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# A mechanistic model for hydrocarbon plumes rising through water

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ABSTRACT

For releases of hydrocarbons from a subsea pipeline, riser, or production facility, the shape of the plume rising through the water must be predicted prior to any assessment of gas dispersion, liquid pools, or fire above the water surface. The location and size of the plume at the water surface are key parameters for subsequent consequence modeling. A mechanistic model has been developed to predict the plume trajectory and size, based on mass and momentum balances and an empirical water entrainment ratio from the literature. With suitable physical property values available, the model is applicable to releases of gas and/or liquid hydrocarbons, predicting the vaporization and vapor expansion due to decreasing hydrostatic pressure as the plume rises through the water. Some validation of the model was obtained with 16 tests in a small-scale transparent tank. The data cover a wide range of flow rates, including both choked and unchoked flow. The predicted and measured trajectories (centerline displacement) agreed reasonably well. Predictions of the model are presented for three fluids. The model is valuable for assessing the consequences of underwater hydrocarbon releases, providing input for subsequent modeling of gas dispersion or liquid pools and pool fires.



## 1. Introduction

If an unplanned release of hydrocarbon occurs from a subsea pipeline, riser, or production facility, the released hydrocarbon will form a plume that rises to the water surface. If the hydrocarbon is liquid, it may vaporize as it rises due to the decrease in hydrostatic pressure. If gas or vapor is present initially or forms from vaporization, it will expand as it rises for the same reason. The velocity of the plume causes water to be entrained into the plume as it rises. Thus, the plume diameter may increase due to vaporization and will increase due to gas expansion and water entrainment. Vaporization and expansion will be affected by the water temperature, which normally increases moving upward through the water column. The hydrocarbon may be assumed to be at the water temperature at any point as it rises, since the heat transfer is extensive. The plume will be moved by any water current, which may vary throughout the water column.

The plume size and location at the water surface are particularly important. Without ignition, the gas leaving the plume will disperse into the air, and the size and velocity of the gas source are important parameters affecting the dispersion. The location of the plume affects the likelihood that an ignition source will be present at that point. The velocity of the gas leaving the water surface affects the likelihood of a stable gas fire on the water surface. If liquid hydrocarbon exists at the water surface, ignition will lead to a pool fire, the area of which is generally the area of the plume at the water surface. If the liquid pool is not ignited, plume modeling provides the initial pool area for subsequent analysis of pool spreading and evaporation.

Another consideration is the effect of the plume on buoyancy of objects impacted by the plume. The fact that the plume density is less than that of the water can cause a floating object to sink. This is generally only a concern for objects close to the release point, since the density of the plume rapidly approaches that of the water. But, for example, a gas release just under a buoyancy can supporting a flexible riser could cause the buoyancy can to sink.

Since hydrocarbon plumes can occur over a wide range of scales and fluid compositions, it is desirable to have a fundamentally based mechanistic model with as much generality as possible.

## 2. Prior work

Analytical and experimental investigation of single phase and multiphase plumes has proceeded for over 50 years. Early work by Morton, Taylor, and Turner in the 1950s (Morton, Taylor, & Turner,

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1956) established the framework of single phase and multiphase plume analysis, and clarified the role of entrainment of the surrounding fluid. Morton, Taylor, and Turner introduced integral methods involving assumed forms of plume velocity and concentration profiles, thereby greatly simplifying the mechanistic modeling of mass and momentum conservation in the axial direction. The role of widely differing densities between the released fluid and the surrounding fluid was elaborated by Morton in the 1960s (Morton, 1965). The application of mechanistic plume analysis to vapor–liquid plumes was made in the 1970s by Mundheim and Fannelop (Mundheim & Fannelope, 1976) and by Fannelop and Skjoen (Fannelope & Skjoen, 1980). Reasonably large-scale experimental validation of plume analysis for vertical air–water plumes was carried out in the early 1980s by Milgram (Milgram, 1983), and reasonable values of the entrainment factor (to be discussed) were suggested.

Beyond the foundational work on which this model is based, plume studies have primarily focused on computational fluid dynamics (CFD) analysis and on specific applications. Bravo, Gulliver, and Hondzo (2007) applied the fluent CFD program to air–water plumes, including some conditions for which the plume oscillated. Dahikar et al. (2010) used a CFD code to predict flow and temperature fields for a reacting jet of HCl gas flowing into aqueous ammonia. Cardoso and McHugh (2010) developed a model for reacting plumes (first-order, irreversible reaction at the surface of the dispersed, buoyant phase), and applied it to $CO_2$ rising in deep oceans. Johansen (2003) qualitatively compared gas/oil blowouts in shallow versus deep water, noting that in shallow to moderate water depths the plume rises to the surface and forms a strong radial flow (to be discussed). In deep, stratified water, formation of separate gas bubbles and oil droplets, dissolution of gas, and formation of gas hydrates may decrease the plume buoyancy such that plume rise terminates. Clote, Olsen, and Sketne (2009) used CFD to model a subsea gas release by coupling a volume of fluid (VOF) and a discrete phase model (DPM) to account for the multiphase effects. Dhotre, Niceno, Smith, and Simiano (2009) applied large-eddy simulation (LES) to gas–liquid flow in a large-scale bubble plume, using the Euler–Euler approach to describe the equations of motion and the Smagorinsky kernel for sub-grid scale modeling.

