Numerical modeling of two-phase liquid-solid movement through pipes

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ABSTRACT

The oil industry is that branch of the world economy that provides energy resources for humanity and the transition to energy produced from renewable resources.
That is precisely why the study of mass transfer (the transport of petroleum fluids through pipelines) represents one of the primary activities in scientific research; the role of this discipline is to provide theoretical support to understand the phenomena that govern these technological processes.
One of the industrial applications of multiphase transport is the movement of multiphase fluids (liquid-solid) through pipes and especially the phenomena of separation of these phases.
Due to the depletion of oil and gas resources associated with deposits discovered before 1990, the extraction of these petroleum fluids faces the presence in the composition of large amounts of sand, salt or paraffin (solid phase), dissolved solids, and present in the liquid phase, which makes the activity of separating, removing and cleaning petroleum fluids from associated sediments, an increasingly present and functional industrial activity for the development of oil and gas exploitations.
That is precisely why a work that analyzes the numerical modeling of the separation process and the simulation of the solid-liquid transport processes through the central pipeline systems is necessary for the economic and detailed design of the machines associated with this industry.
This paper analyzes the behavior of various solid substances in the flow of petroleum liquids. As a result of the laboratory data, we created a numerical model associated with these two-phase flows.

Keywords: oil, gas, solid, fluid, biphasic, pipeline, modeling, separation.

1. INTRODUCTION

For the study of the horizontal flow of two-phase fluid-solid mixtures, good results in the calculation of the pressure drop were obtained using the calculation relations proposed by MOLERUS and WELLMAN [1].
Thus they determined that the total pressure drop can be determined from the relationship:

$$\Delta p = \Delta p_f + \Delta p_p, \quad (1)$$

WhereΔp_ff is due to the fluid, and Δp_p represents the contribution of the solid phase.
The pressure drop, related to the movement of the fluid, has the expression:

$$\Delta p_f = \lambda_f \frac{l}{d} \frac{\rho_f v_m^2}{2}, \quad (2)$$

where $v_m$is the average velocity of the mixture.
In this equation $\lambda_f$is the hydraulic loss coefficient, *l* is the flow distance, *d* is the diameter of the flow area and $\rho_f$represents the density of the analyzed fluids.
The average velocity value helps determine the REYNOLDS number.
To determine the coefficient of longitudinal hydraulic resistanceλ_f, we propose CHURCHILL's equation [2]:

$$\lambda_f = 8\left[\left(\frac{8}{Re_m}\right)^{12} + (A+B)^{-1,5}\right]^{\frac{1}{12}}, \qquad (2)$$

$$A = \left\{-2,457\, ln\left[\left(\frac{7}{Re_m}\right)^{0,9} + 0,27\frac{k}{d}\right]\right\}^{16}, \qquad (3)$$

$$B = \left(\frac{37,350}{Re_m}\right)^{16}. \qquad (4)$$

The contribution of the solid phase to the pressure drop can be determined using the equation:

$$x^* = \frac{\Delta p_p}{C(\rho_p - \rho_f)gl}\left(\frac{v_t}{v_m}\right)^2, \qquad (5$$

Where v_t is:

$$v_t = \sqrt{\frac{4 d_p g}{3 C_r}\left(\frac{\rho_p}{\rho_f} - 1\right)}. \qquad (6)$$

To calculate this speed, enter the ARCHIMEDE number and the REYNOLDS number defined by the equations [3]:

$$Ar = \frac{\rho_f g(\rho_p - \rho_f) d_p^3}{\mu_f^2}. \qquad (7)$$

$$\mathrm{Ar} = 18 Re_p, \qquad (8)$$

If Ar< 3,6;

$$\mathrm{Ar} = 18\, Re_p + 2,7 Re_p^{1,687}, \qquad (9)$$

If 3,6 <Ar< 10^5 and

$$\mathrm{Ar} = \frac{Re_p^2}{3}, \qquad (10)$$

If Ar> 10^5.

For particles of a different shape, than the spherical one, a shape factor k_f is defined (to reduce the effect of this shape on the final calculations) and the volume of the particle is given by the relationship $k_f d_p^3$.

The diameter d_p of the particle is determined from the calculation relationship of the maximum projected surface area of the particle ($\pi d_p^2/4$).

For most minerals or particles transported through the biphasic liquid-solid mixture, kf is between 0.2 and 0.5, and ARCHIMEDE's number can be written in the form [3]:

$$\mathrm{Ar} = \frac{6}{\pi} k_f \frac{\rho_f g(\rho_p - \rho_f) d_p^3}{\mu_f^2}. \qquad (11)$$

In equation (5) C is the volume concentration of the solid phase, on which the parameter x* depends, which can be determined with the help of the relations:

If 0 <C<C_0

$$x^* = x_0, \qquad (12)$$

For C_0<C<C_M

$$x^* = x_0 + 0,1\mathrm{Fr}^*(C - C_0), \qquad (13)$$

Where C_0 = 0,25, C_M = 0,4,

$$\mathrm{Fr}^* = \frac{v_t}{\sqrt{gd\left(\frac{\rho_p}{\rho_f} - 1\right)}}, \qquad (14)$$

$$x_0 = \frac{(v_r/v_m)^2}{1 - v_r/v_m}. \qquad (15)$$

In the above equations v_r is considered to define the mean particle sliding velocity.

This is obtained from figure 1 in which the v_r/v_m ratio is represented as a function of the Froude number related to the particles.

