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Viscous oil flow model development

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DECLARATION

I declare that this is an independent work according to the exam regulations of the Norwegian University of Science & Technology

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Abstract

Understandings of the dispersed phase flow models, stratified flow models and their codes have been carried out which are written in FORTRAN. The development of model is carried out by getting up with many new ideas. The connection between MATLAB and FORTRAN carried out for getting all the needed outputs and made the program more users friendly. New model and its code in FORTRAN have been developed for dispersed flow model and stratified flow model using average emulsion viscosity.

The droplet diffusion model and droplet size models are not much developed yet. Therefore, sensitivity analysis of droplet size closure model and droplet diffusion model carried out. The dispersed water in oil flow experiments having laminar flow behaves differently than dispersed oil in water flow experiments. Parametric study of both these models carried out for laminar and turbulent flows.

The dispersed flow model using average emulsion viscosity is tested by selecting set of oil water mixed flow experiments having 2m/sec velocity. The model gave huge mismatch between experimental simulated dispersed phase fraction distribution profiles. Therefore tuning of model carried out and exact distribution profiles are obtained. The model works well even for stratified mix flows so by implementing this model wrong prediction of flow regime can be avoided. This model can also use to find transition criteria between stratified and mixed flow model.

The stratified flow model has been tested with no dispersion, one way dispersion and by two way dispersion. Two ways dispersion model gave best results. IFE and Grane data are tested by this model. The two way stratified dispersion model is highly interactive therefore sensitive analysis carried out and quite interesting profiles are obtained. Based on these profiles two methods for tuning of stratified flow models are proposed in order to check the undeveloped closure models i.e. droplet diffusion model and droplet size model. The models are tuned by using one method.

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1.0 Introduction

1.1 Multiphase flow in industry

The technology of multiphase flow is in different stage of development although multiphase flow occurs in many industrial processes including transportation of coal, grains and other solids as slurries; development of petrochemicals, but its most common in nuclear and petroleum industry. In spite of that, calculation methods for multiphase flow systems have traditionally been quite inaccurate and unreliable. However now quite reliable models are available which gives better results [1, 3]

In petroleum industry transportation of oil and gas through wells and subsea flow lines generally involves oil, water and gas flow simultaneously. Production of oil and gas becomes more and more difficult due to new shallow and ultra deep discoveries which require accurate design production facilities as it is expensive to make changes in deepwater system [3].

Models which are now available gives better predication of production rates and avoiding problems for building up of hydrates, wax, asphaltenes, scales and particles . The current developments in multiphase flow models made it possible to transport oil and gas to large distance pipelines. There was huge economical savings by use of new developed models in offshore development. For example Sønvit, Ormen lange fields offshore topside installations has been replaced in order to be more economical operation [1].

Further improvement in technology will lead to more economic savings in future fields. In North Sea conditions multiphase is not only the most economical option but even the only one technical feasible solution.

The current models are quite good for low viscosity oil but for high viscous oil these models does not give better prediction. There are many new fields especially in Brazil, Venezuela and some new fields in North Sea e.g Breassary, Grane and Turdis fields operated by Statoil where oil viscosity is much higher.

1.2 Multiphase flow system

1.2.1 Gas-liquid system

As multiphase flow in petroleum industry involves oil, gas and water. Gas-liquid flow systems which are quite common in petroleum industry received adequate attention and wide range of literature available regarding flow pattern, pressure drop and hold up profile for gas-liquid systems. As a result of this many mechanistic models have been developed which gives quite good results [11].

1.2.2 Liquid-Liquid flow system

Flows of two immiscible liquids are encountered in a diverse range of processes and equipments, particularly in the petroleum industry where mixtures of oil and water are transported in pipes over long distances. The optimum design and operation of these pipelines require accurate prediction of pressure drop and hold up. Moreover pressure drop and hold up prediction also plays important role in number of engineering applications such as production optimization, production logging interpretation, down-hole metering and artificial lift design and modeling. Drilling new wells is often accompanied with a high water throughput due to water injection into wells for improved recovery. Today it is possible to get somewhat accurate prediction of oil-water flow characteristics, such as flow pattern, water holdup and pressure gradient which are important in many engineering applications [5].

However, liquid-liquid flows have not been received adequate attention when compared to gas-liquid flows. In fact, gas-liquid systems represent a very particular extreme of two fluid systems characterized by large density and viscosity difference between two fluids. In liquid-liquid systems the density difference between the phases is relatively low. However, the viscosity ratio encountered extends over a range of many orders of magnitude. Oil-water systems represents complex problem in pressure drop prediction due to its complicated rheological behavior. Therefore concept and ideas used for gas-liquid system cannot be applied to liquid-liquid systems [5].

1.3 Flow patterns in Multiphase flow

Flow patterns are used to define the type of flow within the system as many different types of multiphase flow patterns available which are principally governed by the physical properties of the fluids, its superficial velocities and also size and orientation of the pipe. However, due to low density difference between the fluids the effect of gravity diminishes in liquid-liquid flow systems. Pressure drop and hold up within the pipeline depends a lot on type of flow pattern within the pipeline. Main types of flow patterns in gas-liquid system are stratified flow, bubble flow, annular flow and slug flow [4, 5].

1.3.1 Flow patterns in liquid-liquid flow horizontal pipe

Many different flow patterns have been observed in liquid-liquid flow systems. Oil-water flow has been characterized into six main flow patterns after studying the experimental results of Guzhav (1973) and Nadlor (1997). Stratified flow observed at low flow rates where it is gravity dominated and phases are separated as shown in Fig.1.1 ST-S. Further increase in flow rates cause the generation of interfacial waves which are larger than the pipe diameter. There exist water droplets in oil layer and oil droplets in water layer near the interface and this flow pattern is called ST-3L or ST-MI flow shown in Fig.1.1 [11].

With increasing flow rates may be one continuous phase disrupted and there exist one dispersed phase and one continuous phase it is DW/O-O phase at low water cuts or DO/W-W at high water cuts. These type of patterns form unstable emulsions. The entrainment of droplets into continuous phase increases with increase of velocities. Emulsion behaviours for pipe flow and flow in rheometer differ so Models developed based on data from rheometer not valid for this type of flow. The apparent viscosity is an important factor for modeling these types of flow patterns.

Out of stratified flow there exist different types of dispersed flow patterns. In dispersed flow at high water cuts there is O/W dispersion and at low water cut W/O dispersion exist as shown in Fig.1.1. The water cut at which O/W emulsions changes to W/O emulsions is called phase inversion point. The phase inversion point is different for different systems and it depends upon the pressure, temperature, composition of fluids and water cut [5]. As viscosity increases the water fraction required to invert phase decreases. Both these flow pattern has stable emulsion and data from pipe flow conditions and rheometer measurements are much relevant to this [5, 11].

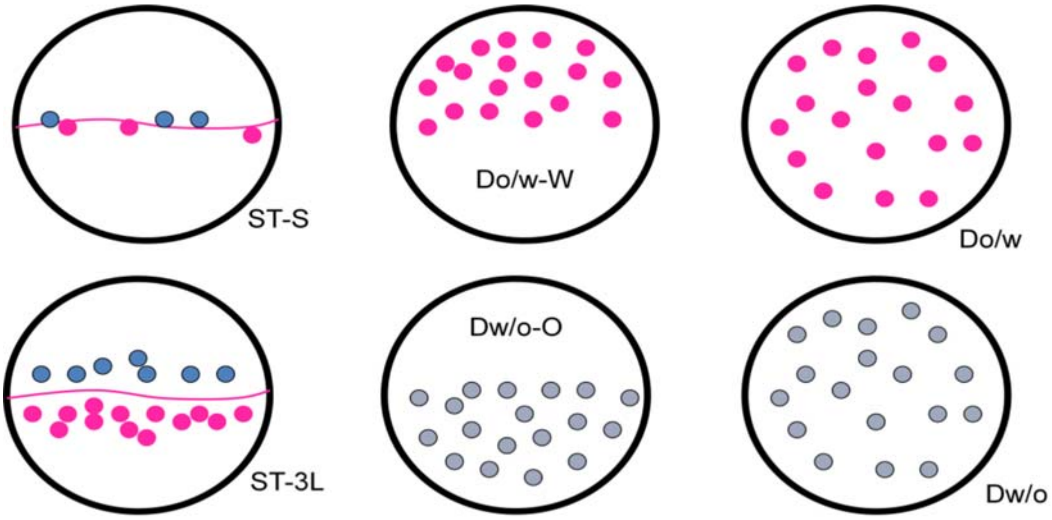

Fig.1.1: Shapes of oil-water flow regimes

Under certain conditions one more flow pattern has been observed called annular core configuration in which one phase is in core and second is in annular side. Oil core flow with water layer in annulus is an important flow pattern to reduce the pressure drop in heavy oil flow transportation. Annular flow with oil core usually not obtained in the oil-water flow with low viscosity oil [5].

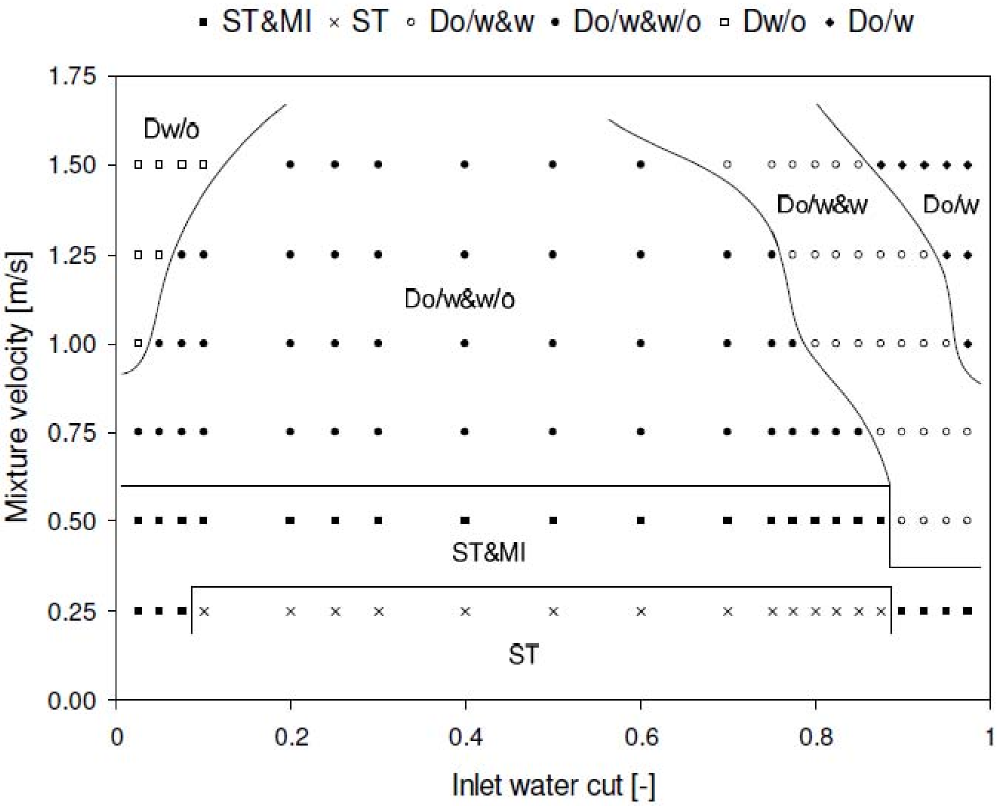

Fig.1.2 Flow pattern map for oil water flow for horizontal pipe

The flow pattern map has been generated by experiments and visual observation by Kumara in multiphase flow laboratory Porsgrunn, Norway. The map is shown in Fig.1.2. It shows that the transition of flow patterns depends upon the mixture velocity and water cut [4]. In this report all these flow patterns are covered.

1.4 Viscous oil Issues

The major issue in viscous oil flow is to get the accurate viscosity of emulsions and to know its stability. The stability of emulsions is characterized by the constant behavior of dispersed phase in continuous phase in term of its dispersity and uniform distribution of dispersed phase in medium over time. This stability is called Kinetic stability where fluid behaves like a single phase flow and emulsion viscosity determination is the only issue.

If the emulsion is highly unstable, phases separated quickly and flow becomes dispersed in one layer and might be separated in other layer. Phase separation due to sedimentation is a typical phenomenon for coarser drops in emulsion resulting in settling or floating of droplets quickly.

However, If the phase separation time is comparable to the transportation time then it takes much time to become fully developed flow and it’s hard to model this type of flow [9, 5].

2.0 Modeling

Below a certain relative velocity between oil and water, oil and water layers are treated as separated flow and both layers are separated but above this velocity it is considered as dispersed flow means both phases are mixed. In this report both dispersed and stratified flow models are discussed.

2.1. Dispersed flow model

The model which is generally used for oil water mixed flow pattern is mixed flow model having closure relation for emulsion viscosity. The general equation of pressure drop for mixture can be written as shown below which is the combination of gravitational and frictional pressure drop.

$$\frac{dP}{dZ} = \frac{\lambda \rho_m \mathrm{U_m}^2}{2D} + \rho_m g Sin\theta ....(2.1)$$

Where λ = friction factor ρ_m = density of mixture $\mathrm{U_m}$ = mixture velocity and θ = pipe inclination

D = pipe diameter, g = gravitational constant

In case of horizontal pipe gravity term is neglected. For wall friction, single phase models are used with mixture density and emulsion viscosity. For laminar flow friction factor is defined as

$$\lambda = \frac{64}{\mathrm{Re}} ....(2.2)$$

For turbulent flow many different equations are available for friction in order to determine friction factor. For smooth pipes Blasius equation can be used and for rough pipes Håland equation can be used.

Blasius equation

$$\lambda = \frac{0.314}{\mathrm{Re}^{-0.25}} ....(2.3)$$

Håland equation

$$\lambda = -1.8 * \log_{10} \left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon}{3.7 * D_h} \right)^{1.11} \right] ....(2.4)$$

Re = Reynold number D_h = Hydraulic radius and ε = roughness factor

Reynold number with mixture density and emulsion viscosity is used for dispersed phase flow.

$$\mathrm{Re} = \frac{\rho_m D_h \mathrm{U_m}}{\mu_m} \text{..................}(2.5)$$

The main issue in oil and water system is the accurate emulsion viscosity estimation.

2.1.1 Calculation of emulsion viscosity

In order to find emulsion viscosity there are many models available in the literature some of the models are given in table 2.1. But all these models are in use to find the global viscosity emulsion in the pipe but when we have unstable emulsion and dispersed phase fraction within the pipe cross section is not uniform then the model should be applied locally and then averaged. All emulsion viscosity model requires dispersed phase fraction as input.

Table2.1: Emulsion viscosity models

Model Name	Equation	Application
Mao & Mardsen	$\eta_r = \exp(-4.4 * \phi)$	W in O emulsions
Mao & Mardsen	$\eta_r = \exp(3.53 * \phi)$	O in W emulsions
Taylor model	$\eta_r = [1+4.5*\phi]$	Concentrated emulsions
Hatschek model	$\eta_r = [1+2.5*(\phi_d + 0.4*\phi_c)]$	Concentrated emulsions
Krieger & Dougherty	$\eta_r = \left[1 - \frac{\phi}{\phi_m}\right]^{2.5*\phi_m}$	Concentrated emulsions
Sendstatd	$\eta_r = \left[1 - \frac{(\phi - S)}{\phi_m}\right]^{-2}$	O-W and W-O emulsions
Gillies	$\eta_r = \exp\left[\frac{1.75 * \phi}{1 - \phi}\right]$	O in W emulsions

$$S = \frac{a_o}{b}\ln\left[\frac{1+\exp\left[-b\left(1-\frac{\phi}{\phi_m}\right)\right]}{1+\exp(-b)}\right]$$

Where η_r is defined as relative velocity and is equals to $\eta_r = \mu / \mu_c$

μ = Emulsions viscosity

μ_c = Viscosity of continuous phase

$a_o = 0.33$; $b = 20$; φ_m =maximum packing factor= 0.7, φ = fraction of dispersed phase, φ_c = fraction of continuous phase, φ_d = fraction of dispersed phase

The factors which affect the emulsion viscosity are droplet size, shear rate, droplet size distribution, Concentration of particles, Temperature, density and viscosity of both phases and interfacial tension. It has been observed from experiments that droplet size have major impact on emulsion viscosity and it increases substantially when droplet size decreases [2].

Studies carried out by Hans (1995) on North Sea crude oil sample for emulsion viscosity and he developed model for emulsion viscosity. The droplet size decreases with increase of shear rate and it has little effect on viscosity at lower concentration but at higher concentration there is a significant change in emulsion viscosity as shown in Fig 2.1 [7].

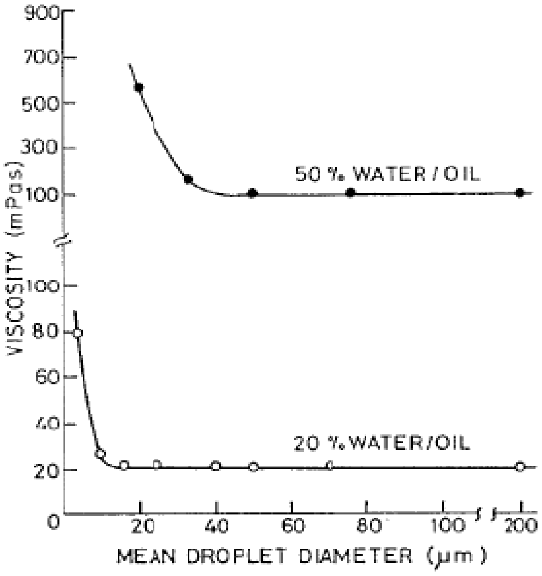

Fig.2.1: Effect of droplet size on emulsion viscosity reported by Thompson et al. (1985)

Emulsion viscosity increases with increase of concentration but a linear effect observed at lower concentration, but at higher concentration there is an exponential change in emulsion viscosity observed [7]. Emulsion viscosity decreases with increase of shear rate as shown in Fig 2.2 and it also decrease with increase of temperature [8].

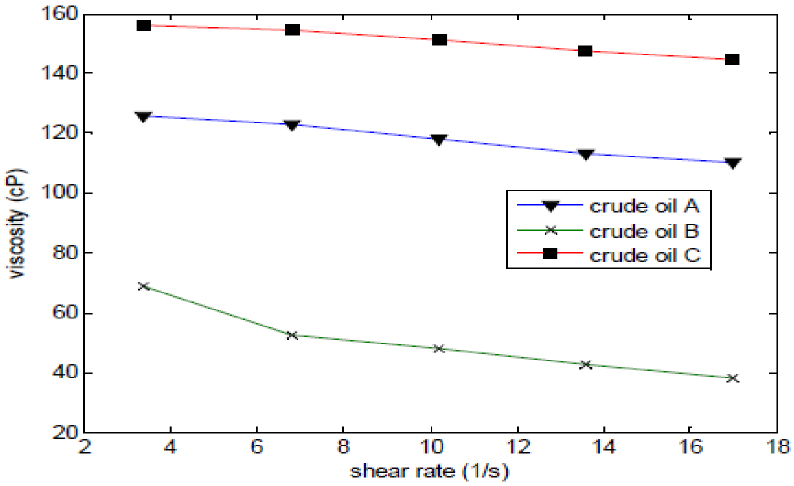

Fig 2.2: effect of shear rate on emulsion viscosity with 20% water cut by A.N. Anila (2010)

Overall, at higher shear rate conditions which are normally operating conditions for most crude oil pipe lines the relative emulsion viscosity is least effected by temperature and water cuts [7].

2.1.2 Implementation of emulsion viscosity:

The most general way is to calculate emulsion viscosity by using uniform dispersed phase fraction. The second way is to determine the local dispersed phase fraction within the pipe cross section, implementing the emulsion viscosity model locally and calculate area averaged emulsion viscosity.

2.1.2.1 Average emulsion viscosity estimation:

Average emulsion viscosity is estimated by using droplet diffusion model which gives local disperse phase fraction. By using the local dispersion, local viscosity is estimated which is than averaged over area. The detail of droplet diffusion model is described below

For steady state flow conditions the particle concentration in a fluid is controlled by balance between the downward flux due to the settling and the diffusive flux due to the shear induced migration and particles are assumed larger so that motion due to Brownian motion is neglected [9, 10].

$$\xi \frac{\partial \phi}{\partial y} + \phi V_t = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

V_t =terminal velocity, ε = diffusion coefficient, φ is the local concentration of dispersed phase in continuous phase, y is the coordinate starting from bottom of pipe or top of pipe depending upon the dispersed phase.

This formulation ignores the deposition of droplets on the pipe wall. Here, y is the coordinator perpendicular to the pipe axis from pipe bottom. n is a parameter concerning the hindered settling effect, n= 3.6 is used in this work. V_T is the terminal velocity of the dispersed phase, which can be calculated by:

$$V_T^2 = \frac{4d\ g\cos\theta\Delta\rho}{3C_D\rho_c} \text{.......................}(2.7)$$

Where d is the droplet diameter, ρ_c is the density of continuous phase. The drag coefficient C_D can be calculated by the model proposed by Ishii & Zuber (1979):

$$C_D = 24\frac{1+0.1\mathrm{Re}_d^{0.75}}{\mathrm{Re}_d} \text{..................}(2.8)$$

$$\mathrm{Re}_d = \frac{d\rho_c V_T}{\mu_c} \text{.......................}(2.9)$$

It can be seen that Eq. (2.7) is a non-linear equation for terminal velocity V_T and an iterative method is required to solve this equation. The whole pipe is divided into 20 parts of equal height.

Diffusion coefficient can be calculated by different formulas depending upon type of flow. For laminar flow diffusion coefficient is approximated by Acrivos(1985) and is defined as

$$\xi = \left(-\gamma r_b{}^2\phi\ \frac{1}{3}\left(1+0.5\exp\left(8.8\phi\right)\right)\right) \text{..............}(2.10)$$

Where r_b is the radius of the particle and is and γ is shear rate. There are many equations available in literature but in the current work it is calculated by the equation (Kolmogorov, 1949, Hinze, 1955, Batchelor, 1959) [9].

$$d_{\max} = 0.725\left(\frac{\sigma}{\rho_c}\right)^{0.6}\left(\frac{D}{2fu_c^3}\frac{\rho_c(1-\alpha_d)}{\rho_{ave}}\right)^{0.4} \text{..................}(2.11)$$

Where σ is surface tension, ρ_c is density of continuous phase, α_d is dispersed phase fraction, ρ_{ave} is average density of fluids, f is friction factor and D is the pipe diameter.

