

# PHASE INVERSION DURING LIQUID-LIQUID MIXING IN CONTINUOUS FLOW, PUMP-MIX, AGITATED TANKS.

R.N.Reeve  
University of Sunderland  
Sunderland  
SR1 3SD

J.C.Godfrey  
University of Bradford  
Bradford  
BD7 1DP

An experimental study of inversion has been made with mixer designs similar to those used industrially for metals extraction in mixer-settler equipment. The impellers were fitted with retreat, curved blades. Double shrouded, centrally located impellers (with and without impeller blades on the shrouds) and a single shrouded bottom located impeller were compared. The impeller diameters were 177mm. The mixing tank was an unbaffled closed tank of square cross-section (300 x 300 mm).

The liquid-liquid systems studied were an aqueous phase containing 1% by weight sodium sulphate and cumene as the organic phase and a system made from cumene / isobutyric acid /1% aqueous sodium sulphate.

Phase inversion under well-mixed conditions has been studied by variation of the organic/aqueous input flow ratios to establish the limiting values for stable operation. Phase inversion under poorly mixed conditions has been studied by determination of the minimum power input necessary to maintain an organic-continuous phase.

Keywords: phase inversion, impeller design, hold-up, power, liquid-liquid, pump-mix

## INTRODUCTION

In liquid-liquid mixing processes two immiscible liquids form a dispersion of one liquid dispersed as drops in the other as continuous phase. There is a lower limit to the volume fraction of continuous phase which is sufficient to prevent inversion. Under laboratory conditions this value can be quite low, 0.1 or lower. Thus there is a wide range of volume fractions, termed the ambivalent region, where either phase can be continuous, dependent on start-up conditions.

The lower limit of the continuous phase volume fraction is determined by the balance of drop breakage and coalescence rates. As the volume fraction of continuous phase falls so coalescence rates increase. The lower limit is reached when coalescence rates exceed breakage rates, the continuous phase becomes the drop phase and vice versa. This process is termed phase inversion. Immediately prior to inversion the drops are very large and, because of their high volume fraction, very crowded and distorted.

Mass transfer or chemical reaction can take place in a dispersion of either continuity. However rates of mass transfer and chemical reaction may be dependent on the choice of

continuous and dispersed phases. Also, in commercial processes, it is often found that one continuity gives better overall performance than the other. In mixer settler applications a specific continuity is often preferred for reasons of lower entrainment in the coalesced phases leaving the settler. In commercial processes inversion can be induced by changes in the flow ratio or physical properties, the latter sometimes caused by contaminants.

Previous investigations of inversion have studied the influence of impeller speed and liquid properties under nominally well-mixed conditions for different mixer types and impeller designs. For plant operation a large ambivalent region is generally assumed to be beneficial to as it permits small variations of operating conditions without the possibility of phase inversion. Differences in results using the same liquid-liquid system with different mixer types would indicate that inversion is dependent upon mixer design as well as liquid properties.

There have been a number of models and correlations proposed to relate phase boundaries and liquid properties (e.g., *Fakr-Din*<sup>1</sup>, *Clarke and Sawistowski*<sup>2</sup>, *Arashmid and Jeffries*<sup>3</sup>, *Selker and Sleicher*<sup>4</sup>, *Luhning and Sawistowski*<sup>5</sup>, *Quinn and Sigloh*<sup>6</sup>, *Yeo et al.*<sup>7</sup>). As yet there is little agreement between the different procedures.

Studies have been made using continuous flow mixers. (e.g. *Rowden et al.*<sup>8</sup>, *Godfrey and Gledhill*<sup>9</sup>, *Hossian et al.*<sup>10</sup>, *Godfrey et al.*<sup>11</sup>, *Guillinger et al.*<sup>12</sup>). One (*Rowden et al.*<sup>8</sup>) used a Davy-type pump-mix impeller similar to those used in the present work. The investigation showed a large ambivalent and very stable organic continuous operation. The position of the phase boundaries was influenced by mass transfer. Details of the impeller design and operating conditions were not given.

Phase inversion has been observed at volume fractions which suggest operation in the ambivalent region. This phenomenon has not been clarified but there are examples where inversion seems due to the presence of crystalline particles (*Gledhill*<sup>13</sup>) and non-steady state mass transfer (*Clarke and Sawistowski*<sup>2</sup>, *Rowden et al.*<sup>8</sup>). It has also been suggested that inversion has a time dependent characteristic (*Gilchrist et al.*<sup>14</sup>). A comprehensive review of phase inversion has recently been published (*Yeo et al.*<sup>15</sup>).

It is known that, in continuous mixers, the relationship between the volume fraction or hold-up in the tank and the flow ratio to the tank is dependent on impeller speed. In the present study this characteristic has been studied for two impeller types. One design is located at mid-height in the tank and the other located at the bottom. Both impeller designs are based on industrial practice and it is quite usual to find that tanks used for solvent extraction are of square cross-section and without baffles. Measurements of hold-up have been made as a function of impeller speed for the two impeller types and a range of operating conditions. Measurements have also been made of power consumption.

The majority of phase inversion studies in batch mixers have involved determining the stability of phases at a particular organic/aqueous ratio under well-mixed conditions. Investigations with flow systems have involved variation of the input organic/aqueous flow ratio to induce phase transformation under well-mixed conditions. During studies of hold-up in continuous flow pump-mixers it was observed that, for organic continuous systems, phase inversion could also be induced by a reduction in impeller speed usually under conditions of inadequate mixing (*Godfrey and Reeve*<sup>16</sup>). The present paper investigates phase inversion by both these methods.

## EXPERIMENTAL

### Mixing Equipment

The mixer geometries used in this study were based on the mid-height Davy design, (*Rowden et al.*<sup>17</sup>), and bottom located General Mills design (*Agers and De Ment*<sup>18</sup>) pump-mix impellers. It was decided to minimise the difference between the mid-height and bottom located impellers to facilitate comparison of results. It was also thought that the retreat blade design of the Davy type, although more expensive to construct, would offer a preferable balance of higher flows and larger drop sizes when compared to the straight blades of the standard General Mills design.

The basic mid-height impeller is therefore the same geometry as the standard Davy design. The impeller is 177mm overall diameter and has eight equi-spaced curved blades, width 26mm. The impeller is shrouded above and below with circular plates of the same diameter as the impeller and 2mm thick. There is a central circular inlet in the lower shroud. There are other versions of the Davy design which have eight additional impeller blades above and eight below the shrouds. The additional spoiler blades can be of either triangular (63x12.6mm above, 36x12.6mm below) or rectangular section (same dimensions), Figure 1.

The tank inlet arrangements for the Davy design require a draft tube to introduce the two liquids directly to the impeller. In this work a later version of the design was used with concentric tubes to introduce the two liquids separately to the impeller, Figure 2(a). The tubes have an internal diameters of 59.5mm (inner) and 88.5mm (outer). This concentric tube design has the advantage of improved pumping characteristics and is also attractive in that it prevents uncontrolled pre-mixing before the liquids reach the impeller. This characteristic may have advantages in improving phase stability. From the literature (*Rowden et al.*<sup>17</sup>) it appears that impeller to draft tube clearance is an important variable, certainly with regard to the pumping characteristics of the impeller, and this has been examined in the present study for the clearance range 0.5-10.5mm.