Equation for a set of values of Fr^* is [4,5]:

$$\mathrm{Fr}_p = \frac{v_m}{\sqrt{g d_p\left(\frac{\rho_p}{\rho_f} - 1\right)}}. \qquad (16)$$

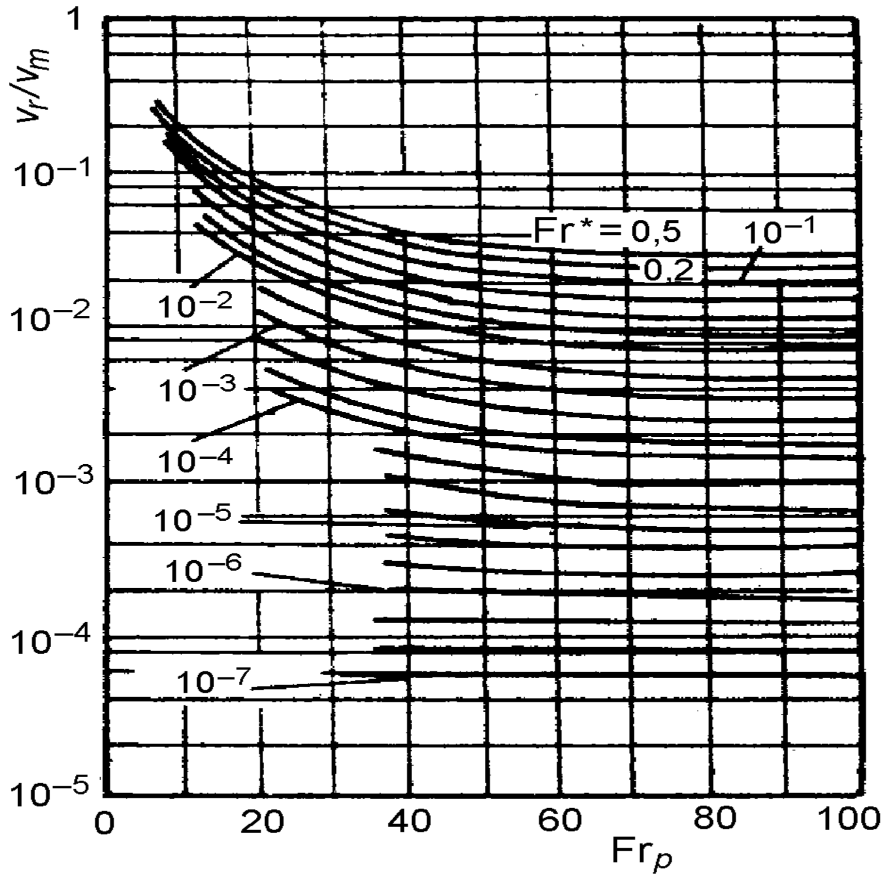

Fig. 1.The ratio v_r/v_m depending on the Froude number associated with the solid particle

2. NUMERICAL MODELS IN ESTABLISHING BIPHASIC MOVEMENT

The analysis of the flow of a particle in a two-phase mixture can be done using the energy conservation equation [6]:

$$\frac{dp}{\rho_m} + gdh + v_m \mathrm{dv}_m + dF = 0, \quad (17)$$

Where:

- V represents the specific volume of the biphasic fluid, m^3/kg;
- ρ_m is the density of the mixture, kg/m^3;
- dh represents the load loss between the two considered points, m;
- dF is the frictional energy loss between the two considered points;
- v_m is the velocity of the mixture, m/s and is determined with the relation:

$$v_m=(q_l+q_g)/A \quad ,(18)$$

- q_l represents the volumetric liquid flow rate, m^3/s;
- q_g is the volumetric gas flow, m^3/s, and A represents the total flow section, m^2.

Denoting by α the angle between the pipe and the horizontal reference plane we get:

$$dh = dz \sin\alpha\,. \quad (19)$$

In whichdz represents the length traveled by the analyzed particle, m.

The angle α has the value 0° for horizontal flow and varies from 0° to +90° for the flow of two-phase fluids in pipes inclined from the bottom up and from 0° to -90° for the flow of two-

phase fluids in pipes inclined from the top in down [7, 8].
Substituting the value of dh in relation 17, the pressure gradient expression is obtained:

$$\frac{dp}{dz} = -\left(\rho_m g \sin\alpha + \frac{\rho_m v_m \mathrm{dv}_m}{dz} + \rho_m \frac{dF}{dz}\right), \tag{20}$$

Which can also be written in the form:

$$-\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_{static} + \left(\frac{dp}{dz}\right)_{acc} + \left(\frac{dp}{dz}\right)_{fr}. \tag{21}$$

The static gradient of the pressure drop can be determined with the relation:

$$\left(\frac{dp}{dz}\right)_{static} = g\rho_m \sin\alpha, \tag{22}$$

Where:

$$\rho_m = \rho_l \varepsilon_l + \rho_g (1-\varepsilon_l), \tag{23}$$

- ρ_l, ρ_g are the densities of the liquid and the gas, kg/m^3,
- ε_l is the fraction of liquid that is given by the ratio of the volume of liquid in an element/the volume of the element.

So equation 23 can be rewritten as:

$$\left(\frac{dp}{dz}\right)_{static} = g\left[\rho_l \varepsilon_l + \rho_g (1-\varepsilon_l)\right] \sin\alpha. \tag{24}$$

To determine the pressure gradient due to acceleration, when the mass of fluid flows through the pipes, the average velocity of the biphasic mixture will be calculated with the relation:

$$v_m = v_{sl} + v_{sg} = \frac{G_l}{\rho_l} + \frac{G_g}{\rho_g}, \tag{25}$$

Where:

- v_{sl} and v_{sg} are the surface velocities of the liquid and gases resulting by dividing the volumetric flow rates by the sections occupied by the liquid and gases, respectively;
- G_l is the ratio between the liquid mass flow rate and the total pipe section, kg/s·m^2,
- G_g is the ratio between the gas mass flow rate and the total pipe section, kg/s·m^2.

