THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on **"VALIDATING SUB-SEA GAS PIPELINE LEAKS DISCHARGE MODEL FOR ARABIAN SEA CONDITIONS"** by **P.C.SRIDHER, SAP ID-500010363** in Partial completion of the requirements for the award of the Degree of Doctor of Philosophy (Engineering) is an original work carried out by him under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

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REVISION HISTORY

Rev	Description	Date	Author
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EVALUATION

Name of Faculty 1	Date	Signature	Remarks

Outstanding ________

Good ________

Satisfactory ________

Meets minimum standards ________

Unsatisfactory ________

Name of Faculty 2	Date	Signature	Remarks

Outstanding ________

Good ________

Satisfactory ________

Meets minimum standards ________

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EXECUTIVE SUMMARY

A number of Gas leaks from subsea pipelines have been recorded in recent years. These occurrences highlight the need for better understanding of the way Gas leaks (plume) behave under water and the risks they present. This requirement was underlined by the submarine gas blowout on the Snorre, an offshore installation of Norway in 2004 and other similar incidents reported world-wide this decade.

The effects of subsea hydrocarbon release 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.

The development of dispersion models for atmospheric leaks has emerged through three major stages over a period of time:

Stage 1: Development/establishing the methodology (Calculation basis);

Stage 2: Validation of results by experimentation and case histories;

Stage 3: Refining of methodology/model based on the feedback from experimentation and case histories.

Whereas, the understanding about the behaviour of a subsea gas release up through the water column (plume raise) is very 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 by experimentation.

In the recent years some research works are done in UK and Norway to study the sub-sea gas leaks plume behaviour for North Sea conditions. However no such research work is carried out in India for Arabian Sea Conditions. Hence, this thesis is aimed at VALIDATING SUB-SEA GAS PIPELINE LEAKS DISCHARGE MODEL FOR ARABIAN SEA CONDITIONS.

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.

The discharge of the gas from the release point to the surface is considered in three zones

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.

Three approaches, of varying complexity, have been used in modelling the discharge of subsea releases in North Sea:

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

The simplest are *empirical models* which consist of those that assume the plume radius to be proportional to the release depth or correlations that have been produced to fit the available experimental data.

Integral models are based on local similarity i.e. the radial profiles of velocity and density defect 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. Entrainment of water into the plume is described using a correlation relating the rate of increase of water flow to the plume centreline properties through the use of an entrainment coefficient, as is used 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 as described in integral models for initial release and integral models for the region of established flow respectively.

The most complex models are represented by Computational Fluid Dynamics (CFD) or field codes 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, they still involve some modelling assumptions, as described in CFD models, and are more resource-intensive to run than integral or empirical models.

The uncertainties exist in the models that include experimentation. The uncertainties for experimentation are, measuring velocity with two phase flow, need to take long time averages of the data and extrapolating the data for real time scenarios. In empirical models, the assumption of plume similarity through both the depth of the sea and over the range of release rates is considered. The flow above the surface is not considered for study. In Integral models, firstly there is a need for an established zone of plume-like behaviour, typical assumptions are entrainment, treatment of the bubble plume as a continuum etc. In CFD models, the main sources of uncertainties are the implementation of additional source terms in conventional codes, the need for very specific and detailed flow data for validation purposes. For CFD and integral models, uncertainty in their prediction increases with increasing flow rates and shallower or deeper water depths.

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 [8] in North Sea for Arabian Sea conditions.

Striking a right balance between accuracy, uncertainty, cost effectiveness and user-friendliness, clearly, the simple empirical 'model' remains most favoured for use in risk assessments.

In this study the available information on the bubble plumes, both theory and experiments was reviewed for the purpose of improving our prediction capabilities of small to medium releases which are common.

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 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.

a. It is assumed that θ, and hence tan θ/2, are fixed parameters which do not vary with release rate or depth.
b. 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** [37] **and Milgram and Erb, 1984** [19] for North Sea.
c. 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 and Fanne1op 1989** [2] for North Sea.

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.[8]

The simple empirical model is the least resource-intensive, user-friendly and, reasonably accurate, is most favoured for use in risk assessments.

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