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Liquid-Liquid Flow in Vertical & Slightly Inclined Pipe: A Review

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Abstract
A study of liquid-liquid flow is important to better comprehend the more complicated scenarios involving two-phase flow. To study this investigation has been done on liquid-liquid flow via conduits of Vertical & slightly inclined flow pipe. The kind of flow regimes. Influences the design and operation of pipelines by determining a critical description of two-phase flow. Characteristics like flow pattern maps with different oil viscosity (μo) different diameters, different inclinations, flow rate and water fraction, water with kerosene, mineral oil, naphthenic oil, mineral oil, N0-15 white industrial oil, Lubrax gear oil, etc. of last two decades are chosen for the two-phase flow. The investigations demonstrated a noticeable difference in flow pattern while flowing through vertical & Slightly Inclined Pipes in different diameters with different viscosity of the oil.

Key Words: Flow Pattern map; Vertical and slightly inclined pipe, Liquid-liquid flow; Pressure drop; Oil-Viscosity (μo).

Nomenclature:

B	Oil bubbles in the water
B_D	Big Drops
$B_{w/o}$	Water in oil bubbly flow
CE W/o	Churn flows with water drops in oil.
CAF	Core Annular flow
CAFS	Core annular with swirling motion and waves at the interface
CAFB	Core Annular with bamboo waves at the interface
$D_{w/o}$	Dispersed water in the oil phase
D_B	Dispersed bubbly
$D_{o/W}$	Dispersed oil in the water phase
$D_{o/w\&(w/oemulsion)}$	Dispersion of oil in water & water in oil emulsion
Dos/w	Oil-in-water slug
$D_{o/wPS}$	Oil dispersion in water pseudo slug flow
$D_{o/w}CT$	Oil dispersion in water Counter current flow
$D_{w/o(w/o\ emulsion)}$	Dispersion of water in oil (water in Oil Emulsion)
O/w Drops	Oil in water Drops
$S_{o/w}$**($O_{s/w}$):**	Slugs of oil in water
$S_{w/o}$	Water in oil slugs flow
TF	Transition flow pattern
UAF	Unstable Annular Flow
VFD $_{o/w}$	Oil in water very fine dispersed flow
W/o(W/O Emulsion)	Water in an oil-water emulsion
W/O Drops	Water in an oil Drops

Introduction
Liquid-liquid flow is a complicated process that involves the movement of two or more incompatible fluids. Al-Azzawi et al.(2021) also called pseudo-homogeneous flow, is frequently encountered in a diverse range of equipment such as extraction columns, cooling devices, continuous reactors, and pipelines used in the transport of crude oil (Mydlarz et al.,2014) processes such as petroleum, geothermal, chemical, petrochemical, foodstuff, and pharmaceutical industries. Through the process energy and oil industries, the real-time flow of two fluids in a pipe (either gas-liquid or liquid-liquid) happens in a variety of applications. Different patterns can emerge

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depending on the fluid characteristics, phase flow rates, and pipe size ranging from dispersed flows to entirely segregated flows.

1.1 Vertical and slightly inclined Flow Pipe

In Vertical and slightly inclined pipes recent works were performed by Yang et al. (2019) & Riano et al. (2019) of which an inclined pipe experiment was performed by Zong et al. (2009), for both horizontal & vertical test sections and Azizi et al. (2016) for the inclination about 15º,45º& 5º& 90º,75º,60º,45º respectively. Summaries are shown in Table (1). Such flow is often encountered in an environment of higher pressure and higher temperature, such as in oil- exploration in the petroleum industry. Water flows from the bottom to the top, and dispersion of fluid occurs as pressure and temperature vary, which is unfavorable since it increases the fluid system's effective viscosity, resulting in increased pressure drop. Because of the reduced pressure drop, great dispersion of oil in water occurs. Immiscible fluid is distributed as droplets of one phase in another at all phases of production, including in reservoirs, manufacturing lines, high-shear pumps, and valves(Schumann et al., 2018). Flow regimes refer to the various shapes and spatial distributions of a pipe's deformable interface. Many methods have been developed to track or deal with the motion of the interface between immiscible fluid-like phase-field methods. This method can be divided into two broad classes such as interface tracking and interface capturing method. Guo et al. (2018) found that as the temperature rises, the S w/o, CE W/o, and churn flow with large water droplets tend to transition into B W/o and D w/o with smaller water drops. According to Yang et al. (2019), when the temperature at a given water proportion increased, the flow pattern maps' borders tended to emerge at lower input water fraction values, and the influence of pressure on the flow patterns was found to be opposite that of temperature(Guo et al., 2018). When oil and water flow uphill in a pipe at the same time, gravity causes the heavier fluid i.e., water flow downwards, according to Ouyang et al. (2003). The greater the difference between water and oil velocities, the stronger the shear stress interface and the greater the likelihood of water being driven upwards, having a high velocity of oil flow. To avoid oil-water mixing, a lower oil flow rate is required. The greater the good deviation, the smaller the wellbore size. So, the three key elements that influence the occurrence of oil-water are well variation, well size, and density of oil. (Ouyang et al.,2003)

