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Investigation of the Impact of Gravity on the Downstream Flow of Fluid in a Bifurcated Channel

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A B S T R A C T

The study analyzed numerically the data obtained from experiment where water, diesel, crude oil and peanut oil are made to represent various categories of fluid samples with similar physical properties. Each of the fluid sample are allowed to flow through a bifurcated channel of 10°, 20°, 30°, 40°, 50° and 60° angles of bifurcation, an experimental process to be iterated for recovery volumes of 100ml, 200ml, 300ml, 400ml and 500ml. result of the dimensionless Froude number for each of the fluid sample were compare and presented based on their physical properties and based on the dimension of the symmetrical channel they flow through.

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INTRODUCTION

The distribution of substance in various forms such as solid, liquid, gas as well as energy has been easily achieved with the application of bifurcation. Broadly classified into the symmetrical and asymmetrical bifurcation. The symmetrical is the splitting of the main channel into two equal daughter channels that are further separated by equal angles measured from the centerline of the main channel. While the asymmetrical bifurcation is the splitting of the main channel into two unequal daughter channels separated by unequal angle measured from the centerline of the main channel. Bifurcation has been utilized naturally by plants to enable the distribution of water and other nutrients from the soil to all its branches. In the human, it is found in the arterial system where they enable the distribution of oxygenated blood to the body tissues and organs. It is also found when a river channel splits up into tributaries.

Here we aim to numerical analyze further the data obtained from the experimental exercise where water, diesel, crude oil and peanut oil are subjected to a flow through six cylindrical bifurcated glass tubes, a procedure that will be iterated for 100ml, 200ml, 300ml, 400ml and 500ml volume of the selected fluid samples flows through the bifurcated channel. And the dimensionless Froude number which could be related to the physical properties of a fluid sample and the channel symmetry considered in this study will be sued to ascertain the inertial force and the gravitational force on the fluid sample.

THEORETICAL REVIEW

Various research works has attempted to explain specific areas and hydrodynamic behaviours and phenomenon associated with flows in a bifurcated channel has been presented since the beginning of this century. As (Anastasiou, Spyrogianni, Koskinas, Giannoglou, & Paras, 2012) replicated the bifurcated arterial system in order to study the pulse driven flow of blood through the human arterial system. Estimating the variation of the wall shear stress cause by the pulse, from the velocity of the localized flow, they were able to show the low Reynolds number of blood flow, the wall shear stress of the small and large arteries, and how they influence the formation of plaque. Also investigating the flow uniformity of the distribution of fluid, a symmetrical bifurcated slow channel was adopted in the experimental study of (Liu, Li, Lew, & Juarez-Robles, 2012) where results of great industrial significance in devices like reactors, heat exchangers, cell etc. were obtained and presented. Research study on bifurcation was further extended (Egbo, Abbey, Ngiangia, Dappa, & Ugoji, 2022) in their experimental investigation of the comparative study of the flow structure of polar solvent and unrefined hydrocarbon, in this study water and crude oil were allowed to flow through six bifurcated channel of different angles, the flow velocity of both fluid samples were computed and analyzed, and the discrepancy of the results obtained base on the physical properties and the angles of bifurcation of the various flow channels they are subjected to. To enhance of the study on bifurcation (Egbo, Hassan, Opuene, Nama, Onoja, &

