CFD ANALYSIS OF OCEAN ENERGY DEVICE FOR OPTIMUM POWER OUTPUT

A thesis submitted in partial fulfilment of the requirements for the degree of Masters of Science in Mechanical Engineering

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ABSTRACT

The objective of this study is to promote the importance of renewable energy particularly obtained from ocean surface waves and application of advanced numerical tools to design such particular devices that can extract much amount of this renewable energy. Now days, due to increase in oil prices and greater damage to the atmosphere, green energy which is both renewable and sustainable has become the demand over the entire globe. There are various forms of renewable energy present in the world. Ocean Wave Energy is one of them that has the potential of about 8000 – 80000 Terra Watts and is sufficient to meet the energy requirement of the world. This form of renewable energy is available 90% of the time at a given site compare with solar and wind energies, which are available only 20 – 30% of the time. The discipline is still in development and academic stages although several prototypes are in operation too. In this thesis, numerical simulation of generated waves and wave force on floating buoys of different dimensions through wave structure interaction have been reported which can serve as the basis for design of floating and onshore wave energy converters. Wave generation has been simulated using commercial code using multiphase fluid Volume of Fluid Model alongwith computation of wave forces through simulation of wave structure interaction by using the same stated numerical code. The wave simulation results has been compared with Airy's Linear Wave Theory. Wave Force on buoys of different dimensions has been computed numerically as the first step in design of wave energy converter for optimization of power output. Grid independence study was carried out using different resolutions for wave's simulation and results on fine grid are in good agreement to analytical results. A maximum error of 5% was reported for different grid resolutions. Compressive Scheme of Implicit Time Discretization Schemes produces much accurate results than other volume fraction schemes of spatial discretization in comparison with analytical results based on Airy's Linear Wave Theory for surface elevation. Force on buoy having larger frontal surface area has greater value in comparison to buoy having lesser frontal surface area during wave structure interaction simulation and variation of force on buoys is an approximate reflection of sinusoidal wave pattern.

Keywords: *Numerical Wave Tank (NWT), Ansys Fluent, Ocean Wave Energy Converter (OWEC), Airy's Linear Wave Theory (LWT), Volume of Fluid (VOF), Waves Surface Elevation, Volume Fraction Schemes, Open Channel Wave Boundary Condition, Numerical Beach Treatment.*

SYMBOLS AND ACRONYMS

h	Depth of Water
H	Wave Height
L	Wavelength
g	Gravitational Acceleration
g_x	Gravitational Acceleration in x- direction
g_y	Gravitational Acceleration in y – direction
g_z	Gravitational Acceleration in z- direction
T	Time Period
d	Depth of Water
c	Wave Celerity
c_g	Group Velocity
u_1	Water Particle Horizontal Velocity
u_2	Water Particle Vertical Velocity
a_1	Water Particle Horizontal Acceleration
a_2	Water Particle Vertical Acceleration
P	Sub Surface Pressure
η	Surface Elevation of Waves
U	Ursell Number
λ	Wave length
u	Velocity in x – direction
v	Velocity in y – direction
w	Velocity in z – direction

$\boldsymbol{\rho}$	Density
t	Time
$\boldsymbol{\mu}$	Viscosity
$\boldsymbol{\alpha}$	Phase Fraction
ρ_a	Density of Air
ρ_w	Density of Water

LWT	Airy's Linear Wave Theory
NWT	Numerical Wave Tank
UDF	User Defined Function
2D	Two Dimensional
3D	Three Dimensional
RANS	Reynolds's Average Navier Stokes
VOF	Volume of Fluid
OWEC	Ocean Wave Energy Converter
CFD	Computational Fluid Dynamics
FOUW	First Order Upwind Scheme
SOUW	Second Order Upwind Scheme
HRIC	High Resolution Interface Capturing
WEC	Wave Energy Converter
CO_2	Carbon Dioxide

Contents

List of Tables

List of Figures

1. INTRODUCTION

Right from the beginning, man is harnessing natural resources particularly energy resources to his advantage and their dependency on various energy resources is increased day by day due to rapid industrial growth and technological development. Broadly, there are two categories of energy resources i.e. nonrenewable and renewable. From many years, nonrenewable sources of energy i.e. fossil fuels are in use to fulfill the energy needs of human and as per report, 85% of energy requirement of entire world is fulfilled by use of fossil fuels. It is noted that the most developed countries of the world are the highest consumers of nonrenewable sources of energy with reference to total energy consumption of the world. The consumption of energy resources over the globe is illustrated as:

Countries / Regions	Consumption
USA	25%
Japan	6%
Western European Countries	15%
China	9%
Rest of the World	45%

Table 1 CONSUMPTION OF ENERGY RESOURCES [1]

When compared the regional consumption with regional production of fossil fuels, it is noted that Middle East region has highest fossil fuels reserves in the entire globe having 61% of the total reserves whereas USA has only 2.4% oil reserves and 3.5% gas reserves, Japan imports 75% of their energy needs and China also imports more than 50% of their energy needs [1]. Thus, this uneven distribution and production of fossil fuels resulted in global energy crisis which is also supported by other factors i.e. surge in demand, tighter supply, political uncertainty in oil producing countries and lack of diversity of the resources.

Supply of fossil fuels in developed countries particularly USA and other western countries was adversely affected in 1973, when members of Organization of Arab Petroleum Exporting Companies (OAPEC) clamped an oil embargo to USA and its aligned members during Israel and Middle East war due to their support to Israel [3].

The above stated oil crisis make the world to thinking. Although the issue was resolved, but the bigger question remained. The world could be subjected to dramatic inflation and economic crunch without any warning, just at the whim of a few oil rich countries. Thus, the world started to think for development of projects to use renewable sources of energy to fulfill their energy requirements [4].

1.1 RENEWABLE ENERGY

1.1.1 INTRODUCTION

Renewable energy can be defined as a resource that is naturally replenished and freely available, the extraction of which does not cause unsustainable deterioration of the environment. There are various forms of renewable energy resources available in the globe and Solar, Wind, Ocean, Geothermal, Biomass / Biofuels, Hydroelectric are the most common renewable energy resources.

1.1.2 HISTORY

Although the man is harnessing the natural resources right from the first, the first attempt was made by a Scottish professor James Blyth by building a cloth sailed wind turbine to power the lights of his cottage in 1887 as the way to extract electrical energy from renewable sources of energy. [5].

The US government, after the oil crisis of the 70s funded a project for large-scale use of wind turbines under the supervision of the United States Department of Energy which was managed by NASA. Through this project, thirteen experimental wind turbines were fabricated, thus giving the path to generation of electricity from wind on a commercial scale [6].

Conversion of ocean energy to electrical energy was first filed in 1799 in Paris, France as a patent by Girard [7]. Since then, significant progress was made in this field. In 1910, Bochaux-Praceiqu also filed a device that converts ocean energy to electrical energy to power his house. This was the first device which derived its energy from oscillation of ocean waves. Statistics shows that between 1855 and 1973, 340 patents relating to device harnessing electrical energy from ocean waves energy had been filed in UK alone [8].

Modern scientific approach to Ocean Energy devices that converts ocean energy to electrical energy was labeled in 1940s after Yoshio Masuda’s experiments [9].

However, the oil crisis of the 1970s lit the tinderbox. Renewable energy R&D activity was significantly gaining momentum due to above stated oil crisis that coupled with the increasing CO_2 foot print. Salter’s Duck also known as Nodding Duck is the most noteworthy among all the research conducted in the ocean waves energy.

It was designed by Stephen Salter of Edinburgh University whose prototype was fabricated under the umbrella of Ready Mixed Concrete and Insituform of UK that supplied some 20kW of power [10].

1.1.3 OVERALL COMPARISON

Below is the table that compares the theoretical available potential of renewable energy resources with conventional fossil fuels and present human's use:

Energy Sources	Power (x 10^{12} W)
Solar	174000
Geothermal	32
Tidal	3
Winds, Waves, Convection and Current	370
Fossil Fuel Reserves	2000
Present World Energy Consumption	40

Table 2 THEORETICAL AVAILABLE ENERGY RESOURCES AND CURRENT ENERGY USE [2]

It is noted that ocean wave energy originate from solar energy in particular, although the most forms of the renewable energy also originates from solar energy. Wind energy contributes 90 Giga Watts of energy, 1% of the total world's demand thus becoming leading commercial production renewable energy source.

When compared to wind and ocean energy, the exergy captured from sun per sq. meter of land is considerable low [11].

1.2 OCEAN ENERGY

The oceans cover 70 percent of the world and harbor a vast untapped source of renewable energy that can be transformed into electricity. There have been many ideas to try to extract some of the energy potential from the ocean through the years. The oldest ones are several hundred years old, and on a global basis there are more than 1000 patents on different constructions to harness this potential.

The forms of ocean renewable sources can be broadly categorized as Ocean Tides, Ocean Waves, Ocean Current, Ocean Thermal Energy Conversion (OTEC) and Salinity Gradient. From the stated, Ocean Tides, Ocean Waves and OTEC are the most well developed.

It can be argued that most of the forms of renewable energy in renewable, and ocean wave energy in particular, originate from solar energy. The temperature difference in wind is caused by sun that results in wind flow. This flow of wind transfers its energy to the waves of the ocean. The mechanism of this energy transfer can be explained as simply the transmission of energy from the wind to the ocean in the form of friction. As wind flows over a body of water, then due to friction, ripples and eddies are formed on the water's surface. These then take the form and shape of waves, thus making it easier for the wind to grip the waves [12].

Below is the figure that exhibits wave phenomena at sea and their propagation:

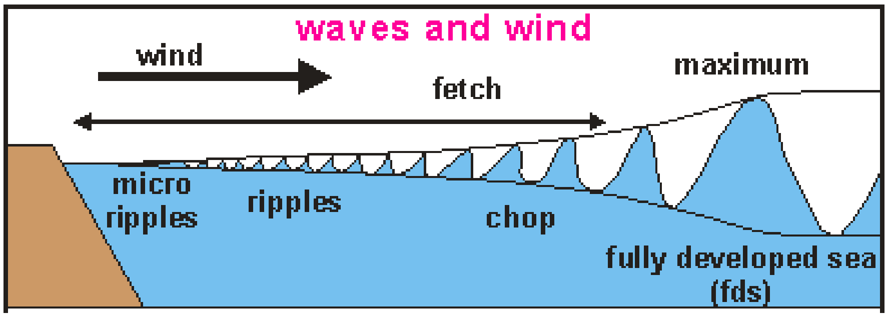

Figure 1: SCHEMATIC OF A SEA WAVE

The energy which can be extracted from the ocean is very easy to predict in comparison to energy extracted from wind and solar sources, and even as five day forecast of this can be prepared [13].

Wave energy is not evenly distributed across the world. It is estimated by the World Energy Council that approximately 2 Tera Watts can be extracted from oceans (wave power) which is almost numerically equivalent to the current energy required by the world. [14]

The diagram below shows Annual average wave energy flux in kW per meter of wave front. [14]

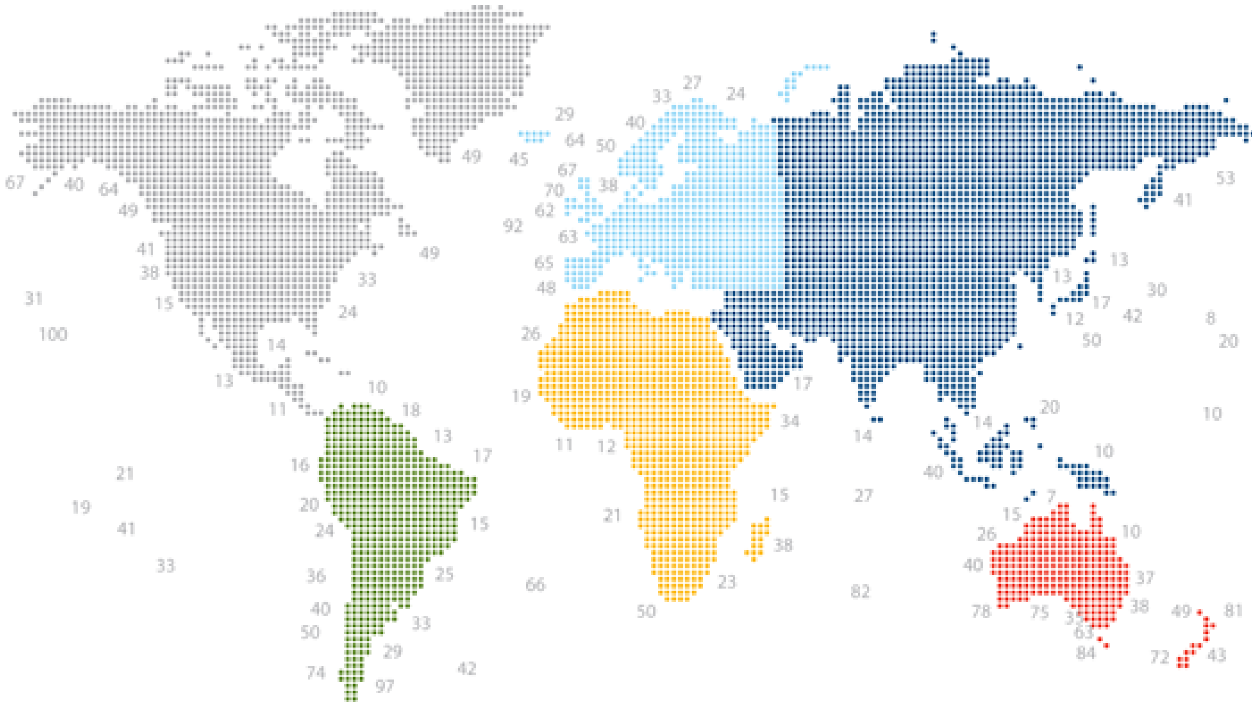

Figure 2: ANNUAL AVERAGE WAVE ENERGY FLUX IN KW PER METER OF WAVE FRONT

1.2.1 BENEFITS OF WAVE ENERGY:

Following are the significant benefits that wave energy presents when used as a renewable source of energy:

1. When compared with other sources of renewable energy it is noted that Sea waves have the highest density of energy [15].

2. The negative impact on the environment caused by this source of renewable energy is minimum [16].

3. The seasonal variation in wave energy follows the electricity demand trend in temperate climates [17].

4. Wave power devices have a capability to generate power 90% of the time, compared to 20-30% range for wind and solar renewable energy producing devices [18].

1.3 OBJECTIVE

1. Simulation of Surface Gravity Waves and their checking against analytical results based on Airy's Linear Wave Theory.

2. Wave forces computation upon wave – structure interaction to serve as the basis for design optimization.

3. Wave – Floating Buoy simulation for design optimization of Buoy under Pitch motion only.

Based on the above stated matter and importance of renewable energy resources particularly wave energy, numerical modeling simulation of surface gravity waves and their checking against analytical results based on Airy's Linear Wave Theory is carried out in this thesis work alongwith computation of wave forces on the floating buoy during wave buoy interaction which can serve as the basis for simulation of Wave – Floating Buoy interaction for design optimization of floating buoy in future.

2. LITERATURE REVIEWED

2.1 WAVES AND WATER MECHANICS

2.1.1 WATER WAVES & ITS CLASSIFICATION [19]

Waves are caused by disturbances and water waves define as the undulatory motion of water.

Waves are broadly classified as:

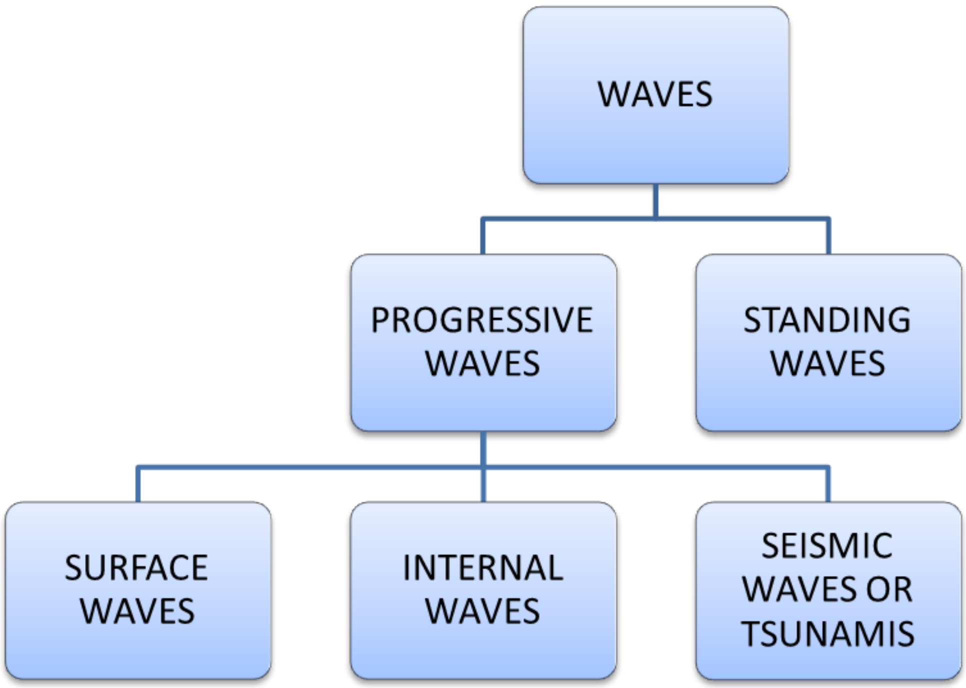

Figure 3: CLASSIFICATION OF WAVES

Surface Waves caused by movement of air / wind across the ocean surface. Also termed as "Surface Gravity Waves".

Internal Waves caused by movement of water of different densities.

Seismic Sea Waves or **Tsunamis** caused by movement of Sea Floor.

2.1.1.1 CLASSIFICATION OF SURFACE WAVES

Waves that are caused by wind flow over surface of oceans are broadly classified with respect to depth of water as follows:

1. Shallow Water Waves ($h \leq L/20$)
2. Intermediate Water Waves ($L/20 < h < L/2$)
3. Deep Water Waves ($h \geq L/2$)

2.1.2 CHARACTERISTICS OF WAVES [19], [20]

Following are the terms associated with wave characteristics:

1. **Still Water Line**: A flat or level section of a stream where no flow or motion of the current is desirable and the water is still.
2. **Crest**: The very topmost part of the wave.
3. **Trough**: The very lowest part of the wave.
4. **Wave Height**: The vertical distance between a wave crest and a trough.
5. **Wavelength**: The shortest distance between any two points on a wave that is in phase.
6. **Wave Period**: The time that a full wave takes to pass a given point.
7. **Wave Frequency**: The number of waves that pass a particular point in a given time period.
8. **Amplitude**: The characteristic height of a crest or depth of a trough.
9. **Significant Wave Height**: The average height of one third of the highest waves.

10. **Significant Wave Period**: The average height of one third of the highest waves.