The bottom located impeller is a modification of the Davy design with only a single, top, shroud. For the reasons of ease of comparison and possibly improved performance a coaxial inlet arrangement is used, Figure 2(b), rather than the single tube used for many bottom located impellers, (*Roberts and McGee*<sup>19</sup>, *Agers and De Ment*<sup>18</sup>). No significant pumping advantage is anticipated but it is anticipated that the elimination of premixing will be advantageous for phase stability. The dimensions of the impeller and inlet draught tubes are as for the mid-height impeller described above. All impellers and draught tubes were made from stainless steel.

All four impeller types were investigated for the inadequately mixed experiments. The well-mixed experiments were restricted to impellers 2, 2a and 3 (Figures 1 and 2(b)).

The mixing tank used was the same for both mid-height and bottom located impellers except for the inlet arrangements discussed above. The tank is of the 'low cube' Davy design, 300x300mm in cross-section and 240mm deep. There are no vertical baffles but with a top closure with an outlet 110mm in diameter. An upper horizontal baffle, diameter 225mm, was used to eliminate the formation of an air vortex. The tank was constructed mainly from stainless steel but with two complete glass walls to allow observation of the phase continuity and phase inversion events and also for measurement of hold-up volume fraction. The tank was constructed so that it may be raised and lowered in a controlled way to allow accurate, pre-calibrated, setting of the impeller to draft tube clearance (0.5-10.5mm). The reason for the use of one tank design is partly for experimental convenience and partly to improve the degree of comparison possible with the two

impeller types. The bottom located impeller design as developed by General Mills (*Agers and De Ment*<sup>18</sup>) uses a conventional baffled cylindrical tank but it is quite usual to find industrial examples of bottom located impellers in square section tanks.

The impellers are driven by a variable speed electric motor drive (0-800 rpm) and power consumption is determined using a shaft torque transducer (2MK 4.4 A-A, British Hovercraft Corporation). Shaft speed was measured by a reflecting tachometer. The flow rate of the two liquids was controlled by a combination of pumps and valves to enable a wide range of flow rates to be examined. Flow rates were controlled by recycle loops and were measured using calibrated rotameters. For the inadequately mixed experiments three residence times (63, 158, 225s) and three flow ratios (3/1, 1/1, 1/2.3) were investigated. A more restricted range of residence time was investigated for the well-mixed experiments (88, 108, 129s). The dispersion generated by the mixer was transferred to a gravity settler and the separated phases to holding tanks (0.23m<sup>3</sup>) for further clarification before returning to the appropriate feed tanks (0.24m<sup>3</sup>). The settler, storage tanks and pipelines were made from stainless steel. The pumps used were vibrating diaphragm types (Chem-Resist type U80 model C) constructed in Teflon.

### Liquid-liquid test system

Two liquid-liquid systems were investigated. The first was an aqueous organic system of moderate interfacial tension (0.036 N/m). The aqueous phase (1006 kg/m<sup>3</sup>, 0.00104 N s/m<sup>2</sup>) contained 1% by weight sodium sulphate. The organic phase was cumene (862.8 kg/m<sup>3</sup> 0.00077 N s/m<sup>2</sup>). The system was chosen to give physical properties similar to those found in commercial operation with kerosene based solvent systems for copper extraction. A second system was used to investigate the properties at lower interfacial tension (0.0168 N/m). It was made up using cumene / isobutyric acid /1% aqueous sodium sulphate to give an isobutyric acid concentration in the aqueous phase of 90.1 kg/m<sup>3</sup> and in the cumene phase of 31.9 kg/m<sup>3</sup>. The aqueous phase had a density of 1006 kg/m<sup>3</sup> and viscosity 0.00108 N s/m<sup>2</sup> and the cumene phase a density of 868 kg/m<sup>3</sup> and viscosity 0.00081 N s/m<sup>2</sup>. Drop size data and hold-up data for the liquid-liquid systems system and test equipment have been reported<sup>20</sup>.

### Technique

The mixer was filled with the chosen continuous phase and then the impeller rotational speed and the throughput of the two phases set to the desired values. The system was allowed to reach steady steady state, from experience requiring four times the average mixer residence time.

For investigations in the well-mixed region the organic/ aqueous flow ratio was altered in stages whilst keeping the total flow constant. Equilibrium was allowed to be reached at each stage before proceeding to the next stage. The stepwise alteration was continued until phase inversion was observed. The flows and agitation were then stopped. After allowing the dispersion to settle and coalesce the interface level between the two phases was measured and the light phase hold-up,  $X_v$ , determined from the volume of the two phases,  $V_l$  and  $V_h$ .

$$X_v = \frac{V_l}{V_l + V_h} \quad (1)$$

For investigations in the poorly mixed region, once steady state had been reached with an organic dispersion, the torque on the impeller shaft was measured and the liquid flows and agitation were stopped. After allowing the dispersion to settle and coalesce the interface level between the two phases was measured and the light phase hold-up,  $X_v$ , determined from the volume of the two phases,  $V_l$  and  $V_h$ . Successive experiments lowering the agitation speed continued until phase inversion occurred. Inversion was, in general, within a few seconds of the lowering of the speed, steady state never having been achieved. Aqueous dispersion investigations in the poorly mixed region followed the same procedure but with no lower limit of agitation speed.

Phase inversion was easily seen by observation. The two continuities had different appearances, the continuous phase always looking more turbulent and brighter than organic continuous. Organic continuous systems always had a small quantity of aqueous phase in the bottom corners of the mixer. In addition the final phase continuity could be determined when the mixer was stopped and the phases were allowed to coalesce. Upward movement of the coalescence interface indicated aqueous continuity and downward movement organic continuity.

Torque measurements were made with an empty mixer at a range of impeller speeds at the start and end of each day to estimate frictional losses. After making allowance for frictional loss in the calculation of torque, the power input,  $P$ , to the mixer was calculated.

## RESULTS

### Well-mixed conditions

As with previous investigations, for both batch and continuous mixers, three distinct regions of operation are observed. When the organic/aqueous flow ratio is high (producing typically  $X_v = 0.8 - 0.9$ ) only organic continuous operation is possible. Conversely, at low ratios, (producing typically  $X_v = 0.2 - 0.4$ ) only aqueous continuous operation can be achieved. At intermediate ratios either continuity can be achieved. For all systems investigated a decrease in rotational speed reduces the stability of organic continuous dispersions, i.e. the limiting value of  $X_v$  is increased. This effect is more pronounced at lower speeds. For aqueous continuous dispersions the effect of reduced impeller speed is different. There is a small but consistent trend toward increased stability, i.e. higher limiting value of  $X_v$ , at lower speed. The effect of reductions in impeller speed is to reduce the width of the ambivalent region (Figure 3(a)).

The width of the ambivalent region (and thus the stability of dispersions) was found to be very dependent on impeller design. The bottom located impeller produces a wider ambivalent region than a centrally located impeller with triangular spoilers (Figure 3(a)). An increase in spoiled area brings an increase in width (Figure 3(b)). For all impellers an increase in clearance between impeller and draught tube reduces the width of the ambivalent region although the limiting values for organic continuous operation are unchanged (Figure 4). Changes in flow rate over the range investigated produced little change in inversion characteristics.