Oluomachukwu, 2022) carried out an experimental study that obtained the velocity profiles of processed hydrocarbon and viscous fluid, in this study six bifurcated glass tubes of angles ranging from 10^o to 60^o were arranged in an incline position for groundnut oil representing the viscous fluid and diesel oil representing processed hydrocarbon to flow through them, as the time for each of the selected fluid sample takes to flow through the various angles of bifurcated flow channels are computed and used for analysis.. various flow analysis for other flow channels with other geometrical designs as (Das, Gaur, Chaubey, Veena, & Khati, 2001) considered a canal cross-section of triangular-trapezoidal augment, which could be approximated to a parabolic shape at the long run, analysis and design of uniform flow condition, dimensionless Froude number of uniform flow in a constrained condition as well as the optimization of a stable parabolic flow channel. They further presented numerical results of the design methods developed in their study. (Elbatran, Aly, Omar, Ahmed & Shabara, 2015) considered a channel geometry of helical dimensions that is commonly used in fluid processing and separation in the industry having considered the kind of complicated flow pattern which will be obtained as a result of centrifugal force and other effects; hence the Computational Fluid Dynamics was adopted as a suitable technique for analysis considering the physical parameters such as the dimensionless Reynolds number, Froude number and the geometrical curvature effect on the fluid. At the end they were able to establish a relationship between the curvature effect, torsion number, flow velocity and the dimensionless Reynolds and Froude numbers. The dimensionless Froude number for different elevation is one of the target variables of the study carried out by (Ng, Tan, Selvarajoo, Haniffah, Kasiman, Lai &Teo, 2022), in this study they considered the weirs flood reduction tendency for flow situation associated with bifurcation, also considering other weir geometries such as U-shape, cross-sectional rectangular and V-notch shape, in the study they were able to compare the velocity profiles of water with the dimensionless Froude number for different elevations, and results further establish a relationship between the outlet discharge ratio, velocity ratio to the weir geometrical dimensions and associated behaviour of flows in a bifurcated channel of weirs control structure. The hydrodynamic flow analysis where the dimensionless Froude number is the core parameter used for the discussion as such (Adegoke & Mutiu, 2006; Fu, Zhou, Xu, Wei, & Wang, 2023) revealed that flow velocity and the gradient of bottom slop as well as flow depth are inversely related to the roughness of a flow surface. They also show that the flow velocity decreases as the channel height decreases. Also, a situation where a local hydraulic jump is formed as result of the mass occupation of a river flood channel, which could be a consequence of the bifurcated, narrower or intersected channel. The local hydraulic jump was shown to enhance the deposition of sediment as relationship between the sediment deposition rate, downstream and upstream dimensionless Froude number, sediment supply rate, particle size and flow discharge are established.

METHODOLOGY

The requirements of this experimental procedure involve materials with known specific characteristics to enable the establishment of a better hydrodynamic analysis and results.

Four fluid samples were selected for this study to stand-in for different categories of fluid samples. Water is selected to represent polar solvent, also required for analysis that will be considered on the universal scale. Vegetable oil is adopted to represent heavy and viscous fluid with density and other physical properties that is very different from water. Crude oil is adopted to represent the category of unprocessed hydrocarbon. While diesel oil is adopted to represent the processed hydrocarbon.

Table 1: the physical properties of the selected fluid samples

S/N	FLUID SAMPLE	DENSITY	VISCOSITY	SPECIFIC GRAVITY
1	Water	997.00	1.00	1000.00
2	Diesel oil	894.33	0.89	885.00
3	Crude oil	920.00	3.28	847.00
4	Peanut oil	919.00	34.6	0.93

- Bifurcated Glass tubes (six different angles)
- Beaker (two 1000ml)
- Retort stand (two)
- Reservoir (15litre capacity)
- Stop watch

A metallic reservoir that will be able to hold at least 10litres of each of the fluid samples is constructed. The reservoir is constructed with a valve at the bottom side to enable flow control of fluid in the course of the experiment.

Six bifurcated transparent glass tubes were also constructed to enable an extensive analysis that may include the explanation of visual observation of the influence of bifurcation on the inertial force on each of the selected fluid samples.

Experimental Setup

The bifurcated ends of the transparent flow channels are position into the two 1000ml beakers for fluid recovery, while the main flow channel is connected to the valve at the bottom of the reservoir to properly collect fluid samples from the reservoir when the valve is open. The bottom of the reservoir where the valve is installed and the main flow channel is connected is kept at a height of 48inches, while the other ends where the bifurcated flow daughter channels are positioned into the beakers for the recovery of fluid samples are kept at a height of 14inches, all from a plain surface.