So we obtain the value of the pressure drop due to the acceleration of the mixture when flowing through the pipes, from the relationship [9]:

$$\left(\frac{dp}{dz}\right)_{acc} = \rho_m v_m \frac{\mathrm{dv}_m}{dz} = \rho_m v_m \left[\frac{d}{dz}\left(\frac{G_l}{\rho_l}\right) + \frac{d}{dz}\left(\frac{G_g}{\rho_g}\right)\right], \tag{26}$$

Assuming that due to the difference between gas and liquid compressibility:

$$\left[\frac{d}{dz}\left(\frac{G_l}{\rho_l}\right)\right] = 0.$$

We can rewrite equation 23 in the forms:

$$\left(\frac{dp}{dz}\right)_{acc} = \rho_m v_m \left[\frac{d}{dz}\left(\frac{G_g}{\rho_g}\right)\right] = \rho_m v_m \left[\frac{\rho_g \frac{dG_g}{dz} - G_g \frac{d\rho_g}{dz}}{\rho_g^2}\right], \tag{27}$$

$$\left(\frac{dp}{dz}\right)_{acc} = \rho_m v_m \left[\frac{\frac{dG_g}{dz}}{\rho_g} - \frac{G_g}{\rho_g^2}\frac{d\rho_g}{dz}\right]. \tag{28}$$

To simplify the calculations, we admit that the change in the gas mass flow rate at the exit or entry of a part of the gas into the solution is extremely small compared to the change in the gas density value:

$$\frac{\frac{d}{dz}(G_g)}{\rho_g} << \frac{G_g}{\rho_g^2}\frac{d\rho_g}{dz},$$

And relation 23 can be rewritten in the form:

$$\left(\frac{dp}{dz}\right)_{acc} = -\rho_m v_m \frac{G_g}{\rho_g^2}\frac{d\rho_g}{dz}. \tag{29}$$

On the other hand, for 1 kg of gas, we can write:

$$\rho_g = \frac{pM_g}{zRT}, \tag{30}$$

$$\frac{d\rho_g}{dz} = \frac{d}{dz}\left(\frac{pM_g}{zRT}\right) = \frac{M_g}{zRT}\frac{dp}{\mathrm{dz}} + \frac{p}{zRT}\frac{dM_g}{dz} - \frac{pM_g}{z^2RT}\frac{dz}{dz} - \frac{pM_g}{zRT^2}\frac{dT}{dz}. \tag{31}$$

Admitting that the sum of the last three terms on the right side of relation (31) is negligible compared to the first term, we obtain:

$$\frac{d}{dz}\left(\rho_g\right) = \frac{M_g}{zRT}\frac{dp}{\mathrm{dz}}. \tag{32}$$

Taking into account relation (32), relation (31) becomes:

$$\frac{d}{dz}\left(\rho_g\right) = \frac{\rho_g}{p}\frac{dp}{\mathrm{dz}}, \tag{33}$$

where p is the pressure at the point where the pressure loss (pressure gradient) is calculated.

Substituting relation (33) into equation (29) we can write the pressure gradient due to the kinetic energy with the equation:

$$\left(\frac{dp}{dz}\right)_{acc} = -\rho_m v_m \left[\frac{G_g}{\rho_g^2}\frac{\rho_g}{p}\frac{dp}{dz}\right] = -\rho_m v_m \frac{v_{sg}}{p}\frac{dp}{dz}. \tag{34}$$

The pressure gradient due to friction is given by the relation:

$$\left(\frac{dp}{dz}\right)_{fr} = \frac{f_{bifazic}\ \rho_{fa} v_m^2}{2d} = \frac{f_{bifazic}\ G_m v_m}{2d}. \tag{35}$$

Where $G_m = G_l + G_g$, and:

$$\rho_{fa} = \rho_l \frac{q_l}{q_l+q_g} + \rho_g\left(1 - \frac{q_l}{q_l+q_g}\right). \tag{36}$$

We note that ρ_{fa} is a weighted density of the mixture, without taking into account the phenomenon of gas sliding through the liquid, being variable depending on the specific weight of the mixture ρ_m (calculated taking into account the phenomenon of particle sliding through the fluid).

Substituting the above relations in equation (27) we obtain [10]:

$$-\frac{dp}{dz} = g\left[\rho_l\varepsilon_l + \rho_g(1-\varepsilon_l)\right]\sin\alpha + \frac{f_{bifazic}\ G_m v_m}{2d} - \frac{\left[\rho_l\varepsilon_l + \rho_g(1-\varepsilon_l)\right]v_m v_{sg}}{p}\frac{dp}{dz},$$

$$-\frac{dp}{dz} = \frac{g\left[\rho_l\varepsilon_l+\rho_g(1-\varepsilon_l)\right]\sin\alpha + \frac{f_{bifazic}\ G_m v_m}{2d}}{1-\left[\rho_l\varepsilon_l+\rho_g(1-\varepsilon_l)\right]v_m v_{sg}/p}. \tag{37}$$

Equation (37) contains two unknowns, namely ε_l required for the calculation of the density of the mixture at a given point and $f_{bifazic}$ required for the calculation of frictional pressure losses.