11. **Phase Velocity**: Velocity of travelling waves.

12. **Group Velocity**: The velocity with which the overall shape of the wave's amplitudes propagates in space.

13. **Wave Number**: Spatial frequency of a wave.

14. **Wave Steepness**: The ratio of Wave Height to Wave Length.

15. **Relative Depth**: The ratio of Wave Height to Water Depth.

16. **Wave Regime**: The ratio of Water Depth to Wavelength.

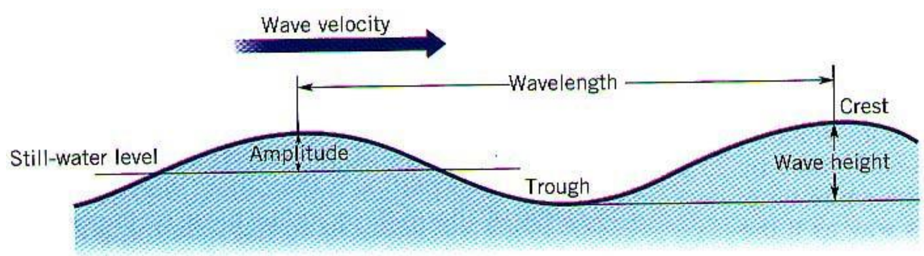

Figure 4: SCHEMATIC OF A WAVE

2.1.3 BREAKING OF WAVES

Waves breaking can occur in both shallow and deep water but due to different mechanisms. In Deep water, hydrodynamic instability causes waves to break. However, Shoaling, Refraction and Diffraction due to change in water depth causes waves to break in Shallow water. Waves breaking in shallow water can be classified into four Breaker types (Galvin; 1968) as [21]:

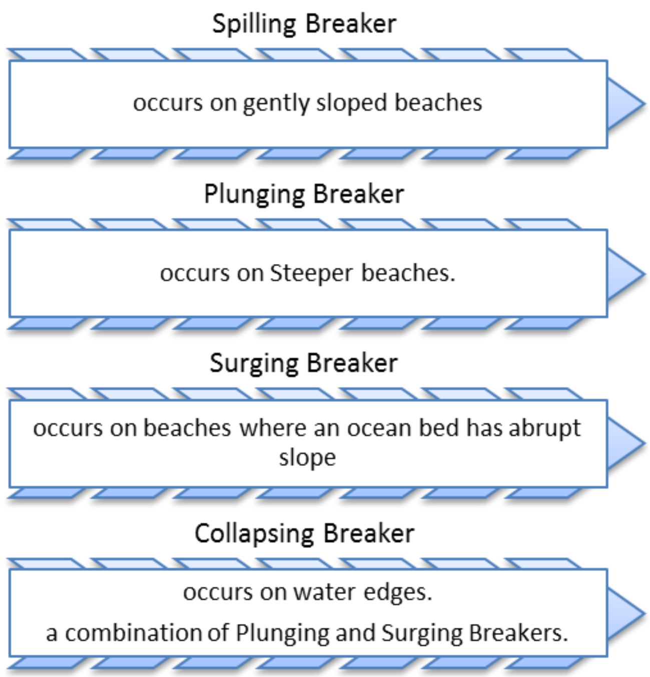

Figure 5: WAVE BREAKER TYPES DESCRIPTION

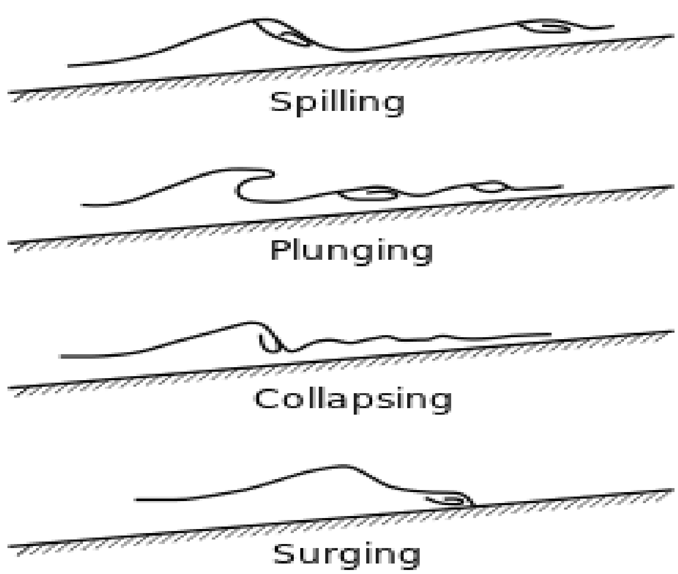

Figure 6: WAVE BREAKING TYPES [22]

2.2 OCEAN SURFACE WAVE THEORIES

Many scientists till now put their efforts to obtain mathematical equations to specify various parameters of ocean surface waves. In view of all the research conducted, wave theories for ocean surface waves are broadly classified into two major categories as follows:

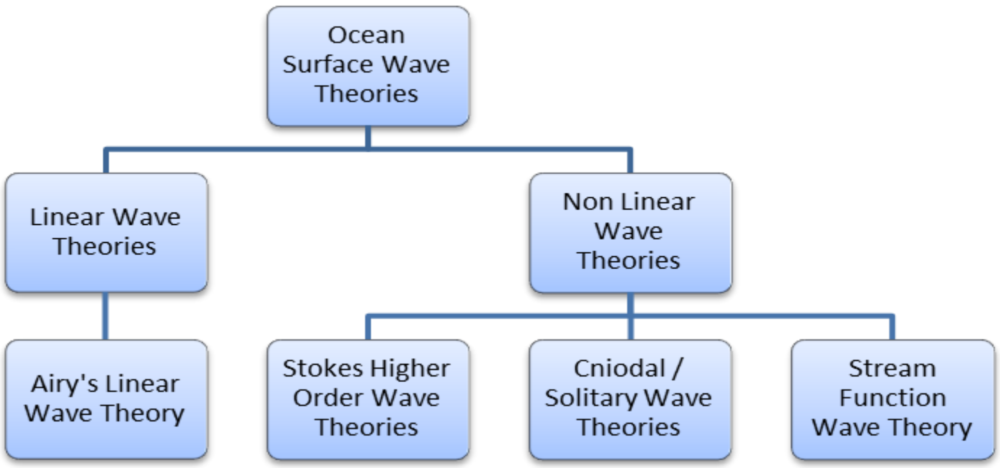

Figure 7: CLASSIFICATION OF OCEAN SURFACE WAVE THEORIES

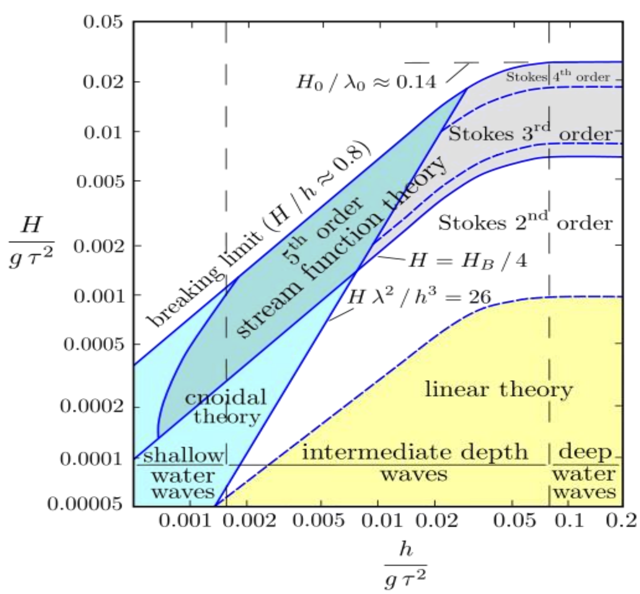

Figure 8: VALIDITY OF SEVERAL THEORIES FOR PERIODIC WATER WAVES [25]

2.2.1 AIRY'S LINEAR WAVE THEORY (LWT) [23]

Airy's Linear Wave Theory also known as Linear Wave Theory is based on Potential Flow Theory and gives linear description of wave's propagation of gravity waves based on the following assumptions:

- Flow is Irrotational.
- Fluid is Incompressible, Inviscid and homogeneous.
- Surface Tension of air-water interface is negligible.
- The CoriolisEffect due to the Earth's rotation may be neglected.
- Pressure at the free surface is uniform and constant.
- The particular wave being considered does not interact with any other water motion.
- The bottom boundary, or bed, is a horizontal, fixed impermeable boundary.
- The wave amplitude is small with respect to the water depth and the waveform is Invariant in time and space.
- Waves are plane or long-crested.

The theory describes the wave motions, including water particle displacement, water particle velocities and water particle accelerations, their kinematics and dynamics, which include wave pressures and their resultant forces and moments.

	Shallow water $\frac{d}{L} < \frac{1}{20}$	**Transitional water** $\frac{1}{20} < \frac{d}{L} < \frac{1}{2}$	**Deep water** $\frac{d}{L} > \frac{1}{2}$
1. Wave profile	Same as >	$\eta = \frac{H}{2}\cos\left[\frac{2\pi x}{L} - \frac{2\pi t}{T}\right] = \frac{H}{2}\cos\theta$	< Same as
2. Wave celerity	$C = \frac{L}{T} = \sqrt{gd}$	$C = \frac{L}{T} = \frac{gT}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$C_0 = \frac{L}{T} = \frac{gT}{2\pi}$
3. Wavelength	$L = T\sqrt{gd} = CT$	$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$L_0 = \frac{gT}{2\pi} = C_0 T$
4. Group velocity	$C_g = C = \sqrt{gd}$	$C_g = \frac{1}{2}\left[1 + \frac{4\pi d/L}{\sinh(4\pi d/L)}\right]C$	$C_g = \frac{C_0}{2} = \frac{gT}{4\pi}$
5. Water particle velocity (a) Horizontal (b) Vertical	$u_1 = \frac{H}{2}\sqrt{\frac{g}{d}}\cos\theta$ $u_2 = \frac{H\pi}{T}\left(1 + \frac{z}{d}\right)\sin\theta$	$u_1 = \frac{H}{2}\frac{gT}{L}\frac{\cosh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\cos\theta$ $u_2 = \frac{H}{2}\frac{gT}{L}\frac{\sinh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\sin\theta$	$u_1 = \frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$ $u_2 = \frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$
6. Water particle accelerations (a) Horizontal (b) Vertical	$a_1 = \frac{\pi H}{T}\sqrt{\frac{g}{d}}\sin\theta$ $a_2 = -2H\left(\frac{\pi}{T}\right)^2\left(1 + \frac{z}{d}\right)\cos\theta$	$a_1 = \frac{g\pi H}{L}\frac{\cosh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\sin\theta$ $a_2 = -\frac{g\pi H}{L}\frac{\sinh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\cos\theta$	$a_1 = 2H\left(\frac{\pi}{T}\right)^2 e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$ $a_2 = -2H\left(\frac{\pi}{T}\right)^2 e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
6. Water particle displacements (a) Horizontal (b) Vertical	$\xi = -\frac{HT}{4\pi}\sqrt{\frac{g}{d}}\sin\theta$ $\zeta = \frac{H}{2}\left(1 + \frac{z}{d}\right)\cos\theta$	$\xi = -\frac{H}{2}\frac{\cosh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\sin\theta$ $\zeta = \frac{H}{2}\frac{\sinh[2\pi(z+d)/L]}{\sinh[2\pi d/L]}\cos\theta$	$\xi = -\frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$ $\zeta = \frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
8. Subsurface pressure	$p = \rho g(\eta - z)$	$p = \rho g\eta\frac{\cosh[2\pi(z+d)/L]}{\cosh[2\pi d/L]} - \rho g z$	$p = \rho g\eta e^{\left(\frac{2\pi z}{L}\right)} - \rho g z$

Table 3: MATHEMATICAL SUMMARY OF AIRY'S LINEAR WAVE THEORY [23]

2.2.2 URSELL NUMBER [24], [26]

To identify the non-linearity of surface gravity waves, Fritz Ursell developed a dimensionless parameter known as Ursell Number. Mathematically, it is represented as:

$$U = \frac{H}{h}\left(\frac{\lambda}{h}\right)^2 = \frac{H\,\lambda^2}{h^3},$$

Equation 1

2.3 WAVE ENERGY CONVERTERS

Machinery able to exploit wave power is generally known as Wave Energy Converter. In quest of finding an alternate of conventional fossil fuel energy systems, research and development are under progress to find a mechanism and machinery that can extract renewable energy efficiently so that it can be utilized as an alternate to conventional fossil fuel energy. Among various renewable sources of energy, wave energy has higher energy density. Many organizations and scientists put their effort to find a device that can harness that great amount of energy.

Wave Energy Converters can be classified as follows:

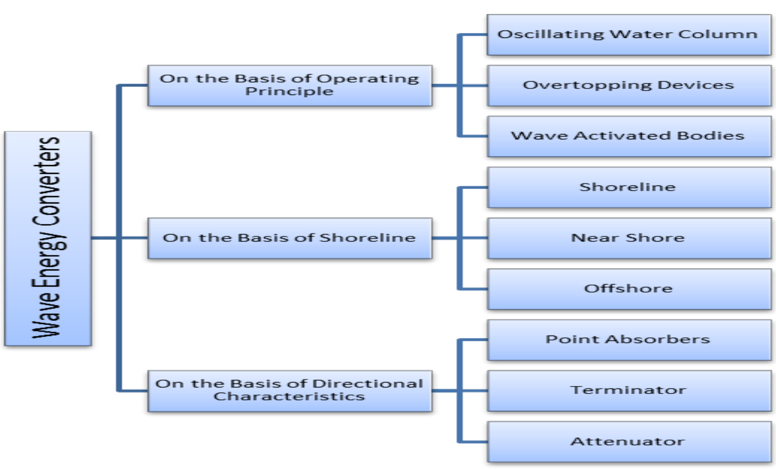

Figure 9: CLASSIFICATION OF WAVE ENERGY CONVERTERS

The existing Wave Energy Devices are summarized as under:

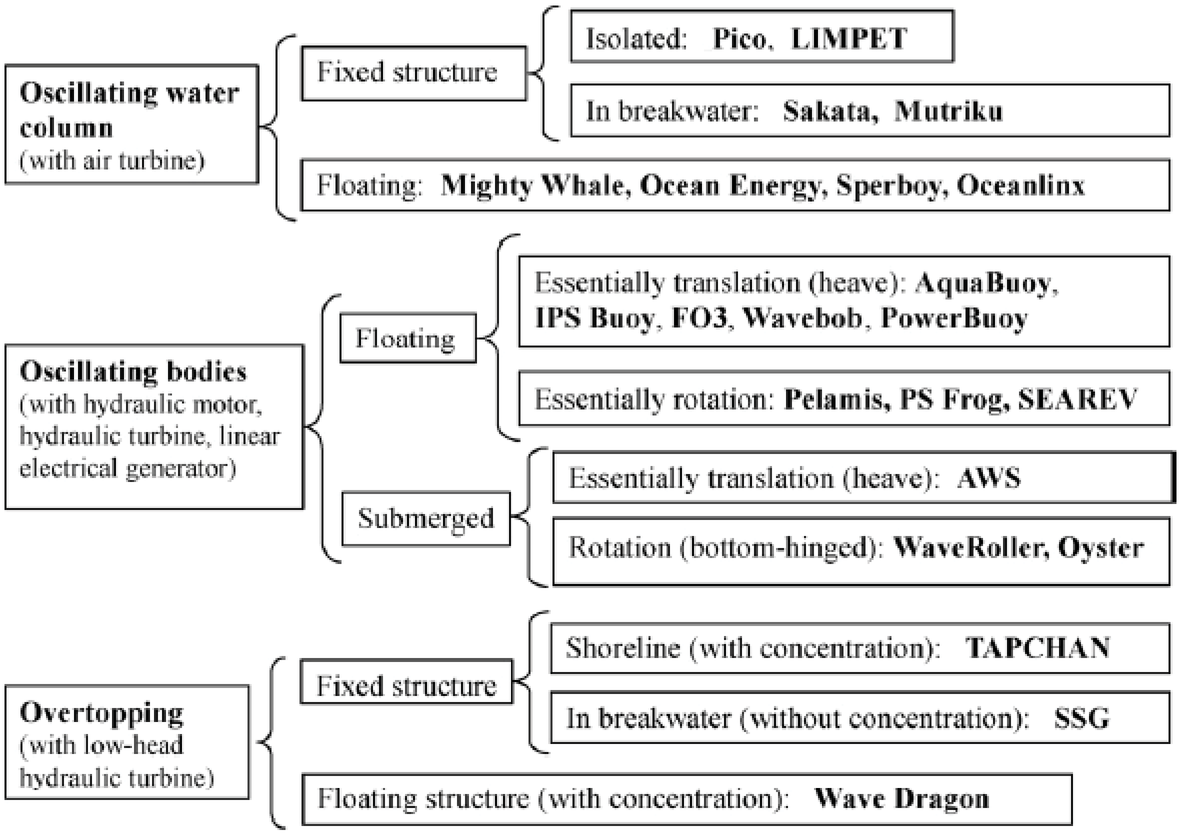

Figure 10: SUMMARY OF THE VARIOUS WAVE ENERGY CONVERTERS, IMAGE REPRODUCED FROM FALCAO (2010) [23]

2.4 RESEARCH PAPERS & THESIS REVIEWED

Isoldi [27] carried out 2D numerical simulation of regular waves through two different approaches by utilizing finite volume code, Ansys Fluent. The approaches used were different with respect to wave inlet boundary condition. Moving wall boundary condition with the aid of UDF alongwith dynamic meshing and velocity inlet function with the aid of UDF were the two numerical approaches used for wave generation. However, the remaining computational domain is solid wall with no slip condition for bottom and boundary opposite to wave generator and top is pressure outlet as atmospheric pressure. It was noted that both the approaches produced same result but moving wall boundary condition required 25% more computational processing time in comparison to velocity inlet function boundary condition.

Qngjie [28] employed Ansys Fluent as computational modeling tool to carry out the validation of numerical simulation of 2D linear regular waves against analytical and experimental outputs. Volume of Fluid as multiphase flow modeling technique was used with dynamic meshing to capture the free surface of waves. The computational domain was bounded by moving wall via a UDF as wave generator while bottom was considered as a solid wall with no slip condition, top as Atmospheric pressure inlet and porous media boundary condition was employed via a UDF at the opposite end of wave generator to avoid wave reflection. It was noted that the results obtained were similar to analytical and experimental ones for linear regular waves.

