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AN ANALYSIS OF SUPERSONIC SEPARATION TECHNOLOGY FOR NATURAL GAS SWEETENING IN SCENARIOS WITH HIGH CO_2 CONCENTRATION

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Abstract: The increase in natural gas production in the area known as the pre-salt of the Santos Basin, associated with high concentrations of CO_2 (up to 80% molar) in the east margin offshore Brazil, has motivated the use of compact technologies, such as supersonic separators, for the treatment of natural gas, with the aim of reducing production costs. Supersonic separators are already used for natural gas dehydration and heavy hydrocarbon removal. The present work aims to analyse the potential of supersonic separators to remove high contents of CO_2 from natural gas. Computational fluid dynamics (CFD) was used to simulate the natural gas flow inside a supersonic separator and define its pressure-temperature profile. The numerical model was validated with data from the literature. Phase envelopes of fluid and gas phase composition in equilibrium with the liquid in the regions of interest were built for scenarios of 45% and 80% CO_2 concentration. Results indicate that the gas may reach pressure and temperature conditions inside the supersonic separator capable of promoting the separation and obtaining treated gas with low CO_2 content.
Keywords: Carbon dioxide, supersonic separation, natural gas, computational fluid dynamic.

INTRODUCTION

In 2022, oil production in Brazil reached a daily average of 3.0 million barrels, where 75.2% of this production came from the pre-salt area of Santos Basin, in the east margin of Brazilian offshore. Besides, the production of natural gas in Brazilian fields has increased by 2.98%, compared with 2021, which represents natural gas production of 138 million cubic meters per day (MMSm3/d, where the gas volumes are at 20 °C and 1.01 bar) (AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS, 2022).

This high production of natural gas in the pre-salt would increase the fluid processing area in the offshore oil production units (FPSO) due to the high gas-to-oil ratio (GOR) found in these fields. For instance, GOR is 400 in the produced fluid of Mero field (AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS, 2022). Additionally, most of the production from the reservoirs in pre-salt has a high concentration of CO2, with some of them as high as 80% molar (D'ALMEIDA *et al.*, 2018).

The available technologies for CO_2 removal are not economically feasible in all ranges, being necessary an evaluation of natural gas characteristics in order to choose the most suitable process. For low CO_2 contents, an absorption process with amines can be used. However, for high contents, up to 90% of CO_2, the gas permeation through polymeric membrane represents lower costs than other conventional technologies. Additionally, considering other guidelines, that is, footprint and power generation limits, explains why membrane technology is being adopted in FPSOs of pre-salt (FRAGA *et al.*, 2015).

Although the CO_2 separation process with membranes is the best option among the conventional ones, the gas processing system still occupies a large part of the topside of an FPSO. Actually, FPSO oil production is limited by natural gas treatment capacity. Therefore, it requires using compact technologies, such as supersonic separators, to treat natural gas, reducing production costs and processing module footprint.

Dehydration of natural gas using supersonic separators is a proven technology. Upon entering the supersonic separator, the gas acquires tangential velocity through internal devices. In the section with geometry similar to a convergent-divergent nozzle, gas accelerates and after the throat flow becomes supersonic, which, due to energy conservation in the system, is responsible for decreasing gas temperature to sufficiently low values to promote the condensation of water or hydrocarbons present in the gas. Due to the tangential velocity component, the liquid is concentrated on the wall of the apparatus and collected before the two-phase mixture reaches the outlet, where the treated gas has lower concentration contaminants than the inlet stream (OKIMOTO *et al.*, 2002). The same principles can be used to remove CO_2 from natural gas, as it is a condensable component.

Many works are studying, through computational fluid dynamics (CFD), the application of supersonic separation to remove water from natural gas. Jassin (2008) has used CFD analyses and observed significant differences in the density and pressure profiles along the convergent-divergent nozzle when using real gas equations of state instead of the ideal gas law at pressures above 100 bar. When comparing the density and pressure profiles using different equations of states and the ideal gas law, Yang et al (2014) have found no significant differences in profiles with inlet pressure below 100 bar. Yang *et al.* (2017) have studied the effects of geometry parameters on the flow inside of a supersonic separator and concluded that 8 to 16 vanes provide an acceptable separation performance.

All these works have simulated the flow inside a supersonic separator without CO_2 in the composition of natural gas. Sun *et al.* (2017) used CFD to study the flow of a binary mixture of methane and CO_2. It was observed that, under the studied conditions, with inlet concentrations above 10%, it was not possible to provide outlet gas with less than 3% of CO_2, indicating that new evaluations were necessary.

This work aims to investigate, using CFD technics, the application of a supersonic separator to remove CO_2 from natural gas in a scenario with high CO2 concentration, which impacts the production development of pre-salt fields.

