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Modeling the flow of gases impure with water

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ABSTRACT: The flow of gases impure with water is necessary to determine the actual flow rates of petroleum fluids and establish techniques for separating these impurities. The article analyzes the flow of wet gases through nozzles, identifying the magnitude of pressure losses following these technological processes.
The prediction equations of specific humidity values ϕ (y) at various system pressures p_1(x) were determined experimentally for the flow of gases with water in the vapor state.
Simultaneously, the flow of gases and water through pipes and nozzles in different phases was analyzed, leveraging cutting-edge technology to create a numerical model (based on artificial intelligence) for determining the type of flow.
The experiments carried out on a system of flow through pipes, in which a 5 mm nozzle was placed, showed that the influence of pressure losses during gas passage is reduced.
It was also found that the flow speed of clean gases does not differ much from the speed of gases mixed with water; thus, only the viscosities of the gas-water mixture vary compared to those of clean gases.
KEY WARDS: gas, humidity, mathematical modeling,

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I. INTRODUCTION

Water can exist in natural gas in the form of vapors, the mixture formed (in this case) can be considered homogeneous during the flow through the pipe and through the holes (nozzles).

If we denote by x_g the mole fraction of gases and by x_a the mole fraction of water, we will have the mass conservation relation in the form [1,2]:

$$x_g + x_a = 1 \quad (1)$$

We can also write the mass fractions of the components m_g and m_a as follows (M_g and M_a, being the molar masses of clean gas and water respectively):

$$m_g = \frac{M_g x_g}{M_g x_g + M_a x_a} \quad (2)$$

$$m_a = \frac{M_a x_a}{M_g x_g + M_a x_a} \quad (3)$$

In our understanding, we defined clean gas as a mixture of gaseous components (*C1-methane,C2-ethane*), which are extracted from the well.

As a result of defining the molecular mass, respectively the mass fractions, we can determine the adiabatic exponent of the analyzed mixture as:

$$\chi = \frac{c_p}{c_v} \quad (4)$$

where c_p is the specific heat of the mixture at constant pressure and c_v is also the specific heat of the analyzed mixture at constant volume.

If we note with c_{pg}, c_{vg} and c_{pa}, c_{va} respectively the determined values of the specific heat for the gas phase and the water phase, it results [3,4]:

$$c_p = m_g c_{pg} + m_a c_{pa} \quad (5)$$

$c_v = m_g c_{vg} + m_a c_{va}$……..………..........…………...……(6)
And we can also determine the kinematic viscosity ν of the water vapor gas mixture as given by the relation:
$\nu = \frac{1}{\frac{x_g}{\nu_g}+\frac{x_a}{\nu_a}}$…………………........………....…......................…(7)
In equation 7, ν_g respectively ν_a are the kinematic viscosities of clean gas and water respectively.
All these considerations indicate that in a mass of natural gas, the amount of embedded water can be defined as a flow of wet gas (q_{Nu}^m), the flow of clean gas (q_N^m) can be determined from the relationship [5]:
$q_N^m = q_{Nu}^m (1 - \varphi \frac{p_a}{p_1})$.............………...….....................…..(8)
In relation 8 φ represents the relative humidity of gases which is equal to zero for dry gases and 1 for gases saturated with water.
I also introduced in relation 8 the values of the partial pressure of water vapor p_a and the pressure at which the measurement of gas flows p_1 was performed.
We can define a coefficient that represents the correction to be made to the wet gas flow to determine the clean gas flow:
$c = 1 - \varphi \frac{p_a}{p_1})$ ....………...….............................…..(9)
In this case, the relative humidity of gases can be considered as the ratio between the mass of water vapor in the unit volume of gases and their mass under saturation conditions:
$\varphi = \frac{p_a}{p_{asat}} = \frac{m_a}{m_{asat}}$...........………....….........................…..(10)
Instead of the relative humidity of gases φ, most often the specific humidity is used, defined as the ratio between the mass of water vapor and the mass of dry gases:
$\phi = \frac{M_a}{M_g} \frac{\varphi\, p_{asat}}{p_a - \varphi\, p_{asat}}$…………....….......................................…..(11)
The water vapor pressure in saturation conditions p_sat is usually a constant (for example for methane with M_g=16.01, at the temperature of 283 K, p_{asat}=0.21 mm Hg=1228 N/m^2).
In table 1 we have given determined values of the specific humidity ϕ and a correction factor c, calculated with the relation:
$c = 1 - \frac{\phi M_a p_a}{M_{asat}(M_a + \phi M_g)} \frac{p_a}{p_1}$ ....….........(12)

Table 1. Values of the correction coefficient c and specific humidity ϕ at various system pressures [5,6]

p_1, bar	35	10	2	1,2
ϕ	0,000395	0,001384	0,006952	0,01163
c	0,99999	0,99995	0,99991	0,9998

Following the laboratory determinations, we were able to write the prediction equations of the specific humidity variation ϕ at various system pressures, the most useful being the power equation (Table 2), (fig. 1).