We can construct numerical relationships to support the pipe pressure loss of two-phase mixtures by introducing the following constants:

$$N_{Fr} = \frac{v_m^2}{gd},\ \lambda = \frac{q_l}{q_g+q_l},$$

$L_1 = exp(-4{,}62 - 3{,}754 \cdot ln\,\lambda - 0{,}481 \cdot ln^2\,\lambda - 0{,}0207 \cdot ln^3\,\lambda);$

$L_2 = exp(1{,}061 - 4{,}602 \cdot ln\,\lambda - 1{,}609 \cdot ln^2\,\lambda - 0{,}179 \cdot ln^3\,\lambda + 0{,}635 \cdot 10^{-3} \cdot ln^5\,\lambda).$

In the analyzes carried out by the authors, it was found that depending on the value of the parameters N_{Fr}, L_1, L_2, the flow of the biphasic mixture can be delimited in:

- for $N_{Fr}<L_1$, biphasic flow is with gravity segregation;
- for $N_{Fr}>L_1$ and $N_{Fr}>L_2$ the flow is uniformly distributed,
- for $L_1<N_{Fr}<L_2$ there is an intermittent flow of the biphasic fluid.

The equations used to calculate the liquid fraction $\varepsilon_l(0)$ and the coefficient C for all flow conditions are given in table 1.

After determining the values of $\varepsilon_l(0)$ and C, the value of the liquid fraction is calculated for a certain angle.

Result:

$$\varepsilon_l(\alpha) = \varepsilon_l(0)\left[1 + C\left(\sin 1{,}8 \cdot \alpha - \frac{1}{3}\sin^3 1{,}8 \cdot \alpha\right)\right]. \tag{38}$$

The correlation that determines the friction factor is given by the relationship:

$$\frac{f_{bifazic}}{f_{fa}} = f\left\{\frac{\lambda}{[\varepsilon_l(\alpha)]^2}\right\} = eS. \tag{39}$$

Where f_{fa} is the sliding phenomenon and can be obtained depending on the obtained Reynolds number:

$$\left((N_{Re})_{fa} = \frac{[\rho_l \lambda + \rho_g (1-\lambda)] \cdot v_m \cdot d}{\mu_l \lambda + \mu_g (1-\lambda)}\right), \tag{40}$$

And from the classical diagrams (Moody), we obtain the value of the *S* factor as:

$$S = \frac{ln(y)}{-0{,}0523 + 3{,}182\, ln(y) - 0{,}872\, [\ln(y)]^2 + 0{,}01853\, [ln(y)]^4}. \tag{41}$$

$$y = \lambda / [\varepsilon_l(\alpha)]^2.$$

Table 1. The equations used to calculate the liquid fraction

Flow regimes through horizontal pipes	Liquid fraction for flow through horizontal pipes	C +	C -
Gravitational segregation	$\varepsilon_l(0) = \frac{0{,}98\lambda^{0{,}4868}}{N_{Fr}^{0{,}0868}}$	$C+ = (1-\lambda)\, ln \frac{0{,}011 N_{lv}^{3{,}359}}{\lambda^{3{,}768} N_{Fr}^{1{,}614}}$	$C- = (1-\lambda)\, ln \frac{4{,}7 N_{lv}^{0{,}1244}}{\lambda^{0{,}3692} N_{Fr}^{0{,}5056}}$
Intermittent	$\varepsilon_l(0) = \frac{0{,}845\lambda^{0{,}5351}}{N_{Fr}^{0{,}0173}}$	$C+ = (1-\lambda)\, ln \frac{2{,}96\lambda^{0{,}365} N_{Fr}^{0{,}0978}}{N_{lv}^{10{,}4473}}$	$C- = (1-\lambda)\, ln \frac{4{,}7 N_{lv}^{0{,}1244}}{\lambda^{0{,}3692} N_{Fr}^{0{,}5056}}$
Suplied	$\varepsilon_l(0) = \frac{1{,}065\lambda^{0{,}5824}}{N_{Fr}^{0{,}0609}}$	C + = 0	$C- = (1-\lambda)\, ln \frac{4{,}7 N_{lv}^{0{,}1244}}{\lambda^{0{,}3692} N_{Fr}^{0{,}5056}}$

For the interval 1<*y*<1,2 the factor *S* is calculated with the relation [11]$S = ln(2{,}2y - 1{,}2)$.
To calculate the pressure gradient at a certain point in the flow of the biphasic liquid-solid mixture, proceed as follows:

- calculate ρ_l , ρ_g,v_{sl}, v_{sg}, v_m, G_m, λ, N_{Fr}, $(N_{Re})_{fa}$ and N_{lv}at the pressure and temperature of the respective point;
- determine *L1* and *L2* and determine the flow regime; ε_l(0) is calculated,
- calculate C, calculate the ratio $\varepsilon_l(\alpha)/\varepsilon_l(0)$;
- determine ε_l((α) and ρ_m;
- determine$f_{bifazic}$ratio and the value of f_{fa} from the Moody charts;
- calculated $f_{biphasically}$;
- determined *dp/dz*.

3. EXPERIMENTAL DETAILS

In order to carry out solid-liquid flow experiments in two phases in a horizontal and vertical pipe, we created the installation presented in figure 2.
The horizontal and vertical pipe is made of transparent acrylic resin so that the flows are clearly visible.
The role of this facility was to investigate and analyze the behavior of different solids in the pipeline at different liquid flow rates.
We introduced various solids, stones with a rough outline, pieces of metal, pieces of broken glass into the flow stream (figure 3).
By opening the tap (valve) on the discharge side of the pump, the flow rate is increased until the water carries the solids through the horizontal pipe and then through the vertical pipe.
1) In the first part of the experiment, we investigated the movement of pieces of broken glass in the pipe.
After starting the pump, the flow rate was increased so that at a speed of about 0.40 meters per second, the pieces of glass began to move (figure 4).