MATHEMATICAL MODELLING

The flow inside the supersonic separator is considered compressible and can be modelled by the mass, linear momentum and energy conservation equations. In order to achieve the maximum potential of supersonic separation technology in removing CO2 from natural gas, inviscid flow was considered in this study. Energy degradation due to viscous fluid was disregarded, getting the maximum potential of gas cooling. Therefore, Equations 1 to 3 govern the present work's single-phase flows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \qquad (1)$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p \qquad (2)$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot [\rho(e + pv)\boldsymbol{U}] = 0 \qquad (3)$$

where p is specific mass, t is time, u is the velocity vector, p is pressure and e represents the total energy.

METHODOLOGY

All simulations were conducted using the ANSYS FLUENT CFD tool package. Results obtained by ARINA (2004) were used in the validation of the modelling and numerical methods. A flow in a convergent-divergent (C-D) nozzle was simulated, representing the typical geometry used in supersonic separators. The SIMPLE algorithm (PATANKAR AND SPALDING, 1972) was used for pressure-velocity coupling in solving the conservation equations. A second-order upwind scheme was used for the interpolation of flow variable values at the face. The convergence criterion adopted was 10^{-6} for the energy equation and 10^{-3} for the other equations. The RK equation

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of state (REDLICH AND KWONG, 1949) was adopted in this work. A grid independence test was performed, and it was observed that a mesh with 245,000 elements no longer influenced the results. The boundary conditions of the simulations were defined as presented by ARINA (2004).

In order to evaluate the capability of the supersonic separator in removing CO_2 from natural gas, the supersonic separator presented in Yang (2014) was used as they used operational conditions close to those of gas treatment. The fluid used was natural gas with a molar percentage of CO_2 equal to 45%. The boundary conditions of the simulations were defined, as presented by Yang (2014). After performing grid independence tests, a mesh with 45,000 elements was adopted.

The capability of removing CO_2 from natural gas was assessed based on phase envelope of fluid and gas phase composition in equilibrium with the liquid in the region of interest, both calculated with Aspen HYSYS process simulator. The P-T curve from flow simulation is then presented in a phase envelope and discussed.

RESULTS AND DISCUSSION

The pressure profile obtained for the convergent-divergent nozzle of ARINA (2004) is shown in Figure 1.

It can be observed in Figure 1 that it was possible to reproduce the literature data of ARINA (2004) for the inviscid flow modelling, and then this condition was adopted in the simulations with a high content of CO_2 under the conditions of YANG (2014).

The pressure and temperature path taken by the gas inside the supersonic separator obtained in the CFD simulation is shown in Figure 2, along with the phase envelope of natural gas with high content of CO_2 (45% CO_2).

According to Figure 2, the gas reaches regions of the phase envelope where the vapour phase has less than 3% CO_2 (mole percentage), which indicates that if the condensed phase were collected at that point, the gas resulting from the process would be with amounts of CO_2 close to those normally desired in offshore production units.

Results from a scenario with 80% CO_2 (mole percentage) in natural gas are shown in Figure 3.

Due to the high CO_2 concentration, the fluid can condensate completely inside the supersonic separator. For that, it was necessary to set the inlet pressure at 80 bar. One can see that the fluid inside the equipment can reach low enough temperatures to get a vapour phase with CO_2 concentration below 9%. At the outlet of the supersonic separator, the fluid is still inside the phase envelope, as the condensate collection was not simulated. It is also important to note that to have a gas treatment with less than 9% CO_2, more than 90% of total fluid mass will condensate, which cannot be feasible in industrial scale.

In a scenario where one does not want to specify CO_2 at such low levels, supersonic separation technology's removal process becomes even more attractive, as the necessary inlet operational conditions would be more easily achieved.

CONCLUSIONS

The simulations indicate that it is possible to reproduce the shock wave obtained in benchmark work through CFD simulations under the mathematical modelling and numerical methods adopted. The consideration of inviscid flow neglects energy losses and provides the maximum potential of supersonic separators.

Gas flow simulations with high CO_2 content indicate that the gas may reach pressure and temperature conditions inside the supersonic separator capable of promoting the separation

