Journal of Advances in Mathematics and Computer Science

Volume 39, Issue 4, Page 90-99, 2024; Article no.JAMCS.114520
ISSN: 2456-9968
(Past name: British Journal of Mathematics & Computer Science, Past ISSN: 2231-0851)

Numerical Modeling of Two-Phase Liquid-Solid Movement through Pipes

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JAMCS/2024/v39i41884

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/114520

Original Research Article

Received: 23/01/2024
Accepted: 27/03/2024
Published: 30/03/2024

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

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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

The analysis of solid-liquid mixture flow through pipes has been presented in several articles, being a field with applications in mining and petroleum engineering [1,2,3].

In laboratory we determined that the total pressure drop can be determined from the relationship:

$$\Delta p = \Delta p_f + \Delta p_p, \tag{1}$$

Where Δp_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:

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

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 ρ_f represents the density of the analyzed fluids.

The average velocity value helps determine the REYNOLDS number.

To determine the coefficient of longitudinal hydraulic resistance λ_f, we propose to the equation [4]:

$$\lambda_f = 8\left[\left(\frac{8}{Re_m}\right)^{12} + (A+B)^{-1,5}\right]^{\frac{1}{12}}, \tag{3}$$

$$A = \left\{-2,457\, ln\left[\left(\frac{7}{Re_m}\right)^{0,9} + 0,27\frac{k_f}{d}\right]\right\}^{16}, \tag{4}$$

$$B = \left(\frac{37,350}{Re_m}\right)^{16}. \tag{5}$$

Where $Re_m$is:

$$Re_m = \frac{\rho_f v_m d}{\mu_f}. \tag{6}$$

Where $\rho_f v_m, \mu_f$are the density, velocity and viscosity of the liquid-solid mixture.

To calculate this speed, enter the ARCHIMEDE number and the REYNOLDS number defined by the equations [3,4,5]:

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

$$Ar = 18 Re_m, \tag{8}$$

If $Ar < 3,6$;

$$Ar = 18\,Re_m + 2{,}7Re_m^{1{,}687}, \tag{9}$$

If 3,6 < Ar < 10^5 and

$$Ar = \frac{Re_m^2}{3}, \tag{10}$$

If Ar > 10^5.

For particles of a different shape ($\rho_p$and d_p is the density and diameter of solid particle), 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, k_f is between 0.2 and 0.5, and ARCHIMEDE's number can be written in the form [3]:

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

2 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 Fig. 1.

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 [6,7].

We introduced various solids, stones with a rough outline, pieces of metal, pieces of broken glass into the flow stream (Fig. 2).

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 (Fig. 3).

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 (Fig. 4).

At a speed of about 0.70 meters per second, the pieces of glass begin to move down the vertical pipe.

2) In the second part of the experiment, we investigated the movement of round stones in the pipe (Fig. 5).
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 [8,9].

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 (Fig. 6).

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. 1. Transport pipe made of transparent acrylic resin

Fig. 2. Solids used (stones, pieces of metal, pieces of broken glass)

