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Modified reduced buoyancy flux model for desalination discharges

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HIGHLIGHTS

- Modified reduced buoyancy flux (RBF) integral model predicts the near-field behaviour of desalination discharges.
- Modified RBF approach incorporates a physical buoyancy loss mechanism.
- Modified RBF model predictions compared with laboratory data and existing integral models
- Modified RBF model predicts effects of the additional mixing noted in previous studies.
- Modified RBF model is superior to existing integral formulations in this respect.

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ABSTRACT

Large-scale desalination facilities are increasingly employed to supplement potable water supplies for many cities, where the demand for water is having a negative impact on the sustainability of natural water resources. A primary environmental concern with the establishment of these large-scale facilities is the effective disposal of the hyper-saline effluent brine, so that harmful effects on the marine environment are minimised. In countries with effective effluent discharge regulations, the negatively buoyant brine is typically released through submerged diffusers, where the ports are inclined towards the ocean surface to aid dispersion processes. Predictive models provide an inexpensive method of considering different sources and ambient design parameters. It has been demonstrated that predictive models developed primarily for positively buoyant discharges significantly underestimate dilution measured by physical studies, when applied to negatively buoyant desalination discharges. It has been shown recently that predicted dilution and geometric parameters can be improved if a reduction in the buoyancy flux of the main flow is incorporated into these models. Here, the reduced buoyancy flux (RBF) approach is modified through the use of a physically based buoyancy loss mechanism. Improvements in the predictive capabilities of the new model are demonstrated through comparisons with predictions from existing models and an extensive range of results from physical studies for geometric, dilution, and velocity parameters.

1. Introduction

The depletion and degradation of natural water sources have created a water demand deficit for many communities, which is generating a rapidly expanding global demand for alternative reliable sources of potable water. This deficit is exacerbated by increased water consumption as populations increase. Seawater reverse osmosis (SWRO) desalination has become a key component in developing a solution to address this deficit because it provides a cost-effective and reliable source of potable water [1,2]. The hypersaline brine effluent produced from the large-scale desalination plants necessary to implement these solutions is disposed of through an ocean outfall for 90% of these plants [3]. Diffuser ports are inclined towards the ocean surface to force the discharge to rise and then fall within the water column, increasing the overall path length and hence initial mixing. The falling discharge impinges the seabed and gravity then drives the flow along the seabed. The brine discharge can damage marine flora and fauna near the disposal site [4]. Therefore, rapid dilution of brine is required to minimise harmful effects within the regulatory mixing zone [5,6], defined as part of the mandatory environmental impact assessment (EIA) required in many European countries, USA, and Australia [7–9]. Predictive models are important for assessing the potential impact of discharges on the environment, because they provide a low cost method to characterise discharge behaviour for different system configurations and ambient conditions [6].

Here we focus on predicting the behaviour of brine effluent prior to impact with the seabed, where the majority of the mixing takes place within the regulatory mixing zone. In this region, the flow behaviour is governed by the discharge parameters (source angle, initial velocity and relative density). The influence of ambient currents on the flow

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behaviour is not considered because such currents tend to enhance the mixing and hence they create less critical discharge scenarios. A schematic diagram of an inclined negatively buoyant jet (INBJ) that results from negatively buoyant brine being discharged through a port that is inclined towards the free surface is shown in Fig. 1. The discharge rises through the water column until the vertical momentum flux reduces to zero, due to negative buoyancy, at maximum height (x_m, z_m). The discharge then falls in the water column and passes through the original source level, where the behaviour can be recorded for comparative purposes and this location is referred to as the return point (x_r, 0).

Earlier physical studies of INBJ behaviour measured dilution and specific geometric parameters using sampling tubes or shadowgraphs [10–13]. Improvements in experimental measuring systems, such as light attenuation (LA) and laser induced fluorescence (LIF) have resulted in more precise and detailed dilution measurements for a relatively wide range of initial source angles [14–23]. There have also been a limited number of experimental studies where the velocity fields of these flows have been measured [17,23]. These studies present some velocity data that was obtained using particle image velocimetry (PIV), however concentration and dilution measurements remained the central focus. More recently, comprehensive velocity field information for INBJs was measured for a wide range of initial conditions using a particle tracking velocimetry (PTV) system [24]. Many of these studies have noted the existence of an unstable density gradient on the inner (lower) side of these flows that results in detrainment of fluid from the main flow [10,19–21,25]. Re-entrainment of the falling fluid into the rising flow has also been reported for higher source angles (70^0 or more), where the horizontal separation between rising and falling regions is sufficiently small for them to interact [15,18,24,26].

Oliver et al. [19] note that the wide variation in dilution data at the return point obtained from previous studies can be attributed, in part, to variations in lower boundary conditions used in the experimental configurations. A lower boundary in the proximity of the source in an experimental study simulates the impingement of desalination brine discharges on the seabed. However, near-field predictive models are not designed to incorporate the effects of a lower boundary on discharge behaviour [6,27]. Therefore, it is difficult to assess the performance of predictive models against data obtained from studies where differing lower boundary conditions have an influence on the experimental results. Oliver et al. [19] and Crowe et al. [24] are two recent physical studies where the lower boundary was sufficiently far from the measuring area to remove any influence from the dilution and velocity data, respectively. Therefore, these studies provide a better basis for comparison with model predictions.