Geometrical Consideration

If the length of the main channel of the bifurcated flow channel is L_m, and the length of the bifurcated daughter channels is $L_d Sin\theta$ *and* $L_d Cos\theta$, where θ is the angle of bifurcation measured from the centerline of the main flow channel. The total length is the given by

$$L_{\perp} = L_m + L_d \sin\theta$$

$$L_{\parallel} = L_m + L_d \cos\theta$$

The average flow distance becomes

$$L = \frac{L_{\perp} + L_{\parallel}}{2}$$

Also, from the arrangement of our experiment where the flow channel is placed at a decline position to enable the fluid to flow down into recoveries. if θ_1 is the angle of declination measured from the normal to the bottom of the reservoir in an anticlockwise direction. And the side opposition this angle θ_1 is the vertical height from the tip of the bifurcated daughter channels to the normal from valve normal to the reservoir. Using the trigonometric relation and the Pythagoras theorem the sides, angle θ_1 were obtained.

Experimental Procedure and Mathematical Formalism

The fluid samples were allowed to flow through a distance defined by the length of the bifurcated flow channel whose total length also depends on the angle of bifurcation θ. If the interval of time *t,* it takes to recover 100ml, 200ml, 300ml, 400ml and 500ml as they flow through the total length *L*, of the bifurcated flow channel. Then the flow velocity for each of the angle is given by

$$v = \frac{L}{t}$$

As the fluid is released from the reservoir as the valve is open, it senses a resistance that consequently and suddenly alters the flow pattern and structure after which the fluid must have exerted some magnitude of inertial force. The ratio of the inertial force exhibited by each of the fluid samples to the gravitational force is given by the dimensionless Froude Number, which is given by expression [Hubert, 2004; Osman & Seshadri Iyer 2021; Rapp, 2016]

$$Fr = \frac{v}{\sqrt{gL}}$$

Where *v,* is the flow velocity, g is the acceleration due to gravity given as $g = {g}/{\sin\theta}$, and *L* is the flow distance defined by the total length.

RESULTS AND DISCUSSION

For a realistic values of the downstream angle θ, flow distance which is the total length of the bifurcated channels, the density, viscosity and other physical properties of water, diesel, crude oil and peanut oil, the profiles of results are presented in Figure 1, a figure that contains the six plots corresponding to the six bifurcated flow channels of angles 10°, 20°, 30°, 40°, 50° and 60°, where the flow Froude number for each of the selected fluid samples were compared against 100ml, 200ml, 300ml, 400ml and 500ml recovery volumes. Figure 2, 3, 4, and 5 are profiles of results of the dimensionless Froude number plotted against the recovery for water, diesel oil, crude oil and peanut oil respectively.

The dimensionless Froude Number of the flows through a bifurcated pipe is computed using the average flow velocity from the point of bifurcated. The figure 1 which contains the graphs for the six angles of bifurcation considered in this study.

