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Numerical Modeling of the Fluids Petroleum Flow Through the Supersonic Separator

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ARTICLE INFO	ABSTRACT
Published online: 07 October 2024 **Corresponding Author:** Timur Chis	In the context of increasing concerns regarding the amplification of the thermal effects of climate change, the Council of the European Union has proposed the reduction (up to the elimination) of the use of fossil fuels. For this purpose, the implementation of new ecological (renewable) fuels is being analyzed to reduce the carbon dioxide footprint, natural gas being the transition fuel. Also, in the next period, an increase in the demand for methane, the exploitation of condensate deposits, those with natural gas mixed with acid gases (containing hydrogen sulfide, carbon dioxide, and nitrogen), as well as oil deposits with associated natural gas, which will require their treatment (to eliminate saline or non-saline water, mechanical impurities, of condensate and acid gases). At the same time, the exploitation of offshore deposits in deep waters will be emphasized, which will lead to the location of treatment equipment on the seabed. The present work discusses the simulation of natural gas treatment processes, focusing on the separation from methane (in the supersonic field) of water, condensate, and acid gases.

KEYWORDS: oil, gas, water, supersonic separator,

I. INTRODUCTION

The development of treatment techniques (drying, conditioning, separation) for contaminated natural gases is due to the implementation of processes necessary to remove water (present in gases from the saline aquifer), detritus (sand), and impurities associated with extraction (paraffin, ceresin, clay, and traces of chemical substances used in the treatment stage of productive layers) [1] .

Following the exploitation of gas deposits with condensate (gases containing higher fractions of hydrocarbons), as well as complex gas structures (containing hydrogen sulfide, carbon dioxide, nitrogen, mercury, and other impurities), there is a need to treat them (by removing impurities), in order not to affect the process of transportation, processing, and transformation, into energy or highly salable chemical products, of the extracted natural gases.

The analyses carried out on a set of samples taken from the natural gas extracted from Romania in the period 2020-2025 indicated the presence of some amounts of impurities and heavy components that depend on:

- the nature of the gas reserve (associated with crude oil deposits, not associated with or stored in shale),
-the geographical and petrographic location of the productive field,
- the way of formation of productive formations,
-the composition of the hydrocarbon-water-impurities system.

The chemical composition of natural gas typically indicates that it consists mainly of methane, ethane, and propane.

However, natural gas is also saturated with impurities that make it necessary to treat and condition it (natural gas must be dried and decontaminated) before it is delivered for use. The presence of these impurities can lead to the internal corrosion of the transport and processing facilities (as a result of the deposition of water particles and the hitting of their walls by the sand particles), to the blocking of the facilities (as a result of the formation of cryohydrates) as well as of the decrease in the commercial value of natural gas.

Water vapor and hydrogen sulphide are the impurities that must be eliminated due to the consequences of their action on transport and storage systems (corrosion of technological installations and/or the formation of sulfuric acid, which has catastrophic effects on the safety of the installations and the employees who operate them).

Dehydration is an extremely important process necessary to ensure safe pipeline delivery. Free water initiates the formation of hydrates.

Hydrates can lead to a reduction in the diameter of the transmission pipeline and subsequently to the blocking of the natural gas transport capacity of the pipeline.

Water also contributes to pipe corrosion (by forming galvanic deposits) and reduces natural gas's calorific value.

It is also essential that natural gas be dehydrated and decontaminated for the final catalytic and cryogenic processes applied in C3+ fraction separation technologies or for use as an automotive fuel (LNG).

Most industrial processes and facilities using natural gas require a high methane purity.

Therefore, condensate (NGL) or heavier hydrocarbons (C5+ fractions) must be separated below the methane dew point.

Traditional natural gas conditioning and condensate (NGL) extraction methods consist of facilities with high capital and operating costs.

The design and operation of these facilities are highly dependent on the quality of the natural gas and the productivity of the production well.

Traditional dewatering and decontamination units contain moving (rotating) devices and parts and require complex maintenance operations (with specialized staff employed).

Also, frequent maintenance and control of the installations are necessary, activities that lead to non-compliant gas production when they are started.

One of the newest techniques used in separating water from natural gas is their treatment in a supersonic flow (flow field) using a device (the supersonic separator).

This technique of separating water (dehydration process) and condensate (desalination process) is used more and more (especially in the small spaces of offshore platforms), the first research on the separation of fluids in the sonic field being carried out in 1972 [3].