For laminar flow maximum share rate is calculated by equation.

$$\gamma = \frac{8U_i}{D_{hi}} \text{..............................}(2.12)$$

Where 'i' is the number of divisions, U_i is the local velocity and D_{hi} is the local hydraulic radius. This model can also be implemented by using uniform velocity and uniform hydraulic radius. In order to implement the model locally, it needs local velocity and local hydraulic radius which is defined by the equation 2.15 and 2.13 respectively which is defined in my previous project work.

$$D_{hi} = 2r_i \sin \delta_i \text{.................................}(2.13)$$

r_i = radius of each layer shown in Fig.2.2 and it can be calculated by the formula

$$r_i = \sqrt{-h_i^2 + 2h_i R} \text{..............................}(2.14)$$

$$U_i = U_m\left[1-\left(\frac{hi}{R}\right)^2\right] \text{..}(2.15)$$

R is the radius of the pipe and h_i is the height of the each layer from bottom shown in figure 2.3

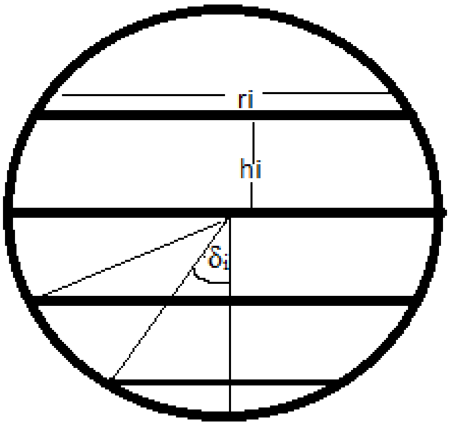

Fig.2.3: Pipe cross section layers

For turbulent flow the diffusion coefficient is calculated by correlations defined by (Taylor, 1954).

$$\xi_T = 0.026 v^* D_{h,c} \qquad (2.16)$$

Where the friction velocity of continuous field v^* is calculated by $v^* = u_c \sqrt{f/2}$. Normally the wall friction coefficient is used to calculate the friction velocity. Considering the interfacial friction at the interface, the averaged frictional coefficient is calculated by the following formulation

$$f = \frac{S_k f^w + S_i f^i}{S_k + S_i} \qquad (2.17)$$

Where f^w, f^i are the walls and interface friction factor respectively [9].

All the equations (2.7-2.17) are used in equation 2.6 and local dispersion is estimated

2.1.3 Implementation of the dispersed phase flow model using average emulsion viscosity

The following method has been developed for implementation of dispersed phase flow model with average emulsion viscosity. The input parameters to model are superficial velocities, phase densities, viscosities, interfacial tension, pipe roughness and pipe angle. The loop of implementation is shown in figure 2.4. The initial alpha_c and alpha_d values are set on the basis of water cut but after getting the phase velocities alpha_c and alpha_d values are updated which are used to estimate uniform emulsion viscosity. The uniform emulsion viscosity is used in droplet size closure model. After droplet size calculation all the inputs for droplet diffusion model become available except, the dispersed phase fraction at the interface which is set initially at phase inversion point. Dispersed phase distribution obtained locally from droplet diffusion model is used to calculate local emulsion viscosity and both these parameters are averaged over area as shown by equation.

$$\phi_{avg} = \frac{\sum_{i=1}^{n} A_i \phi_i}{A_{tot}} \qquad (2.18)$$

$$u_{avg} = \frac{\sum_{i=1}^{n} A_i u_i}{A_{tot}} \qquad (2.19)$$

Where φ_{avg} and u_{avg} are average droplet fraction and average emulsion viscosity respectively, A_{tot} is total flow area of dispersed layer. A_i, u_i and φ_i are local flow area, emulsion viscosity and dispersed phase fraction respectively.

Iteration of diffusion model carried out until emulsion viscosity difference between inlet and outlet of droplet diffusion model becomes less than 0.000001.When it gets converged, Iteration starts again until difference between average dispersed phase droplet fraction calculated by equation 2.18 and actual dispersed phase fraction at the inlet of model, become less than 0.01.The dispersed phase fraction at the interface is used as a varying parameter for dispersed phase fraction convergence.

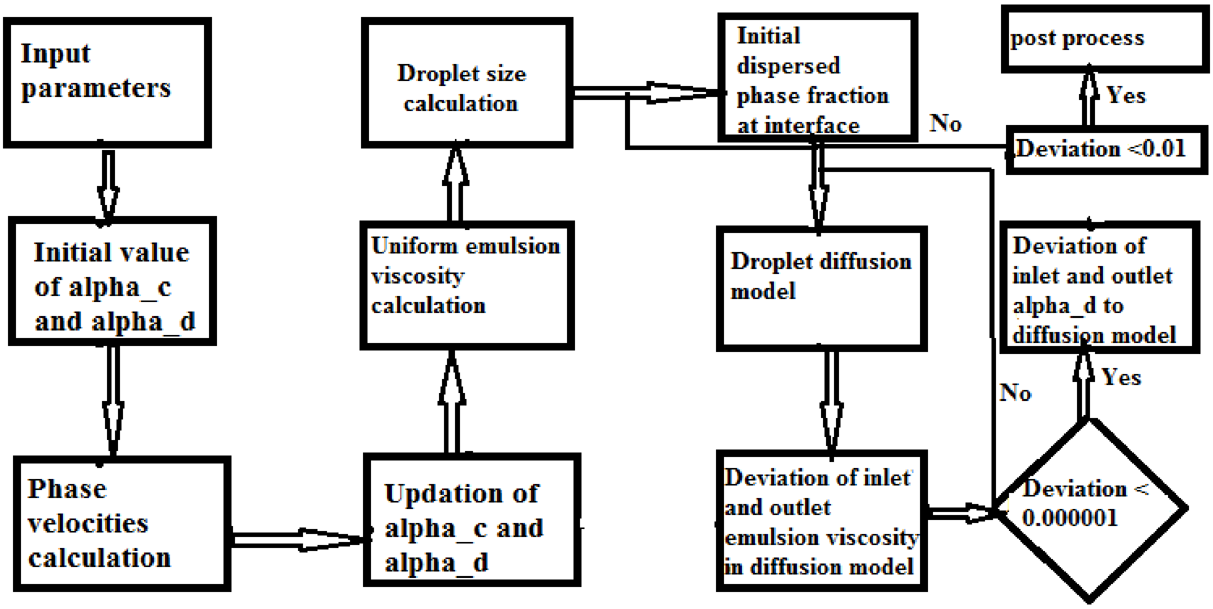

Fig. 2.4: Implementation scheme for dispersed phase flow model using uniform emulsion viscosity

2.2 Stratified Flow model

The stratified flow model code was available with uniform emulsion viscosity it is developed with implementing average emulsion viscosity. The model is available to run in three modes.

1) No dispersion
2) One way dispersion
3) Two way dispersion

The model with no dispersion is general one in which iteration carried out in order to solve hold up equation 2.20 by using Newton, s method. There is no entrainment considered in no dispersion model.

$$\frac{\tau_o S_o}{A_o} - \frac{\tau_\omega S_w}{A_w} + \tau_{i,ow} S_{i,ow}\left(\frac{1}{A_o} + \frac{1}{A_w}\right) - (\rho_\omega - \rho_o) g \sin\theta = 0 \text{............(2.20)}$$

$$\tau_o = \frac{1}{2} f_o \rho_o U_o{}^2 \text{...(2.21)}$$

$$\tau_w = \frac{1}{2} f_w \rho_\omega U_w{}^2 \text{..............................(2.22)}$$

Where, τ_o = oil shear stress, τ_w = water shear stress, $S_{i,ow}$ = interface perimeter, $\tau_{i,ow}$ = interfacial shear stress, A_o = Oil cross sectional area, A_w = water cross sectional area, S_o = oil wetted perimeter, S_w = water wetted perimeter, f_w = Water friction factor and f_o = Oil friction factor

The non-linear algebraic equations [2.20] obtained that has to be solved iteratively with respect to in-situ water fraction. A number of closure relations including wall friction and inter facial friction model have to be incorporated in the model to obtain consistent prediction of the pressure gradient and the in-situ oil and water fractions [5].

2.2.1Wall and interfacial perimeters

If the holdup of the continuous layer is known, the wall and interfacial perimeters of each continuous layer are function of half-angle β as indicated in Figure 5.1. The half angle β can be approximated by:

$$\beta = \pi\alpha_{cw} + \left(\frac{3\pi}{2}\right)^{1/3}\left[1 - 2\alpha_{cw} + \alpha_{cw}^{1/3} - \left(\alpha_{co}^{1/3}\right)\right] \text{.................}(2.23)$$

Where α_{co}, α_{cw} are the volume fractions of continuous oil and water layers respectively. If both oil-in-water and water-in-oil droplets exist in the flow, we have:

$$\alpha_{cw} = \alpha_w + \alpha_{dow} \text{.........................}(2.24)$$

$$\alpha_{co} = \alpha_o + \alpha_{dwo} \text{.........................}(2.25)$$

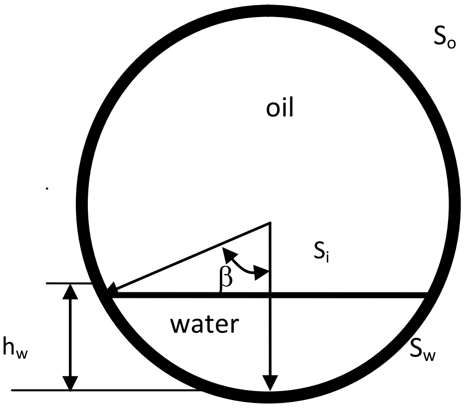

Fig.2.5. Schematic of stratified two-phase flow

The wetting and interface perimeters are defined as:

$$\begin{aligned} S_o &= (\pi - \beta)D \\ S_w &= \beta D \qquad (2.26) \\ S_i &= D\sin\beta \end{aligned}$$

Where D is the pipe diameter

2.2.2 Hydraulic diameter of continuous layer

Hydraulic diameter is needed for wall friction and interface friction calculations. There are two ways to define the hydraulic diameter of continuous layer for a stratified flow: open- and closed-channel. For a gas-liquid system, normally, the closed-channel model is used for gas and open-channel model is used for liquid. For an oil-water flow, the closed-channel model is used for oil and the open-channel model is used for water. The hydraulic diameter of continuous layer is used for calculation of wall and interfacial friction.

For viscous oil-water two-phase flow the oil layer flow may be laminar and the definition of hydraulic diameter of the continuous layers becomes an important issue. The two different definitions are:

$$D_{co} = \frac{4A_{co}}{S_o + S_i} = \frac{\pi D^2 \alpha_{co}}{S_o + S_i} \quad \text{(closed channel)} \tag{2.27}$$

$$D_{co} = \frac{4A_{co}}{S_o} = \frac{\pi D^2 \alpha_{co}}{S_o} \quad \text{(open channel)} \tag{2.28}$$

$$D_{cw} = \frac{4A_{cw}}{S_w + S_i} = \frac{\pi D^2 \alpha_{cw}}{S_w + S_i} \quad \text{(closed channel)}$$

$$D_{cw} = \frac{4A_{cw}}{S_w} = \frac{\pi D^2 \alpha_{cw}}{S_w} \quad \text{(open channel)}$$

In the current model closed-channel model is used [9].

2.2.3Wall friction and Interface friction model

Different correlations are available for interfacial friction factor and wall friction calculations. However, in the current work Classical model is used for interfacial friction calculation and Churchill (1977) model formulated by (Yang, 2009) was implemented for wall friction calculations. Both these models are confidential and not reported here.

2.2.4 Stratified flow model with no dispersion

In case of stratified flow model non linear equation 2.20 is iterated by assuming holdups. The value of holdup where this equation converged gives hold up value. This hold up is used to calculate pressure drop by equation 2.1which is applied separately for both phases and then these both pressure drops are added.

2.2.4 Stratified flow model with one way dispersion

This model is same as no dispersion model except that entrainment of dispersed phase is included here. The entrainment of dispersed phase is calculated by droplet diffusion model which is explained in dispersed flow model. Phase inversion point determines whether it will be oil phase dispersed in water or water phase dispersed in oil. The entrained fraction is determined locally by droplet diffusion model and then averaged over area. Uniform emulsion viscosity was been use in the earlier model for calculating the friction factors and other parameters. Average emulsion viscosity is implemented in current work for calculating different parameters which are emulsion viscosity dependent. Average emulsion viscosity is estimated by using droplet let diffusion model. Diffusion model gives local dispersed phase fraction which is used to calculate local emulsion viscosity and it is averaged over area in order to get average emulsion viscosity.

2.2.5 Stratified flow model with dual dispersion

Stratified models are also implemented by using dual dispersion. In case of dual dispersion there is dispersion of oil and water and also water in oil for entrainment calculations. This model is highly interactive and difficult to get numerical solutions. Both ways dispersion is highly competitive model as both phases dispersed into each other. If one phase dispersion decreases it automatically increase the other phase dispersion. In case of two ways dispersion 3 equations solve simultaneously so its numerical solution is quite complex. More details are not given in this report as it is highly confidential material.

2.3 Fortran and Matlab Connection

The code was available in FORTRAN by which dll file is created and model runs by excel environment. The connection between the Excel file and FORTRAN was created in highly complex way which is not user friendly. It is difficult to get the data out from dll file by using excel environment especially when more parameters are to be analyzed. MATLAB script is made which connects dll file with MATLAB and results are obtained in excel file. It is very easy to use that software and you can get any desired parameter out and analyze the data. The script is added in the Appendix C.

3.0 Sensitivity analysis

Sensitivity analysis of droplet size, droplet diffusion model carried out in order to check the dependence of these models on different parameters. These sensitivities are used for tuning of models.

3.1 Sensitivity analysis of droplet size

Droplet size of dispersed phase depends mainly on continuous phase velocity, interfacial tension, pipe diameter and density of the phases. The interfacial tension and density of the phases are almost constant in all the experiments. So dependence of droplet size on viscosity, velocity and pipe diameter and water cut are analyzed.

There is no effect of viscosity observed on droplet size. It also remains same at all water cuts if the continuous phase velocity is constant. The effect of continuous phase velocity and pipe diameter on droplet size is shown in figure 3.1.

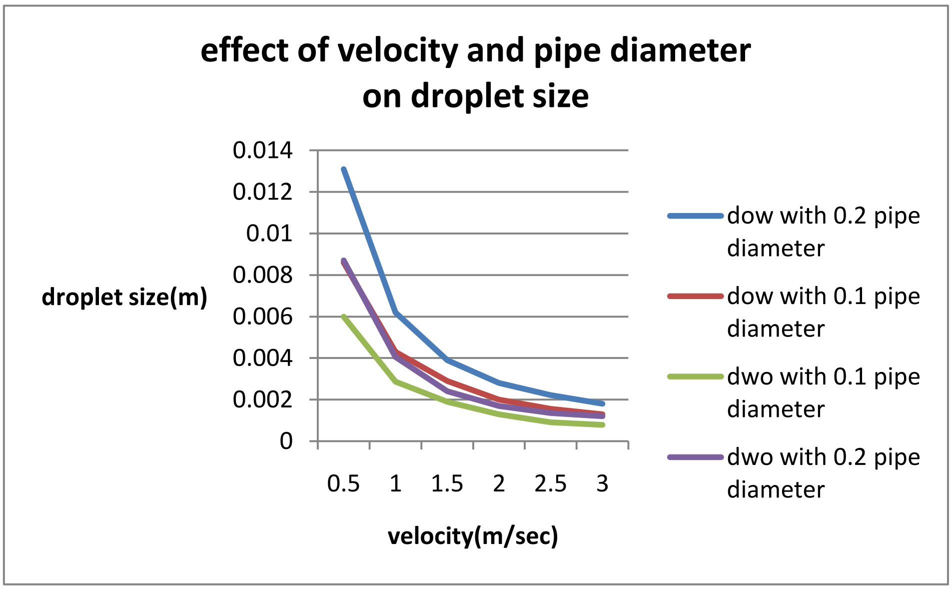

Fig. 3.1 sensitivity analysis of droplet size model for different pipe diameter and velocities

3.2 sensitivity analysis of droplet diffusion model

Sensitivity analysis of droplet diffusion model is carried out by varying different parameters i.e. droplet size, eta_factor, viscosity, velocity and n-factor. The sensitivity analyses of these parameters are described below.

3.2.1 Effect of droplet diameter

The droplet diffusion equation is different for laminar flow and turbulent flow. Mostly dispersed water in oil experiments has laminar flow while dispersed oil in water has turbulent flow. The sensitivity of dispersed phase fraction profile for dispersed water in oil is much different than dispersed oil in water as shown in figure (3.2-3.4).

The effect of droplet size is much prominent when dealing with laminar flow as shown in figure 3.2 and also in equation 2.10. The profile becomes flatter as droplet size increases

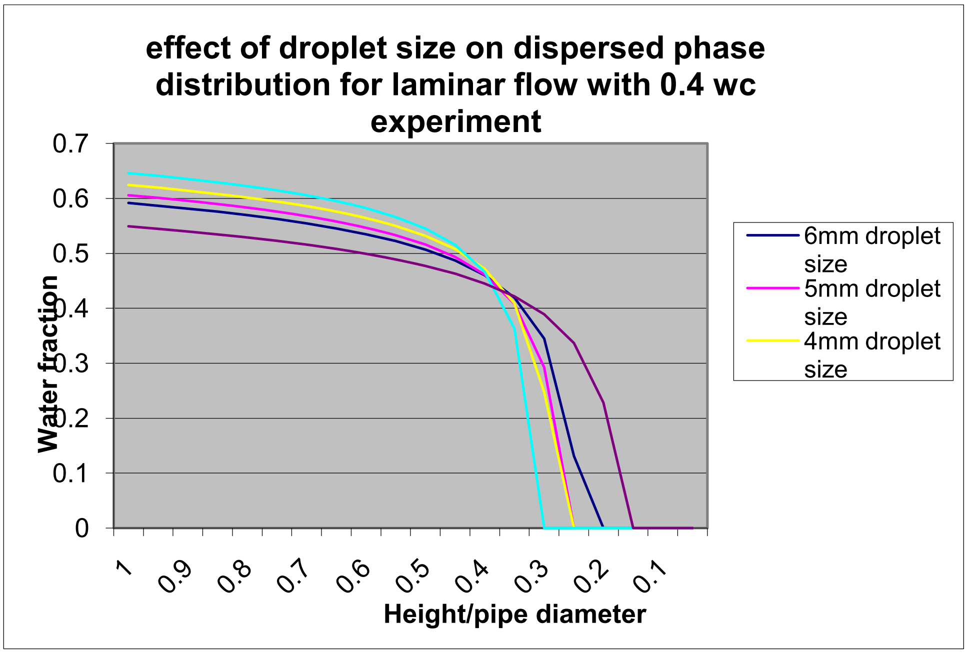

Fig. 3.2 effect of droplet size on dispersed phase distribution for laminar flow with 0.4 wc, 1m/sec velocity and 0.1m pipe diameter

The dispersed phase distribution profile for laminar flow is much sensitive to droplet size. It is difficult to iterate the sensitive changes for dispersed flow with ordinary method therefore, droplet size smaller than 3mm were not selected for laminar flow. As distribution profile is much sensitive to drop let size so it can be use as a manipulating parameter for better prediction of dispersed phase distribution for laminar flow.

In case of turbulent flow experiments, dispersed phase distribution is not much sensitive with changes in droplet size as compared to laminar flow but profile become slightly flatter with decrease of droplet size shown in figure 3.3.

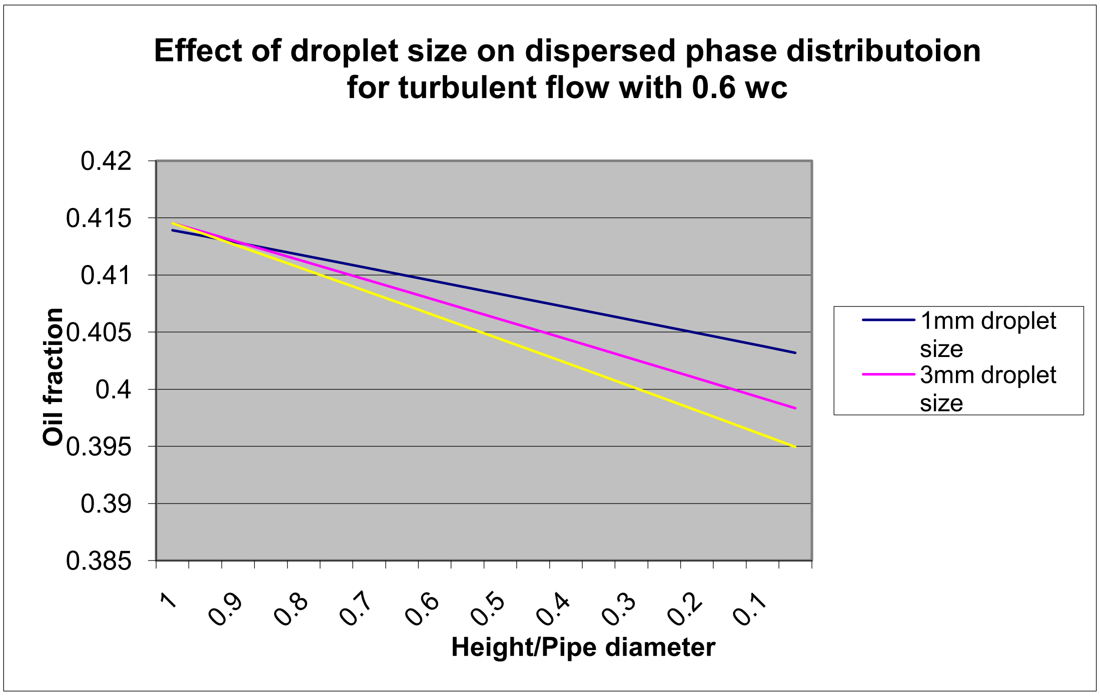

Fig. 3.3 effect of droplet size on dispersed phase distribution for turbulent flow with 0.6 wc, 2m/sec velocity and 0.078m pipe diameter

It is clear from the above figure 3.3 3that there is small change in dispersed phase distribution with change of droplet size. As drop let size increase from 1mm to 5mm there is only 0.01 change in dispersed phase fraction at the bottom of the pipe.There is only small change in dispersion observed with change of droplet size.

