ANALYSIS AND COMPARISON OF FLOW PATTERN MAPS IN HORIZONTAL OIL WATER FLOW

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Abstract

In a recent paper, carried out a study on flow structure in horizontal oil water flow using mineral oil with viscosity and density of 12 cP and 875 kg/m^3 respectively, in a 25 mm ID pipe made from acrylic material. They observed six (6) different flow patterns at different superficial oil and water velocities. Since when a mixture of two immiscible fluids flows simultaneously in a channel, the two phases can distribute themselves in several configurations based on the physical properties of the fluids, the operational variables and the geometry of the channel. This paper compares the flow pattern map obtained by with some flow pattern maps available in literature. The comparison shows some similarities and differences in the observed flow patterns. For instance, all the investigators observed transition from stratified to Dual continuous flow pattern, while only few observed transition from stratified to bubbly flow pattern.

Keywords: Stratified flow, Dual continuous flow, flow transition, flow pattern

INTRODUCTION

The simultaneous flow of two immiscible fluids (e.g. oil and water) in pipes is a common phenomenon in chemical and petrochemical industries. It is known that the fundamental difference between single and two–phase flow is the existence of flow patterns in two–phase flow. When a mixture of two fluids flows simultaneously in a channel, the two phases can distribute themselves in several configurations. The configurations adopted is largely dependent on the physical properties of the fluids, like densities and viscosities, the operational variables such as flow–rate and volume fraction of each phase, and the geometry of the channel (pipe material, diameter and inclination etc). The flows are usually *stratified* at low velocities, but as the flow rate increases, transition from *stratified* to *non–stratified* flow patterns occurs. The need to understand the different types of flow pattern that may occur in liquid–liquid flow is of immense importance as design variables such as pressure drop, mass and heat transfer coefficients, hold–up, rate of chemical reactions etc are strongly dependent on flow pattern structure. Also, in many applications such as the design of water–lubricated pipelines, production strings in oil wells, and artificial lift methods, the understanding of oil–water flow behaviour is of significant importance. Yet determination or prediction of flow pattern is a central problem in two–phase flow analysis (Al–Wahaibi, 2006). The understanding of oil–water flow in pipes can be crucial in determining the amount of free water in contact with the pipe wall that could cause corrosion/erosion problems. Hence the need to understand the behaviour of oil–water flow system cannot be over emphasized. Knowledge of the distinctive features of oil–water mixtures, together with those for gas–liquid systems, can be used in the future as a basis to understand the more complex case of gas–oil–water mixtures.

Based on his own experiments and the results of previous investigators for horizontal flows, Trallero (1996) reclassified flow pattern into six, while Nädler & Mawes (1997) classified flow pattern into seven. Charles *et al*. (1961) used equal density oil–water mixtures as working fluids and observed the flow pattern of *oil–slugs–in–water* in the horizontal flow. Russell & Charles (1959) observed *Annular* flow when they introduced water into viscous crude oil to reduce the pressure gradient along the pipeline. Beretta *et al*. (1997) studied the flow patterns of oil–water horizontal flow in a 3mm small diameter pipe. They found that all flow patterns observed by Arirachakaran *et al*. (1989) for gas–liquid flow also occur in liquid–liquid horizontal flow in the small pipe. Angeli & Hewitt (2000) and Raj *et al.* (2005) used acrylic pipe with the same ID (25.4 mm) and oil of different physical properties. Amongst the flow pattern observed by the latter was *bubbly* flow pattern which was not reported by the former. Also, Lovick & Angeli (2004) used a stainless steel pipe, and mineral oil as working fluids ($\mu_o/\mu_w = 6$, $\rho_o/\rho_w = 0.83$ and σ = 39.6 mN/m) and classified flow pattern into *Stratified* flow, *dual continuous* flow, *dispersion of water in oil* and *dispersion of oil in water*. Al–Wahaibi *et al.* (2007) used acrylic pipe with ID = 14 mm and oil having the same physical properties with that used by Lovick & Angeli (2004), they observed *bubbly* flow, slug flow and *annular* flow patterns in their study, but Lovick & Angeli (2004) did not report these flow patterns.

