1. INTRODUCTION

1.1 Chapter Overview

This chapter contains various definitions used in this thesis; details research motivation, overview of research model in pictorial form, overview of research approach, contribution of research, and outline of thesis chapters.

1.2 Definitions & Abbreviations

1.2.1 Definitions

1.2.1.1 Centreline velocity

It is defined as the distance measure from the centreline of the jet where the local mean velocity is equal to half of the local centreline mean velocity.

1.2.1.2 Computational fluid dynamics (CFD)

CFD is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.

1.2.1.3 Consequence Analysis

Consequence analysis quantifies vulnerable zone for a conceived incident.

1.2.1.4 Consequence Analysis modelling

Modelling the generation of a toxic and/or flammable vapour cloud from a release and the resulting possible toxic, flammable, and explosion hazards.

1.2.1.5 Discharge

Release of gas/ air under liquid.

1.2.1.6 Dispersion

Release of gas in open atmosphere

1.2.1.7 Entrainment coefficient

The ratio of lateral (entrainment) velocity to plume-rise velocity of plume is the entrainment coefficient. Plumes that rise due to buoyancy or momentum become diluted with surrounding fluid, where the rate of dilution is proportional to the rise rate of the plume. The entrainment coefficient is this constant of proportionality.

1.2.1.8 Flow rate/ release rate

Volumetric flow rate is the volume of fluid which passes through a given surface per unit time. SI Unit for flow rate is m^3/ sec.

1.2.1.9 Hazard

Hazard is the potential to cause harm to People, Environment, Asset and Reputation (PEAR) of an organisation.

1.2.1.10 Hydrodynamics

The study of dynamics of fluids in motion or the scientific study of the motion of fluids, under the influence of internal and external forces.

1.2.1.11 IRPA

Individual Risk Per Annum, this is the chance of an individual becoming a fatality. An IRPA of 1 x 10-3 would mean for each individual, every year, there is a 1 in 1000 chance of a fatal accident.

1.2.1.12 PLL

Potential Loss of Life is proportional to the sum of all the IRPAs. In simple terms PLL is related to IRPA by the relationship IRPA = PLL x fraction of time an individual is offshore per year.

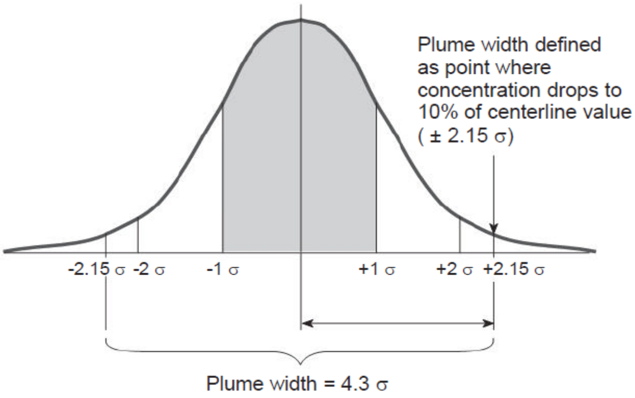
1.2.1.13 Plume

A structure or form that is like a mushroom: a plume of subsea gas discharge.

1.2.1.14 Plume density

Plume density is the mass of plume gases per unit volume. The SI unit is kg/m^3

1.2.1.15 Plume width (Gaussian shape)



1.2.1.16 Quantitative Risk Assessment (QRA)

Quantitative risk assessment (QRA) is a formal systemized approach for hazards identification and ranking. The final rating number provides a relative ranking of the hazards. Fire and Explosion Index (F&EI) is an important technique employed for hazards identification process. Consequence analysis then quantifies the vulnerable zone for a conceived incident.

1.2.1.17 Risk

Risk = Hazard Potential (Consequence) x Frequency of incident happening (failure).

1.2.1.18 Salinity

Salinity is the saltiness or dissolved salt contents (sodium chloride, magnesium, calcium sulphates and bi-carbonates) of the body of water.

1.2.1.19 Temperature

Temperature is a measurement of the average kinetic energy of the molecules in an object or system and can be measured with a thermometer or a calorimeter. It is a means of determining the internal energy contained within the system.

1.2.2 Abbreviations

CFD	Computational Fluid Dynamics
DNV	Det Norske Veritas
DPM	Discrete Phase Model
F&EI	Fire and Explosion Index
HSE	Health & Safety Executive
IIT-M	Indian Institute of Technology, Madras
IRPA	Individual Risk Per Annum
LCWM	Long Crested Waves Maker
MEWM	Multi-Element Wave Maker
PEAR	People, Environment, Asset and Reputation
PIV	Particle Image Velocimetry
PLL	Potential Loss of Life
PSA	Petroleum Safety Authority
QRA	Quantitative risk assessment
VOF	Volume of Fluid

ZOEF Zone of Established Flow

ZOFE Zone of Flow Establishment

ZOSF Zone of Surface Flow

1.3 Research motivation

A number of incidents involving hydrocarbon leaks from wells, subsea installations and pipelines have been recorded in recent years like submarine gas blowout on the Snorre, an offshore installation in 2004 and like the ones that are listed below. While the understanding of atmospheric gas dispersion is far advanced, *the need for better understanding of the way hydrocarbon emissions behave under water and the risks they present need to greatly improve which is the prime motive behind this research work.*

Some of the sub-sea gas pipeline leaks reported in this decade:

April 29, 2001

Texaco Exploration and Production Pipeline segment no. 10393

South Marsh Island, Block 236 Water Depth: 14 feet

An incoming 2-inch gas lift line was ruptured. The break caused damage to the upper work deck, handrails, flow line, and riser. The line appeared to have been pulled from the structure prior to the rupture possibly by a shrimp vessel since the line was buried. Personnel working on an adjacent well heard the bleeding gas, reported the incident to Texaco personnel who immediately shut-off the supply of gas to the line. No injuries or pollution were reported.

January 3, 2002

Chevron USA Inc. Pipeline segment no. 13154

West Cameron, Block 48 Water Depth: 22 feet

During an ESD shut-in, the 10-inch incoming shutdown valve closed, but the safety system on the platform failed to operate. Shortly after, the platform operators noticed gas bubbles in the water approximately 300 feet from the platform. The pipeline, which was 37 years old, was allowed to bleed for 90 minutes, and was later found to have ruptured in three places. It appears that the safety system failure was due to freezing problems in the ¼-inch tubing, which runs approximately 40 feet to the transmitter.

January 15, 2002

Transcontinental Gas Pipeline Company Pipeline segment no. 1526

Vermillion, Block 67 Water Depth: 40 feet

The operator at an adjacent platform reported a pipeline rupture with a fire on the water, located ½ to ¾ miles west of their location. Within 2 hours Transco confirmed it was their pipeline, a 16- inch gas pipeline. The pipeline was shut it in and the fire ceased. No injuries or pollution were reported.

July 6, 2002

ChevronTexaco Corporation Pipeline segment no. 3540

South Marsh Island, Block 217 Water Depth: 15 feet

The pipeline was reported as having ruptured, with the ensuing fire having flames 100 feet high. The location of the rupture was 6000 feet north of SM 217 A. The flames lasted for 2 hours. The pipeline PSL shut-in the platform at the time of the rupture.

January 7, 2003

Walter Oil & Gas Corporation Pipeline segment no. 11052

South Timbalier, Block 260 Water Depth: 303 feet

A vessel moored 2.2 miles from the platform snagged the associated gas pipeline while retrieving its anchor. The vessel began pulling up the anchor and halted the operation an hour later when the Captain realized he had snagged a heavy object. Ten minutes later, the Captain noticed fire and smoke under the platform and notified the USCG. Subsequently, the platform operator felt several jolts to the platform that intensified in strength and eventually rocked the platform. The operator shut-in the platform's two producing wells. About 10 minutes later, the platform was jolted again: the gas pipeline broke loose and an explosion and fire erupted from the severed pipeline beneath the platform. The three individuals on the platform at the time evacuated the facility via helicopter. The vessel had been moored outside of the designated lightering area per the instructions of the Mooring Master. The Mooring Master and the Captain were unaware of any pipelines in the mooring area as apparently neither one had a copy of the pipeline overlay to the NOAA nautical chart.

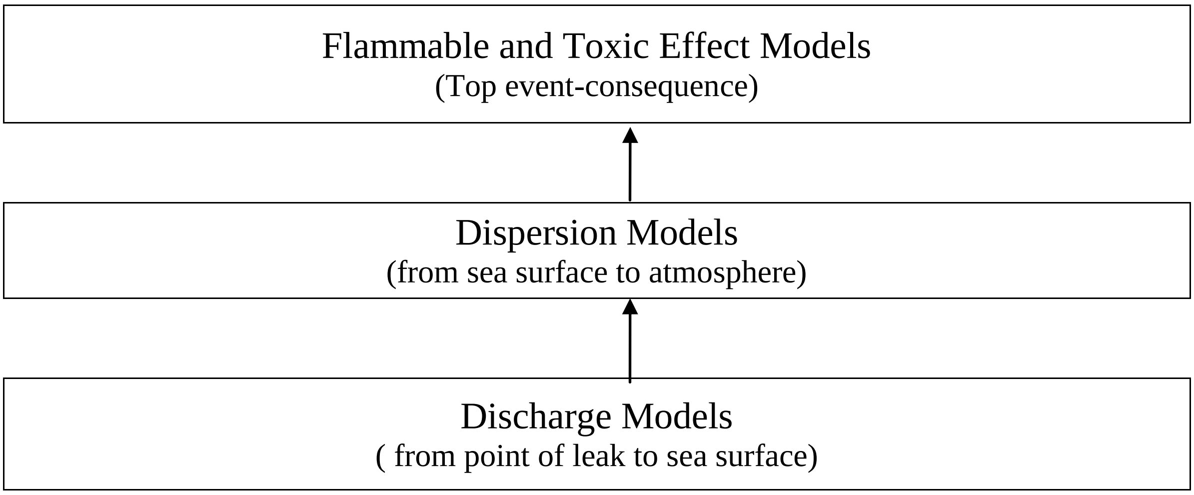
December 2, 2003

South Pipeline Company, LP Pipeline segment no. 5105

Eugene Island, Block 39 Water Depth: 10 feet

A dredge barge, dredging the Atchafalaya Channel for the Corp of Engineers, impacted and severed the 20-inch gas pipeline. The barge was dredging the channel floor to a depth of 22 feet BML in the vicinity of the pipeline; however, the burial depth of the pipeline was not known. A representative of the pipeline company was not on board at the time of incident. The project engineer did not account for the length of the dredge (420 feet) in determining where to halt dredging operations relative to the location of the pipeline. The pipeline caught on fire as a result of the impact from the dredge. Approximately 1,500 feet of pipe was pulled apart or ripped.

1.4 Overview of research model



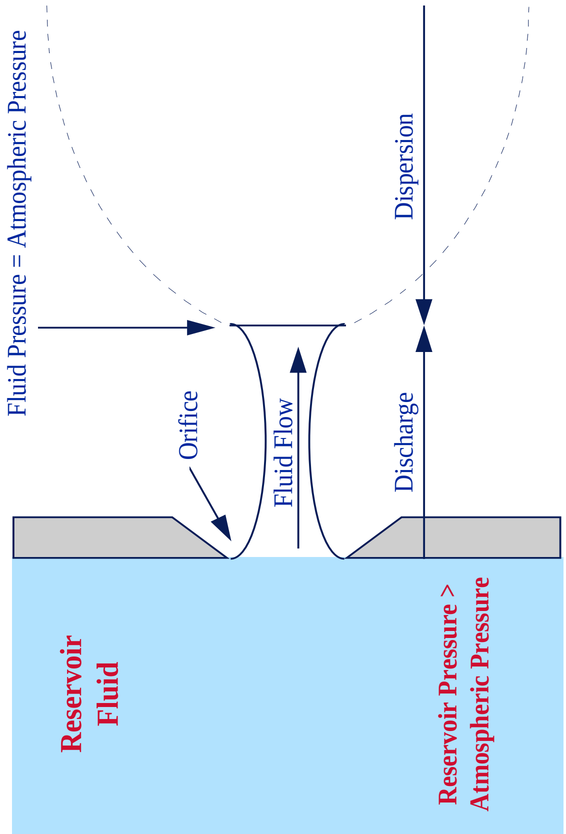


Fig1.1: Gas dispersion model

1.5 Overview of research approach

INPUT *(Literature survey)*	→	PROCESS *(Lab-scale Experimentation)*	→	OUTPUT *(Validate model for Arabian Sea Conditions)*
Identify & Study various discharge models that are currently being used in North Sea with respect to plume discharge (initial release of plume from the point of leak to the sea surface) from Consequence point of view		Identify the optimal gas discharge (plume raise) model that best suits Arabian Sea conditions Validate the identified model for Arabian Sea conditions by lab-scale experimentation		Cost effective, reliable, user-friendly Sub-Sea Gas dispersion model that is tested and validated for Arabian Sea Conditions

1.6 Contribution of this research

The outcome of this research will greatly benefit the Indian oil and gas industry by means of validating the accuracy of Risk Assessment (Consequence modelling part) of the sub-sea gas pipelines leaks so as to implement specific safety measures to protect the precious national assets.

1.7 Outline of Thesis chapters:

Chapter No.	Chapters	Chapter Outline
1.	Introduction	This chapter contains various definitions used in this thesis; details research motivation, overview of research model in pictorial form, overview of research approach, contribution of research, and outline of thesis chapters.
2.	Literature survey	This chapter lists chronological order of research done worldwide, researcher(s) and contribution. Identifies the most popular discharge models that are currently being used in North Sea.

3.	Research Problem	This chapter introduces the research problem, highlights the implications of the research problem and the influence of research problem on Indian oil and gas industry.
4.	Research Outline	This chapter lists the chronological order of researches done in the area of gas discharge model development in North Sea, UK, the stages involved in the development of atmospheric gas dispersion models and approach adopted in the development of gas discharge model for sub-sea releases. Outlines the critical factors involved in the identification of optimal gas discharge model for Arabian Sea conditions based on North Sea experience/feedback.
5.	Model validation	This chapter details the outcome of lab scale experimentation conducted for validating the Sub Sea Gas discharge model (Empirical /cone model) established for North Sea for Arabian Sea conditions.
6.	Models for research problem's competence	This chapter analyses in details, the features of empirical, integral and CFD models used in North Sea.
7.	Conclusions & future research	This chapter covers the summary of conclusions of this thesis and the scope for further research.

2. LITERATURE SURVEY

2.1 Chapter overview

This chapter lists chronological order of research done worldwide, researcher(s) and contribution. Identifies the most popular discharge models that are currently being used in North Sea, UK.

