Entrainment through Rotation in Multiphase System

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Entrainment through Rotation in Multiphase System

A Thesis submitted in partial fulfilment of the requirements of the degree of

Master of Technology

in

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by

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(Roll Number: 214ME3318)

based on research carried out under the supervision of

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May, 2016

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TO

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Assistant Professor

May 30, 2016

CERTIFICATE

This is to certify that the work presented in this dissertation entitled "***Entrainment through Rotation in Multiphase System***" by ***CHANDRAKANT PRADHAN***, Roll Number **214ME3318**, is a record of original research carried out by him under my supervision and guidance in partial fulfilment of the requirements for the degree of ***Master of Technology* in *Mechanical Engineering***. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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DECLARATION OF ORIGINALITY

I, ***Chandrakant Pradhan***, Roll Number **214ME3318** hereby declare that this thesis entitled ***"Entrainment through Rotation in Multiphase System'*** represents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "References". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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ABSTRACT

The transient flow of immiscible liquids by using rotational motion is investigated. The solution was calculated by solving the transient 2-D momentum, continuity, turbulence equations by using Volume of Fluid method. The dynamics of entrained fluid which is penetrated in to other has been studied. To analyse it we used one rotor and two rotor system inside two different size of conduit. Two phase i.e. water-kerosene and three phase i.e. water-kerosene-diesel flow has been used to carry out the simulation. All the results obtained through the numerical simulations are used to make the effective analysis of entrainment phenomenon of the multiphase flow and also helpful to make comparative study on volume fraction. The presence of complex fluid topologies and multiple fluid flow over a cylinder is a challenging computational problem. The present paper establishes the study of entrainment phenomenon between two and three fluid pair (i.e. water-kerosene, water-kerosene-diesel, water-petrol) using rotational motion.

Key words: ***Entrainment, Void fraction, Penetration, VOF, Multiphase flow***.

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LIST OF FIGURES

NOMENCLATURE

Symbols	*Quantity*	*SI unit*
d	***Diameter of the rotor***	**m**
a	***Tank size***	**m**
ω	***Rotational speed of rotor***	**Rad/s**
u	***Magnitude of velocity along x-direction***	**m/s**
v	***Magnitude of velocity along y-direction***	**m/s**
$\vec{V}$	***Velocity vector***	**-**
P	***Pressure force***	**N/m^2**
k	***Turbulent kinetic energy***	**-**
ρ	***Density***	**kg/m^3**
μ	***Dynamic viscosity***	**$N - s/m^2$**
∇	***Differential operator***	**-**
ε	***Turbulent dissipation rate***	**-**
$\vec{\tau}$	***Stress tensor***	**-**
$\rho\vec{g}$	***Gravitational body force***	**N**
$\vec{F}$	***External body force***	**N**
V_q	***Volume of the phase***	**m^3**
α_q	***Volume fraction***	**-**

CHAPTER-1: INTRODUCTION AND LITERATURE SURVEY

In this section detailed explantion of the phenomenon and its existence is given. The practical applicaion of the phenomenon have been discussed with the literature review coverin the work that has alreay been done. The gaps in the literature have been poined out and the aims and objectives of the present work, in accordane with the gaps found, have been listed.

1.1 Introduction

Entrainment phenomenon carried out in hydrodynamic field is to understand the flow dynamics of fluid-fluid entrainment. It is a complex and interesting phenomenon in which deformation of fluid takes place across their interfaces when subjected to some external flux or instability. Stratified layer is defined as a clear and distinguishable interface which separates two immiscible fluid. Through the inerfaces heat and mass transfer can occurs. In this study we are trying to achieve entrainment by providing an external turbulent rotation between the interfaces of the stratified fluid layers with the help of a horizontal rotating cylinder. This is called entrainment through rotation. Entrainment through rotation is relatively new area of research and doing work on this phenomenon is of great importance for chemical reactions which were bounded due to immiscibility. The study of entrainment phenomenon is helpful to understand the concepts of mixing and important for study of climatic conditions. Entrainment through rotation is having plenty of application in the field of oil and gas industries, chemical and petrochemical industries, gas-liquid chemical reactors, pharmaceutical industry, immiscible fluids chemical reactions and numerous others. Entrainment phenomenon carried out in hydrodynamic field is to understand the flow dynamics of fluid-fluid entrainment.

1.2 Literature survey

Based on the title of the project I searched and analysed various research papers and journals. Some papers are more related to topic which I have studied. ARUP K DAS (2015) presented an experimental study on entrainment phenomenon in gas-liquid stratified layers by using rotational motion. They used 2 techniques, first is Ink Dispersion technique and second is

Particle Image Velocimetry to investigate the air mass entrainment in water and also to find out its entrainment trajectories. They also analysed the depth of penetration as well as the radius of curvature of air entrainment. K HARBY (2014) explained bubble entrainment study and flow patterns of vertical plunging water jet. All these things did by them to find out jet impact velocity, inception velocity, penetration depth and volumetric flow rate of entrained air bubble. Pitot tube is for measuring jet velocity. TUAN TRAN (2013) studied the entrainment of air on liquid surfaces during impact of droplets. They observed impact of drop on a deep pool, with highlighting the trapped layer of air under the droplets from its establishment to its break. They found that due to its own weight droplet is falling, impact velocity of drop varied by adjusting needle height, velocity is measured by high speed camera, side view camera is slightly tilted upwards to look at impacting point, and working fluid is silicon oil with different viscosity. BAGUL R K (2013) carefully studied the various experimental, analytical and numerical investigation on issues of entrainment. They investigated the literature on the basis of analytical development, experimental studies, Empirical correlation, Numerical models. Finally they experienced that in gravity separation of two phase flow, the droplet generated at the interface either fall back into liquid or are carried along with the flow. KULKARNI and PATWARDHAN (2013) have studied the phenomenon of gas entrainment in stirred tanks by CFD modelling. They distinguished between onset conditions and non-onset condition in CFD. BROUILLIOT and LUBIN (2013) have numerically simulated entrainment of air in a plunging liquid-jet. They have developed the numerical model for classical VOF- PLIC model i.e. Volume of Fluid method with piecewise Linear Interface Construction method of YOUNGS (1982). They have also used LES turbulence model. They studied the dynamics of air entrainment by the jets impacting on the surface of the water in a tank. GREEN, G.A. (1991) have developed analytical model for induction of bubble entrainment between stratified liquid layers. The entrainment efficiencies have been calculated. Greene et al. (1988) have also studied the strength of the entrainment by measuring the volume of entrained liquid. Different liquid pairs were used in experimental runs.