At a speed of about 0.55 meters per second, the pieces of glass move along the horizontal pipe but stop at the elbow of the vertical pipe (figure 5).
At a speed of about 0.70 meters per second, the pieces of glass begin to move down the vertical pipe.

Fig.2. Transport pipe made of transparent acrylic resin

Fig. 3.Solids used (stones, pieces of metal, pieces of broken glass)

2) In the second part of the experiment, we investigated the movement of round stones in the pipe (figure 6).
After starting the pump, the flow speed increased to a speed of about 0.40 meters per second, when the round stones start to move slightly.
At a speed of about 0.45 meters per second, the round stones move along the horizontal pipe, but stop at the bend in the vertical pipe (figure 7).
At a speed of about 0.60 meters per second, some round stones begin to move up the vertical pipe.
At a speed of about 0.80 meters per second, all the round stones travel up the vertical pipe.

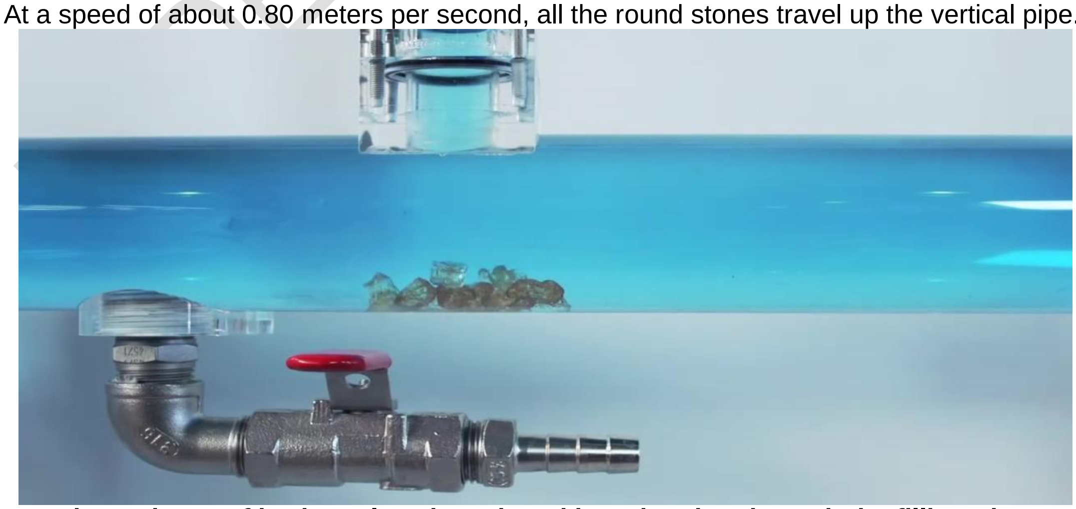

Fig.4. Pieces of broken glass introduced into the pipe through the filling pipe

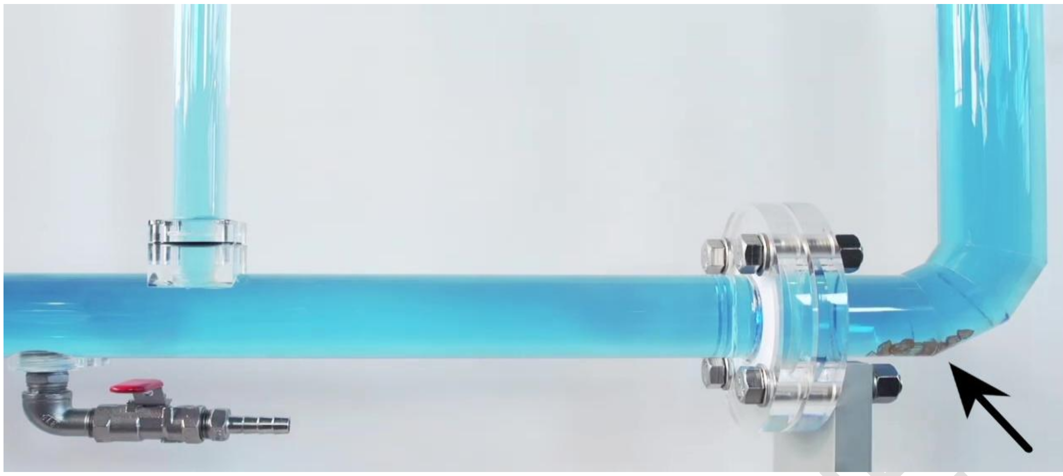

Fig.5. The pieces of glass stop at the elbow of the vertical pipe

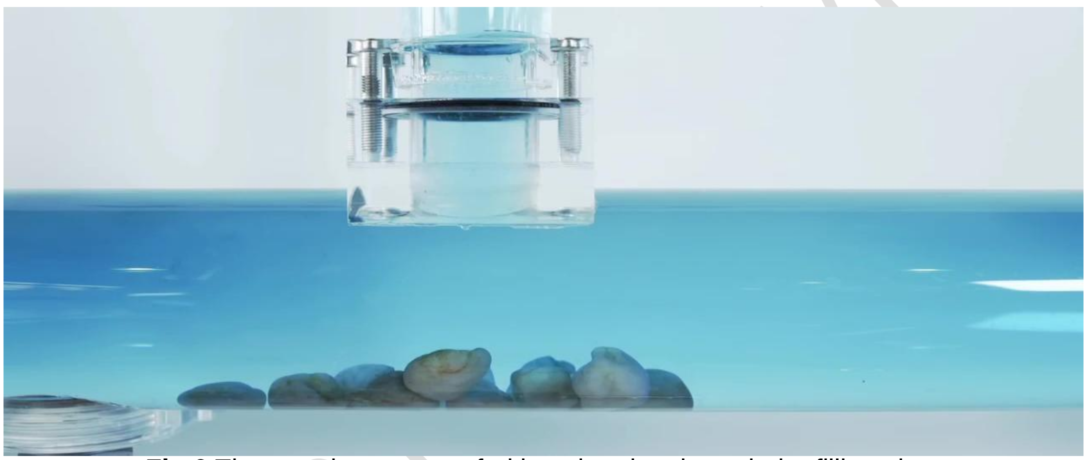

Fig.6. The round stones are fed into the pipe through the filling pipe

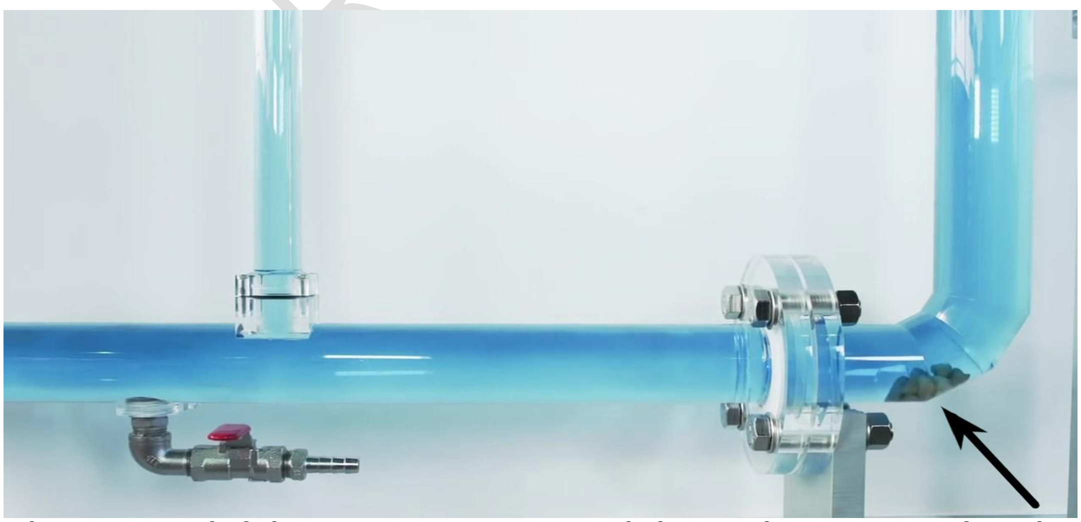