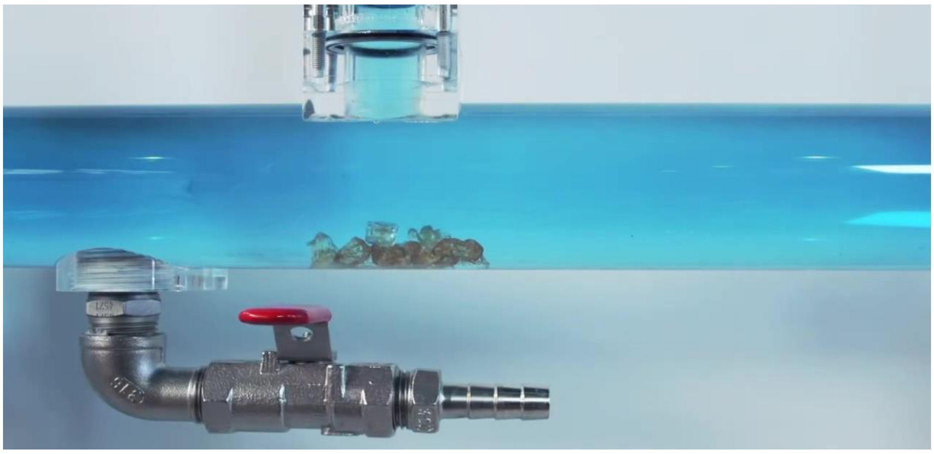

Fig. 3. Pieces of broken glass introduced into the pipe through the filling pipe

Fig. 4. The pieces of glass stop at the elbow of the vertical pipe

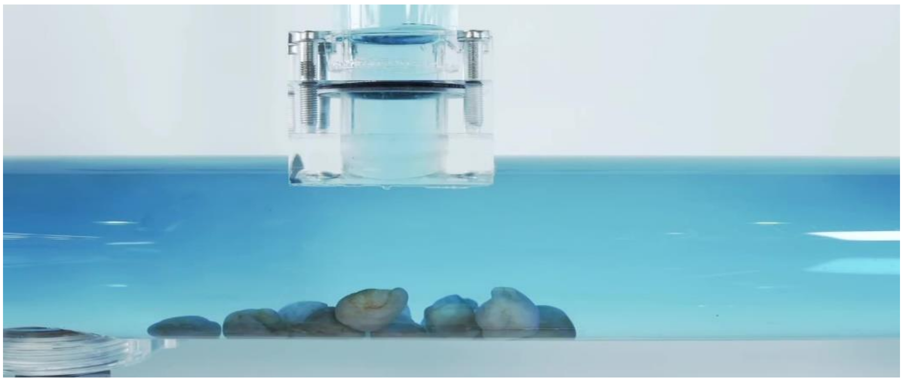

Fig. 5. The round stones are fed into the pipe through the filling pipe

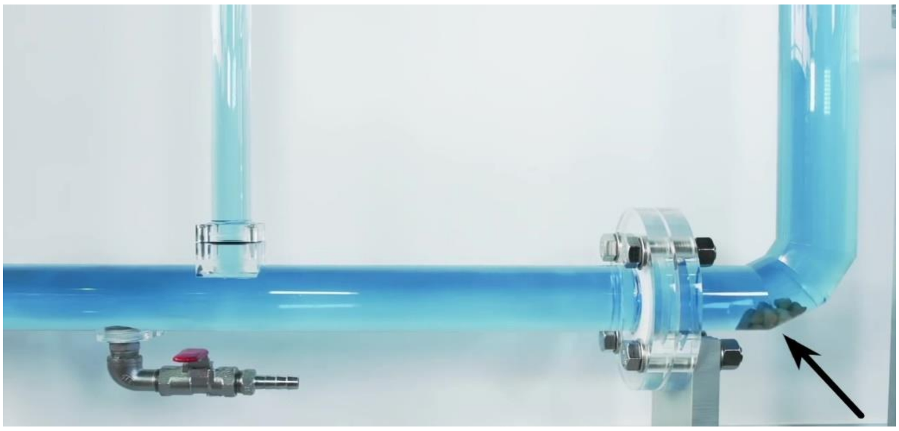

Fig. 6. At a speed of about 0.45 meters per second, the round stones move along the horizontal pipe but stop at the bend in the vertical pipe

3) In the third part of the experiment, we investigated the movement of stones with rough contours (Fig. 7, 8, 9).

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 (Fig. 8).

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.