1.3 Gaps in the literature

Some research had done on the entrainment phenomenon in multiphase flow between air and liquid. Most of them concentrated on bubble entrainment. There has been no effort yet to make the study of entrainment in two phase and three phase stratified liquid layers by using rotational motion.

1.4 Aim and objective

To investigate the entrainment phenomena of one liquid in to the other is the main aim by using rotational motion. Here the objective is to study the pattern of entrainment and to analyse the variation of volume fraction w.r.t. time and penetration rate by-

- Varying the diameter of rotor
- Varying the rotor speed
- Varying the liquid pair used
- Number of stratified layer

CHAPTER-2: PROBLEM DESCRIPTION

A cubic container contains two and three immiscible liquids which are separated to each other. These liquids will form an interface in the tank where the upper part from the interface occupied with high density fluid and lower part occupied with low density fluid. In the first case rotor is placed at the centre of the tank and interface. For second case the top layer penetrates into the middle and the middle layer penetrates into the bottom layer. The pattern of entrainment, volume fraction entrained and growth of penetration will be studied for different cases by varying the rotor speed (ω), rotor diameter (d) container dimension, number of rotor, fluid pair.

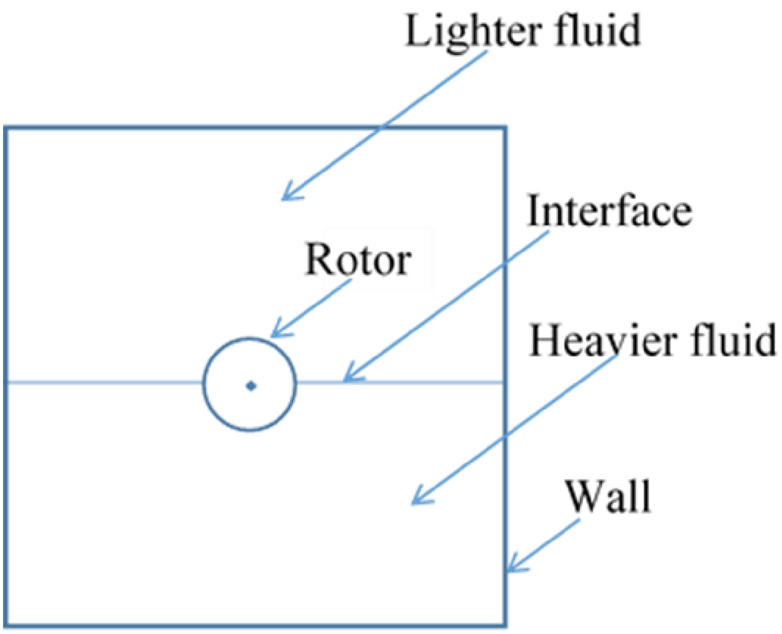

Figure 2.1 One rotor one layer system

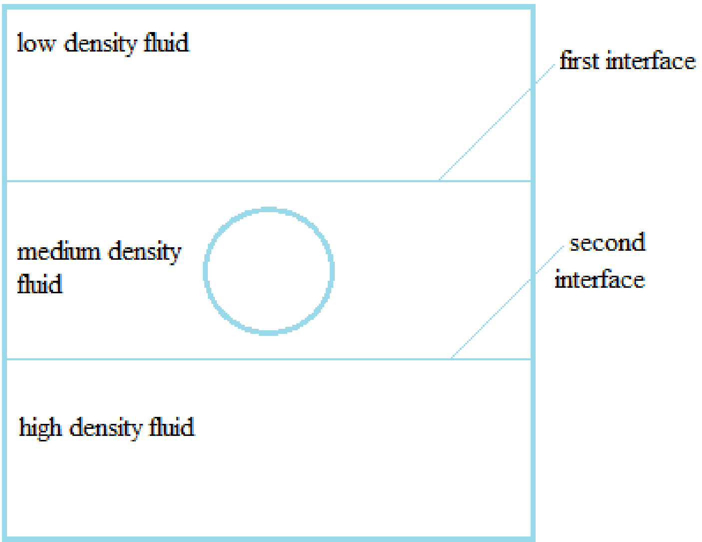

Figure 2.2 One rotor two layer system

Following cases were considered for simulation by varying the tank size, rotor diameter, rotor speed, fluid pair, positon number of rotor.

A). 1 LAYER_1 ROTOR

- a = 100 mm, d = 20 mm, ω = 20, 30, 40, 50 rad/s
- a = 100 mm, d = 30 mm, ω = 20, 30, 40, 50 rad/s
- a = 200 mm, d = 20 mm, ω = 20, 30, 40, 50 rad/s
- a = 200 mm, d = 30 mm, ω = 20, 30, 40, 50 rad/s

B). 2 LAYER_1 ROTOR

- a = 100 mm, d = 20 mm, ω = 20, 30, 40, 50 rad/s
- a = 100 mm, d = 30 mm, ω = 20, 30, 40, 50 rad/s
- a = 200 mm, d = 20 mm, ω = 20, 30, 40, 50 rad/s
- a = 200 mm, d = 30 mm, ω = 20, 30, 40, 50 rad/s

CHAPTER-3: METHODOLOGY

The given problem can be solved in different ways like experimental, numerical simulation, and by using computational codes. Here numerical simulation has been opt for solving the problem and deduce useful data for the same. Numerical method has been used to simulate the phenomenon entrainment. The commercial solver ANSYS has been used for the same. Simulations have been carried out for 2-dimensional cases.

3.1 Grid pattern and meshing

Based on the geometrical model and after verification it is found that the triangular meshing is best suitable for the simulation.