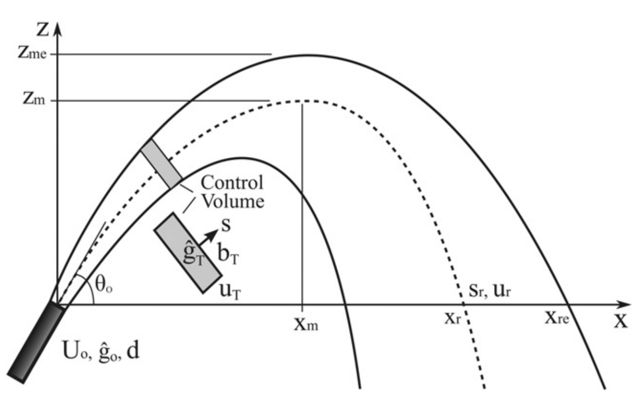

Fig. 1. Schematic diagram of an inclined negatively buoyant jet with top-hat modelling control volume shown. Parameters defined as: horizontal and vertical distances to maximum centreline height (x_m, z_m), vertical distance to the outside edge (z_{me}), horizontal distance to return point and to outside edge (x_r, x_{re}), centreline path length to maximum height and return point (s_m, s_r), mean centreline velocity at maximum height and return point (u_m, u_r), initial and top-hat velocity (U_o, u_T), initial and top-hat reduced gravity ($\hat{g}_o$, $\hat{g}_T$), initial inner source diameter (d), and top-hat discharge width (b_T).

Integral models of these flows are commonly employed to predict the behaviour of submerged discharges. The models numerically integrate a system of differential equations developed from mass, momentum, and buoyancy flux requirements, with simplifying assumptions used for closure. CorJet [5] and VISJET [28] are commercial models used in industry to predict desalination brine discharge behaviour. CorJet is the integral model applied within the CORMIX software to simulate the behaviour in unlimited ambient conditions. CORMIX is a collection of hydrodynamic models, invoked through a length-scale based classification scheme, which are interconnected to predict discharge flow behaviour [1,6]. VISJET is a flow visualisation tool [28], which provides a three-dimensional display of flow behaviour predicted by the JETLAG integral model [29,30]. These commercial models assume the conservation of mass, momentum, and buoyancy fluxes and use the entrainment assumption to close the system of equations. Their development was based to a large extent on the need to predict the behaviour of positively buoyant jets that result from municipal wastewater discharges into the ocean [6]. Dilution and velocity predictions from commercial models significantly underestimate experimental coefficients obtained from physical experiments across the range of initial discharge angles typically considered for desalination discharges [19,24,31]. It has been noted previously that these models do not incorporate the effects of detrainment observed during the physical experiments, which enhances the mixing of the effluent and hence the measured dilutions are higher than predicted.

An analytical model has been proposed for INBJs [16], based on relationships developed for positively buoyant jets [32]. This analytical model separates INBJs into distinct jet and plume regions and utilises conservation relationships for these idealised flow regimes to determine flow parameters. The discharge is initially modelled as a deflected pure jet and when the jet to plume transition is reached, a deflected plume model is implemented. Predictions from these analytical solutions compare more favourably with measured coefficients for dilution than the more sophisticated integral models commonly utilised in industrial applications. Recent attempts to improve the predictions by integral models include the work of Yannopoulos and Bloutsos [33] and the original reduced buoyancy flux (RBF) model by Oliver et al. [34]. Mass, momentum and buoyancy fluxes of the main or primary flow are not conserved in the model proposed by Yannopoulos and Bloutsos [33]. Changes in these fluxes are dependent on local parameters and are designed to capture the effects of the detrainment process. Volume and momentum fluxes are conserved in the RBF model [34], however the buoyancy flux of the primary flow is reduced. Oliver et al. argue that the consistency between geometric parameter predictions of flux conserving commercial models and experimentally measured data suggests that the detrainment process does not have a substantial influence on momentum fluxes. Although the implementations differ, both models introduce a mechanism that enables contaminated material to be detrained from the main flow. Incorporating this effect increases dilution predictions at the maximum height and the return point for both models.

The RBF model has the advantage that it retains the simplicity of existing integral model approaches and does not require the adjustment of a coefficient to fit existing data. However, the model utilises the experimental observation that the rate of centreline dilution in the jet region of INBJs is similar to that of a pure jet. This condition determines the amount of contaminated material leaving the main flow and it is applied until the flow reaches maximum height. Here, we make use of a similar framework, but develop a more physically based mechanism for the detrainment of fluid from the main flow. The development of this modified RBF model is outlined in the following section. The buoyancy loss mechanism is based on local flow parameters for the full path length of the flow. Predictions from all models are then compared with measured geometric parameters, dilution, and velocity data from physical studies for source angles ranging from 15° to 75°.