2 \quad x < x_{th} \quad (1)$
Divergent	$A(x) = 3,5 - \frac{x-L_{th}}{x_{th}} \left(6 - 4,5 \left(\frac{x-L_{th}}{x_{th}} \right) + \left(\frac{x-L_{th}}{x_{th}} \right)^2 \right) \quad x > x_{th} \quad (2)$

In Table 1, x_{th} represents the position of the throat relative to the nozzle inlet, x is the current position, and L_{th} is the length of the constant area section.

The dimensions of the equipment, presented in Figure 2, are summarized below:

- inlet diameter of the nozzle: 1,78 cm;
- throat diameter: 1,128 cm;
- length of the constant area section: 5 cm;
- length of the convergent section: 5 cm;
- length of the divergent section: 5 cm.

The convergent-divergent nozzle is 10 cm long, while the other configuration including the constant area section is 16 cm long.

During the experiments, the inlet pressure was adopted as the main operational variable, being adjusted by a regulating valve to values of 2, 4, 5 and 6 bar in the tests with the convergent-divergent nozzle. For the configuration including the constant area section, the pressure was adjusted to 5 and 6 bar. Pressure, temperature and humidity were monitored using a data acquisition system with a sampling rate of 1 s. The volumetric flow rate was measured using turbine-type flow meters installed at the inlet and outlet of the system. Each experimental condition was evaluated in triplicate.

The pressure was measured at nine different points along the convergent-divergent nozzle, distributed between the inlet and outlet and through the equipment. For the configuration including the constant area section, the pressure was measured at nine points through the nozzle and at the inlet and outlet. Humidity and temperature were measured in two points, located at the inlet and outlet of the line.

RESULTS AND DISCUSSIONS

The pressure profile obtained for different pressure inlet (for both geometry configurations) are presented in Figure 3. In Figure 4, the same results are presented as a function of the measurement point along the nozzle, excluding the points located at the inlet and outlet.

For all experimental conditions, a pressure drop in the convergent section was observed, followed by a partial recovery in the divergent section. However, the profiles show that the flow acceleration was not sufficient to establish a supersonic flow at any of the inlet pressure or geometries analyzed. Consequently, no abrupt discontinuities were observed in the pressure profile that could be associated with the formation of the shock waves.

Figure 3 – Pressure profiles inside the convergent-divergent nozzle (a) and separator (b), considering the inlet and outlet points of the line.

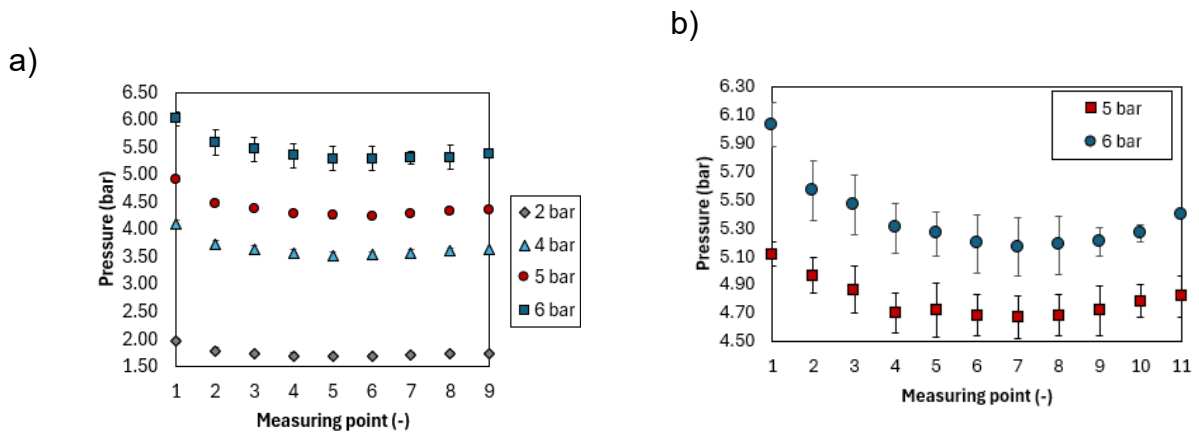
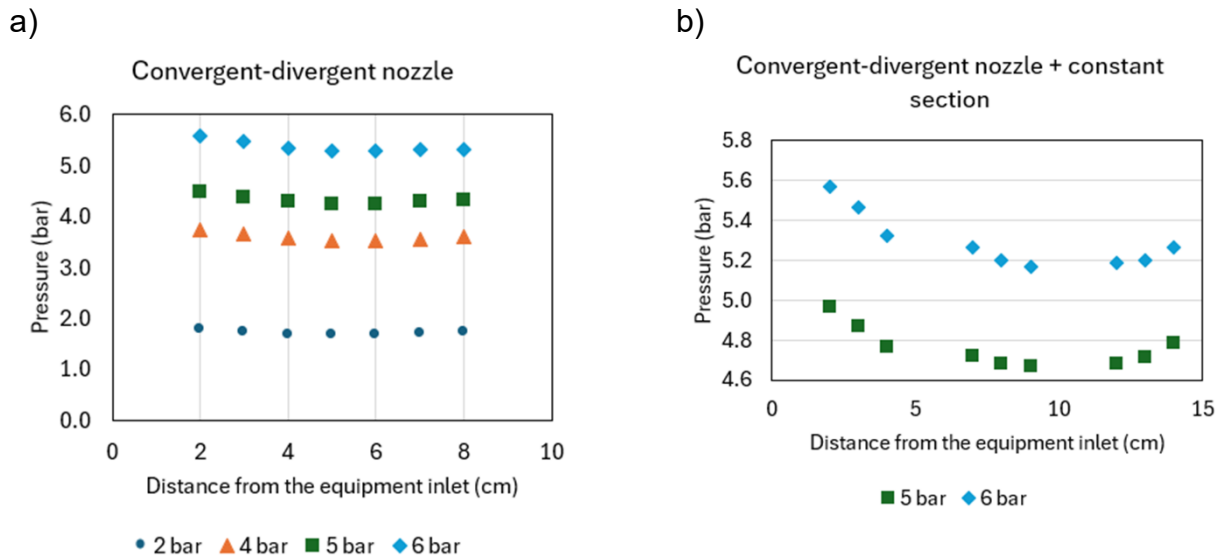