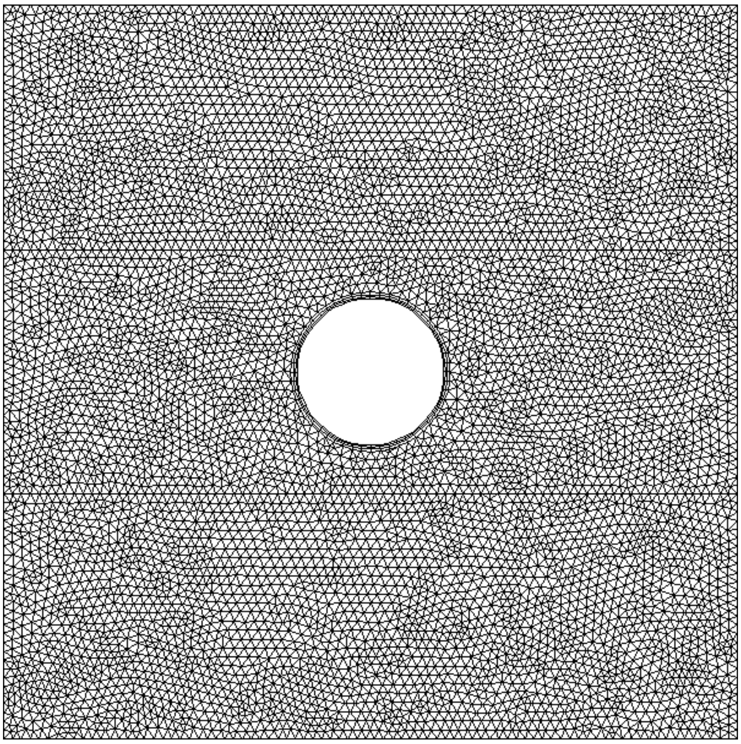

Figure 3.1 Meshing of one rotor system

3.2 Models

The simulation for this problem consists of 2D space, transient as 1st order implicit and k-epsilon turbulence viscous model with standard wall functions. The VOF method uses a phase indicator function, sometimes also called a colour function, to track the interface between two or more phases. The indicator function has value one or zero when a control volume is entirely filled with one of the phases and a value between one and zero if an interface is present in the control volume. Hence, the phase indicator function has the properties of volume fraction.

3.3 Boundary conditions

The boundary conditions for the given problem includes giving all four side as stationary wall with no slip (U_x=0, U_y=0) condition, while the rotor as moving wall has given rotational speed(ω) with no slip (Ux=0, Uy=0) condition.

3.4 Material properties

Fluid pairs used for the given problem are water-kerosene, water-diesel, water-diesel-kerosene. Properties of all these fluids are given below-

Table 3.4.1: Material Properties

Fluid	Density (kg/m^3)	Sp. Heat C_p (J/kg-K)	Viscosity (kg/m-s)	Thermal conductivity (W/m-K)	Molecular weight (kg/kg-mol)
Water	998.2	4182	0.001003	0.6	18.0152
Kerosene	780	2090	0.0024	0.149	167.31
Diesel	730	2090	0.0024	0.149	142.284
Petrol	830	2050	0.00332	0.135	221.16

3.5 Governing equations

The governing equations that are solved in ANSYS are continuity, momentum, turbulence modelling and volume fraction equations. Since VOF model is used, the momentum equation is the same for all the phases, and a weighted average is used for the properties.

- Continuity Equation $\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{V}) = 0$

Here ρ is density of fluid, $\vec{V}$ is velocity vector.

- Momentum equation

$$\frac{\partial}{\partial t}\left(\rho \vec{V}\right) + \nabla \cdot \left(\rho \vec{V}\vec{V}\right) = -\nabla P + \nabla \cdot \left[\mu \left\{\left(\nabla \vec{V} + \nabla \vec{V}^T\right) - \frac{2}{3}\nabla \cdot \vec{V}\ \bar{\bar{I}}\right\}\right] + \rho \vec{g} + \vec{F}$$

Here P is the static pressure, $\rho \vec{g}$ is the gravitational body force and $\vec{F}$ is the external body forces.

- Turbulence modelling (k-ε equation)

For kinetic energy k

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$$

For dissipation rate ε

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_i}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1i}\frac{\varepsilon}{k}(G_k + C_3 G_b) - C_{2i}\rho\varepsilon 2k + S_\varepsilon$$

Where μ_t is called as turbulent viscous coefficient and is given as $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$

- Volume Fraction Equation

The volume of phase q is given by,

$$\mathrm{V}_q = \int \alpha_q dV$$

$$\sum_{q=1}^{n} \alpha_q = 1$$

Here α_q is volume fraction.

CHAPTER-4: RESULTS AND DISCUSSION

All results obtained through numerical simulation are described sequentially.

4.1 One rotor one stratified layer

The entrainment phenomenon of the case one rotor one stratified layer as shown in figure 1 (a) is described here with water-kerosene fluid pair. The rotor is placed at the interphase of these two immiscible liquid. The hydrodynamics of phase contour, velocity vector plot (for *a*=100 mm, *d*=20 mm) at different time steps for different rotational speed have been given in figure 4.1.1, 4.1.2 and 4.1.3 respectively. For a particular case (a=100 mm, d=30 mm, ω=50 rad/s), variation of volume fraction w.r.t time and is shown in figure 4.1.6.

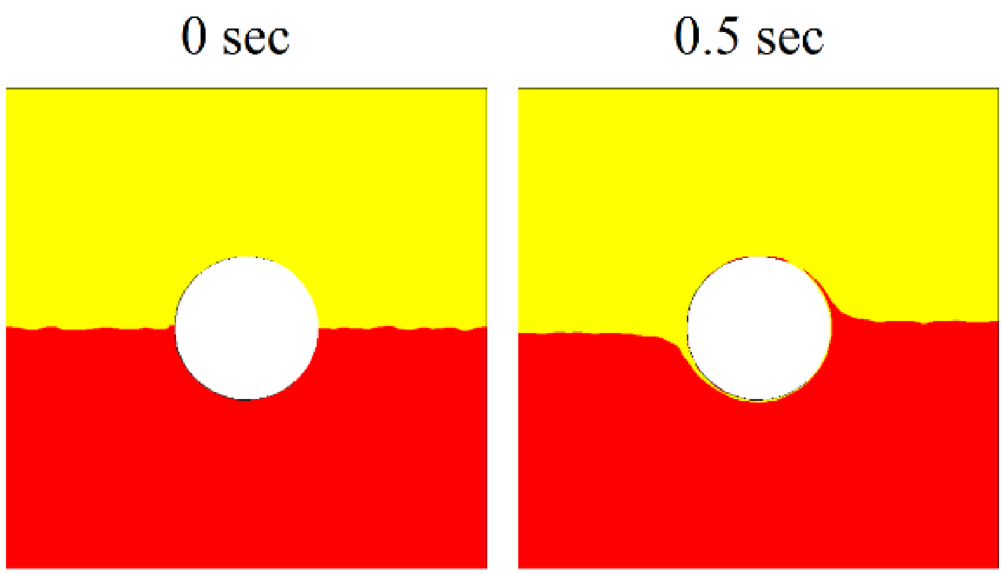

Figure 4.1.1: Phase contours at 0 sec and 0.5 sec for 20 rad/s (a =100 mm and d =20 mm, water-kerosene pair)