Table 2. Equations for predicting specific humidity values ϕ (y) at various system pressures p_1(x)

Equation tipe	Equation forms	R^2
Of power	y= 0,0139x$^{-1,003}$	1
Exponential	y = 0,0077e$^{-0,091x}$	0,832
Straight	y = -0,0003x + 0,0081	0,5861
Logarithmic	y = -0,003ln(x) + 0,0105	0,8857
Polynomial degree II	y = 3E-05x^2 - 0,0013x + 0,0114	0,9155
Polynomial degree III	y = -2E-05x^3 + 0,0008x^2 - 0,0083x + 0,0205	1

And for the correction coefficient *c(y)* (figure 2) we determined a relationship following the measurements, which is also of power and has the form (R^2 = 0.8069):
y = 0,9998x^{5E-05} ....…...........................(13)

For M_a the value of 18.016 was considered and the analyzed natural gases were considered to be saturated ($p_a = p_{asat}$).
In this case φ=1 and the pressure p_a can be determined with the relation:
$p_a = x_a p_1$ ....…...(14)

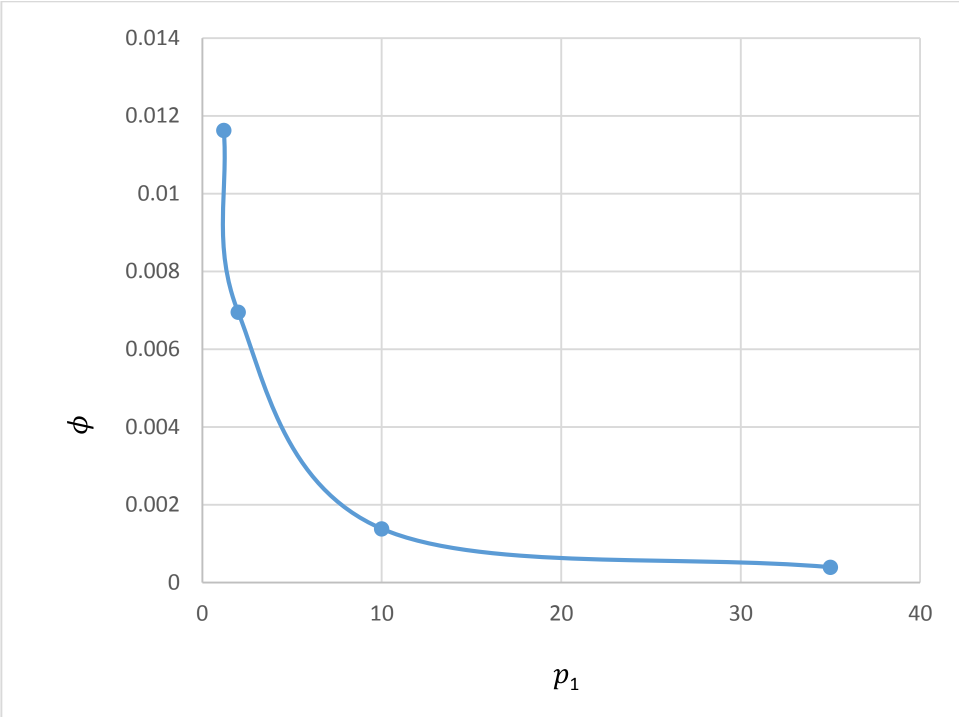

Figure 1: Variation of specific humidity ϕ (y) at various system pressures p_1(x)