2.2 Chronological order of research done and researcher(s) and contribution

Table 2.1: Research done and researcher(s) and contribution

Order	Name of Researcher	Area of Research done
1.	Ditmars & Cederwall (1974)	The work of Ditmars & Cederwall pre-dates that of Milgram, and differs in a number of respects. Firstly, they invoke the Boussinesq assumption to simplify the momentum equation, such that the mean density of the mixture of gas and fluid is identical to that of the fluid alone. This difference in density is of course retained for the generation of buoyancy forces. Secondly, no account is taken of the increase in momentum flux due to transport by turbulent fluctuations. [6]
2.	Mc Dougal (1978)	McDougal (1978) extended the model developed by Ditmars & Cederwall (1974) to include the effect of a release in a stratified environment. [23]
3.	Peng Robinson equation of state, (1976)	A compositional model is used to predict the hydrocarbon phase behavior and thermo-dynamical properties. The calculations are based on the concept of an equilibrium constant, K value, defined as the ratio of the mole fraction of the component in the gas phase, to the mole fraction of the same component in the liquid phase. Unlike a single component fluid, a multi component mixture exhibits a phase envelope rather than a single equilibrium curve. This implies that pressures and temperatures inside the phase envelope, both liquid and gas phases exists in equilibrium. [34] The Peng-Robinson equation is expressible in terms of the

		critical properties and the acentric factor. The equation is applicable to calculations of fluid properties in natural gas processes and is expected to provide good accuracy for the scenarios intended for the release model.
4.	Scorer (1978)	Developed Zone of formation model for calculating mean gas concentration above an underwater release (plumes with excess of buoyancy).
5.	Fazal & Milgram (1980)	Developed an integral formulation which assumes the mean fluid velocity and mean density defect within the plume are assumed to take the form of Gaussian distributions. [13]
6.	Fannelop & Sjoen (1980)	Fannelop & Sjoen (1980) again proceeding Milgram (1983) developed a model based upon the work of Ditmars & Cederwall (1970) [5]. However a number of differences exist in the representation of buoyancy, the inclusion of the bubble slip velocity, and the use of top-hat as well as Gaussian velocity profiles. [12]
7.	Milgram & Van Houten (1982)	The Milgram model for the zone of established flow was also used by Milgram & Van Houten (1982) in a paper which again compared experiments at small scale with computed data, and presented the results of large scale calculations. [26]
8.	Milgram (1983)	Produced data related to empirical correlations for the plume diameter and the gas velocity.[27]
9.	Milgram & Burgees (1984)	They have compared both theories with experimental data for surface currents gathered at Bugg Spring. [24]
10.	Wilson (1988) [48] and Milgram and Erb (1984) [25]	The value of the model constants used varies significantly. The cone angle is generally given as between 10-12°, although some sources quoted values of up to 23°. The lower values closely match that of 10° given by Wilson (1988) and Milgram and Erb (1984) [25]. However, it should be noted that this cone angle is

		defined as that of the subsea plume and does not include the effect of radial flow, which is known to occur near the sea surface.
11.	Billeter and Fanne1op (1989)	Billeter(1989) and Fanne1op (1989) state that the 'boil area', where the bubbles break through the surface, has approximately twice the diameter of the bubble plume as determined in the absence of surface interaction. Although this observation is yet to be confirmed by detailed measurements, it would give an explanation for the use of cone angles of up to 23^0 [3]
12.	Loes & Fannelop (1989) Billeter & Fannelop (1989)	They have undertaken measurements of the gas concentration above field scale and laboratory-scale underwater releases which show that the concentration profile appears to be Gaussian. The Integral model was used to compare predictions of bubble rise time for a variety of release rates against trials data (Loes & Fannelop (1989)) using a range of established values for the entrainment coefficient (α), bubble terminal velocity, bubble drag coefficient etc. Reasonable agreement was achieved when the entrainment coefficient for the spherical cap was taken as 0.15. [22]
13.	Moros & Dand (1990)	Described the application of the PHOENICS commercial CFD code to the calculation of surface current with an objective being to assess the displacement of vessels in the vicinity of the blow out. [30]
14.	Fannelop, Hirschberg & Kuffer (1991)	Reported a comparison of theory and experiment for the case of a 2 dimensional surface current. [11]
15.	Computational Fluid Dynamics	CFD involves the computation, on a suitable grid, of the solution to the Navier-Stokes equations of fluid motion. Genera)

	(CFD) models by Moros & Ryall 1992	purpose CFD models are now available and have been used in a range of applications, including dispersion of the above-sea part of a subsea release, (Moros & Ryall 1992). CFD modeling is resource-intensive, and requires careful setting up of boundary conditions and sub-models. It is particularly useful in determining the effects of obstructions, but is not in general use otherwise. [29]
16.	Moros & Ryall (1992)	The distance to which the flammable envelope of the gas extends will depend on ambient conditions, such as wind speed and atmospheric stability, as well as the source conditions. The dispersion of the gas is typically modelled using Gaussian and integral models, for example the WS Atkins computer codes PLUME and SLUMP, which are used for buoyant gas and dense gas releases respectively. [29]
17.	Swan & Moros (1993)	Extended the use of CFD to a comparison of such numerical predictions of bubble plume behavior with both experimental data and the results from integral models. [44]
18.	Bettelini & Fannelop (1993)	Developed an integral model for the initial phase of subsea release due to a blow out or pipeline rupture. [2]
19.	Navier-Stokes	Developed equation of fluid flow (CFD models)
20.	WS Atkins Computer code	The assumption of similarity of plume concentration and velocity profiles is combined with entrainment relationships to produce a set of equations which are then integrated along the trajectory of the plume. Plume momentum and buoyancy, and ambient wind speed and turbulence all affect the dispersion through these modeled equations.
21.	Hassan Abdulmouti & Tamer Mohamed	Particle Image Velocimetry (PIV) is used to measure the field flow velocity by analyzing the motion of the seeded particles in the flow. This data can be used for measuring the process

	Mansour (2006)	parameter and this data can be used by CFD model for more accurate results. [18]
22.	Fannelop and Bettellini (2007)	Developed plume model for very large bubble set in broken gas pipeline. [10]
23.	Schalk Cloete et al (2009)	CFD modeling of plume and free surface behavior resulting from a sub-sea gas release. [40]
24	Hassan Abdulmouti (2011)	The gas flow rate, the bubble size and the internal two-phase flow structure of the bubble plume determines the characteristics of the surface flow. The structure of the bubble plume is studied in detail using numerical simulation (Eulerian-Lagrangian) model and by using flow visualization and image processing measurements. [15]

2.3 Chapter Summary

Three approaches, of varying complexity, have been used in modelling the discharge of subsea releases. The following are the types of discharge models commonly used in North Sea:

i. Empirical/ Cone model
ii. Integral Model
iii. Computational Fluid Dynamic (CFD) model

3. RESEARCH PROBLEM

3.1 Chapter overview

This chapter introduces the research problem, highlights the implications of the research problem and the influence of research problem on Indian oil and gas industry.

3.2 Introduction to Research Problem

The field of consequence modelling for hydrocarbon releases in open atmospheric conditions is highly developed and has evolved over a period of time in stages as explained below-

Stages	**Year**	**Developments/ Advancements in the field of Atmospheric gas discharge models**
Stage-1	Early 80's	No computer software was available to predict the consequences of hydrocarbon releases. Only equations from the books were used to calculate the consequences.
	1985	WAZAN, software was developed by M/s Technica sponsored by UN. This software had stand alone modules for basic consequence analysis. The equations were taken from available academic literature e.g. Gaussian dispersion equation used for gas dispersion modelling.
Stage-2	1990s	HD Gas model was developed as Gaussian plume model proved not to be correct for heavier than air gases.
Stage-3	Late 1990s	Stand alone models were transformed into toolkits where transition from one module to another can be automatic rather than based upon analyst judgment.
	2000+	A lot of experimental work in the field of Hydrocarbon release consequences and the case histories damage information available has been used to fine tune the models.

As on today, only very limited consequence models are available for sub-sea gas pipe line leaks especially to predict gas plume discharge behaviour. Some preliminary research work is done for North Sea conditions in UK by Health & Safety Executive (HSE), UK, Det Norske Veritas (DNV) & Shell Global Solutions and for Norwegian Sea by Petroleum Safety

Authority (PSA), Norway. *However no such research is done in India specific to Arabian Sea Conditions.*

The following main factors were considered for experimentation:

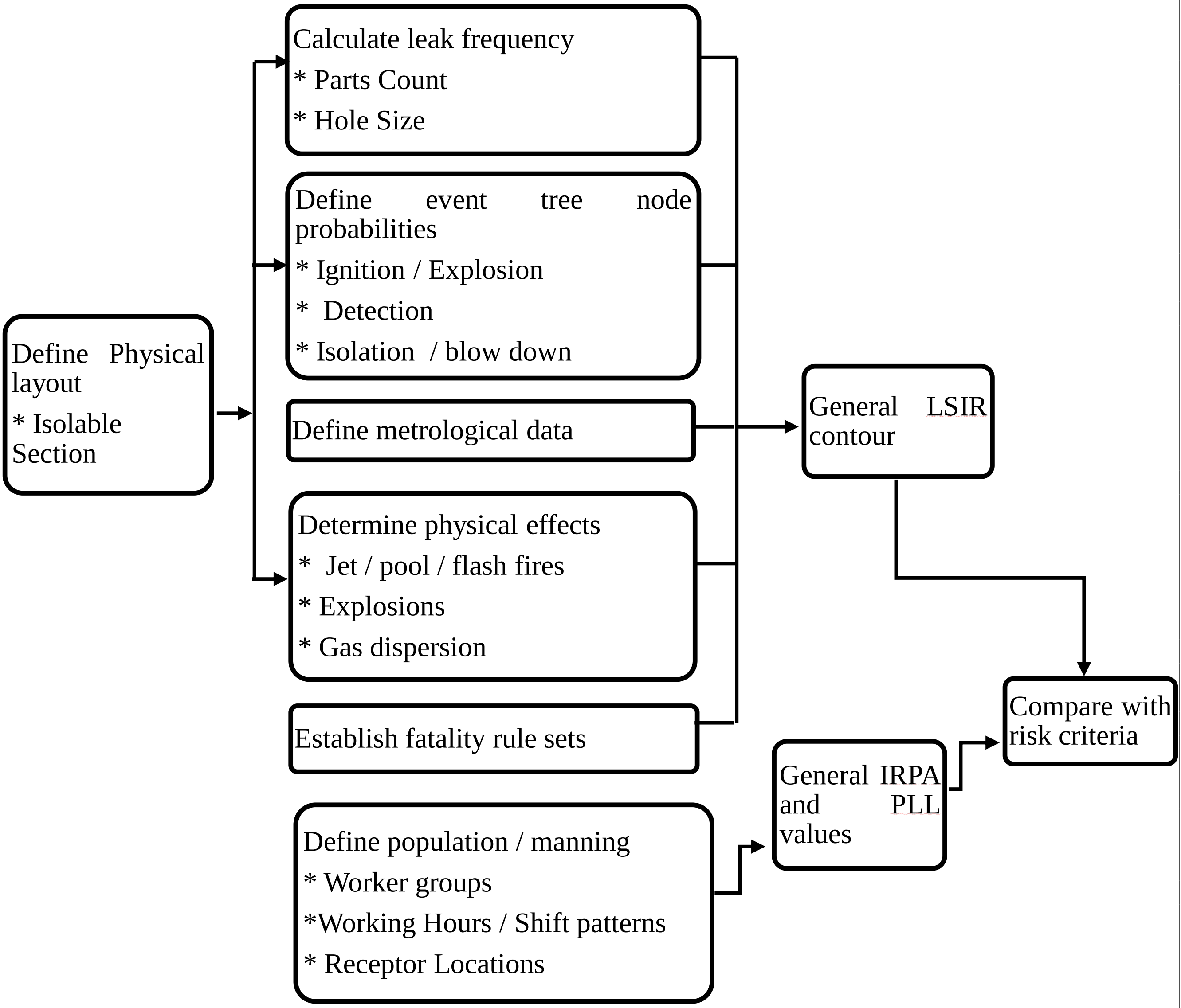
a. Release rate (kg/s)
b. Gas density (kg/m^3)
c. Depth of release (m)
d. Vertical sea temperature (^0C)
e. Salinity (grams of salt per litre of water)

3.3 Implications of research problem

The effects of a subsea release as the hydrocarbon plume reaches the surface will depend on a number of factors, including whether the release is liquid or gas. For a liquid release, the buoyancy will result in the leaked material spreading on the surface to form either a polluting slick, or an expanding pool fire. For a gas release, although the buoyancy is rather greater, significant drag forces will cause the plume to break up and rise to the surface as a series of bubbles. On breaking surface, ignition of the gas plume would result in a sea surface fire with different characteristics to those incorporated into the usual pool and jet fire models. Alternatively, and more likely, the plume will begin to disperse in the atmosphere, and may be diluted to a concentration below the lower flammable limit before there is any possibility of encountering an ignition source. A further effect of a gas bubble plume is the reduction in the stability of floating vessels, due to either the loss of buoyancy, or, more likely, due to the radial outflow of water which has been entrained into the plume.

Consequence models are used to predict the physical behaviour of hazardous incidents mainly flammable & toxic releases. Some models only calculate the effect of a limited number of physical processes, like discharge or radiation effects. More complex models interlink the various steps in consequence modelling into one package.

The field of consequence modelling for hydrocarbon releases in open atmospheric conditions is highly developed, and there are several commercially available computer programs to model the discharge, dispersion and fire/explosion effects of gases and liquids. Some of these techniques are relatively simple, and are suitable for manual analysis, and have commonly been implemented in customized spreadsheets. More complex models are available in stand-alone format and also as part of linked software or toolkits.



3.4 Influence of research problem on Indian Oil & Gas industry

The outcome of this research will greatly benefit the Indian oil and gas industry for enhancing the correctness of Risk Assessment (Consequence modelling part) of their subsea gas pipelines leaks so as to implement specific safety measures to protect the precious national assets.

3.5 Chapter Summary

The better the understanding of subsea gas pipeline leak scenario for a specific sea conditions, the correctness of consequence analysis shall be greatly improved and specific controls can be put in place to manage the safety risks.

4. RESEARCH OUTLINE

4.1 Chapter overview

This chapter outlines the objectives of this research and methodology involved.

4.2 Objectives

The objectives of this thesis are:

a. To identify various sub-sea gas discharge models that are currently being used in North Sea with respect to plume discharge (initial release of plume to the sea surface from the point of leak);
b. To study & analyse the accuracy and uncertainty levels of various discharge models used in North Sea based on the feedback received from lab scale experimentation and limited filed trial carried out so far;
c. Identify the most optimal discharge model suitable for Arabian Sea conditions striking a right balance between i) accuracy, ii) uncertainty, iii) cost-effectiveness and iv) user-friendliness;
d. Validate the chosen model for Arabian Sea Conditions based on lab-scale experimentation.

4.3 Chapter summary

The understanding about the behaviour of a subsea gas release up through the water column is limited from risk assessment point of view. The hydrodynamic basis for bubble-plume flows is reasonably well understood, but the solutions of the associated equations, depend on a large number of parameters that can only be evaluated from experiments. Hence this thesis is based on the experimentation.

5. Validation of discharge model for Arabian Sea Conditions by experimentation

5.1 Chapter overview

This chapter details the outcome of lab scale experimentation conducted in IIT-M lab for Arabian Sea conditions.

5.2 Operationalization of research model's competence

Lab scale experimentation was held at Department of Ocean Engineering, Indian Institute of Technology, Madras (IIT-M) for validating the Empirical/Cone gas discharge plume model established by T.K.Fannelop & M.Bettelini, 2007 [10] in North Sea for Arabian Sea conditions.

