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MODELING THE RISK OF ABNORMAL FUNCTIONING OF OIL AND GAS WELL BREAKOUT PREVENTERS

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Abstract: *Eruptive manifestations in the oil and gas industry can create environmental pollution (soil, water, subsoil, air), especially destruction of equipment, and discomfort for employees and the population in the area. Also, one of the most disastrous effects of an eruptive manifestation is represented by the level of productive losses and the determination of work safety zones. We discussed the zoning of the deadly, hospitalization and discomfort hazards of uncontrolled eruptive manifestations on employees and populations in the area of activity of the well, as well as the modeling of these effects according to the diameter of the eruptive pipe, the depth of the drilling, the pressure of the productive layer, the wind speed, the length of the open flame and the evacuation rate.*
Keywords: *eruptive manifestations, eruption prevention, hazard zoning, numerical modeling.*

1. INTRODUCTION

During the drilling carried out to explore or exploit oil and/or natural gas deposits, there were also uncontrolled eruptions.

These (serious) technical accidents can occur driling works [1,2]:

"-During the crossing of the productive layer, as a result of the penetration of the fluids that saturate this layer into the drilling fluid,

-Result of the pressure variation during the drill string extraction maneuver,

-Result of carrying out pistoning or sleeve operations of the productive layer and/or the tubing string,

As a result of the seals' failure on the columns' flanges or the eruption heads (the appearance of fluid leaks in the form of a jet)."

2. MODELING OF THE FREE FLOW OF GASES THROUGH EXPLOSION PREVENTERS

The free flow of gases through ruptured (loose and open) ducts and fully open blowout preventers can be modeled using Wilson's equation [3,4,5].

The exception to this theory is the last 200 borehole diameters, where the process is adiabatic due to the high end-of-pipe acceleration.

$$Q(t) = \frac{Q_0}{(1+\alpha)}\left(e^{\frac{-t}{\alpha^2\beta}} + \alpha e^{\frac{-t}{\beta}}\right) \quad (1)$$

Where:

- Q is the exhaust flow rate (kg s^{-1}),
- Q_0 represents the flow before the failure or uncontrolled eruption (pipe rupture) occurs (kg s^{-1}),
- α is a dimensionless mass conservation factor,
- β represents the dimensionless time rate of uncontrolled runoff production.

Given that the gas discharge occurs at atmospheric pressure, the initial flow rate is considered to be given by the condition that the area where it is determined (flow conditions) is identical to where the point of discharge into the atmosphere occurs:

$$Q_0 = p_0 A_h \sqrt{\frac{\gamma M_w}{R T_g}\Gamma^{-1}} \quad (2)$$

Where:

- p_0 is the pipe pressure (Pa),
- A_h represents the area of the exhaust pipe (m2),

- M_w is the molecular weight of the gas (kg/mol),
- γ is the ratio between the heat capacity at constant pressure and at constant volume of the gas

$$\Gamma = (\frac{\gamma+1}{2})^{\frac{\gamma+1}{\gamma-1}} \quad (3)$$

The dimensionless time rate, β, of uncontrolled runoff production can be determined with the relation [3]:

$$\beta = \frac{2}{3}\,\tau_p K_F \Gamma^{3/2}\, K_H^{-3}((1+\frac{K_H^2}{K_F\Gamma})^{\frac{3}{2}}-1)(4)$$

$$\tau_p = \frac{L_p}{c} \quad (5)$$

$$K_F = \frac{d_p}{\gamma\mu L_p} \quad (6)$$

$$K_H = \frac{A_h}{A_p} \quad (7)$$

$$c = (\frac{\gamma RT}{M_W})^{1/2} \quad (8)$$

In the above equations, we have:

- L_p represents the length of the pipe, m,
- c is the speed of sound in the pipe, m/s,
- d_p is the pipe diameter, m,
- μ represents the Darcy-Weisbach friction coefficient,
- A_p is the area of the pipe (m^2).