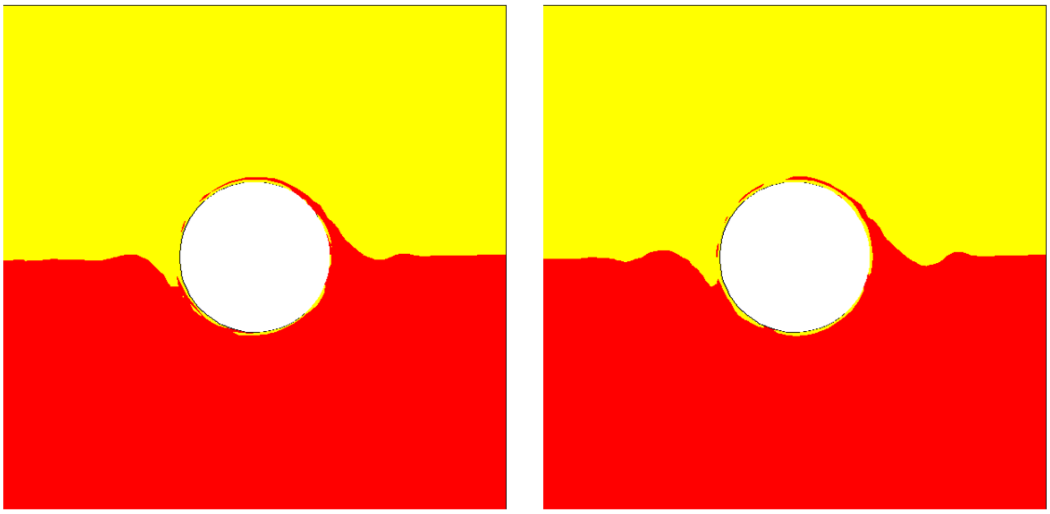

Figure 4.1.2: Phase contours at 2 sec and 4 sec for 20 rad/s (a =100 mm and d =20 mm, water-kerosene pair)

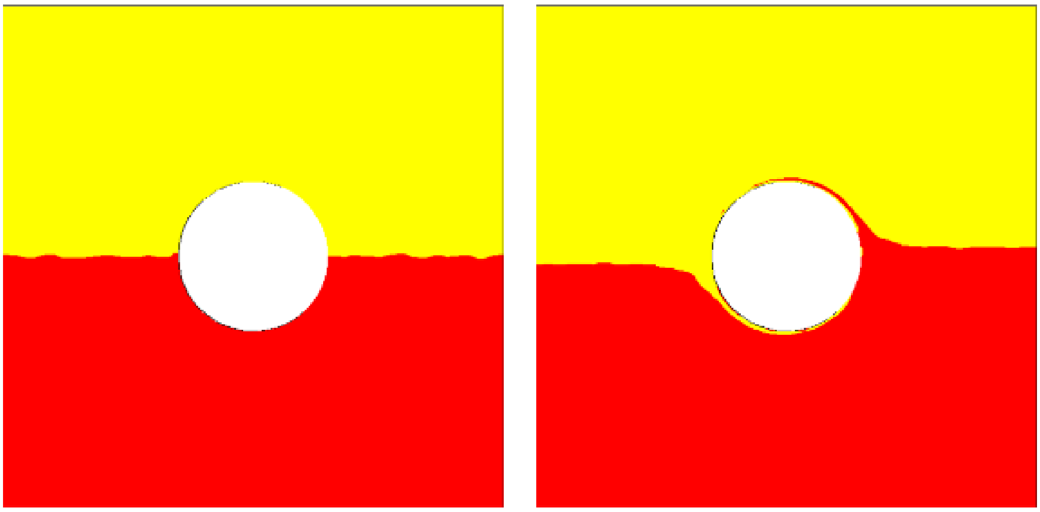

Figure 4.1.3: Phase contours at 0 sec and 0.5 sec for 30 rad/s (a =100 mm and d =20 mm, water-kerosene pair)

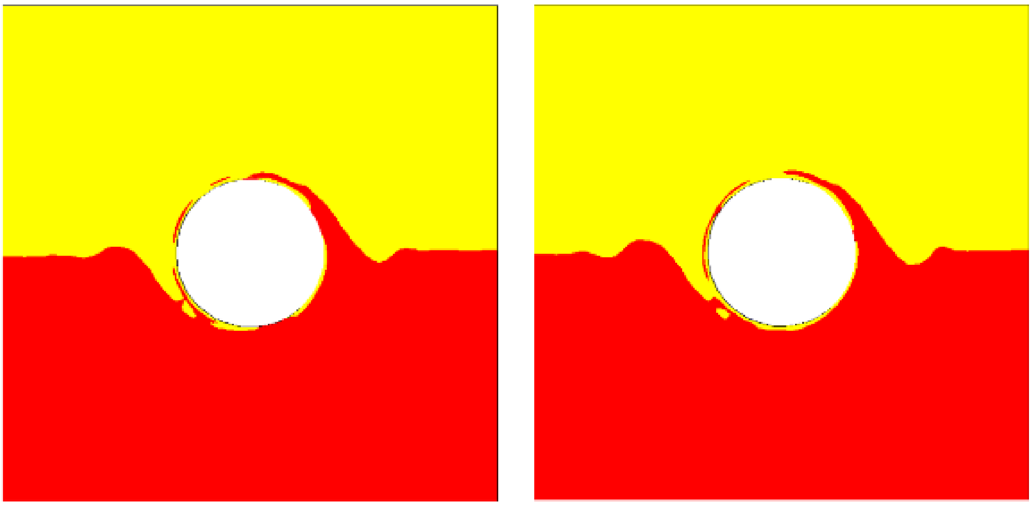

Figure 4.1.4: Phase contours at 2 sec and 4 sec for 30 rad/s (a =100 mm and d =20 mm, water-kerosene pair)