5.3 Scale refinement

Scale of IIT-M experimentation: 1: 100

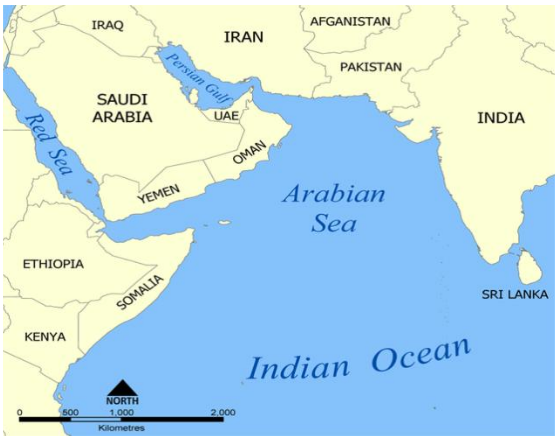
Most laboratory experiments uses gas flow rates of less than 1 kg/s and depths smaller than 10 mtrs. [10]

5.4 Empirical validation of constructs

Maximum depth : 750 mtrs

Mean depth : 90 mtrs

Sea temperature : 6 - 17^{o} C



Maximum depth : 4652 mtrs

Mean depth : 2734 mtrs

Sea temperature : 24 - 29^{o} C

Table 5.1: Comparison between Fannelop et al and IIT-M experimentation

S.N	Parameters	Used in T.K.Fannelop & M.Bettelini experimentation	Used in IIT-M experimentation
a.	Flow media	Air due to safety reasons.	Air
b.	Height of water column (Sea depth)	50 m 100 m 200 m 300 m 400 m Scale 1:100	500 m 750 m 1000 m 1500m Scale 1:100
c.	Leakage/ Flow rates	$0.00253 m^3/s$ $0.00505 m^3/s$ $0.00758 m^3/s$ $0.0112 m^3/s$ In the Risk Level Project, hydrocarbon leaks are categorized into three groups according to the leakage rate: • Major leak Greater than 10 kg/s (kg per second), • Medium leak 1 – 10 kg/s and • Minor leak 0.1-1 kg/s. [19] Even a gas leak with the lowest recorded leakage rate (0.1 kg/s) has a considerable accident potential – corresponding to the amount released by 2000 gas burners.	$0.00253 m^3/s$ $0.00505 m^3/s$ $0.00758 m^3/s$ $0.0112 m^3/s$
d.	Temperature	6^oC	24^oC
e.	Salinity	34 - 35 grams of salt per litre of water	32 – 37 parts per thousand

5.4.1 Experimentation

Factors for Experimentation:

One problem associated with designing suitable experiments is that of scaling. For air bubbles rising in a plume in a water tank, the “typical” bubble size will be about 10 mm regardless of whether the tank is 1 m or 10 m deep. This means the bubble dimension relative to plume (or flow) dimension will not be the same. *The bubble size will be largely determined by the surface tension gas-to-water, and it is difficult to tailor this to fit desired scaling relationships. The presence of hydrocarbons in the gas will reduce the surface tension and hence the bubble size, but not enough to make much difference. For reasons of safety, most laboratory experiments are carried out using air.* For offshore tests, natural gas may be a practical alternative.

In the laboratory 10 m appears to be a practical upper limit for the plume depth whereas in offshore applications 50 m to 500 m could be of interest. In recent years a number of laboratory experiments have been conducted with tank depths of the order of 1 m.

In this thesis also a test tank of 1m depth and shallow water basin of 1.5 m is used at the Department of Ocean Engineering, IIT-M which is equipped with world-class under sea water testing facility. The details and outcome of experimentation are as below-

Fig 5.4.1: World-class wave basin facility at IIT-M. 30mx30mx3m deep equipped with Multi-Element Wave Maker (MEWM), 52 paddles capable of producing short and Long Crested Waves Maker (LCWM) capable of producing regular and random waves.

Fig 5.4.2: Test tank 2mx1.5mx1.25m height with graduation scales fitted for measuring plume height and diameter.

5.4.1.1 Experimental Setup:

Fig 5.4.3: Pespex pipe of 2inch diameter and12inches length with 1inch aperture with 3/4th inch brass gas inlet nozzle.

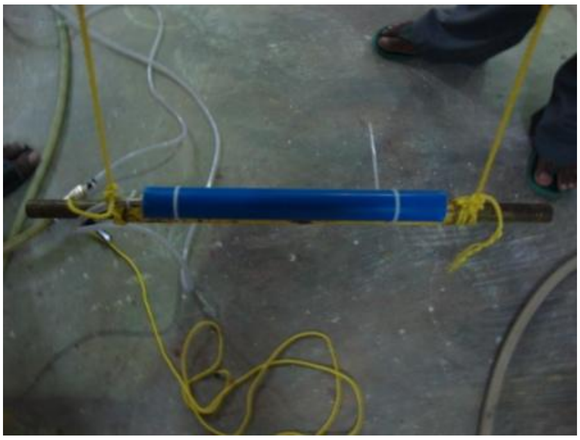


Fig 5.4.4: Pespex pipe assembly connected to 3/4th inch air hose with rope and mounting arrangement with dead weight.

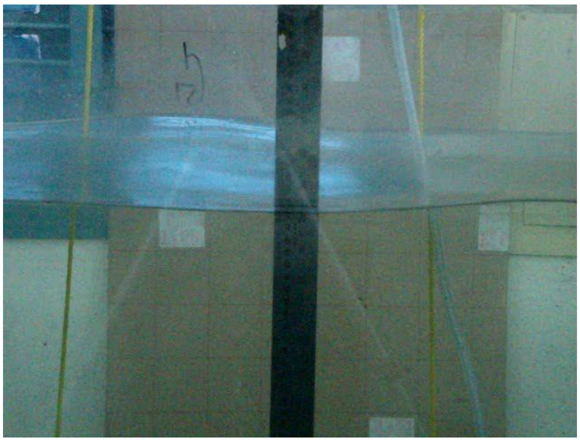


Fig 5.4.5: Vertical graduation scale attached to test tank

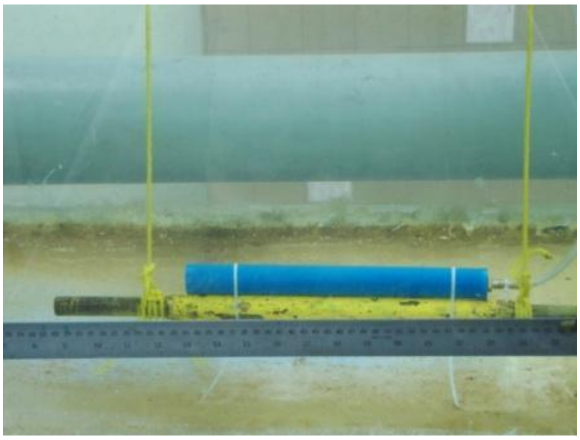


Fig 5.4.6: Horizontal graduation scale attached to test tank

5.5 Plume behaviour in Test tank (water depth 1m)

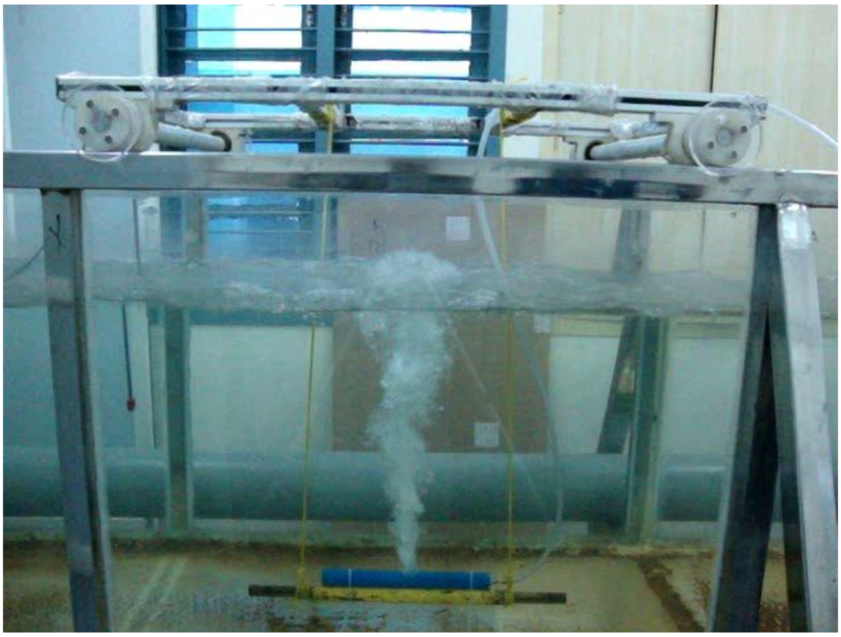


Fig 5.5.1 : Plume behaviour at
Depth : 1m
Flow Rate : 0.00253m^3/s

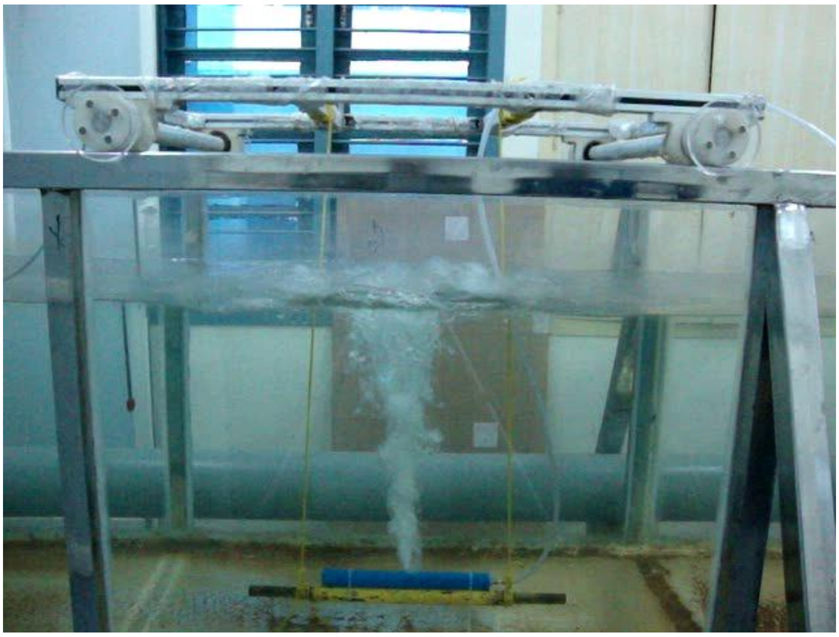


Fig 5.5.2 : Plume behaviour at
Depth : 1m
Flow Rate : 0.00505m^3/s

Fig 5.5.3 : Plume behaviour at
Depth : 1m
Flow Rate : 0.00758m^3/s

Fig 5.5.4 : Plume behaviour at
Depth : 1m
Flow Rate : 0.0112m^3/s

5.6 Measurement of plume characteristics

The plume height and diameter were measured by horizontal and vertical scale mounted on the test tank.