The friction factor can be determined using Blevins' relation[6]**:**

$$\mu = \frac{0{,}25}{(0{,}57-\log(\frac{\varepsilon}{d_p}))^2} \quad (9)$$

Where ε represents a roughness coefficient equal to 0.0001 m for smooth pipes and 0.002 m for rough pipes**.**

$$0{,}01 \le \varepsilon \le 0{,}02 \quad (10)$$

When the report $\frac{K_H^2}{K_F\Gamma}$ has a low value, then it can be approximated:

$$\beta \approx \tau_p K_H^{-1}\sqrt{\Gamma} \quad (11)$$

(in the case of small leakage diameters or uncontrolled eruption).

If the gas outlet pipe is open to a large diameter

$$((K_H^2/K_F\Gamma) > 30$$

then equation 11 can be approximated as follows:

$$\beta \approx \frac{2}{3}\tau_p\sqrt{K_F} \quad (12)$$

The total mass of gas, stored in the pipe, at the time of eruption, is determined from the gas equation:

$$M_T = \frac{p_0 A_p L_p M_W}{RT} \quad (13)$$

And the mass conservation factor is:

$$\alpha = \frac{M_T}{\beta Q_0} \quad (14)$$

Considering that on the final length equal to 200 diameters of the pipe there is an isothermal movement of gases (adiabatic cooling), the exit temperature of the gas is equal to the value given by the relationship:

$$T_f = T_g(\frac{p_0}{p_{ia}})^{\frac{(\gamma-1)}{\gamma}} \quad (15)$$

Where:

- T_g is the outlet gas temperature at the end of the pipe (K),
- p_0 represents the ambient pressure (Pa),
- p_{ia} is the pressure at the adiabatic-isothermal interface (Pa).

$$p_{ia} = \frac{Q_c}{A_p} \quad (16)$$

In the isothermal-adiabatic contact zone, the model proposed in this work starts from the consideration that there is an infinite reservoir connected to the pipe and therefore the discharged flow rate will be given by the relation:

$$Q = A_p\rho_{ia}v_{ia} \quad (17)$$

Where v_{ia} is the gas velocity at the isothermal/adiabatic interface, and ρ_{ia} is the gas density in that calculation area.

$$v_{ia} = \frac{c}{\gamma} \quad (18)$$

$$\rho_{ia} = \rho_r\frac{p_{ia}}{p_r} \quad (19)$$

In the above relation the term r refers to the reservoir.

By inserting Ma's number into relation 15 we can create a relation that defines the rate of gas escape in an eruptive manifestation, namely:

$$\int_0^{L_p}\frac{\mu}{d_p}dL = \int_{Ma^2}^{\frac{1}{\gamma}}\left(\frac{1-\gamma Ma^2}{\gamma Ma^4}\right)dMa^2 \quad (20)$$

By inserting Ma's number into relation 15 we can create a relation that defines the rate of gas escape in an eruptive manifestation, namely:

$$K_F = \left[\frac{c^2-\gamma v_{ir}^2}{\gamma v_{ir}^2} - \frac{c^2-\gamma v_{ia}^2}{\gamma v_{ia}^2} + 2\ln\left(\frac{v_{ir}}{v_{ia}}\right)\right]^{-1} \quad (21)$$

Where v_{ir} represents the gas velocity at the reservoir-pipeline interface.

Also, the pressure at the adiabatic/isothermal interface p_{ia} is:

$$p_{ia} = \left(\frac{v_{ir}}{v_{ia}}\right)\left(p_r - \frac{1}{2}\rho_r v_{ir}^2\right) \quad (22)$$

The algorithm for calculating gas evacuation from the pipeline (through uncontrolled eruption) is performed by multiplying the calculation of its release rates at different times.

If n is the total number of time steps, then each new time step is calculated from the previous one using a Newton-Raphson iteration scheme to find the roots of the equation:

$$F(t_{i+1}) = \frac{M_T}{n} - \int_{t_i}^{t_{i+1}} Q(t)dt \quad (23)$$

where $t_{(i)}$ is the time (60 seconds interval) instant for the calculation, previous and $t_{(i+1)}$ is the new time instant.