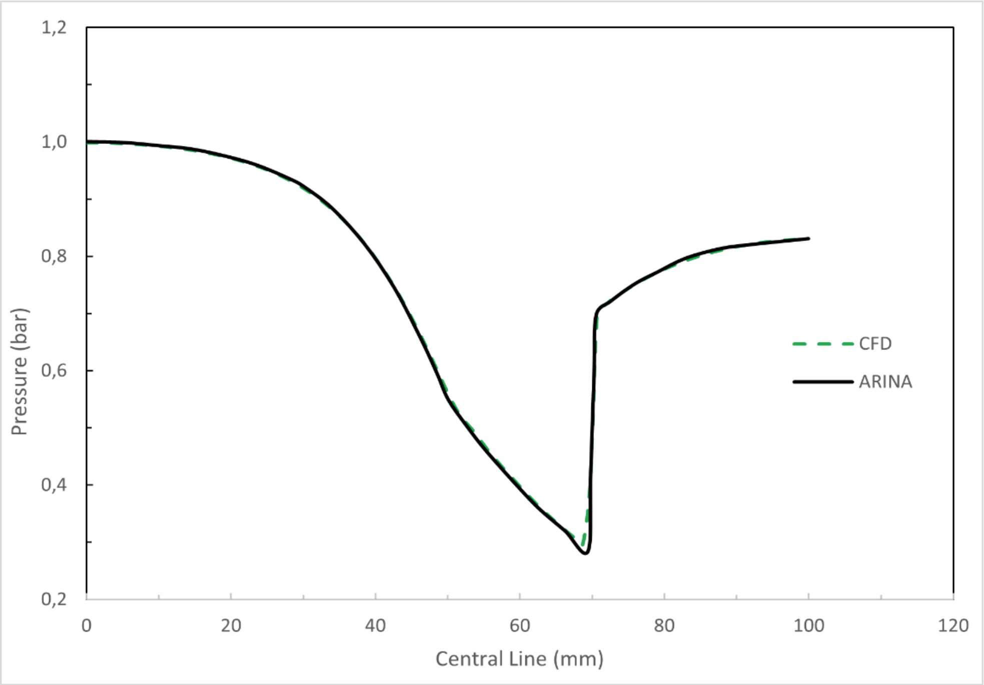

Figure 1: Comparison between the pressure profiles obtained in this work and by ARINA (2004).

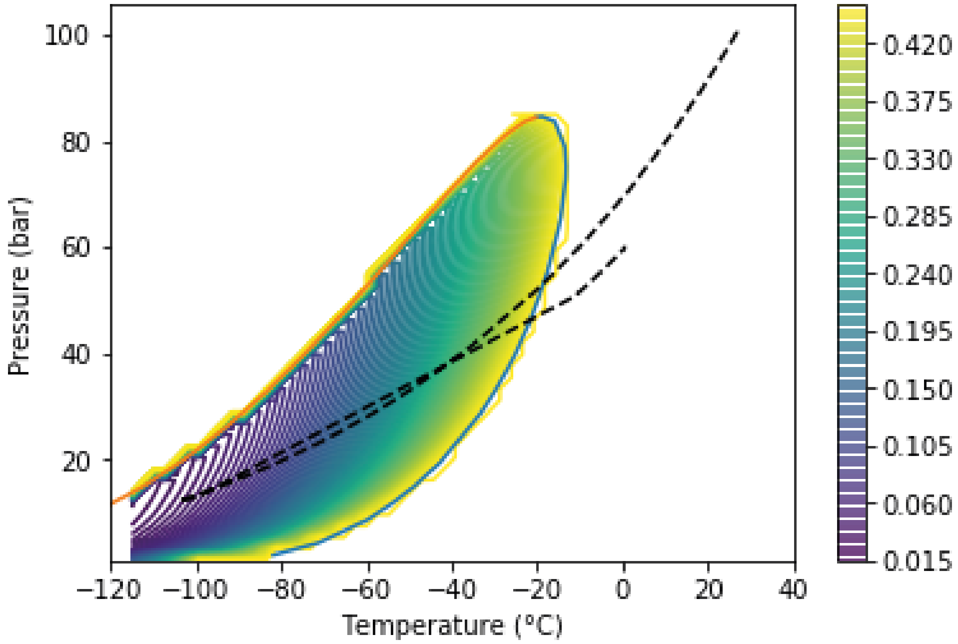

Figure 2: Phase envelope and P-T path of high CO_2 natural gas inside the supersonic separator obtained with CFD simulation (dashed line in black. Scenario of 45% CO_2 in natural gas. Colour map indicates the concentration of CO_2 in the vapour phase.