Parameters with impact on the flow patterns

Russell *et al*. (1959); Guzhov (1973); Oglesby (1979), and more recently Trallero (1996); Angeli & Hewitt (2000); Lovick & Angeli (2004); Raj *et al*. (2005) all carried out experimental work on the effect of mixture velocity or superficial oil and water velocities on flow pattern in liquid–liquid system. In general they observed that low mixture velocities allow the flow to be separated or *stratified*, while high mixture velocity disperses the flow. However, dispersed flows may appear at low velocities provided the water cut is very low or very high. Charles *et al*. (1961) and Arirachakaran *et al*. (1989) used oil with viscosities of 6.29, 16.8 and 65.0, and 4.7, 58 and 115 cP to investigate the effect of viscosity on flow pattern. From their findings, viscosity seems to have little effect on the observed flow patterns for oil/water flows. The sequence or the number of observed flow patterns was the same, but transitions from one flow regime to another appeared at different superficial velocities when oils of different viscosities are used. Nadler & Mawes (1997) also carried out experiment using oil with viscosities 22, 27 and 35 cP, they observed that slight difference in viscosity does not significantly affect observed flow pattern. Charles *et al*. (1959) and Fuji *et al*. (1994) used fluid with same density and did not observe *stratified* flow in their studies. Other researchers like Trallero (1997); Nadler & Mawes (1997); Angeli & Hewitt (2000); Raj *et al*. (2005); Al–Wahaibi *et al*. (2007) used fluids of different densities and observed *stratified* flow in their studies.

The wetting properties of the pipe used can also influence the flow patterns as investigated by Angeli & Hewitt (2000). They carried out oil–water flow pattern experiments with two different pipes having the same diameter but made from different materials (steel and acrylic). They observed substantial differences in flow pattern and phase distribution between the acrylic resin and the stainless steel pipes. The tendency for dispersion was found to be greater than in the acrylic tube. In general materials that are more readily wetted by oil favour oil continuous dispersions and those having preference for water favours water continuous dispersions (Angeli & Hewitt, 2000). The isolated effect of pipe diameter has not received much attention. Documented works appears to be limited to those of apart from the works of Wegmann & Rohr (2006); Mandal *et al*. (2007). In their work, Mandal *et al*. (2007) investigated the effect of pipe diameter on flow pattern using pipe with 25 and 12 mm internal diameter made of acrylic material, and water and kerosene as test liquids (ρ = 787 kg/m^3; μ = 1.2 cP). Their interest was to check the effect of pipe diameter less than 25 mm on flow pattern as Brauner & Moalem–Moron (1992) have reported that small diameter pipes with predominant effect of surface tension are usually defined by Eőtvős number (Eq. 1) greater than 1, and Coleman & Garimella (1999) reported that pipe diameter does not influence flow patterns for pipes with internal diameter greater than 10 mm.

$$Eo = \frac{4\pi^2\sigma}{(\rho_w - \rho_0)gD^2} \dots\dots\dots\dots 1$$

This paper tries to bring out the extent to which some of the factors mentioned above affect flow pattern distribution in horizontal oil water flow system. This was achieved by comparing the flow pattern map obtained by Yusuf *et al*. (2010) with flow pattern maps observed by different researchers who studied flow patterns in horizontal liquid–liquid flow using different pipe configurations and oil viscosities.