3. RISK MODELING EQUATIONS FOR UNCONTROLLED ERUPTIONS

In the analysis of the evolution of the state of danger for employees and visitors, we created for the first time in the specialized literature:

a. The evolution of the explosive front that can cause deaths in the case of employees and visiting personnel,

b. The evolution of the explosive front that can cause accidents with hospitalization in the case of employees and visiting personnel,

c. The evolution of the explosive front that can produce accidents without hospitalization in the case of employees and visiting personnel.

The model started from the identification of the following results in the event of a blowout at a natural gas well:

a. The length of the open flame, m,

b. Natural gas discharge rate, kg/min,

c. Fatal injury area, m (10 kw/m^2),

d. Injury area with hospitalization, m (5 kw/m^2),

e. Injury area with small burns, m (2 kw/m2).

For the calculation we took:

a. Different positions of the blowout preventer, (%), (100, 75, 50, 25, 10, 8), relative to the diameter of the drill pipe (which we took as 146 mm),

b. Different depths of the drill pipe, (m), (1000, 2000, 3000),

c. Different pressures of the productive layer, (atm.), (50, 100, 200, 300).

For the first simulation, the ambient temperature and wind speed are 25ºC and 5 m/s.

The equation describing the diameter of the fatal injury zones, m (10 kw/m^2) (*Y*) as a function of the eruptive pipe diameter, mm (*X1*), drilling depth, m (*X2*), productive layer pressure, bar (*X3*), wind speed, m/s (*X4*), open flame length, m (*X5*) and evacuation rate, kg/min (*X6*) is as follows:

Y=8,544-0,169 X1 -0,00018 X2 -0,00012 X3+ 2,798 X5 +0,00084 X6 (24)

Where R^2 is 0,9898.

The error values of each term on the right side of the equation are:

Table 1

The error values of each term on the right-hand side of Eq. 24

	Coeficients	***The standard error***
Firs member	8,544466816	0,730714041
X1	-0,169501144	0,054405653
X2	-0,0001875	0,00016048
X3	-0,000128725	0,002667262
X4	0	0
X5	2,798673554	0,546998642
X6	0,000845557	3,52706E-05

The equation that describes the diameter of the injury zones that has the effect of hospitalization of the injured person, m (5 kw/m^2) (*Y*) depending on the diameter of the eruptive pipe, mm (*X1*), the depth of the drilling, m (*X2*), the productive layer pressure, bar (*X3*), the wind speed, m/s (*X4*), the length of the open flame, m (*X5*) and the evacuation rate, kg/min (*X6*) is the following (R^2 is 0,9846):

Y=7,545-0,295 X1 -0,00018 X2 - 0,00025 X3+ 4,889 X5 +0,00109 X6 (25)

The equation that describes the diameter of the injury zones without hospitalization of the injured person, m (2 kw/m^2) (*Y*) depending on the diameter of the eruptive pipe, mm (*X1*), the drilling depth, m (*X2*), productive layer pressure, bar (*X3*), the wind speed, m/s (*X4*), the length of the open flame, m (*X5*) and the evacuation rate, kg/min (*X6)* is the following:

Y=6,578-0,295 X1 -0,518 X2 -0,0004 X3+ 8,804 X5 +0,0015 X6 (26)

Where R^2 is 0,9996.

Table 2

The error values of each term on the right-hand side of Eq. 25

	Coeficients	*The standard error*
First member equation	7,545249	0,77756
X1	-0,29576	0,057894
X2	-0,00025	0,000171
X3	0,003929	0,002838
X4	0	0
X5	4,889683	0,582066
X6	0,001093	3,75E-05

Table 3

The error values of each term on the right-hand side of Eq. 26

	Coeficients	*The standard error*
First member equation	6,5789437	1,040141975
X1	-0,518411858	0,077444254
X2	-0,000404167	0,000228437
X3	0,0093981	0,003796739
X4	0	0
X5	8,804525875	0,778630513
X6	0,001555064	5,02063E-05

4. MODELING OF GAS FLOW THROUGH BLOWOUT PREVENTERS DEPENDING ON WEATHER CONDITIONS AND RESERVOIR PRESSURE

In what follows I have created several equations to describe:

a. The values of the gas discharge rate (kg/min) and the flame height of the flue gas jet,
b. Fatal accident areas, with or without hospitalization (kW/m^2),

Function of:

a. The pressure of the productive layer (bar),
b. Well depth (m),
c. Wind speed (m/s),
d. Temperature of the working area (ºC).