Fig.7.At a speed of about 0.45 meters per second, the round stones move along the horizontal pipe but stop at the bend in the vertical pipe

3) In the third part of the experiment, we investigated the movement of stones with rough contours (figure 8, 9, 10).
At a speed of about 0.45 meters per second, the first stones begin to move.
At a speed of about 0.50 meters per second, the stones move along the horizontal pipe but stop at the bend in the vertical pipe (Figure 7).
At a speed of about 0.80 meters per second, some stones begin to move down the vertical pipe.
At a speed of about 0.85 meters per second, all the stones travel up the vertical pipe.

Fig.8.Stones with rough contours and surfaces

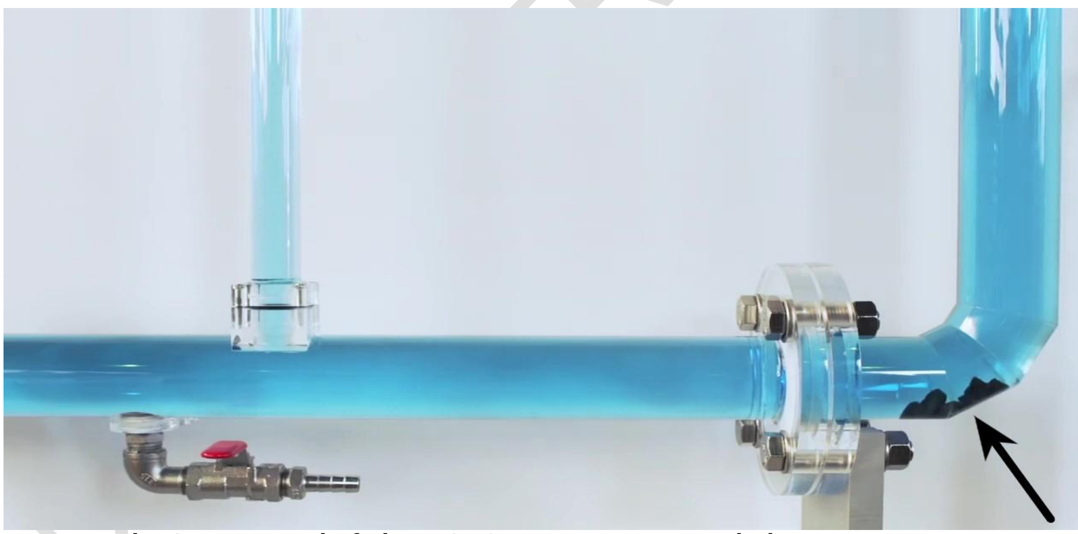

Fig. 9.At a speed of about 0.50 meters per second, the stones move along the horizontal pipe, but stop at the elbow of the vertical pipe

4) In the fourth part of the experiment, we investigated the movement of small steel parts such as nuts and bolts in the pipe (figure 10).
At a speed of about 0.60 meters per second, the first parts begin to move.
At a speed of about 0.90 meters per second, the pieces travel along the horizontal pipe but stop at the bend at the vertical pipe.
At a speed of about 1.20 meters per second, the first pieces begin to move up the vertical pipe.
At a speed of about 1.70 meters per second, all remaining nuts travel up the riser.