The supersonic separator is a new technology for gas separation. The conceptual design of this separation system uniquely combines concepts from aerodynamics, thermodynamics, physical separation, and fluid dynamics, thus resulting in innovative conditioning (in terms of water separation techniques and condensate) of extracted natural gas.

Supersonic field fluid separation techniques were first patented by Alferov and his collaborators in 2002 and Betting with an advanced research group in the petroleum industry 2003 [4].

However, the first industrial application of this separation technique was realized in 2003, when a team of engineers from Twister BV patented and presented an industrial separator (initially for water from natural gas and later for condensate from natural gas) [5].

These devices have been installed in the offshore oil fields of Petronas and Sarawak Shell Berhad (SSB) [6].

Alferov and his collaborators also developed a supersonic separator, which they named Supersonic Separator Technologies (“3S”).

The supersonic separator provides condensation of water and wellbore condensate, preventing subsequent gas hydration in the treatment process.

It is a static device that requires little maintenance and can be placed in production areas where human activity is reduced.

At the same time:

- does not need moisture inhibitors,
- it has no moving parts,
- is environmentally friendly,
- ensures energy conservation,
- does not produce industrial waste.

The technology simultaneously achieves gas decontamination (extraction of CO2, sulfur, etc.), dehydration (water removal), and condensate extraction in a single processing unit.

A supersonic separator usually comprises a Laval Nozzle, a cyclone, and a diffuser.

II. MATHEMATICAL MODDELING OF FLUID FLOW IN SUPERSONIC SEPARATOR

In the supersonic separator, the thermodynamic properties change along the axial length of the nozzle.

Therefore, the position of a point along the nozzle is a critical parameter in modeling. However, nozzle geometries differ by design.

In general, the geometric configuration of the nozzle is defined by a specific convergent-divergent structure.

For example, in Arina's work [2], the geometric equations of the Laval nozzle are:

$$\frac{A(x)}{A_t} = 2,5 + 3\left(\frac{x}{x_t} - 1,5\right)\left(\frac{x}{x_t}\right)^2 \text{ where } x \leq x_t$$

$$\frac{A(x)}{A_t} = 3,5 - \frac{x}{x_t}\left(6 - 4,5\frac{x}{x_t} + \left(\frac{x}{x_t}\right)^2\right) \text{ where } x \geq x_t$$

Where A_t is the area of the convergent-divergent section.

Many comprehensive studies have been conducted to thoroughly analyze the air behavior in a convergent-divergent nozzle, specifically without side flows, ensuring the validity of the findings.

Air is a binary mixture of oxygen (21%) and nitrogen (79%).

The nozzle's inlet, throat, and outlet diameters are 130 mm, 26 mm, and 130 mm, respectively.

The diverging section of the nozzle is 600 mm long.

In the created model, the temperature of 288 K, the pressure of 0.1 MPa, and the velocity of 0.239543 Ma were taken at the nozzle entrance.

The nozzle specifications, particularly the back pressure of 0.083049 MPa and the area ratio (Aout/At) of 1.5, significantly influence the air behavior. (Aout is the area of the outlet section and At is the area of the convergent-divergent section).

The model accurately predicts the conditions at the four fundamental points (since no lateral flow emerges): the throat, before the shock wave, after the shock wave, and at the nozzle exit.

The calculation relationships are as follows:

$$y = -0{,}001x^6 + 0{,}0441x^5 - 0{,}7925x^4 + 7{,}5067x^3 - 39{,}499x^2 + 109{,}39x - 124{,}48$$

$$z = -1{,}064x^6 + 46{,}919x^5 - 853{,}04x^4 + 8175{,}8x^3 - 43520x^2 + 121871x - 139953$$

Where x is the pressure measurement length (dm), y is the measured pressure (MPa), and z is the measured temperature (K).

Similar to Arina's results, the shock wave occurs at a length equal to 6.2 dm. Before the shock wave, the simulation predicts a temperature and pressure of 210 K and 0.0236 MPa, respectively.

Along the shock wave, the temperature increases to 325 K while the pressure rises to 0.07 MPa.

For a gas consisting of methane, ethane, and propane with molar compositions of 96.044%, 2.98%, and 0.976%, respectively, we also studied the behavior of the two-phase flow through the convergent-divergent assembly with an area ratio $Aout/At$ of 5.