1.2. Diverse configuration of the Vertical &inclined Flow pipe

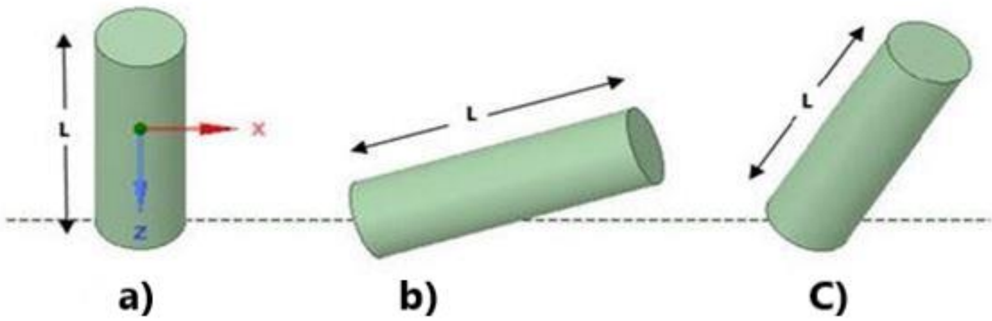

Figure 1 Sketches of common pipeline positioned in (a) 0^0 (b) 15^0& (c) 45^0 Vertical& slightly inclined pipe.

Table 1 Summary of previous studies on liquid-liquid flow in Vertical & inclined pipe

Sl.No.	Author (Year)	Diameter (mm)	Length (mm)	Oil Physical Properties (Kg/m3, mPas)	Pipe material	Superficial Velocity (or Mixture velocity) (m/s)	Flow direction	Study Aims	Pressure gradient data
1	Jin et al. (2003)	125	N/A	δ_{water} =998.δ_{oil}=N/A	N/A	U_m = 0.054	Upward	Flow pattern identification based on kinetic wave	N/A

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								theory.	
2	Lucas et al. (2009)	80	2.5	δ_{water} =998.δ_{oil}=N/A	Perspex	U_{os}=0.025 to 0.276	Upward	Determined the local oil volume fraction distribution.	N/A
3	F.A. Hamad et al. (2010)	77.8	4.2	δ_{water}=998.$\delta_{kerosene}$ =787	Acrylic	U_{so}=0 to 0.232	Upward	Evaluated hot-film. Dual optical and pitot tube probe.	YES
4	Xu et al. (2010)	50	3.5	δ_{water}=998. δ_{oil} =860	Perspex	U_{so}=0 to 1.24	Upward & Downward	Investigated phase inversion and frictional pressure.	YES
5	Du et al. (2012)	20	4	δ_{water} =998. δ_{oil}=856	N/A	U_{so}=0.258 to 3.684	Upward	Flow pattern and water hold–up measurement.	N/A
6	Barral et al. (2013)	38	8	δ_{water} = 998 δ_{oil}=830	Acrylic	U_{mix}=0.6 (ST)	Upward & Downward	The transition from stratified flow to dual continuous flow was the subject of study.	N/A
7	Mylarz et al. (2014)	30	7.12	δ_{water}==998 δ_{LAN15} =872	Plexiglass	U_{so}=0.025 to 0.578	Upward	Identified flow pattern and measured holdup.	N/A
8	Wang et al. (2015)	25	3	δ_{water} = 998. δ_{oil}= 841	Acrylic	U_{so}=0.2	Upward	Studied phase-isolation of upward oil-water flow.	YES
9	Faraz et al. (2015)	50	1	δ_{water} =998 $\delta_{kerosene}$ =787	Transparent	N/A	Upward	Created an online measuring system with ERT as its primary component.	YES
10	Y.F.Han et al.	20	2.8	δ_{water}==1000 $\delta_{industrial\ white\ oil}$ =845	N/A	U_m=0.0184 to 0.268	Upward	Studied Flow patterns	N/A