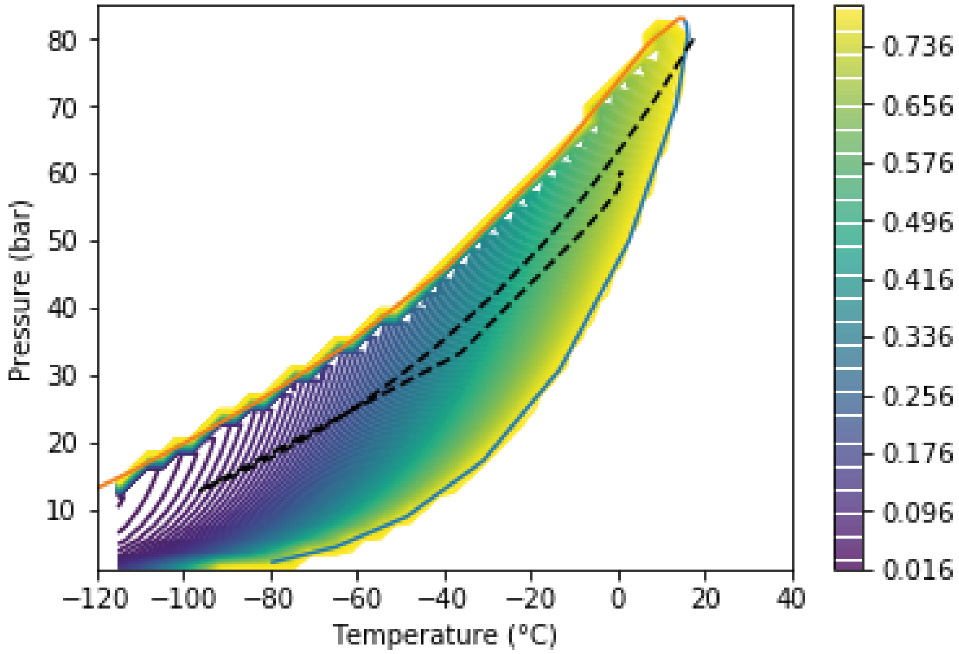

Figure 3: Phase envelope and P-T path of high CO_2 natural gas inside the supersonic separator obtained with CFD simulation (dashed line in black. Scenario of 80% CO_2 in natural gas. Colour map indicates the concentration of CO_2 in the vapour phase.

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and obtaining treated gas with low CO_2 content. However, further studies are required to understand how viscous effects and latent heat released within the supersonic separator may affect the present results and conclusions.

REFERENCES

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS. **Boletim da Produção de Petróleo e Gás Natural - 2022**. Rio de Janeiro: Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2022. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/boletins-anp/boletins/arquivos-bmppgn/2022/encarte-e-boletim-dezembro-2022.pdf

CASTIER, M. **Modeling and simulation of supersonic gas separations.** Journal of Natural Gas Science and Engineering, v. 18, 2014. http://www.sciencedirect.com/science/article/pii/S1875510014000754.

D'ALMEIDA, K.S.; VILELA, P.C.; CARDOSO, R.A.; FERNANDES, R.F.; SOUZA, M.F.F. **Ocorrência de CO2 em Campos Petrolíferos Na Margem Leste Brasileira**. In: Congresso Brasileiro de Geologia, 49, 2018, Rio de Janeiro.

FRAGA, C.T.C; PINTO, A.C.C.; BRANCO, C.C.M.; PIZARRO, J.O.S.; PAULO, C.A.S. **Brazilian Pre-Salt: An Impressive Journey from Plans and Challenges to Concrete Results**. In: Offshore Technology Conference, 2015, Houston.

JASSIM, E., ABDI, M., MUZYCHKA, Y. **Computational fluid dynamics study for flow of natural gas through high-pressure supersonic nozzles:** part 1. Real gas effects and shockwave. Petroleum Science and Technology, v. 26, n. 15, pp. 1757-1772, 2008.

KARIMI, A.; ABDI, M. **Selective removal of water from supercritical natural gas**. In: SPE Gas Technology Symposium, 2006, Calgary, AB, Canada.

OKIMOTO, F.; BROUWER, J. M. **Supersonic gas conditioning**. World Oil, v. 223, p. 89, 2002.

S.V PATANKAR; D.B SPALDING. **A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows**. International Journal of Heat and Mass Transfer, v. 15, pp. 1787-1806, 1972.

Redlich, O.; Kwong, J. N. S. **On the thermodynamics of solutions**. V. An equation of state. Fugacities of gaseous solutions. Chemical Reviews, 44(1), 233-244, 1949.

SUN, W., CAO, X., YANG, W., et al. **Numerical simulation of CO_2 condensation process from CH_4-CO_2 binary gas mixture in supersonic nozzles"**. Separation and Purication Technology, v. 188, n. Supplement C, pp. 238 – 249, 2017. http://www.sciencedirect.com/science/article/pii/S138358661730196X.

YANG, Y., WEN, C., WANG, S., et al. **Numerical Simulation of real gas flows in natural gas supersonic separation processing**, Journal of Natural Gas Science and Engineering, pp. 829 – 836, 2014.

YANG, Y., LI, A., WEN, C. **Optimization of static vanes in a supersonic separator for gas purification**, Fuel Processing Technology, v. 156, n. Supplement C, pp. 265 – 270, 2017. http://www.sciencedirect.com/science/article/pii/S0378382016304908>.