D. Malcangio [29] carried out the numerical simulation of surface waves through utilization of two finite volume codes namely Ansys CFX and Ansys Fluent to investigate the accuracy and efficiency of one solver over other solver. The simulation was carried out for 2D domain. The computational domain was bounded by moving wall via a UDF / CEL as wave generator to replicate piston type wave maker, top boundary as pressure outlet indicating atmospheric pressure condition in Ansys Fluent while as solid wall with no slip condition in Ansys CFX and remaining boundaries of domain are solid wall with no slip condition for both solvers. Fine Mesh was utilized at the interface while coarse mesh was used at the remaining domain. It was noted that both the numerical solvers produced surface elevation and velocity of waves in good agreement to analytical results. However, it was also noted that Ansys CFX will solve only 3D problems while Ansys Fluent has its own 2D solver and UDF in the form of displacement and velocity were required for CFX and Fluent respectively.

Anant Lal [30] employed Ansys CFX 3D solver to simulate regular waves for validation against analytical results of wave maker theory. The computational domain was bounded by moving wall via a CFX Expression Language command as wave generator while bottom and wave outlet boundaries were solid walls with no slip condition. However, the top boundary of domain was assigned atmospheric pressure. It was noted that the surface elevation of waves were independent of mesh density and turbulence model. It was also noted that the surface elevation obtained from numerical simulation were in good agreement with the surface elevation obtained from Wave Maker Theory.

Emmanuel [31] employed finite volume code, COMET fluid solver of CD-Adapco Group to coupled fluid – structure interaction simulation of a floating wave energy device (vertical cylinder) to assess power output in a 3D numerical wave flume by determining motion of the buoy from the dynamic solution of the fluid flow solver. Buoy was restricted to move in vertical direction only. FORTRAN language code was used to determine the instantaneous position of the buoy. COMET fluid solver was based on continuity equation; Navier stokes equation and bulk transport equation for volume fraction as governing equations. The numerical model was consisted of grids of finer mesh at the region of wave structure interaction and coarse mesh at far fields to damp out the waves, thus prevent reflection of waves. The numerical domain was bounded by piston wave generator to generate linear regular progressive wave of small amplitudes at one wall while the bottom, top and the other walls are considered as solid walls with no slip condition. Newton's second law of motion was used to describe the translator motion of the buoy. Finally, array of two buoys were also analyzed.

Yoon Huwan Choi [32] carried out numerical study on the design of floater to generate wave energy. Floater (horizontal cylinder) is a floating wave energy device and very much resemblance to Pelamis Offshore Wave Energy Converter. Pelamis utilizes kinetic energy horizontally and vertically due to their design. In their study, Ansys CFX for multiphase flow, a finite volume code was used to simulate the numerical model. Ansys CFX utilizes Reynolds Average Navier Stokes fluid flow solver, thus leading towards continuity equation, navier stokes equation and bulk transport equation as the governing equations. The solution domain is bounded by a piston type wave maker for generation of linear progressive waves of small amplitudes at one wall, while bottom wall is considered as solid wall with no slip condition, top wall is considered as wall with static atmospheric pressure due to open to atmosphere and the wall opposite to wave generator is considered as the wall with static pressure due to water depth. Buoy was allowed to move vertically (heave motion) and rotate along y-axis (pitch motion). Design of Floater was optimized by performing analysis for different floater lengths & diameter, wave heights and angular velocity. Absorbed power was computed by considering only the pitch motion. The rotational kinetic energy is given as,

$$K.E = (I\omega^2)/2$$

Where, I is the Moment of Inertia about y-axis and ω is the angular velocity of buoy.

Finnegan [23] performed wave structure interaction of a vertical cylinder in Time Domain by using Ansys CFX, finite volume method software and in Frequency Domain method by using Ansys AQWA, boundary element method software. Optimization of NWT was found to depend upon the wave height, wavelength, still water level / depth of water, maximum heave response of buoy and dimensions of buoy that were under study. Sphere of Influence meshing technique was utilized to optimize mesh at wave structure interfacing. Input boundary condition is the wave generator that generates linear sinusoidal progressive waves of small amplitudes in comparison with wavelengths. Bottom and boundary opposite to wave maker are solid walls with no slip condition while top wall is open to atmosphere. Wave dampening was achieved through modeling of boundary opposite to wave maker as beach slope with coarse mesh. Total time for simulation was ten times the wave period while the time step interval was achieved by dividing wavelength into 50 intervals. Linear regular waves interacted with floating buoy yields wave excitation forces, total wave forces on the structure in Time Domain while dynamic heave response and maximum stresses in Frequency Domain.

In view of above it is cleared that simulation of waves and their verification with the analytical results will provide the way to carry out the simulation of wave – structure interaction. Hence, in this thesis work simulation of surface gravity waves are carried out alongwith their verification with analytical results that is utilized for wave – buoy structure interaction for design optimization of floating buoy to enhance optimum power output.

3. MATHEMATICAL MODELING

3.1 GOVERNING EQUATIONS

Reynolds Averaged Navier Stokes Equation (RANS) also known as momentum equation and Continuity Equation are the two basic governing equations regarding this thesis work. The equations are mathematically represented as:

RANS Equation

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$$

Equation 2

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$$

Equation 3

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z$$

Equation 4

Continuity Equation

$$\frac{\partial \rho}{\partial t}+\nabla.(\rho U)=0$$

Equation 5

Where, ρ is the density of the mixture, p is the pressure, g is gravitational acceleration and u, v and w are velocity components along x, y and z axes respectively whereas μ is the dynamic viscosity of the fluid (mixture) and U is the velocity composed of velocity components.

3.2 ANSYS FLUENT

3.2.1 INTRODUCTION

Ansys Fluent, the product of Ansys Inc. is one of the renowned tools utilized for computational modeling of fluid flow, turbulence, heat transfer and reactions in many industries and organizations for research and design work. Based on the requirement of the marine or offshore industry or organizations, Ansys Fluent introduced modern features in Ansys Fluent Release 12 and onwards through which free surface gravity waves either linear or nonlinear having finite depth can easily be simulated without utilization of dynamic meshing. The basics of these functions of this finite volume based numerical tool are as follows:

3.2.2 VOLUME OF FLUID (VOF) MODEL

Volume of Fluid is the Multiphase model utilized for capturing free surface between two or more phases and based on the assumption that the working fluids are immiscible or not interpenetrating. The model utilizes phase fraction (also known as volume fraction) to determine the fractions of each phase in each cell of computational mesh. The equation for volume fraction is as follows;

$$\frac{\partial \alpha}{\partial t} + \nabla .(\alpha\, U) = 0$$

Equation 6

Where, U is the velocity composed of velocity components and α is the phase fraction. Phase fraction will vary between 0 and 1. For a cell completely fill with water, α is 1 and for a cell completely fill with air, αis 0.

The density of the mixture is utilized in the RANS and continuity equation and mathematically expressed as;

$$\rho = \alpha\rho_a + (1-\alpha)\rho_w$$

Equation 7

3.2.3 OPEN CHANNEL WAVE BOUNDARY CONDITION

Open Channel Wave Boundary Condition is an option available in Ansys Fluent through which surface gravity waves propagation is simulated by using velocity inlet as wave generation boundary condition instead of conventional method of moving wall via a UDF for wave generation boundary condition with the aid of dynamic meshing. This feature in Ansys Fluent is capable of generating shallow, intermediate and deep water waves with reference to Airy's Linear Wave Theory, Stokes Wave Theories and Cnoidal Wave Theory as inputted. Various checks regarding the applicability of wave theory for input wave conditions are also carried out before simulation runs which validate the correctness of wave and wave theory.

Numerical Beach Treatment is also an important feature that is available in this option which damped out the waves at bottom and wave outlet wall to avoid reflection.

Ansys Fluent carry out the Wave Breaking Limit check for wave regime which is represented as;

DIMENSIONLESS WAVE PARAMETER	MAXIMUM THEORETICAL LIMIT	MAXIMUM PRACTICAL LIMIT
Relative Depth	0.78	0.55
Wave Steepness	0.142	0.1

Table 4 ANSYS FLUENT WAVE BREAKING LIMIT CHECK

3.3 OCEAN WAVE ENERGY CONVERTER FABRICATED AT PNEC, NUST [33]

An OWEC has been developed at PNEC as an onshore device. Hydraulic mechanism was used to convert ocean energy absorbed by floating buoy into electrical energy. The system works in such a manner that the waves interaction causes the buoy to perform heave and pitch motion and the linkage transfers that motion of buoy into linear reciprocating motion of pistons in hydraulic cylinders which pressurized the fluid or oil in an accumulator that is used to run generator ultimately.

The schematic of the fabricated OWEC is as follows:

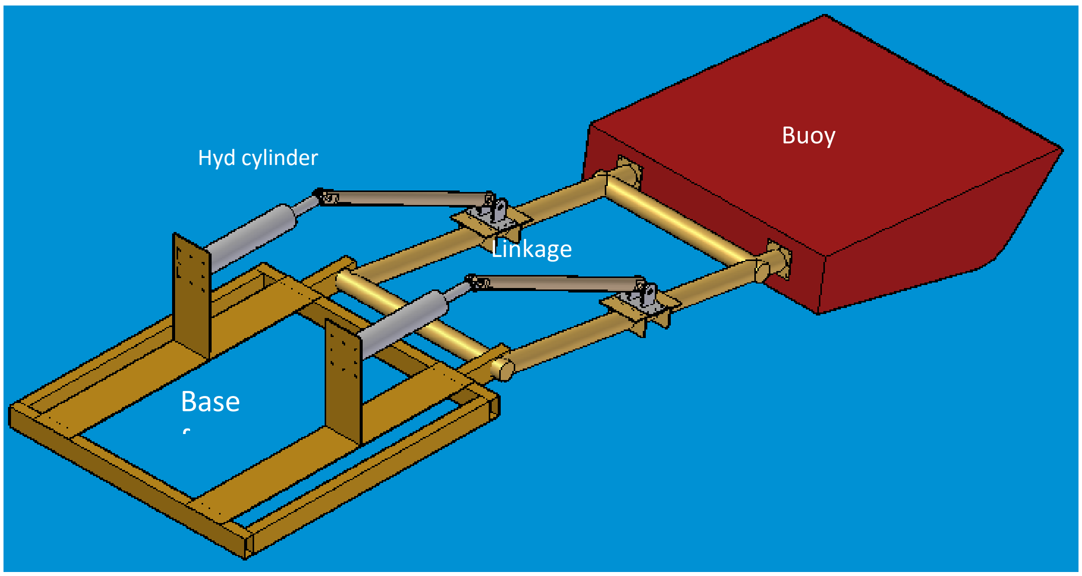

Figure 11: OWEC FABRICATED AT PNEC [33]

The schematic of the Power Take Off system of fabricated OWEC is as follows:

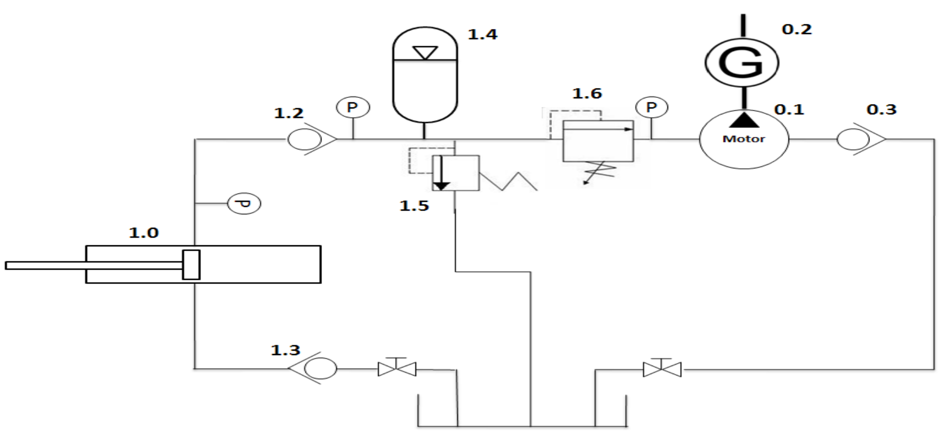

Figure 12: POWER TAKE OFF SYSTEM OF OWEC FABRICATED AT PNEC [33]

The components of this system are:

1.0 Hydraulic cylinder

1.2, 1.3, 0.3 Non Return Valve (NRV)

1.4 Gas filled hydraulic accumulator

1.5 Pressure relief valve

1.6 Pressure regulator

0.1 Motor

0.2 Generator

Note: The above utilized symbols and marking are as per the **ISO/R 1219 standard**.

3.3.1 FLOATING BUOY [33]

The dimensions of floating buoy of OWEC are as follows:

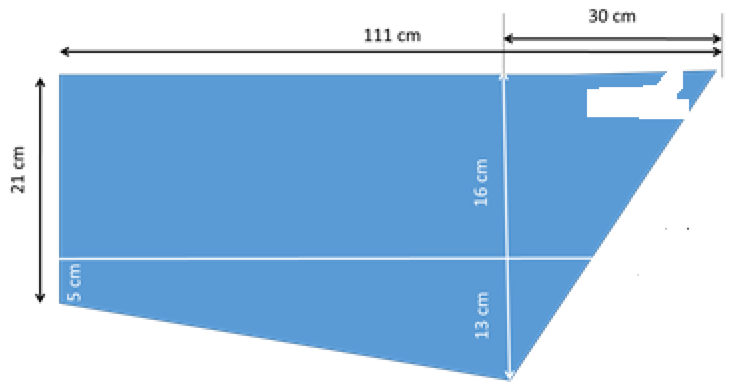

Figure 13: 2D DRAWING OF FLOATING BUOY FABRIACTED AT PNEC [33]

3.3.2 WAVE CHARACTERISTICS & ESTIMATED WAVE POWER [33]

Significant Wave Height = 0.3 m

Wave Speed = 1.73 m/s

Power per wave crest length = 360 W/m

4. SIMULATION AND RESULTS

4.1 NUMERICAL SIMULATION OF WAVES

In this thesis work, 2-D numerical simulation of waves is carried out by utilizing Ansys Fluent as numerical tool. Simulation is carried out in such a manner that verification of numerical results against analytical results is conducted for different volume fraction schemes available in Implicit Time discretization scheme of multiphase modeling of Ansys Fluent to find out best scheme which produced accurate results and then that scheme is utilized to perform grid independency.

4.1.1 VOLUME FRACTION SCHEME CASES

The cases for Schemes of Volume Fraction are summarized as under:

Case 1 – First Order Upwind

Case 2 – Second Order Upwind

Case 3 – Compressive

Case 4 – Modified HRIC

Case 5 - QUICK

The subject schemes are the spatial discretization schemes in Ansys Fluent that supports the solution of volume fraction equations through time discretization schemes of Ansys Fluent so that the tracking of interface(s) between the phases can be carried out through solution of continuity equation for the volume fraction. The above stated schemes are briefly described as:

First Order Upwind Scheme is that which produces results accuracy to first order and interpolates or calculates field variable value at the cell faces by assuming that all cell center values are same throughout the cell.

Second Order Upwind Scheme produces an accuracy of results to second order and cell faces values are interpolated or calculated through Taylor Series Expansion of cell centroid solution.

QUICK Scheme produces an accuracy of results upto higher orders for cell face values and their calculation based on weighted average of second order upwind and central interpolations of the variable.

Modified HRIC Scheme is a composite NVD scheme that consists of a nonlinear blend of upwind and downwind differencing.

Compressive Scheme is the second order reconstruction scheme that is based on piece wise linear scheme for interpolation.

Based on the above stated descriptions, numerical wave simulation is carried out in this thesis work to identify which scheme has more accuracy.

4.1.2 GEOMETRY SET UP

The dimensions of numerical model for simulation of waves are dependent upon the following:

Type of waves required to simulate

Amplitude of Waves

Still Water Level

Damping of Waves (Dissipation of Wave Energy)

Length and Height of Fabricated Buoy (Object)

Distance from Wave Generator at which Standing Waves becomes negligible (Dean & Dalrymple)

Based on the above factors, a rectangular geometrical domain of 10m height and 50m wide is developed for wave's simulation. The schematic is shown as;

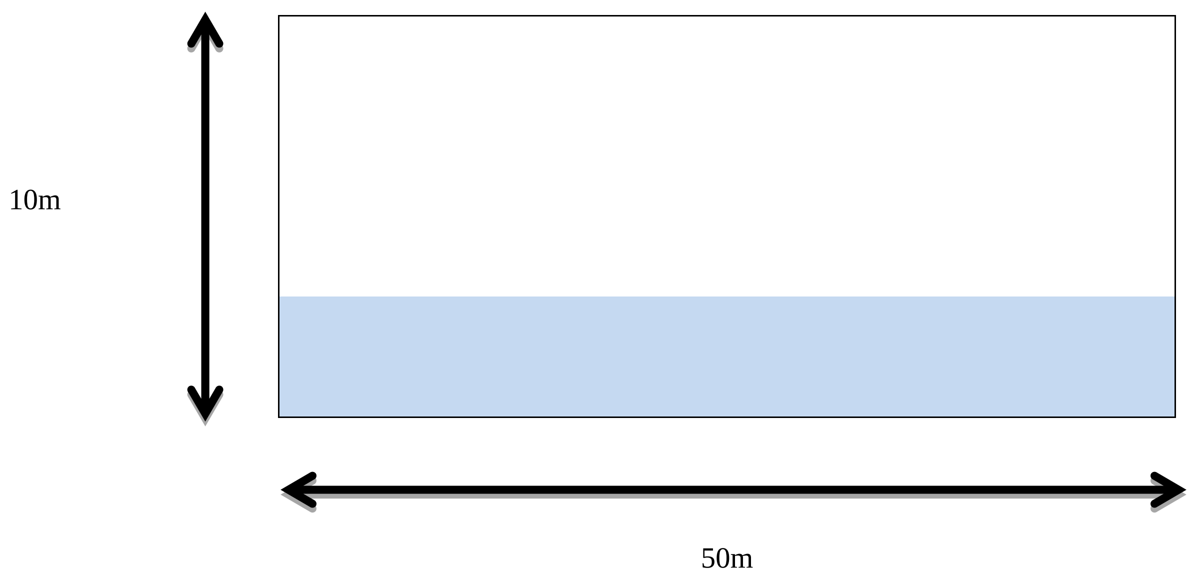

Figure 14: NUMERICAL WAVE TANK

4.1.3 MESH SET UP

4.1.3.1 FOR DIFFERENT VOLUME FRACTION SCHEMES

The square structured mesh having **871** numbers of cells is created for subject scenario. The mesh is shown as:

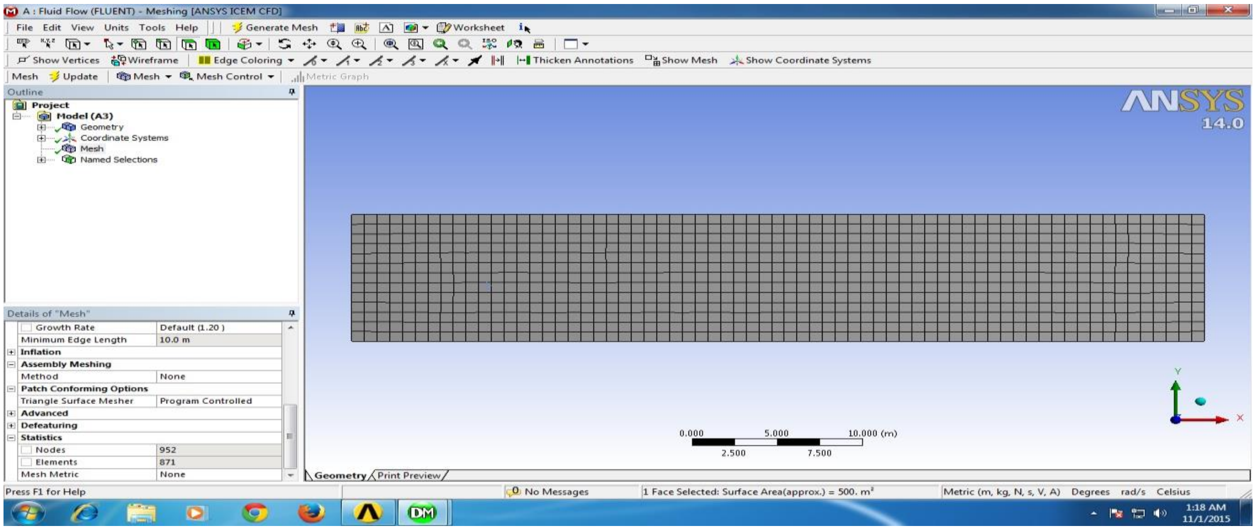

Figure 15: NUMERICAL WAVE TANK MESHING FOR USE IN SIMULATION OF WAVES FOR DIFFERENT VOLUME FRACTION SCHEMES

Below is the figure showing Mesh Checking:

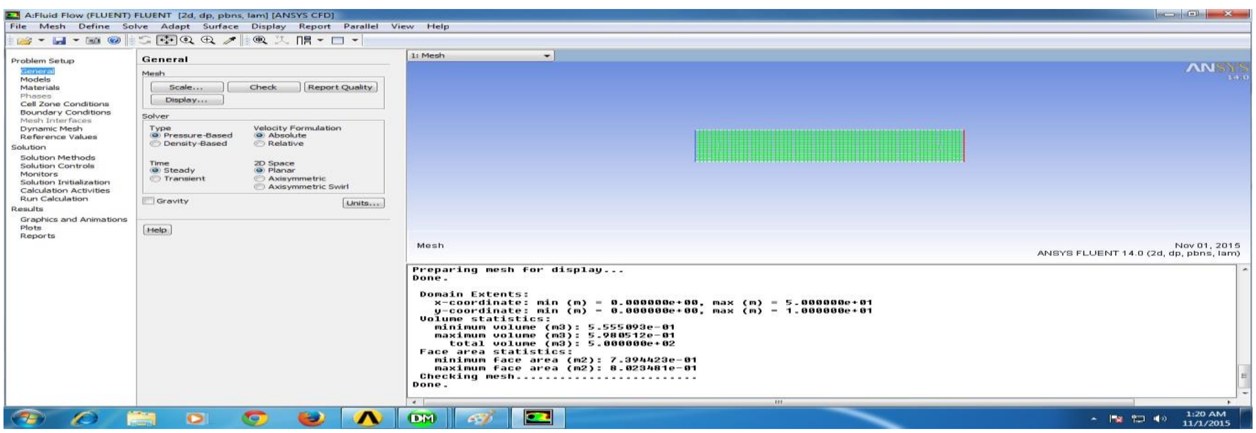

Figure 16: MESH CHECKING IN ANSYS FLUENT FOR FIGURE 15 MESH

4.1.3.2 FOR GRID INDEPENDENCY

The square structured meshes are used to carry out the grid independency of waves with different quantity of cells as listed below:

Case	Mesh Size	Total Cells
6	Coarse	80

7	Medium	312
8	Normal	871

Table 5 MESH TABLE OF NWT FOR GRID INDEPENDENCY CHECK

Schematic of meshes are as follows:

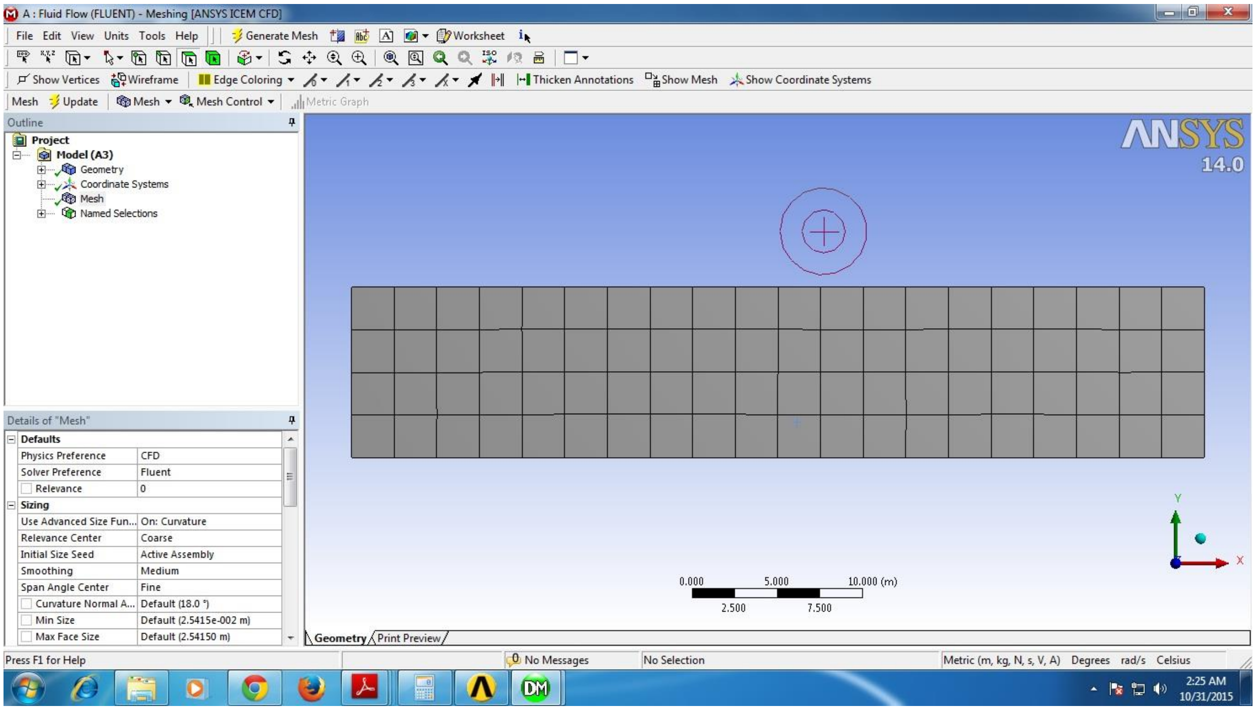

Figure 17: MESH OF NWT FOR CASE NO. 06 OF TABLE 5

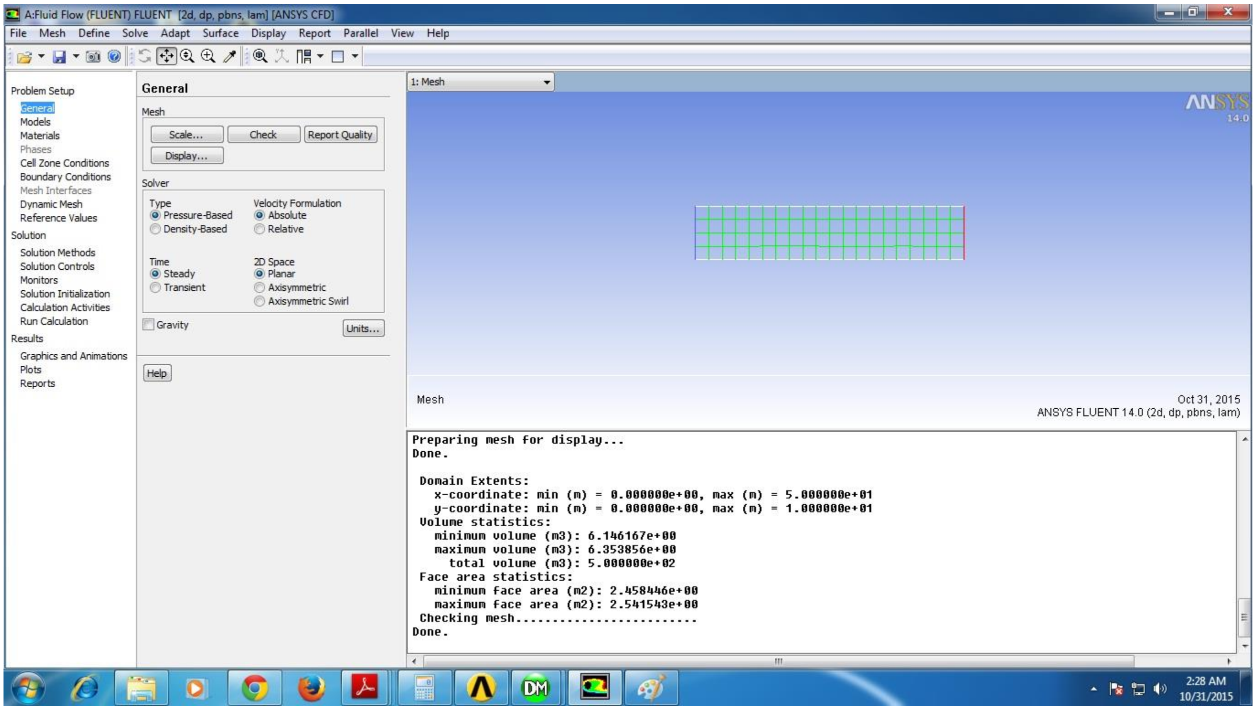

Figure 18: MESH CHECKING IN ANSYS FLUENT FOR FIGURE 17 MESH

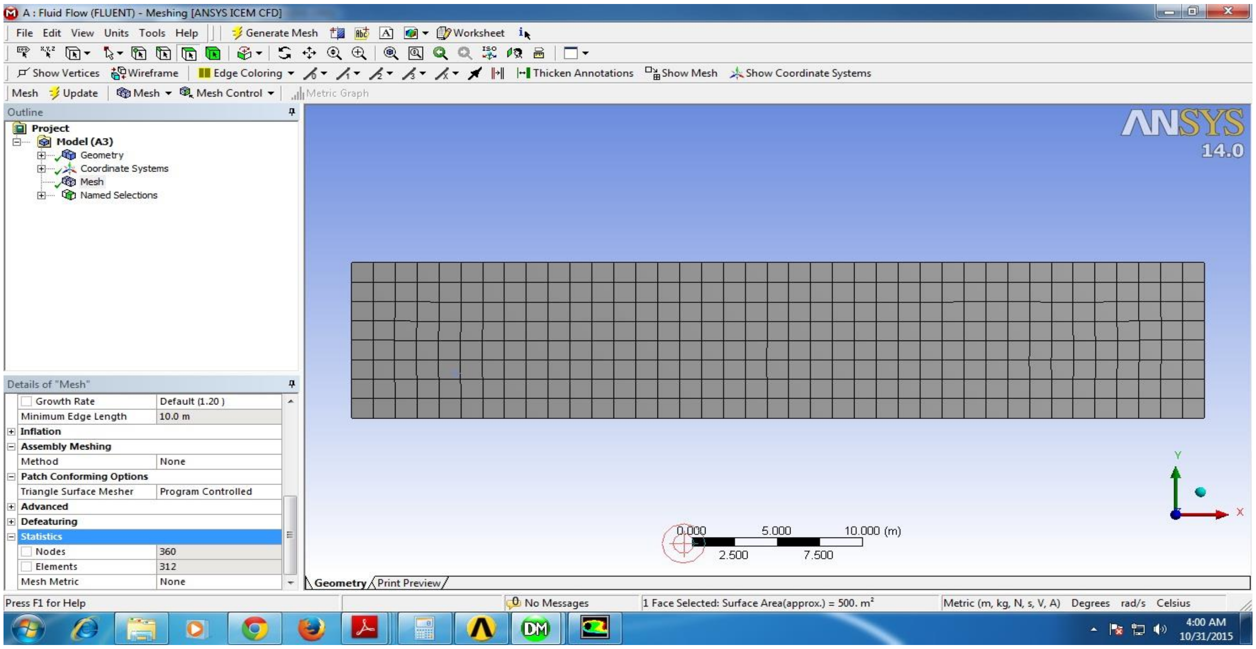

Figure 19: MESH OF NWT FOR CASE NO. 07 OF TABLE 5

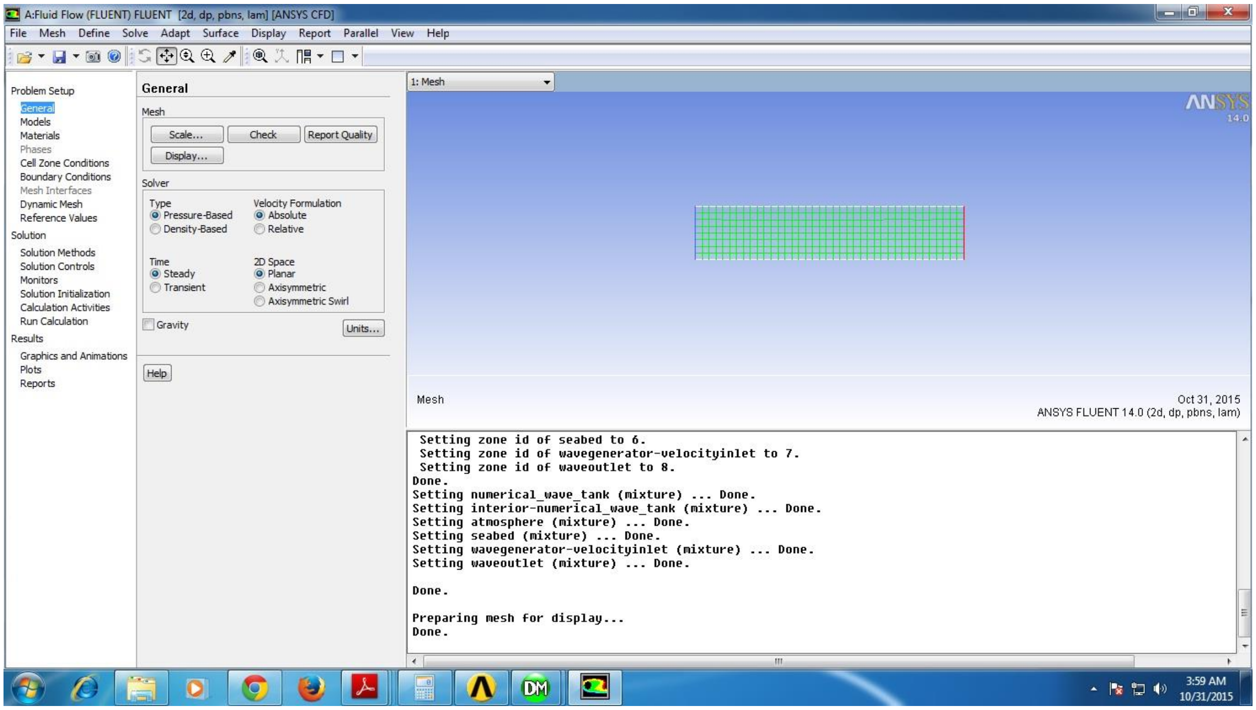

Figure 20: MESH CHECKING IN ANSYS FLUENT FOR FIGURE 19 MESH

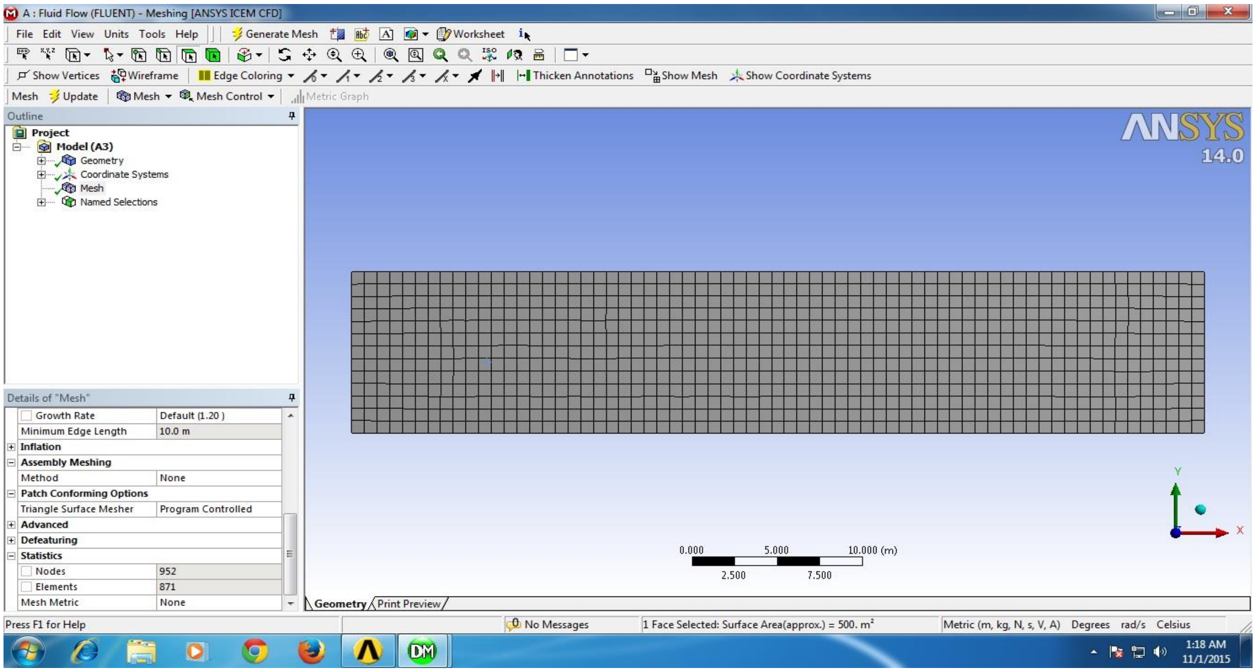

Figure 21: MESH OF NWT FOR CASE NO. 08 OF TABLE 5

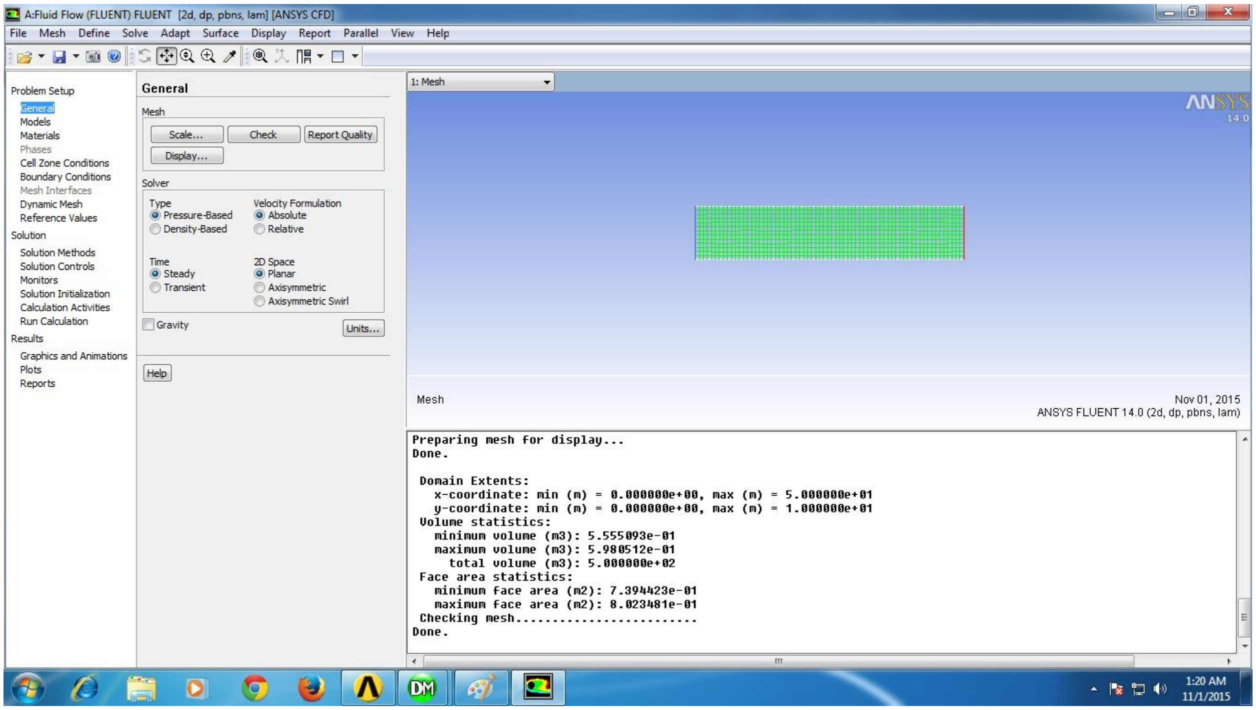

Figure 22: MESH CHECKING IN ANSYS FLUENT FOR FIGURE 21 MESH

4.1.4 PHYSICS & SOLUTION SET UP

4.1.4.1 ANSYS FLUENT MODEL

Multiphase Model, Volume of Fluid alongwith Implicit Time Discretization Scheme, Implicit Body Force and Open Channel Wave Boundary condition is utilized for waves simulation.