In case of Transition flow when reynolds number is between 1400-2800 the overall effect of droplet size is almost nil. Smaller the droplet size, greater is the dispersed phase fraction at the one end of pipe while smaller at the other as shown in figure 3.4.

As droplet size incrseases from 1mm to 5mm there is increase of 0.01 dispersed phase fraction at the top of pipe but decrease of 0.01 fraction at the bottom. So overall there is no effect on dispersed phase distribution or entrainment observed in case of transition flow.

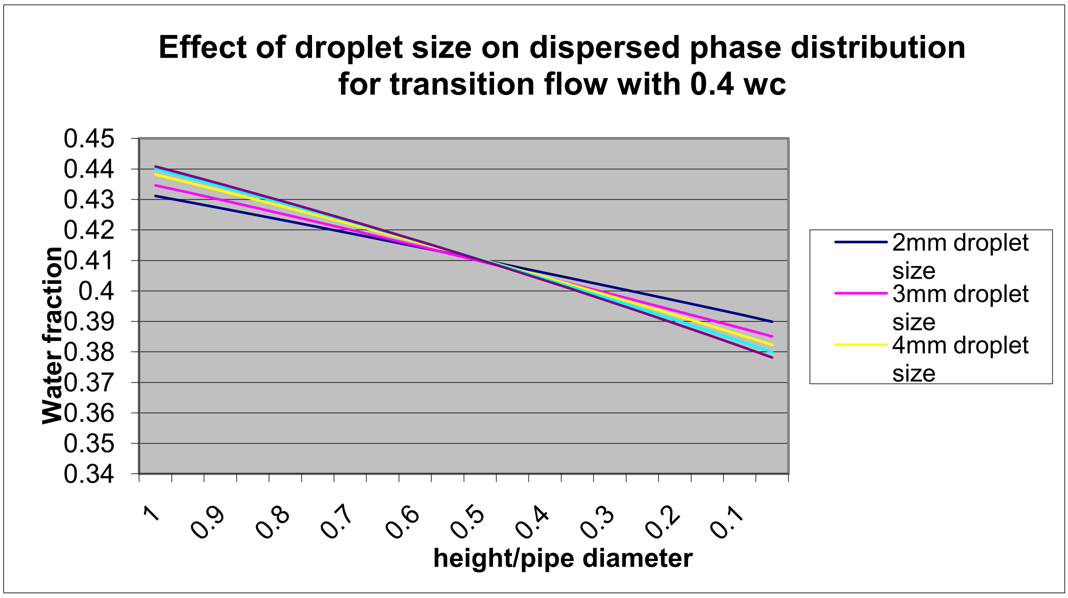

Fig. 3.4 effect of droplet size on dispersed phase distribution for transition flow having 1700 reynolds number with 0.4 wc, 2m/sec velocity and 0.078m pipe diameter

3.2.2 Effect of eta factor on dispersed phase distribution

After sensitivity analysis of droplet size it was observed that laminar flow is very sensitive to droplet size but it has negligible effect on turbulent flow. Therefore, different parameters have been analyzed in order to get to know about the sensitivity of dispersed phase distribution in turbulent flow. It is observed that turbulent flow distribution is sensitive to eta_factor which is 0.026 in the model. This factor is reduced and it is observed that there is little effect on distribution until 0.0005 but if we go down than it, there is significant change observed in distribution as shown in figure 3.5.

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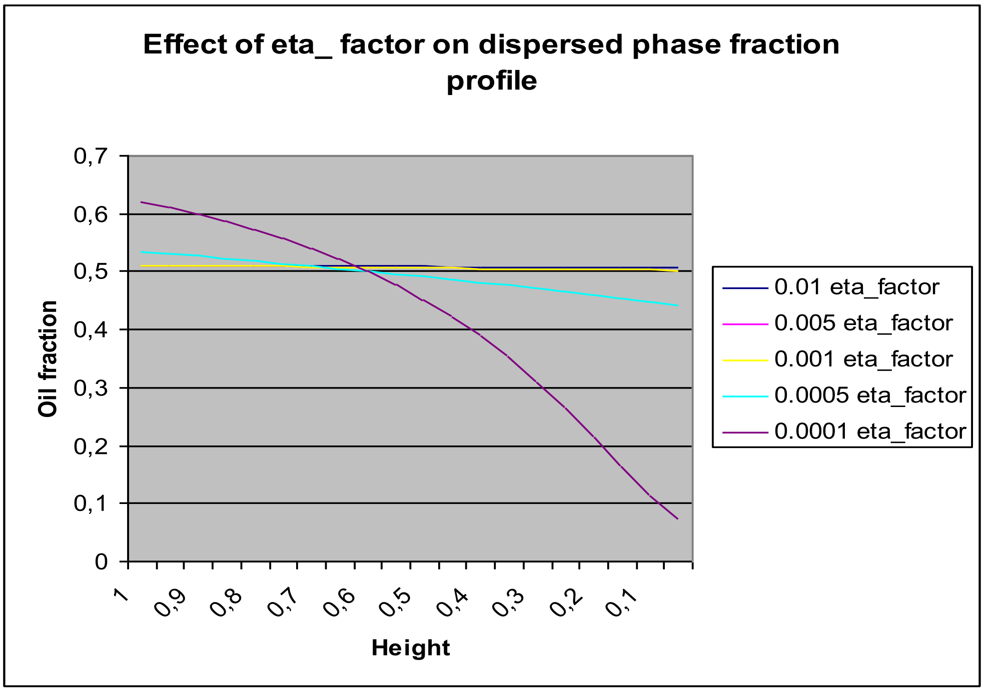


Fig. 3.5 effect of eta_factor on dispersed oil fraction for experiment having 2m/sec velocity, 33cp viscosity and 0.5 water cut

3.2.3 Effect of viscosity on dispersed phase distribution

The droplet diffusion model was also analyzed for different viscosities but no effect was observed in case of dispersed oil in water experiments having turbulent flow and there is small effect observed in case of laminar flow. The curve becomes bit flatter with increase of viscosity.

3.2.4Effect of n-factor on dispersed phase distribution

The n-factor is used in equation in order to calculate terminal velocity. The effect of n-factor dispersed phase distribution is studied and it is observed that the curve become flatter as n factor increases as shown in figure 3.6. This figure plotted for dispersed water in oil phase having laminar but same behavior is observed for dispersed oil in water phase having turbulent flow. The graph for turbulent flow is not plotted here. The value of n is kept at 3.6 for the current work.

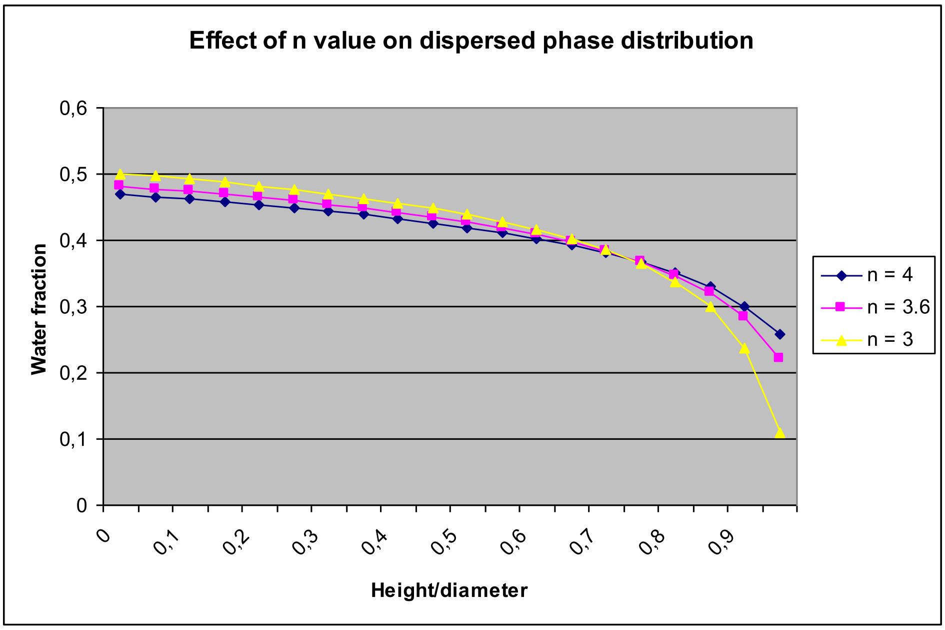


Fig .3.6. Plot of dispersed phase fraction with values of n for experiment having 0.4 water cut and laminar flow

3.2.5 Effect of velocity on dispersed phase distribution

The sensitivity analysis of different velocities carried out with fixed water cut of 0.6 experiment. The eta_factor was fixed at 0.0005. It was observed that profile becomes flatter as the velocity increases and it become fully dispersed flow when the flow is increase from 1m/sec. The distribution profile is very sensitive to velocity in case of turbulent flow as shown in figure 3.7. In case of Laminar flow the distribution is not much sensitive if it is compared to turbulent flow as shown in figure 3.8.

From the figure it can be analyzed that transition between stratified to disperse flow is different for dispersed oil in water than dispersed water in oil. In case of dispersed water in oil the flow pattern seems totally dispersed flow at 1m/sec velocity but in case of dispersed oil in water flows it seems stratified at 1 m/sec. This observation can further be investigated for finding transition criteria.

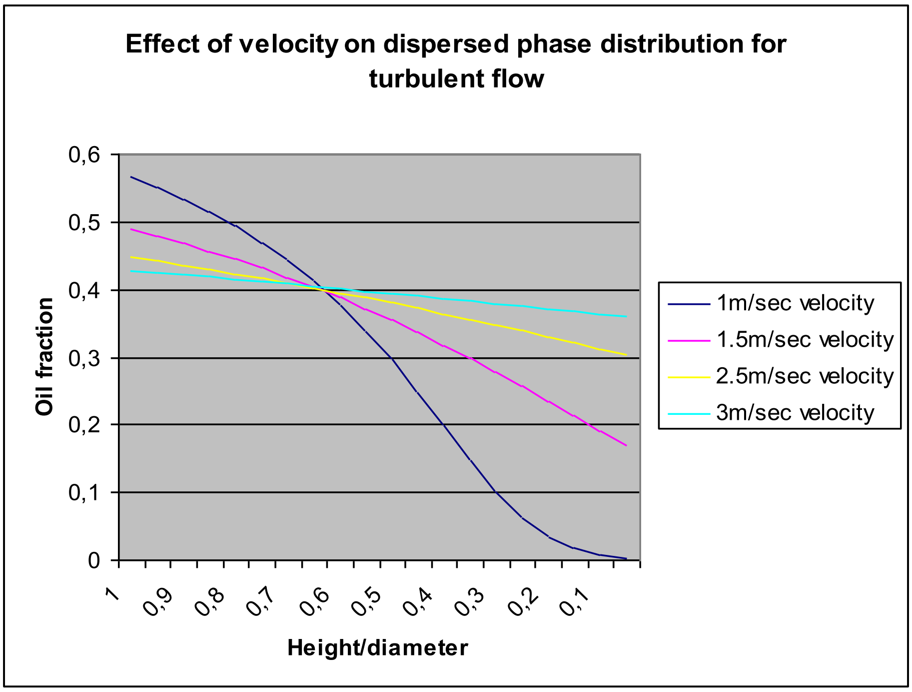


Fig. 3.7 effect of velocity on dispersed phase distribution for turbulent flow experiment having water cut of 0.5

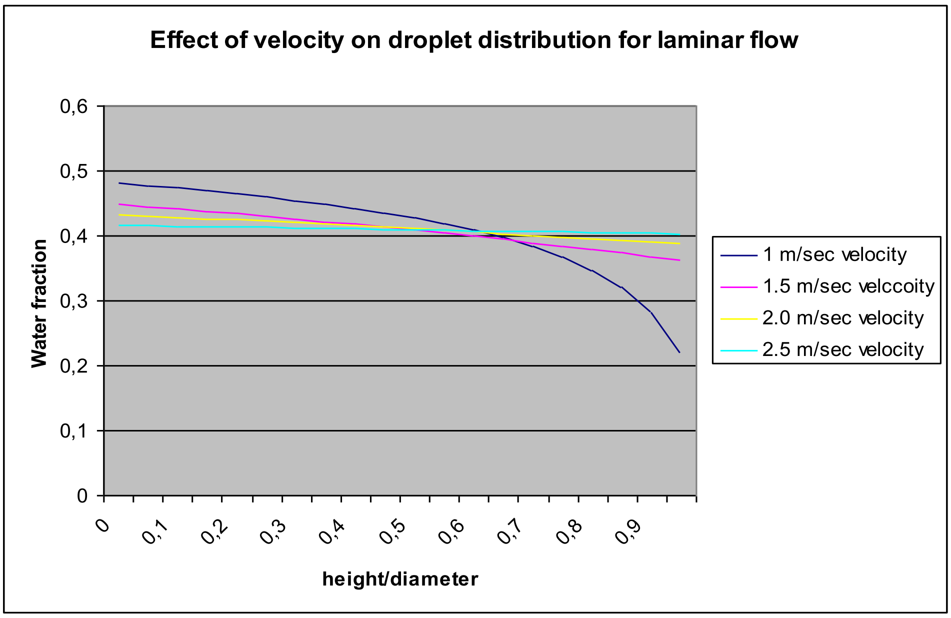


Fig. 3.8 effect of velocity on dispersed phase distribution for laminar flow experiment having water cut of 0.6

3.2.6 Analysis of local and uniform velocity model

Local model velocity is defined as a model where local velocity and local hydraulic radius is used to find laminar flow eta_factor while uniform velocity model uniform velocity model uses uniform velocity and uniform hydraulic radius throughout the pipe cross section

The droplet diffusion model for laminar flow need local velocity and local hydraulic radius in order to implement it in best way but it also gives good results by using uniform velocity and overall hydraulic radius of continuous phase. Local model gives almost same dispersed phase fraction at the interface for all water cuts and it distribute the dispersed phase fraction more uniformly throughout the pipe as compared to uniform velocity model as shown in figure 3.9. Uniform model gives quite varying dispersed phase fraction at the interface and end sharply as at the end.

The Local model can be implemented well if the size of division is large enough that it does not have too small local hydraulic radius. Small hydraulic radius results in infinite concentration and then it is difficult to iterate. Local model is implemented well with equal size of divisions rather than unequal pipe divisions. Uniform model can be implemented both with equal and unequal size of divisions. It is also observed that for 0.5 m/sec experiments local velocity model implemented very well and gives better results than uniform model analyzed in data analysis chapter.

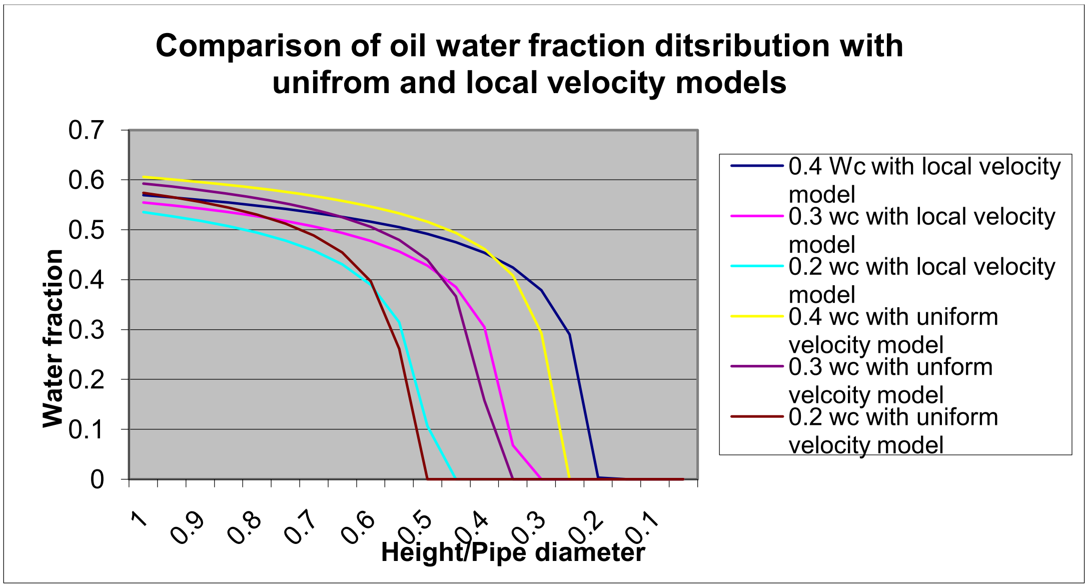


Fig. 3.9 Local and uniform velocity model comparison for different water cuts having velocity of 1m/sec and pipe diameter of 0.1m

3.3 Discussion

It was observed that droplet size is dependent on velocity, interfacial tension and pipe diameter while it is independent of viscosity and water cut.

Droplet diffusion model is very sensitive to droplet diameter for laminar flow but for turbulent flow it has almost no effect. There is no effect of viscosity observed for both laminar and turbulent flow. Both laminar and turbulent flow distribution is effected by changing the n parameter and distribution profile become flatter as n factor is increased.

The distribution profile for turbulent flow is much sensitive to phase velocity. As the velocity increase profile becomes flatter sharply while in case of laminar flow the profile is not much sensitive. This velocity sensitivity analysis can also help in finding transition criteria.

The turbulent flow is very sensitive to eta factor when it is reduced below 0.0005. There is small change observed in profile if the eta_factor remains below 0.0005. However, the profile gets down sharply if the eta_factor decreased below 0.0005. This is probably due to high interfacial friction factor.

Local velocity model gave good results in comparison to uniform velocity model but it could not implement at higher velocity and when number of divisions are not of equal size. So it is recommended to implement local velocity model at 0.5 m/sec atleast and further work to implement it at 1 m/sec can be investigated.

4.0 Data anlaysis

Grane data dispersed phase flow experiments with 2m/sec velocity are analyzed with dispersed flow model using average emulsion viscosity and compared it with dispersed flow model using uniform emulsion viscosity. Stratified model is tested for Grane data and IFE data with 1m/sec and 0.5 m/sec velocity. Tuning of Stratified model is also carried out.

4.1 Dispersed flow data model Analysis

Few experiments from Grane data were selected and the model using average emulsion viscosity and uniform emulsion viscosity is implemented.

4.1.1 Dispersed phase fraction distribution profile estimation

The local dispersed phase fraction of these experiments was measured by traverse gamma densitometer are available. The above model is analyzed for matching the dispersed phase experimental measured fraction with simulated fraction but it gives huge mismatch between the experimental and model profile. In order to determine the correct dispersed phase distribution profile different analysis has made**.** All the experiments have water cut in the range from 0.5 to 0.8 so all these are dispersed oil in water flow experiments.

In the current work Krieger & Dougherty emulsion viscosity model is used for emulsion viscosity calculations. For all the experiments the model gives very flat dispersed phase distribution profile. In order to make good distribution, droplet size increased to 5mm but it did not brought any change in curve. Afterwards Eta_factor was decreased from 0.026 to 0.001. A good match of experimental and simulation curve obtained for all four experiments with 0.001 eta_factor value. The curves for all four experiments are shown in figures (4.1-4.4).