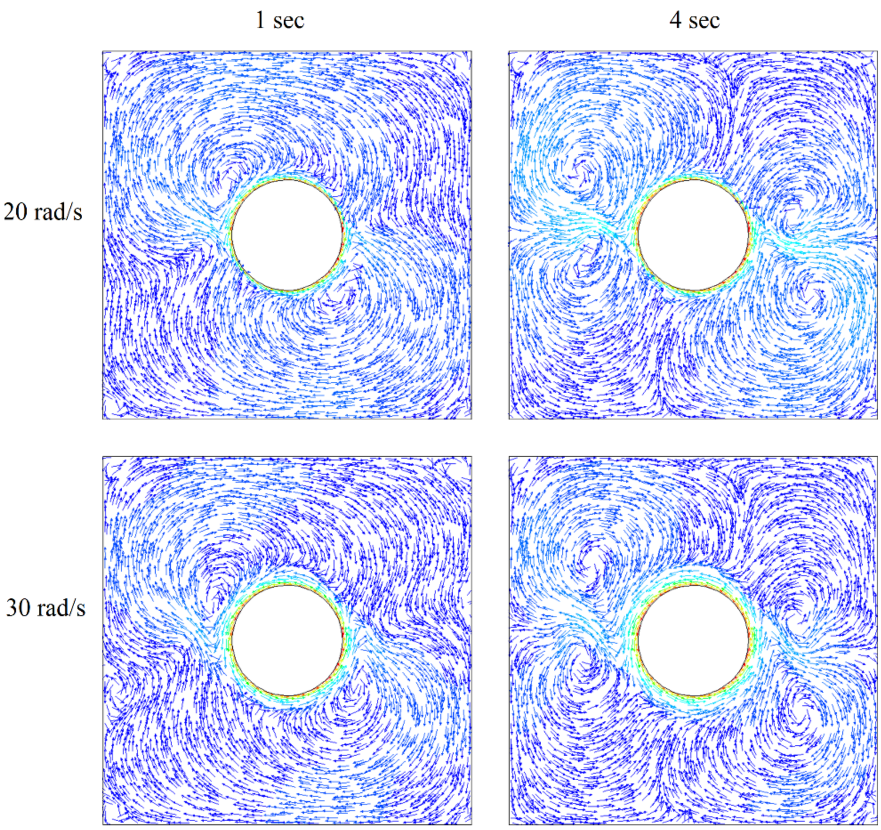

Figure 4.1.5: Velocity vector plot at different time instants for 2 different speed (a =100 mm and d =20 mm)

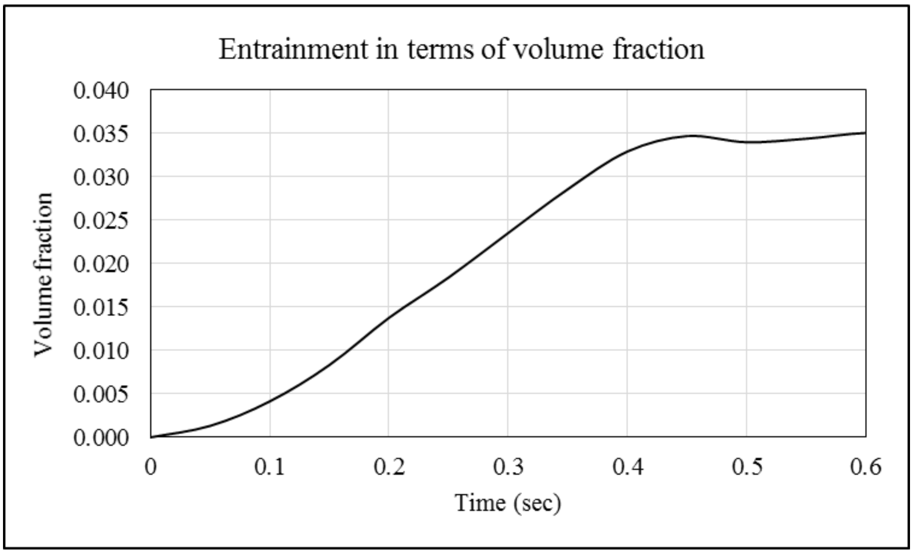

Figure 4.1.6: Variation of volume fraction w.r.t. time (for a=100 mm, d=30 mm, ω=50 rad/s)

Effect of rotor speeds

For the case 1 considering tank size of 100 mm and rotor diameter of 20 mm, the effect of rotor speeds on entrainment in terms of volume fraction shown in figure 4.1.7. The volume fraction of water entrained in the region of kerosene is increasing with respect to time by varying the rotor speed.

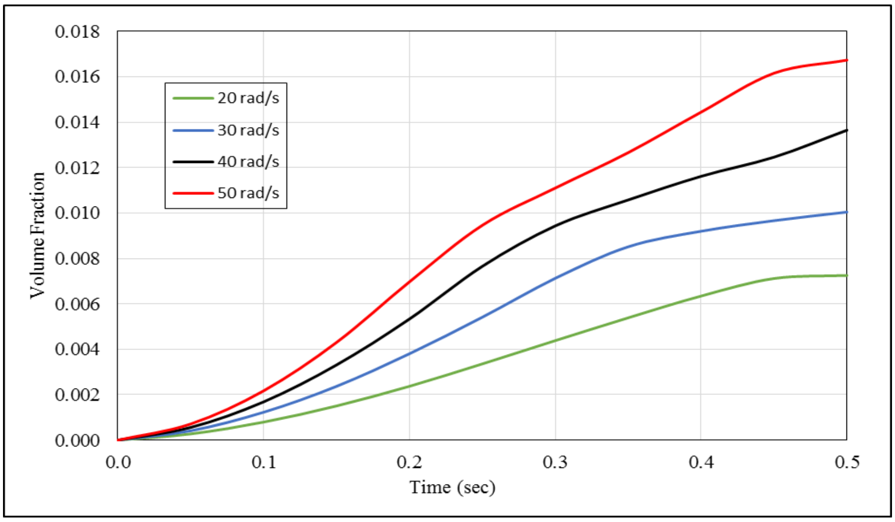

Figure 4.1.7: entrainment in terms of volume fraction entrained w.r.t time (for water-kerosene pair)

Effect of rotor diameter

For the case 1 considering tank size of 100 mm and particular rotor speed of 50 rad/s, the effect of rotor diameter in terms of volume fraction is shown by figure 4.1.8. It is clearly shown in figure 4.1.8 that volume fraction is increasing by increasing rotor diameter with respect to time.