4.1.4.2 CONDITIONS & PROPERTIES

Conditions & Properties used in the CFD set up are as follows:

- Surface Tension at the air – water interface is negligible.
- Air Temperature: 25^0C

- Air Density: 1.185 kg/m^3

- Model is homogeneous with isothermal heat transfer condition.

- Water Temperature: 25^0C

- Viscosity of water: 8.899×10^{-4} kg/ms

- Density of Water: 1025 kg/m^3

4.1.4.3 NUMERICAL DOMAIN BOUNDARY CONDITIONS

Till now various approaches are used for defining boundary conditions for numerical simulation of waves. The boundary conditions used are as:

Left Boundary Condition; Velocity Inlet Boundary Condition is used due to selection of Open Channel Wave Boundary Condition, an Ansys Fluent advanced feature for generation of surface gravity waves of finite depth.

Bottom Boundary Condition; is assigned a solid wall with no slip condition.

Top Boundary Condition; is assigned a solid wall with no slip condition.

Right Boundary Condition; is assigned a solid wall boundary condition.

Numerical Beach Treatment is used to damp out the waves at the bottom of tank and at the wave outlet region to avoid reflection.

During literature review, it was noted that most of the researchers employed a UDF with moving mesh technique for wave's generation in Ansys Fluent. However, dissipation of wave's energy at the end of Numerical Wave Tank was accomplished by utilization of coarse mesh at still water line and slope beach at wave outlet from Finnegan [23], porous media via a UDF at wave outlet by Qingjie. Du [28], coarse meshing towards the wave outlet domain by Malcangio [29], slope beach with coarse mesh in the wave outlet domain by Anant Lal [30], coarse meshing with far field by Emmanuel [31] and entire domain of same mesh by Isoldi [27].

4.1.4.4 WAVE PARAMETERS AND CONDITIONS USED IN VELOCITY INLET BC

Uniform Velocity Magnitude = 1.73 m/s

Amplitude = 0.15 m

Free Surface Level (Still Water Level) = 3 m

Wave Theory = First order Airy's Wave Theory

Waves = Shallow / Intermediate

4.1.4.5 SOLUTION CONTROLS AND METHODOLOGY

The Solution Methodology details utilized for different volume fraction schemes and grid independency cases are as follows:

Solution Controls		Options Adopted
Pressure Velocity Coupling		PISO
Spatial Discretization	Gradient	Least Square Cell Based
	Pressure	Body Force Weighted
	Momentum	Second Order Upwind
	Transient Formulation	Bounded Second Order Implicit with NITA
Volume Fraction Scheme		As per Case Nos. 1, 2, 3, 4, 5.

	Compressive
Solution Initialization	Standard
Open Channel Initialization Method	Wavy
Time Stepping Method	Fixed
Time Step Size	0.001
No. of Time Steps	5000

Table 6 SUMMARY OF SOLUTION CONTROLS & METHODOLOGY USED IN SIMULATION

4.2 WAVE STRUCTURE INTERACTION FOR WAVE FORCE COMPUTATION ON BUOYS

In this numerical thesis, wave forces on buoys of different dimensions also computed through wave structure interaction alongwith simulation of waves alone. Ansys CFX, a commercially available numerical tool is utilized for wave structure interaction for calculation of wave forces on buoys at different time. Two buoys were used in this simulation to identify the forces on their frontal surface.

4.2.1 BUOY GEOMETRY SET UP

The buoy used in this simulation has following dimensions:

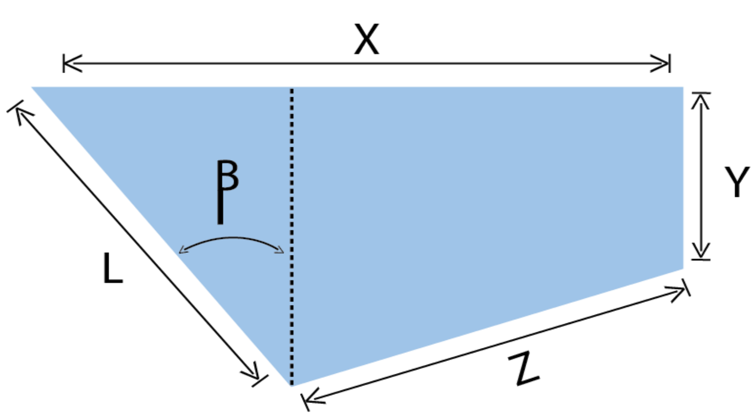

Figure 23 FLOATING BUOY

Buoy	X (mm)	Y (mm)	Z (mm)	L (mm)	β
1	978	210	814	335	30°
2	1110	210	814	417	46°

Table 7 FLOATING BOUY DIMENSIONS USED IN WAVE STRUCTURE SIMULATION

4.2.1 MESH SET UP

Mesh set up for both buoys are simple blocked mesh as shown:

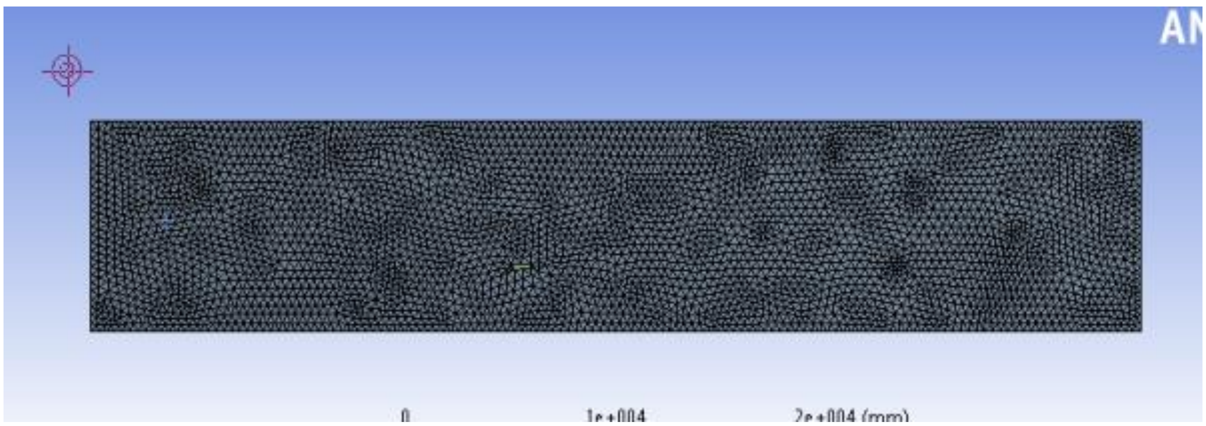

Figure 24 MESH OF DOMAIN FOR WAVE STRUCTURE INTERACTION

4.2.2 PHYSICS AND SOULTION SET UP

Volume of Fluid (VOF) model of Multiphase Fluid Model of Ansys CFX is used in this simulation while conditions and properties of fluids are same as used in Ansys Fluent alongwith Numerical Domain Boundary Conditions. Wave Parameters are also same as used in Ansys Fluent simulation while the solution controls has little changes with respect to Ansys CFX recommended practices.

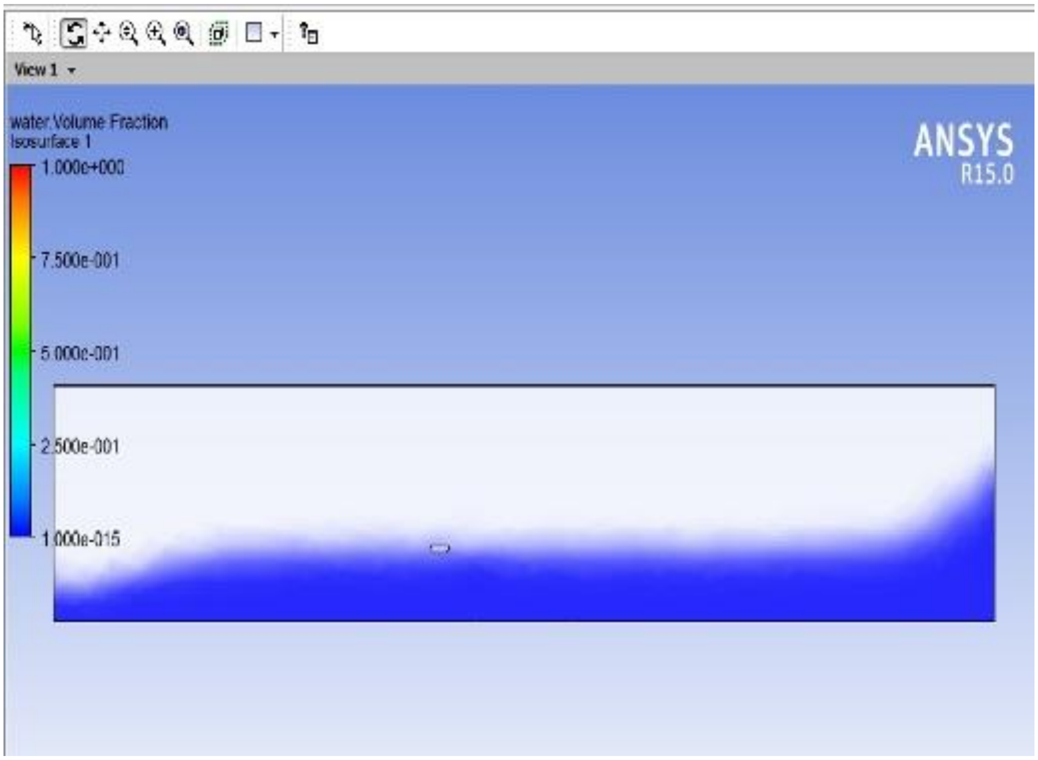

Figure 25 WAVE STRUCTURE INTERACTION COUNTOURS PLOT

4.3 RESULTS

4.3.1 NUMERICAL WAVES SIMULATION

4.3.1.1 VOLUME FRACTION SCHEMES

4.3.1.1.1 CASE NO. 01 – FIRST ORDER UPWIND SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the FOUW produces approximately the same plot as analytical one with maximum reported error of 7%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

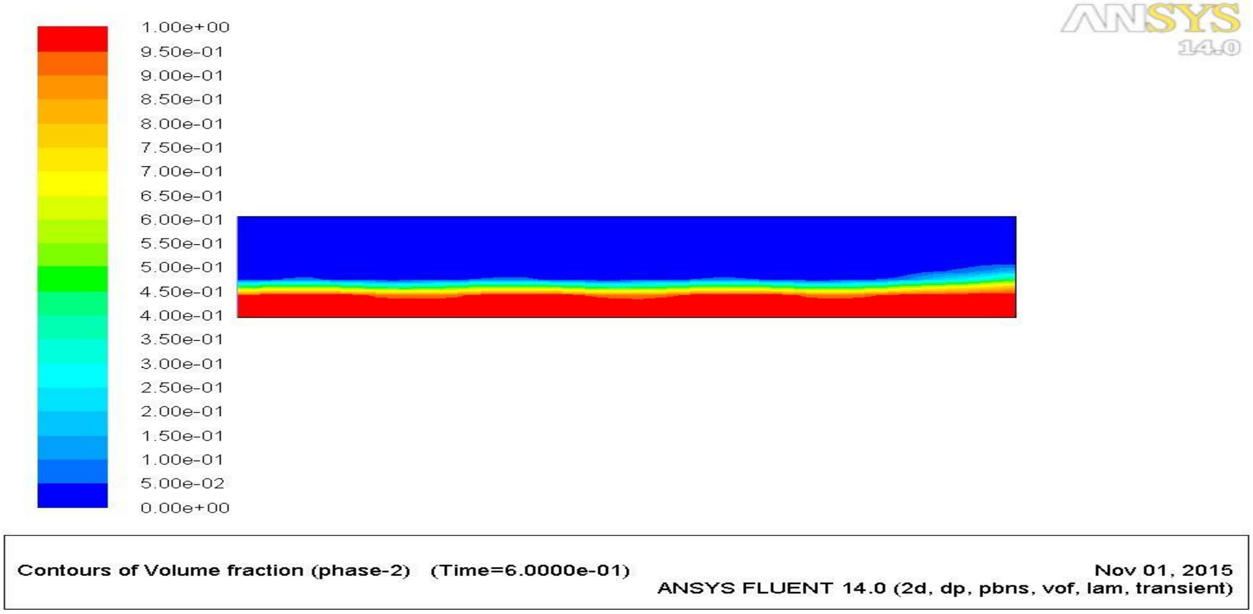

Figure 26: CONTOURS OF WATER FRACTION FOR CASE NO. 01

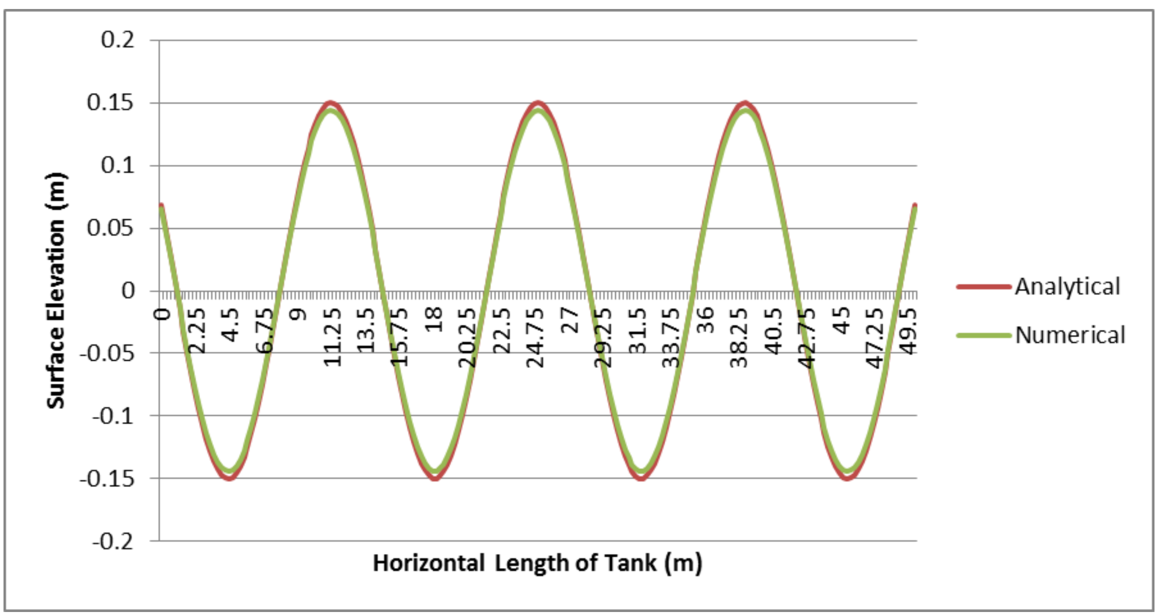

Figure 27: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 01

4.3.1.1.2 CASE NO. 02 – SECOND ORDER UPWIND SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the SOUW produces approximately the same plot as analytical one with maximum reported error of 6.3%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