Table 4.1

Experiment	Oil velocity (m/ sec)	Water velocity (m/ sec)	Oil viscosity (pa-sec)	Water viscosity (pa-sec)	Pipe roughness (m)	Pipe angle (degrees)	Interfacial tension (Nm)	Water cut
OW-23	1	0.5	0.033	0.00055	0.000008	0	0.0167	0.5
OW-24	0.6	0.4	0.033	0.00055	0.000008	0	0.0167	0.4
OW-25	0.7	0.3	0.033	0.00055	0.000008	0	0.0167	0.3
OW-26	0.8	0.2	0.033	0.00055	0.000008	0	0.0167	0.2

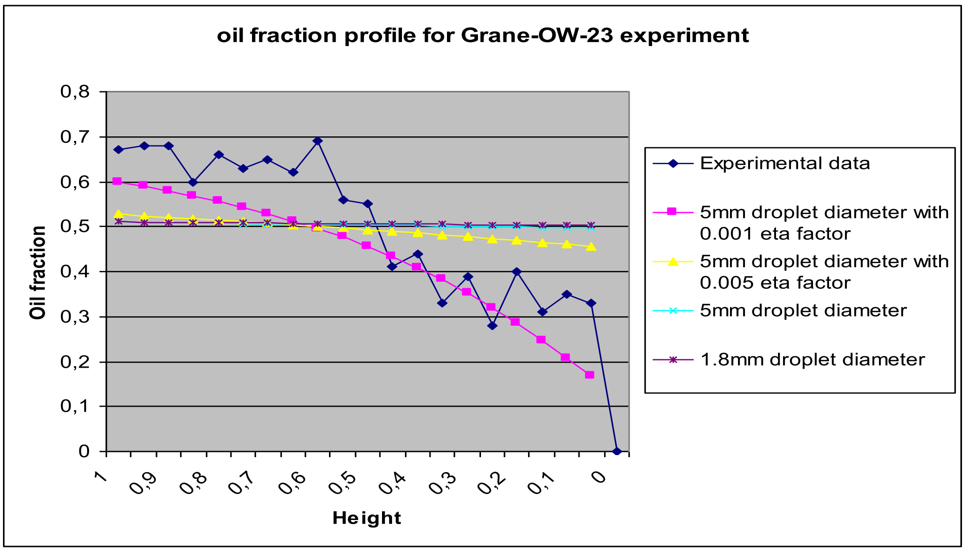


Fig.4.1 Dispersed phase experimental and simulated distribution profile with different eta_factor and droplet size values for 0.5 water cut experiment

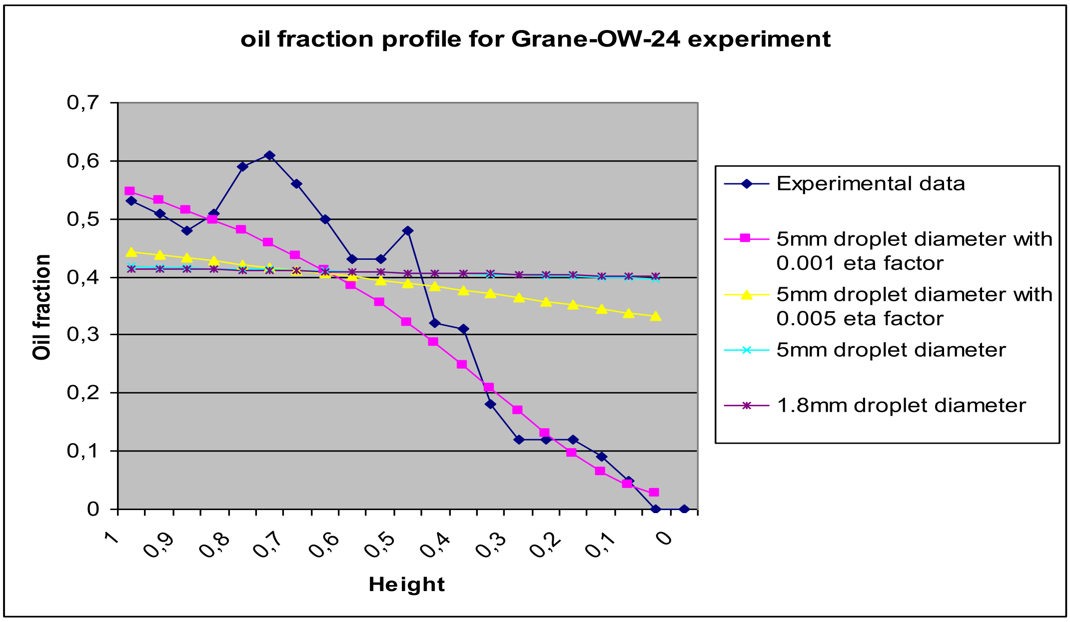


Fig. 4.2 Dispersed phase experimental and simulated distribution profile with different eta_factor and droplet size values for 0.6 water cut experiment

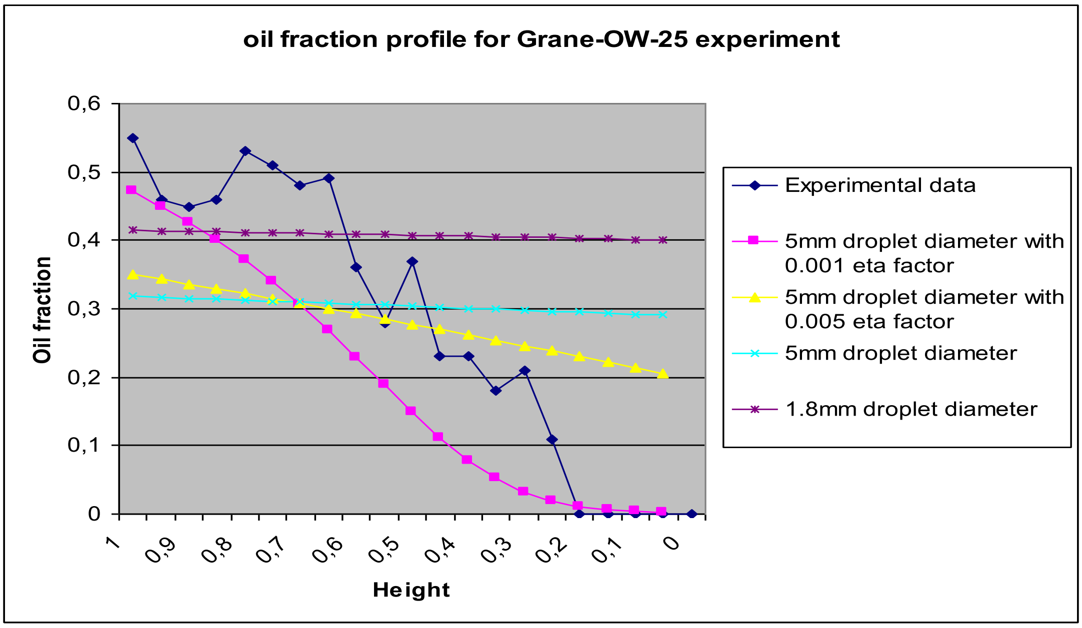


Fig. 4.3 Dispersed phase experimental and simulated distribution profile with different eta_factor and droplet size values for 0.7 water cut experiment

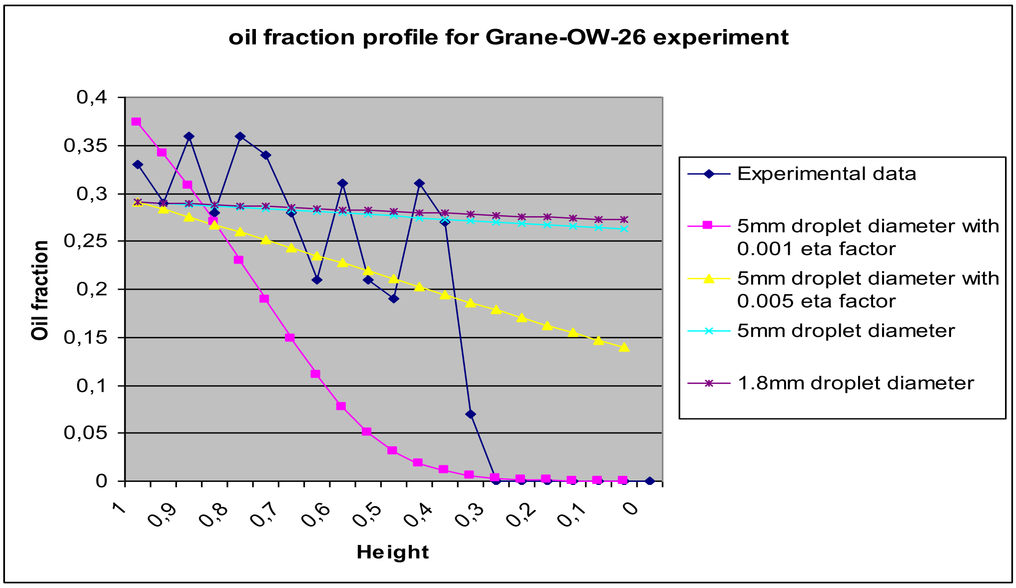


Fig. 4.4 Dispersed phase experimental and simulated distribution profile with different eta_factor and droplet size values for 0.8 water cut experiment

It can be seen from the above figures (4.1-4.4) that droplet diffusion model behaves same like experimental work. It is observed that eta_factor of 0.001 gives a good match of simulated and experimental curve. So it is recommended that eta factor should be atleast 0.001 for turbulent flow experiments. There is no effect of droplet size observed in all experiments due to oil in water dispersion which causing turbulent flow.

From the entire figures it is observed that dispersed phase fraction at the interface calculated by both model and experimental changes as water cut changes. It is better option to make a small change in dispersed phase fraction at the interface with change of water cut. This technique is implemented in dispersed phase flow model in the current work.

4.1.2 Emulsion viscosity estimation

Grane data dispersed phase flow experiments having 2m/sec velocity was tested with uniform emulsion viscosity model and average emulsion viscosity model but there is small change observed in viscosities as shown in figure 4.5

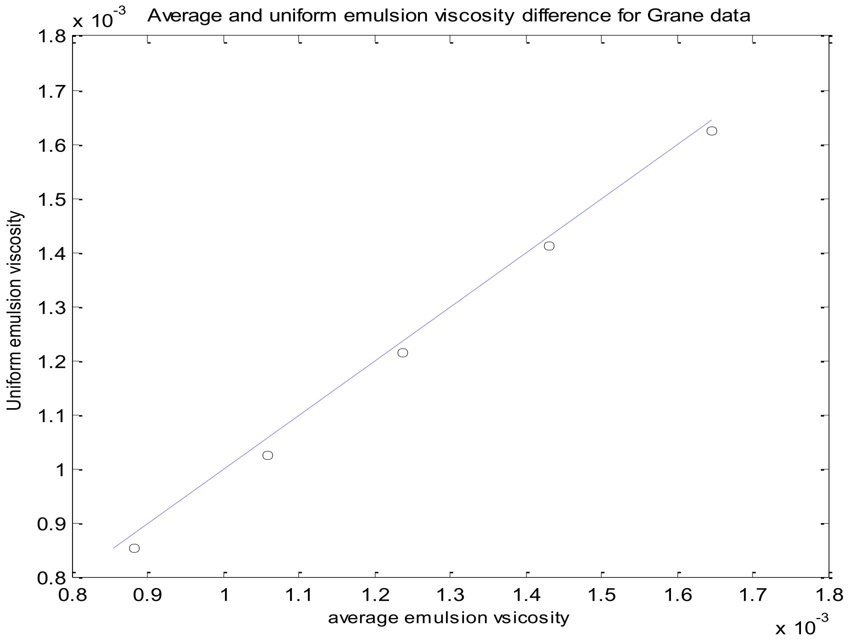


Fig.4.5: Comparison of emulsion viscosity calculated by average emulsion viscosity model and uniform emulsion viscosity model

All the experiments are turbulent flow dispersed oil in water experiments. As water has very low viscosity so its emulsion viscosity is not much sensitive to oil fraction but in case of dispersed water in oil laminar flow experiments, the emulsion viscosity is much sensitive to water fraction**.** Average emulsion viscosity model will give huge difference in emulsion viscosity prediction if implemented in water in oil experiments. There was no data available for dispersed flow water in oil experiments so this model was not tested for it. The implementation of this model for water in oil dispersion is of interest and it should be analyzed in future.

4.1.3 Pressure drop Estimation

A good pressure drop prediction is obtained by using both uniform and average emulsion viscosity model. Pressure drop equation for both is shown in figure (4.6-4.7).

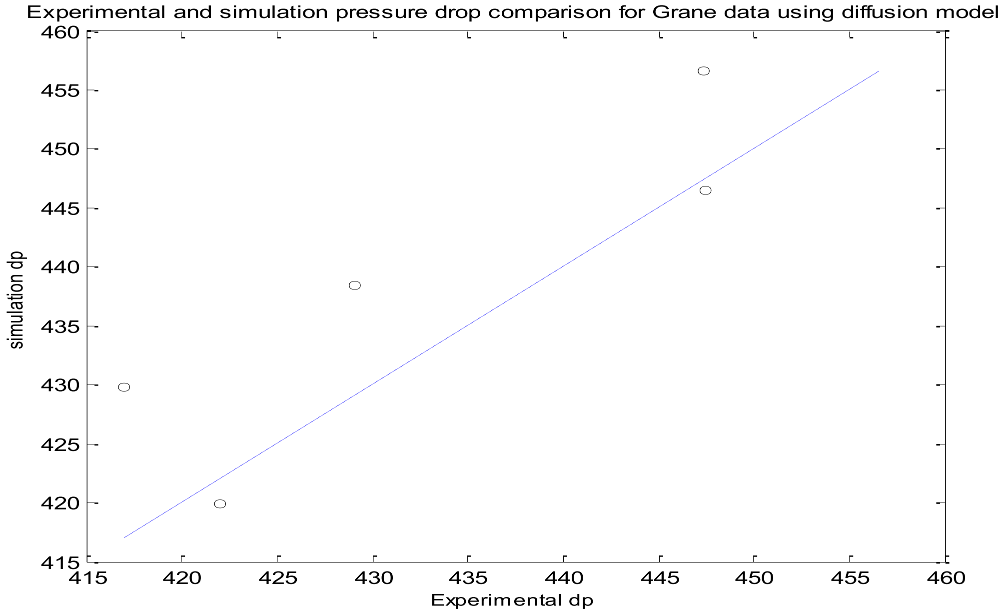


Fig. 4.6: Pressure drop for Grane data dispersed flow experiments with 2m/sec velocity using average emulsion viscosity data

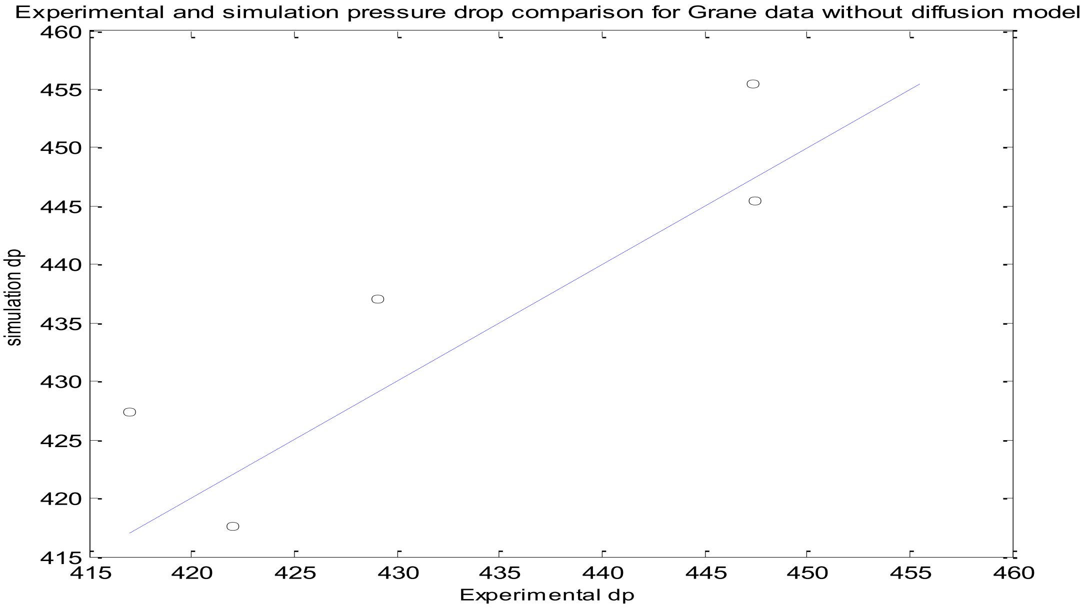


Fig. 4.7: Pressure drop for Grane data dispersed flow experiments with 2m/sec velocity using uniform emulsion viscosity data

4.1.4 Model convergence

The Iterations are carried out in order to converge, average dispersion calculated by droplet diffusion model and dispersed phase fraction calculated by dispersed flow model using slip velocity. This scheme is shown in figure 2.4

It was observed that number of iterations increase as the difference between oil fraction and inversion point increases and maximum iteration went until 80. The varying parameter in this iteration scheme is dispersed phase fraction at the interface which is set initially at phase inversion point. So, number of iteration increase as difference between phase inversion point and oil fraction at the inlet of pipe increases. Oil fraction at the inlet of pipe is calculated by superficial velocities.

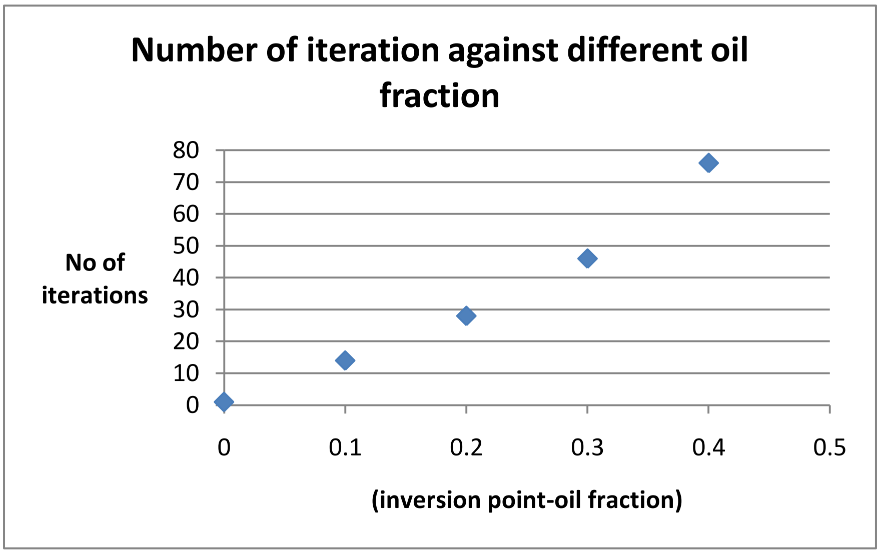


Fig. 4.8: Number of iteration against (inversion point-oil fraction)

4.1.5 Comparison of dispersed flow model using average emulsion viscosity against OLGA ponit model

The results obtained by average emulsion viscosity model are compared with OLGA point model. The OLGA over predicts the pressure drop at higher water cut probably due to wrong prediction of flow regime**.** But if the average emulsion viscosity is implemented than chances of wrong transition criteria prediction are very less. This model can also be implemented well with stratified mixed flows as shown in figures (4.1-4.3). By using this model implementation of transition criteria will be easy and it will be more reliable as this model also well predicts stratified mixed flows with higher dispersion. The wrong flow regime prediction can also overcome by using this model.

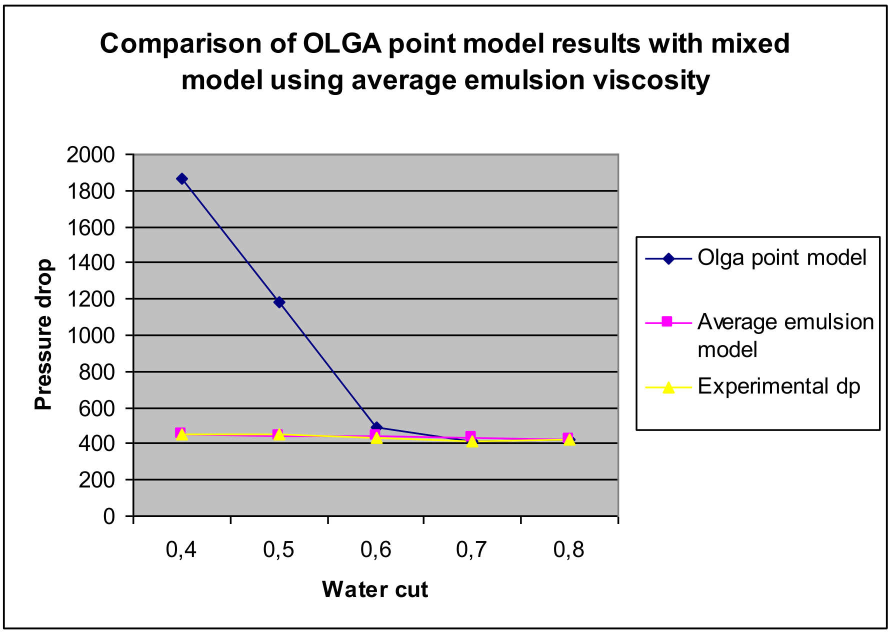


Fig.4.9 Comparison of OLGA point model pressure drop prediction against mixed model using average emulsion viscosity for Grane data with 2 m/sec velocity

4.1.6 Discussion

Excellent results are obtained by both average emulsion viscosity model and uniform emulsion viscosity model for dispersed flow oil in water experiments. However, if both these model apply to water in oil experiments, huge difference in emulsion viscosity will be observed and average emulsion viscosity will be much better than uniform emulsion viscosity. There is no data available for dispersed phase flow water in oil experiments so it was not been tested.

Even though good results obtained by both models, but model using average emulsion viscosity has an advantage over the model using uniform emulsion viscosity model. The model using average emulsion viscosity model give good results even with some stratified mixed flow experiments. If the transition criteria for stratified to disperse flow cannot judge the flow regime well this model still will be able to predict the pressure quite better than model using uniform emulsion viscosity.

This model has resemblance to the stratified flow model where entrainment is calculated by droplet diffusion model so this model can be implemented well with it.

4.2 Stratified flow model analysis

Grane data and IFE stratified data having velocity of 0.5m/sec and 1m/sec are tested with three types of models as below.

1) no dispersion
2) one way dispersion
3) Two way dispersion

All these experiments are separated flow or mixed stratified flows. Average emulsion viscosity calculated by local dispersion, Classical interfacial friction model and Churchill's wall friction model are used in the current work. Interfacial friction model with water as driving force is used. Krieger & Dougherty model is used for emulsion viscosity determination. Local velocity and local hydraulic radius is used in order to calculate eta_factor for 0.5m/sec velocity experiments. Equal sized divisions are used for diffusion droplet model.

The results obtained by implementing this model give very flat dispersed phase distribution curve. Tuning of the model carried to get good dispersion profile. The droplet diffusion model and droplet size model are not well proven and not been implemented in any oil and water system so tuning is done by changing the parameters of these two models. Droplet size calculated by current model was very high especially for 0.5m/sec experiments where it approaches to 1cm. It is reduced to half so that it does not exceed 5mm in order to keep the model more realistic. This reduction is also needed in order to tune model.

The second tunings was carried out by eta_factor for turbulent flow. The value of eta_factor reduces from 0.026 to 0.0001-0.000001 depending upon the viscosity and velocity. As the viscosity increase the eta_factor also increases starting at 0.0001 for 33 cp data and 0.000001 at 153cp. The results of all the experimental data is shown in figure below. It is observed that dispersion increases with increase of velocity.

4.2.1 Two way dispersion analysis

It was observed that two ways dispersion model is highly competitive. If dispersed water in oil increases it decreases oil in water dispersion and similar behavior observed if water in oil dispersion decreases. The analysis of two ways dispersion carried out as shown in figures (4.10-4.11). The eta factor was kept constant at 0.0005 for this analysis.