A reduction of interfacial tension of the liquid-liquid system increases the stability of aqueous continuous dispersions, but a similar reduction of organic continuous stability means that the width of the ambivalent region is unchanged (Figure 5).

## Inadequate mixing

Mixing quality for continuous liquid-liquid mixing can be quantified in terms of the relationship between the flow ratio  $X_f$  and the mixer volume fraction or hold-up,  $X_v$ , and the effect of impeller speed. Data are presented here as the relationship between hold-up ratio,  $X_v/X_f$ , and specific power,  $P/V$  (Figure 6(a)). Empirically, the system can be considered to be well mixed when the hold-up ratio is approximately one and a change in specific power only produces a small change in hold-up ratio.

We have previously reported this relationship for aqueous continuous systems<sup>20</sup>, in the form of an S-shaped curve. For similar conditions of mixing and flow all impellers investigated showed the same relationship between hold-up ratio and specific power. Changes in flow rate or flow ratio causes changes in power requirement and curve shape. An increase in flow ratio causes the slope of the middle section to increase and reduces the power requirement for good mixing. An increase in total flow results in a shift with respect to specific power without any change in curve shape.

We noted that organic-continuous systems followed similar-shaped curves at intermediate and high values of hold up ratio but that operation at the lower values was not possible due to inversion at low specific power values. The present work (Figure 6(a)) confirms similar trends for the centrally-located impeller with additional rectangular blades (impeller 2a).

For aqueous continuous operation the relationship between hold-up ratio and specific power was found to be the same for all of the impellers tested. However for organic continuous operation the relationship is dependent on impeller type (Figure 6(b)). The impeller with rectangular spoilers (impeller 2(a)) and the bottom-located impeller (impeller 3) required lower specific power for the same result when compared with the other impellers and the relationship between hold-up ratio and specific power was similar to that observed in aqueous continuous tests (Figures 6(a) and 6(b)).

Impeller design also showed an effect on phase inversion. Experiments for a flow ratio of  $X_f = 0.5$  showed that the bottom located impeller could maintain a stable dispersion at a hold-up ratio of 0.7 while the centrally located impeller without spoilers inverted at a ratio of 0.9 (Figure 6(b)). It can also be seen that the specific power values are very different.

An investigation of the effect of increasing flow rates over a wide range showed a small increase in the minimum holdup ratio required to maintain an organic continuous dispersion. The minimum specific power remained unchanged (Figure 7).

When the ratio of organic to aqueous flows to the mixer was increased stability was improved both in terms of the specific power required and the minimum level of hold-up ratio that could be achieved (Figure 8).

The effect of impeller to draught tube clearance on stability was small.

A comparison of performance for liquid-liquid systems of different interfacial tension showed a marked effect on both hold-up and stability characteristics of organic continuous dispersions, the lower interfacial tension system being better in both respects (Figure 9). Similar observations were made for aqueous continuous dispersions.

## DISCUSSION

### Well-mixed conditions

The experimental results are generally similar to those previously recorded for pump-mix operation (Rowden *et al.*<sup>8</sup>) and other continuous or batch studies.

As in previous works, the choice of continuous phase has a significant effect on the stability of the dispersion. In almost all cases it was observed that aqueous continuous systems were more stable, in terms of the minimum volume fraction of aqueous phase which would allow stable operation. In this sense the present results are very different from those of Rowden *et al* where the opposite applies but where a different liquid-liquid system was used. (The width of the ambivalent region reported by Rowden *et al.* is narrower, at about 0.5 volume fraction units compared to values of the order of 0.6 reported here.) The influence of equipment design may be as significant as the physical property variables. The stability characteristics of one mixer can be quite unlike another.

The influence of increased impeller speed in the present studies was to give a moderate increase in stability for organic continuous systems. The nature of this trend is for the limiting volume fraction at inversion to approach an asymptotic value at higher impeller speeds. In discussion of the work of Kumar *et al.*<sup>21</sup>, Yeo *et al.*<sup>15</sup> suggest that, when the drop phase is the heavier phase, it is easier for drops to return to the impeller where there may be wetting and redispersion effects and, thus, impeller speed effects. For aqueous continuous systems any effect of impeller speed on stability was small with a slight tendency to reduced stability at higher speed. In this case the organic drops are the lighter phase and are unlikely to wet the stainless steel impeller, so perhaps impeller speed effects, following the arguments of Kumar *et al.* and Yeo *et al.*, are less likely.

The arguments regarding wetting and dispersion are not consistent with the impeller speed effects observed by Rowden *et al* where there are significant effects of impeller speed on the stability of both aqueous and organic continuous systems, particularly aqueous continuous.

In attempting to understand the influence of agitation on stability it is interesting to look at the effect of spoiler blades. In comparing two centrally located impellers, one with triangular blades and the other with rectangular blades, it can be seen that, while the effect of impeller speed was small as discussed above, there was a significant increase in stability when using the larger, rectangular blades. One outcome of additional blades is to improve circulation and therefore the uniformity of the mixture. Increased circulation will also increase the number of breakage and coalescence events.

Increased circulation can also be achieved by increasing the clearance between impeller and inlet tube. Unfortunately the results for the effect of clearance are inconclusive, no effect on organic continuous systems and a small decrease in stability for aqueous continuous systems.

Another line of enquiry is to examine the recent model of Yeo *et al.*<sup>7</sup>, relating inversion volume fraction to interfacial area by way of drop size:

$$\frac{\phi_{o,i}}{1 - \phi_{o,i}} = \frac{d_{32\ o,w}}{d_{32\ w,o}} \quad (2)$$

Using values for drop size determined from a correlation for the present mixing equipment<sup>20</sup> a value for volume fraction of dispersed phase at inversion can be estimated. This proves to be independent of impeller speed, similar to the experimental findings, but the value obtained, at  $\phi = 0.39$ , is significantly lower than typical experimental values, i.e.  $\phi > 0.8$ . This discrepancy is probably due at least in part to inadequacies in the drop size correlation for high values of dispersed phase volume fraction. An alternative way of looking at the model is to use it to estimate drop size at inversion for an observed volume fraction. For the bottom located impeller, running at 500 rpm, inversion from organic continuous to aqueous continuous occurs at a dispersed phase volume fraction  $\phi \sim 0.8$ . This gives an estimate of drop size at inversion of 240  $\mu\text{m}$ , compared with correlation generated values of  $d_{\text{max}} = 120\mu\text{m}$  and  $\phi = 0.38$ . The larger drop size is quite consistent with observations made during inversion studies.

When the results for two values of interfacial tension are compared it is seen that the trends are similar to those observed in earlier works - aqueous continuous systems were more stable than organic continuous, there was little effect of impeller speed on the stability of aqueous systems and increased impeller speed gives increased stability for organic continuous systems. There is also a significant effect of impeller speed on the degree of stability, that is the volume fraction of continuous phase at inversion. The data for higher interfacial tension shows increased stability for aqueous continuous systems and decreased stability for organic continuous systems. The behaviour of the organic continuous systems is consistent with the observations of Norato et al.<sup>22</sup> and earlier work as discussed by Yeo et al.<sup>15</sup>. However the behaviour of the aqueous continuous system is the opposite of what has been previously observed - i.e. observations of increased stability with decreased interfacial tension. There is no obvious explanation for the observations of the present work. It should also be noted, in contrast to previous studies, that the width of the ambivalent region remains the same when interfacial tension is changed. The increase in width of earlier studies is not observed.