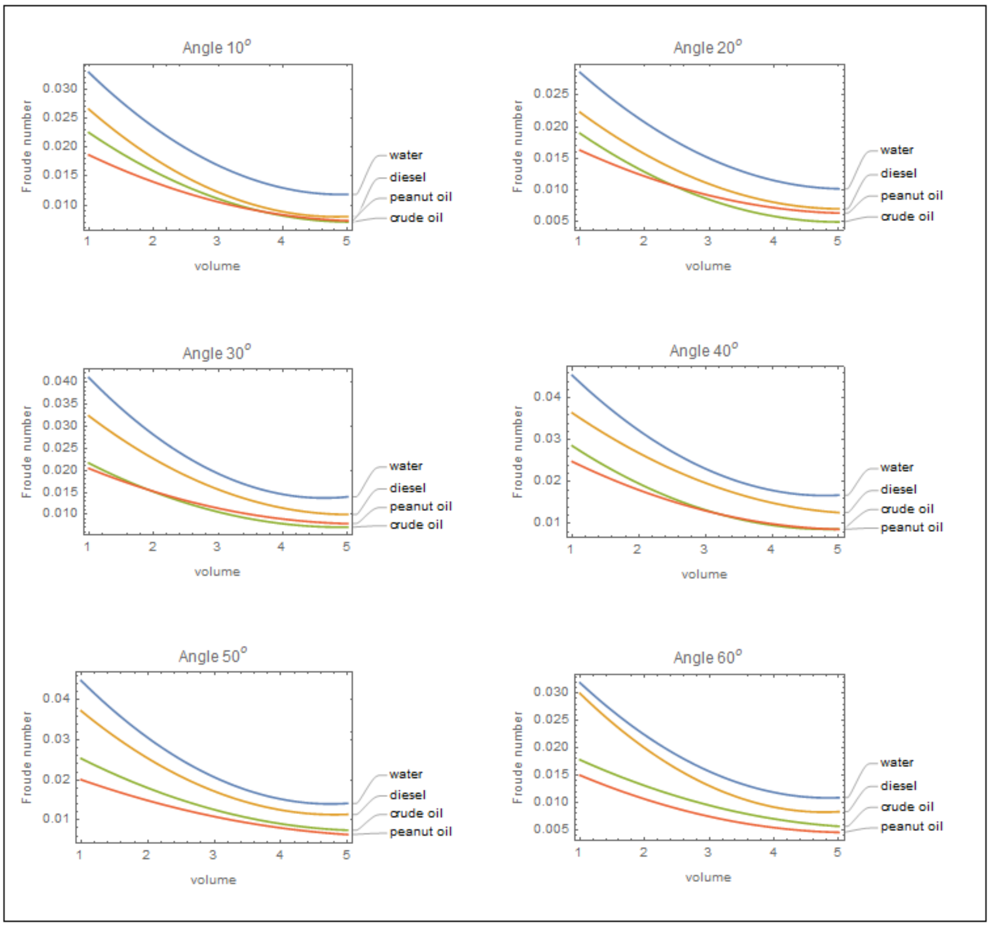

Figure 1 Profiles of angles of the dimensionless Froude number for all volumes

The graphs are plots of dimensionless Froude number on the vertical axis against the designated recovery volumes on the horizontal axis. The various colors of trends appearing on the graph are as follows, blue, brown, lemon and orange trends representing water, diesel oil, crude oil and vegetable oil respectively. The pattern and arrangement of the trend representing the selected fluid sample that flow through the symmetrically bifurcated pipe of bifurcated angle of 10^o. The slope of the trend representing the water sample, shows a much higher gradient between the recovery volumes of 100ml to 300ml respectively represented by 1 and 3, when compared to the value of the gradient between 300ml to 500ml respected by 3 and 5 on the horizontal axis. The same behavior is observed for the water sample for bifurcated angles of 20^o, 30^o, 40^o, 50^o and 60^o presented in the figure 1. Water also shows the significant values of the Froude number throughout all recovery stages of the designated volume when compared to diesel, crude oil and vegetable oil for all the selected angles of the bifurcated channel. Diesel oil is the fluid sample that shows a much higher value of the dimensionless Froude number next to water, for all recovery volumes and all through the selected angle of bifurcated the trend representing crude oil is next to diesel, while vegetable oil appears to show the least values of the dimensionless Froude Number amongst the selected fluid samples in this experiment for all recovery volume, through the selected angle of bifurcation. The implications of the result obtained is that the, points representing the relatively small recovery volumes (i.e 1-3) is characterized by higher Froude Number to volumes ratio is dominated by the gravitational force component of this dimensionless Froude number. In this flow regime the impact of bifurcation is not really observed because of the relatively small time associated with the flow process. The inertial force component of the dimensionless Froude number begins to increase proportionately as the designated recovery volume begin to increase, which is observed from the trends as they begin to appear parallel to the horizontal axis from 300ml to 500ml. Hence at these stages a flow regime which is a consequence of the inertial force component of the dimensionless Froude Number begins to dominates the entire flow process. The trends further show that the dimensionless Froude number for water which attains a maximum of 0.045 values at bifurcated angle of 40^{o} and 50^{o}, will less likely generate wave due to the impact of bifurcated despite the dominating of the gravitation at the initial flow regime. Implication also shows that as the density of the selected fluid sample increase from water, diesel, to crude oil and groundnut oil, the lower the dimensionless Froude Number observed from the results of this study. The discrepancy between the trends is a consequence of their respective physical properties such as density and viscosity, which is directly related to the impact of the gravitational force component at the dimensionless Froude number of the fluid samples.