MATERIALS AND METHODS

Flow pattern in horizontal liquid–liquid flows were studied experimentally by different researchers as reported in the introduction. For the purpose of comparison with the flow pattern maps observed by Yusuf *et al.* (2010), the flow pattern maps obtained by Nädler & Mewes (1996); Trallero *et al*. (1997); Angeli & Hewitt (2000); Raj *et al*. (2005); Al–Wahaibi *et al*. (2007) are selected for comparison. Table 1 showed the oil–water properties and pipe diameter used by the investigators. These flow pattern maps were reconstructed in Figure 1–5 in such a way that all the flow patterns observed by various researchers are classified into *stratified*, *bubbly, annular*, *dual continuous, dispersion of oil in water*, and *dispersion of water in oil flows*

Table 1: Summary of fluid systems, properties, pipe materials and diameters used in different studies

Authors	Pipe ID (mm)	Pipe Material	Oil properties			
			μ(mPas)	ρ(kg/m^3)	σ(mN/m)	
Trallero *et al*. (1997)	50.1	Acrylic	29.6	850	36	0.377483
Nädler & Mewes (1997)	59	Perspex	35	841	–	–
Angeli & Hewitt (2000)	25.4	Acrylic	1.6	801	17.0	0.522745
Raj *et al.* (2005)	25.4	Acrylic	1.2	787	45	1.292788
Al–Wahaibi *et al.* (2007)	14	Acrylic	5.5	828	39.4	4.613956
Yusuf *et al.* (2010)	25.4	Acrylic	12	875	20.1	0.983967

As explained in Lovick & Angeli (2004), the regions described in Trallero *et al*. (1997); Nädler & Mawes (1996) as *stratified* flow with mixing at the interface (ST and MI) and *dispersion of oil in water* and water in oil ($D_{o/w}$ and $D_{w/o}$) were classified as *dual continuous* flow. The region defined as *stratified* with mixing at the interface, layer of water in oil dispersion (W–in–O) and water or layers of dispersions (W– in–O, O– in–W) and water, were also classified as *dual continuous* flow. The region described in Angeli & Hewitt (2000) as *stratified* wavy/drops, mixed layer, and the three layer flow observed by Angeli & Hewitt (2000) and Raj *et al.* (2005) were classified as *dual continuous* flow. The region described as *dispersion of oil in water* with layer of water at the bottom in Nädler & Mawes (1997); Trallero (1997); Raj *et al*. (2005) were classified as *dispersion of oil in water* flow as there is only one continuous phase in the flow. The region described in Raj *et al*. (2005) as plug flow was assumed to be *bubbly* flow in this study.

RESULTS AND DISCUSSION

Stratified Flow Pattern

Similar to Yusuf *et al.* (2010), all the researchers observed *stratified* flow pattern in their studies. This is because the occurrence of *stratified* flow is majorly a function of density difference between the two fluids. They all used fluids with density ratio $\left({}^{\rho_o}/_{\rho_w}\right)$ less than unity, hence they observed *stratified* flow pattern. The only difference in all the studies was the extent to which stratified flow occurred. Trallero *et al*. (1997) and Nädler and Mawes (1997) observed *stratified* flow up to superficial water velocity of about 0.2 and 0.22m/s respectively, and superficial oil velocities of about 0.2m/s. While in Yusuf *et al.* (2010), *stratified* flow was observed up to superficial water and oil velocities of 0.48 and 0.33m/s. Angeli and Hewitt (2000), and Raj *et al*. (2005) used acrylic pipe with similar ID (25.4 m/s) for their studies, they observed *stratified* flow up to U_{sw} of about 0.23 and 0.3m/s and U_{so} of about 0.35m/s, respectively. Al–Wahaibi *et al*. (2007) used acrylic pipe of 14mm ID and oil with ${}^{\mu_o}/_{\mu_w}$ of 5.5, and with ${}^{\rho_o}/_{\rho_w}$ of 0.83. They observed *stratified* flow up to superficial water and oil velocities of 0.5m/s and 0.45m/s, respectively.