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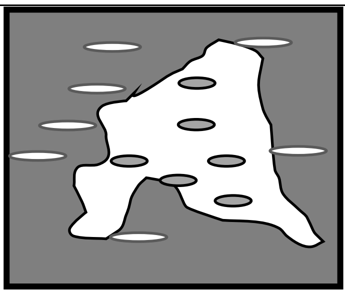
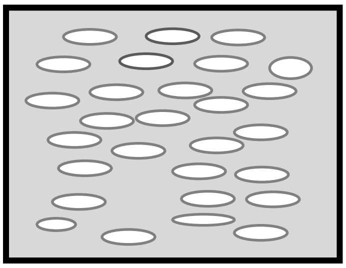
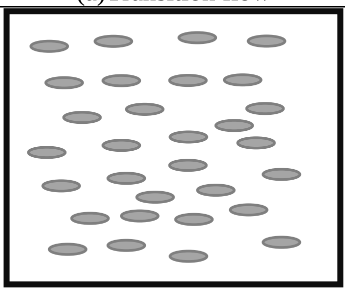
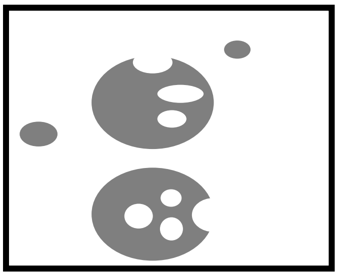
	(2018)							and holdup phenomena at low velocity.	
11	Burlitski (2017)	38	3.2	δ_{water}= 998 $\delta_{ExxsolDL40}$=830	N/A	U_m=2	Upward & Downward	Studied transition from stratified flow to disperse flow pattern.	YES
12	Riano et (2019)	50.8	12	δ_{water}=998 δ_{oil}=860	Glass	U_{so}=0.3 to 0.8	Upward	Studied thin water film in unstable annular flow.	N/A
13	Yang et al. (2019)	0.02	2	$\delta_{water=}$998 δ_{oil} =857	Stainless steel	V_m=0.131	Upward & Downward	Examined oil-water flow pattern under high temperature.	YES

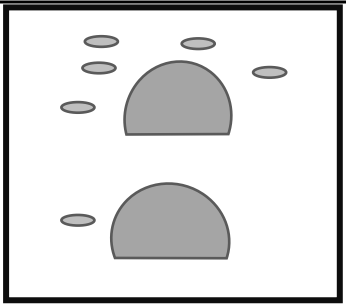
From the above literature, it is clear that limited investigations on the influence of pipe inclination on particle-turbulence interactions in liquid-liquid flows, Further, Inadequate understanding of flow regime transitions in liquid-liquid flows inside slightly inclined pipes and their impact on pressure drop and flow stability, particularly for high-viscosity and non-Newtonian fluids. Lack of comprehensive investigations into phase inversion phenomena (e.g., dispersed phase inversion) and the associated mechanisms occurring in liquid-liquid flows within slightly inclined pipes. Insufficient development of reliable heat transfer models for liquid-liquid flow in pipes with slight inclinations, hindering the optimization of heat exchange processes in inclined systems. Hence, the Current study aims to give insight into the hydrodynamics of flow patterns and flow pattern maps within slightly inclined pipes, and flow stability for high viscous oil is considered.


(a)Transition flow

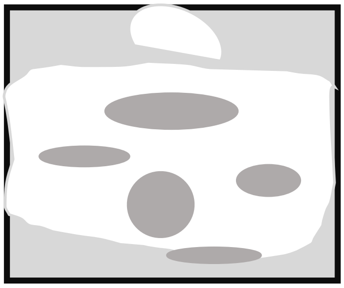

(d)Water in oil bubbly


(b)Oil in water bubbly


(e)Churn



(c)Creep



(f)Oil in water slug

Figure 2 Schematic representation of flow pattern in vertical & slightly inclined pipe

Table 2 Details of the graphs studied in Vertical & slightly inclined pipe flow pattern maps