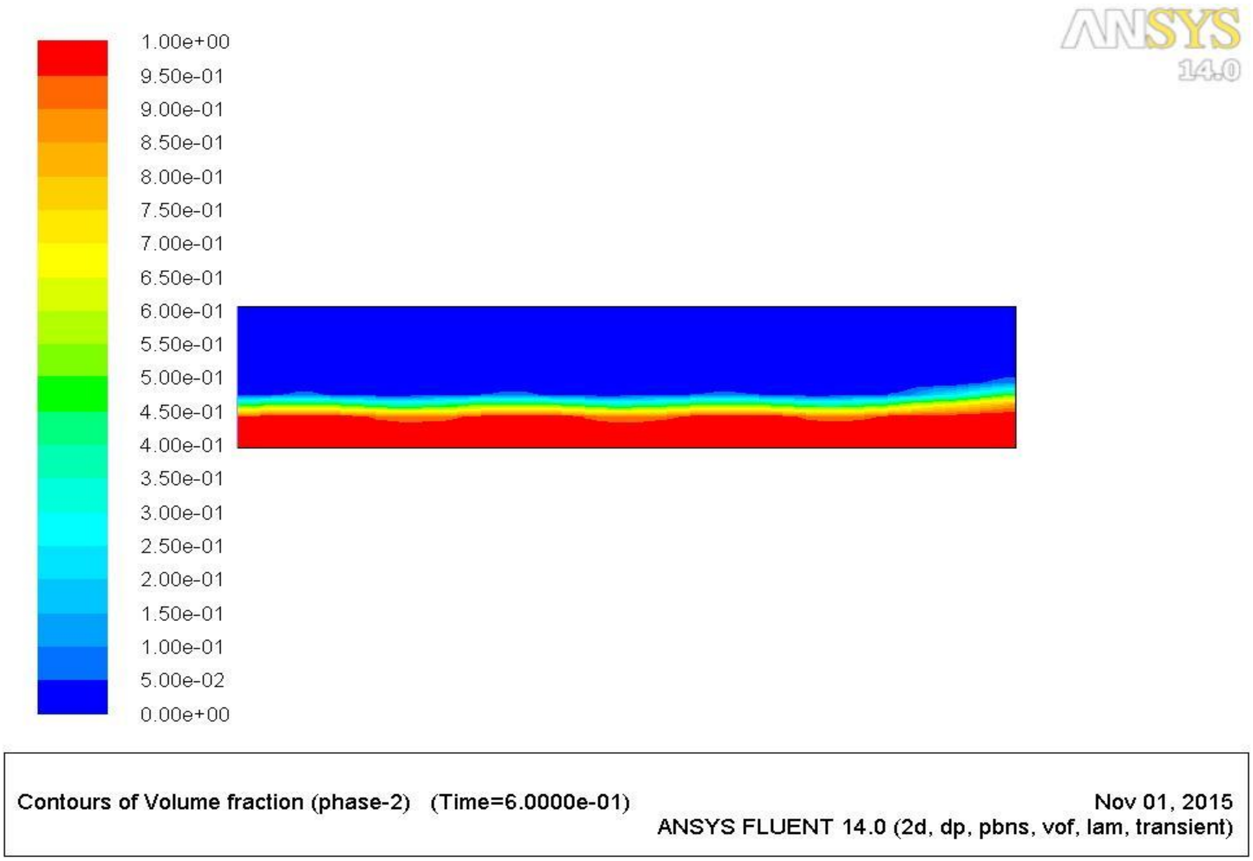

Figure 28: CONTOURS OF WATER FRACTION FOR CASE NO. 02

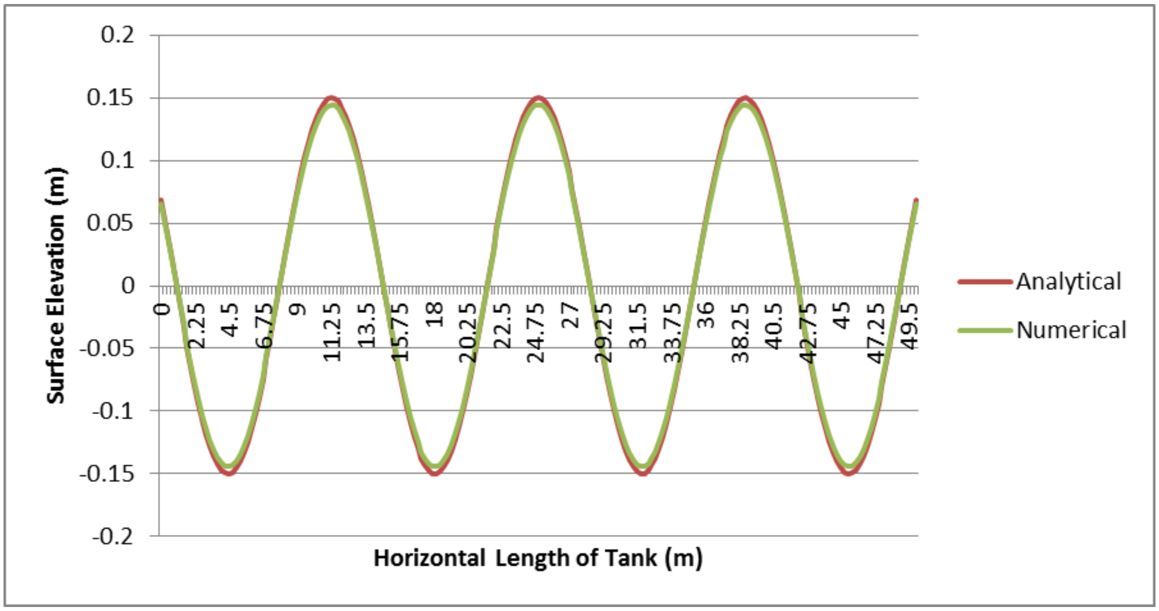

Figure 29: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 02

4.3.1.1.3 CASE NO. 03 – COMPRESSIVE SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the Compressive Scheme produces approximately the same plot as analytical one with maximum reported error of 5%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

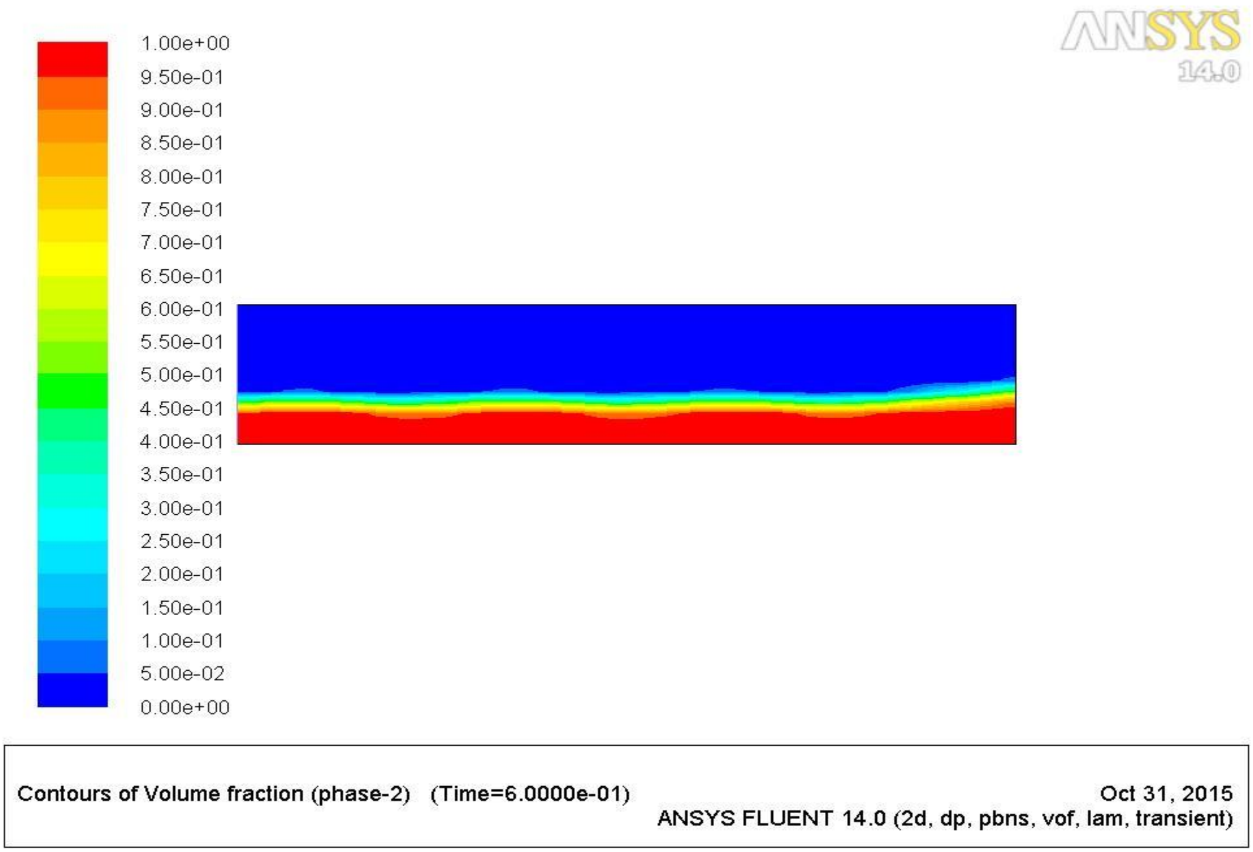

Figure 30: CONTOURS OF WATER FRACTION FOR CASE NO. 03

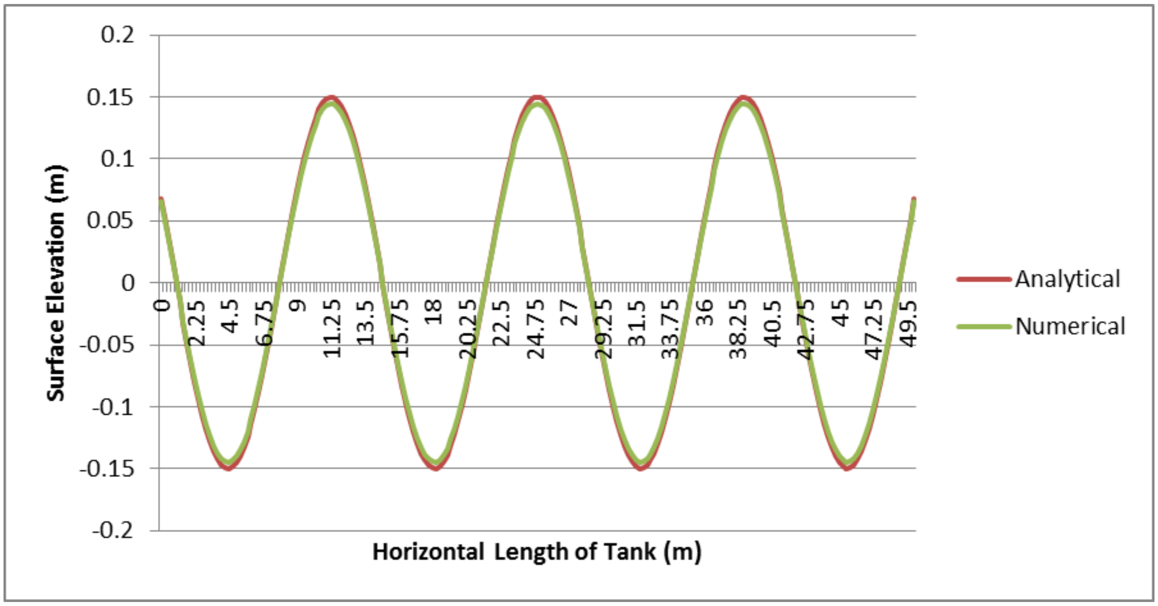

Figure 31: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 03

4.3.1.1.4 CASE NO. 04 – MODIFIED HRIC

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the Modified HRIC Scheme produces approximately the same plot as analytical one with maximum reported error of 5.4%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

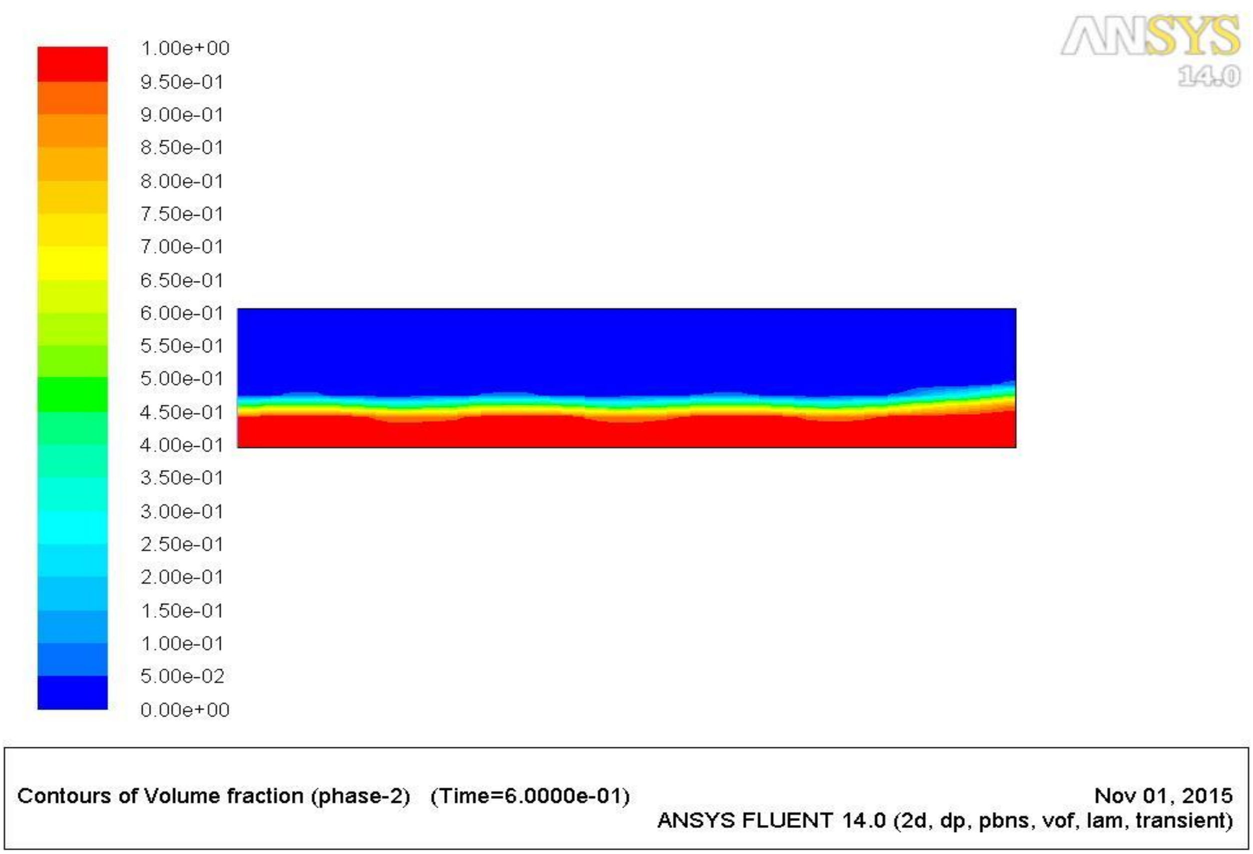

Figure 32: CONTOURS OF WATER FRACTION FOR CASE NO. 04

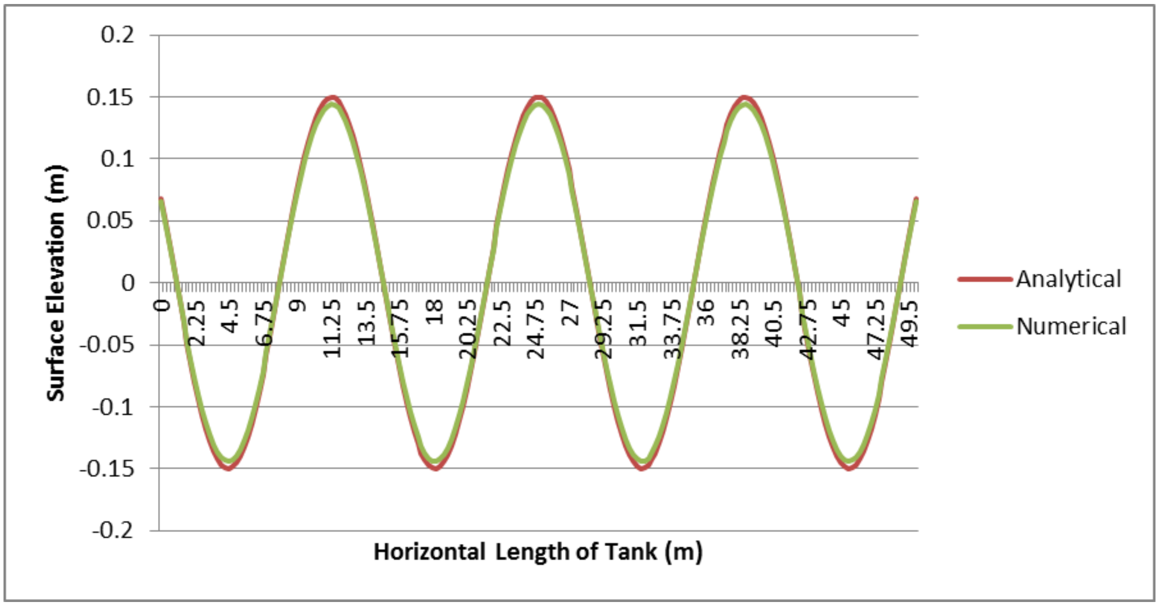

Figure 33: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 04

4.3.1.1.5 CASE NO. 05 – QUICK

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the QUICK produces approximately the same plot as analytical one with maximum reported error of 6%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