Variation equation of the diameter of the fatal injury zone (*Y*) (10 kw/m^2), depending on:

- productive layer pressure, bar (*X1*),
- wind speed, m/s (*X2*),
- temperature, º C (*X3*),
- Length of open flame, m (*X4*),
- Evacuation rate, kg/min (*X5*),

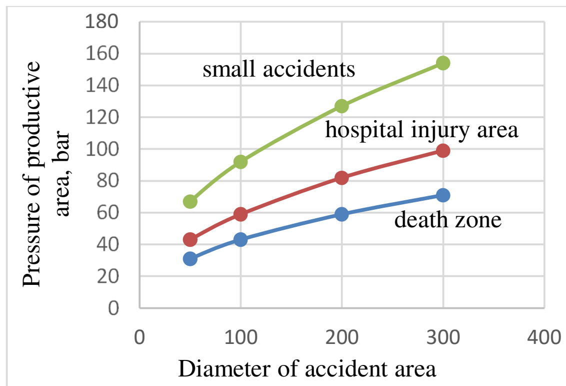

Fig.1. The variation of the diameter of the areas of fatal injury, with or without hospitalization (kW/m^2) depending on the pressure of the productive layer (bar)

Y=-44,3077786-0,225861111 X1 +0,22566139 X2 -0,08867012 X3 +5,029962653 X4 + 0,002041408 X5 *(27)*

Where R^2 is 0,9995.

Table 4

The error values of each term on the right-hand side of Eq. 27

	Coeficients	*The standard error*
First member equation	-44,3077786	4,979229736
X1	-0,225861111	0,09673483
X2	0,22566139	0,038930142
X3	-0,08867012	0,031029939
X4	5,029962653	0,363093041
X5	0,002041408	0,000569154

Variation equation (28) of the diameter of the Injury Zone with hospitalization, m (5 kw/m^2), depending on:
- productive layer pressure, bar (*X1*),
- wind speed, m/s (*X2*),
- temperature, ° C (*X3*),
- length of open flame, m (*X4*),
- evacuation rate, kg/min (*X5*),

$$Y=-55{,}7927833-0{,}254216999\,X1 +0{,}228057717X2 - 0{,}131313788\,X3 +6{,}598540386\,X4 + 0{,}002517563\,X5 \quad (28)$$

Where R^2 is 0,9998.

Variation equation (29) of the diameter small burn injury zone, m (2 kw/m^2), depending on:
- productive layer pressure, bar (*X1*),
- wind speed, m/s (*X2*),
- temperature, ° C (*X3*),
- the length of the open flame, m (*X4*),
- evacuation rate, kg/min (*X5*),

$$Y=-86{,}00117517-0{,}489410055\,X1 +0{,}204721792\,X2 -0{,}210459724\,X3 +10{,}27790407\,X4 + 0{,}004468704\,X5 \quad (29)$$

Table 5

The error values of each term on the right-hand side of Eq. 28

	Coeficients	*The standard error*
First member equation	-55,7927833	4,406411758
X1	-0,254216999	0,085606312
X2	0,228057717	0,034451561
X3	-0,131313788	0,027460209
X4	6,598540386	0,321322279
X5	0,002517563	0,000503678

Table 6

The error values of each term on the right-hand side of Eq. 29

	Coeficients	*The standard error*
First member equation	-86,00117517	7,737721087
X1	-0,489410055	0,150325889
X2	0,204721792	0,060497426
X3	-0,210459724	0,048220514
X4	10,27790407	0,564246446
X5	0,004468704	0,000884466