For the same flow rate, the plume behavior at varying depths

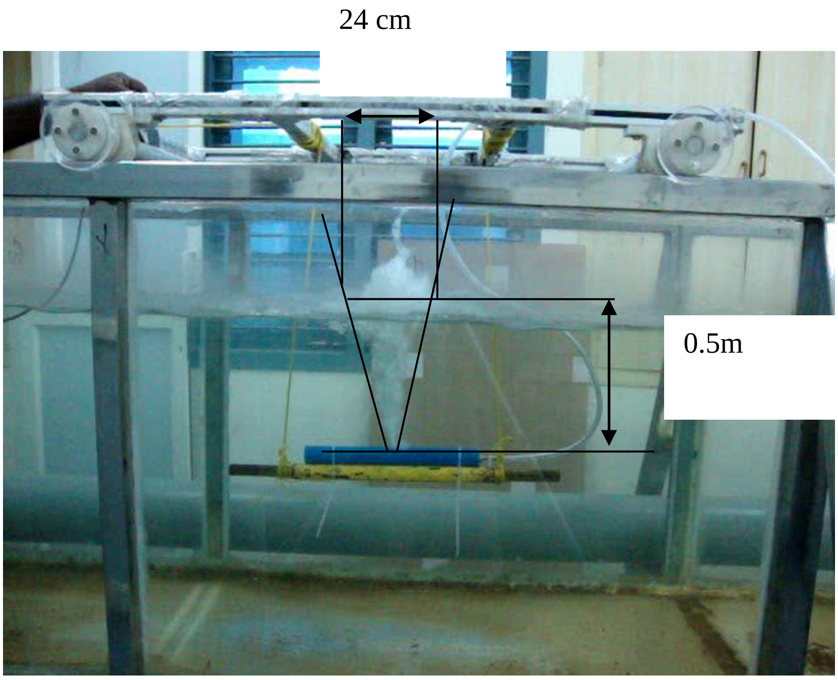


Fig 5.6.1 : Plume behaviour at
Depth : 0.5m
Flow Rate : $0.0112 m^3/s$

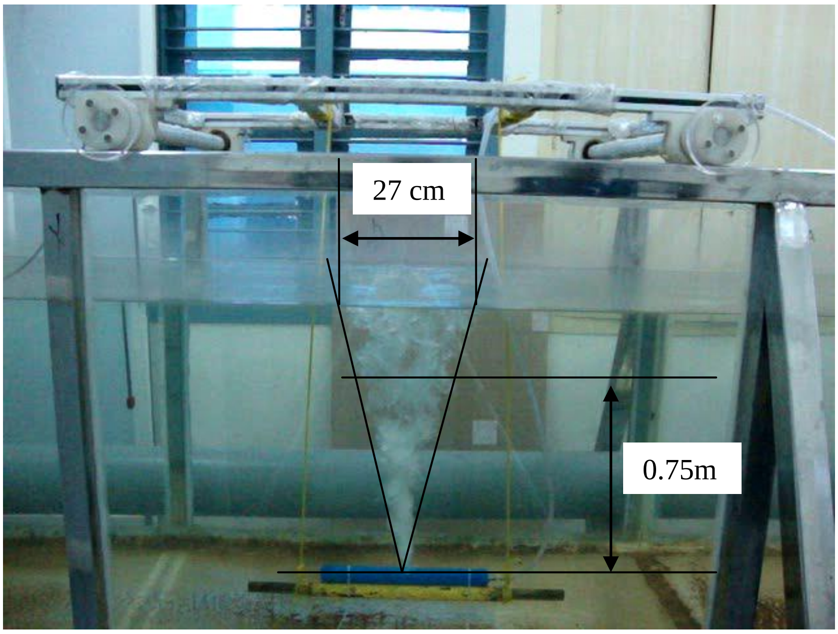


Fig 5.6.2 : Plume behaviour at
Depth : 0.75m
Flow Rate : $0.0112 m^3/s$

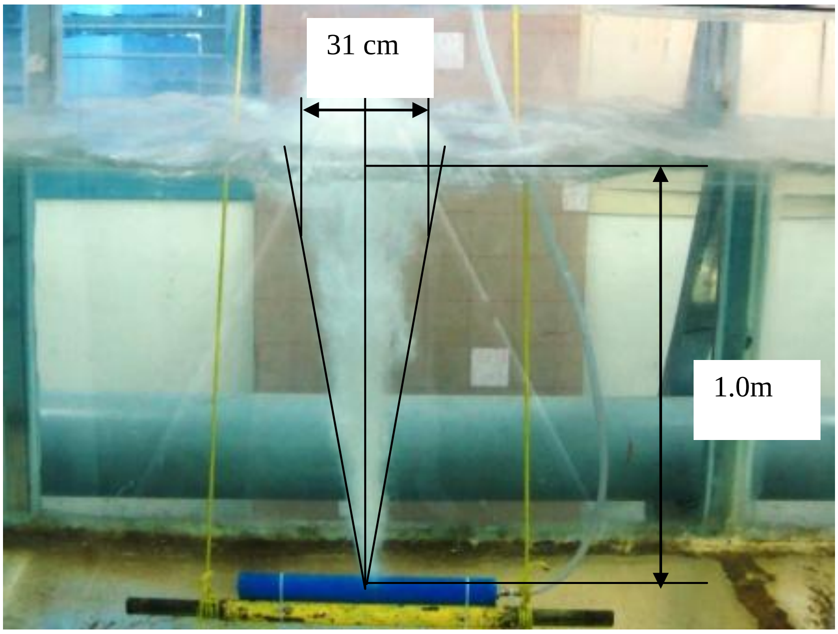


Fig 5.6.3 : Plume behaviour at
Depth :1m
Flow Rate : 0.0112m^3/s

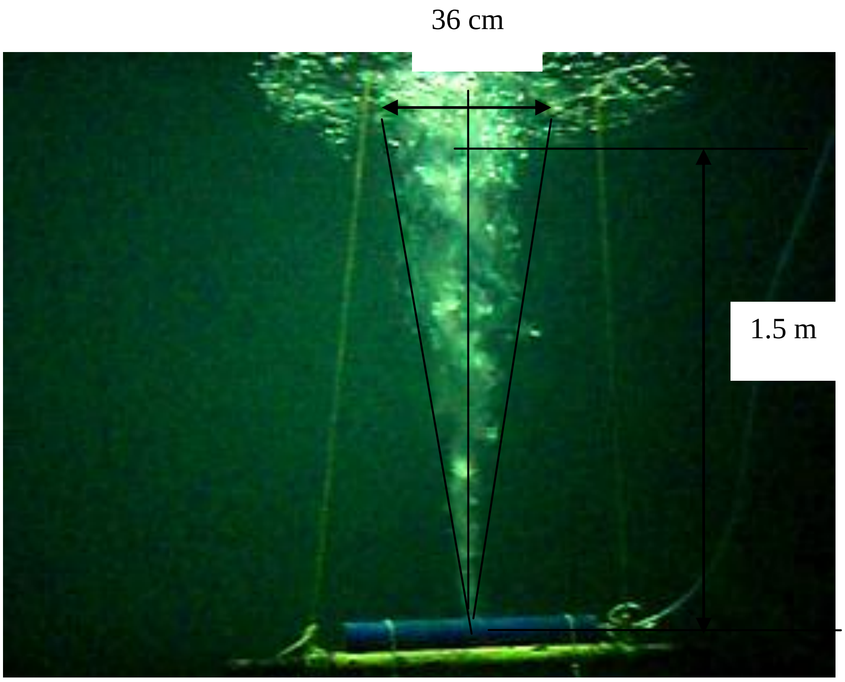


Fig 5.6.4 : Plume behaviour at
Depth : 1.5m
Flow Rate : 0.0112m^3/s

5.7 IIT-M experimentation results for Arabian Sea conditions

Arabian Sea plume characteristics

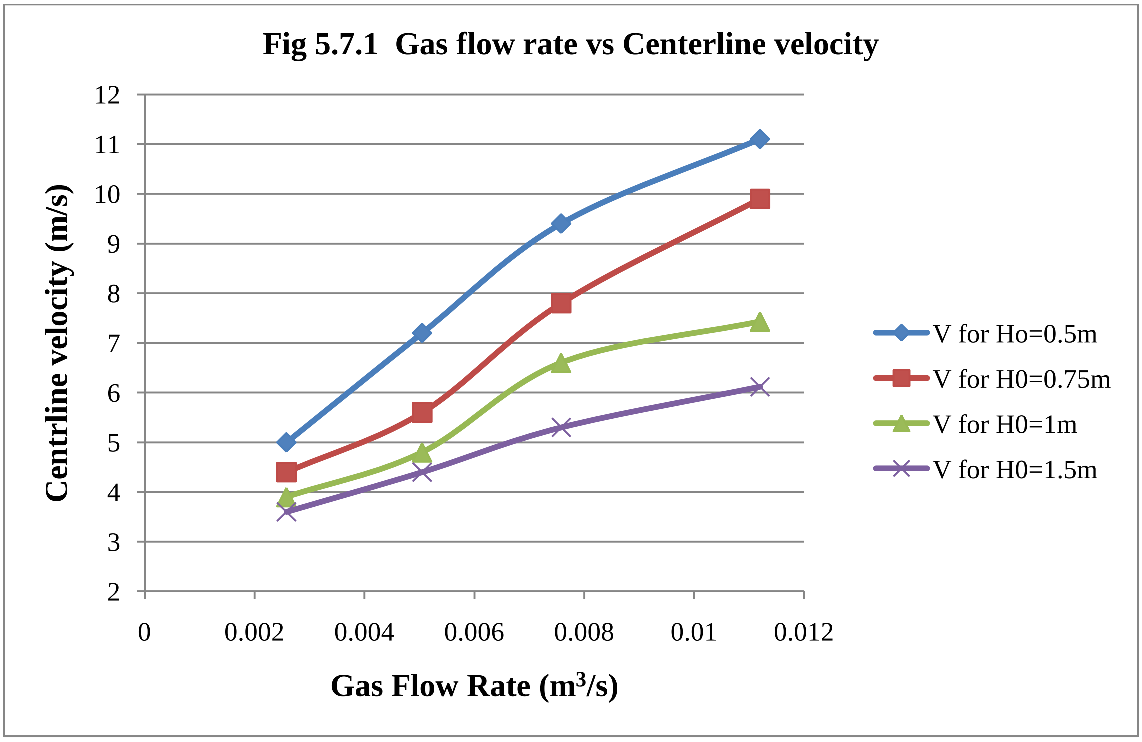


Table 5.2: Gas flow rate and centreline velocity for various depths for Arabian Sea conditions

Vg (m3/s)	V for Ho=0.5m	V for H0=0.75m	V for H0=1m	V for H0=1.5m
0.00253	5	4.4	3.9	3.6
0.00505	7.2	5.6	4.8	4.4
0.00758	9.4	7.8	6.6	5.3
0.0112	11.1	9.9	7.43	6.12

From fig 5.7.1, one can see that at a particular ocean depth (Ho), the centreline velocity (V) of the plume is increasing with respect to gas flow rate (Vg).

At constant Ho, V α Vg

For the lesser ocean depth the change in flow rate has more effect on centerline velocity of the plume when compared to higher depth.

Arabian Sea plume characteristics

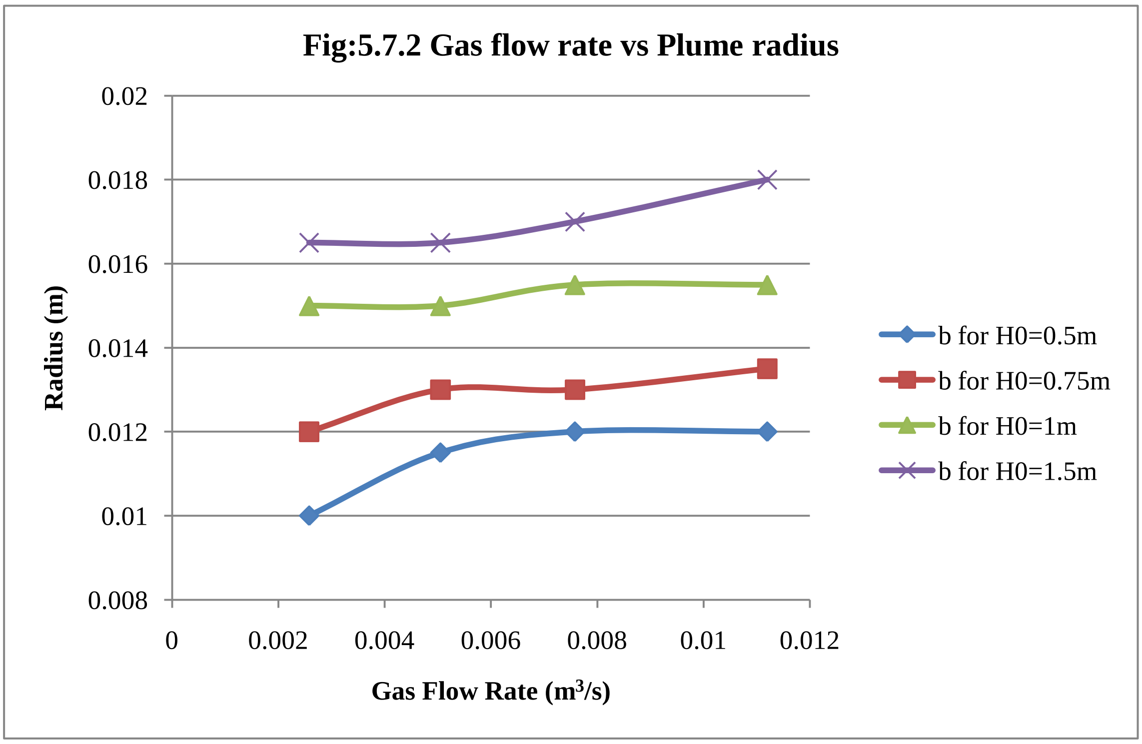


Table 5.3: Gas flow rate and plume diameter for various depths for Arabian Sea conditions

Vg (m3/s)	**b for H0=0.5m**	**b for H0=0.75m**	**b for H0=1m**	**b for H0=1.5m**
0.00253	0.01	0.012	0.015	0.0165
0.00505	0.0115	0.013	0.015	0.0165
0.00758	0.012	0.013	0.0155	0.017
0.0112	0.012	0.0135	0.0155	0.018

The gas flow rate does not have significant effect on plume radius. At a given flow rate, there is a significant increase in the plume radius with increasing ocean depth. This is because as the depth increases the surface tension acting on the bubble plume also increases. The maximum difference in radius is observed at higher depth.

At constant Vg, b α Ho

Higher radius of the plume indicates wider cover area and hence a higher fire and explosion risk. A large area further increases the possibility of coming in contact with the ignition source.

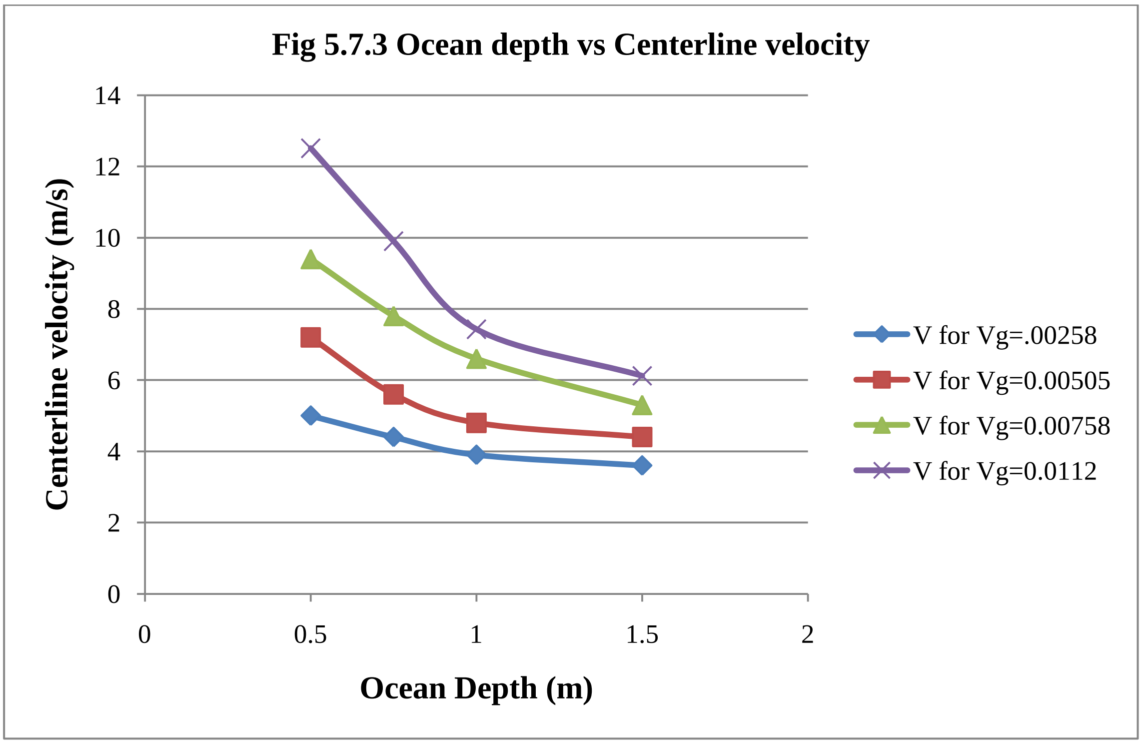


Table 5.4: Ocean depth and centreline velocity for various flow rates for Arabian Sea conditions

Ho(m)	V for Vg=0.00253	V for Vg=0.00505	V for Vg=0.00758	V for Vg=0.0112
0.5	5	7.2	9.4	11.1
0.75	4.4	5.6	7.8	9.9
1	3.9	4.8	6.6	7.43
1.5	3.6	4.4	5.3	6.12

As the ocean depth increases (flow distance also increases), the frictional forces acting along the length of flow also decrease the velocity of flow thus leading to gradual decrease in flow velocity with increasing ocean depth. Velocity is also dependent on the gas flow rate i.e., as the flow rate increases, the velocity also increases. The hydrostatic pressure acting on the plume (bubbles) increases with depth but due to surface tension the bubble breaks and a balance is maintained for the plume to flow.

Arabian Sea plume characteristics

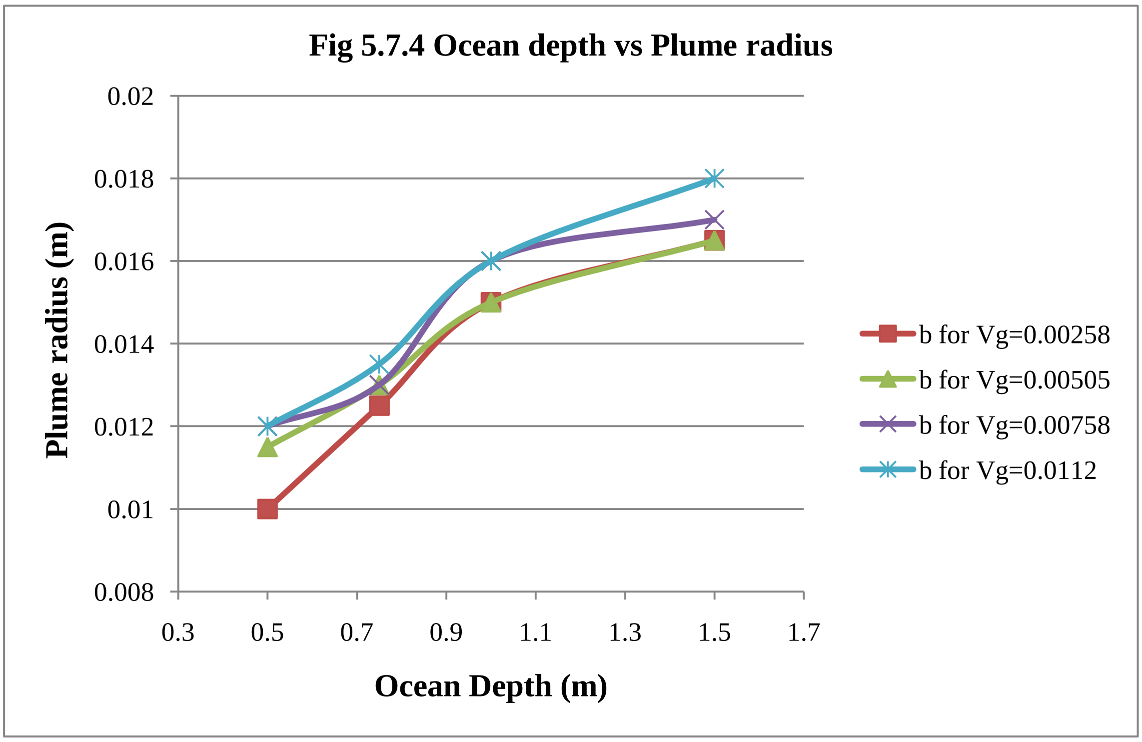


Table 5.5: Ocean depth and plume radius for various flow rates for Arabian Sea conditions

Ho(m)	**b for Vg=0.00253**	**b for Vg=0.00505**	**b for Vg=0.00758**	**b for Vg=0.0112**
0.5	0.01	0.0115	0.012	0.012
0.75	0.0125	0.013	0.013	0.0135
1	0.015	0.015	0.016	0.016
1.5	0.0165	0.0165	0.017	0.018

The initial pressure of the gas released from the pipe is high, the gas coming out from the pipe expands thus the plume diameter increases as it advances. Also the hydrostatic pressure acting on the plume bubbles surface decreases as the plume raises in the water which allows the plume to further diverge its flow. As the flow rate is increased, the pressure of flow also increases which has very small effect on the diameter of plume. The maximum difference in diameter of plume was observed to be 0.004m at a depth of 0.5m in comparision with flow rates of 0.00253 and 0.0112m^3/s. Hence when compared to flow rate, ocean depth has got very significant effect on the diameter of the plume.