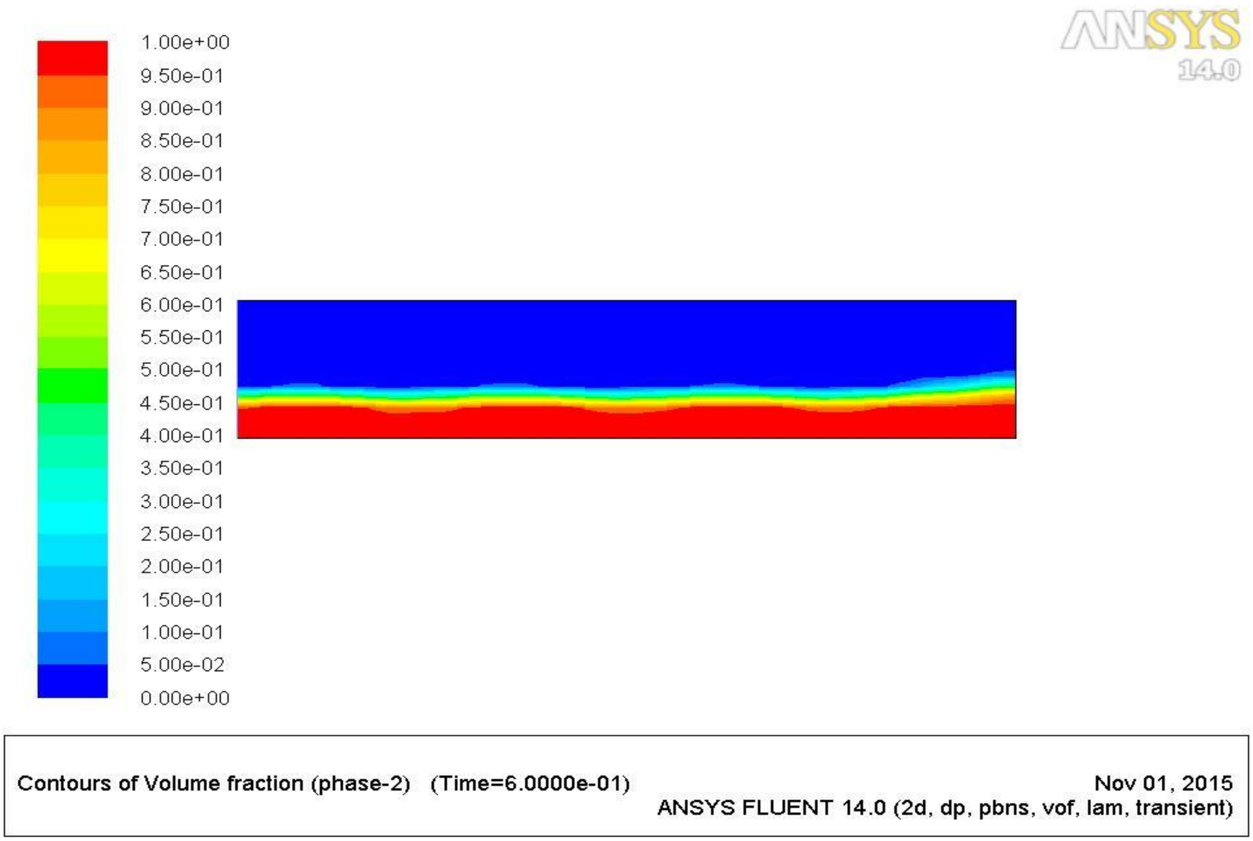

Figure 34: CONTOURS OF WATER FRACTION FOR CASE NO. 05

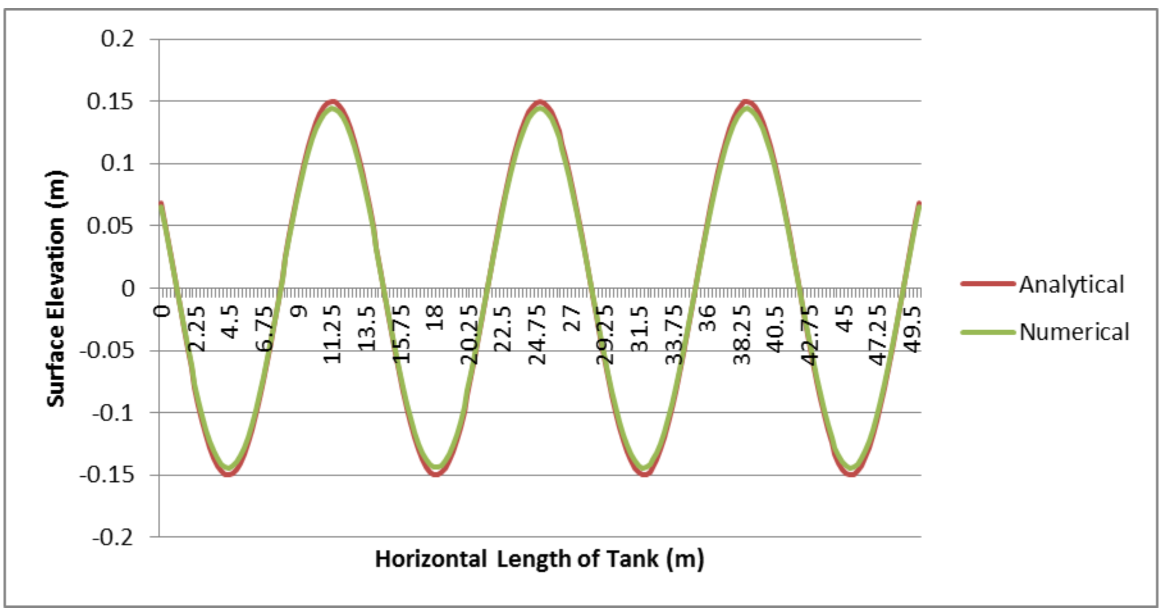

Figure 35: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 05

4.3.1.2 GRID INDEPENDENCY

4.3.1.2.1 CASE NO. 06 – FINE MESH WITH COMPRESSIVE SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the Compressive Scheme with Fine Mesh produces approximately the same plot as analytical one with maximum reported error of 5%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

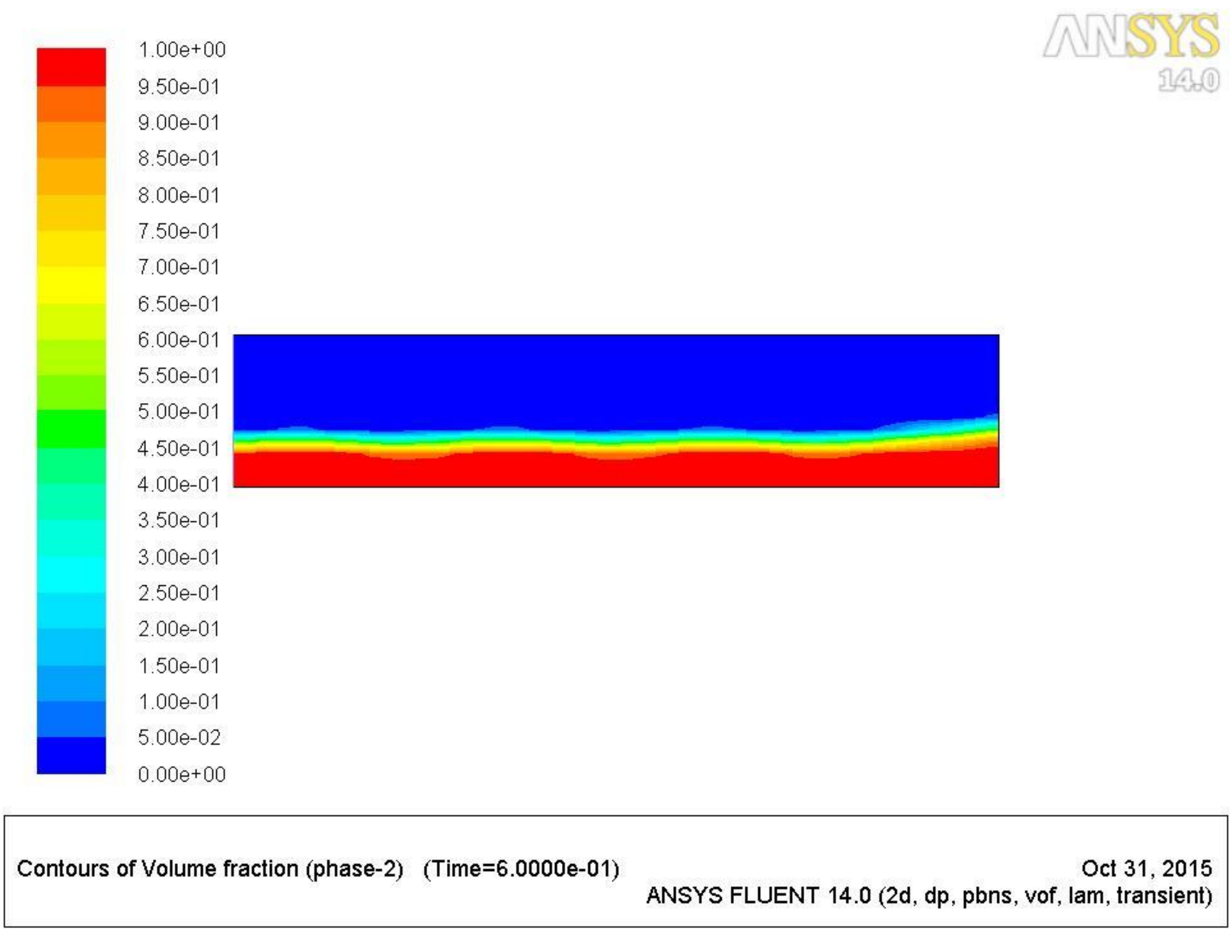

Figure 36: CONTOURS OF WATER FRACTION FOR CASE NO. 06

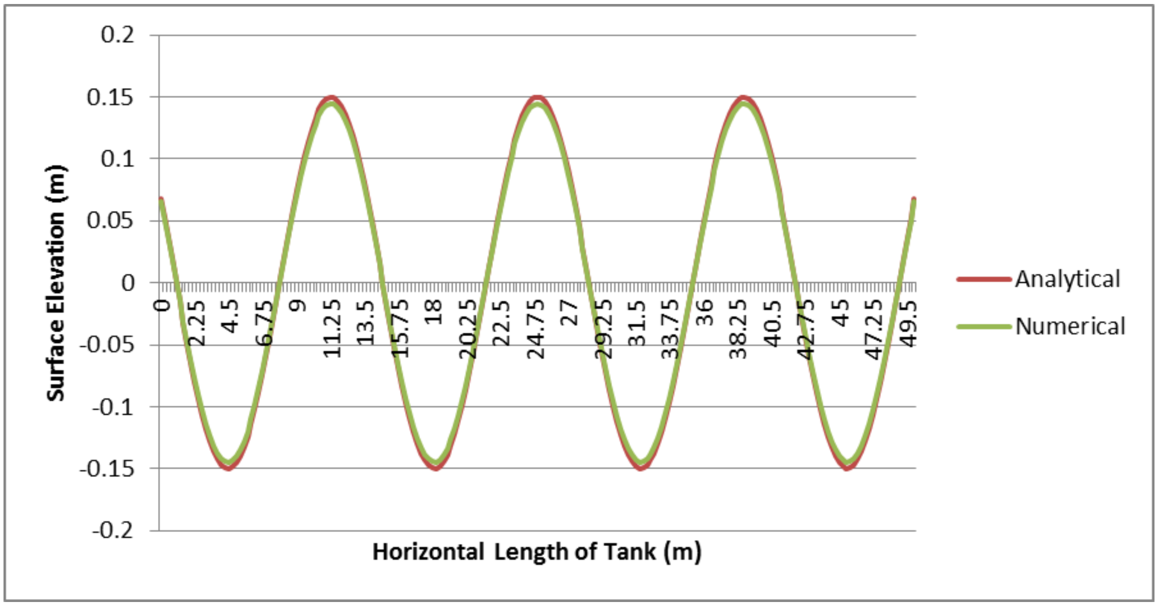

Figure 37: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 06

4.3.1.2.2 CASE NO. 07 – MEDIUM MESH WITH COMPRESSIVE SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the Compressive Scheme with Medium Mesh produces approximately the same plot as analytical one with maximum reported error of 6%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

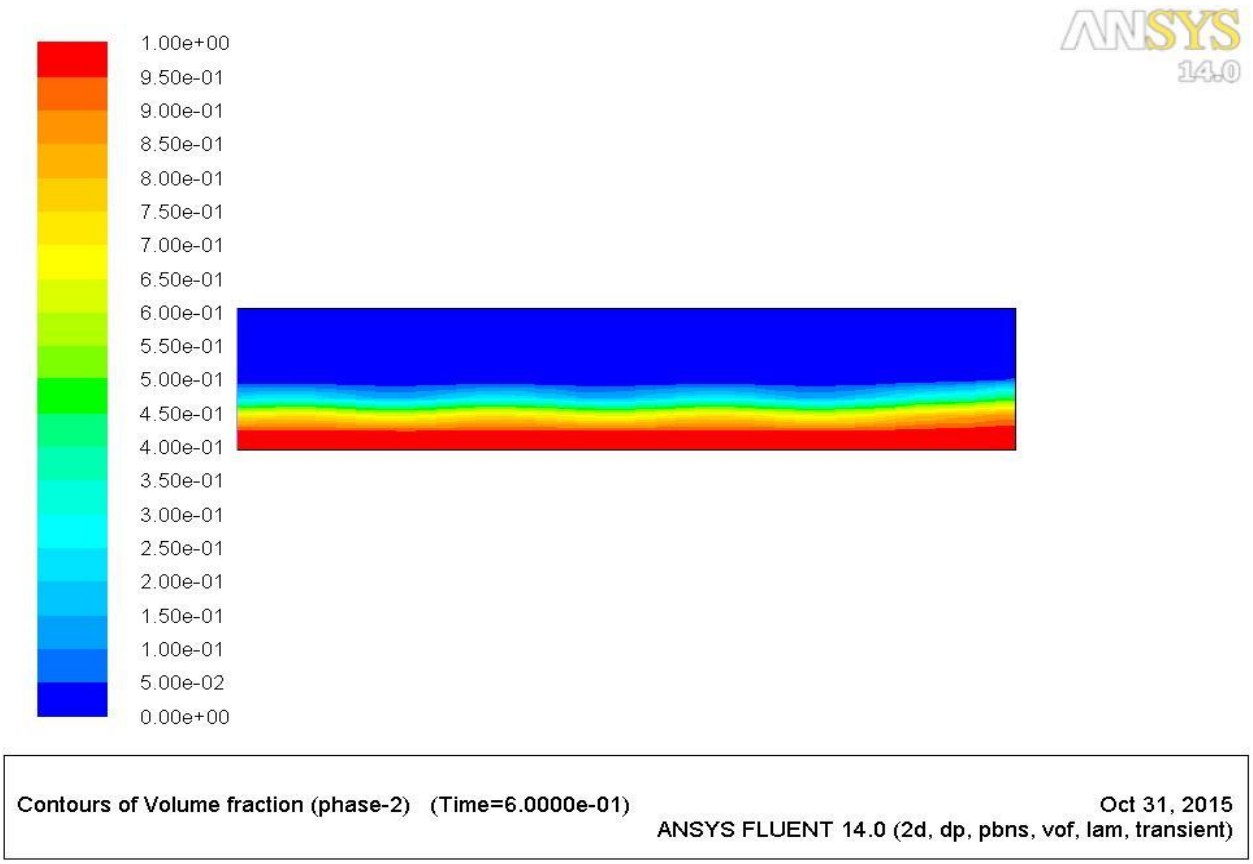

Figure 38: CONTOURS OF WATER FRACTION FOR CASE NO. 07

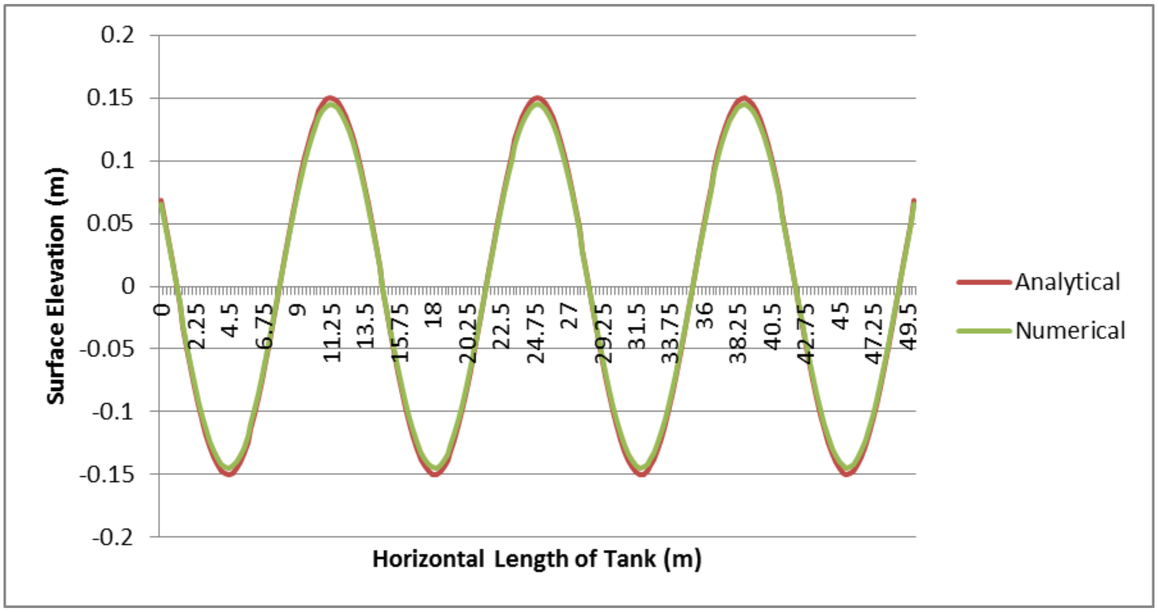

Figure 39: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 07

4.3.1.2.3 CASE NO. 08 – COARSE MESH WITH COMPRESSIVE SCHEME

Surface Elevation of waves was plotted against the length of numerical tank and then compares it with Analytical plot based on LWT. It is noted that the Compressive Scheme with Coarse Mesh produces approximately the same plot as analytical one with maximum reported error of 7.5%. Contours of volume fraction of phase 2 i.e. secondary phase (water) and surface elevation plot are as follows:

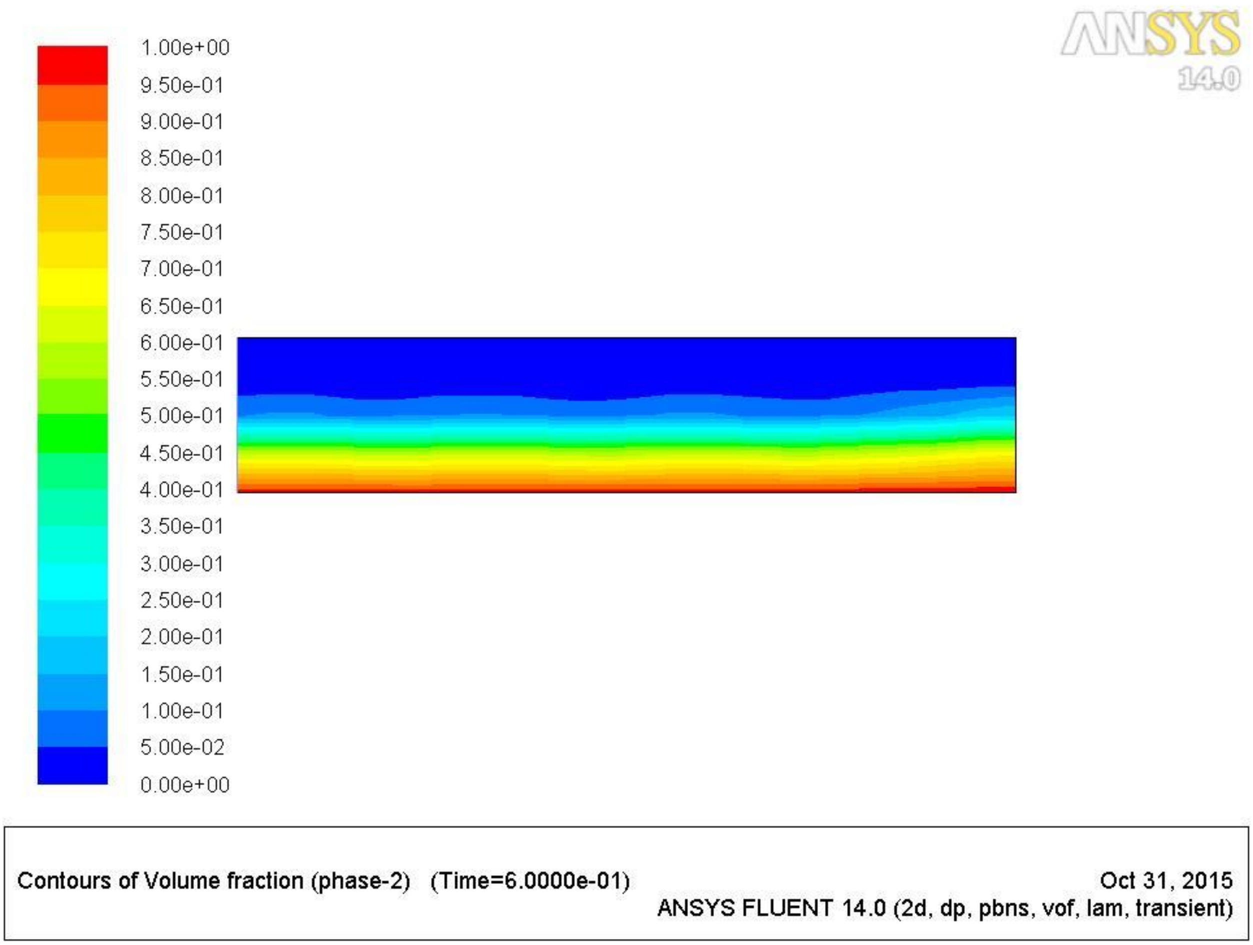

Figure 40: CONTOURS OF WATER FRACTION FOR CASE NO. 08

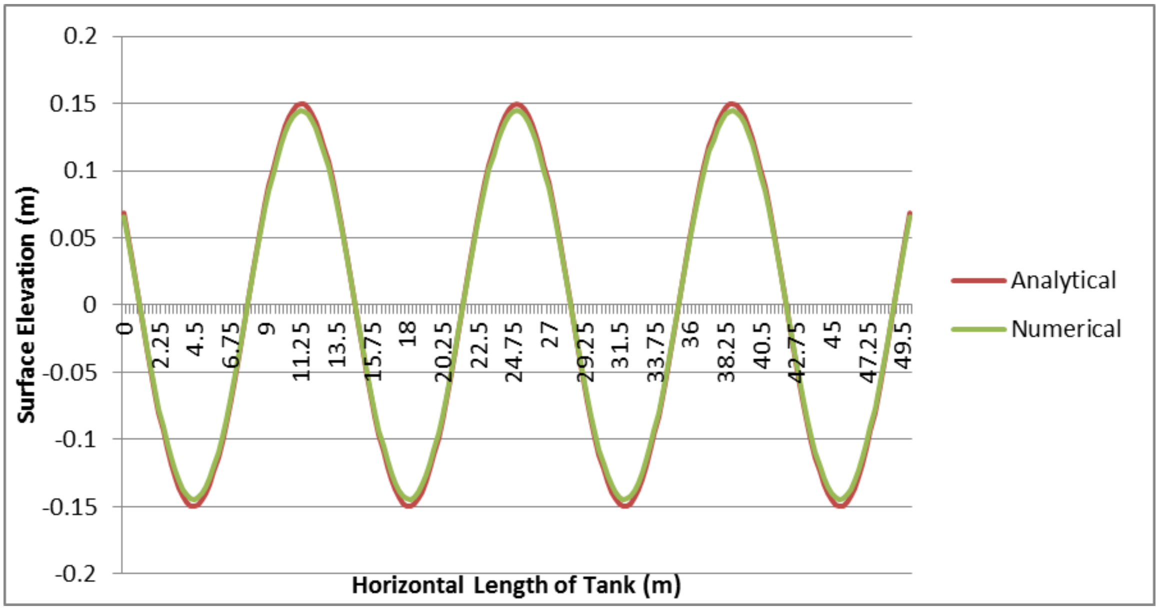

Figure 41: PLOT OF WAVE SURFACE ELEVATION AGAINST LENGTH OF NWT FOR CASE NO. 08

4.3.2 WAVE STRUCTURE INTERACTION

Wave forces are calculated on Buoy during simulation at different seconds and they are as follows:

4.3.2.1 WAVE STRUCTURE INTERACTION ON BUOY "1"

Wave force computed during wave structure interaction on buoy "1" is reflecting an approximate sinusoidal wave pattern.

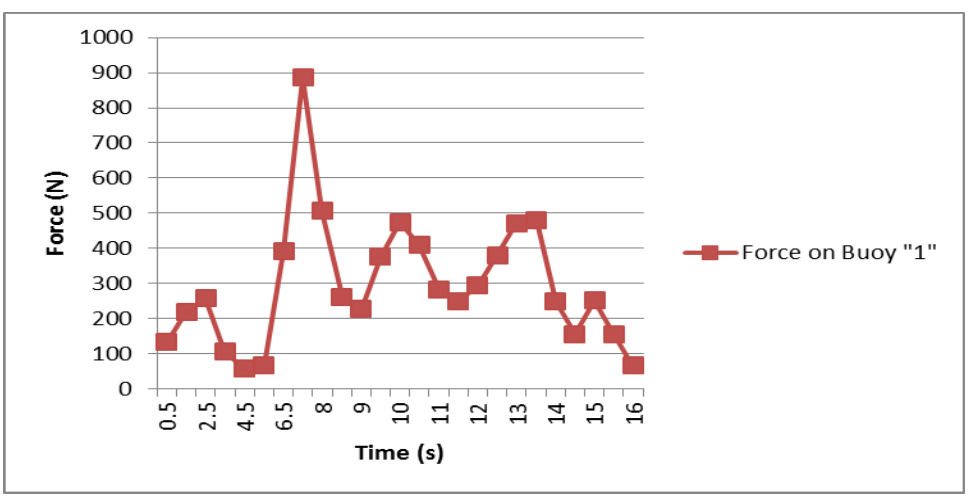

Figure 42 WAVE FORCES ON BUOY "1"

4.3.2.2 WAVE STRUCTURE INTERACTION ON BUOY "2"

Wave force computed during wave structure interaction on buoy "2" has also an approximate reflection of sinusoidal wave pattern.

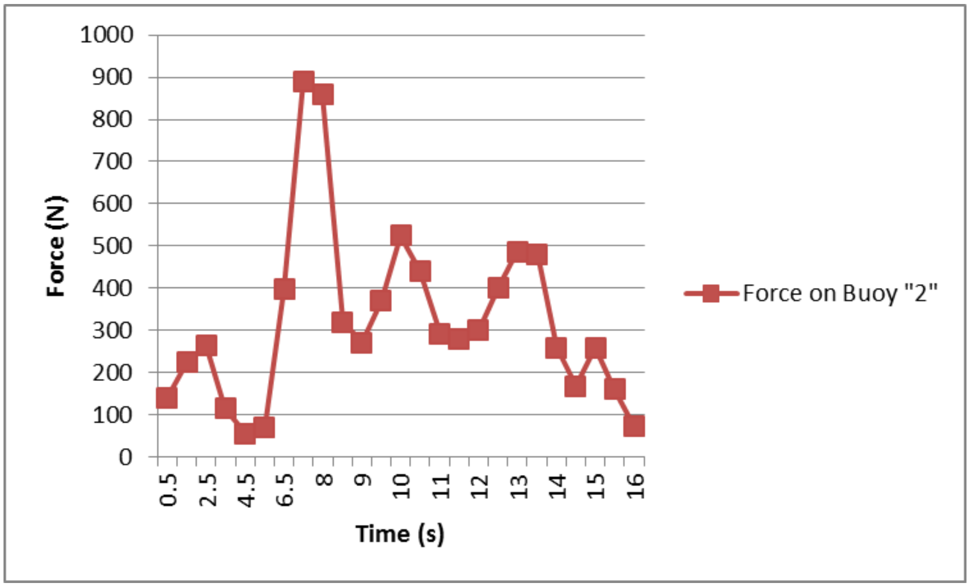

Figure 43 WAVE FORCES ON BUOY "2"

4.3.2.3 COMPARISON

It is noted that wave force on buoys of different dimensions has sinusoidal wave pattern computed during simulation of wave structure interaction through Multiphase Fluid code of Volume of Fluid model of Ansys CFX code and buoy having larger frontal surface has greater wave force on it against bouy of lesser frontal surface.

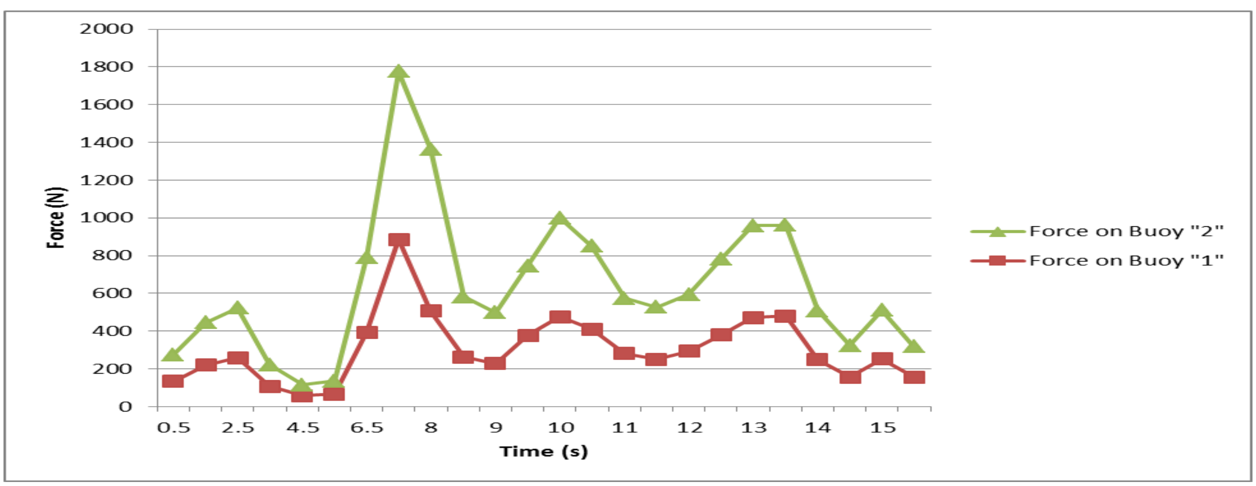

Figure 44 WAVE FORCES ON BUOY "1" & BUOY "2"

5. CONCLUSION

Numerical Simulation of Surface Gravity Waves alongwith computation of wave forces on floating buoys having different dimensions for design optimization is carried out in this thesis work. Ansys Fluent Multiphase Fluid, Volume of Fluid model alongwith Implicit Time Discretization Scheme, Open Channel Wave Boundary Condition and Numerical Beach Treatment option of Ansys Fluent is utilized for different volume fraction schemes (First Order Upwind, Second Order Upwind, Compressive, QUICK and Modified HRIC) of spatial discretization and then the most accurate scheme is used to study grid independency for Numerical Simulation of Waves. In this study of waves simulation, Velocity Inlet Boundary Condition is used alongwith other three boundaries as solid wall with no slip condition and numerical beach treatment to dampen out the waves to avoid refraction and reflection of waves. Moreover, Ansys Fluent Wave Surface theory selection is also checked based on wave parameters used as input for simulation of waves through Open Channel Wave BC checking and it is found that selected wave theory is found satisfactory for provided input wave parameters. Ansys CFX is used as a numerical tool to simulate wave structure interaction while all wave parameters, properties and conditions of fluid and numerical domain boundary conditions are same as used in Ansys Fluent. The simulation results for waves simulation are summarized as that the surface elevation of surface gravity waves when simulated through Compressive Scheme of spatial discretization for implicit time discretization has more accurate result among other volume fraction schemes in comparison to surface elevation plotted with reference to Airy's Linear Wave Theory while the simulation results for wave buoy interaction yields that the buoy having larger frontal surface area has greater wave force on it in comparison to buoy having lesser frontal surface area and force on both buoys have an approximate reflection of sinusoidal wave pattern. The processing time has variation in between 3% to 7% for different volume fraction schemes during numerical wave's simulation. It is also noted that the simulation of surface gravity waves through utilization of Compressive Scheme for fine grid among grids of different resolutions has good agreement with analytical results based on Airy's Linear Wave Theory and maximum of 5% error reported.

5.1 RECOMMENDATIONS FOR FUTURE WORK

The subject field is quiet important for marine engineers and those who are in relation with ocean energy technology as well as with wind energy. Based on the technological advancement and availability of advanced systems and software's, following are the recommendations:

- Simulation of Surface Gravity Waves with different time stepping methods available in Ansys Fluent.
- Simulation of Higher Order Non Linear waves through Ansys Fluent.
- Simulation of Wave Structure Interaction for optimization of Wave Energy Converter (Buoy) with different materials and sizes to optimize the design and metallurgy.

REFERENCES

[1] Global Energy Crisis by Irshad Ali Sodhar (FSP) –
the allpapers.com/papers/CSS/English/Complete Topic Base Essays

[2] Project: Energy Harvesting Eel, University of Adelaide, School of Mechanical Engineering, 2008.

[3] Daniel Yergin, The Prize: The Epic Quest for Oil, Money, and Power (New York: Simon and Schuster, 2008), p. 587.

[4] Barsky, R.; Kilian, L. "Oil and the Macro economy Since the 1970s". CEPR Discussion Paper No. 4496 1001: 48109–1220. Retrieved June 7, 2010.

[5] ` Hardy, Chris (6 July 2010). "Renewable energy and role of Marykirk's James Blyth". The Courier. D. C. Thomson & Co. Ltd.

[6] Peter Asmus, Reaping the wind: how mechanical wizards, visionaries, and profiteers helped shape our energy future Island Press, 2001 ISBN 1-55963-707-2 pages 54-56

[7] Clément et al. (2002). "Wave energy in Europe: current status and perspectives". Renewable and Sustainable Energy Reviews 6 (5): 405–431

[8] THE DEVELOPMENT OF WAVE POWER - A TECHNO-ECONOMIC STUDY
J M Leishman, Economic Assessment Unit and G Scobie, Fluid Mechanics Division, 1976.
www.mech.ed.ac.uk/research/wavepower/0-Archive/EWPP%20archive/1976%20Leishman%20and%20Scobie%20NEL.pdf

[9] "Wave Energy Research and Development at JAMSTEC funded by the Science and Technology Agency (STA).

[10] New Scientist: Nodding duck to take a bow on Loch Ness, published on the 18th of November, 1976.

[11] Rath, B.B (April 2009). 'Harvesting Alternate energies from our Planet' www.tms.org/jom.html

[12] Boud, R. 'Status and Research and Development Priorities -2003", wave and marine current energy.

[13] http://www.seafriends.org.nz/oceano/waves.html.

[14] Carnegie Wave Energy Limited is the ASX-listed inventor, owner and developer of the patented CETO wave energy technology that converts ocean swell into zero-emission renewable power and desalinated freshwater. Carnegie has raised over $45m to fund the development of the CETO technology and employs unique rapid prototyping utilizing computational simulation, wave tank testing, and scaled in-ocean testing at its private Wave Energy Research Facility and onshore/offshore test site and commercial scale in-ocean testing at Garden Island, Western Australia.

[15] Clément, A., McCullen, P., Falcˇao, A., Fiorentino, A., Gardner, F., Hammarlund, K., Lemonis, G., Lewis, T., Nielsen, K., Petroncini, S., Pontes, M.-T., Schild, B.-O., Sjöström, P., Søresen, H. C., and Thorpe, T.Wave energy
In Europe: current status and perspectives. Renew. Sust. Energy Rev., 2002, 6(5), 405–431.

[16] Thorpe, T. W. A brief review of wave energy, Technical reportno. R120, Energy Technology Support Unit (ETSU), A report produced for the UK Department of Trade and Industry, 1999.

[17] BDrew, A R Plummer, and MN Sahinkaya: A review of wave convertor technology, published on 16 June 2009; DOI: 10.1243/09576509JPE782

[18] Power buoys. The Economist, 19 May 2001.

[19] Chapter No. 08 "Waves and Water Dynamics" from Essentials of Oceanography – Seventh Edition by Harold V. Thurman, Alan P. Trujillo

[20] Charles Chew, Leong See Cheng, Chow Siew Foong: Physics A Course for 'O' Level, 2004, pg. 194.

[21] Galvin, C.J. Jr., (1968), "Breaker type classification on three laboratory beaches", Journal of Geophysical Research, 73(12), pp. 3651-3659.

[22] https://en.wikipedia.org/wiki/Breaking_wave

[23] PHD Thesis: Wave-Structure Interaction of Offshore Wave Energy Converters by William Finnegan under the supervision of Dr. Jamie Goggins of NUI Galway University of Ireland

[24] https://en.wikipedia.org/wiki/Ursell_number

[25] Le Méhauté, B. (1976), An introduction to hydrodynamics and water waves, Springer, ISBN 0-387-07232-2

[26] Ursell, F (1953). "The long-wave paradox in the theory of gravity waves". Proceedings of the Cambridge Philosophical Society 49 (4): 685–694.

[27] Computational Modeling of a Regular Wave Tank by M.N. Gomes, C.R. Olinto, L.A.O. Rocha, J.A. Souza and L.A. Isoldi.
Universidade Federal Do Rio Grande
Engenharia Térmica (Thermal Engineering), Vol. 8 • No 01 • June 2009 • p. 44-50

[28] 2D Numerical Simulation of Waves by Qingjie. Du and Y.C. Dennis. Leung.
Department of Mechanical Engineering, The University of Hong Kong, China.
World Renewable Energy Congress 2011 – Sweden, Marine & Ocean Technology. pp. 2183 – 2189.

[29] Numerical Simulations of Water Wave Propagation by Volume of Fluid Approach by D.Malcangio, M. Torresi, G. Pascazio and A.F. Petrillo.
34th IAHR World Congress - Balance and Uncertainty
33rd Hydrology & Water Resources Symposium
10th Hydraulics Conference

26 June - 1 July 2011, Brisbane, Australia

[30] CFD Simulation and Validation of Flap Type Wave-Maker by Anant Lal and M. Elangovan. World Academy of Science, Engineering and Technology. International Journal of Mathematical, Computational, Physical, Electrical and Computer Engineering Vol:2, No:10, 2008

[31] Application of fluid-structure interaction simulation of an ocean wave energy extraction device by Emmanuel B. Agamloh, Allan K. Wallace and Annette Von Jouanne. Renewable Energy 33 (2008) 748 – 757

[32] Numerical study on design for wave energy generation of a floater for energy absorption by Kui Ming Li, Nanjundan Parthasarathy, Yoon Hwan Choi and Yeon Won Lee. Journal of Mechanical Science and Technology 27 (1) (2013) 3999 – 4005

[33] Final Year Project: Optimization of a Wave Energy Conversion System (WECS) by Arsalan Ali Bugti, Moaz Ahmed and Qadir Nawaz of PNEC, NUST (2012).

[34] Ansys Fluent Theory Guide Release 14

[35] Ansys Fluent User Guide Release 14

[36] Ansys CFX Theory Guide Release 15

[37] Ansys CFX Solver Guide Release 15