Figure No.	Author	Diameter (mm)	Length(m)	Fluid	Density (kg/m^3)	Viscosity (mPas)
3	Xu et al.(2010)	50	3.5	White Oil	860	44
				Water	998	1
4	Zong et al.(2010)09	125	6	No.15 industrial white oil	856	11.984
				Water	998	1
5	Jana et al.(2006)	25.4	1.5	kerosene	792	1.3
				Water	998	1
	Bonilla Rian et al.(2019)	50.8	12	Mineral oil	860	220
				Water	998	1
	Coelho et al.(2019)	27	8	Lubrax gear oil	945	2750
	Du et al.(2012)	20	0.4	No.15 industrial white oil	856	11.984
				Water	998	1
6	Yang et al.(2019)	0.02	2	Oil		85.113
				Water	998	1
	Guo et al.(2018)	0.01 m	2	Naphthenic oil	1.899g/cm3	584.24
				Water	998	1

Flow Pattern

Inertia, buoyancy, viscous force, and gravity force are the four main forces that affect the flowing fluid and control the stability of a particular flow pattern as discussed in Sr. (a) - (p) for different setups of vertical & slightly inclined pipe.

a) Churn Flow:

Higher flow rates cause the slug flow bubbles to deflate, creating an unstable flow regime where bigger gas bubbles begin to burst. This result in a very turbulent flow pattern with both phases distributed, thus the name churn flow.

b) W/o Emulsion:

When the superficial Oil velocity is high enough, the shift to $D_{w/o}$ (w/o emulsion) occurs.

c) O/w drops:

The o/w drops flow pattern is the fundamental flow structure for low superficial oil and water, where the oil is spread in the water as comparatively big bubbles. Similar to this is the w/o drops flow pattern, where water is spread in oil in a relatively huge bubble.

d) $D_{w/o(w/o\ emulsion)}$:

When the superficial oil velocity is high enough, the transition to $D_{w/o}$ (w/o emulsion) occurs.

e) $D_{o/w\ PS}$:

The $D_{O/W\ PS}$ pattern is predominating for both U_{so} and U_{sw} in the range of 0.0052-0.3306 m/s.

f) TF:

TF flow pattern regions are quite narrow. When mixing velocity is increased a very small transition between the oil in the water phase and the water in the oil phase is seen in the TF flow pattern. Jin et al. (2003) claim that wave propagation characteristics can spread the phase and happen at water hold-ups between 0.2 and 0.6. There isn't a continuous phase in this phase.

g) $D_{o/w}$:

When the rate of mixing increases, the oil phase is disseminated into the water phase, and the water is continuous.

h) B: (Oil bubbles in water):

This happened when the water flow was decreased, due to the agglutination of oil droplets from the $D_{O/W}$ pattern and the creation of bigger pieces (bubbles) that travel in the continuous medium of water.

i) $S_{o/w}$ ($O_{s/w}$):

This flow pattern develops when there is insufficient turbulence mixing energy to distribute the oil phase, which happens at low mixing velocities.

j) CAFS: (Core annular with swirling motion and waves at the interface):

This flow is characterized by the existence of a continuous rotating gas core in the center and a thin liquid sheet close to the wall. The interface between the phases is not smooth due to the intense sheer force of the gas stream, instead being covered in a complicated wave pattern. CAF pattern was seen above 37%vol. of oil cuts, with helical movements up to around 55%.

k) CAFB :(Core annular with bamboo waves at the interface):

The oil core moves more quickly than the water annulus, which is slowed down by the wall effects, in this instance due to buoyancy forces.

l) $VFD_{o/w}$:

When phase transitions occur at speeds more than 1 m/s, extremely small oil droplets are spread throughout the water.

m) Dos/w (Oil-in-water slug):

Low oil-water mixture velocity causes to occur such a flow pattern. As a result, the oil droplets coalesce into large bubbles of various sizes and even slugs because the turbulence energy in this situation is insufficient to disperse the oil phase.

n) Disperse Bubbly:

With slow phase velocities, the flow is bubbly. With greater water superficial velocities (U_{SW} > 1 m/s), the droplets become smaller and more finely scattered due to the shearing force produced by the water phase's increasing turbulence. The "dispersed bubbly flow pattern" is what is meant by this.

l) Core annular:

High kerosene velocities caused by the abrupt coalescence of the oil fragments result in a continuous core, which compels the water to flow as an annular film around the walls.

o) Unstable Annular:

Two different types of oil formations can flow in unstable annular flow. In the first, the oil body had an uneven form (worm-like), while in the second, the oil body had an extended core surrounded by various-sized oil droplets.

p) Big Drops

Oil was organized in globules of medium and large sizes and flowed in the water-dominated zone in big-drops flow.