Results of the dimensionless Froude number against designated volumes for the selected angle is presented in figured 2. For all the fluid samples.

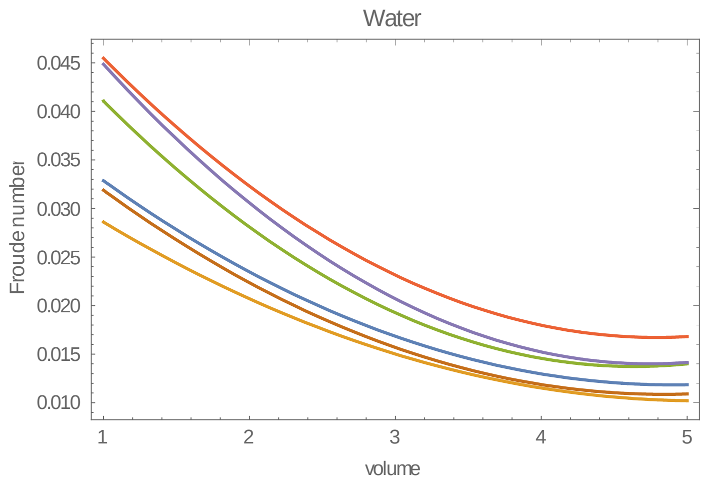

Figure 2 Profile of water for all angles of bifurcation

The pattern of result obtained from the water sample shows the following order of decreasing dimensionless Froude number from the orange trends, purple, light green, blue, dark-brown and light brown trends respectively representing 40^{o}, 50^{o}, 30^{o}, 10^{o}, 60^{o} and 20^{o} angles of bifurcation. The discrepancy in the result shows how significant bifurcation angles influences the stability of flow represented by the Froude number, as seen in the figure 2 we can easily see that the influence of gravity on the flow process increases according to the pattern on result state, and this gravitational influence increases further in a continues flow situation as indicated by the linear drop in the dimensionless Froude number as the recovery volume increases.