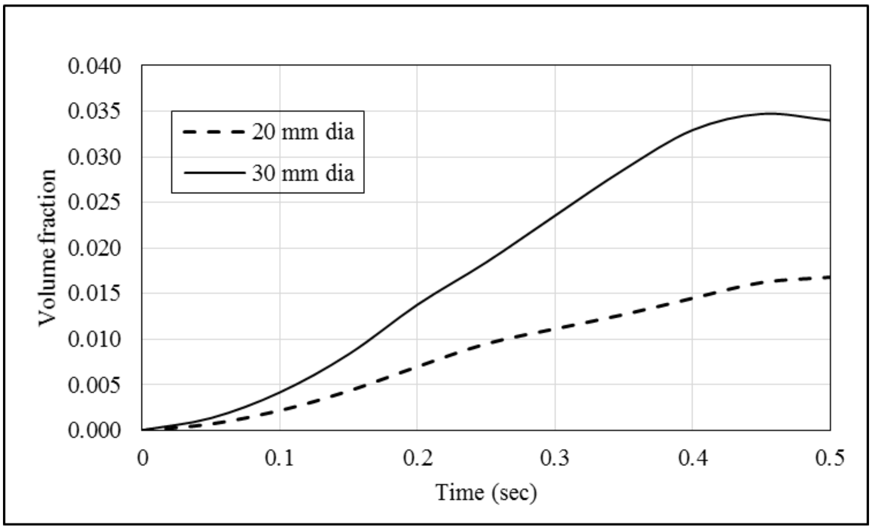

Figure 4.1.8: Effect of rotor diameter on entrainment in terms of volume fraction w.r.t. time (for water-kerosene pair)

Effect of fluid pair

For the case 1 considering tank size 100 mm, rotor diameter of 20 mm and particular rotor speed of 30 rad/s, the effect of two different fluid pair in terms of volume fraction is shown by figure 4.1.9 Here two pair water-kerosene and petrol-water are considered for the simulation.

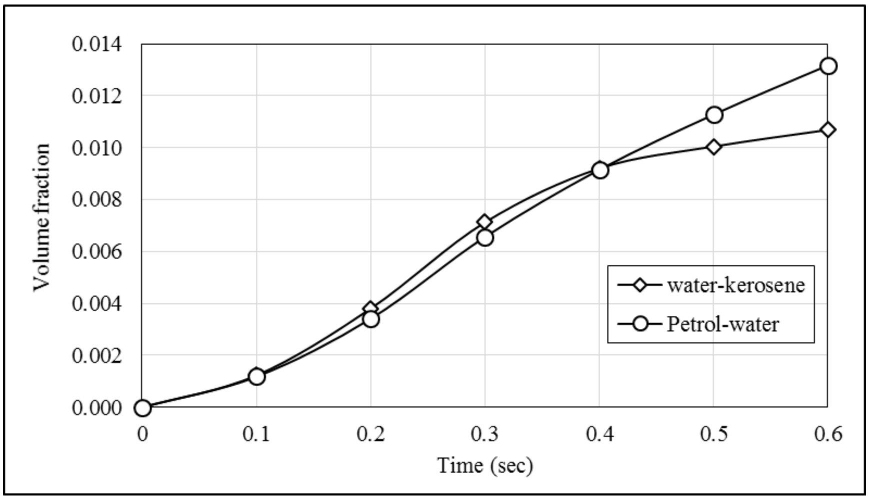

Figure 4.1.9: Effect of fluid pair on entrainment in terms of volume fraction w.r.t. time (for water-kerosene pair)

Effect of container size

For the case 1 considering rotor diameter of 20 mm and particular rotor speed of 30 rad/s, the effect of rotor diameter in terms of volume fraction and in terms of chute height is shown by figure 4.1.10.

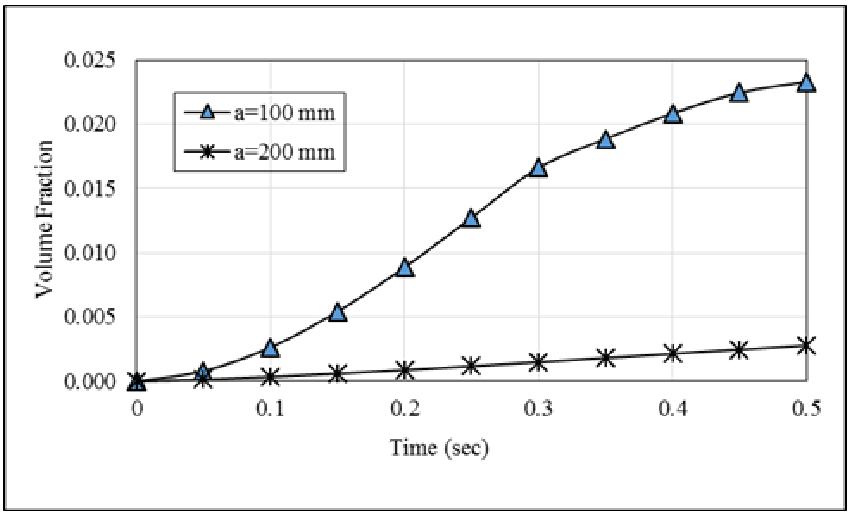

Figure 4.1.10: Effect of container size on entrainment in terms of volume fraction w.r.t. time (for water-kerosene pair)

4.2 One rotor two stratified layers

The entrainment phenomenon of the case one rotor two stratified layers as shown in figure 1 (b) is described here with water-kerosene-diesel fluid pair. The rotor is placed at the center of the container as well as center of the region filled with kerosene. Entrainment phenomenon noticed at both the interfaces. The hydrodynamics of phase contour (for *a*=100 mm and *d*=20 mm) at different time instant for different rotor speeds is shown in figure 4.2.1, 4.2.2, 4.2.3, 4.2.4 respectively.

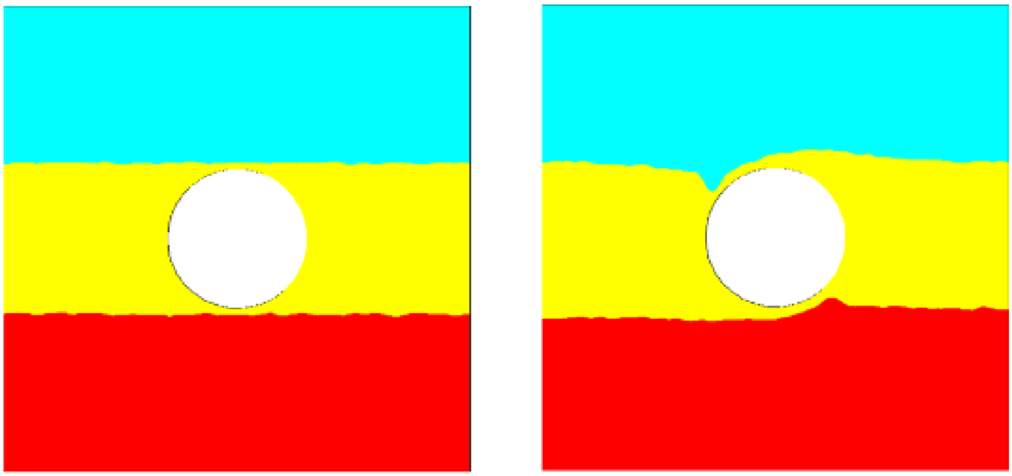

Figure 4.2.1: Phase contours at 0 sec and 0.52 sec for 20 rad/s (*a* =100 mm and *d* =20 mm)