Dow = dispersed oil in water Dwo = dispersed water in oil

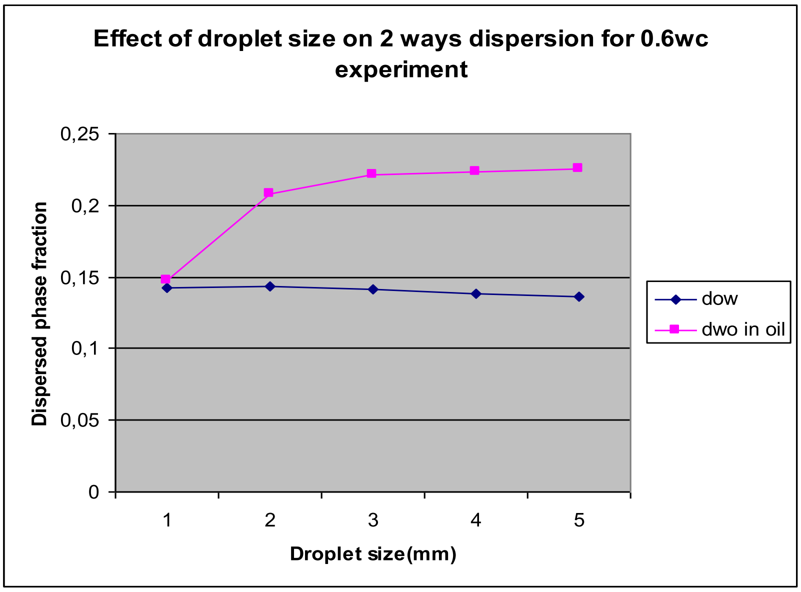


Fig. 4.10: Effect of droplet size on dispersed phase fractions using two way dispersion for experiments having 0.6 wc and 1 m/sec velocity and inversion point of 0.55 wc

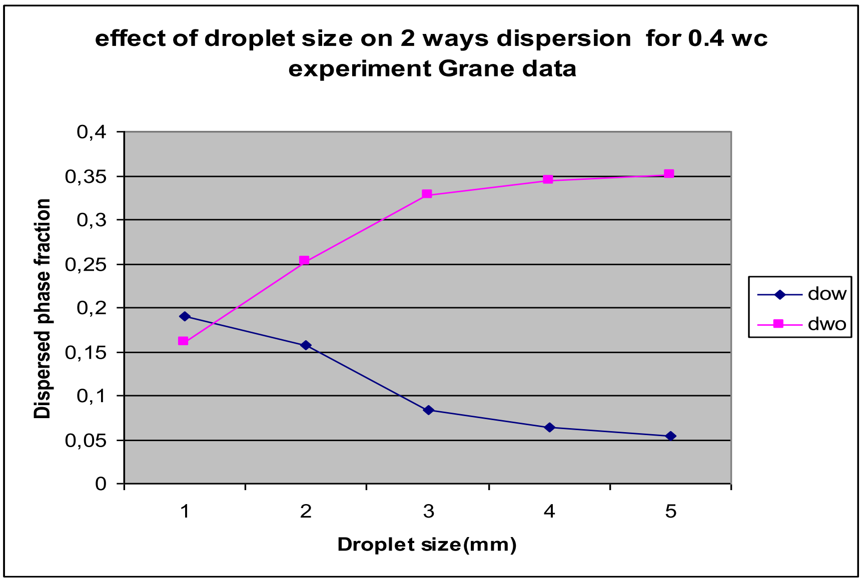


Fig. 4.11: effect of droplet size on dispersed phase fractions using two way dispersion for experiments having 0.4 wc and 1 m/sec velocity and inversion point of 0.55 wc

It is observed from the figure 4.10 that if the water cut is greater than phase inversion point the increase of droplet size increases water in oil dispersion but there will be no effect on oil in water dispersion. However, if the water cut is less than phase inversion dispersed water in oil increases with increase droplet size and oil in water dispersion decreases with same quantity. These behaviors are quite interesting and can be use to tune the droplet diffusion and droplet size model.

After fixing the droplet size to 2.5 mm the effect of eta_factor was observed on two way dispersion shown in figure 4.12. It was observed that there is almost negligible effect observed on dispersed water in oil dispersion with decrease of eta_factor. However, oil in water dispersion decreases significantly with decrease of eta_factor.

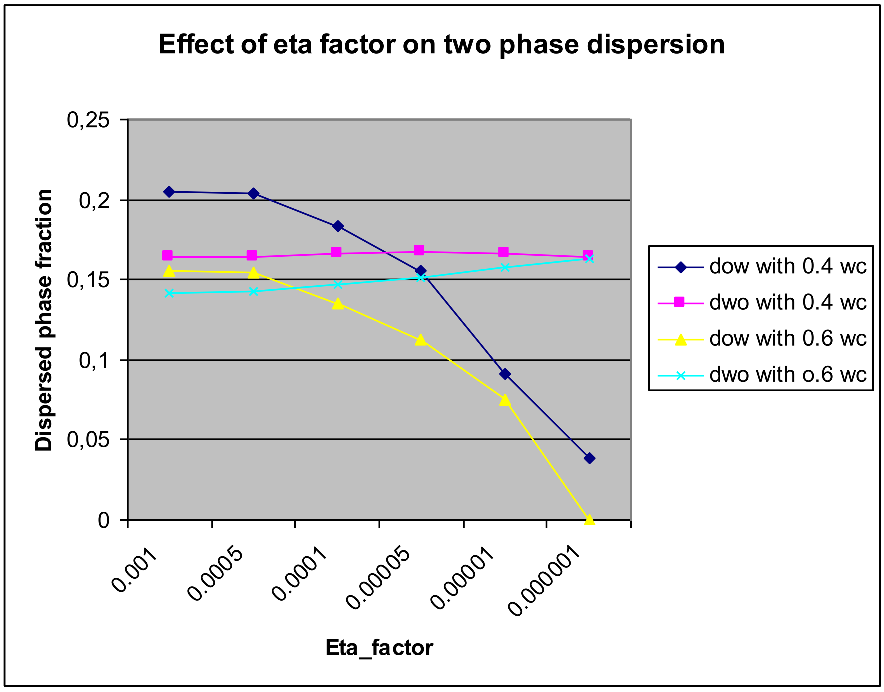


Fig. 4.12: effect of droplet size on dispersed phase fractions using two way dispersion for experiments having 0.4 wc and 1 m/sec velocity and inversion point of 0.55 wc

4.2.2 Tuning methods for stratified flow models

As we see the behavior of two way dispersion in figures (4.9-4.12) with change of eta_factor and droplet size. After analyzing the above behavior the two methods are proposed which are described below. The method-I is implemented in current work and Second method is not tested due to shortage of time.

Method I:

The following technique has been developed for tuning of stratified flow model and it is implemented in current work.

1) Tune the interfacial friction and wall friction factor well that it gives good prediction of pressure drop at 0.2-0.8 water cuts for separated flow experiments and under prediction at very high and low water cuts. This is to be done without dispersion model. This point is not done in this report.
2) Run the simulations with two way dispersion and check the droplet size. If the droplet size is too large reduce it to maximum of 5mm. Note that droplet size does not have much effect on turbulent flow.
3) Tune the model with eta_factor reduce it to different value and check the pressure drop prediction. In case of two way dispersion both phases are much interactive and this eta_factor not only effects the turbulent flow distribution, it also effects the laminar flow distribution due to interaction. The eta_factor of 0.0001 can be use as a starting point and it should decrease with increase of viscosity.

Method II

The second proposed method is given below

1) Tune the interfacial friction and wall friction factor well that it gives good prediction of pressure drop at 0.2-0.8 water cuts for separated flow experiments cut and under prediction at very high and low water cuts. This is to be done without dispersion model. This point was not done in this report.
2) Run the simulations with two way dispersion and check the eta_factor value. Decrease the eta_factor to more realistic region. It should be decrease atleast until 0.0001 factors with current interfacial friction factor. It will also get down if interfacial friction factor decrease.

3) Tune the model with droplet size reduction and checking the pressure drop prediction and comparing it with experimental results. But it is tricky to tune the model by droplet size as different behavior is observed at water cut above inversion point and below inversion point as shown in figures (4.10-4.11). The droplet size variation is more interactive in two way dispersion in comparison to eta_factor especially at water cut below inversion point.

Method-I is easy to implement as all the parameters get fixed and there is only change in dispersed oil in water friction with change of eta_factor.

4.2.3 Results of experimental data

Pressure drop, hold up prediction and entrainment is plotted below for all the experimental data are plotted below against water cut. The figures are segregated with respect to mixture velocity and oil viscosity. All figures are plotted against water cut due to different behavior observation at different water cuts.

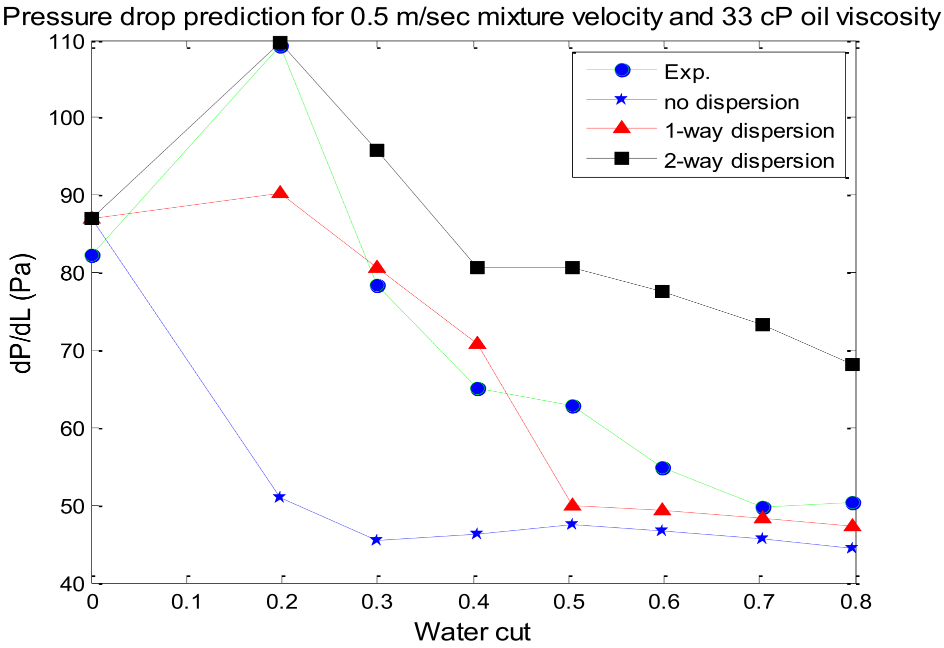


Fig. 4.13 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for Grane 0.5m/sec velocity and 33cp data

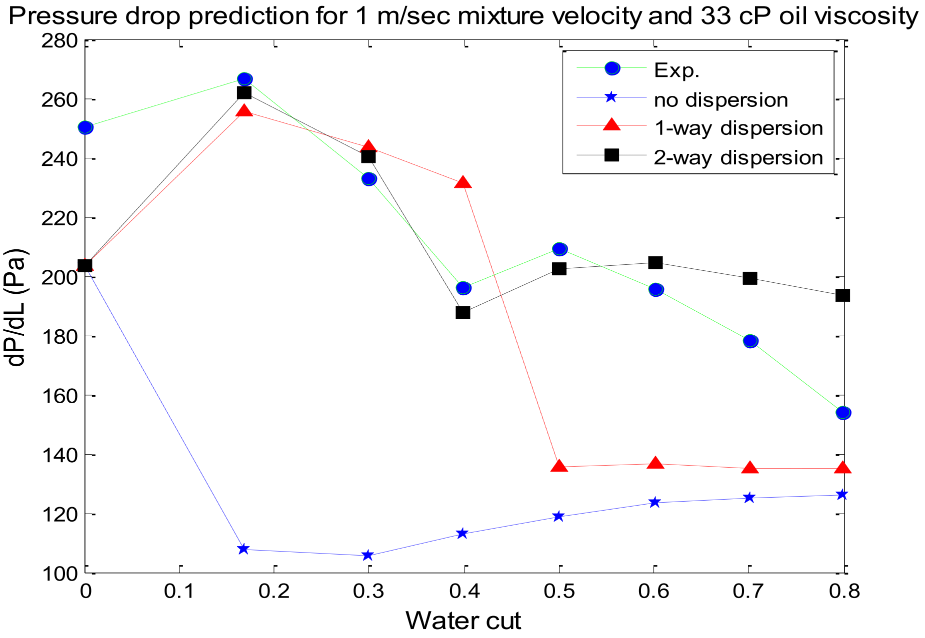


Fig. 4.14 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for Grane 1m/sec velocity and 33cp data

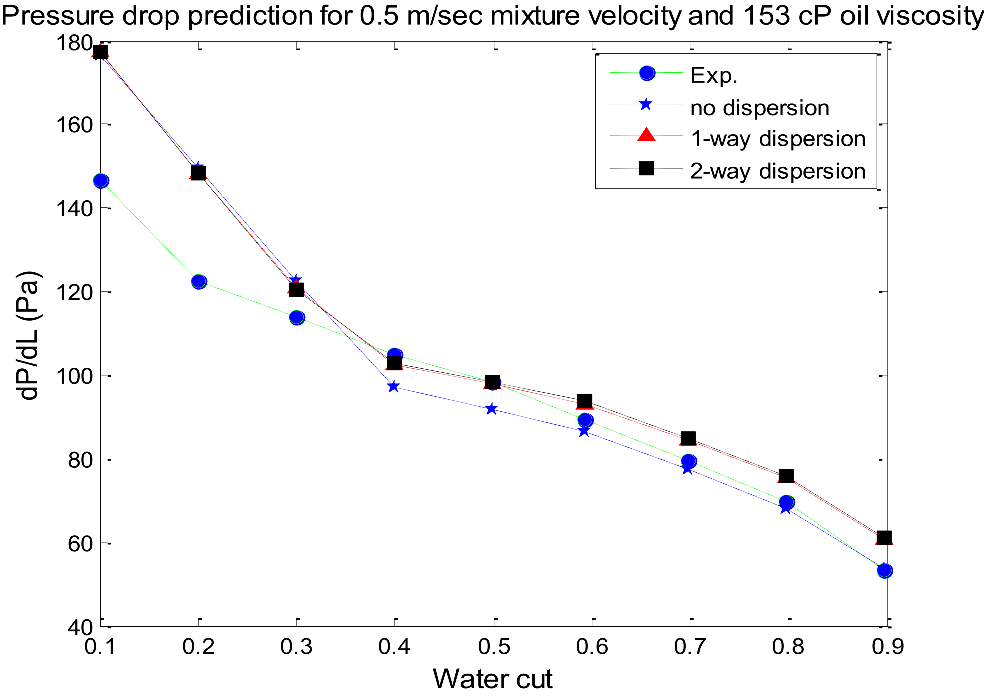


Fig. 4.15 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 0.5m/sec velocity and 153cp data

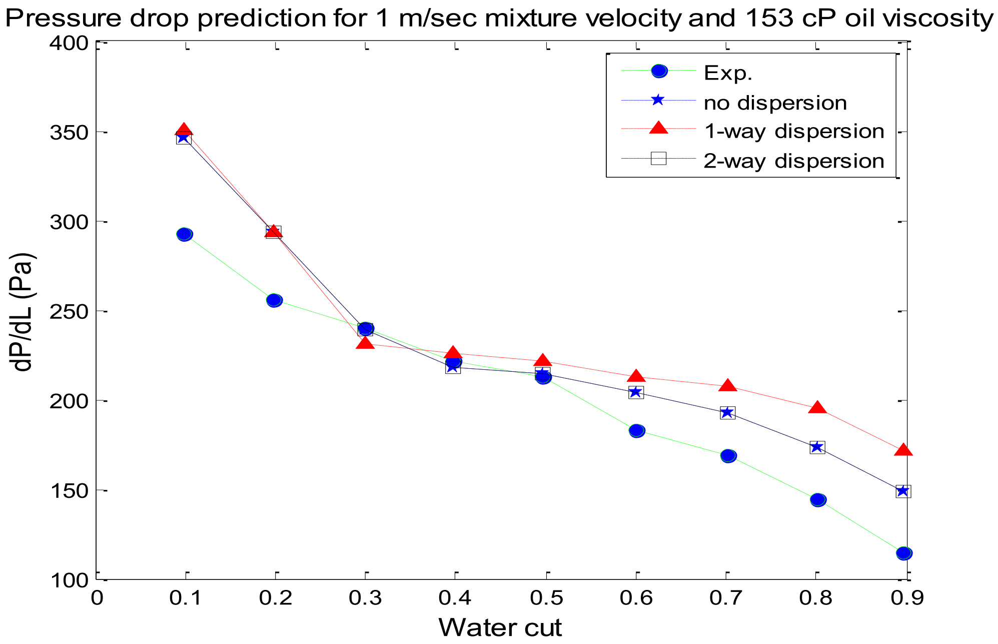


Fig. 4.16 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 1m/sec velocity and 153cp data

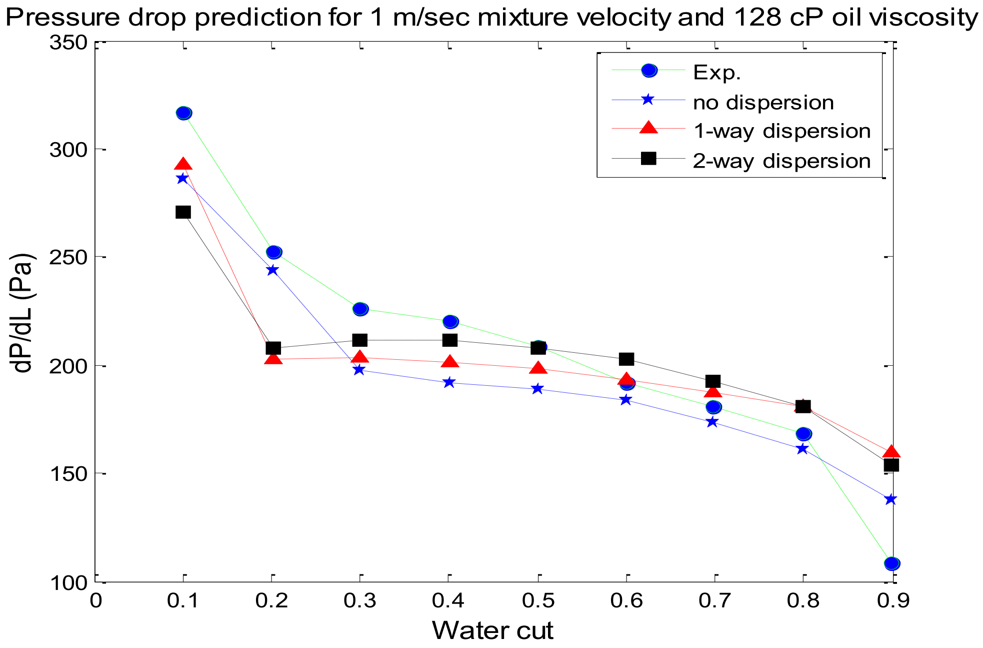


Fig. 4.17 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 1m/sec velocity and 128cp data

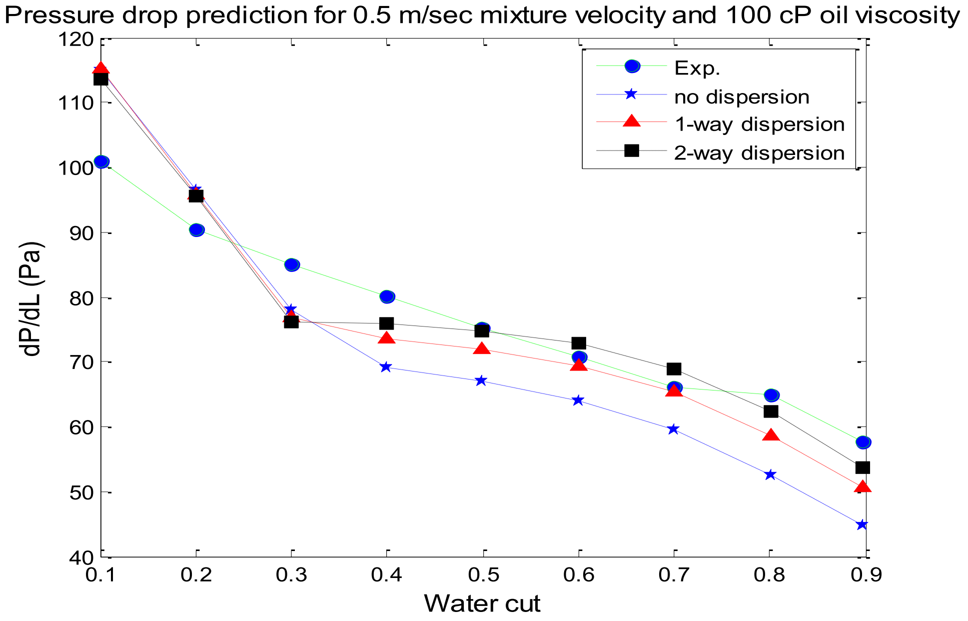


Fig. 4.18 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 0.5m/sec velocity and 100cp data

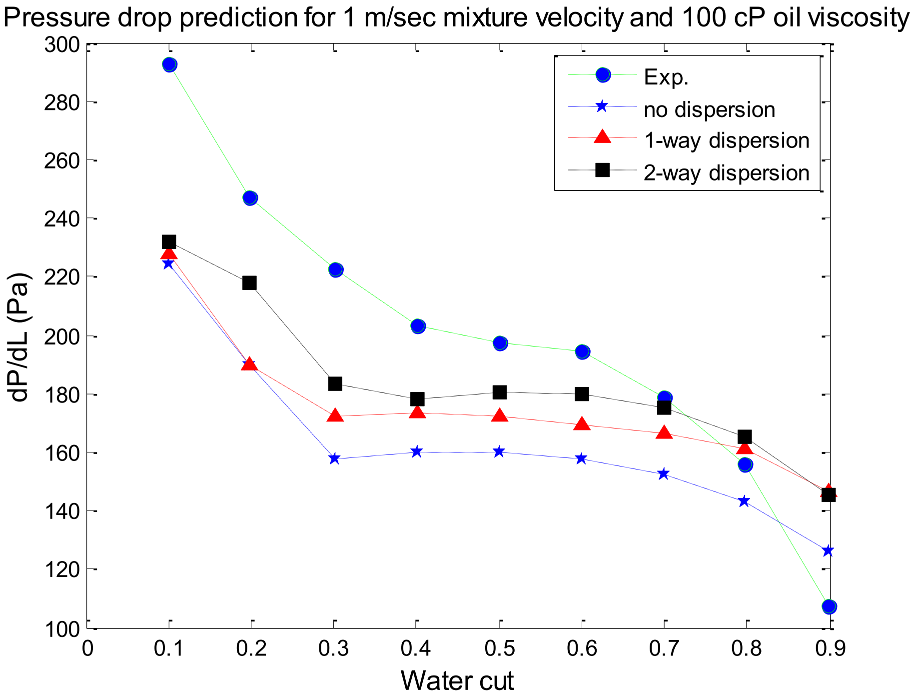


Fig. 4.19 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 1m/sec velocity and 100cp data

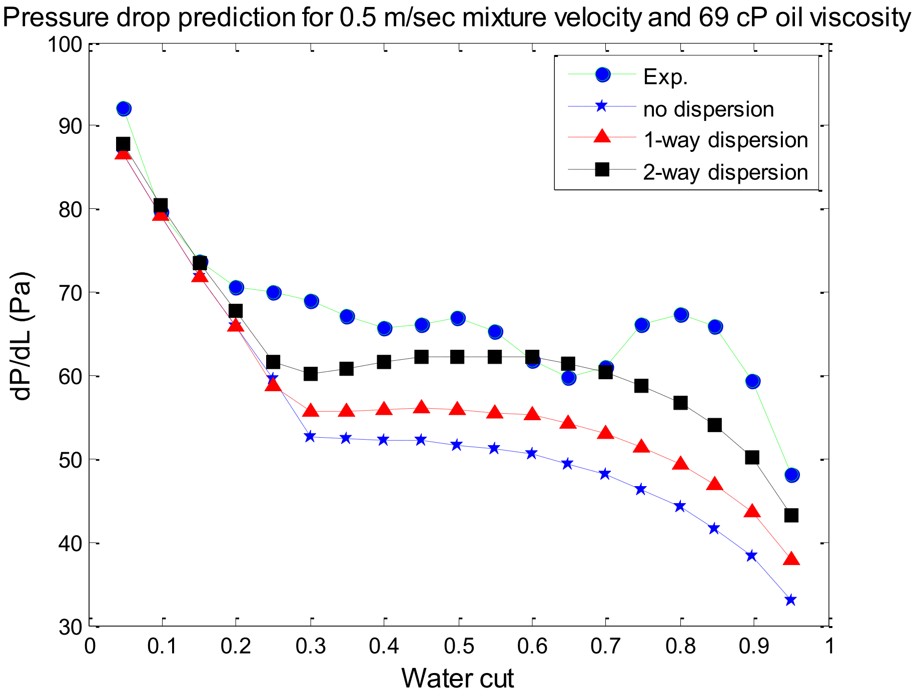


Fig. 4.20 comparison of pressure drop prediction by using no dispersion, one way dispersion and two way dispersion model against experimental results for IFE 0.5m/sec velocity and 69cp data

4.2.4 Discussion

It is quite clear from the figures (4.13-4.20) that two ways dispersion gives much better pressure drop prediction in comparison to without dispersion and one way dispersion model.