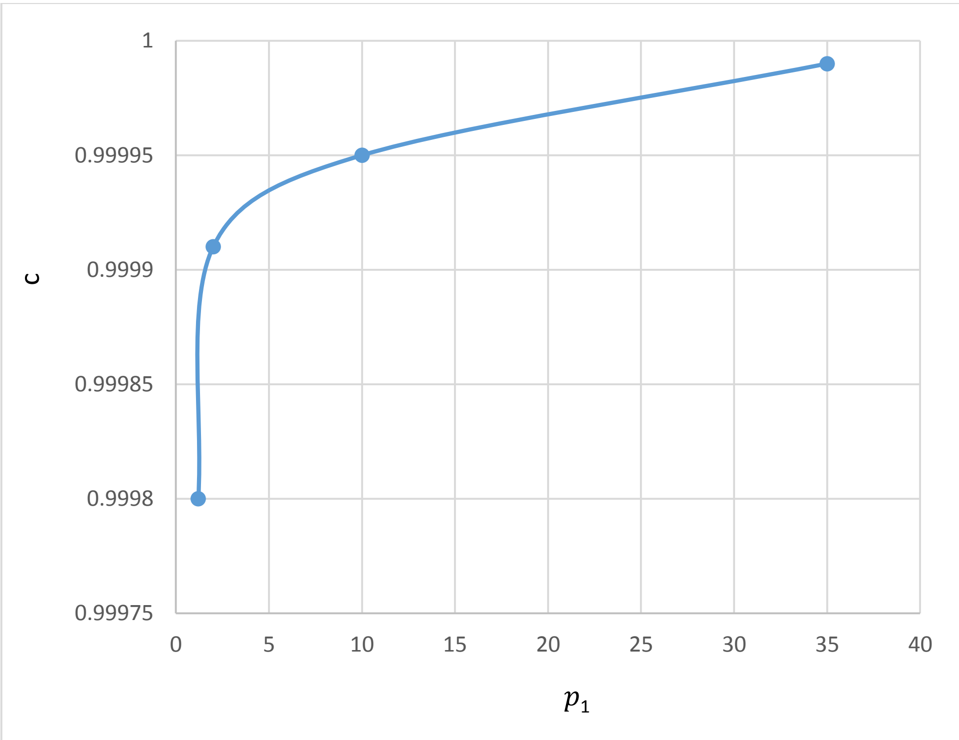

Figure 2: Variation of the correction factor *c(y)* at various system pressures p_1(x)

II. FLOW OF A TWO-PHASE SYSTEM THROUGH A NOZZLE

The flow of a two-phase fluid through a nozzle is best defined by Bernoulli's equation:

$$\frac{v_1^2}{2} + \frac{\chi}{\chi-1}\frac{p_1}{\rho_1} = \frac{v_2^2}{2} + \frac{\chi}{\chi-1}\frac{p_2}{\rho_2} + \frac{\Delta p}{\rho_m} \quad (15)$$

In equation 15 v is the average velocity in the cross section, χ is the adiabatic exponent of the fluid, p is the pipe pressure, and $\rho_{1,2}$ and ρ_m are the fluid densities before the nozzle and after the nozzle and the average density in the minimum section.
The pressure drop due to the nozzle Δp has the expression:
$\Delta p = \rho_2 \frac{v_2^2}{2}\frac{l}{d}\lambda$ ....(16)
If we take into account the continuity equation:
$\rho_2 v_2 = \rho_1 v_1$..(17)
And from the equation of state:
$\frac{p_1}{\rho_1^\chi} = \frac{p_2}{\rho_2^\chi}$..(18)
We can determine the flow equation at the exit of the nozzle:
$v_2 = \frac{\sqrt{\frac{2\chi}{\chi-1}\frac{p_1}{\rho_1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\chi-1}{\chi}}\right]}}{\sqrt{1+\frac{\rho_2}{\rho_m}\frac{l}{d}\lambda-(\frac{p_2}{p_1})^2}}$..(19)
Where l and d represent the length and diameter of the nozzle.
If we use the equation of state written in the form:
$\frac{p_m}{\rho_m^\chi} = \frac{p_2}{\rho_2^\chi}$..(20)
Then the flow equation at the exit of the nozzle becomes:
$v_2 = \frac{\sqrt{\frac{2\chi}{\chi-1}\frac{p_1}{\rho_1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\chi-1}{\chi}}\right]}}{\sqrt{1+\xi\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}$ ....(21)
In equation 21 we introduced a characterization factor of local pressure losses given by the relation:
$\xi = \frac{l}{d}\lambda$..(22)
Considering that gases mixed with water flow through the nozzle, equation 22 can be written in this case in the form:
$\frac{v_g}{v_{ga}} = \frac{\sqrt{1+\xi_{ga}\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}{\sqrt{1+\xi_g\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}$..(23)
In the equation above we have the velocity of gases expressed as v_g and the velocity of gases with water content expressed as v_{ga}.
Therefore, the flow of clean gases Q_g is related to the flow of gases Q_{ga} that also contain water by the relation:
$\frac{Q_g}{Q_{ga}} = \frac{\sqrt{1+\xi_{ga}\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}{\sqrt{1+\xi_g\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}$..(24)
In the gas-water separation systems, it was found that the flow speed of the clean gases does not differ much from the speed of the gases mixed with water, thus only the viscosities of the gas-water mixture vary compared to the clean gases (values thus expressed by the parameters ξ_{ga} and ξ_g.
If we want to correct the value of the gas flow (thus knowing the value of the exit velocity v_2 ,, we can rewrite equation 24 in the form:
$v_{2g} = \frac{v_{2gt}}{\sqrt{1+\xi_g\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}}-(\frac{p_2}{p_1})^{\frac{2}{\chi}}}}$ ....(25)