Bubbly Flow Pattern

Few investigators have reported bubbly flow pattern in liquid–liquid system. Raj *et al*. (2005); Al–Wahaibi *et al*. (2007) observed *bubbly* flow in their studies. Raj *et al*. observed bubbly flow within a wider range of superficial water and oil velocities (U_{sw} and U_{so} = 0.38 m/s – 0.7 m/s and 0.03 m/s – 0.14 m/s, respectively) compared to Yusuf *et al*. (2010) and Al–Wahaibi *et al*. (2007). Al–Wahaibi *et al.* (2007) observed *bubbly* flow within superficial water and oil velocities of 0.4m/s – 0.8 m/s and 0.09 m/s, respectively. In Yusuf *et al.* (2010), *bubbly* flow pattern was observed within superficial water and oil velocities of 0.54 m/s – 0.9 m/s and 0.06 m/s – 1.0 m/s, respectively. However, Trallero *et al*. (1997); Nädler & Mawes (1997); Angeli & Hewitt (2000) did not report *bubbly* flow pattern in their studies. This may largely be due to the larger diameter pipes used in their studies.

Although, Angeli & Hewitt (2000) used pipe of the same diameter with Yusuf *et al*. (2010) and Raj *et al.* (2005) and did not observe bubbly flow pattern. This may be due to the low interfacial tension of the oil used in their study (σ = 17 Nm/s) compared to 20.1 and 40 Nm/s used by Yusuf *et al.* (2010); Raj *et al.* (2005), respectively. As bubbly flow pattern is a function of Eötvös number. Large Eötvös number favours the occurrence of bubbly flow pattern (Poesio, 2008). From Table 1, the calculated Eötvös number for Angeli & Hewitt (2000); Yusuf *et al.* (2010); Raj *et al.* (2005) are 0.5227, 0.9839 and 1.2927, respectively. The small interfacial tension which is responsible for the small Eötvös number in Angeli and Hewitt is likely the reason why they did not observe bubbly flow pattern in their study.

Dual Continuous Flow Pattern

Dual continuous flow pattern occurred within superficial water and oil velocity of 0.1–0.95 m/s and 0.14–0.95 m/s respectively in the work of Yusuf, *et al.* (2010). All the researchers (Nädler and Mawes, 1997; Trallero, 1997; Raj *et al*., 2005; Angeli & Hewitt, 2000; Al–Wahaibi *et al*., 2006) reported DC flow in their studies. Trallero *et al*. (1997); Nädler & Mawes (1997) observed early formation of DC flow as U_{sw} increase compared to this study. This is likely due to the larger pipe diameter used in their studies. Al–Wahaibi *et al*. (2007) used a smaller pipe diameter and observed late transition to DC flow pattern compared to Yusuf, *et al.* (2010). Also, Angeli & Hewitt (2000); Raj *et al.* (2005) reported early formation of DC flow as superficial water velocity increases. This can be attributed to the low viscosity of the oil used for their studies. As explained in Yusuf *et al.* (2011) lower viscosity difference causes higher instability as superficial water velocity increases. All the investigators observed late transition from stratified to DC flow as superficial oil velocity increases compared to Yusuf *et al*. (2010). This is due to viscosity difference; smaller viscosity difference causes stability as .

superficial oil velocity increases (Yusuf, 2011). Though, large pipe diameter favours stability as superficial oil velocity increases, but maybe the effect of viscosity is more pronounced. Hence, Trallero *et al.* (1997); Nädler & Mawes (1997) observed later transition from stratified to DC flow.

Annular Flow Pattern

Akin with the observation by Yusuf, *et al.* (2010); Al–Wahaibi *et al*. (2007) observed *annular* flow in their study. The flow pattern was observed within superficial water and oil velocity of 0.6–0.8 m/s and 0.38–0.44 m/s, respectively. Other investigators (Nädler and Mawes, 1997; Trallero, 1997; Raj *et al*., 2005; Angeli & Hewitt, 2000) did not report *annular* flow in their works. This is likely due to the large pipe diameter used in Nädler & Mawes, (1997); Trallero (1997). Annular flow is favoured by small pipe diameter (Al–Wahaibi, 2006). Raj *et al*. (2005); Angeli & Hewitt (2000) did not observe annular flow despite using the same ID pipe with Yusuf, *et al.* (2010) this study. This is likely due to the low viscosity oil used in their studies. As reported in Grassi (2008), high oil viscosity favours the formation of annular flow pattern.