The no way dispersion model under predicts the pressure drop at water cut above the inversion point, this under prediction decreases with increase of viscosity and it matches with experimental data for 153cp experiments. At higher water cut there will be some dispersion of oil in water so pressure drop prediction should be bit higher at higher water cuts when using model without dispersion. The model gives peak in pressure drop at lower water cut this is probably due to higher interfacial friction factor. This means that interfacial friction factor model works better when the water cut is in range between 0.2-0.8. The peak at water cut below 0.3 is actually observed due to sharp increase in ratio of wetted perimeter to hydraulic radius when the water cut is lowered below 0.3 water cut this is shown in figure 4.21.

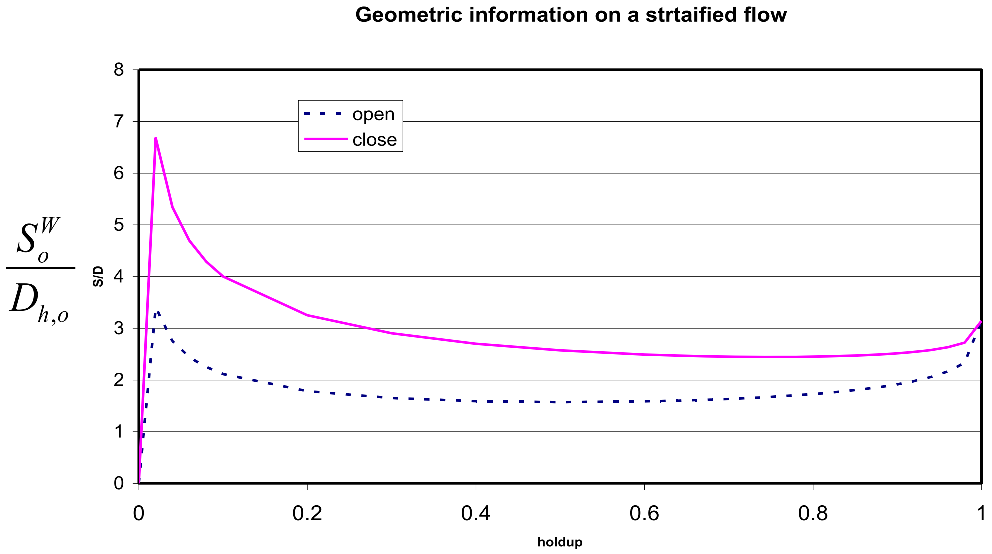


Fig.4.21 Plot of water holdup against wetted perimeter to hydraulic radius ratio of oil

Where, S_o = oil wetted perimeter, $D_{h,o}$= oil layer dyraulic radius

The same behavior is observed with 1m/sec data but the pressure drop is under predicted at all water cuts. All the experiments at 1m/sec have dispersion so the pressure drop will increase when dispersion will incorporate.

Overall stratified flow model without dispersion gives better results for the experiments without dispersion. But it should under predict the pressure drop at lower water cut and over predict the pressure drop at higher water cut because there will be water in oil dispersion at low water cut and oil in water dispersion at higher water cut. The water in oil dispersion will increase the pressure drop at low water cuts and oil In water dispersion should decrease the pressure drop at high water cuts which is expected to be observed in one way and two way dispersion model.

One way dispersion model gives better prediction than no dispersion but it still under predicts if it is compared to two ways dispersion model. There is increase of pressure drop observed at higher water instead of decreasing but there was no data point's available with water cut higher than 0.8. In the water cut region between 0.2-0.8 there is oil in water dispersion and it increased the pressure drop as shown in all the experiments. But in case of lower water cut it works according to expectations and there is dispersion of water in oil which increases pressure drop.

Two ways dispersion model gives much better results than without dispersion and one way dispersion for all the experiments. It gives good prediction of pressure drop for most of the experiments except at very low water cut. This error is probably due to high interfacial friction factor or high wetted perimeter to hydraulic diameter ratio which is shown in figure 4.21. The second factor for error at high water cut suspected to be due to low oil in water dispersion as expected. The entrainment calculated by simulations is shown in figures in appendix B. There is more water in oil dispersion even at higher water cuts but note that no data point was available for water cut greater than 0.8. With this interfacial factor this tunning works well and gave good pressure drop prediction at higher at water cuts greater than 0.2. At lower water cut the problem is high wetted perimeter.

eta_factor is used as tuning parameter. The eta_factor depends upon the velocity and friction factor as shown in equation 2.16. This friction factor is function of inter facial friction and wall friction as shown in equation 2.17. If this friction factor does not predict well it will increase the velocity factor and ultimately eta_factor increases. This eta_factor is used is tuning parameter. So in order to overcome this error, inter facial friction factor should be predicted well in order to make better tuning by eta_factor and droplet size. In this report interfacial friction and wall friction analysis has not been carried out.

The above technique of improving the model works quite well if the holdup predictions are better but this model under predicts the hold up as shown in appendix A. This means that water layer is moving very fast in comparison to oil layer. Possible reason for water hold up under prediction is seems to be due to non slip velocity between oil droplet and continuous layer. This problem can be overcome by increasing interfacial friction factor which will slow down the water movement and water hold up will increase. This will cause more entrainment and increases pressure drop prediction at low water cut. But it will reduce the pressure drop predictions at high water cut. Pressure drop prediction can be tuned for water cut below 0.7 but for lower water cut different technique can be implemented.

In case of dispersed phase flow analysis the dispersed phase fraction at the interface was varied a bit as the water cut changes which reduced the more flat behavior of the curve. This technique can also be use in stratified flow systems.

Conclusion

Understanding of the dispersed phase flow models and stratified flow models have been carried out which are written in FORTRAN. The connection between MATLAB and FORTRAN carried out for getting all the needed outputs and made the program more users friendly. New model and its code in FORTRAN have been developed for dispersed flow and stratified flow using average emulsion viscosity. So average emulsion viscosity is implemented which give better results than uniform viscosity.

The droplet diffusion model and droplet size models are not much developed yet. Therefore, sensitivity analysis of droplet size closure model and droplet diffusion model carried out. It was observed that droplet let size is much sensitive to pipe diameter and phase velocity. The droplet diffusion model depends upon many parameters. The main parameters which effect the distribution are droplet size, eta_factor, n-factor and velocity. The dispersed water in oil flow experiments having laminar flow behaves differently than dispersed oil in water flow experiments. The parametric study of both models carried out for both laminar and turbulent flow. The local and uniform velocity model was analyzed and it was observed that local model gives better result but it’s difficult to converge at higher velocities and when numbers of divisions are unequal. The local model implemented well for 0.5m/sec data.

The dispersed flow model with averge emulsion viscosity is tested by selecting set of oil water mixed flow experiments having 2m/sec velocity and water cut is in 0.5-0.8 range. The dispersed phase fractional distribution was available for the selected experiments which were measured with traverse gamma. The model gave huge mismatch between simulated and experimental dispersed phase fraction distribution profile. The model is tuned by reducing eta_factor value to 0.001. After tuning all the four experiments exact distribution profile is obtained which matches experimental profile. This model works well even for stratified mixed flows so by implementing this model wrong prediction of flow regime can be avoided. This model can also use to find transition criteria between stratified and mixed flow model.

The stratified flow model has been tested with no dispersion, one way dispersion and by two way dispersion. IFE and Grane data having 0.5m/sec and 1 m/sec velocity and 0.1-0.9 water cut are tested by this model. The two way stratified dispersion model is highly interactive therefore sensitive analysis carried out and quite interesting profiles are obtained. Based on these profiles two methods for tuning of stratified flow models are proposed in order to check the undeveloped physical closure models i.e. droplet diffusion model and droplet size model.

The tuning of the stratified flow model is carried out by method-I and perfect results are obtained. The eta_factor is reduced from 0.0001 to 0.000001. Among the three models, two ways dispersion model gave the best results for pressure drop prediction except at low water cut where the pressure drop is over predicted due to high wetted perimeter/friction.

Due to a complex coupling between the wall and the interfacial shear stresses, droplet size and droplet diffusion, there is a need to have much more experimental work and study is to be carried out.

Future work

A lot of work is still remaining in order to implement this model in more robust and efficient way. The first work is to implement the correct interfacial friction factor after finding the correct interfacial friction. For tuning of model a good physical model for droplet size is needed for better prediction of droplet size. The work did in this report will help a lot in parametric study and tuning of the model can be done by the above mentioned methods.

The second challenge is to find the exact transition criteria for stratified to disperse flow. In this regard sensitivity analysis of distribution profile by velocity and Grane data analysis can give a lot of information. Dispersed phase model developed in this report should be checked with water in oil experiments in order to implement that model.

References:

[1] Ove Bratland; Pipe flow 2: multiphase flow assurance; 2010; pp 3-5.

[2] Rijender Pal; Novel method to correlate emulsion viscosity data; physicochemical and engineering aspects 137(1998) 275-286

[3] James P.Brill; Modeling multiphase flow in pipes; Thewayahead; Vol. 6; 2010

[4] Kumara, Halvorsen, B.M. & Melaaen,M.C.; Pressure drop, flow pattern and local water Volume fraction measurements of oil-water flow in pipes; Thesis; Telemark University College Porsgrunn, Norway.

[5] Neima Brauner; Liquid-liquid two phase systems; PHD Thesis; Tel Aviv University Israel.

[6] Johann Sjoblom; Emulsion and emulsion stability; 2nd ed.; Taylor and Francis group; 2006; pp 3,185

[7] Hans, P.R; Correlations for predicting Viscosity of W/O Emulsions based on North Sea Crude Oils; SPE 28968; 1995

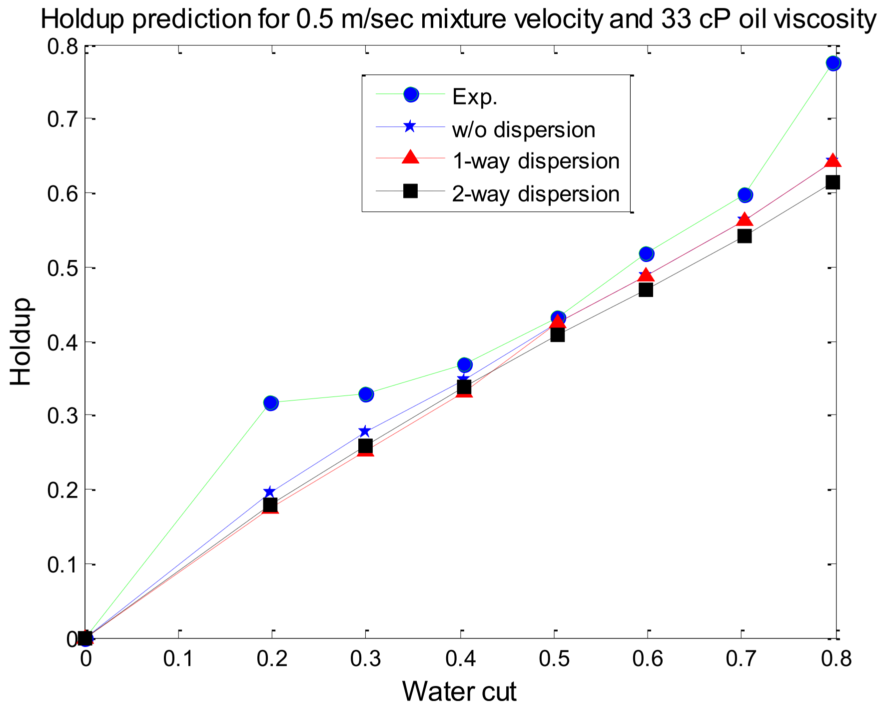
[8] A.N. Ilia Anisa, and Abdurahman H.Nour; Affect of Viscosity and Droplet Diameter on water-in-oil (w/o) Emulsions: An Experimental Study; World Academy of Science, Engineering and Technology 62; 2010

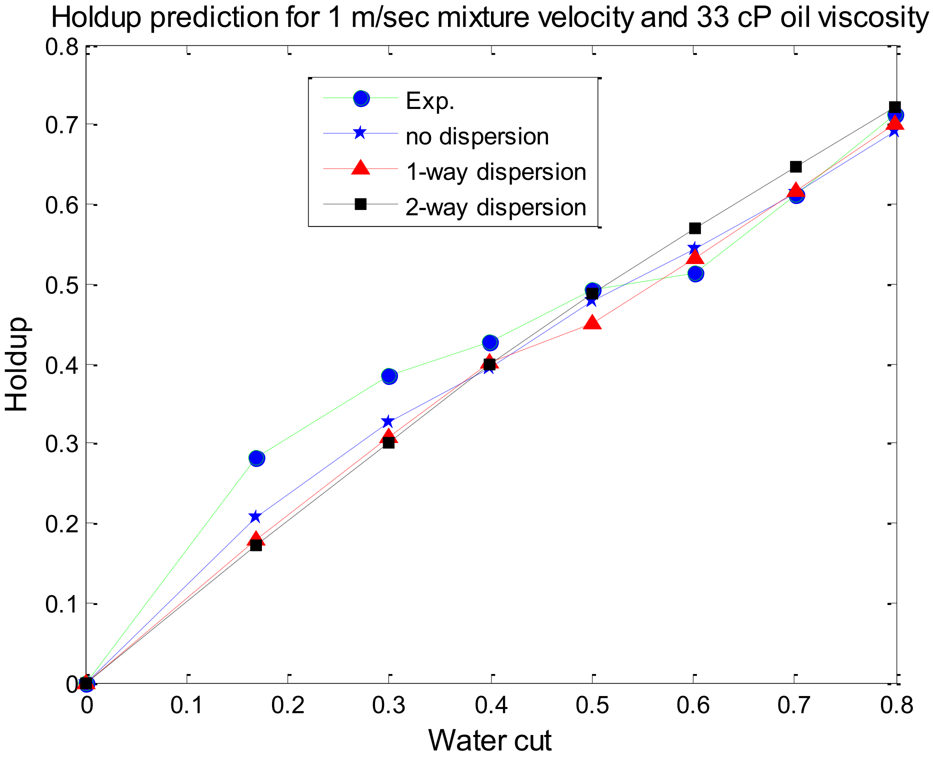
[9] Zhilin Yang; Physical models for viscous oil water flow; Zhilin Yang; Statoil report; 2010

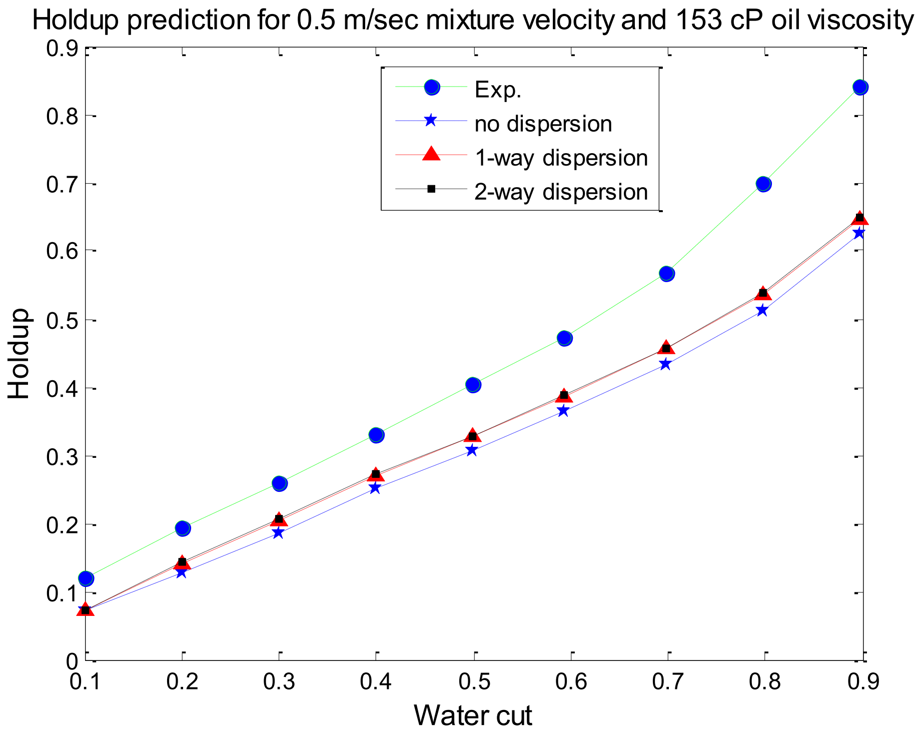
[10] Asal Amiri; Cross sectional model for determining rheology in settling slurries: Effect of solvent, particle size and density; PHD thesis; NTNU, Trondheim Norway; 2010

[11] Juse Luis Trallero; Oil water flow patterns in horizontal pipes; Phd thesis; The University Of Tulsa; 1995

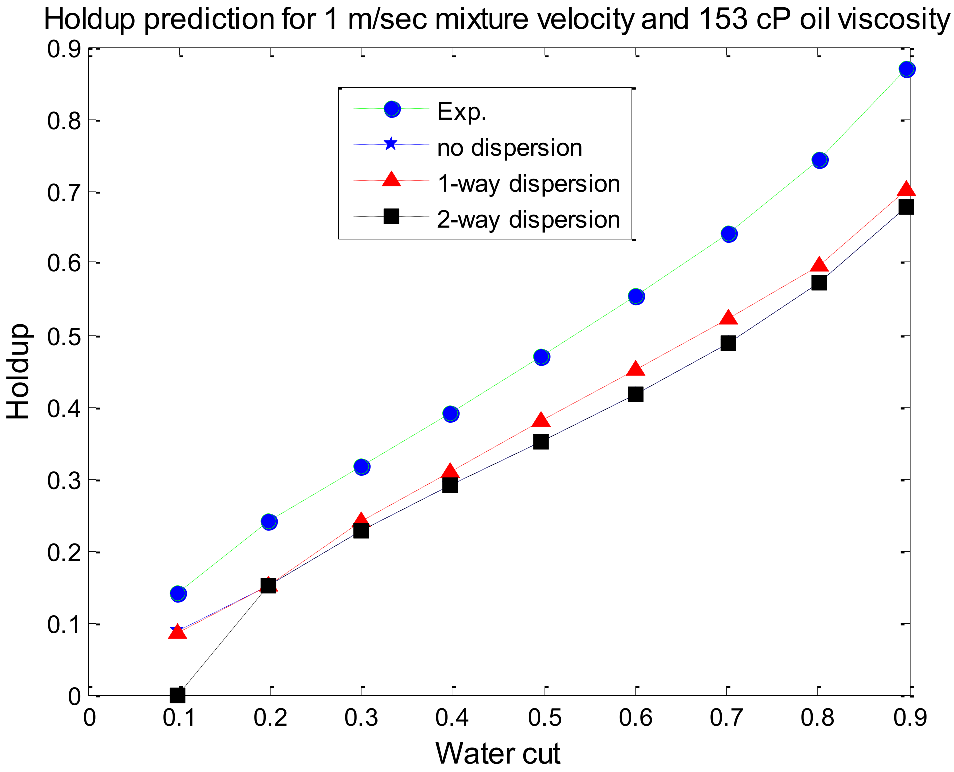
APPENDIX A: Water holdup figures for stratified flow