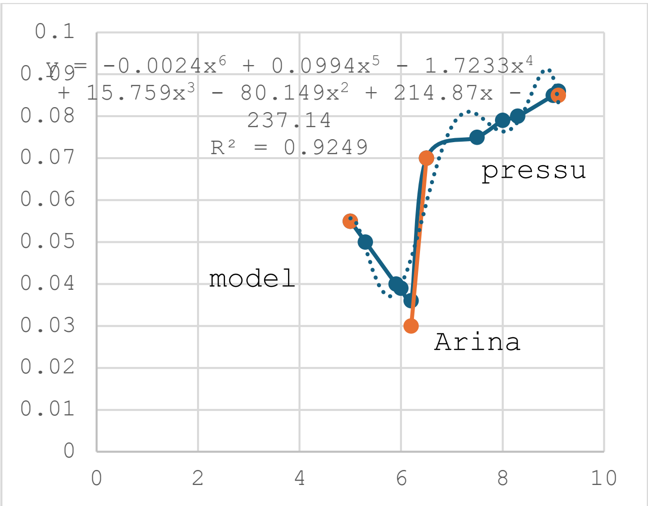

Fig.1. Pressure of model Arina, mathematical model and experimental model (MPa) function by distance of measurement (x)

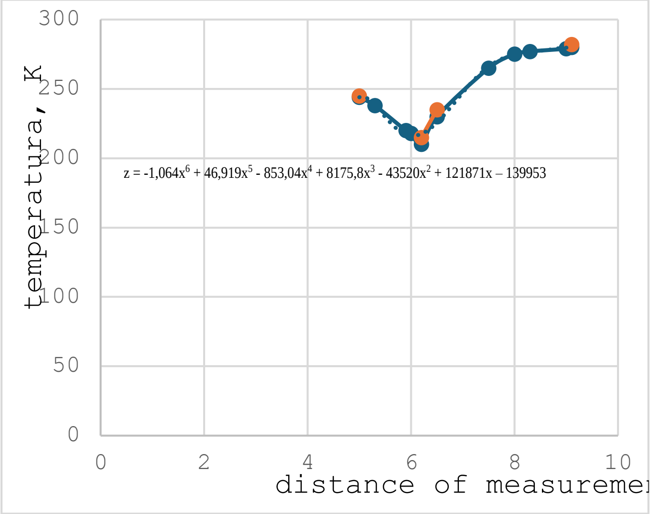

Fig.2. Temperature of model Arina, mathematical model and experimental model (K) function by distance of measurement (x)

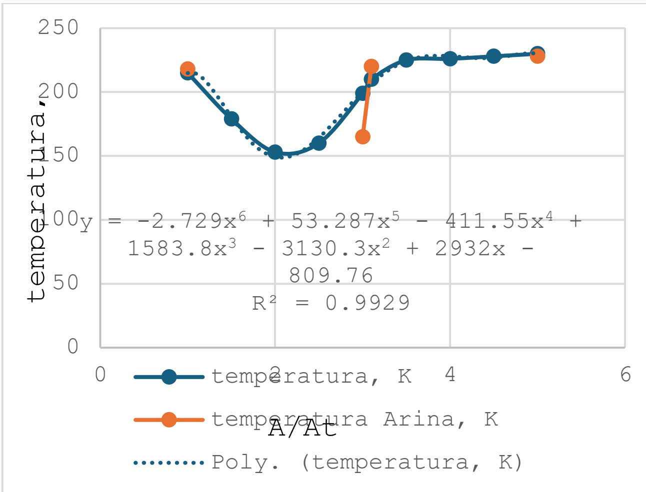

Fig. 3.Temperature variation of the two-phase fluid (natural gas) in the convergent-divergent device

The equations of temperature and pressure variation along the convergent-divergent device are:

y = -2.729x6 + 53.287x5 - 411.55x4 + 1583.8x3 - 3130.3x2 + 2932x - 809.76 (5.44)

z = -0.106x6 + 2.1467x5 – 16.929x4 + 64.984x3 – 123.14x2 + 102.67x – 22.654 (5.45)

where y and z are the temperature (k) and pressure (MPa) and x is the value of the A/At ratio.