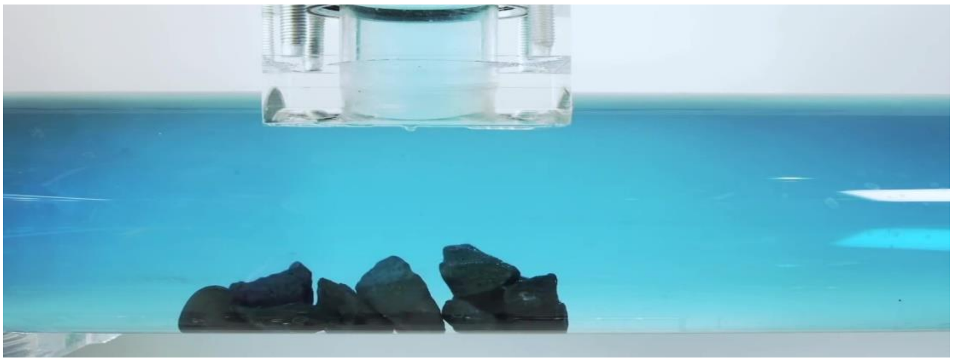

Fig. 7. Stones with rough contours and surfaces

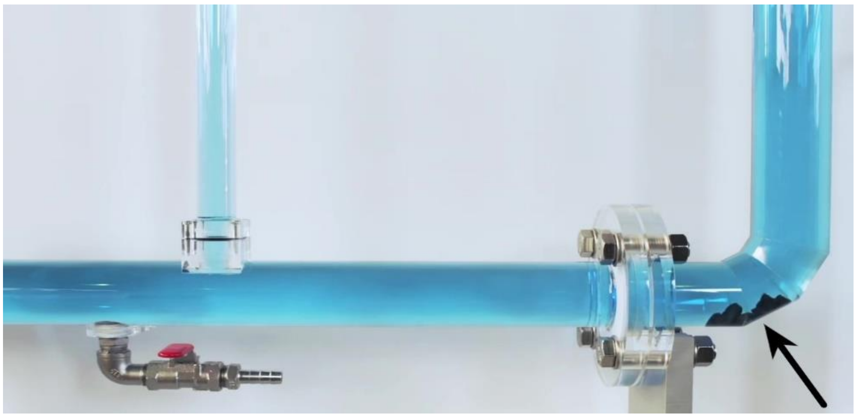

Fig. 8. At a speed of about 0.50 meters per second, the stones move along the horizontal pipe, but stop at the elbow of the vertical pipe

4) In the fourth part of the experiment, we investigated the movement of small steel parts such as nuts and bolts in the pipe (Fig. 9).

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 (Fig. 10).

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

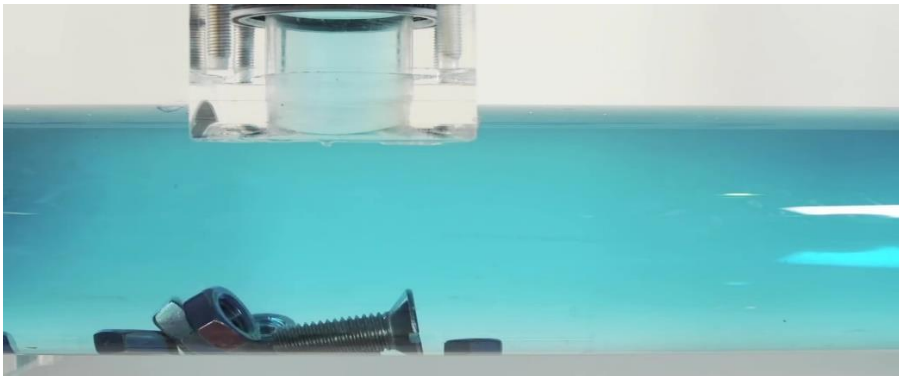

Fig. 9. Movement of small steel (metal) parts in the pipeline

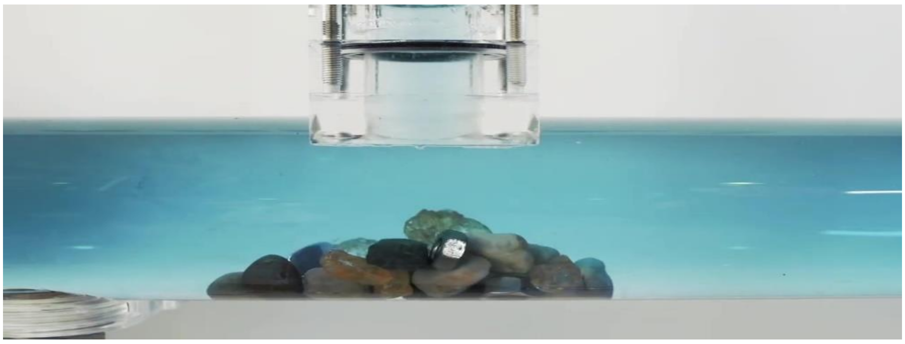

Fig. 10. Rocks, pieces of broken glass and pieces of metal in the pipe

3 Results and Discussion

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 1 and 2).