Consolidated readings

Table 5.6: Experimental results

S.N	**Ho (m)**	**Flow rate (m^3/s)**	**Radius (m)**	**Centre-line velocity (m/s)**
1.	0.5	0.00253	0.01	5
2.	0.5	0.00505	0.0115	7.2
3.	0.5	0.00758	0.012	9.4
4.	0.5	0.0112	0.012	11.1
5.	0.75	0.00253	0.0125	4.4
6.	0.75	0.00505	0.013	5.6
7.	0.75	0.00758	0.013	7.8
8.	0.75	0.0112	0.0135	9.9
9.	1	0.00253	0.015	3.9
10.	1	0.00505	0.015	4.8
11.	1	0.00758	0.016	6.6
12.	1	0.0112	0.016	7.43
13.	1.5	0.00253	0.0165	3.6
14.	1.5	0.00505	0.0165	4.4
15.	1.5	0.00758	0.017	5.3
16.	1.5	0.0112	0.018	6.12

Results from experimentation:

Parameter varied	**Range**	**Comments**
	PRIMARY PARAMETERS	
Water depth Height of water column (Ocean depth)	500 - 1500m	Hazard range increases with water depth because the plume diameter increases with increasing ocean depth.
Leakage/ flow rate/ release rate	0.00253-0.0112m^3/s	Hazard range increases with release rate due to wide spread of dispersion above sea. For low release rates (typically below 0.1 – 1kg/s), result in very restricted hazardous zones. This imply that ignition of such releases is extremely unlikely.
Sea temperature	24^0C	Sea temperature does not have any significant effect on plume behavior.
Gas density	1	Air has being taken for experimentation for safety reasons.
Salinity	32 – 37 parts	Salinity does not have any significant effect on

	per thousand	plume behavior.
Sea current	0 - 1.5m/s	Shifts location of surfacing plume but may have an impact on risk.
Source diameter/ diameter of release opening	2.54cm (1 inch)	Source diameter is chosen based on the real case data available for pipeline failures recorded by HSE Executive, UK.
Release direction	Upwards	Momentum loss due to downward and sideward release is not considered.

5.8 Chapter Summary

The plume model established through IIT-M experimentation for Arabian Sea conditions very well matches the Plume model established by Fannelop T.K. & Bettelini M., 2007 [10] in North Sea which is discussed in chapter 6.

The plume radius and centreline velocity are directly influenced by ocean depth.

The salinity and temperature do not have significant effect on the plume behaviour.

6. MODELS FOR RESEARCH PROBLEM'S COMPETENCE

6.1 Chapter overview

This chapter analyses in details, the features of commonly used Subsea gas discharge models in UK for North Sea conditions [37].

6.2 Competing models for research problem

The following are the types of Subsea gas pipeline leaks discharge models commonly used in North Sea.

a. Empirical/ Cone model
b. Integral Model
c. Computational Fluid Dynamic (CFD) model

Empirical models are the simplest one which assume the plume radius to be proportional to the release depth or correlations that have been produced to fit the available experimental data.

The mathematical equations of hydrodynamics are the basis for the development of integral model and CFD.

In *Integral models*, the radial profiles of velocity and density are assumed to have a similar form at different heights within the plume. The plume properties can be represented, using for example Gaussian profiles, by their plume centreline values. A correlation relating to the rate of increase of water flow to the plume centreline properties through the use of an entrainment coefficient, as is used for including entrainment of water (liquid entrainment) in single phase plume modelling. Gas continuity, and equating the increase in momentum to the buoyancy forces, allows the plume properties to be calculated in a step-by-step manner as the height above the release is incremented. Separate models have been produced for the ZOEF and the ZOSF.

Computational Fluid Dynamics (CFD) is the most complex models which solve the Navier Stokes equations of fluid flow. Their advantage over integral models is that effects such as entrainment and turbulent transport of momentum are modelled directly and do not require the use of empirical constants. However CFD models still involve some modelling assumptions and are more resource-intensive to run than integral or empirical models as described below.

6.2.1 Cone/ empirical model

Taylor's study of line plumes used as breakwaters was initially published in 1955. Taylor Morton and Turner formulated the fundamental theory for turbulent single-phase plumes in 1956 [28]. Their paper has been a prime reference for later plume studies, first in meteorology, and subsequently in bubble-plume hydrodynamics studies. Most relevant are the papers by Fanneløp and Sjøen (1980) [12] and the plume measurements published by Sjøen (1983) and Milgram (1983) [27]. A large number of studies, both in research and in engineering applications, are based on these papers.

Simple cone models assume either that the bubble plume has a cone of angle θ, or, equivalently, that the radius at the surface is a fixed proportion of the depth: i.e. b (z) =z tan (θ/2) his 'model' is illustrated in Fig 6.1.

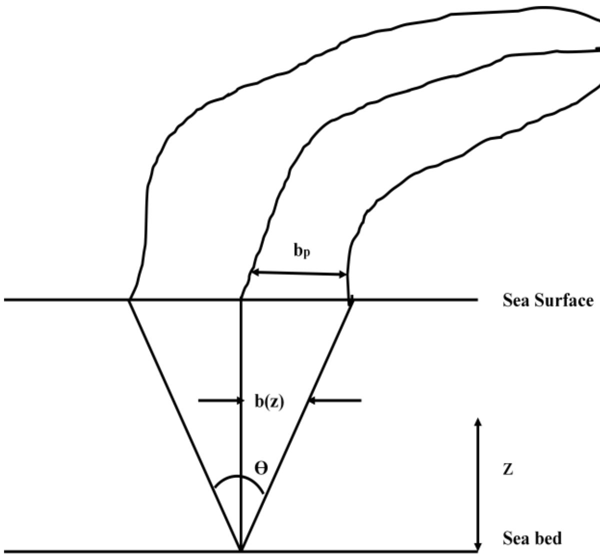


Fig: 6.1 Subsea discharge based on simple cone model

It is assumed that θ, and hence tan θ/2, are fixed parameters which do not vary with release rate or depth. The value of the model constants used varies significantly. Generally, the cone angle is given as between 10-12°. Lower values closely match that of 10° that is given by **Wilson, 1988** [48] **and Milgram and Erb, 1984** [25]. This cone angle is defined as that of the subsea plume and does not include the effect of radial flow, which is known to occur near the sea surface.

The ‘boil area’, where the bubbles break through the surface, has approximately twice the diameter of the bubble plume as determined in the absence of surface interaction. Although this observation is yet to be confirmed by detailed measurements, it would give a justification for the use of cone angles of up to 23^0 **Billeter and Fanne1op 1989** [3].

Uncertainty in Results from Empirical Model [37]:

These models are clearly the simplest of those considered, and has the following limitations:

- They assume complete plume similarity through both the depth of the sea, and over the range of release rates considered;
- There is no dependence of the diameter of the surfacing plume on the release rate;
- No predictions are provided for concentration or gas velocity immediately above the surface;
- Some uncertainty exists in the effective diameter at the surface, resulting in a factor of around 2 on recommended cone angles.

In view of these limitations, accuracy is not expected to be high, and is difficult to assess.

6.2.2 Integral Models

The dispersion of the gas from the release point to the surface is considered in three zones illustrated in Fig.6.2:

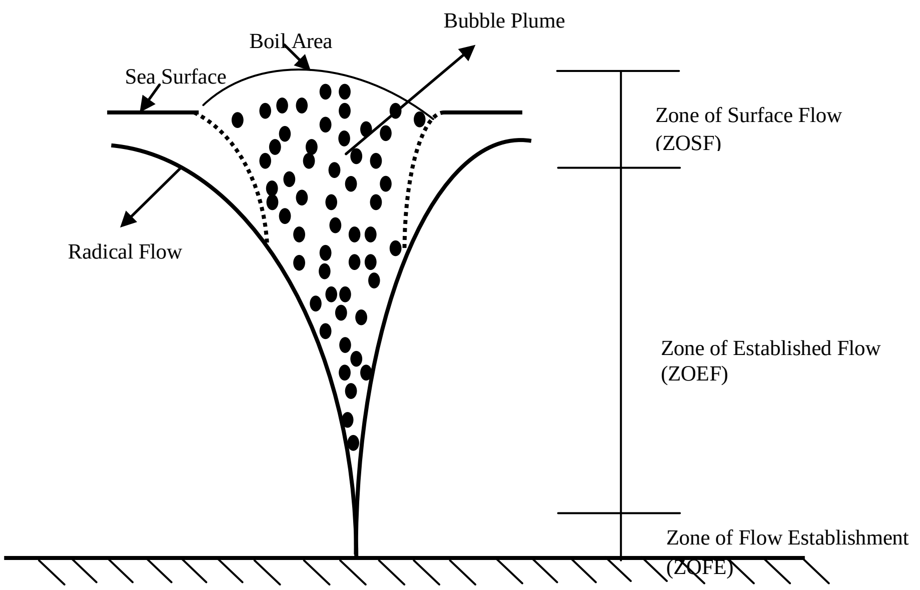


Fig: 6.2 Idealised subsea bubble plume

Zone of Flow Establishment (ZOFE): The region between the release point and the height at which the dispersion appears to adopt a plume-like structure. At this height the effects of initial release momentum are considered to be secondary to the momentum induced by buoyancy.

Zone of Established Flow (ZOEF): The plume-like region of dispersion which extends from the ZOFE to a depth beneath the free surface which is of the order of one plume diameter.

Zone of Surface Flow (ZOSF): The region above the ZOEF where the plume interacts with the surface causing widening of the bubble plume and radial flow of water at the surface.

6.2.2.1Governing Equations (Integral Form)

The distance from the source is denoted by ‘z’ and the horizontal distance from the plume axis by ‘r’. An over bar is used for all quantities dependent on both r and z, while this is omitted for quantities dependent only on z. The index (o) is used for values at the source. For quantities in the plume the index (p) is used, while the gas and water phases are denoted with the indices (g) and (w) respectively.

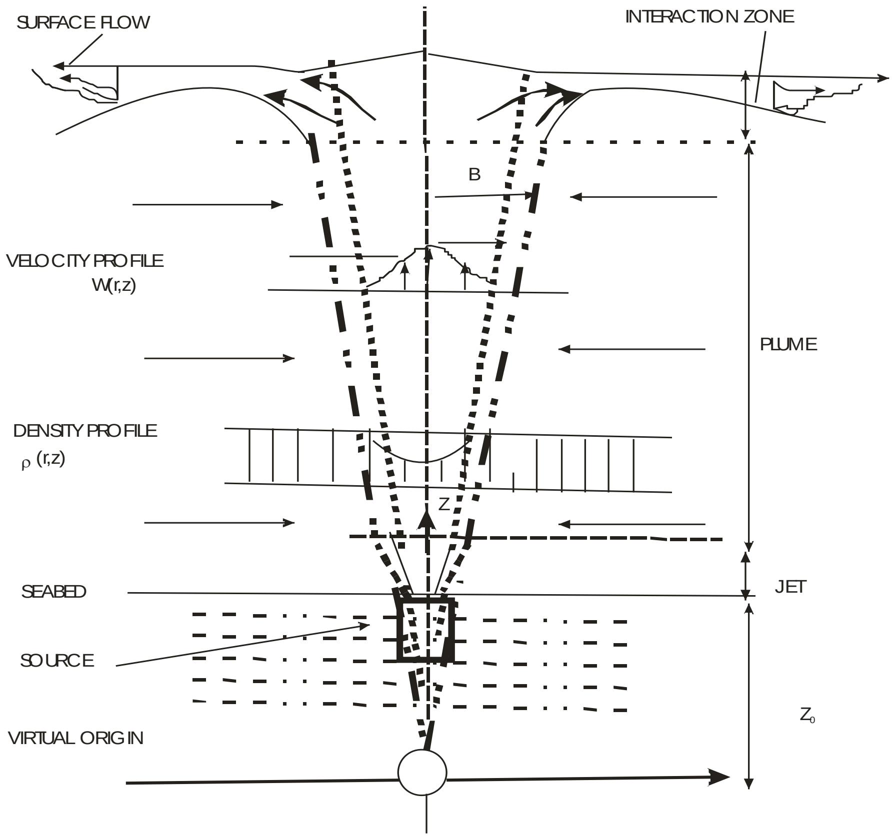


Fig: 6.3 Steady-state bubble plumes with surface flow

The gas expansion is represented by means of the polytrophic relation

$$\frac{\rho_g(z)}{\rho_g(0)} = \left[\frac{p(z)}{p(0)}\right]^{1/n} \qquad \textit{(eqn.-1)}$$

The momentum equation for the plume established by Fannelop et al (2007) [10]

$$\frac{d}{dz}\left(\varphi_2 w^2 b^2\right) = \varphi_4 \frac{g\dot{V}_0}{\pi\left(w + \varphi_4 w_s\right)}\left[\frac{H}{H - z}\right]^{1/n} \qquad \textit{(eqn.-2)}$$

Empirical Coefficients

The empirical parameters required are summarized, estimates for the expected range of variation and the values recommended are presented in Table 6.1. The plume development is sensitive to variations in the entrainment coefficient α. Variations of the remaining parameters in their expected uncertainty ranges have only a minor influence on the results. Only results based on the Gaussian profile assumption is more realistic.

Gas expansion

The gas expansion is assumed to be isothermal (n = 1), as an adiabatic process would result in an unrealistically large drop in temperature for the rising gas.

Entrainment coefficient α

The entrainment coefficient α has had been found to increase with increasing gas flow rates. This can be accounted for by means of a semi-empirical correlation proposed by Milgram [27]:

$$\alpha = K\frac{F_r}{A + F_r} \qquad \textit{(eqn.-3)}$$

Width Ratio λ

The range of variation in λ is smaller and the effect on the plume development is much less important. The lower values correspond also here to laboratory experiments, whereas for very large scales λ is expected to approach unity.

Bubble Slip Velocity U_b

The typical values of bubble slip velocity are 28-30 cm/s for bubbles of 0.2-1.5 cm diameter. For larger diameters the value rises to 35-40 cm/s, but in the turbulent plume the bubbles tend to be unstable and to break up into smaller sizes. Milgram's [27] analysis is based on a value of 0.35 m/s. A slightly smaller value of 0.3 m/s will be used herein. Because the influence of this parameter is known to be weak, its effect will not be investigated in more detail.