Flow pattern map

Maps of the measured flow patterns at vertical & slightly inclined pipes are shown in Figure 3-6. For Vertical upward & Downward, 15° & 45° inclined and high & low viscous oil respectively.

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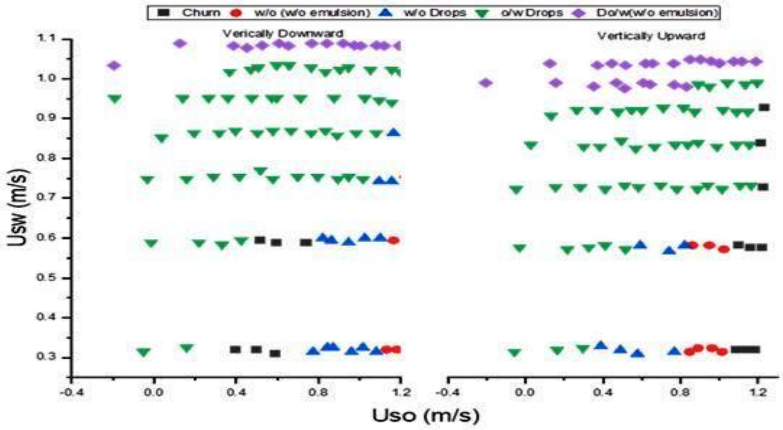

Figure 3 Due to, a larger slip velocity in downward flow than that in upward flow for the same input conditions, the transition from water-dominated flow to oil-dominated flow takes place under a much lower superficial oil velocity contribution in the vertical downward. (Xu et al.,2010)

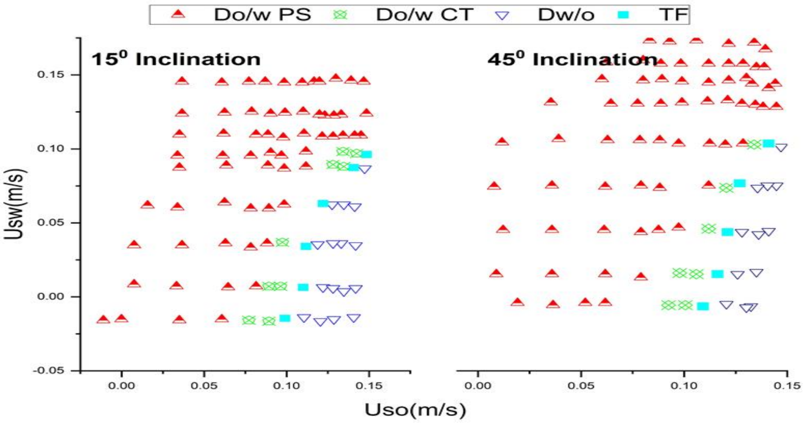

Figure 4 Do/wPS flow pattern predominates and Do/w CT & TF are narrow in both the inclination (Zong et al., 2010)