And in the rendered simulation we can find that the shock wave is present at A/At values equal to 2 where the temperature is 153 K and the pressure is 1.5 and then it suddenly increases to the value of 210 K and the pressure is 5.8 Mpa.

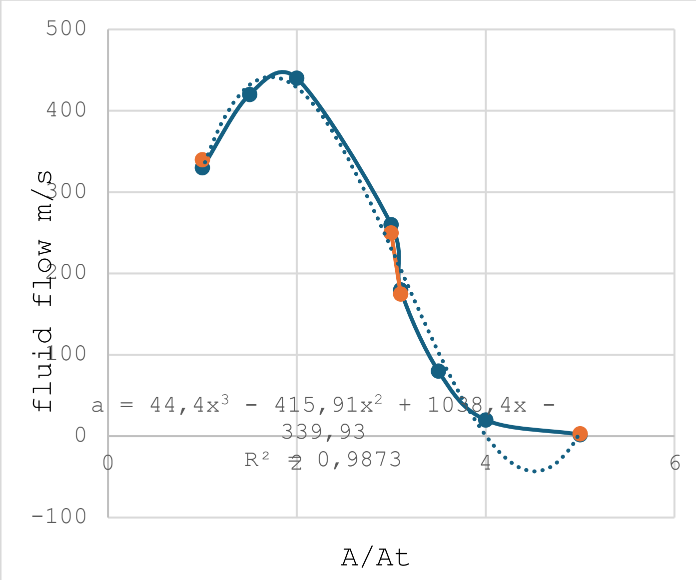

Fig. 4. Variation of the velocity of the two-phase fluid (natural gas) in the convergent-divergent device

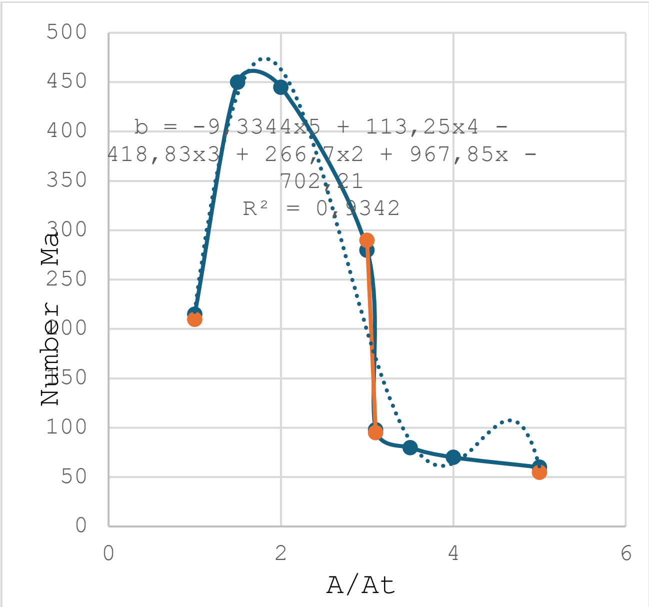

Fig.6. Variation of the Ma number for two-phase fluid (natural gas) flow in the convergent-divergent device

$a = 44{,}4x^3 - 415{,}91x^2 + 1038{,}4x - 339{,}93$

$b = -9{,}3344x^5 + 113{,}25x^4 - 418{,}83x^3 + 266{,}7x^2 + 967{,}85x - 702{,}21$

In the above equations a and b are the fluid velocity (m/s) and Ma number and x is the area ratio A/At.

It is interesting to analyze the evolution of the separation of methane and ethane gas fractions until the appearance of the shock wave.

In this case, a reduced separation tendency can be observed with the logarithmic prediction equations.