In relation 25, I entered a gas velocity value v_{2gt} (considered theoretical), which is equal to the value:
$v_{2gt} = \sqrt{\frac{2\chi}{\chi-1}Z_1 R_g T_1 (1-\left(\frac{p_2}{p_m}\right)^{\frac{\chi-1}{\chi}}}$ ....(26)
I denoted by R_g the universal gas constant, Z_1 and T_1 being the state data of the gases entering the nozzle (i.e. the deviation factor from the perfect gas law and the temperature).
We can also write the same relationship for wet gases, namely:

$$v_{2ga} = \sqrt{\frac{2\chi}{\chi-1} Z_1 R_{ga} T_1 \left(1 - \left(\frac{p_2}{p_m}\right)^{\frac{\chi-1}{\chi}}\right.} \quad \text{.................................(27)}$$

Since R_{ga} differs from R_g and the values of the two speeds will differ.

III. EXPERIMENTAL MODELING OF THE FLOW OF A TWO-PHASE SYSTEM THROUGH A NOZZLE

In the hydraulics laboratory of the Petrol-Gaze University in Ploiești, we studied the flow of a gas (air in this case) mixed with water, through several nozzles.

For this purpose, a device consisting of a tube with a diameter of 50 mm and a length of 100 mm was built.

The tube was designed to accommodate two 2 mm and 5 mm diameter nozzles (6mm length), mounted approximately 70 mm from the tube inlet and 24 mm from the tube outlet.

A jet of water was passed through the 5 mm nozzle and the pressure drop was measured.

Values were calculated for:

$$\xi = \frac{\Delta p}{\rho_a \frac{v_a^2}{2}} \quad \text{..(28)}$$

And also the Reynolds number as:

$$Re = \frac{\rho_a v_a d}{\mu_a} \quad \text{...(29)}$$

The experimental data are shown in Table 3 and Figures 3 and 4.

The density of water was taken as 1000 kg/m^3, the viscosity of water equal to the value of 10^{-3} N s/m^2.

It is observed that the local loss coefficient ξ decreases rapidly with the increase of the flow velocity, then from a value of Re number close to 6000 the curve flattens.

The variation equations of the Re number and the local pressure losses as a function of the water velocity are given in table 4 and in the following:

$$Re = 500\ v_a + 9 * 10^{-12} \quad \text{...(30)}$$

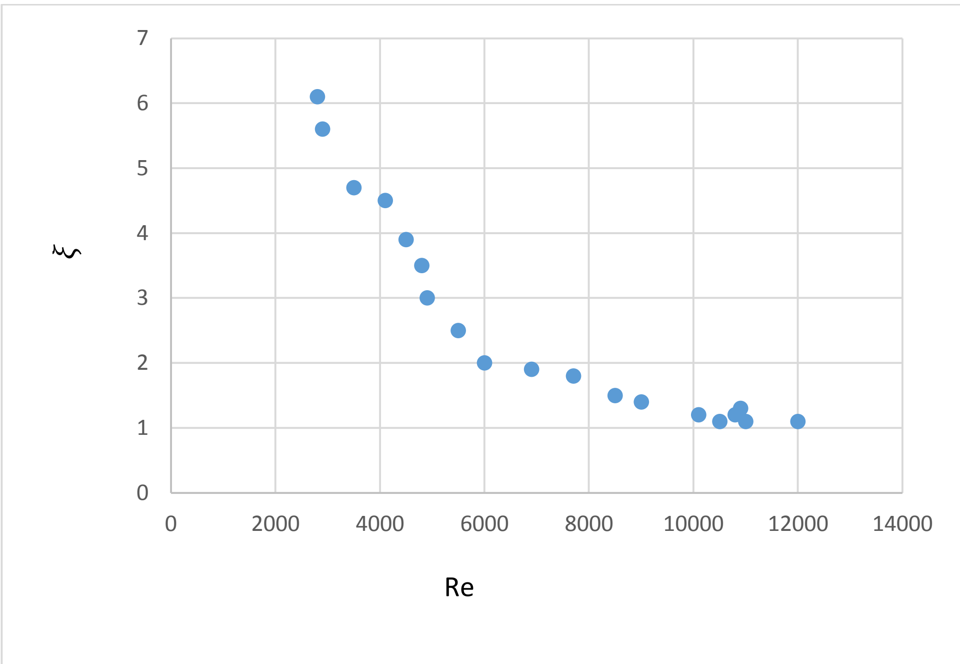

Figure 3: The variation of the Re number depending on the local pressure losses

Table 3. Variation of Re number and local pressure losses ξ at various values of water velocity when flowing through a 5 mm nozzle.

Water velocity, m/s v_a	Pressure drop N/m^2	Pressure drop bar	Re number	Local pressure losses ξ
5,6	95648	0,95648	2800	6,1
5,8	94192	0,94192	2900	5,6
7	115150	1,1515	3500	4,7
8,2	151290	1,5129	4100	4,5
9	157950	1,5795	4500	3,9
9,6	161280	1,6128	4800	3,5
9,8	144060	1,4406	4900	3
11	151250	1,5125	5500	2,5
12	144000	1,44	6000	2
13,8	180918	1,80918	6900	1,9
15,4	213444	2,13444	7700	1,8
17	216750	2,1675	8500	1,5
18	226800	2,268	9000	1,4
20,2	244824	2,44824	10100	1,2
21	242550	2,4255	10500	1,1
21,6	279936	2,79936	10800	1,2
21,8	308906	3,08906	10900	1,3
22	266200	2,662	11000	1,1
24	316800	3,168	12000	1,1