Thus, while the stability characteristics observed in the present pump-mix impeller studies are similar to some aspects of previous studies in other mixer types, the case of aqueous continuous systems is different from earlier work. The effect of impeller speed is negligible and increased interfacial tension brings increased stability. As the differences with previous work are so marked it would be reasonable to question the present experimental data. As can be seen in the figures provided, the generalisations made above apply to a range of impeller speed and although some of the differences are small, the trends in the data are consistent and there is little scatter. It may be worth noting, when considering the differences with previous experiments, that the present mixer is comparatively larger, continuous and uses pump-mix type impellers. Because of the larger size behaviour relating to wetting effects will be less marked.

#### Comparison with inadequately mixed experiments

There were many similarities in the results for inadequately mixed and well-mixed test conditions. Inversion from organic to aqueous continuous under 'inadequately mixed' conditions occurred when  $X_v$  approached the organic-continuous limit determined in the corresponding 'well-mixed' experiments (Figure 10(a)). The minimum  $X_v$  was found to be higher on the hold-up curve at lowest impeller speed, reflecting the similar increase in  $X_v$  of the organic-continuous limit. In all cases the minimum conditions for a stable dispersion on the hold-up curve were at a slightly higher  $X_v$  than the limit position determined by, or extrapolated from, the well-mixed experiments ( $\Delta X_v =$

0.1- 0.2). The minimum impeller speeds are often on the steep part of the hold-up curve, where a small decrease in impeller speed produces a proportionally larger drop in  $X_v$ . Given that the trend of the position of the organic continuous limit is to higher  $X_v$ s (i.e. reduced stability) with a decrease in the spoiled area (Figure 3(a)), it would be anticipated that the boundary for the centrally-located impeller without spoilers would be in the 0.35 - 0.45 region because of the reduced level of agitation. This would explain the very limited operational range of impeller 1 under organic-continuous conditions.

This similarity holds when comparisons are made at different interfacial tensions (Figure 10(b)) and suggests a novel method of comparison regarding changes in organic-continuous limit with operating conditions or liquid-liquid system. It seems appropriate to compare the phase boundaries at impeller speeds corresponding to the minimum position of organic-continuous stability on the corresponding hold-up curve. Using this method with the data shown in Figure 10(b) a small extrapolation would be necessary on the low interfacial tension organic continuous limit but it indicates that  $X_v$  for phase inversion at these comparative points would be very similar. If this method of comparison is used for different impeller types (the comparative positions are shown by the letter M on Figures 3(a) and 3(b)) the similarity of centrally located impellers is emphasised, as also is the difference between the centrally located impellers and bottom located impellers.

The similarity between the limiting volume fractions found in all comparative sets of data in our current investigations leads to the intriguing possibility of linking theoretical interpretations of phase inversion with those for interpreting conditions necessary for good mixing. This will be the subject of future investigations.

## NOMENCLATURE

$d_{32}$	Sauter mean drop diameter (m)
o/w	oil in water dispersion
w/o	water in oil dispersion
D	impeller diameter (m)
$M_x$	minimum impeller speed with impeller X for organic continuity ( $s^{-1}$ )
N	impeller speed ( $s^{-1}$ )
P	impeller power (W)
$Q_h$	flow rate of the heavy phase ( $m^3/s$ )
$Q_l$	flow rate of the light phase ( $m^3/s$ )
V	volume of mixing tank ( $m^3$ )
$V_h$	volume of heavy phase in mixing tank ( $m^3$ )
$V_l$	volume of light phase in mixing tank ( $m^3$ )
$X_v$	hold-up of light phase in mixing tank (-)
$X_f$	nominal hold-up determined from flow ratio (-)
$\phi_{o,t}$	organic phase hold-up at phase inversion

## REFERENCES

1. Fakhr-Din, S.M., PhD thesis, Univ. of Manchester, (1973) "Phase inversion and droplet size measurements in agitated liquid-liquid systems".
2. Clarke, S.I. and Sawistowski, H., (1978) "Phase inversion of stirred liquid/liquid dispersions under mass transfer conditions", *Trans.I.Chem.E.* 56, 50
3. Arashmid, M. and Jeffreys, G.V.,(1980) "Analysis of the phase inversion characteristics of liquid-liquid dispersions", *A.I.Chem.E.J.* 26, 51
4. Selker, A.H. and Sleicher, C.A., (1965) "Factors affecting which phase will disperse when immiscible liquids are stirred together", *Can. J. Chem. Eng.* 43, 298
5. Luhning, R. W. and Sawistowski, H., (1971) "Phase inversion in stirred liquid-liquid systems", *ISEC '71*, 873
6. Quinn, J.A. and Sigloh, D.B., (1963) "Phase inversion in the mixing of immiscible liquids", *Can. J. Chem. Eng.* 41, 15
7. Yeo, L.Y., Matar, O.K., Perez de Ortiz, E.S. and Hewitt, G.F., (2002) " A simple predictive tool for modelling phase inversion in liquid-liquid dispersions", *Chem. Eng. Sci.* 57, 1069
8. Rowden, G.A., Scuffham, J.B., Warwick, G.C.I. and Davies, G.A., (1975) "Considerations of ambivalence range and phase inversion in hydrometallurgical solvent extraction processes", *I.Chem.E. Symposium Series no.42* paper 17
9. Godfrey, J.C. and Gledhill, J., (1983) "Phase inversion and entrainment characteristics of LIX 64N in Escaid and water", *ISEC'83*, 176
10. Hossain, K.T., Sarker, S., Mumford, C.J. and Phillips, C.R., (1983) "Hydrodynamics of mixer-settlers", *Ind. Eng. Chem. Process Des. Dev.* 22, 553
11. Godfrey, J.C., Fraux, A. and Reeve, R.N., (1990) "Phase inversion in mixer-settlers" *Solvent Extraction 1990*, T. Sekine (ed), 1393
12. Guilinger, T.R., Grisinlingas, A.R. and Erga, A., (1988) "Phase inversion behaviour of water-kerosene dispersions", *Ind. Eng. Chem. Res* 27, 978
13. Gledhill, J., M.Phil. thesis, University of Bradford, (1980) "The influence of solids on mixer-settler performance"
14. Gilchrist, A., Dyster, K.N., Moore, I.P.T. and Nienow, A.W., Carpenter, K.J., (1989) "Delayed phase inversion in stirred liquid-liquid dispersions", *Chem. Eng. Sci.* 44, 2381
15. Yeo, L.Y., Matar, O.K., Perez de Ortiz, E.S. and Hewitt, G.F., (2000) "Phase inversion and associated phenomena", *Multiphase Science and Technology*, 12, 51

16. Godfrey, J.C. and Reeve, R.N., (1984) "Minimum Conditions for liquid-liquid mixing in continuous flow, pump-mix, agitated tanks", *I.Chem.E. Symposium series No 146*, 421
17. Rowden, G.A., Scuffham, J.B. and Warwick, G.C.I., (1974) "The effect of changes in operating conditions in operating organic/aqueous ratio on the operation of a mixer-settler", *Proc. Int. Conf. on Solvent Extraction*, Paper 45:81
18. Agers, D.W. and De Ment, E.R., (1972) "The evaluation of the new LIX reagents for the extraction of copper and suggestion for design of commercial mixer-settler plants", *TMS paper selection, A 72-87, The Metallurgical Society of AIME, New York*, 31
19. Roberts, J. and McGee, J., (1980) "Mixing index as a performance indicator of pump-mix type mixers on continuous flow systems", *Proc. Int. Conf. on Solvent Extraction*, Paper 80:21
20. Godfrey, J.C., Obi, F.I.N., Reeve, R.N., (1989) "Measuring drop size in continuous liquid-liquid mixers", *Chem. Eng. Prog.*, 85, 61
21. Kumar, S., Kumar, R., Gandh, K.S., (1991) "Influence of the wetting characteristics of the impeller on phase inversion", *Chem. Eng. Sci.*, 46, 2356
22. Norato, M.A., Tsouris, C., Tavlarides, L.L., (1998) "Phase inversion studies in liquid-liquid dispersions", *Can. J. Chem. Eng.*, 76, 486

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Minerals Industry Research Organisation (MIRO) and also the interest shown by members of MIRO during the experimental programme.