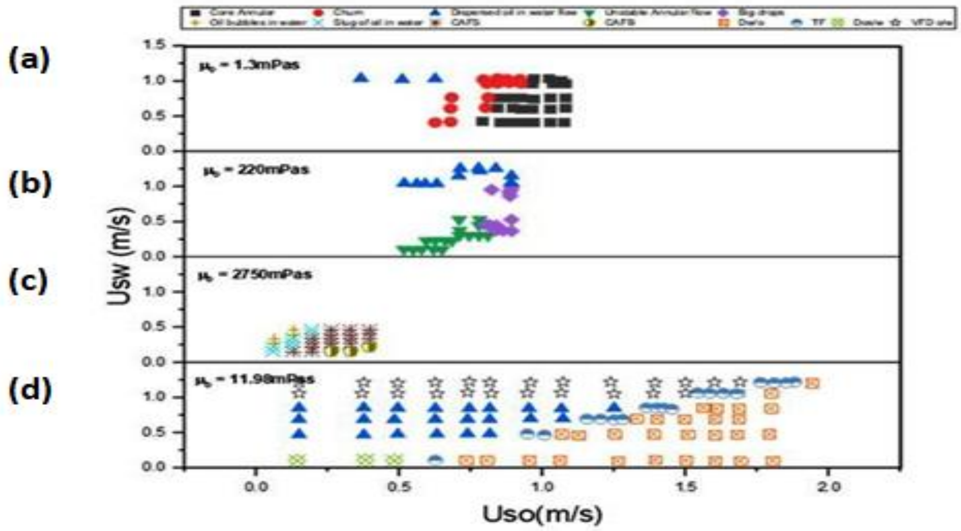

Figure 5 At lower viscosity due to a quick coalescence of the oil phase at higher kerosene velocity Core Annular flow emerged (Jana et al., 2006). (b) At high viscosity together with high diameter dispersed flow patterns occur at lower oil superficial velocity (Bonillarian et al., 2019). (c) The emergence of CAF is at

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higher viscosity (Coelho et al., 2019) (d) Low viscosity together with low diameter has dispersed flow in a dominant flow pattern (Du et al., 2012)

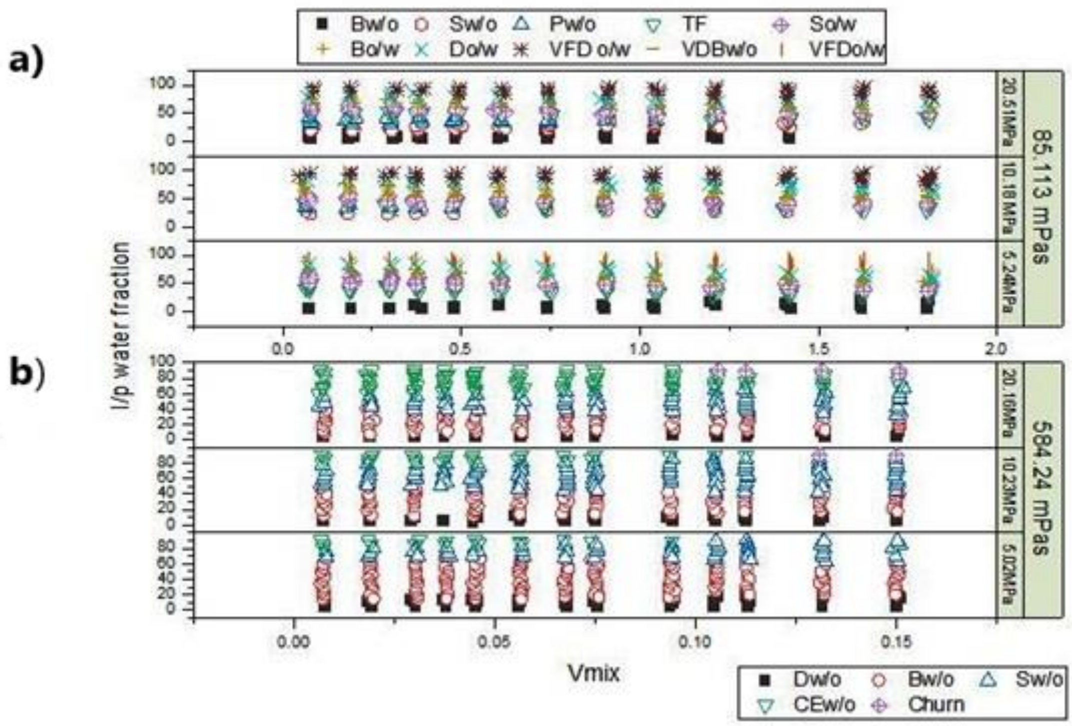

Figure 6 Bw/o is common in all cases at low i/p water fraction. Except at intermediate pressure at low viscous oil shown in Figure (b) (Yang et al., 2019). The churn flow pattern is only visible at higher viscous & at higher pressure (Guo et al., 2018)