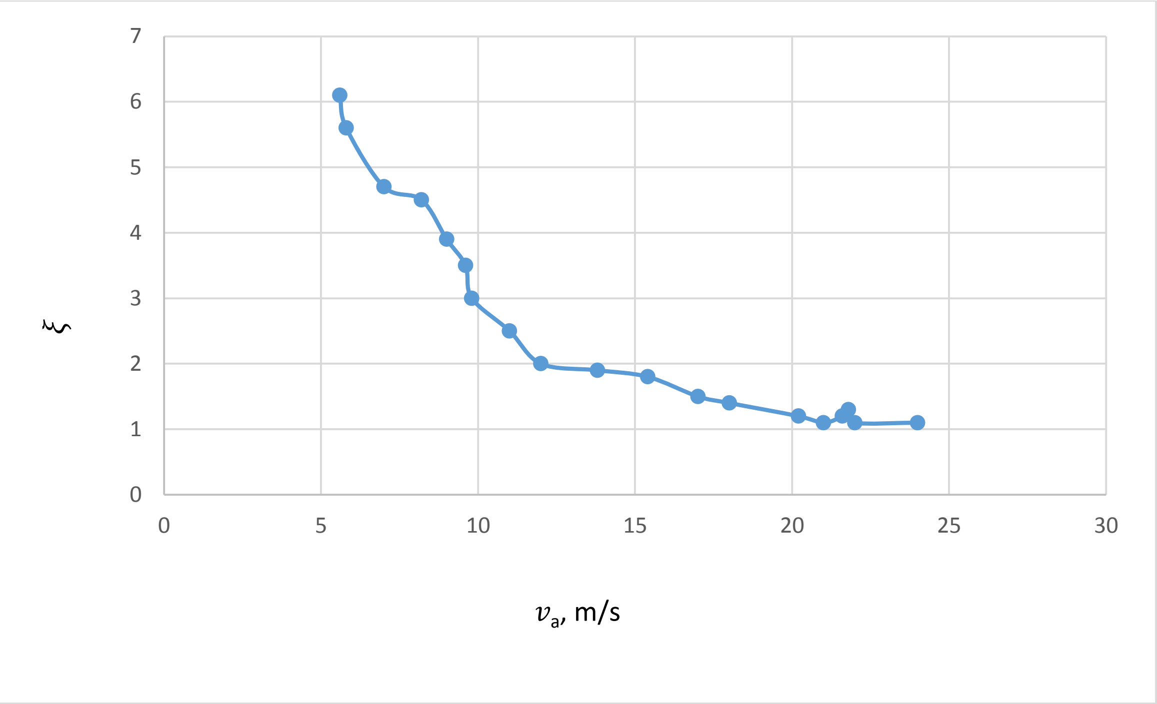

Figure 4: The variation of local pressure losses depending on the water velocity

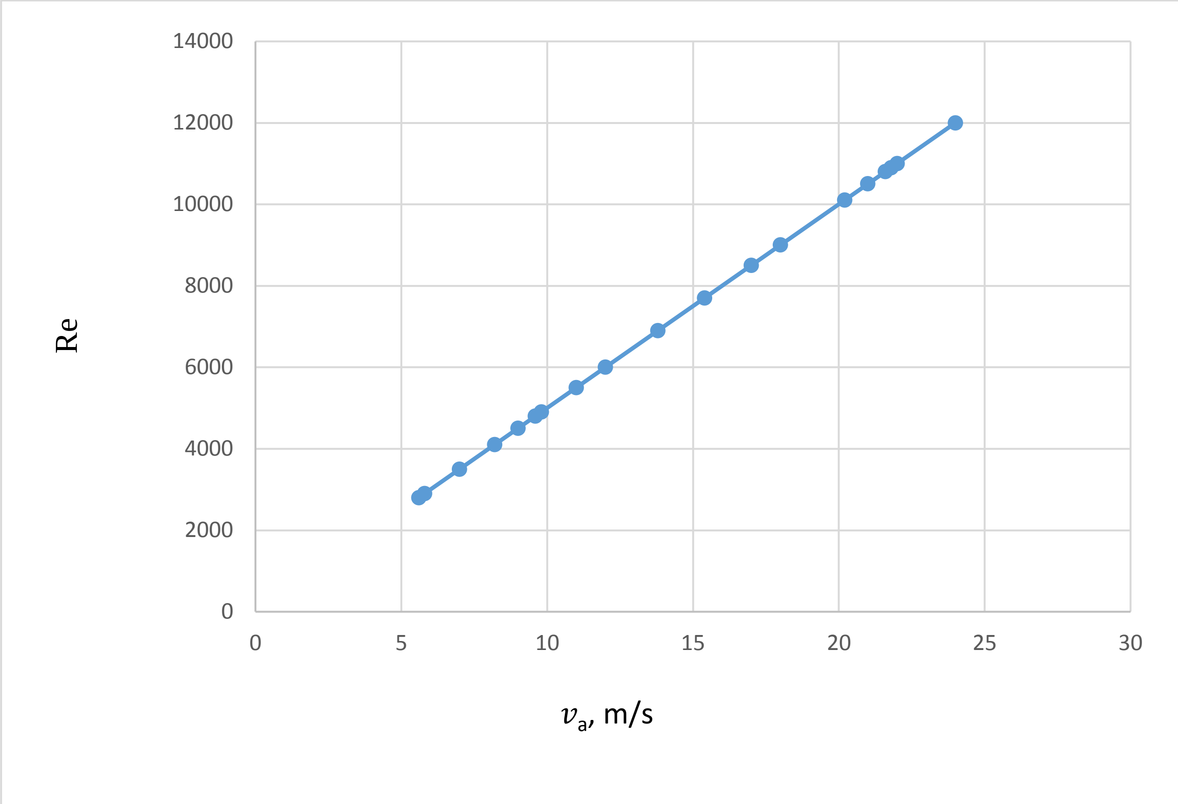

Figure 5: The variation of the pressure Re number as a function of the water velocity

Table 4. Types of equations valid for describing the variation of local pressure losses as a function of water velocity when passing through a 5 mm nozzle

Equation type	Value (y este ξ iar x este v_a)	R^2
Exponential	$y = 8{,}4272e^{-0{,}094x}$	0,9446
Logarithmic	y=-3,318 ln(x) +11,106	0,9339
Power	$y = 53{,}349x^{-1{,}248}$	0,9767
Polynomial	$y = -1E\text{-}06x^6 + 0{,}0001x^5 - 0{,}0052x^4 + 0{,}1142x^3 - 1{,}2648x^2 + 6{,}0888x - 4{,}1131$	0,9885