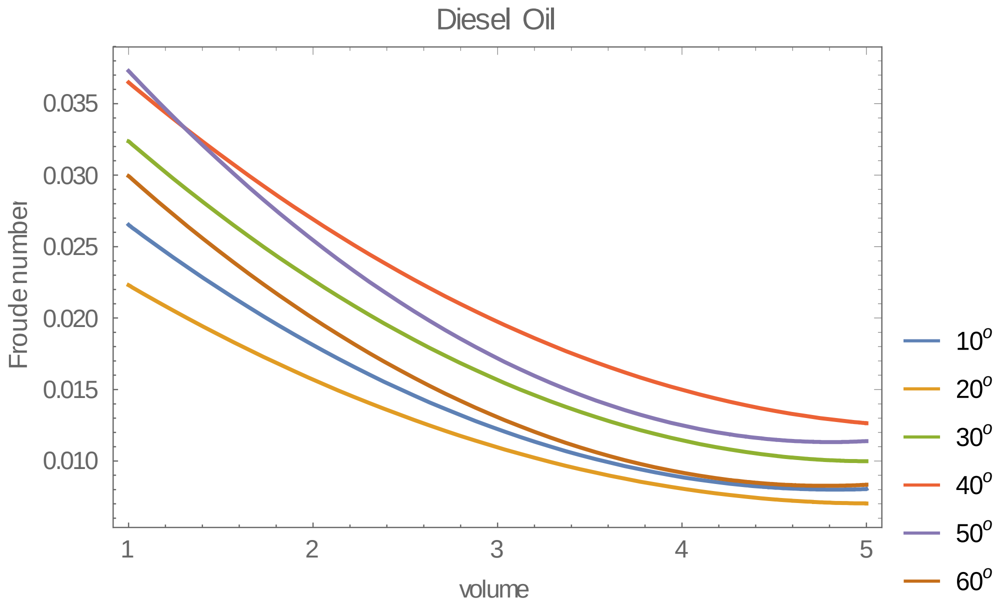

Figure 3 Profile of diesel for all angles of bifurcation

While for diesel oil the dimensionless Froude number decreases from orange, purple, light-green, dark-brown, blue and light–brown, respectively representing 40°, 50°, 30°, 60°, 10° and 20° angles of bifurcation. The spacing in-between the trendlines of the profile of results presented in Figure 3 for diesel indicates the sensitivity of this fluid sample to bifurcation, which can also be interpretated as the susceptibility of the density and viscosity of diesel to bifurcation. The pattern of result on this figure also indicates the order of increasing gravitational force impact over the inertial force component of the dimensionless Froude number, an action that increases proportionately as the recovery volume increases.

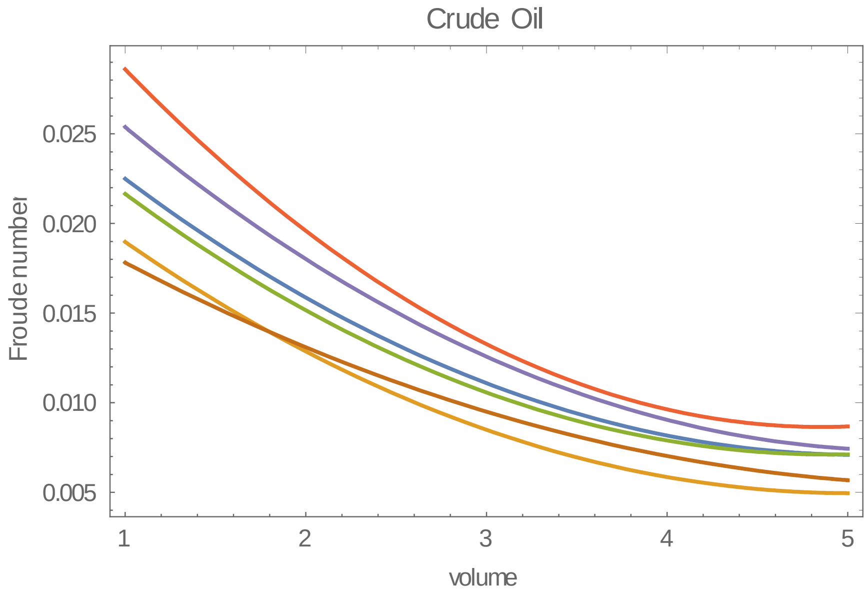

Figure 4 Profile of crude oil for all angles of bifurcation

For crude oil, the pattern of result obtained shows orange, purple, blue, light-green, brown and light brown representing 40°, 50°, 10°, 30°, 60° and 20° angles of bifurcation respectively. The result profiles of result presented in figure 4 for crude oil shows how the influence of gravity in this flow situation increase from 40°, to 50°, through 10°, 30°, 60° and 20°, that is according to the pattern presented for this fluid sample. And as the recovery volume increase, as linear decrease in the trends is observed which indicates a linear increase in the influence of the gravitational force component of the Froude number over the inertial force component of the dimensionless parameter.