Table 1. Water properties used in experiments

Density	1000 kg/m^3
Viscosity	1 Pa s

Table 2. 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 glass d=0,007	0,4	0,6
Broken glass d=0,008	0,55	0,77
Stone, d=0,08	0,4	0,6
Stone d=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 3. 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 3):

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 4 and Table 5).

Table 4. 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 5. 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	$y = 0{,}0083x^3 + 7E\text{-}15x^2 - 0{,}0083x + 0{,}4$	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	$y = 0{,}0083x^3 + 7E\text{-}15x^2 - 0{,}0083x + 0{,}4$	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

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 [10,11]:

$$v_{crit} = F_l(2Dg(s-1))^{1/2} \qquad (12)$$

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 [12,13].

Table 6. 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.

Competing Interests

Authors have declared that no competing interests exist.

References

[1] Aini Amran N, Nor Adibah Mustapha S. Oil–Water Separation Techniques for Bilge Water Treatment [Internet]. Resources of Water. IntechOpen; 2021.
Available from: http://dx.doi.org/10.5772/intechopen.91409.

[2] Titiloye EO, Babatunde AJ, Dada MS. Mathematical modelling of two layered blood flow through a tapered artery with overlapping stenotic condition, Ilorin Journal of Science. 2016;3(2):208-223.

[3] Dada MS, Babatunde AJ, Mohammed MT. Fluid analysis of Double-layered blood flow through a tapered overlapping stenosed artery with a porous wall, JHMTR. 2022;9:189-196.

[4] Brown PS, Bhushan B. Bioinspired materials for water supply and management: water collection, water purification and separation of water from oil. Phil. Trans. R. Soc. A. 2016;374.

[5] Bhushan B, Jung YC. Natural and biomimetic artificial surfaces for superhydrophobicity, self-cleaning, low adhesion, and drag reduction. Prog. Mater. Sci. 2011;56:1–108.
DOI:10.1016/J.PMATSCI.2010.04.003.

[6] Park YH, Kim HJ. Formulation and stability of horse oil-in-water emulsion by HLB system. Food Sci Biotechnol. 2021;30(7):931-938
DOI: 10.1007/s10068-021-00934-8.
PMID: 34395024; PMCID: PMC8302701,

[7] Agrawal SS, Gregory GA, Govier GW. An Analysis of Horizontal Stratified Two Phase Flow in Pipes. Can. J. Chem. Eng. 1973;51(3):280-286.

[8] Sevigny R. An Investigation of Isothermal, Co-current, Two-Fluid, Two-Phase Flow in an Inclined Tube, N.Y. University of Rochester, ProQuest Dissertations Publishing; 1962.

[9] Mamaev VA. The movement of gas-liquid mixtures in pipes, Moscow, Nedra. 1978;270.

[10] Govier GW, Omer MM. The Horizontal Pipeline Flow of Air-Water Mixtures, Can. J. Chem. Eng. 1962' 40(3):93-104.

[11] Gould TL, Ramsey EL. Design of Offshore Gas Pipelines Accounting for TwoPhase Flow" SPE 4844, Presented at SPE-European Meeting, Amsterdam, The Netherlands; 1974.

[12] Hoogendoorn CJ. Holdup in Gas-Liquid Flow, Chemical Engineering Science, Elsevier. 1959;9(4):205-217.

[13] Mandhane JM, Gregory GA, Aziz K. A Flow Pattern Map for Gas-Liquid Flow in Horizontal Pipes. Int. J. of Multiphase Flow, Elsevier. 1974;1(4):537-553.

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