We find that the best calculation equation is the polynomial one.
Air with a density of 1.2928 kg/m^3 and a dynamic viscosity of 0.0000102 N s/m^2 was also circulated through the two nozzles.
And in this case we calculated its value:

$$\xi = \frac{\Delta p}{\rho_m \frac{v_m^2}{2}} \qquad (31)$$

Where ρ_m is the average air density, and the average pressure is calculated with the equation:

$$p_m = \frac{2}{3}\left(p_1 + \frac{p_2^2}{p_1 + p_2}\right) \qquad (32)$$

We also calculate the average air speed with the relation:

$$v_m = \frac{\rho_2 Q_2}{\rho_m \frac{\pi d^2}{4}} \qquad (33)$$

Where Q_2 is the volumetric flow and p_1, p_2 are the pressures measured at the ends of the nozzles.
I calculated in the first step the number of *Re* for the two mounted nozzles of 5 mm and 2 mm.
In gas wells we can consider that the appearance of water will influence the gas flow as follows:

$$\frac{Q_{ga}}{Q_g} = \frac{\sqrt{1+\xi_g\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}} - \left(\frac{p_2}{p_1}\right)^{\frac{2}{\chi}}}}{\sqrt{1+\xi_{ga}\left(\frac{p_2}{p_m}\right)^{\frac{1}{\chi}} - \left(\frac{p_2}{p_1}\right)^{\frac{2}{\chi}}}} \qquad (34)$$

Table 5. Measured data for a 5 mm nozzle

Re	v_a (m/s)	ξ
10000	15,77	1,2
20000	31,55	1,4
30000	47,33	1,5
40000	63,11	1,6
50000	78,89	1,7
60000	94,67	1,8
70000	110,45	1,9

Table 5. Measured data for a 2 mm nozzle

Re	v_a (m/s)	ξ
10000	15,78	0,5
20000	31,56	0,6
30000	47,34	0,7
40000	63,12	0,8
50000	78,90	0,9
60000	94,68	1
70000	110,46	1,1

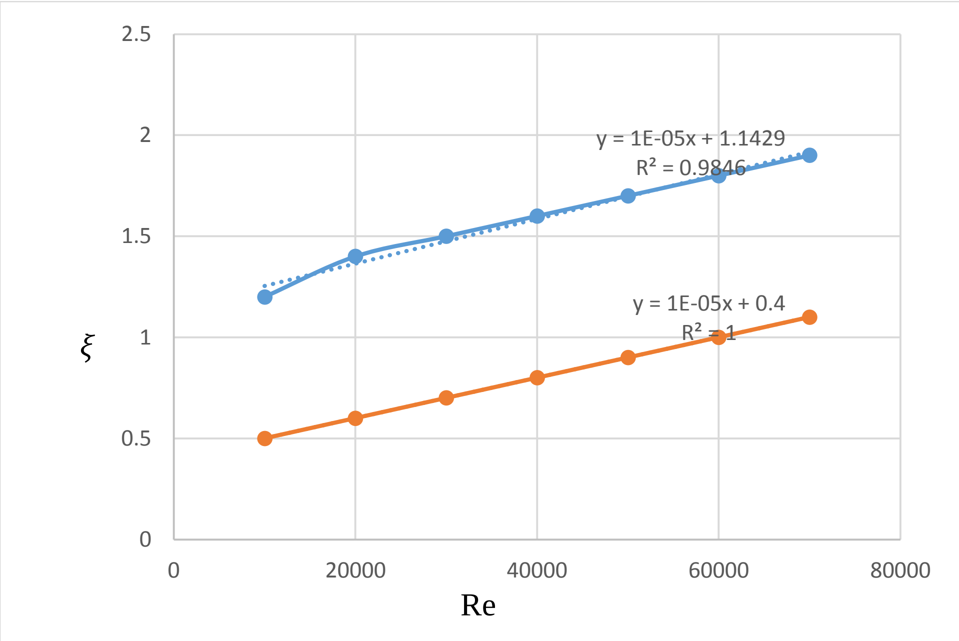

Figure 6: Variation of local pressure losses as a function of Reynolds number for 5 mm and 2 mm nozzles

We observe a slight increase in local pressure losses with increasing Reynolds number.

Given that the report $\frac{p_2}{p_1}$ has values between the values 1 and$\left(\frac{2}{\chi+1}\right)^{\frac{\chi}{\chi-1}}$, get:

$$\frac{p_m}{p_1} = \frac{2}{3}\frac{1+\frac{p_2}{p_1}+\left(\frac{p_2}{p_1}\right)^2}{1+\frac{p_2}{p_1}} \quad \text{..........(35)}$$

We also get:

$$\frac{p_2}{p_m} = \frac{p_2}{p_1} - \frac{p_1}{p_m} = \frac{3}{2}\frac{\left(1+\frac{p_2}{p_1}\right)\frac{p_2}{p_1}}{1+\frac{p_2}{p_1}+\left(\frac{p_2}{p_1}\right)^2} \quad \text{..........(36)}$$