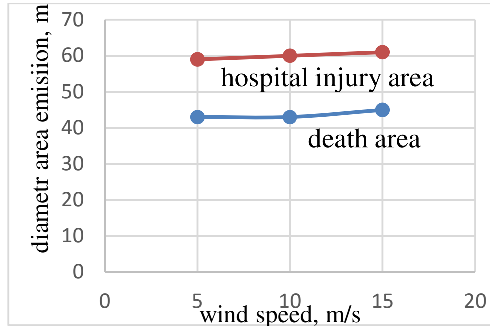

Fig. 2. The variation of the diameter of the areas of fatal injury, with hospitalization (kW/m^2) depending on the wind speed (m/s)

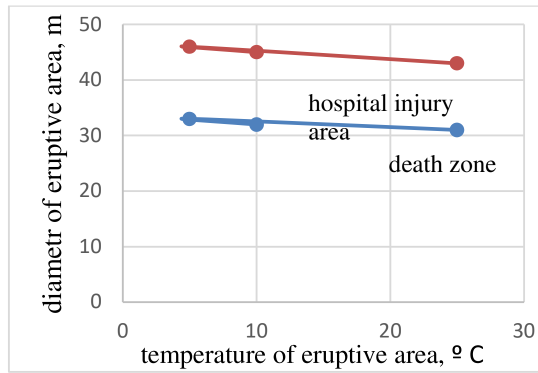

Fig. 3. Variation of the diameter of the areas of fatal injury, with hospitalization (kW/m^2) as a function of the ambient temperature (m/s)

At the same time, we built a relationship (30) between the length of the open flame (m), the diameter of the eruptive pipe, the depth of the borehole (m) and the layer pressure (bar).

$$Y=-0{,}96370487 + 0{,}106200923\,X1 -7{,}997E-20\,X2 +0{,}004180791\,X3 \quad (30)$$

Where R^2 is 0,9970.

Table 7

The error values of each term on the right-hand side of Eq. 30

	Coeficients	*The standard error*
First member equation	-0,96370487	0,138398452
X1	0,106200923	0,000852055
X2	-7,997E-20	3,81398E-05
X3	0,004180791	0,000444117

5. CONCLUSION

The conclusions of these simulations indicate the following:

a. The fatal injury zone, m (10 kw/m^2) is between 31 m and 74 m when the wind speed differs between 5 and 15 m/s,

b. The area of fatal injury, m (10 kw/m^2) is between 33 m and 75 m when the ambient temperature differs between 5 and 10 º C,

c. The length of the free flame is between 14 and 16 m,

d. The evacuation rate is between 8440 and 52000 kg/min depending on the ambient temperature, wind speed and pressure of the productive layer,

e. Fatal injury area, m (10 kw/m^2) is between 31 m and 10 m when the diameter of the blast pipe is between 8 % and 100 % of the diameter of the blast pipe at a constant pressure of 50 bar,

f. The fatal injury zone, m (10 kw/m^2) is between 31 m and 68 m when the pressure of the productive layer increases from 50 bar to 300 bar (at the same 100% diameter),

At an opening of the blowout preventer of 8% of the diameter of the blowout pipe, the diameter fatal injury zone, m (10 kw/m^2) is a maximum of 10 m.

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Modelarea riscului de funcționare anormală a prevenitoarelor de erupție de la sondele de petrol și gaze

Manifestările eruptive din industria petrolului și gazelor pot duce la poluarea mediului ambient (sol, apă, subsol, aer), și în special la distrugerea utilajelor, și disconfort pentru angajați și populația din zonă. De asemenea, unul dintre cele mai dezastruoase efecte ale unei manifestări eruptive este reprezentat de nivelul pierderilor productive și determinarea zonelor de siguranță a muncii. În materialul de față am discutat despre zonarea pericolelor mortale, de spitalizare și de disconfort ale manifestărilor eruptive necontrolate asupra angajaților și populațiilor din zona de activitate a sondei, precum și modelarea acestor efecte în funcție de diametrul conductei eruptive, adâncimea forajului, presiunea stratului productiv, viteza de evacuare a flăcării, viteza vântului. Lucrarea se bazează pe experiențe de teren și pe analiza mai multor erupții necontrolate.

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