Figure 1: Davy impeller designs

- (a) Impeller 1
- (b) Impeller 2
- (c) Impeller 2a

Figure 2: Mixer geometries

Figure 3(a): Effect of impeller design on ambivalent region

Figure 3(b): Effect of spoiled area on ambivalent region

Figure 4: Effect of impeller/draught tube clearance on ambivalent region

Figure 5: Effect of interfacial tension on ambivalent region

Figure 6(a): Effect of specific power on hold-up

Figure 6(b): Effect of impeller on minimum specific power for organic continuous stability

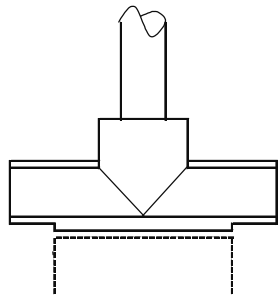
Figure 7: Effect of flow on minimum power for organic continuous stability

Figure 8: Effect of organic/aqueous ratio on organic continuous stability

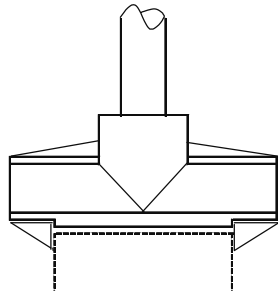
Figure 9: Effect of interfacial tension on organic continuous stability

Figure 10(a): Comparison of minimum  $X_v$  for organic continuous stability

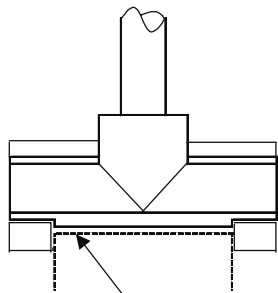
Figure 10(b): Comparison of minimum  $X_v$  at different interfacial tensions



(a) curved blade impeller



(b) curved blade impeller with triangular blades

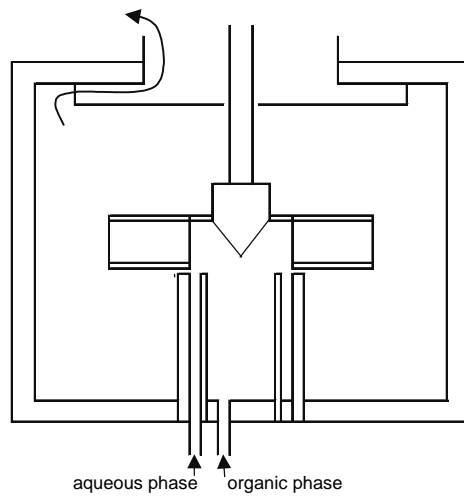


position of draught tube

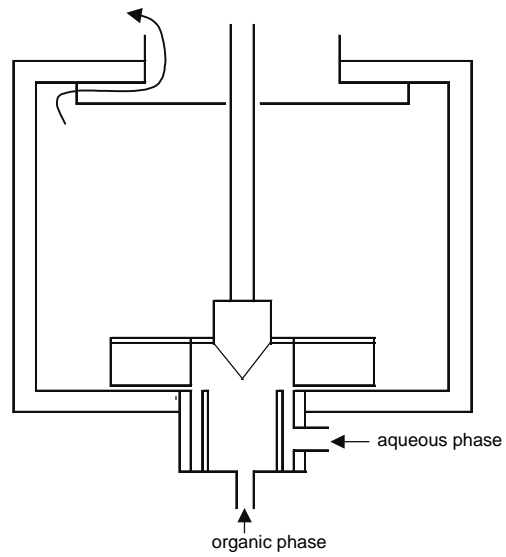
(c) curved blade impeller with rectangular blades

Figure 1: Davy-type impeller designs

(a) Impeller 1 (b) Impeller 2 (c) Impeller 2a



a) Mid-height Impeller in Square Cross-section Tank



b) Bottom-located Impeller in Square Cross-section Tank

Figure 2: Mixer geometries

Impeller 3 is shown in Figure 2(b)