Dispersion of oil in water and water in oil (Do/w and Dw/o) flow pattern

The dispersion of oil in water or water in oil is a function of turbulence of the flow. Once the viscous and the velocity forces which causes instability overcomes the interfacial forces that causes stability of the flow, the flow will eventually transform to dispersion of oil in water or dispersion of water in oil depending on which of the fluids is the continuous phase. All the investigators observed dispersed flow patterns. Except for Al–Wahaibi *et al.* (2007) did not investigate up to dispersed flow region

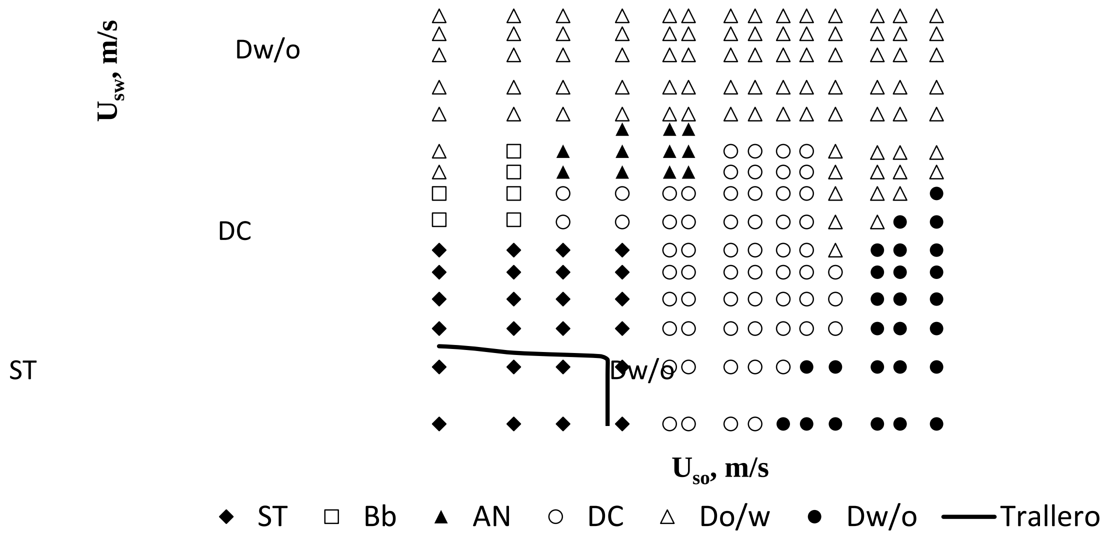

Fig. 1: Comparison of flow pattern map obtained in this study with the flow pattern maps obtained by Trallero (1996)