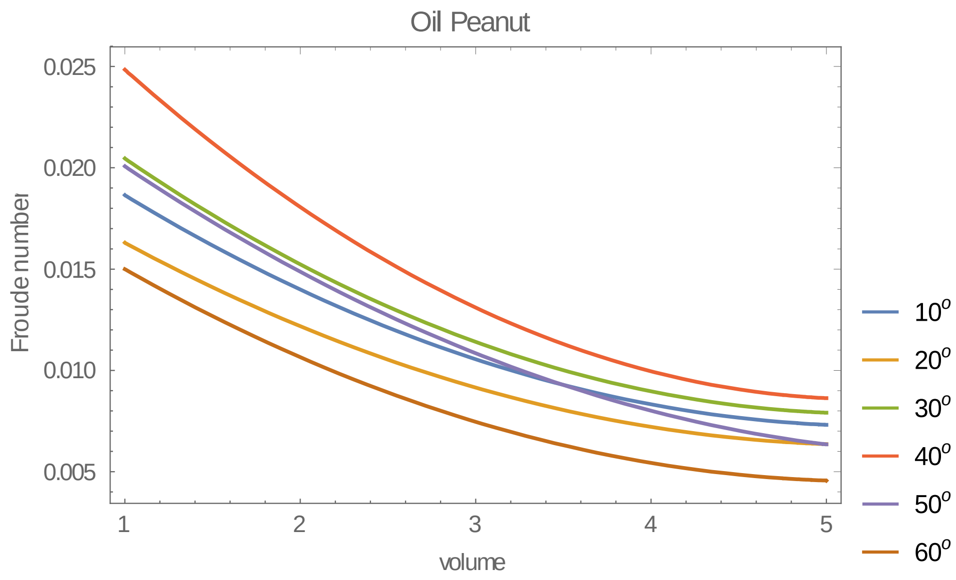

Figure 5 Profile of peanut oil for all angles of bifurcation

The pattern of result obtained for peanut oil, which shows that the dimensionless Froude number decreases from the orange, light-green, purple, blue, light-brown and dark-brown corresponding to the following angles, 40°, 30°, 50°, 10°, 20° and 60° respectively. Results presented in Figure 5 for peanut oil show an overlap between trendlines, indicating resistance to the effects of the bifurcation angles for the overlapping angles. The influence of gravity increases according to the pattern of result state, and proportionately increase linearly with volume for all angles of bifurcation represented by trendlines.

Considering the geometry and symmetry of the flow trajectory considered in this experimental study, the implication of the result obtained subsequently show that the effect of inertial force due to the angle of bifurcation is more significant in some angle of bifurcation than the others for the selected fluid sample. The average flow pattern deduce from all the fluid sample for all angle of bifurcation is 40°, 50°, 30°, 10°, 60° and 20° which corresponds perfectly with the flow pattern observed for water. This further suggest that water which is regarded as a universal solvent should be adopted in all hydrodynamic experiment, and used as a reference fluid. Analysis based on the average flow pattern of this experiment shows that, bifurcation alters the state of fluid flow, measure on the scale of the dimensionless Froude number experiment force experienced by a fluid flowing through a bifurcated flow channel, and that as a consequence flow through a bifurcated channel tends stabilize and produce a tranquil flow.

CONCLUSIONS AND RECOMMENDATIONS

Hydrodynamic analysis whose application is found almost in all work of life, also naturally for the transportation solid mineral as well as in hydraulic jumps, this study has guided us to the conclusions that

- For some angles of bifurcation, flow is less likely to attain the critical or supercritical state, as the angle of bifurcation has been shown to enhance the influence of the gravitational force component of the dimensionless Froude number.
- The influence of gravity on fluid as they flow through various angles of bifurcation becomes more significant in a continuous flow situation, which indicates that in application sediment formation, and the deposition of gravels and other solid minerals will most likely be formed and found at the sites of maximum gravitational influence

The influence of Inertial has shows less effect on viscous fluid. Hence, the higher the viscosity of a fluid sample, the higher the gravitational impact on that fluid, and the lower the influence of the inertial force on the fluid as it flows. Also, the lower the viscosity of a fluid sample, the lower the gravitational force and the higher the inertial force components of the dimensionless Froude number.

FURTHER STUDY

This advanced research will explore in depth the impact of gravity on the downstream flow behavior of fluids in bifurcated channels, with the aim of understanding its influence on velocity distribution, pressure, and flow direction changes, and identifying solutions that can be optimized to improve the efficiency of fluid channel systems in bifurcated situations.

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