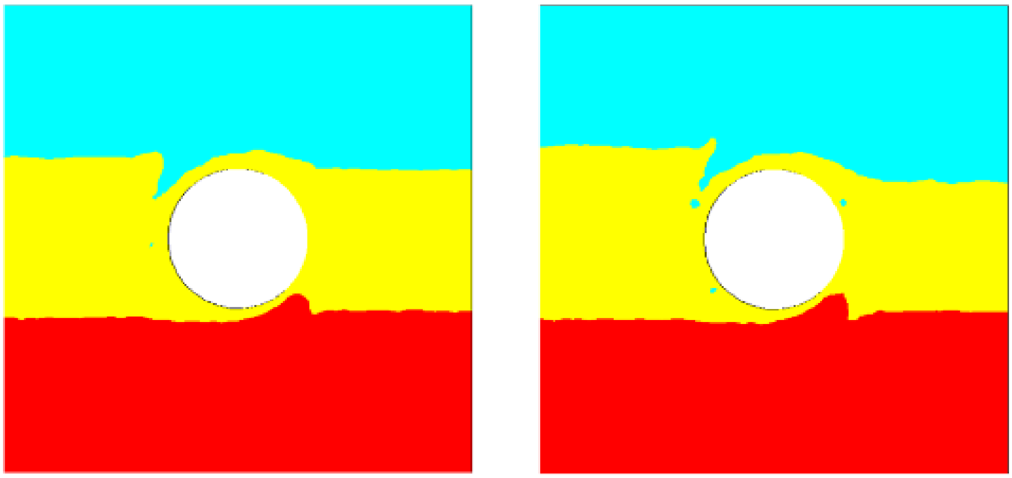

Figure 4.2.2: Phase contours at 2 sec and 4 sec for 20 rad/s (a =100 mm and d =20 mm)

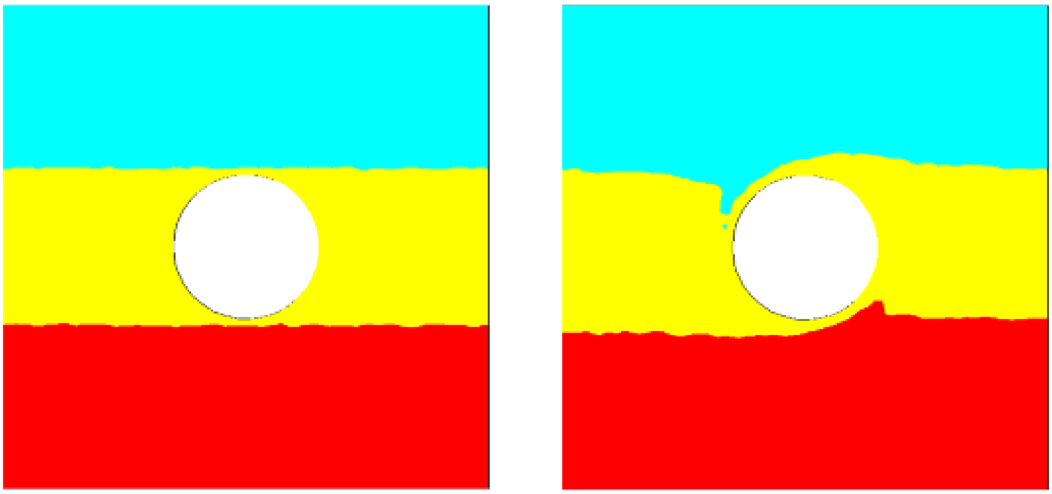

Figure 4.2.3: Phase contours at 0 sec and 0.52 sec for 30 rad/s (a =100 mm and d =20 mm)

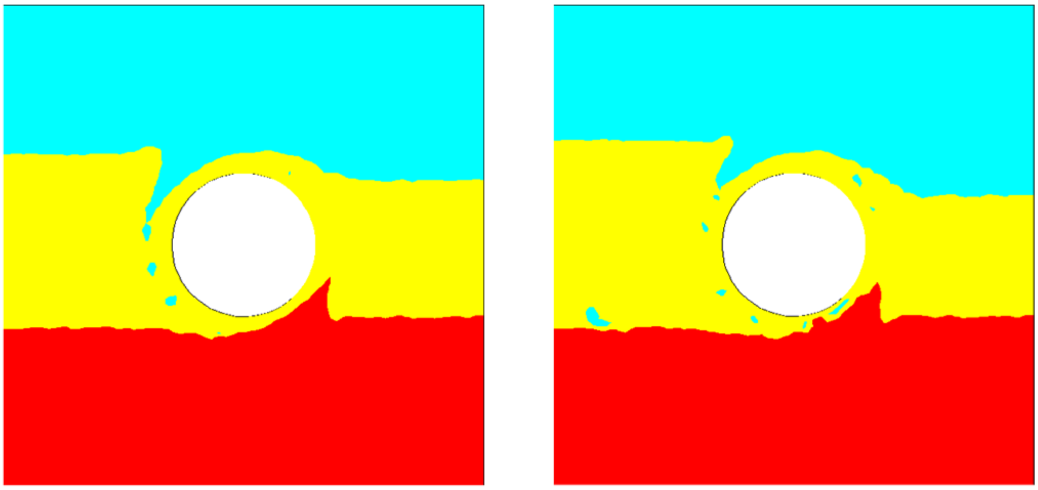

Figure 4.2.4: Phase contours at 2 sec and 4 sec for 30 rad/s (*a* =100 mm and *d* =20 mm, diesel-kerosene-water pair)

Effect of rotor speeds

For the case 2 considering tank size of 100 mm and rotor diameter of 20 mm, the effect of rotor speeds on entrainment in terms of volume fraction of diesel entrained in kerosene is shown in figure 4.2.5. Volume fraction of diesel entrained within kerosene region is calculated.