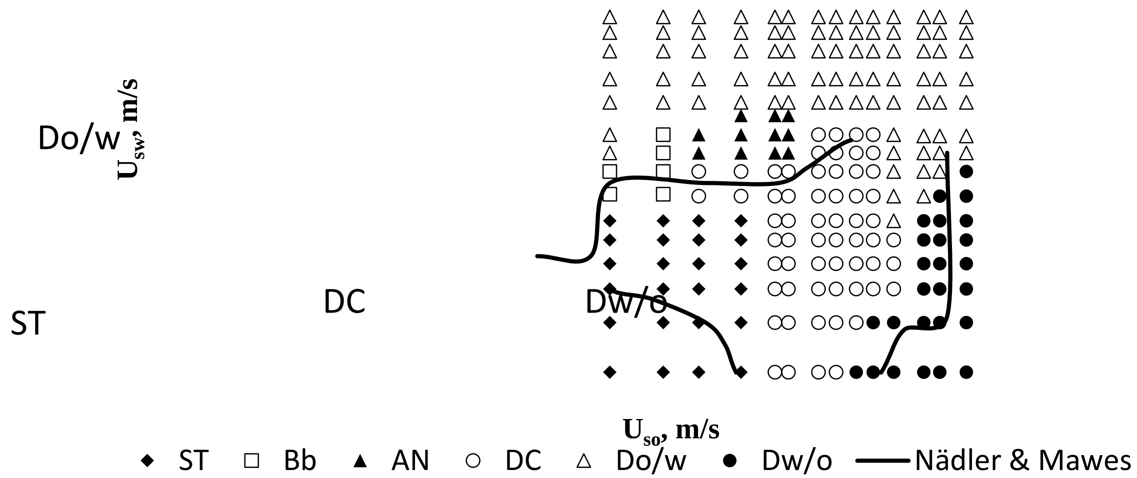

Fig. 2: Comparison of flow pattern map obtained in this study with the flow pattern boundaries obtained by Nädler & Mawes (1997)

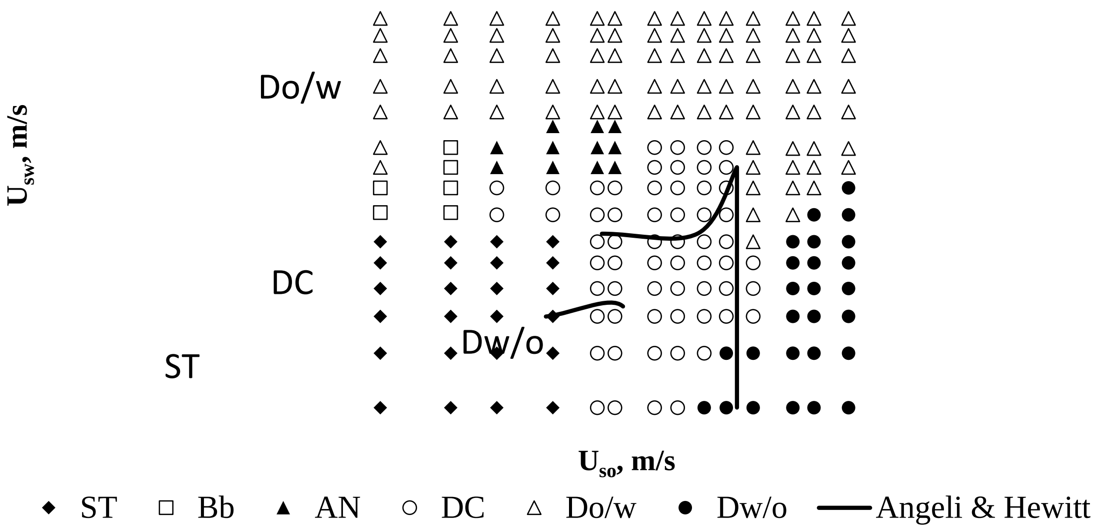

Fig. 3: Comparison of flow pattern map obtained in this study with the flow pattern boundaries obtained by Angeli & Hewitt (2000)