5) In the fifth part of the experiment, we would investigate the movement (consisting of stones, broken glass pieces and metal pieces) through the pipe (figure 11).
At a speed of about 0.40 meters per second, the first solids begin to move.
Glass and stones are separated from the mixture.
At a speed of about 0.45 meters per second, pieces of broken glass and stones move along the horizontal pipe but stop at the bend of the vertical pipe.
At a speed of about 0.55 meters per second, pieces of glass begin to move up the vertical pipe.
At a speed of about 0.70 meters per second, all the stones start moving down the vertical pipe.
At a speed of about 1.70 meters per second, all remaining nuts and bolts begin to move up the riser

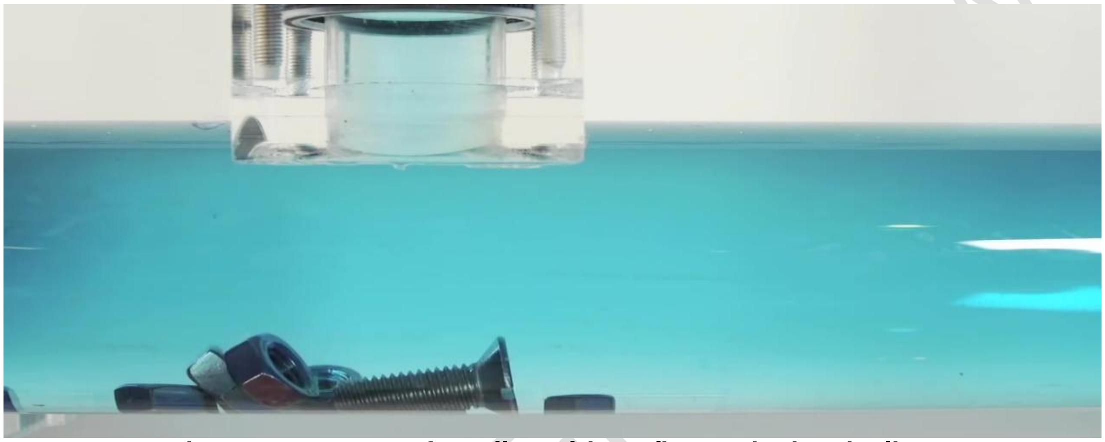

Fig. 10. Movement of small steel (metal) parts in the pipeline

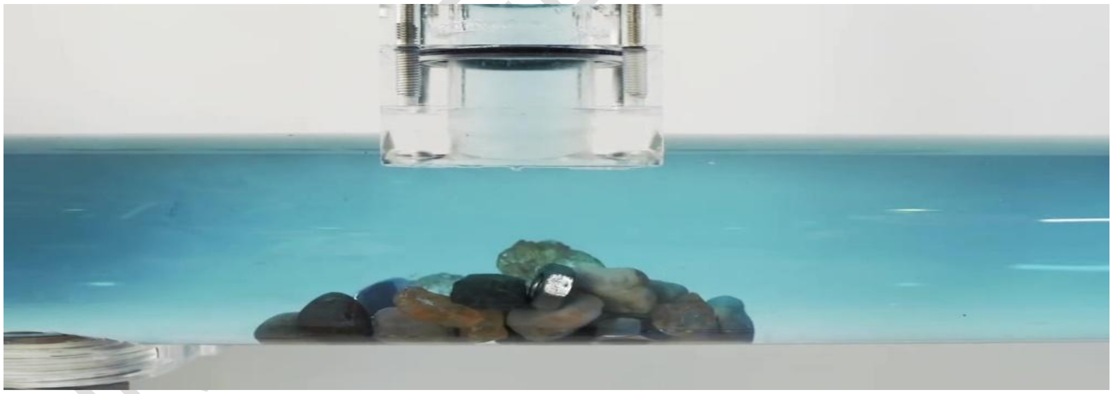

Fig. 11.Rocks, pieces of broken glass and pieces of metal in the pipe

3. Result and discution

The experiments created by us had the role of determining the role of the constructive parameters on the flow parameters of the biphasic liquid-solid mixture.
Thus we tried and managed to determine:

a. The influence of the diameter of the solids on the critical speed,
b. The influence of the mass of solids on the critical speed,
c. The behavior of solids in the biphasic mixture.

In the first experiment we chose several types of solids to be used in their movement through the liquid.We used water as a moving fluid with the following properties in table 2.

We studied the critical (start of motion) velocity for the flow of solids in the horizontal pipe and the vertical pipe (Table 3 and 4).

Table2. Water properties used in experiments

Density	1000 kg/m^3
Viscosity	1 Pa s

Table 3.Critical velocity of solids flow through horizontal and vertical pipe, m/s

Solid composition	Critical velocity of solids flow through horizontal pipe, m/s	Critical velocity of solids flow through horizontal pipe, m/s
Broken glass d=0,005	0,3	0,5
Broken glassd=0,007	0,4	0,6
Broken glassd=0,008	0,55	0,77
Stone, d=0,08	0,4	0,6
Stoned=0,009	0,5	0,8
Stone d=0,01	0,7	0,9
Iron, d=0,1	0,7	1,7
Iron, d=0,2	0,9	1,9

Table 4. Reynolds number at different values of critical velocity of solids flow through horizontal and vertical pipe

Solid composition	Reynolds number for horizontal pipe flow,	Reynolds number for vertical pipe flow
Broken glass d=0,005	15	25
Broken glass d=0,007	20	30
Broken glass d=0,008	27,5	38,5
Stone, d=0,08	20	30
Stone d=0,009	25	40
Stone d=0,01	35	45
Iron, d=0,1	35	85
Iron, d=0,2	45	95

In the III stage of the project we measured (Table 5):
a. The critical velocity at the beginning of movement on the horizontal section of the pipe,
b. Velocity of the homogeneous liquid-solid mixture on the horizontal section of the pipe,
c. The critical velocity at the beginning of movement on the vertical section of the pipe,
d. Velocity of the homogeneous liquid-solid mixture on the vertical section of the pipe.
Following the measurements we were able to determine the equations of motion of the fluid-solid mixture (Table 6 and table 7).
At the end of the experiment, we analyzed the flow velocity obtained experimentally and through our calculation equations against the relation from the specialized literature [10]:

$$v_{crit} = F_l(2Dg(s-1))^{1/2} \quad (42)$$

Where $F_l$is a non-uniformity factor of the solid material in the liquid flow, $D$is the flow diameter, $g$is the gravitational acceleration and $s$is the surface area of the particle.