Figure 4 – Pressure profiles inside the convergent-divergent nozzle (a) and separator (b) as a function of the distance from the equipment inlet.



For inlet pressure varying for 2 to 6 bar, the pressure profile inside the convergent-divergent nozzle showed an initial pressure drop at the first measurement points, followed by a minimum value (which corresponds to the closest point to the throat) and by a gradual pressure recovery along the divergent section. Increasing the pressure at the inlet, higher flow rates were observed. Also, the pressure drop along the nozzle was intensified. Nevertheless, even for the higher inlet pressure, the measured pressure along the nozzle showed smooth and continuous variations, characteristic of subsonic flows and flows near the critical regime ($Mach = 1$).

The configuration including the constant area section, where the flow was evaluated for inlet pressures of 5 and 6 bar, also showed continuous pressure profiles along the equipment. The pressure variation was more distributed along the length and, consequently, the pressure recovery occurred more gradually, with no abrupt changes, for both 5 and 6 bar.

Although high pressure recoveries were obtained in both geometries, the comparison between both of them (for equivalent pressure inlet) have revealed differences in the pressure profiles along the axis. For the convergent-divergent nozzle, the pressure recovery occurred mainly in the divergent section. However, for the geometry which includes the constant area section, the recovery was more distributed along the equipment, with smoother gradient pressure along the flow. Additionally, this configuration provided a slightly higher-pressure recovery than that observed in the conventional convergent-divergent nozzle. This difference, although small, has shown that the presence of a constant area section influences the pressure recovery even in the absence of supersonic velocities.

The absence of the supersonic regime for all experimental conditions evaluated in this study is related to the operation limitations of the system used to generate the compressed air, particularly the flow rate. From the perspective of the compressible flow theory, the establishment of supersonic velocities in a convergent-divergent nozzle depends on the flow choking at the throat, where the mass flow rate reaches its critical value that results in a Mach number equal to the unity. This condition was not achieved in all the operation conditions, even for inlet pressure on the order of 6 bar.

Despite the absence of supersonic velocities, the results showed that the nozzle geometry has a direct influence on the flow dynamics. The constant section area promoted a more gradual pressure recovery and a shift on the point of minimum pressure. This effect can be interpreted as a flow stabilization region prior to the divergent section, reducing sharper local gradients and contributing to smoother pressure profiles when compared to those obtained in the convergent-divergent nozzle. Therefore, the presence of a constant area section can also contribute to a supersonic separation since it acts as a flow stabilization before the divergent expansion. This intermediate region tends to reduce sharp local gradients of pressure and velocity, allowing the flow to reach the divergent section in more uniform conditions. In supersonic separators of natural gas, the efficiency of process is strongly related to the flow stability, to the position and intensity of the minimum pressure and temperature regions, as well as the controlled formation of shock waves downstream (Wen et al., 2011). This is particularly important in the supersonic regime because flows with sharp local gradients or non-uniformities tend to anticipate or intensify shock waves, which can locally increase pressure and temperature, impairing the condensation of heavier components and, consequently, the separation efficiency.

The pressure recovery observed (approximately 89% for the convergent-divergent nozzle and 94% for the geometry which includes the constant area section) can be considered to be high, yet consistent with the experimental conditions used in the tests. The absence of shock waves means the lack of a dissipative mechanism associated with the abrupt conversion of kinetic energy into internal energy. In subsonic regimes, the acceleration and deceleration occur continuously, with pressure recovery being predominantly governed by the efficiency of the diffusion process and viscous losses, such as friction with the nozzle walls. This results in smooth and continuous pressure profiles.

At the convergent section, the fluid accelerates and the pressure drops. However, in the divergent section, the fluid decelerates, with a progressive conversion of kinetic energy into static pressure, which characterizes a diffusive pressure recovery. If shock waves were observed, an abrupt increase in pressure would be expected, along with

more significant irreversible losses of total pressure, resulting in lower efficiency of overall pressure recovery.

Finally, the error bars associated with the measurement of pressure remained small, indicating good reproducibility of the experiments. In some points along the axis, particularly in regions farther from the inlet, a moderate increase of the uncertainties was observed. This is possibly due to local fluctuations of the flow, to higher sensibilities to distributed losses and to the propagation of the uncertainties associated with the measurement along the nozzle.

CONCLUSION

The results, even under subsonic flow, allowed for a comparison of different geometries in the proposed separation unit. It was concluded that the presence of the constant section promotes a redistribution of the pressure gradient, highlighting the influence of geometry even outside supersonic conditions. The observation of the geometric effect confirmed that geometric modifications impact the pressure profile under different operating conditions and affect flow stability. Further investigations involving higher flow rates, different constant-section lengths and combination of experimental tests and numerical simulations may contribute to the understanding of supersonic flow and to the improvement of the design of these devices based on the preliminary results of this study.

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