NSUK Journal of Science & Technology, Vol. 2, No. 1&2, pp 130-139 2012

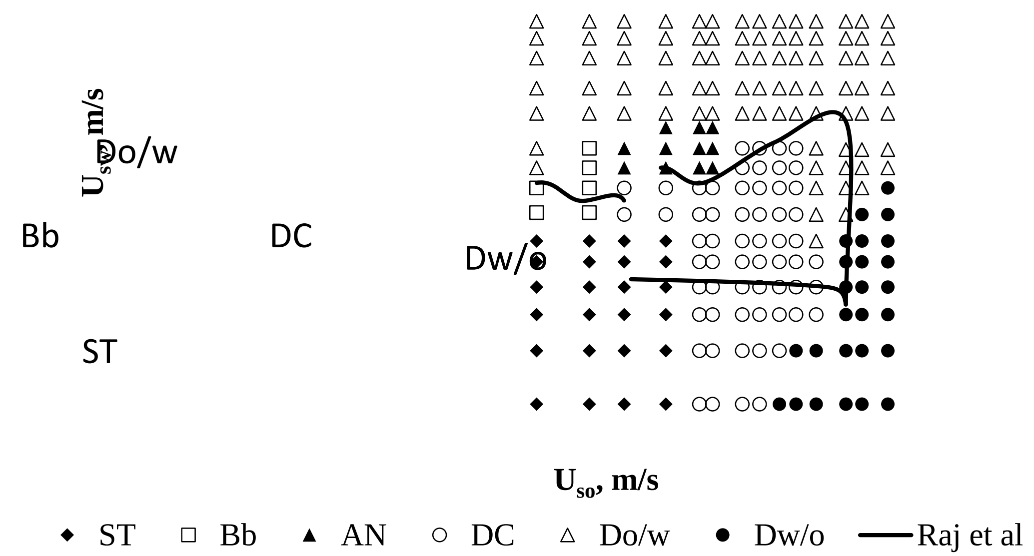

Fig. 4: Comparison of flow pattern map obtained in this study with the flow pattern boundaries obtained by Raj *et al.* (2005)

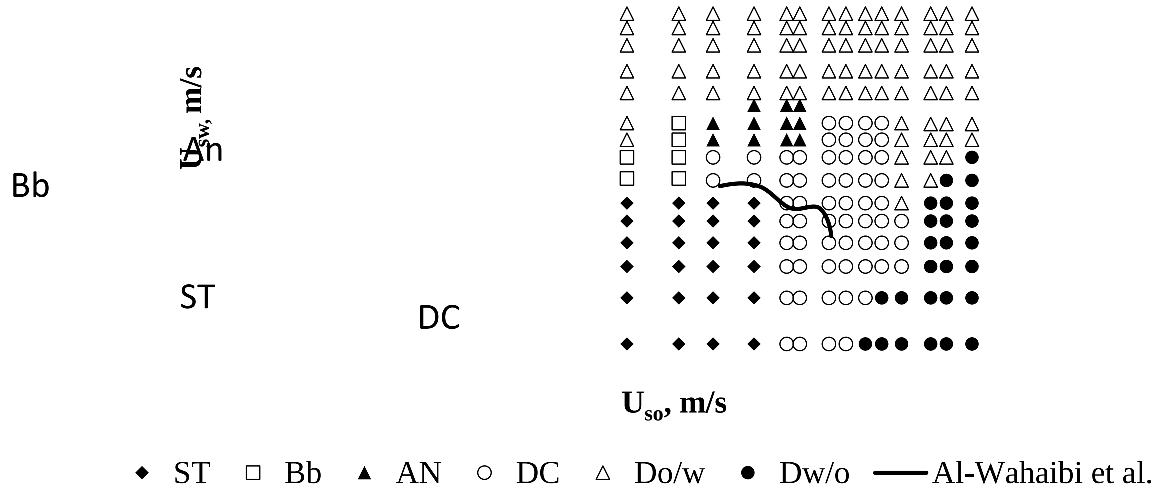

Fig. 5: Comparison of flow pattern map obtained in this study with the flow pattern boundaries obtained by Al–Wahaibi *et al.* (2007)

CONCLUSION

From the comparisons made in this study, it is evident that pipe material, pipe diameter and oil property have significant effect on the kind of flow pattern that occur in horizontal oil water flow, and the extent to which these flow patterns occurred. Also, bubbly and annular flow patterns in horizontal oil water flow are favoured to occur in a small diameter channels due to small.

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