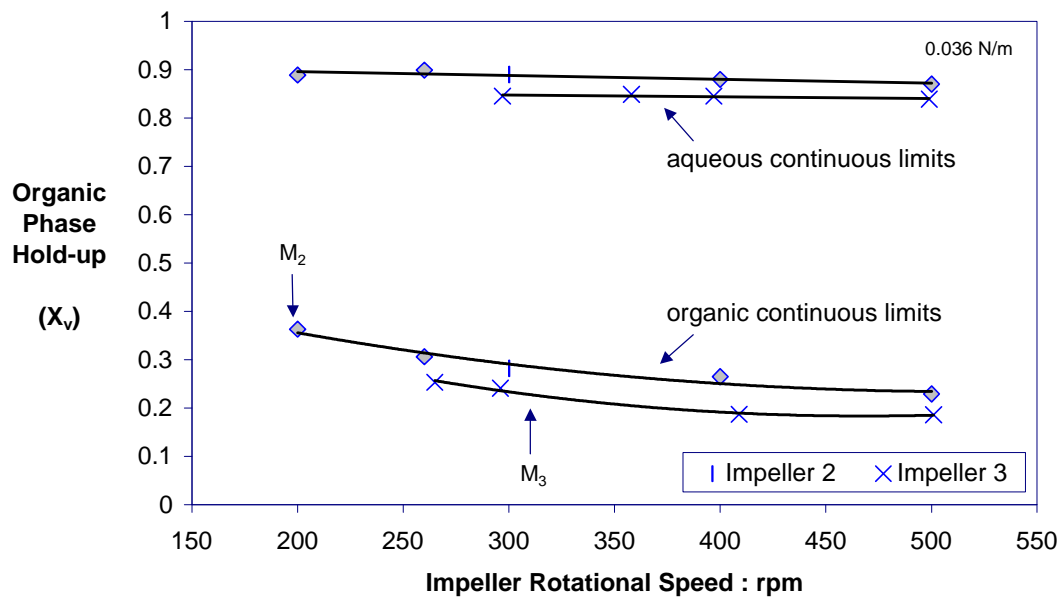


Figure 3(a): Effect of impeller design on ambivalent region

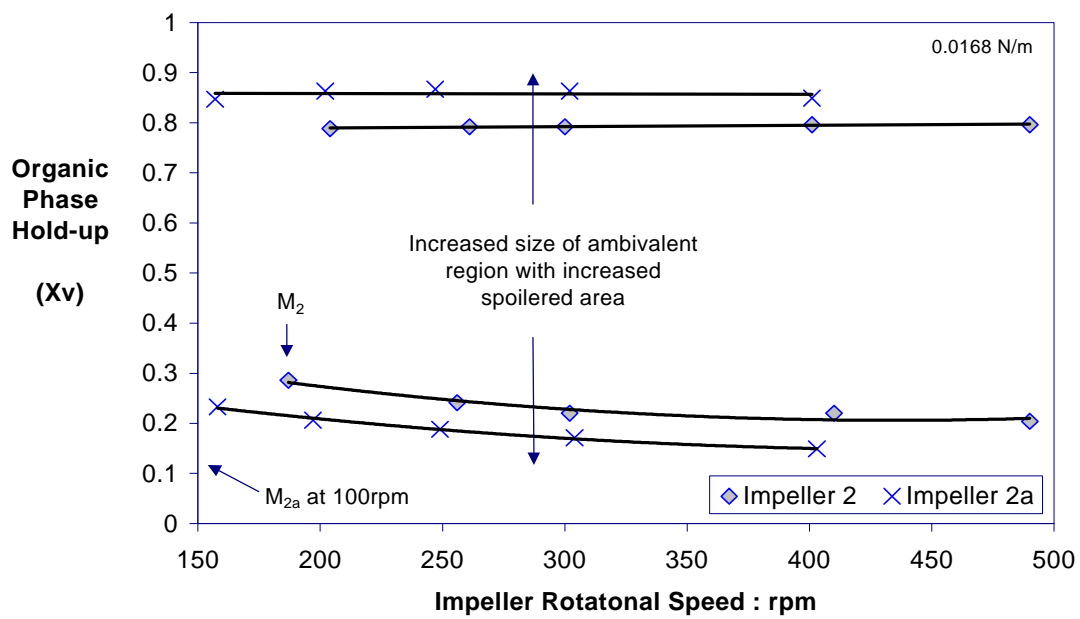


Figure 3(b): Effect of spoiled area on ambivalent region

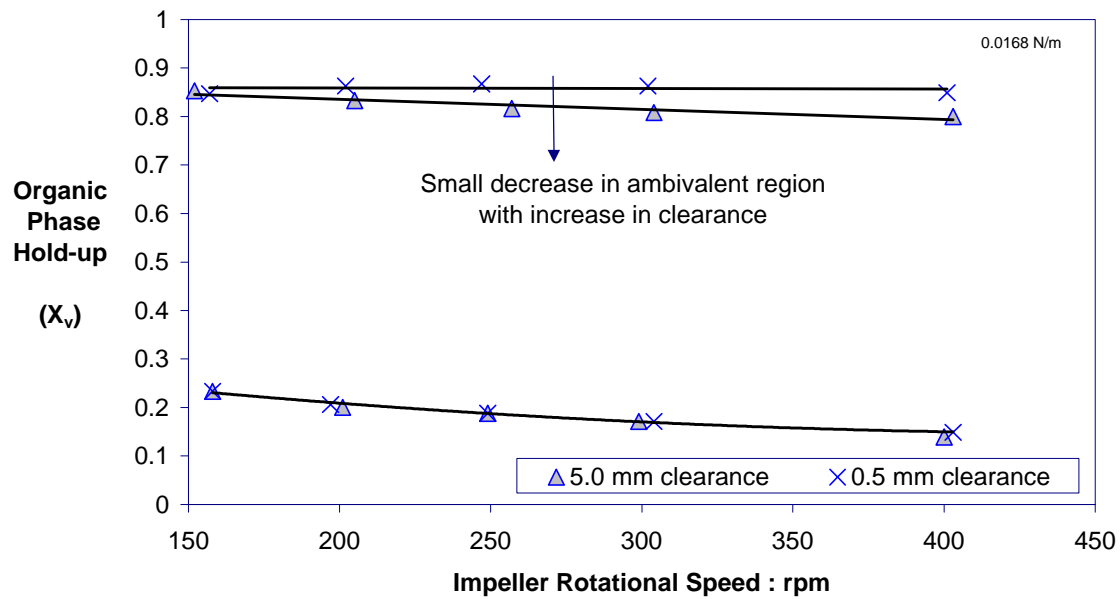


Figure 4: Effect of impeller / draught tube clearance on ambivalent region