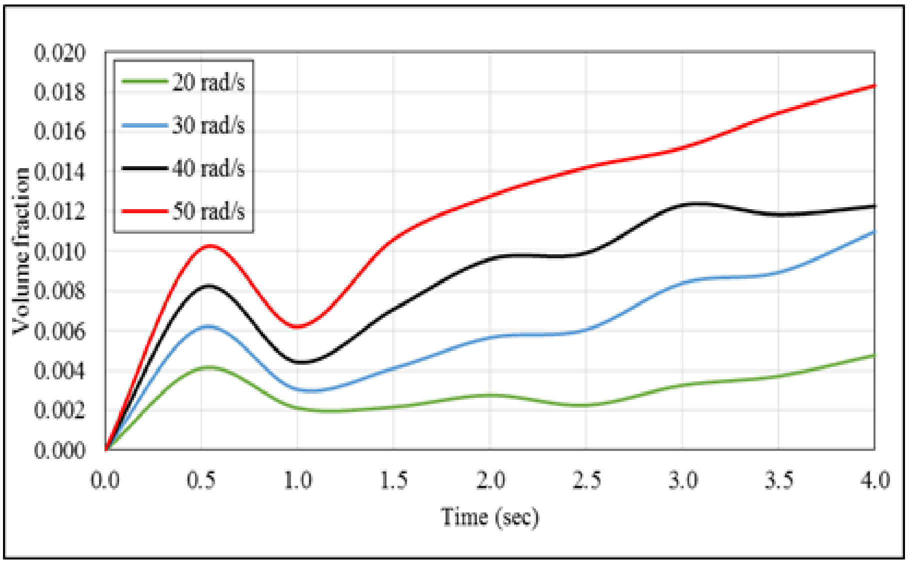

Figure 4.2.5: Effect of the rotor speed on entrainment in terms of volume fraction entrained of diesel in kerosene w.r.t time (for water-kerosene-diesel)

Effect of rotor diameter

For the case 2 considering tank size of 100 mm and rotor speed of 30 rad/s, the effect of rotor diameter on entrainment in terms of volume fraction of diesel entrained in kerosene is shown in figure 4.2.6. Volume fraction of diesel entrained within kerosene region is calculated.

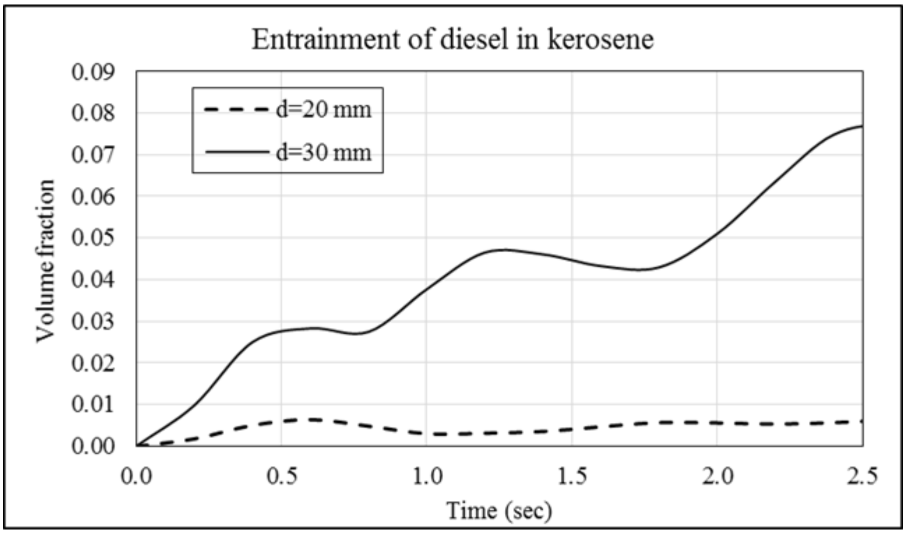

Figure 4.2.6: Effect of the rotor diameter on entrainment in terms of volume fraction entrained of diesel in kerosene w.r.t time (for water-kerosene-diesel)

Effect of container size

For the case 2 considering rotor diameter of 30 mm and rotor speed of 30 rad/s, the effect of rotor diameter on entrainment in terms of volume fraction of diesel entrained in kerosene is shown in figure 4.2.7. Volume fraction of diesel entrained within kerosene region is calculated.

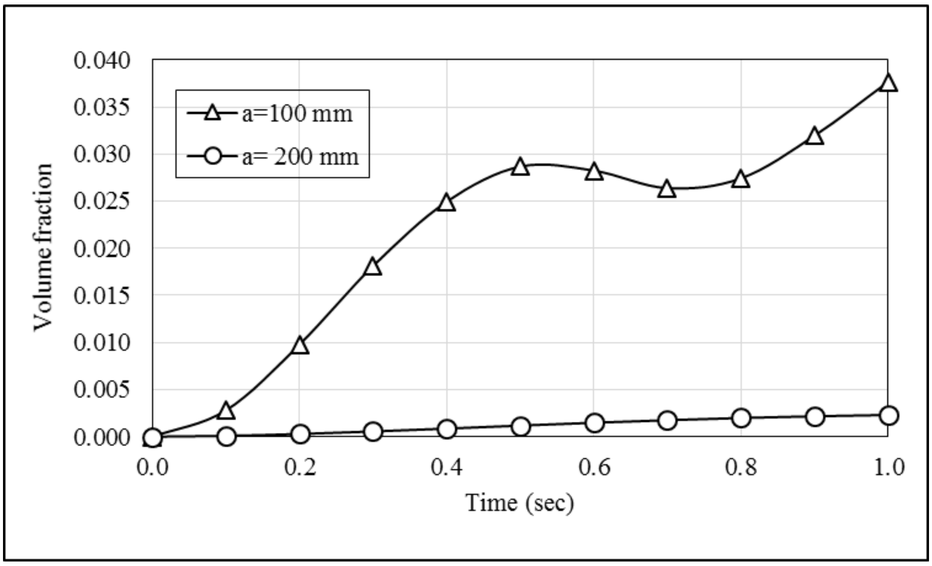

Figure 4.2.7: Effect of the container size on entrainment in terms of volume fraction entrained of diesel in kerosene w.r.t time (for water-kerosene-diesel)

CHAPTER-5: CONCLUSION

The phenomenon of entrainment over cylinder(s) which rotates at different speeds has been carried out based on volume of fluid model and governing equations. The volume fraction of the entrained fluid has been analysed. It is established that when a cylinder is rotated on the interface of two fluids, an entrainment zone is formed. This entrainment zone is varying with time as per direction of the cylinder rotation. It is found that one fluid is penetrates in to other and its rate of entrainment is varying with time. It is also noticed that the fraction of volume depends on the various parameters like speed of rotor(s), diameter of rotor, fluid pair used, and size of the conduit. A comparative study is also done between all the cases with respect to time to check the phenomenon of entrainment by taking account of effect of speeds, effect of diameter of rotor, effect of fluid pair used, and effect of size of the tank. In all the cases volume fraction varies with time.

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