Table 5. Values of the velocity of the two-phase mixture depending on the sliding of the solids in the flow

Solid composition	Critical velocity in the horizontal pipe, m/s	The speed of movement of the homogeneous mixture when flowing in the horizontal pipe, m/s	Critical velocity in the vertical pipe, m/s	The speed of movement of the homogeneous mixture when flowing in the vertical pipe, m/s
Broken glass d=0,005	0,3	0,35	0,5	0,7
Broken glass d=0,007	0,4	0,45	0,6	0,9
Broken glass d=0,008	0,55	0,66	0,77	1
Stone, d=0,08	0,4	0,45	0,6	0,9
Stone d=0,009	0,5	0,6	0,8	1,2
Stone d=0,01	0,7	0,8	0,9	1,5
Iron, d=0,1	0,7	1,4	1,7	1,9
Iron, d=0,2	0,9	1,6	1,9	2,2

Table 6. Equations of motion of two-phase liquid-solid mixture flow (x is flow distance, y is fluid flow velocity, m/s)

Solid composition	The exponential equation of motion of the liquid-solid biphasic mixture	The coefficient of determination of the accuracy of the relationship to scientific research, R^2	The polynomial equation of motion of the solid-liquid biphasic mixture	The coefficient of determination of the accuracy of the relationship to scientific research, R^2
Broken glass d=0,005	$y = 0,2121e^{0,2899x}$	0,9847	$y = -0,0083x^3 + 0,1x^2 - 0,1917x + 0,4$	1
Broken glass d=0,007	$y = 0,2828e^{0,272x}$	0,9574	$y = 0,0083x^3 + 7E-15x^2 - 0,0083x + 0,4$	1
Broken glass d=0,008	$y = 0,4468e^{0,1948x}$	0,9851	$y = 0,02x^3 - 0,12x^2 + 0,33x + 0,32$	1
Stone, d=0,08	$y = 0,2828e^{0,272x}$	0,9574	$y = 0,0083x^3 + 7E-15x^2 - 0,0083x + 0,4$	1
Stone d=0,009	$y = 0,3536e^{0,2914x}$	0,9749	$y = 0,0167x^3 - 0,05x^2 + 0,1333x + 0,4$	1
Stone d=0,01	$y = 0,5112e^{0,2404x}$	0,8772	$y = 0,0833x^3 - 0,5x^2 + 1,0167x + 0,1$	1
Iron, d=0,1	$y = 0,87\ln(x) + 0,7338$	0,9917	$y = 0,05x^3 - 0,5x^2 + 1,85x - 0,7$	1
Iron, d=0,2	$y = 0,9246\ln(x) + 0,9154$	0,9966	$y = 0,0667x^3 - 0,6x^2 + 2,0333x - 0,6$	1

Table 7. The absolute error of the critical velocity (of the exponential, polynomial relationship and that of the specialty literature) versus the experimentally determined critical velocity (m/s)

Solid composition	experimentally determined critical speed m/s	critical speed determined with the exponential or logarithmic relationship, m/s	critical velocity determined with the polynomial relation, m/s	critical speed determined with relation 42	the absolute error of the exponential or logarithmic relationship	the absolute error of the numerical relation 42
Broken glass d=0,005	0,3	0,31	3,23%	0,3029	0,97%	36,67%
Broken glass d=0,007	0,4	0,41	2,44%	0,403	0,75%	11,25%
Broken glass d=0,008	0,55	0,559	1,61%	0,551	0,18%	3,09%
Stone, d=0,08	0,4	0,41	2,44%	0,405	1,25%	5,50%
Stone d=0,009	0,5	0,52	3,85%	0,503	0,60%	6,40%
Stone d=0,01	0,7	0,71	1,41%	0,709	1,29%	4,57%
Iron, d=0,1	0,7	0,701	0,14%	0,7007	0,10%	4,29%
Iron, d=0,2	0,9	0,92	2,17%	0,91	1,11%	5,00%

4.CONCLUSION

In the flow of gas-liquid mixtures moving in the pipe, it is found that the phase velocities are not similar.
In the horizontal and ascending sections of the pipes, the velocity of the gas phase is higher than that of the liquid, and in the descending sections of the pipes, the velocity of the gas phase is lower than that of the liquid.
Within the studies and experiments carried out within this scientific research program, we consider as our own contributions the following aspects promoted for the first time in the specialized literature:
a. We were able to analyze the multiphase flow of petroleum fluids through the ascending and descending pipelines,
b. We created a facility to analyze two-phase liquid-solid flow so that we can experimentally determine the critical transport velocity of the solid phase,
c. We were able to create an exponential, logarithmic and polynomial numerical model that provides data on the flow of two-phase liquid-solid fluids in risers and vertical pipes,
d. I compared this numerical model with the results obtained worldwide, the simulation being the closest to the experimental data,
e. We analyzed the effect of the curvature of the transport systems on the solid particles in the flow of liquids transported through pipes.

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