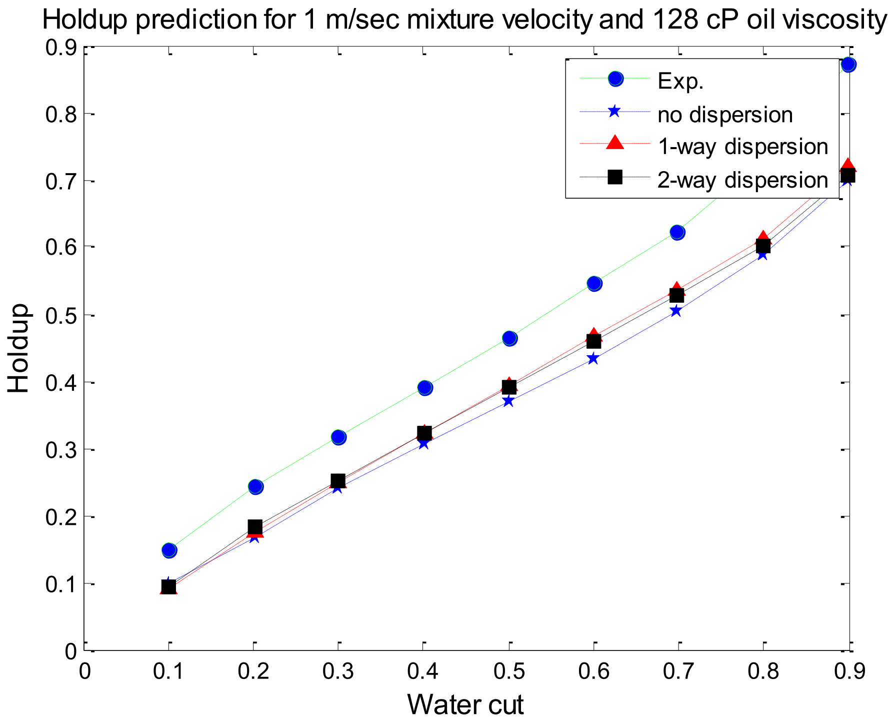


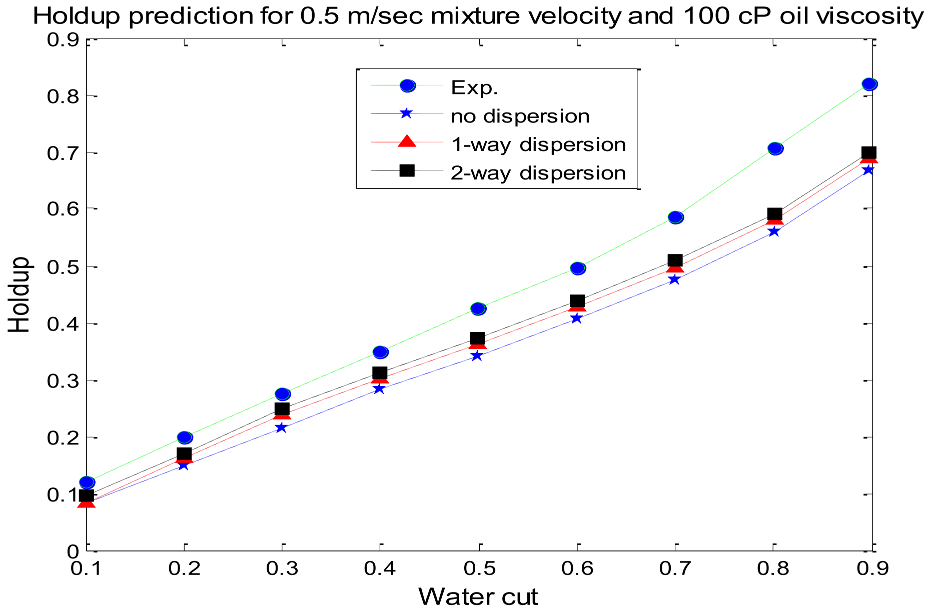


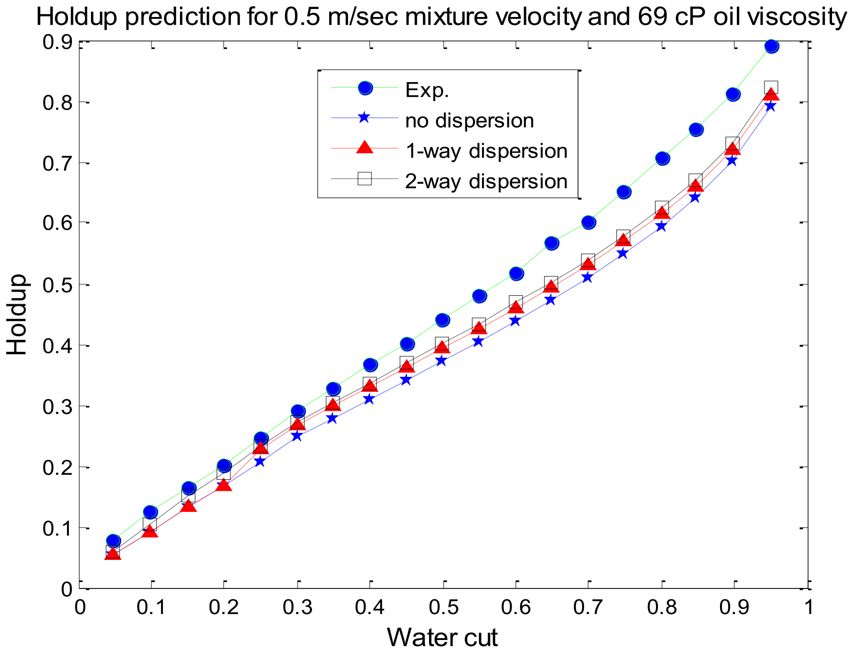
Holdup prediction for 0.5 m/sec mixture velocity and 153 cP oil viscosity

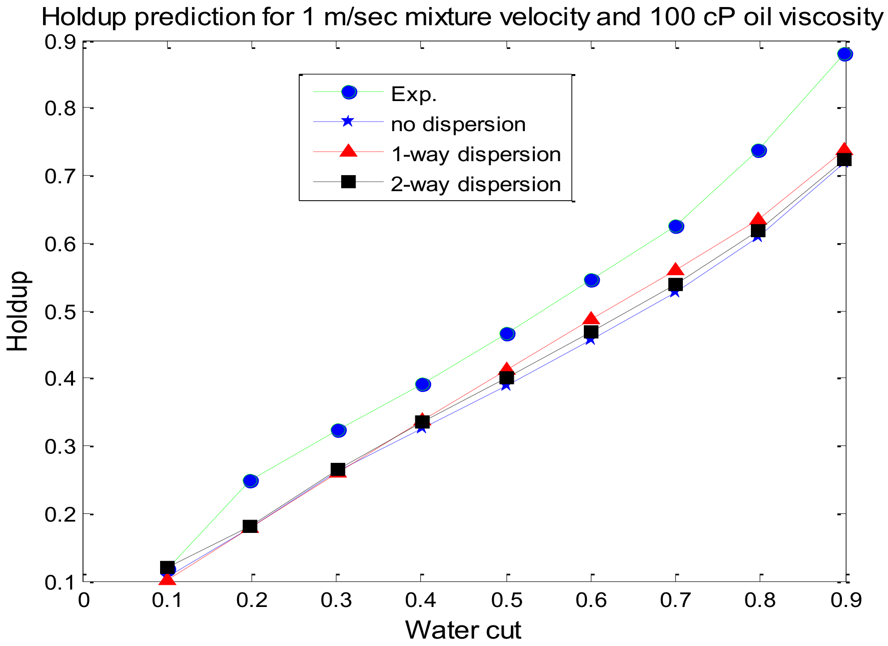


Holdup prediction for 1 m/sec mixture velocity and 153 cP oil viscosity

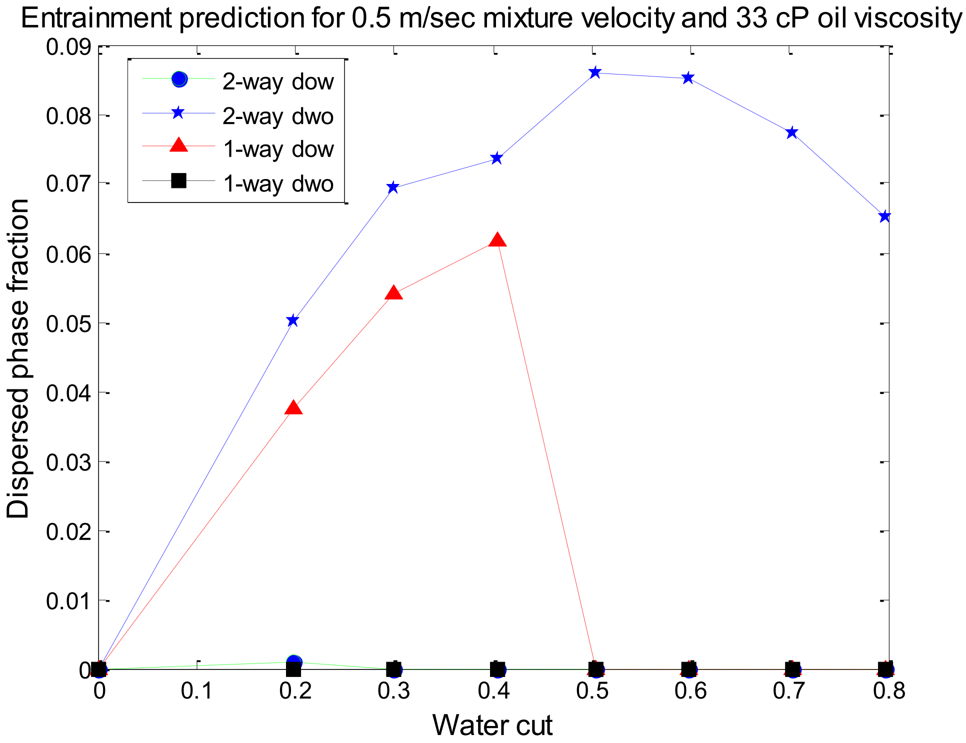

Holdup prediction for 1 m/sec mixture velocity and 128 cP oil viscosity
Holdup
Water cut
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Exp.
no dispersion
1-way dispersion
2-way dispersion

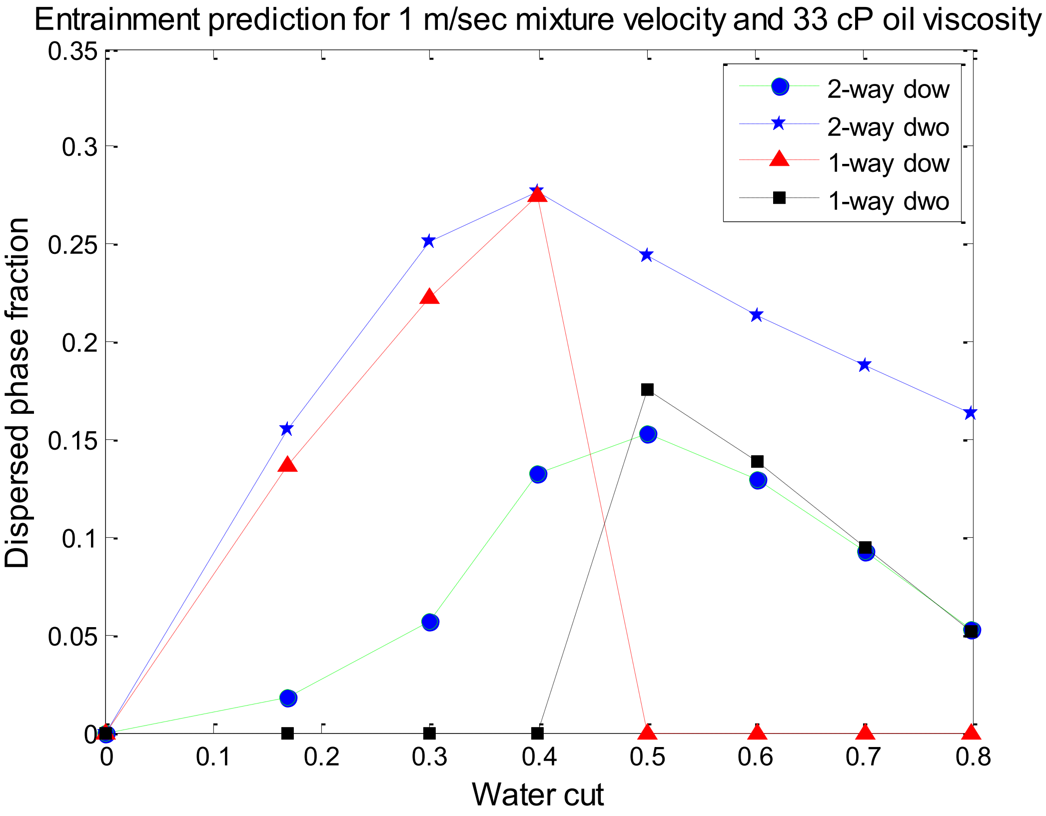

Holdup prediction for 0.5 m/sec mixture velocity and 100 cP oil viscosity
Holdup
Water cut
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Exp.
no dispersion
1-way dispersion
2-way dispersion

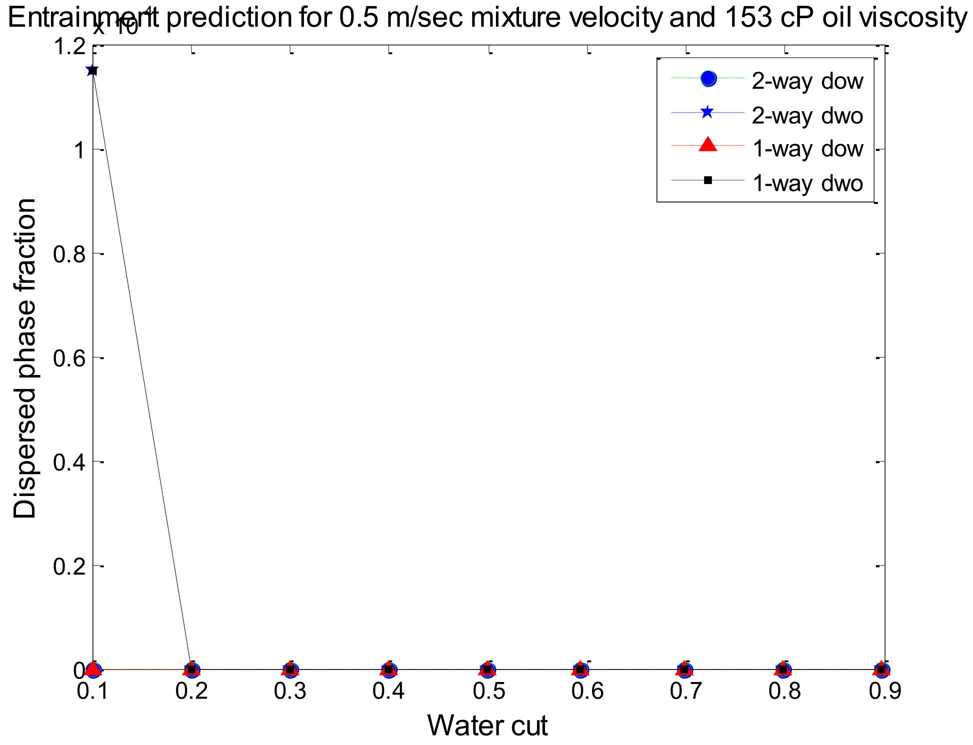

Holdup prediction for 0.5 m/sec mixture velocity and 69 cP oil viscosity
Exp.
no dispersion
1-way dispersion
2-way dispersion
Holdup
Water cut
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

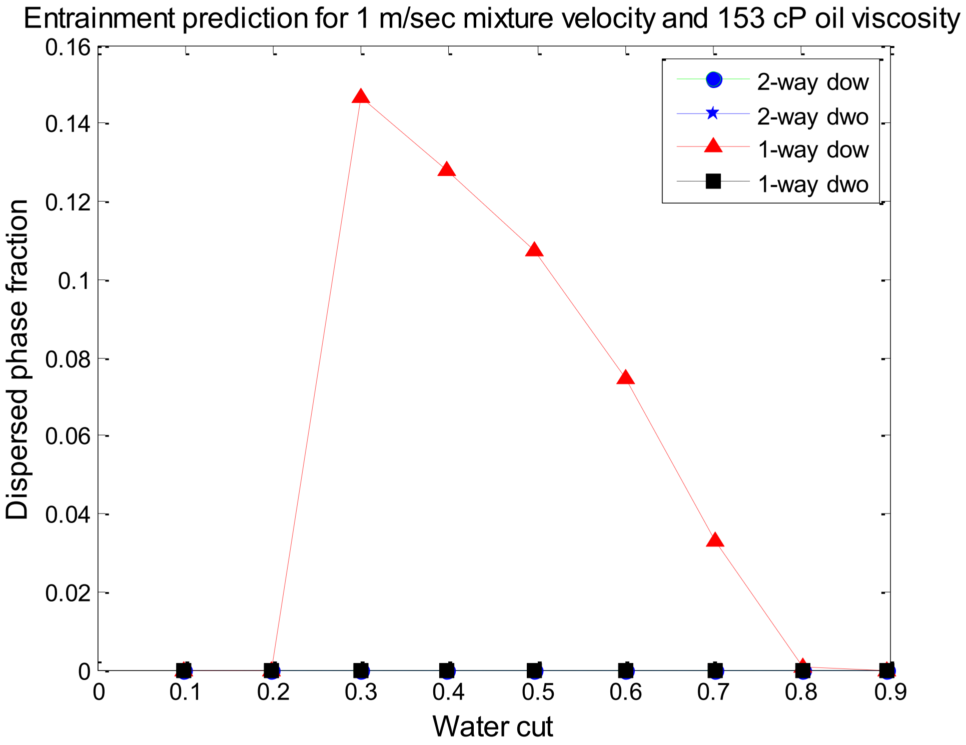

Holdup prediction for 1 m/sec mixture velocity and 100 cP oil viscosity
Exp.
no dispersion
1-way dispersion
2-way dispersion
Holdup
Water cut
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