Clearly, CFD analysis picks up effects not included in the model discussed in this paper, such as plume oscillation. And there are many applications for which chemical reactions in plumes are important. But for analyzing the consequences of underwater hydrocarbon releases, these effects are not important, and it is valuable to have an analytical model that does not require CFD expertise.

In the studies cited above, plume curvature caused either by current or plume horizontal momentum was not analyzed or measured. Plumes were either directed vertically upward or were too short to have significant buoyancy-induced curvature.

Some work has been done on angled plumes. Lane-Serff, Linden, and Hillel (1993) developed a model for a fluid injected at an angle to vertical into a denser, stationary fluid. They conducted some experiments with saltwater injected into a tank of fresh water. The model assumes that the fluid is incompressible and that the density difference between the two fluids is small (the Boussinesq approximation). The authors point out that the density difference decreases rapidly moving away from the source, which is also shown by the model discussed in this paper.

Neto, Zhu, and Rajaratnam (2008) addressed horizontal plumes. They conducted experiments to investigate the behavior of horizontal gas–liquid injection in a water tank. Dimensionless correlations were proposed to describe bubble characteristics and the trajectory of the bubble plumes and water jets as a function of the gas volume fraction and the densimetric Froude Number. The intended application was aeration and mixing.

For consequence analysis where the plume location at the water surface is important and releases can have any initial orientation and density, calculation of the interaction among initial momentum, plume buoyancy, and current is crucial. This work fills the need for a mechanistic model that captures all momentum effects as well as plume buoyancy and current.

## 3. Analysis and model

A mechanistic analysis has been performed using a methodology similar to Morton, Taylor, and Turner (Morton et al., 1956). A "tophat" (sharp-edged) profile for velocity and gas fraction has been assumed in the cross-plume direction. Plume velocity and gas fraction are assumed uniform from the plume centerline to the plume radius ($b$), i.e., the plume edge. At that point, the plume velocity ($U$) drops discontinuously to the external current velocity ($U_w$), and the gas mass fraction ($f_g$) drops discontinuously to zero. Fig. 1 shows a schematic representation of the plume and the nomenclature.

In a manner similar to both Morton and Fannelop, differential equations for conservation of both gas and liquid mass and momentum were written in the plume axis direction denoted by $s$. Overall mass conservation yields:

$$\frac{d}{ds}\left(b^2\rho_p U\right) = 2\rho_w b\alpha U\left(1-\frac{U_w}{U}\sin\theta\right) \quad (1)$$

Entrainment of the external fluid into the plume is specified through an entrainment factor, $\alpha$. The entrainment factor is the ratio of the radial velocity of the external fluid into the plume to the axial velocity of the plume at that point.

Assuming a hydrostatic pressure variation imposed by the surrounding fluid, overall conservation of momentum in the axial direction yields:

$$2U^2\rho_w b\alpha\left(1-\frac{U_w}{U}\sin\theta\right)+\left(b^2\rho_p U\right)\frac{dU}{ds}=b^2 g\cos\theta\left(\rho_w-\rho_p\right) \quad (2)$$

The mass of released fluid (often hydrocarbon) is conserved along the plume axis, which yields:

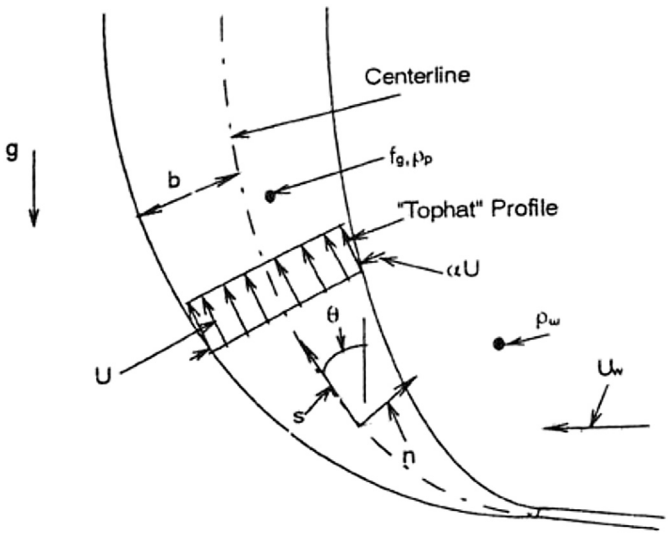


**Fig. 1.** Plume schematic and nomenclature.