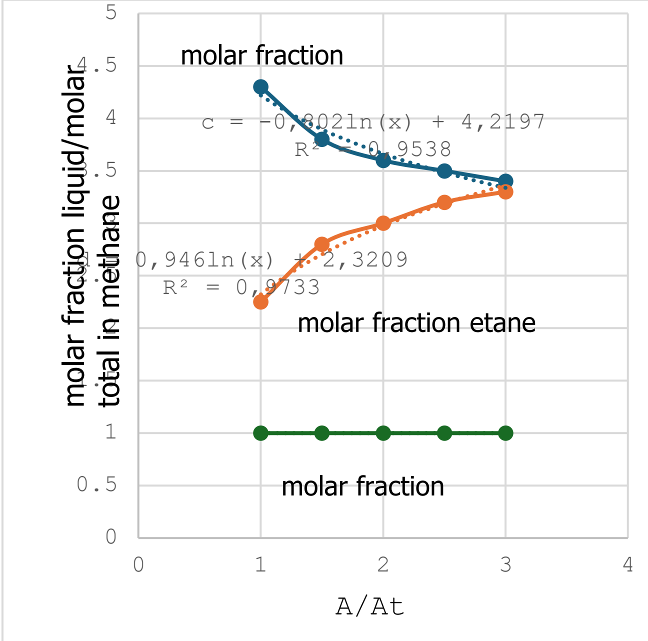

Fig. 7. Variation of molar fraction liquid/molar total in methane

$c = -0{,}802\ln(x) + 4{,}2197$

$d = 0{,}946\ln(x) + 2{,}3209$

where c and d are the ratios given by liquid mole fraction/total methane mole fraction and liquid mole fraction/total ethane mole fraction.

III. CONCLUSION

Following the analysis of the performed experiments, we can say that a flow of a multiphase fluid through a supersonic separator leads to the appearance of the following phenomena in the device (during the flow):

a. In the case of airflow (similar to the results of Arina), the shock wave occurs at a length equal to the value of 6.2 dm.

b. Before the shock wave, the simulation predicts a temperature and pressure of 210 K and 0.0236 MPa, respectively.

c. Along the shock wave, the temperature rises to 325 K, while the pressure rises to 0.07 MPa.

For a gas consisting of methane, ethane, and propane with molar compositions of 96.044%, 2.98%, and 0.976%, respectively, the study of the behavior of the two-phase flow through the convergent-divergent assembly with an area ratio $Aout/At$ of 5 indicates:

a. The shock wave is present at A/At values equal to 2, where the temperature is 153 K, and the pressure is 1.5, then suddenly increases to 210 K, and the pressure is 5.8 Mpa.

If we plot the evolution of the fluid speed and the Ma number, we observe a consistent positioning of the shock wave. Specifically, the shock wave appears at values of the speed of 260 m/s and a Ma number of 280.

c. After the shock wave appears, the values decrease to 180 m/s and 95 Ma's number.

Also, until the appearance of the shock wave, a vaporization of methane and an increase in liquid values of ethane are observed, propane not being affected by the flow (there is no vaporization of it).

In the last part of the analysis of fluid flow behavior through the supersonic separator, we can see that for a gas mixture:
- The temperature at which the formation of the shock wave occurs for a multiphase mixture of gases is 105% higher than in the case of the flow of a fluid consisting of methane, ethane and propane,
- The pressure at which the formation of the shock wave takes place is for a multiphase mixture of gases 176% lower than in the case of the flow of a fluid consisting of methane, ethane and propane,
- The minimum pressure at which the formation of the shock wave takes place is 0.036 MPa (in the case of air), 4.5 MPa (in the case of a fluid consisting of methane, ethane and propane) and 3 MPa
- The minimum temperature at which the formation of the shock wave takes place is 210 K (in the case of air), 199 K (in the case of a fluid consisting of methane, ethane and propane) and 145 K in the case of a multiphase mixture of gases,
- The values obtained by applying relations are close to those determined by Arina, which proves the efficiency of our calculation program.

Following the studies carried out, the numerical models have great working potential as a fast and precise tool for simulating and designing supersonic water separation plants from natural gases.
Although numerical models are less comprehensive and detailed than CFD models, they have been shown to produce accurate results comparable to those of CFD models and experimental data.
Thus, these models are an excellent tool for preliminary designs requiring lower computational loads.
The objective of this article was to present a rigorous one-dimensional thermodynamic model to simulate the supersonic separator.
The aim of the model is to improve certain aspects of the literature and introduce a technique for determining the position of the lateral flow and shock wave.
Notable disadvantages of existing works in the literature include:
- not taking into account the multiphase flow,
- the modeling of the nozzles is carried out without projecting lateral flows,
- the use of working fluids in a simplified way (maximum 2 phases and two compounds),
- the calculation of the thermodynamic speed of sound, which is an essential parameter for finding the Mach number, is not fully simulated,
- the eddy flow is not taken into account,
- high computational loads are required,
- The simulation period for the entire separation process was not fully modeled.
This article addresses some of these aspects by providing a more rigorous, faster, and more accurate model for supersonic separation.

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