Momentum Amplification Factor ϒ

The momentum amplification factor is defined as the ratio of total momentum flux to the momentum flux carried by the mean flow [27] and is a measure for the momentum flux due to turbulent fluctuations. Large values of this parameter are found in small-scale laboratory experiments. This is the case also for the phenomenon known as plume wandering. As the bubbles become very small in comparison with the plume dimensions, bubble dynamics and interactions become less important and the flow behaves like a single-phase fluid. It follows that Momentum Amplification Factor can be expected to approach unity. This is confirmed by the analysis carried out by Milgram [27].

$$\Upsilon = \frac{M(z)}{2\pi \int (U2\ (U2(r,z)\ p\ f1 - f\ (r,z) + (U(r,z) + UJ\,2p(z) f(r,z) r.dr.}$$

(eqn.-4)

Table 6.1 Recommended Values for empirical parameters for application:

S.No	Parameter	Range	Recommended Value
1.	n	1- c_p/c_v	1
2.	α	0.06 - 0.15	0.1
3.	λ	0.6 - 1.0	0.8
4.	U_b	0.1 - 0.4m/s	0.3m/s
5.	ϒ	1-2	1

As shown by Fanneløp and Sjøen [12], the governing equations for a steady plume, Eqn. 1 and Eqn.2 admit a closed form similarity solution only if the slip velocity U_b is neglected and the buoyancy term in Eqn. 2 are constant. For distances from the source of the order of $p_a/(g\rho_w)$, this is a reasonable approximation. The similarity solution is

$$b = \frac{6}{5}\frac{\alpha}{\varphi_1} z \qquad \textit{(eqn.-5)}$$

$$w = \frac{1}{2}\left[\frac{25}{6\pi}\,\frac{\varphi_1^2\varphi_4}{\varphi_2}\,\frac{g\dot{V}_0}{\alpha^2}\right]^{1/3} z^{-1/3} \qquad (eqn.\text{-}6)$$

$$c = \frac{\varphi_4 \dot{V}_0}{\varphi_3 \pi b^2 w} = const.z^{-5/3} \qquad (eqn.\text{-}7)$$

6.2.2.2 Integral models for the Zone of Established Flow (ZOEF)

The integral models are developed form physical processes model. The leading assumptions for bubble and plume dynamics have supported the development of integral models in a manner similar to that used for thermally buoyant plumes. The general integral formulation given by **Milgram, 1980** following on from a report by **Fazal & Milgram** [13], serves as a good example as described below.

Firstly, the mean fluid velocity, and the mean density defect within the plume are assumed to take the form of Gaussian distributions, i.e.

$$U(r,z) = U(z)\, e^{\frac{r^2}{b^2}} \qquad (eqn.\text{-}8)$$

$$\rho_w - \rho_p(r,z) = S(z)\, e\, \lambda^{2\frac{r^2}{b^2}} \qquad (eqn.\text{-}9)$$

Rew et al [37] have solved the following equations using a numerical integration scheme which approximates derivatives in z using a simple finite difference, scheme, and then solves for the centreline gas fraction S(z), the centreline velocity U(z) and the plume width b(z) using Newton iteration.

$$2\alpha U(z).b(z) = \frac{d}{dz}\left\{ U(z).b^2(z) \left\{ 1- \frac{\left\{\lambda^2 S(z)\right.}{[1+\lambda^2][\rho_w + \rho_g(Z)]} \right\} \right\} \qquad (eqn.\text{-}10)$$

$$\frac{q_T H_T}{H_B - z} = \frac{\pi\lambda^2 b^2(z) S(z)}{\rho_w - \rho_g(z)}\left[\frac{U(z)}{1+\lambda^2} + U_b\right] \qquad (eqn.\text{-}11)$$

$$g\lambda^2 S(z)b^2(z) = \frac{d}{dz}\left[\gamma b^2(z)\left\{U^2(z)\left[\frac{\rho_w}{2} - \frac{\lambda^2 S(z)}{1+2\lambda^2}\right] + \frac{\lambda^2 U_b \rho_g(z) S(z)}{\rho_w - \rho(z)}\left[\frac{2U(z)}{1+\lambda^2} + U_b\right]\right\}\right]$$

(eqn.-12)

6.2.2.3 Integral models for the Zone of Surface Flow (ZOSF)

The mass flux integral equation for Integral models for the Zone of Surface Flow is written as:

$$m_F = \rho_w 2\pi r \int_0^\infty V(r,Z)dZ \qquad \textit{(eqn.-13)}$$

and the momentum flux of the fluid as:

$$M_P = \rho_W 2\pi r \int_0^\infty V^2(r,Z)dZ \qquad \textit{(eqn.-14)}$$

As with the vertical plumes, conservation laws for mass and momentum are applied in the form of an entrainment relation for the former, and the assumption that no external forces (i.e. buoyancy or viscous effects) are acting on the radial flow, giving:

$$\frac{d}{dr}\left(\pi^{\frac{3}{2}}\rho_w h_w V_w r\right) = 2\pi r \rho_w \beta V_m \ \textit{and} \qquad \textit{(eqn.-15)}$$

$$\frac{d}{dr}\left[\left[\frac{\pi^3}{2}\right]^{\frac{1}{2}}\rho_w h_w V_w^2 r\right] = 0 \qquad \textit{(eqn.-16)}$$

Uncertainty in results from Integral Models [37]:

The accuracy of the integral models is most sensitive to:

- the need for an established zone of plume-like behaviour;
- the entrainment assumption, and the constancy of coefficients and for the plume and the free surface flow region;

- the treatment of the bubble plume as a continuum, based upon the assumptions regarding bubble dynamics cited in section Bubble Dynamics;
- the value of λ deduced from experimental observation.

However it is not clear how closely full scale blowouts conform to the plume-like model which forms the basis of the integral formulation, since the gas flow rates used in experiments are so low. It might even be the case that the so called zone of flow establishment is the dominant region for gas flow rates of $30Nm^3$/sec or more in 'shallow' water depths of 30-40m, typical of the southern part of the North Sea.

The experimental data point towards the entrainment assumption being inappropriate even for small scale experiments. The evidence for this conclusion relates to the apparent dependence of a continuous gas flow rate, bubble plume radius, centreline velocity, turbulence intensity and bubble separation as cited by **Fannelop & Sjoen 1980** [12].

6.2.3 CFD Models

Three different multiphase CFD methods were evaluated to assess their applicability by Schalk Cloete et al [40]. These include the Eulerian-Eulerian multi-fluid approach, the Eulerian-Eulerian mixture model and also a combined model consisting of the Eulerian-Lagrangian discrete phase model (DPM) and the Eulerian-Eulerian volume of fluid (VOF) model. The VOF variant of the Eulerian-Eulerian multiphase approach is specifically designed for the tracking of sharp interfaces between various phases and the bubble plume was tracked with the DPM. The coupled DPM and VOF model was therefore identified for quantitative studies of subsea gas release. The VOF model solves for conservation of mass as represented by below equation.

$$\frac{d}{dr}(r_\phi \rho_\phi) + \nabla.(r_\phi \rho_\phi U_\phi) = m \qquad \textit{(eqn.-17)}$$

$$\frac{d}{dt}(r_\phi \rho_\phi U_\phi) + \nabla.(r_\phi \rho_\phi U_\phi . U_0 - r_\phi T_{F\phi} \nabla U_\phi) = r_\phi S_{F\phi} \qquad \textit{(eqn.-18)}$$

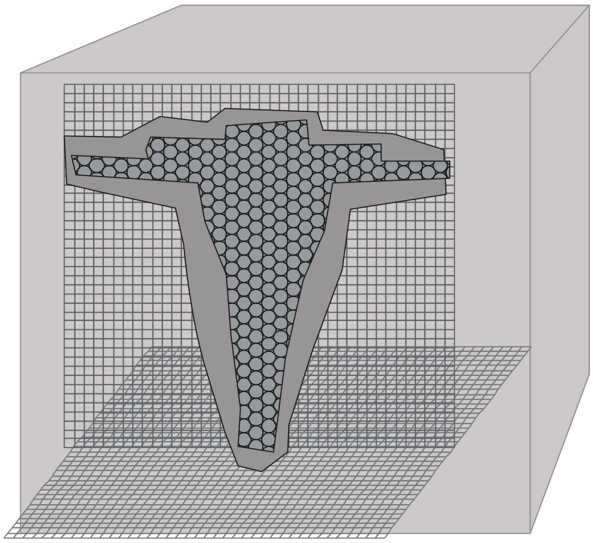


Fig 6.4 Cross section of the grid used in the coupled DPM-VOF simulation

The DPM tracks discrete particles through the domain in the Lagrangian sense by implementing a force balance over each particle:

$$\frac{d\vec{u}_p}{dt} = F_D\left(\vec{u} - \vec{u}_p\right) + \frac{\vec{g}\left(\rho_p - \rho\right)}{\rho_p} + \vec{F}_p \qquad \textit{(eqn.-19)}$$

The bubble trajectory is predicted by integrating the equation of motion (Domgin et al):

$$\frac{dv}{dt} = F_D(u - v) + g\left(\rho_p - \rho\right)\Big/\rho_p + \frac{1}{2}\frac{\rho}{\rho_p}\frac{d}{dt}(u - v) + \frac{\rho}{\rho_p}\frac{du}{dt} \qquad \textit{(eqn.-20)}$$

A Lagrangian equation of motion for each discrete bubble was given as:

$$\rho_g(z)\frac{dV_i}{dt} = -\frac{3\mu_i}{4d_b}(V_i - U_i)C_D R_e + \rho_w U i\frac{\partial U_i}{\partial x_i} - \frac{\rho_w}{2}\left[\frac{dV_i}{dt} - U_i\frac{\partial U_i}{\partial x_i}\right] - (\rho_w - \rho_g(z))g_i$$

(eqn.-21)

Equation 21 represents a balance between the bubble acceleration, bubble drag, pressure gradients, bubble added inertia forces and buoyancy.

The generation of turbulence by the bubbles is modelled by assuming that production and dissipation are in balance, and that therefore the total turbulent kinetic energy generated within each cell is;

$$P_b = \frac{q(z)}{N\Delta V}\sum_{n=1}^{N} F_i(V_i - U_i)dt \qquad \textit{(eqn.-22)}$$

Thus the turbulence production is due entirely to the sum over all bubbles in a cell of the power ($F_i(V_i - U_i)$) required to overcome bubble drag, integrated over the time taken by the bubble to traverse the cell.

Uncertainty in Results from CFD Models [37]:

The main sources of uncertainty for CFD models concern:

- the implementation of additional source terms in conventional CFD codes;
- the need for very specific and detailed flow data for validation purposes.

The additional source terms required in the momentum and turbulence transport equations are based upon many of the assumptions on bubble dynamics described earlier. It is not clear how well these behave when the volume fraction of liquid is low, as would be the case for high gas flow rates.

Secondly, the problem of validating CFD models in general is exacerbated by the need for detailed measurements of velocity distribution, turbulence etc. It is difficult to measure such quantities accurately for two phase flows.

6.3 Most optimal model

An important consideration when using subsea dispersion models is the resource required to use them, potentially for a large number of scenarios. *Clearly, the simple empirical 'model' is the least resource-intensive, user-friendly and, reasonably accurate, is most favoured for use in risk assessments.*

Table 6.2: Comparison of Models

Types of models	Accuracy	Uncertainty	Cost	User-friendliness
Empirical	Medium	Medium	Low	High
Integral	Medium	Medium	Medium	Medium
CFD	High	Medium	High	Low

6.4 Methodology

The hydrodynamic basis for bubble-plume flows is reasonably well understood, but the solutions of the associated equations, depend on a large number of parameters that can only be evaluated by experimentation.

Experiments are conducted to observe real time gas plume behaviour underwater for the given conditions. Experiments (mostly small-scale) are carried-out for various flow rates and depths. The physical data obtained from experimentation is used to validate the theoretical models.

6.4.1. Experimentation - Comparing empirical plume model established in North Sea with IIT-M experimentation for Arabian Sea conditions

Plume variables as function of gas flow rate for different ocean depths- North Sea plume characteristics.

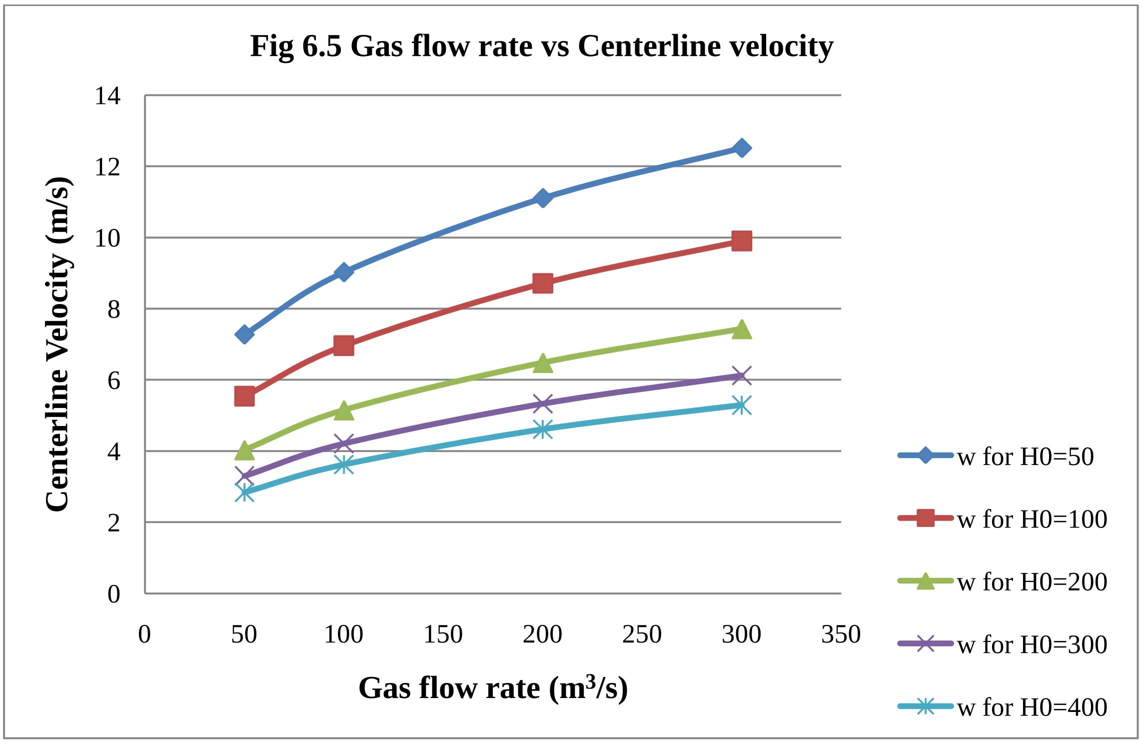


Table 6.3: Gas flow rate and centreline velocity for various depths for North Sea conditions

Vg(kg/s)	**w for H_0= 50**	**w for H_0= 100**	**w for H_0= 200**	**w for H_0= 300**	**w for H_0= 400**
50	7.27	5.54	4.03	3.3	2.84
100	9.02	6.96	5.15	4.21	3.62
200	11.1	8.71	6.48	5.33	4.61
300	12.5	9.9	7.43	6.12	5.29