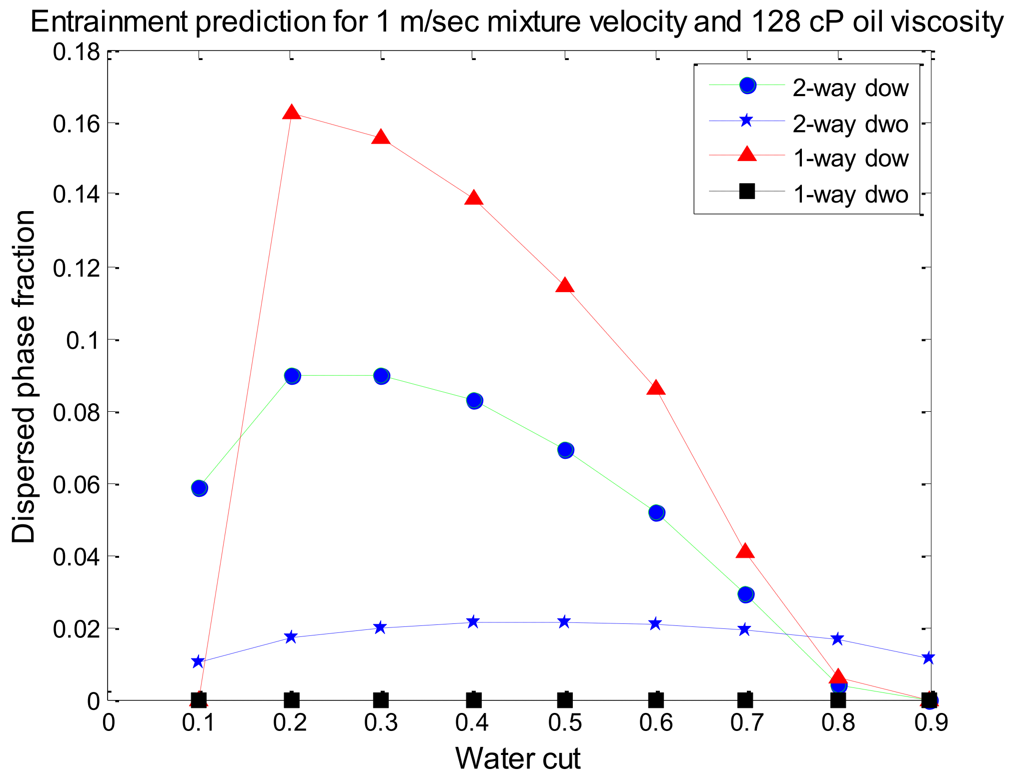
Appendix B: Figures for entrainment

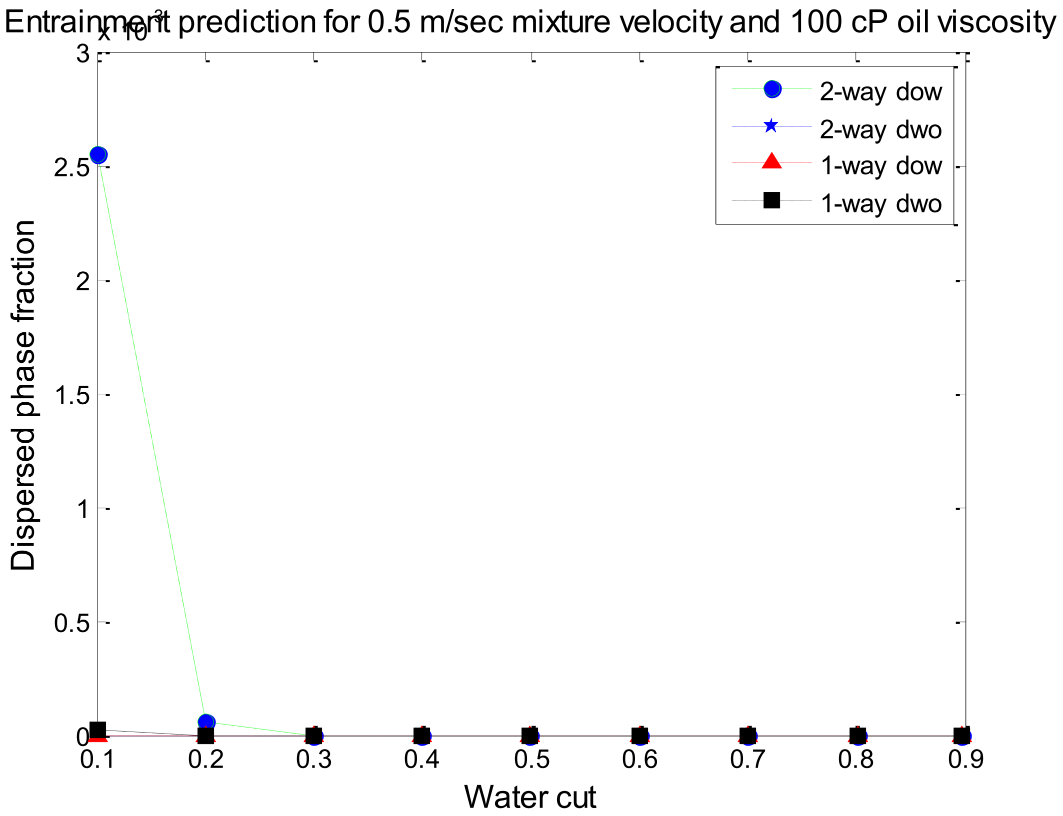


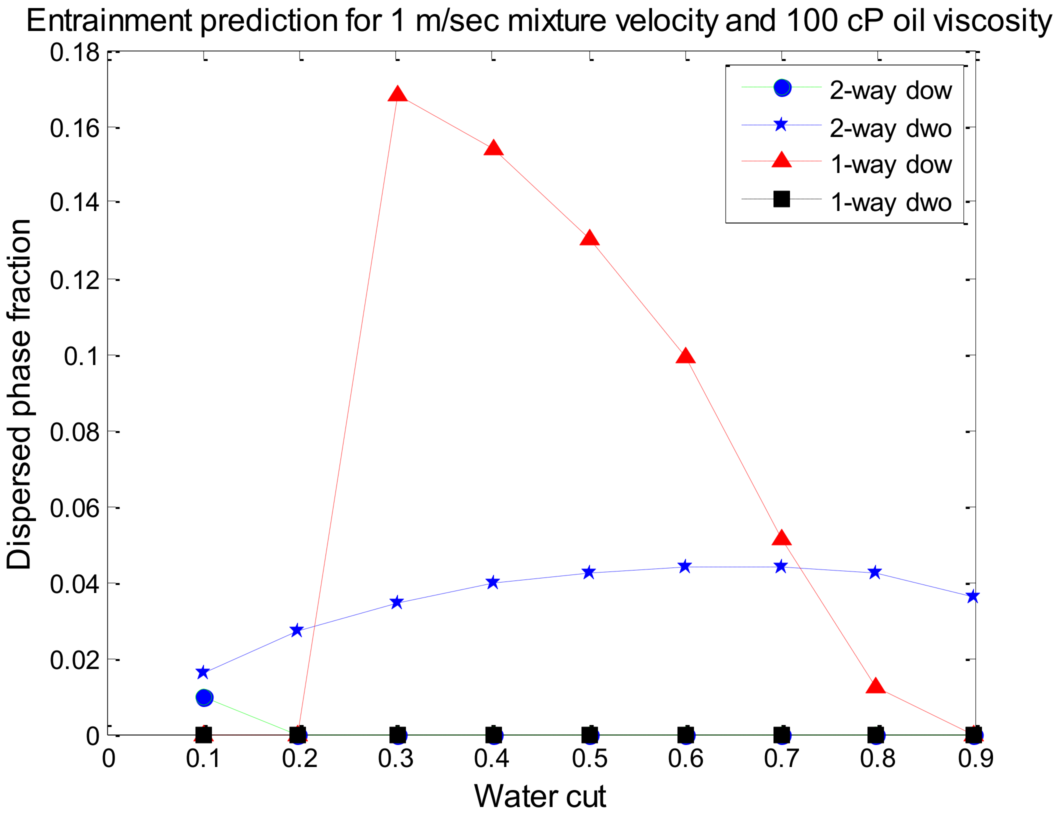


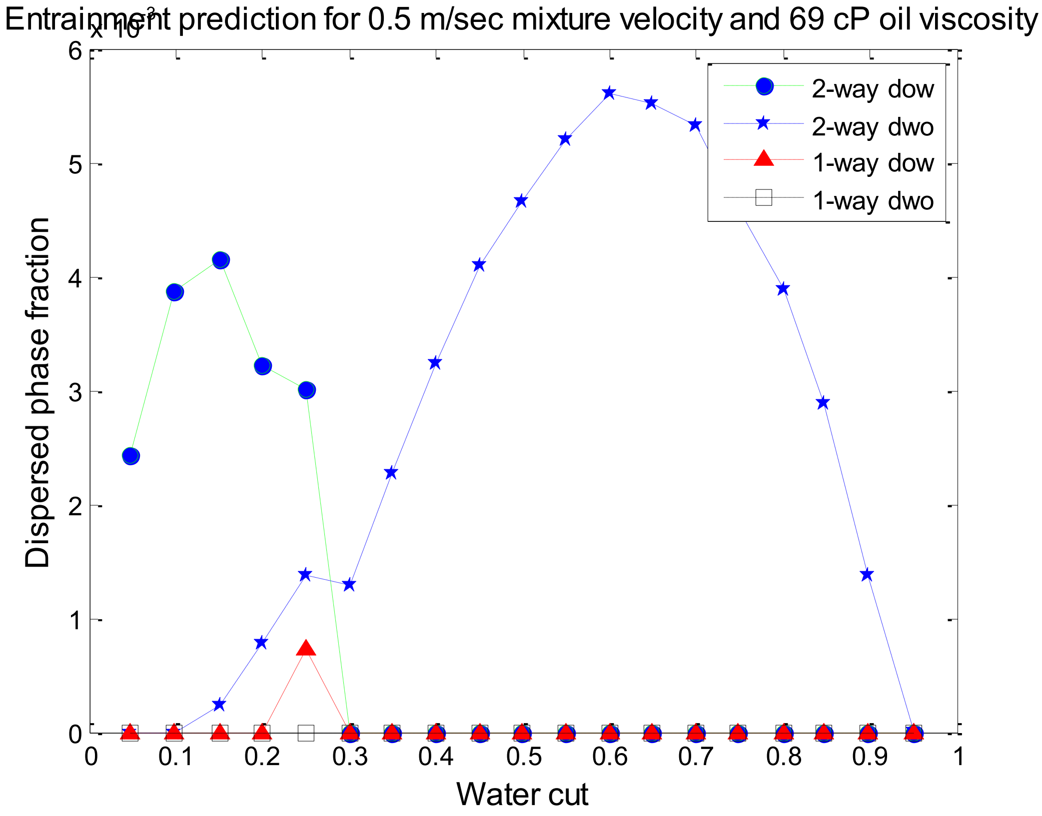

Entrainment prediction for 0.5 m/sec mixture velocity and 153 cP oil viscosity
x 10^-4
Dispersed phase fraction
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Water cut
2-way dow
2-way dwo
1-way dow
1-way dwo


Entrainment prediction for 1 m/sec mixture velocity and 153 cP oil viscosity
Dispersed phase fraction
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Water cut
2-way dow
2-way dwo
1-way dow
1-way dwo


Entrainment prediction for 1 m/sec mixture velocity and 128 cP oil viscosity
Dispersed phase fraction
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Water cut
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
2-way dow
2-way dwo
1-way dow
1-way dwo


Entrainment prediction for 0.5 m/sec mixture velocity and 100 cP oil viscosity
x 10^-3
Dispersed phase fraction
3
2.5
2
1.5
1
0.5
0
Water cut
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
2-way dow
2-way dwo
1-way dow
1-way dwo


Entrainment prediction for 1 m/sec mixture velocity and 100 cP oil viscosity
Dispersed phase fraction
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Water cut
● 2-way dow
★ 2-way dwo
▲ 1-way dow
■ 1-way dwo


Entrainment prediction for 0.5 m/sec mixture velocity and 69 cP oil viscosity
x 10^{-3}
Dispersed phase fraction
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water cut
● 2-way dow
★ 2-way dwo
▲ 1-way dow
□ 1-way dwo

APPENDIX C : MATLAB SCRIPT

```
%PointModelVector = {'Olga4.16' 'Olga5.3' 'Olga6.2' };
clc;
clear all;
PointModelVector = {'statoil'};
for ipointmodel = 1:length(PointModelVector)
    PointModelName = char(PointModelVector(ipointmodel));
    switch PointModelName

         case 'statoil'
            ExcelFileForResults   = 'stratfinal.xls';


    end

 Experiments = {'datasheet'} ;

 Code = char(Experiments);
DataBankPath = 'C:\Users\Ahsan Nazir\Desktop\thesis18thjune\dispersed1\stratfinal.xls';
OutputPath = 'C:\Users\Ahsan Nazir\Desktop\thesis18thjune\dispersed1\';
DatabankName = 'stratfinal.xls';


Nu_of_Experiments = length(Experiments);
Rowcounter = 63;
dummy =cell(100,100);
xlswrite([OutputPath ExcelFileForResults],dummy,1,'T63:EA143') ;

clear dummy;

%for i1 = 1:Nu_of_Experiments

 %  i2 = 1;
   DataBankParameters = struct('No_of_rows',1,'Sheet',1,'Sheetrange','A:B');
    DataBankGroups = struct('Index',[1:2]);

            DataBankParameters.No_of_rows = 81;
            DataBankParameters.Sheet = 1;
            DataBankParameters.Sheetrange = 'B63:R143';


            DataBankGroups.Index = [1:81];
```

```
   %[ExperimentalData,DatabankParameters,DatabankGroups] =
Read_Data1(Code,DatabankPath);
    %DatabankParameters.No_of_groups;
   ExcelSheetRowVector = DataBankGroups.Index;
   Number_of_elements_in_group = length(ExcelSheetRowVector) ;

 %
    [g,h] =
xlsread(DataBankPath,DataBankParameters.Sheet,DataBankParameters.Sheetrange);

   for i3 = 1:Number_of_elements_in_group


        ExperimentalData(i3).hol  = g(i3,17);
        ExperimentalData(i3).dpl  = g(i3,1);
        ExperimentalData(i3).Ugs  = g(i3,5);
        ExperimentalData(i3).Uos = g(i3,6);
        ExperimentalData(i3).Uws = g(i3,7);
        ExperimentalData(i3).Rhog = g(i3,8);
        ExperimentalData(i3).Rhoo = g(i3,9);
        ExperimentalData(i3).Rhow = g(i3,10);
        ExperimentalData(i3).Visg = g(i3,11);
        ExperimentalData(i3).Viso = g(i3,12);
        ExperimentalData(i3).Visw = g(i3,13);
        ExperimentalData(i3).Sigg = g(i3,14);
        ExperimentalData(i3).Sigo = g(i3,15);
        ExperimentalData(i3).Sigw = g(i3,16);
        ExperimentalData(i3).Diam = g(i3,2);
        ExperimentalData(i3).Angle = g(i3,4);
        ExperimentalData(i3).Roughness = g(i3,3);

            ExperimentalInputData =
ExperimentalData(ExcelSheetRowVector(i3));

                    switch PointModelName

                        case 'statoil'

[alpha,Re,Su_wfrict,info,RegimeID,dpdx,CPEQO,HHLO,CPEQW,HHLW, diamhydro,
concdiff, visceff] =
statoil_6_2(ExperimentalInputData,Rowcounter,OutputPath,ExcelFileForResults);
                            %[alpha,Re,Su_wfrict,info,Regimeid,dpdx] =
statoil_6_2(ExperimentalInputData,Rowcounter,OutputPath,ExcelFileForResults);
                        otherwise
                    end

                    xlsrange = ['S' int2str(Rowcounter) ':DZ'
int2str(Rowcounter)];
                    clear ResultsVector
                    ResultsVector = {alpha(1) alpha(2) alpha(3) alpha(4)
alpha(5) alpha(6) alpha(7) alpha(8) alpha(9)...
                                     Re(1) Re(2) Re(3) Su_wfrict(1)
Su_wfrict(2) Su_wfrict(3)...
```

```
                                    info RegimeID(1) RegimeID(2) dpdx
CPEQO(1) CPEQO(2) CPEQO(3) CPEQO(4) CPEQO(5) CPEQO(6) CPEQO(7) CPEQO(8)
CPEQO(9) CPEQO(10) CPEQO(11) CPEQO(12) CPEQO(13) CPEQO(14) CPEQO(15)...
                                    CPEQO(16) CPEQO(17) CPEQO(18) CPEQO(19)
CPEQO(20) HHLO(1) HHLO(2) HHLO(3) HHLO(4) HHLO(5) HHLO(6) HHLO(7) HHLO(8)
HHLO(9) HHLO(10)...
                                    HHLO(11) HHLO(12) HHLO(13) HHLO(14)
HHLO(15) HHLO(16) HHLO(17) HHLO(18) HHLO(19) HHLO(20)...
                                    CPEQW(1) CPEQW(2) CPEQW(3) CPEQW(4)
CPEQW(5) CPEQW(6) CPEQW(7) CPEQW(8) CPEQW(9) CPEQW(10) CPEQW(11) CPEQW(12)
CPEQW(13) CPEQW(14) CPEQW(15)...
                                    CPEQW(16) CPEQW(17) CPEQW(18) CPEQW(19)
CPEQW(20)  HHLW(1) HHLW(2) HHLW(3) HHLW(4) HHLW(5) HHLW(6) HHLW(7) HHLW(8)
HHLW(9) HHLW(10)...
                                    HHLW(11) HHLW(12) HHLW(13) HHLW(14)
HHLW(15) HHLW(16) HHLW(17) HHLW(18) HHLW(19) HHLW(20) diamhydro(1)
diamhydro(2) diamhydro(3) diamhydro(4) diamhydro(5) diamhydro(6) diamhydro(7)
diamhydro(8) diamhydro(9) concdiff visceff(1) visceff(2) visceff(3)};

                     xlswrite([OutputPath
ExcelFileForResults],ResultsVector,1,xlsrange)


                     alphawater = alpha(3) + alpha(9);
                          WC = ExperimentalInputData.Uws /(
ExperimentalInputData.Uws+ExperimentalInputData.Uos);
                          figure(1);
                          set(gcf,'Position',[200 200 600
480],'Visible','ON');


                          figure(2);
                          set(gcf,'Position',[500 200 600
480],'Visible','ON');


                           figure(3);
                          set(gcf,'Position',[500 200 600
480],'Visible','ON');


                      %    figure(3);
                      %    set(gcf,'Position',[700 200 600
480],'Visible','off');



                          set(0,'CurrentFigure',1)
                          plot(ExperimentalInputData.dpl,dpdx
,'ko','MarkerSize',5);
                          hold on;

                          set(0,'CurrentFigure',3)
                          plot(WC, dpdx ,':ko','MarkerSize',5);
                          hold on;

                          set(0,'CurrentFigure',3)
```

```
                          plot(WC, ExperimentalInputData.dpl ,'--
rs','LineWidth',2,...
                          'MarkerEdgeColor','k',...
                           'MarkerFaceColor','g',...
                           'MarkerSize',10) ;

                          hold on;


                          set(0,'CurrentFigure',2)

                          plot(ExperimentalInputData.hol, alpha(9)
,'ko','MarkerSize',5);
                         hold on;

                          set(0,'CurrentFigure',2)

                          plot(ExperimentalInputData.hol, alpha(7)
,'bs','MarkerSize',5);
                          hold on;
                          set(0,'CurrentFigure',2)
                          plot(ExperimentalInputData.hol, alphawater
,'rv','MarkerSize',5);
                          hold on;



              dpdxmax1(i3) =
max(ExperimentalData(i3).hol,ExperimentalData(i3).dpl);
              dpdxmin1(i3) =
min(ExperimentalData(i3).hol,ExperimentalData(i3).dpl);

              holmax1(i3) = max(alphawater,ExperimentalData(i3).hol);
              holmin1(i3) = min(alphawater,ExperimentalData(i3).hol);

                Rowcounter = Rowcounter + 1;
   end
                         dpdxmax = max(dpdxmax1);
                         dpdxmin = min(dpdxmin1);
                         holmax = max(holmax1);
                         holmin = min(holmin1);
                       set(0,'CurrentFigure',1)
                       plot([dpdxmin dpdxmax],[dpdxmin dpdxmax],'-.b');
                       title(' experimental against simulted dp for Grane-
stratified-data without entrainment ');
                       xlabel('Experimental
dp','FontSize',9,'FontWeight','normal')
                       ylabel('Simulation dp
','FontSize',9,'FontWeight','normal')

                       set(0,'CurrentFigure',2)
                       plot([0 1],[0 1],'-.b');
                      title(' experimental against simulted holdup for Grane-
data without entrainment ');
```

```
                       xlabel('experimental
holdup','FontSize',9,'FontWeight','normal')
                       ylabel('simulation
holdup','FontSize',9,'FontWeight','normal')
                       legend('dwo','dow','Water-holdup')

                        set(0,'CurrentFigure',3)
                      % plot([0 1],[0 1],'-.b');
                      title(' Plot of water cut against pressure drop with
0.5m/sec velocity ');
                       xlabel('Water cut','FontSize',9,'FontWeight','normal')
                       ylabel('pressure
drop','FontSize',9,'FontWeight','normal')
                       legend('Two way dispersian dpdx','Experimental dpdx')
  end
```

Script-2

```
function
[alpha,Re,Su_wfrict,info,RegimeID,dpdx,CPEQO,HHLO,CPEQW,HHLW,diamhydro,concdi
ff,visceff] =
statoil_6_2(ExperimentalInputData,Rowcounter,OutputPath,ExcelFileForResults)

%------------------------------------------------------------------------
%     Input/output variables
%------------------------------------------------------------------------
%     Input:
%
usuper(1)         = ExperimentalInputData.Ugs;      %      Double Precision,
intent(in)::    usg      !  (m/s) gas superficial velocity
usuper(2)          =  ExperimentalInputData.Uos;    %      Double Precision,
intent(in)::    usht     !  (m/s) oil superficial velocity
usuper(3)          =  ExperimentalInputData.Uws;   %       Double Precision,
intent(in)::    usw      !  (m/s)  water superficial velocity
nPhases            = 3;                             %      Integer precision,
intent(in)::   nphases !   (-) Number of phases


rhoin(1)          = ExperimentalInputData.Rhog;    %       Double Precision,
intent(in)::    rog         (kg/m3) gas density
rhoin(2)           =  ExperimentalInputData.Rhoo;  %       Double Precision,
intent(in)::    roh         (kg/m3) oil density
rhoin(3)           =  ExperimentalInputData.Rhow;  %       Double Precision,
intent(in)::    row         (kg/m3) water density
visin(1)           = ExperimentalInputData.Visg;   %       Double Precision,
intent(in)::    visg        (ns/m2) gas viscosity
visin(2)          = ExperimentalInputData.Viso;   %        Double Precision,
intent(inout):: vish        (ns/m2) oil viscosity
visin(3)           =  ExperimentalInputData.Visw;  %       Double Precision,
intent(inout):: visw        (ns/m2) water viscosity
```

```
sigma(1)          = ExperimentalInputData.Sigg;    %       Double Precision,
intent(in)::    sighg      (N/m) gas/oil surface tension
sigma(2)           =  ExperimentalInputData.Sigo;  %       Double Precision,
intent(in)::    sigwh      (N/m) water/oil surface tension
sigma(3)           =  ExperimentalInputData.Sigw;  %       Double Precision,
intent(in)::    sigwg      (N/m) water/gas surface tension
D                 = ExperimentalInputData.Diam;   %       Double Precision,
intent(in)::    diam       (m) pipe inner diameter
angle             = ExperimentalInputData.Angle;  %       Double Precision,
intent(in)::    angle      (deg.) pipe inclination with horizontal
rough             = ExperimentalInputData.Roughness;%     Double Precision,
intent(in)::    rough      (m) absolute pipe wall rougness

%
%     Output:
%
alpha(1)          = 1.;      %      Double Precision, intent(out)::   al
(-) gas volume fraction
alpha(2)          = 1.;      %      Double Precision, intent(out)::   alh
(-) oil volume fraction
alpha(3)          = 1.;      %      Double Precision, intent(out)::   alw
(-) Water volume fraction
alpha(4)          = 1.;      %      Double Precision, intent(out)::   gah
(-) gas droplets in oil volume fraction
alpha(5)          = 1.;      %      Double Precision, intent(out)::   gaw
(-) gas droplets in water volume fraction
alpha(6)          = 1.;      %      Double Precision, intent(out)::   be
(-) oil droplets in gas volume fraction
alpha(7)          = 1.;      %      Double Precision, intent(out)::   bec
(-) oil droplets in water volume fraction
alpha(8)          = 1.;      %      Double Precision, intent(out)::   wa
(-) water droplets in gas volume fraction
alpha(9)          = 1.;      %      Double Precision, intent(out)::   wac
(-) water droplets in oil volume fraction
Re(1)             = 1.;      %      Double Precision, intent(out)::   ug
(-) Reynolds number of gas
Re(2)             = 1.;      %      Double Precision, intent(out)::   ud
(-) Reynolds number of oil
Re(3)             = 1.;      %      Double Precision, intent(out)::   uh
(-) Reynolds number of water
Su_wfrict(1)      = 1.;      %      Double Precision, intent(out)::   uw
(pa/m) gas pressure drop
Su_wfrict(2)      = 1.;      %      Double Precision, intent(out)::   dpzf
(pa/m) Oil pressure drop
Su_wfrict(3)      = 1.;      %      Double Precision, intent(out)::   dpz
(pa/m) Water pressure drop

%
info              = 1;      %       Integer Precision, intent(out)::   Info
(-) Covergence
RegimeID(1)       = 1;      %       Integer Precision, intent(out)::   regime
id         (-) Gas-liquid flow regime
RegimeID(2)       = 1;      %       Integer Precision, intent(out)::   Regime
id         (-) Liquid-liquid flow regime
dpdx              = 1.;      %      Double Precision, intent(out)::   dpdx
(pa)Pressure drop
```

```
%u(1:9)             = 1.;
CPEQO(1:20)        = 1.;
HHLO(1:20)         = 1.;
CPEQW(1:20)        = 1.;
HHLW(1:20)         = 1.;
diamhydro(1:9)     = 1.;
concdiff           = 1.;
visceff(1:3)       = 1.;

%     loading library with point model ifehyd

      Library_name = 'PMnew';

      if ~libisloaded(Library_name)
        loadlibrary(Library_name,'PMnew_v2.h');
      end

%
     [nPhases, D,rough,...
      angle, usuper,rhoin,...
      visin, sigma,alpha,...
      RegimeID,dpdx, info,...
      Re,Su_wfrict,CPEQO,HHLO,CPEQW,HHLW, diamhydro, concdiff, visceff] =
calllib(Library_name,'SolutionEntry',nPhases, D,rough,...
      angle, usuper,rhoin,...
      visin, sigma,alpha,...
      RegimeID,dpdx, info,...
      Re, Su_wfrict,CPEQO,HHLO,CPEQW,HHLW, diamhydro, concdiff, visceff);%
CPEQO, HHLO, CPEQW, HHLW);




     unloadlibrary(Library_name)

      return



     end
```