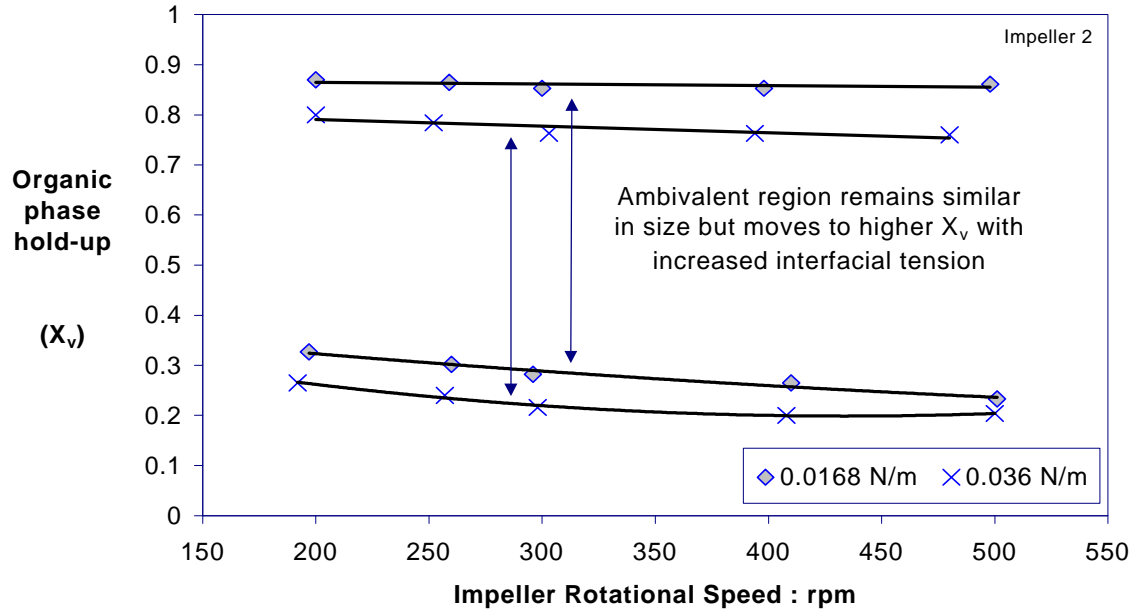


Figure 5: Effect of interfacial tension on ambivalent region

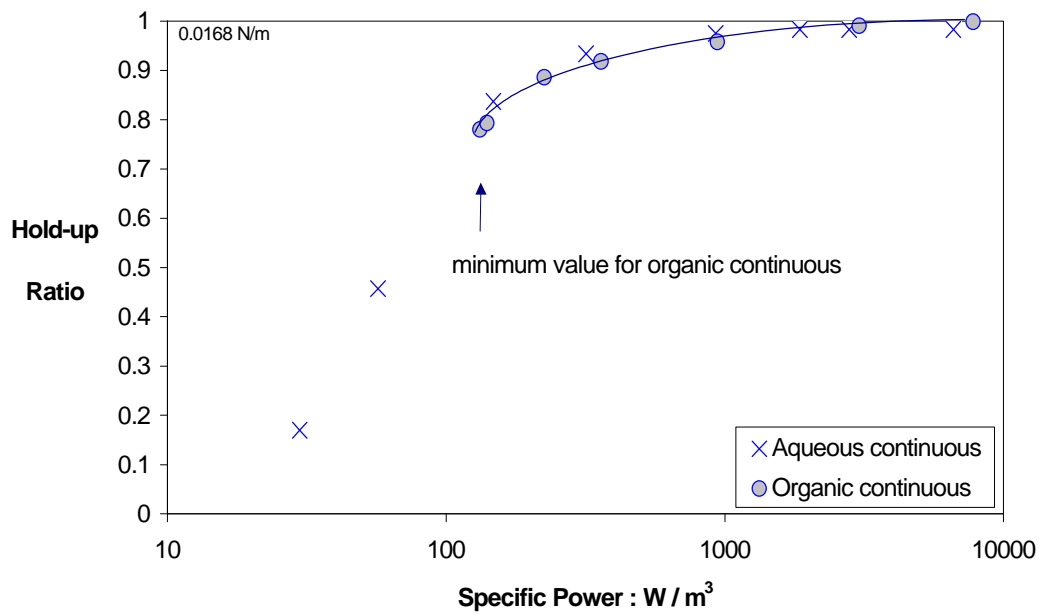


Figure 6(a): Effect of specific power on hold-up

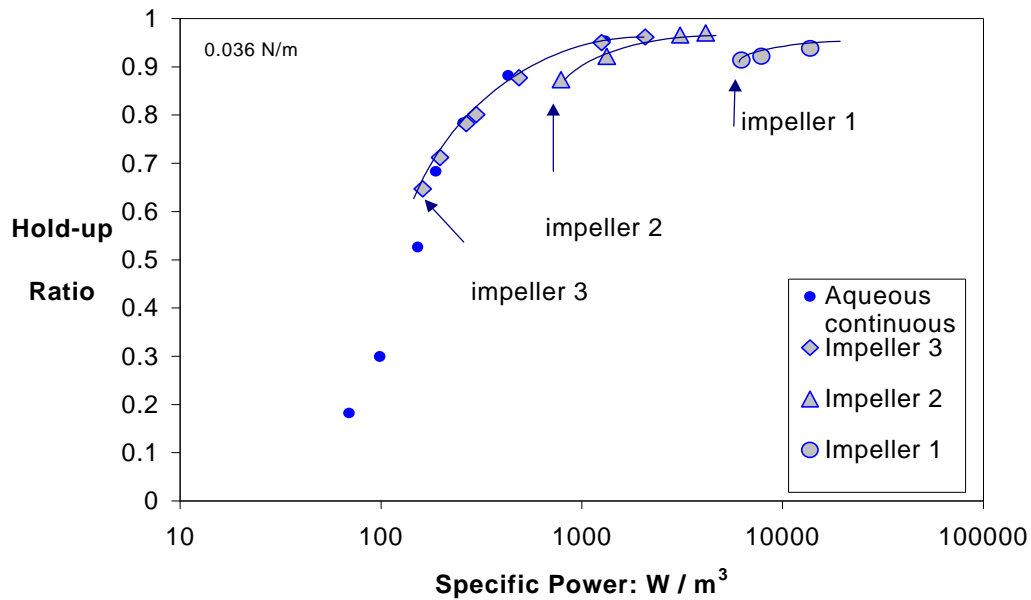


Figure 6(b): Effect of impeller on minimum specific power for organic continuous stability