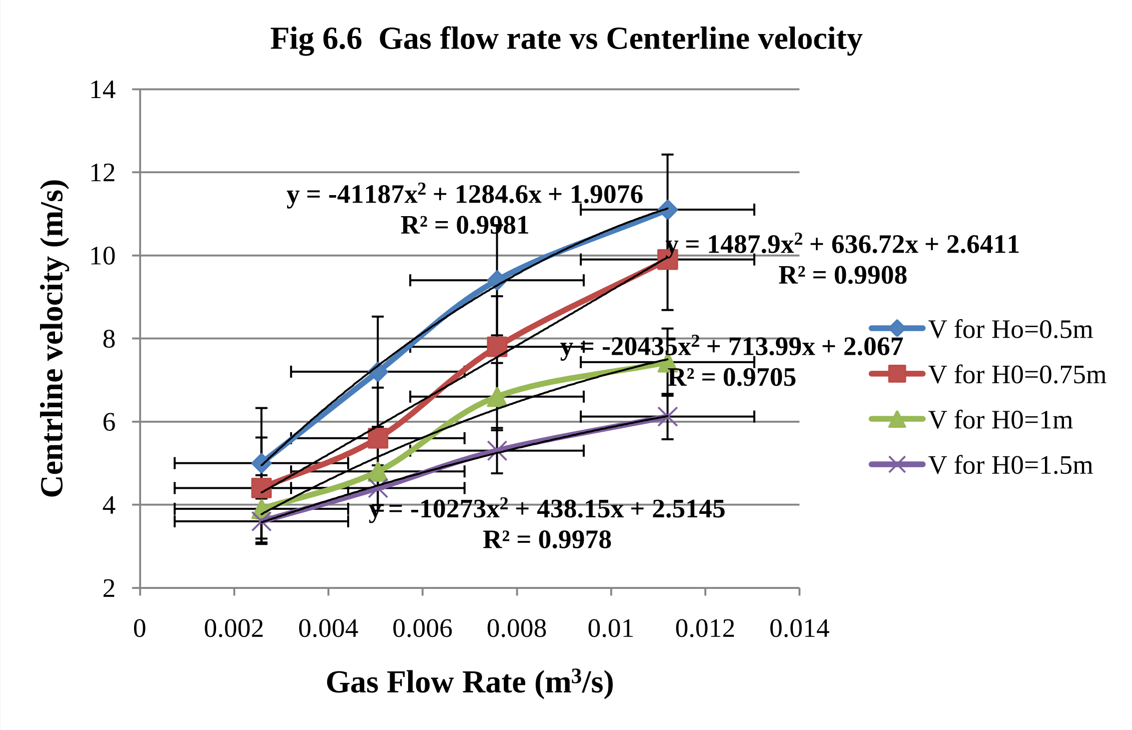


Table 6.4: Gas flow rate and centreline velocity for various depths for Arabian Sea conditions

Vg (m3/s)	V for Ho=0.5m	V for H0=0.75m	V for H0=1m	V for H0=1.5m
0.00253	5	4.4	3.9	3.6
0.00505	7.2	5.6	4.8	4.4
0.00758	9.4	7.8	6.6	5.3
0.0112	11.1	9.9	7.43	6.12

North Sea plume characteristics

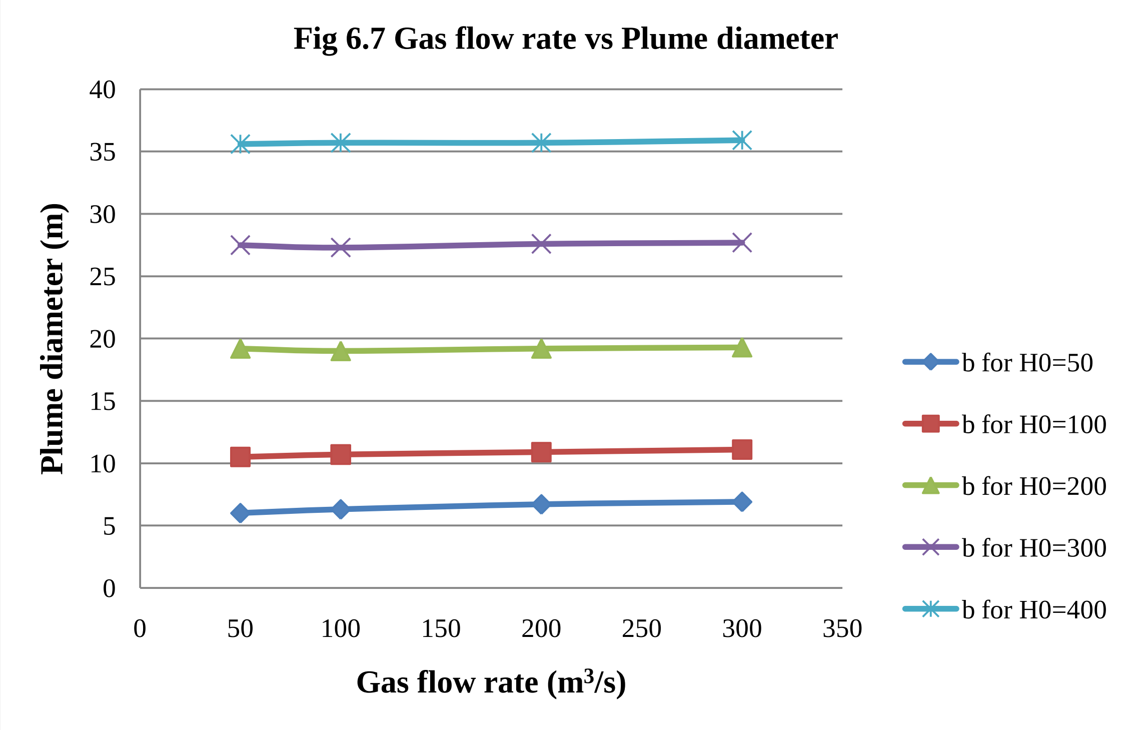


Table 6.5: Gas flow rate and plume diameter for various depths for North Sea conditions

Vg (kg/s)	b for H0=50	b for H0=100	b for H0=200	b for H0=300	b for H0=400
50	6	10.5	19.2	27.5	35.6
100	6.3	10.7	19	27.3	35.7
200	6.7	10.9	19.2	27.6	35.7
300	6.9	11.1	19.3	27.7	35.9

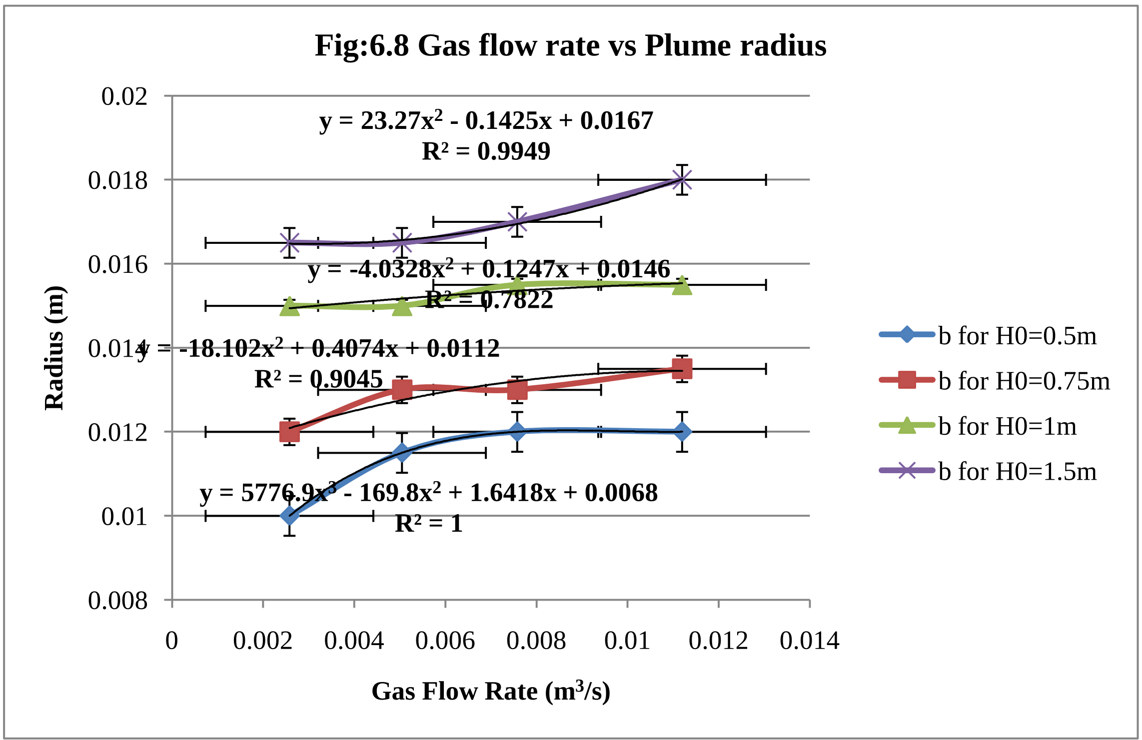


Table 6.6: Gas flow rate and plume diameter for various depths for Arabian Sea conditions

Vg (m3/s)	**b for H0=0.5m**	**b for H0=0.75m**	**b for H0=1m**	**b for H0=1.5m**
0.00253	0.01	0.012	0.015	0.0165
0.00505	0.0115	0.013	0.015	0.0165
0.00758	0.012	0.013	0.0155	0.017
0.0112	0.012	0.0135	0.0155	0.018

North Sea plume characteristics

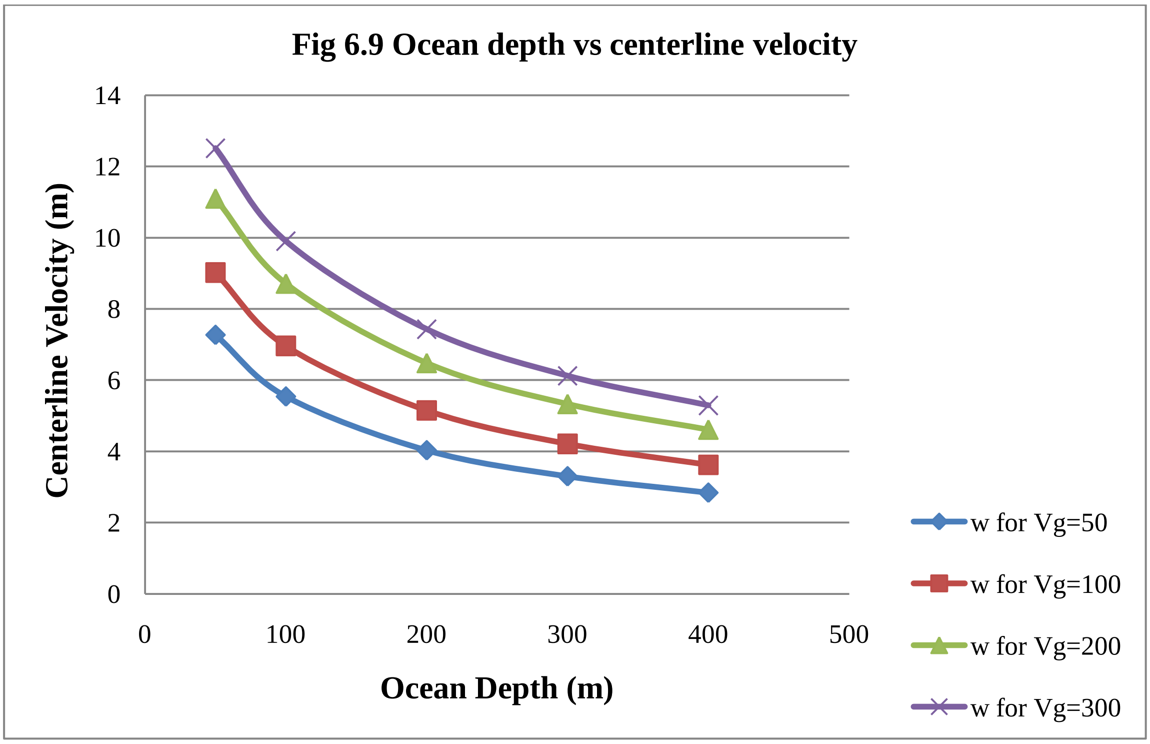


Table 6.7: Ocean depth and centreline velocity for various flow rates for North Sea conditions

Ho(m)	w for Vg=50	w for Vg=100	w for Vg=200	w for Vg=300
50	7.27	9.02	11.1	12.51
100	5.54	6.96	8.71	9.9
200	4.03	5.15	6.48	7.43
300	3.3	4.21	5.33	6.12
400	2.84	3.62	4.61	5.29

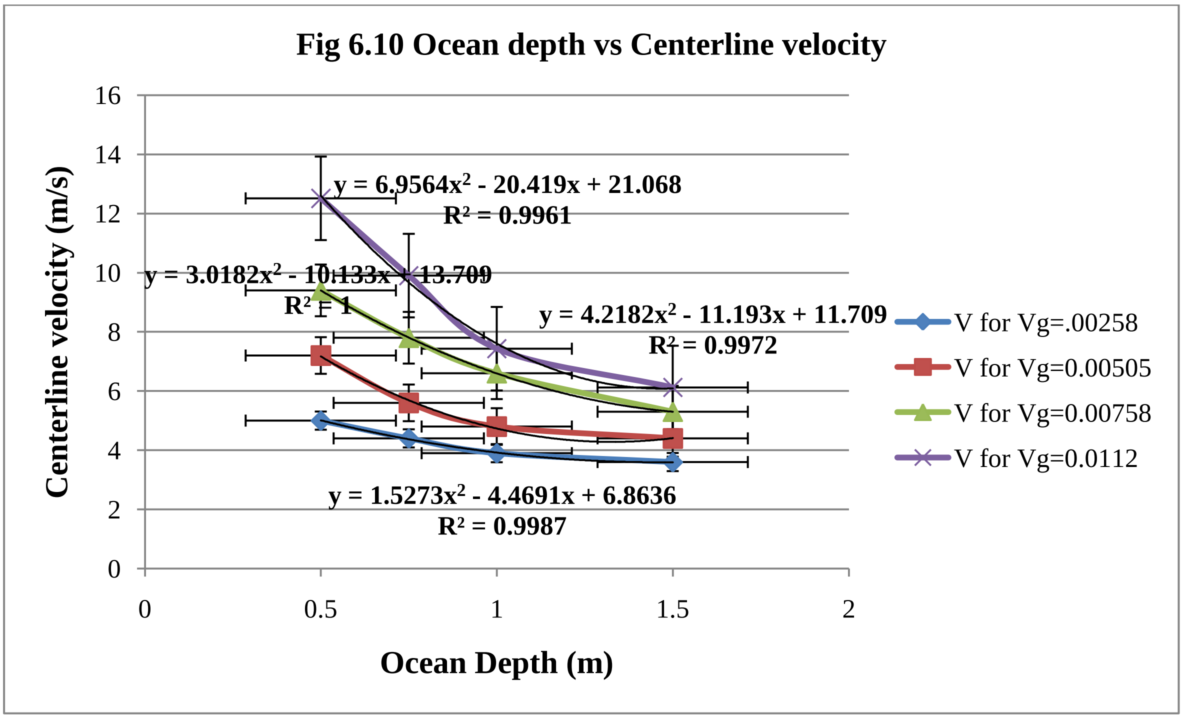


Table 6.8: Ocean depth and centreline velocity for various flow rates for Arabian Sea conditions

Ho(m)	V for Vg=0.00253	V for Vg=0.00505	V for Vg=0.00758	V for Vg=0.0112
0.5	5	7.2	9.4	11.1
0.75	4.4	5.6	7.8	9.9
1	3.9	4.8	6.6	7.43
1.5	3.6	4.4	5.3	6.12