And finally we have the debit equation:

$$\frac{Q_{ga}}{Q_g} = \frac{\sqrt{1+\xi_g\left(\frac{3}{2}\frac{\left(1+\frac{p_2}{p_1}\right)\frac{p_2}{p_1}}{1+\frac{p_2}{p_1}+\left(\frac{p_2}{p_1}\right)^2}\right)^{\frac{1}{\chi}}-\left(\frac{p_2}{p_1}\right)^{\frac{2}{\chi}}}}{\sqrt{1+\xi_{ga}\left(\frac{3}{2}\frac{\left(1+\frac{p_2}{p_1}\right)\frac{p_2}{p_1}}{1+\frac{p_2}{p_1}+\left(\frac{p_2}{p_1}\right)^2}\right)^{\frac{1}{\chi}}-\left(\frac{p_2}{p_1}\right)^{\frac{2}{\chi}}}} \quad \text{...(37)}$$

The flow equation can also be written in the form:

$$\frac{Q_{ga}}{Q_g} = \frac{\sqrt{a+b\xi_g}}{\sqrt{a+b\xi_{ga}}} \quad \text{...(38)}$$

$$\frac{Q_{ga}}{Q_g} = \frac{Re_{ga}}{Re_g} \text{...(39)}$$

But considering the linear equations that define the graphs in figure 6 we get:

$\xi = 10^{-5}\, Re \; + \; 0{,}4$ for the 2 mm nozzle

$\xi = 10^{-5}\, Re \; + 1{,}1429$ for the 5 mm nozzle.

We can also write for gases with or without water:

$$\xi_g = a + bRe_g \quad \text{..(40)}$$

$$\xi_{ga} = c + dRe_{ga} \text{...(41)}$$

And finally we get:

$$Q_g = \frac{Q_{ga}Re_g}{Re_{ga}} = \frac{Q_{ga}\frac{\xi_g-a}{b}}{\frac{\xi_{ga}-c}{d}} \text{..(42)}$$

In the above equations, *a*,*b*,*c* and *d* are correction coefficients obtained from experimental data processing.

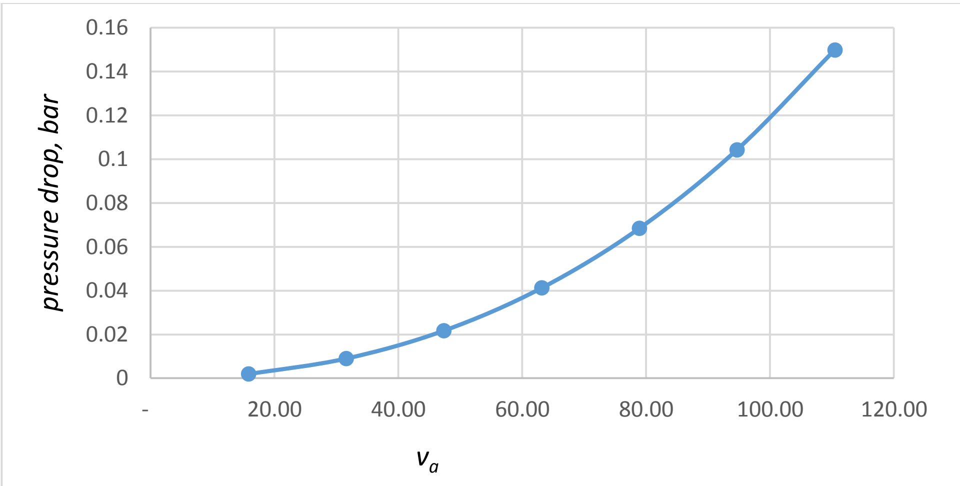

Figure 7. Variația căderii de presiune funcție de viteza gazului prin duza de 5 mm

IV. CONCLUSIONS AND RECOMMENDATIONS

In this paper We analyzes the behavior of gas flow (mixed with reservoir water) through nozzles, the focus being on understanding the phenomenology of water behavior during movement and the determination of pressure losses when a two-phase fluid flows through nozzles.

The contributions presented in the paper and the results of the numerical and experimental analyzes carried out are the following:

a. we determined the prediction equations of the specific humidity values at various pressures of the biphasic fluid (during flow),

b. we found that the flow speed of clean gases does not differ much from the speed of gases mixed with water, thus only the viscosities of the gas-water mixture vary compared to those of clean gases,

c. we determined equations that describe the variation of local pressure losses as a function of water and air velocity when passing through a 5 mm nozzle

d. we found that the influence of pressure losses when passing a gas through a 5 mm nozzle are reduced.

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