Table 3 Flow Pattern map range for superficial velocity

Pattern			**Churn**		**W/o Emulsion**		**W/o drops**		**O/w drops**		**$D_{o/w(w/o\ emulsion)}$**	
Viscosity (mPas)	**Pipe dia.(mm)**	**Orientation/ Degree**	**U_{so} (m/s)**	**U_{sw} (m/s)**	**U_{so} (m/s)**	**U_{sw} (m/s)**	**U_{so} (m/s)**	**U_{sw} (m/s)**	**U_{so} (m/s)**	**U_{sw} (m/s)**	**U_{so} (m/s)**	**U_{sw} (m/s)**
44	**50**	Vertically Upward	0.4-0.8	0.3-0.6	1.0-1.2	0.3-0.6	0.8-1.2	0.3-0.9	0.0-1.2	0.3-1.0	-0.2-1.2	1.0-1.1
		Vertically downward	1.0-1.2	0.3-0.9	0.8-1.0	0.3-0.6	0.4-0.8	0.3-0.6	0.0-1.2	0.3-1.0	-0.2-1.2	1.0-1.1
Pattern			**$D_{o/w\ PS}$**		**$D_{o/w\ CT}$**		**$D_{w/o}$**		**TF**			
11.984	125	15^0	0.0-0.15	-0.025-0.15	0.075-0.15	-0.025-0.1	0.10-0.15	-0.025-0.08	0.1-0.15	-0.025-0.1	**N/A**	
		45^0	0.0-0.15	-0.025-0.15	0.075-0.15	-0.025	0.12-0.15	-0.025-	0.11-0.14	-0.025-	**N/A**	

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				-0.1		0.09		0.1		
Pattern		**Do/w**		**B**		**$S_{o/w}$**		**CAFS**		**CAFB**
2750	**27**	0.05-0.05	0.4-0.5	0.05-0.15	0.28-0.5	0.05-0.2	0.1-0.5	0.1-0.4	0.12-0.5	0.28-0.40	0.12-0.3
Pattern		**VFD o/w**		**Dw/o**		**Do/w**		**Dos/w**		**TF**	
11.984	**20**	0.257-3.5	1.4737-2	0.65-4.5	0.184-2	0.257-1.55	0.38-075	0.4-3.5	0.1842-0.1842	0.55-4	0.184-2
Pattern		**Disperse Bubbly**		**Bubbly**		**Churn**		**Core annular**			
1.3	**25.4**	0.05-1	1-1	0.08-0.15	0.08-1	0.2-0.8	0.08-1	0.4-1.5	0.08-1	**N/A**	
	Pattern	**Unstable Annular**		**Big Drops**		**Do/w**					
220	**50.8**	0.3-0.65	0.1-0.3	0.65-0.8	0.2-1.1	0.3-0.8	1.1-2	**N/A**			

Result & Discussion

Comparison is made for water with higher viscous oil ranging from 1.3 - 2750 mPas Viscous Oil at 10 - 125 mm (Di) diameter pipe. Referring to Figure 3 a larger slip velocity in the downward flow transition from water-dominated flow to oil-dominated flow takes place under a much lower superficial oil velocity. , In vertical inclined pipe i.e. at 15o & 45o inclined pipe both Do/w CT & TF flow patterns are least found depicted in Figure 4. In Figure 5, Core Annular flow emerged at lower viscosity due to a quick coalescence of the oil phase at higher kerosene velocity and also at higher viscosity together with high diameter dispersed flow patterns occur at lower oil superficial velocity. At high viscosity together with high diameter dispersed flow pattern occurs at lower oil superficial velocity. Low viscosity together with low diameter has dispersed flow in the dominant flow pattern in a vertical pipe. The emergence of CAF is at higher viscosity found for Lubrax gear oil. Low viscosity together with low diameter has dispersed flow in a dominant flow pattern At higher viscous oil, For the same input conditions, the transition from water-dominated flow to oil-dominated flow takes place under a much lower superficial oil velocity contribution in the vertical downward due to, larger slip velocity in a downward flow. In Figure 6.Bw/o is common in water with Naphthenic oil at a low i/p water fraction. Except at intermediate pressure at low viscous oil.

Conclusions

This review paper presented several previously employed liquid-liquid flows via the conduit of vertical & slightly inclined pipe. The following remarks are pertinent :

- In vertical & slightly inclined the flow pattern that is observed are unique from other configuration namely: Churn flow, CAFS, CAFB, Unstable Annular, W/o emulsion, etc.
- Stratified flow patterns are not observed in vertical & Slightly inclined pipes.
- The churn flow pattern is only visible at higher viscous & at higher pressure
- The emergence of Core Annular flow is easy at a higher superficial velocity of lower viscous oil comparatively lower diameter pipe, but on higher diameter pipe dispersion of fluid takes place.
- The direction of flow also affects the transition of water dominant to oil dominant flow especially at higher viscous oil at lower superficial velocity.

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