North Sea plume characteristics

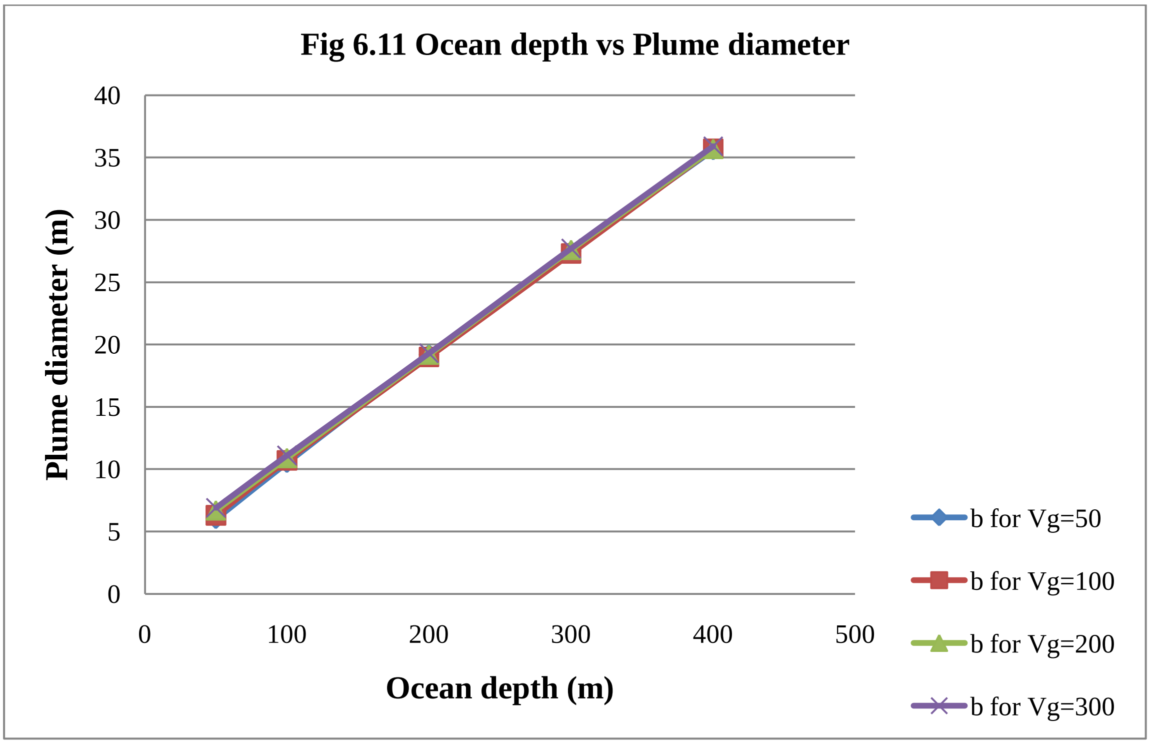


Table 6.9: Ocean depth and plume diameter for various flow rates for North Sea conditions

Ho(m)	**b for Vg=50**	**b for Vg=100**	**b for Vg=200**	**b for Vg=300**
50	6	6.3	6.7	6.9
100	10.5	10.7	10.9	11.1
200	19.2	19	19.2	19.3
300	27.5	27.3	27.6	27.7
400	35.6	35.7	35.7	35.9

Arabian Sea plume characteristics

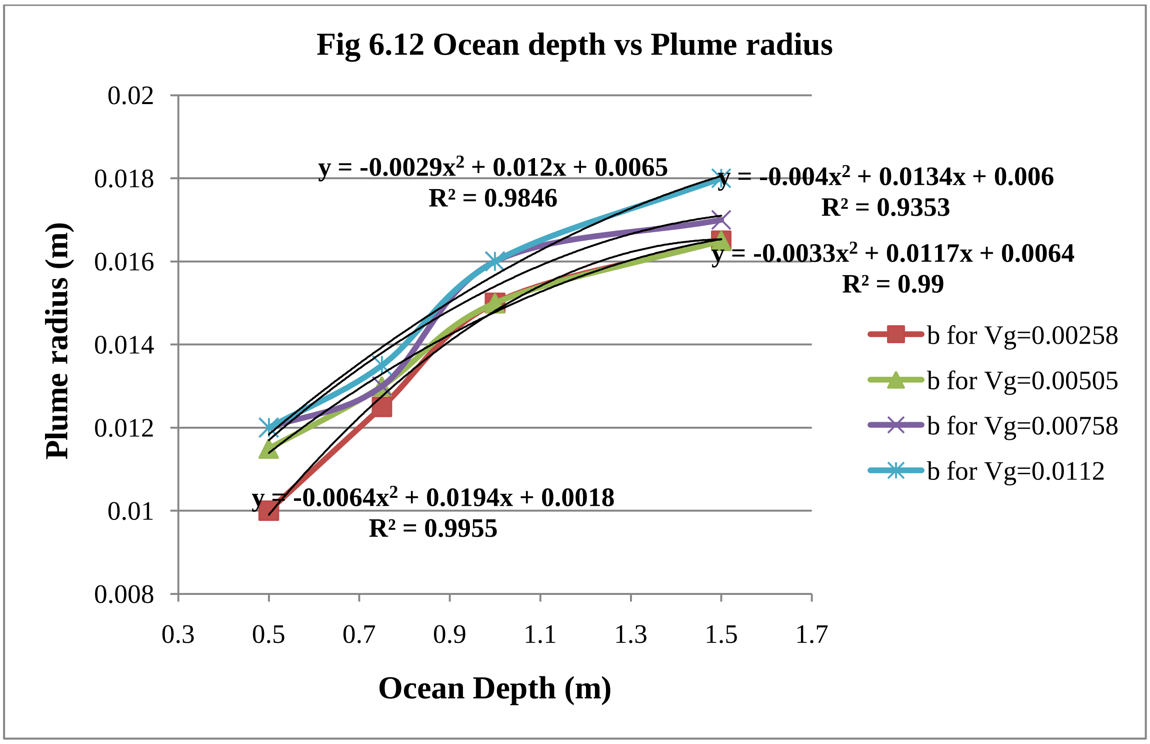


Table 6.10: Ocean depth and plume radius for various flow rates for Arabian Sea conditions

Ho(m)	**b for Vg=0.00253**	**b for Vg=0.00505**	**b for Vg=0.00758**	**b for Vg=0.0112**
0.5	0.01	0.0115	0.012	0.012
0.75	0.0125	0.013	0.013	0.0135
1	0.015	0.015	0.016	0.016
1.5	0.0165	0.0165	0.017	0.018

6.5 Chapter summary

- Very simplistic empirical cone model are most suited for all situations.
- Intermediate integral models are seldom used for real risk assessment. They are only used in research studies.
- CFD has not been extensively applied in risk assessment studies due to prohibitive cost, special competency requirements and special software requirement and other complexity involved.

7. CONCLUSIONS AND FUTURE RESEARCH

7.1 Chapter overview

This chapter summarises the critical findings, recommendations and conclusions of this research work that includes extensive literature survey and lab-scale experimentation.

7.2 Summary of research findings

The following main factors were considered for experimentation:

- Release rate (m^3/s)
- Gas density (kg/m^3)
- Depth of release (m)
- Vertical sea temperature (^0C)
- Salinity (grams of salt per litre of water)

The plume radius and centreline velocity are directly influenced by ocean depth. The salinity and temperature do not have significant effect on the plume behaviour.

a. The simple empirical model is the least resource-intensive, user-friendly and, reasonably accurate, is most favoured for use in risk assessments for Arabian Sea Conditions.
b. The gas discharge plume model established for Arabian Sea conditions very well matches with the plume model for North Sea sub-sea gas releases established by Fannelop T.K. & Bettelini M.
c. Simple cone models assume either that the bubble plume occupies a cone of angle θ, or, equivalently, that the radius at the surface is a fixed proportion of the depth: i.e. b (z) =z tan (θ/2). This 'model' is illustrated in Fig.6.1 This cone angle is defined as that of the subsea plume and does not include the effect of radial flow, which is known to occur near the sea surface.
d. The value of the model constants used varies significantly. The cone angle is established as between 10-12°. Lower values closely match that of 10° there by validating the results established by **Wilson, 1988 and Milgram and Erb, 1984** for North Sea.
e. The 'boil area', where the bubbles break through the surface, has approximately twice the diameter of the bubble plume as determined in the absence of surface interaction. This

observation is confirmed by detailed measurements and justifies the use of cone angles even up to 23^0 as established by **Billeter, 1989 and Fanne1op 1989** for North Sea.

7.3 Contributions of this research

The outcome of this research will greatly benefit the Indian oil and gas industry for enhancing the accuracy of Risk Assessment (Consequence modelling part) of their sub-sea gas pipelines leaks so as to implement specific safety measures to protect the precious national assets.

7.4 Limitations and future research

Physical understanding of plume behaviour

- In real case, the drift of the subsea bubble plume could be significant for deeper waters. This need to be studied further.
- Wave and sea roughness effects on the surfacing plume and its interface with the atmosphere need to be studied in depth as part of gas dispersion studies.
- It is assumed that the bubble plume is driven by the gas buoyancy. However for larger releases, there may be a significant jetting length before buoyancy takes over, and this may be significant compared with the water depth.
- Release orientation should also be considered for large releases, or those in shallow water. For example, a release directed downward will have its momentum destroyed, and probably behave as a bubble plume, whereas one directed upwards will be more jet- like. Horizontally directed jets would probably result in buoyant plumes offset from the release point by the initial jet throw.
- The effects of high initial release momentum or two- phase release on either the plume behaviour or the jetting length is taken into account (i.e. approximately the zone of flow establishment). This is an interesting area of future research.

Plume interface at sea surface

- The interface between bubble plume and atmospheric dispersion is the area of greatest uncertainty. This needs an in-depth study.
- Interface models only exist for zero wind lighter-than-air releases. Incorporation of more realistic interface modelling will almost certainly reduce dispersion distances to LEL for small scale releases.

- The effects of high ocean currents on plume behaviour are an area of further research.

Applications in risk assessment

- Uncertainty in modelling exists for high release rates with high initial momentum. Though uncertainty will be greatest for high release rates (greater than 60 Nm^3/s) and at low water depths where jetting effects are significant. This is an area of interest of further research.
- Uncertainties in risk calculations would be reduced if subsea dispersion modelling, and particularly the modelling of the surface interface, were to be improved. At present, interface modelling exists only for low momentum, buoyant releases. Further in-depth study is needed for high momentum jet releases.

Modelling of sea surface fires

Correlations for flame length are available for fires from the buoyancy through to the momentum dominated regime, but, at present, are not validated for gaseous sea surface fires. Similarly, parameters such as flame tilt and drag of the flame base are poorly defined and no consideration is given to the concentration profile of the surfacing plume on the flame shape. Heat fluxes within and external to sea surface fires are currently estimated from those of land-based pool and jet fires and no consideration is given to the effect of entrained water causing a reduction in best output.

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APPENDIX

APPENDIX-A

NOMENCLATURE

b	radius or subsea plume
b(r)	surface current depth as a function of radial coordinate
B(z)	buoyancy force per unit depth
b(z)	radius of sub-sea plume as a function of depth (z)
b_p	radius of subsea plume at the surface
c	void fraction
C_D	bubble drag coefficient
c_p	specific heat capacity at constant pressure of ambient air bubble diameter
c_v	specific heat capacity at constant volume of ambient air bubble diameter
D	diameter of flame base (diameter of boil area above the subsea release)
d_b	bubble diameter
d_{max}	maximum bubble diameter
D_r	effective diameter of rupture
f(r,z)	local mean gas fraction
Fi	drag force exerted on the i^{th} bubble
Fr	Froude number
g	acceleration due to gravity
H_B	total pressure bead at level of gas release
H_o	depth of release
H_T	atmospheric pressure head
h_w	half depth of surface radial flow
k	fluid turbulent kinetic energy
m	source mass flow rate
M(z)	plume momentum
m_F	mass flux of plume at surface
M_F	momentum flux of plume at surface
N	number of bubbles per unit volume
p(z)	pressure at height z above sea bed
P_b	turbulent kinetic energy generated
q(z)	gas volume flux as a function of water depth

Q(z)	volumetric flow rate of the liquid component within the plume
q_t	gas volume flow rate at atmospheric pressure
r	general radial coordinate
r	volume fraction of phase within plume
r_B	radius of the boil area above the subsea release
Re	bubble Reynolds number
S(z)	density defect along plume centreline
$S_{F\varnothing}$	source term for phase in transport equations
T_a	ambient temperature
$T_{f\varnothing}$	diffusion coefficient for phase
$U_\varnothing$	velocity vector for phase $\varnothing$
U(r,z)	local vertical fluid velocity
U(z)	centreline plume velocity as a function of depth (z)
U_b	bubble slip velocity
U_i	component of fluid velocity vector
U_o	initial gas release velocity
V	volume flow rate of entrained air
V(r,z)	horizontal plume velocity at surface
V_g	volume flow rate of gas mean surface flow velocity
V_i	instantaneous bubble velocity vector
V_m	mean surface flow velocity
w	centreline velocity
z	Vertical distance from the source (positive towards the surface)
Zo	height of the control volume

Greek

a	plume entrainment coefficient
β	entrainment coefficient for surface flow
ε	turbulent kinetic energy rate of dissipation
λ	ratio of inner gas plume radius to total plume radius
φi	Shape parameters
Θ	subsea plume cone angle (figure 6.1)
ϒ	momentum amplification factor
Δ	operator representing small but finite change
Δ∨	CFD code cell volume
ρ_a	density of ambient air
$\rho_g(o)$	density of gas at source (o)
$\rho_g(z)$	density of gas at quarter depth (z)
$\rho_\varnothing$	density of phase in multi-phase flow
$\rho_p(r,z)$	local mean density within plume density of gas at atmospheric pressure
ρ_w	mass density of sea-water
ν_t	eddy viscosity
μ	liquid molecular viscosity
∇	gradient operator

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BIO-DATA OF THE AUTHOR

Sridher is a Mechanical Engineer and a qualified Safety practitioner. He has over 25 years of experience in managing Health, Safety & Environment (HSE), Quality Management (QMS), and Enterprise-wide Risk Management (ERM) in petrochemicals, oil & gas and power industries.

Sridher has presented several technical papers in national & international seminars and conferences. He has also published technical papers in leading magazines and journals.

Published papers

Validating Sub-Sea gas pipeline leaks discharge model for Arabian Sea Conditions, in "Indian Safety Engineer" journal, vol: 11 No.2, Apr-Jun 2011.

Papers accepted for publishing

Validating Sub-Sea gas pipeline leaks discharge model for Arabian Sea conditions, in "National Safety Chronicle" by National Safety Council of India (NSCI), Mumbai and in "Chemical News" magazine by Indian Chemical Council (ICC), Mumbai.

Conference presentations

"Effective management of OH&S in large scale power projects", National workshop by International Finance Corporation (IFC), World Bank Group at New Delhi, Feb 2011.

"Benchmark Safety Practices", at National Safety Health, & Environment (SHE) Confluence 2012 organised by Dept. of Factories, Boilers, Industrial Safety & Health, Govt. of Karnataka at Bangalore on 04th Mar 2012.

State level seminar on "Behavioural Based Safety" organized by National Safety Council, Maharashtra chapter, 15th Sep 2012 at Mumbai.

International Conference on Safety at IIT-Gandhinagar, 14-15th Oct 2012.

Professional memberships

Member of the National Safety Council of India

Fellow Member of Safety Engineers Association (India)

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e) Table of contents;

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g) Body of the thesis;

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i) Appendices, and;

j) Index;

k) Brief bio-data of the author.

**Submitted to:

Assistant Registrar
University of Petroleum & Energy Studies
Bidholi Campus: Energy Acres, P.O. Bidholi
Via-Prem Nagar
DEHRADUN – 248 007