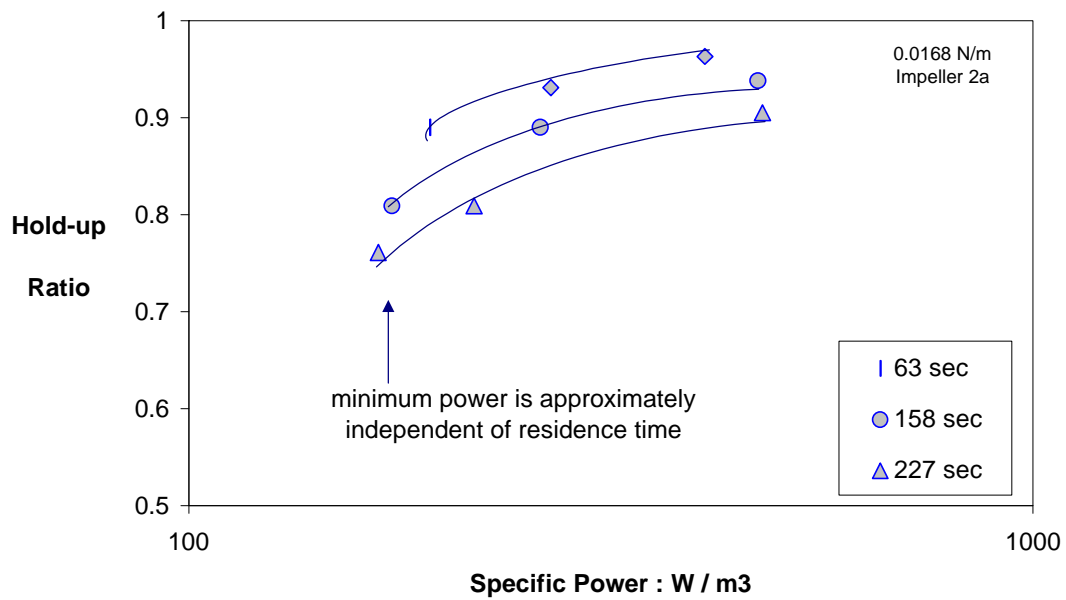


Figure 7: Effect of flow on minimum power for organic continuous stability

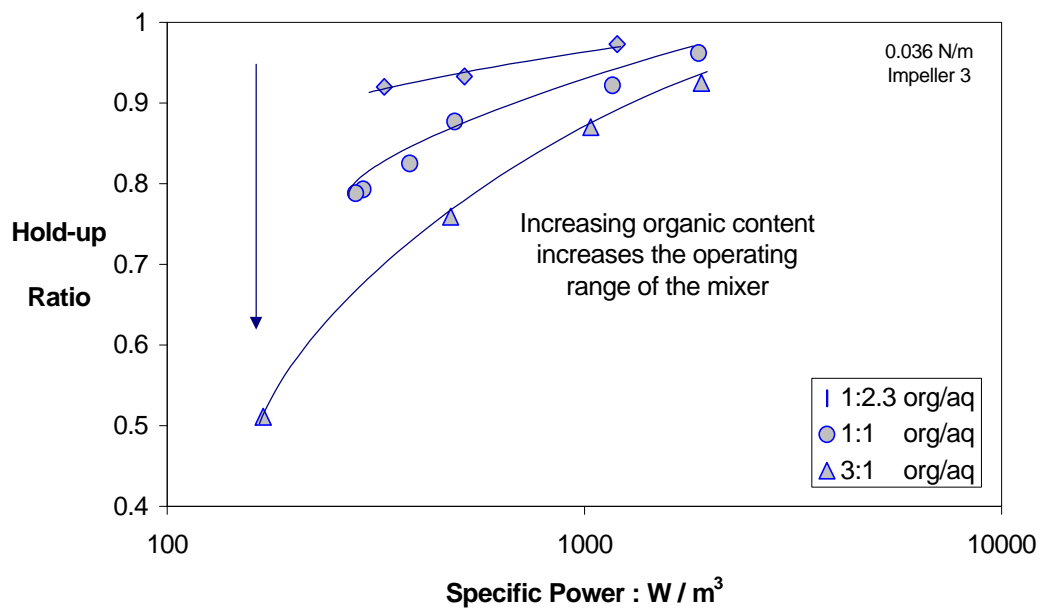


Figure 8: Effect of organic/aqueous ratio on organic continuous stability

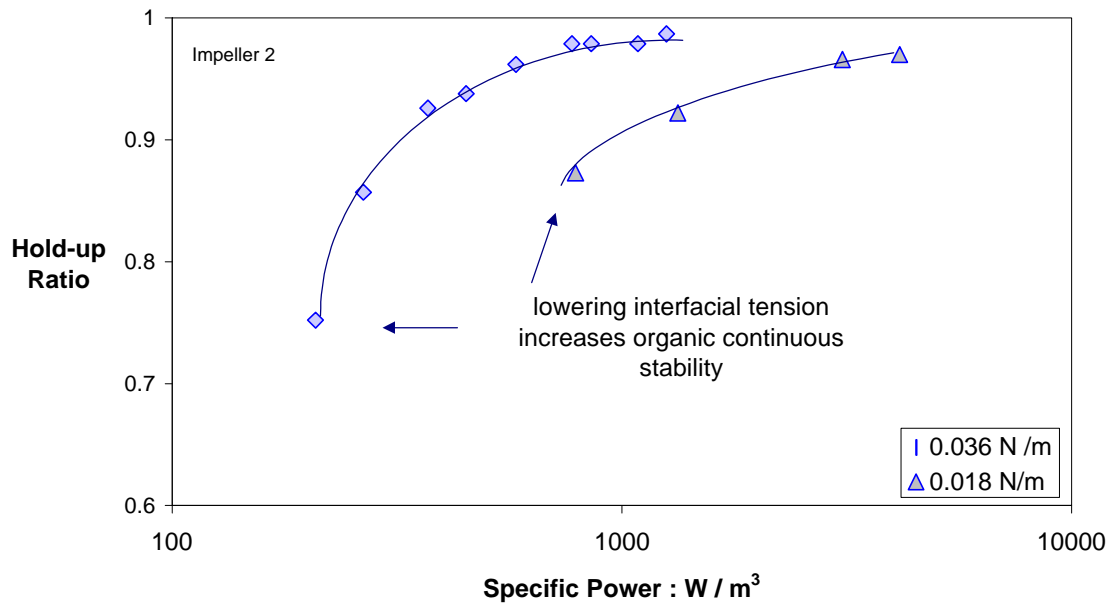


Figure 9: Effect of interfacial tension on organic continuous stability

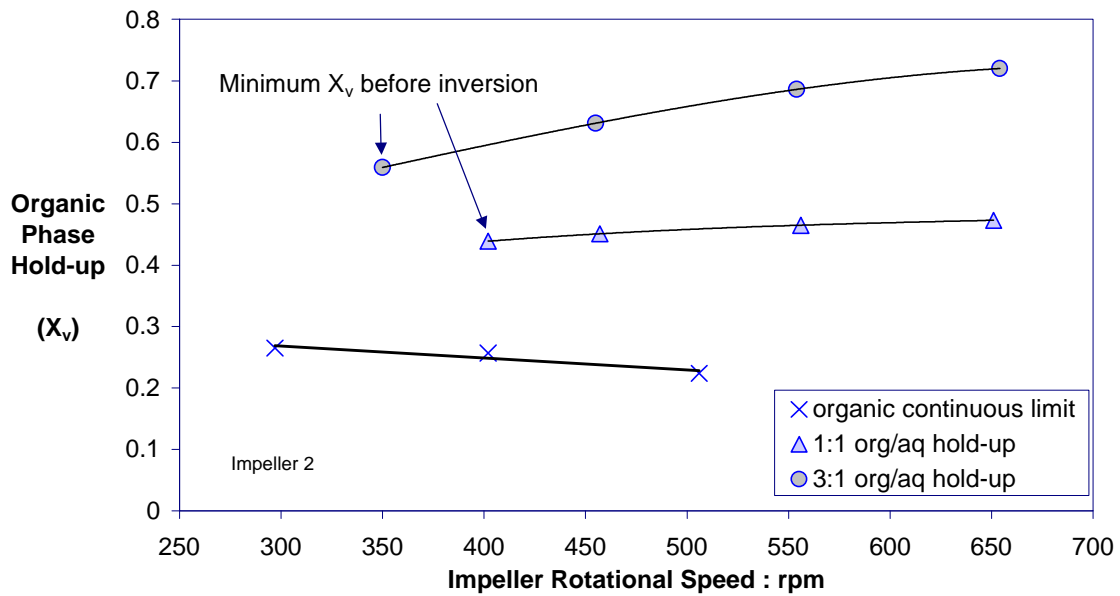


Figure 10(a) Comparison of minimum  $X_v$  for organic continuous stability

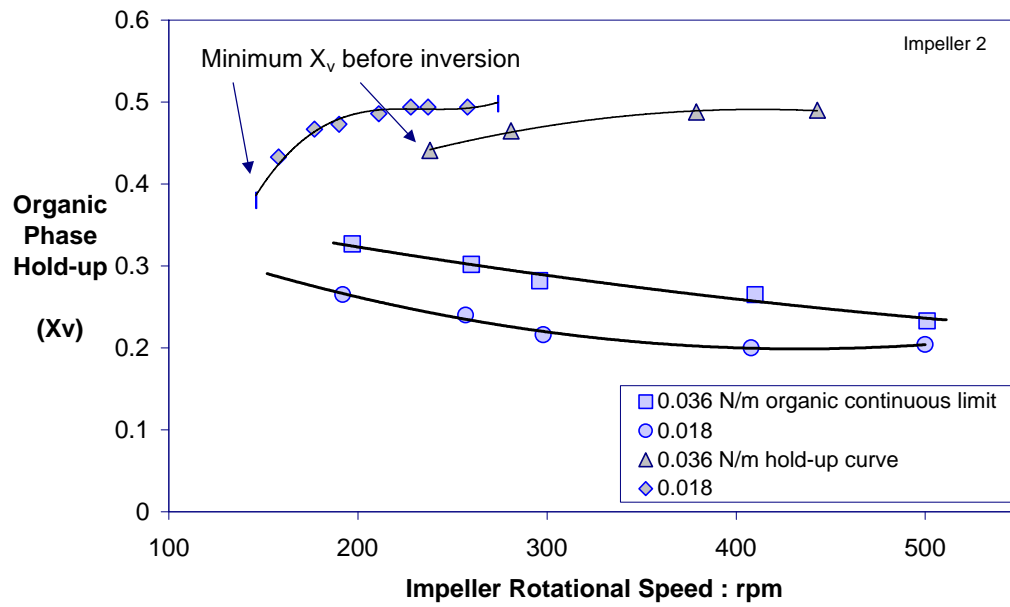


Figure 10(b): Comparison of minimum  $X_v$  at different interfacial tensions