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Spreading Radius of Fountains After Impinging an a Free Surface

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Abstract

Laboratory experiments and dimensional considerations were used to investigate the spreading radius of axisymmetric fountains after they impinged upon the free surface of the initially homogeneous and quiescent ambient environment. The distance to which the fountain fluid spread, before plunging downwards as the result of negative buoyancy, was found to be a function of the source radius, the source Froude number and the depth at which the fluid was injected. For example, the greater the source Froude number (and hence initial momentum) the greater the spread of the surface flow for the same injection depth and source radius. Experimental data and simple scaling considerations were used to an equation for predicting the spreading distance. The results show the need for further studies to quantify mixing processes and dilution rates.

Introduction

When a dense fluid is steadily injected vertically upward into a miscible and less dense fluid, a fountain-type structure forms [1,2,3,4]. The denser fluid penetrates to a finite height, whereupon it stops, and then falls back as an annular plunging plume around the upward flow. Surrounding ambient fluid is constantly being entrained into the plunging plume, while the rising inner jet can entrain only outer plume fluid. The net result is that, as the injected fluid travels through the ambient, its volumetric flow rate increases and its mean density decreases. Fountains also occur in the reverse case, when lighter fluid is injected vertically downward into a denser ambient [5].

For submerged fountains with a relatively large momentum in comparison to the negative buoyancy, the maximum height of rise will be considerably greater than the radius of the source [4]. This means that the source is effectively a point and the virtual origin of the flow is at the injection point. The maximum height of rise of a submerged vertical fountain within a homogeneous quiescent ambient, z_m, can therefore be written as (following the notation of [4]):

$$\frac{z_m}{r_o} = CFr_o \tag{1}$$

here r_o is the source radius, C is a constant, $Fr_o = w_o/(r_o g'_o)^{1/2}$ is the source Froude number, w_o is the average flow velocity, $g'_o = g\left(r_o - r_a\right)/r_a$ is the reduced gravity, r_o is the initial fountain density, r_a is the density of the ambient and g is the acceleration due to gravity, all of which are defined at he source. The value of C has been found to be in the range 2.46-3.7 [3,4,6,7,8].

When z_m exceeds the depth (H) of a homogeneous quiescent ambient with a free surface, the momentum contained within the negatively buoyant fountain fluid will deform the surface upwards. The resultant horizontal pressure gradient and remaining momentum then forces the fluid to spread laterally as a radial surface jet. At some radius, the negative buoyancy of the jet will cause it to fall below the surface and plunge downwards (see Figure 1). Impinging fountain-type structures are found in many engineering applications; for example, the heating of large open structures is often achieved by using fan-driven heaters at the ceiling level [4]. It is expected that as Fr_o increases (for the same H and r_o) the plunge point radius will increase, as is the case for energetic bubble plumes (eg [9]). Baines et al. [4] found that for impinging fountains in a confined tank (where the side-walls play an important role in the overall mixing behaviour) there was an expansion is diameter of the surface flow as the ratio z_m/H was increased. However, no values or relations were given for this in their work.

While various studies have examined the height to which a fountain can rise no experimental or numerical work has been sighted that specifically examines the lateral spread of impinging fountain fluid as it moves along a free surface. Using laboratory experiments and scaling considerations this paper examines this issue when the receiving ambient is initially quiescent and homogeneous.

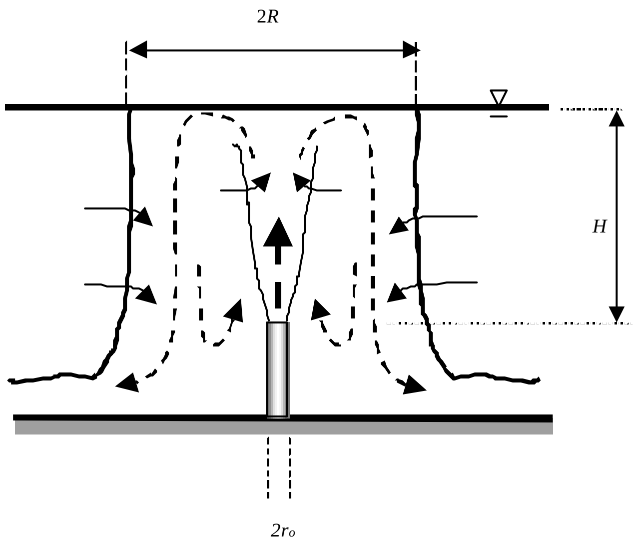

Figure 1. Schematic representation of a vertical fountain impinging on a free surface. Dashed arrows indicate dominate flow directions while dashed arrows indicate dominant entrainment paths..

Experimental Methodology

To support the experimental objectives of this study, detailed experiments were conducted within a 2 x 2 x 0.4 m glass sided tank. This tank was found to be large enough to avoid strong recirculation patterns developing in the ambient by the fountain flow, given that experiments were run only for short periods once the fountain flow was well established. Trials revealed that strong convection cells did not establish (even though the Rayleigh number was high), which again was the result of the short experiment times.

A solution of salty water (initial fountain fluid) was pumped upward into the fresh water-filled tank through a vertical tube of 1 cm diameter and length of 10 cm. Before entering the tube the water passed through a 2 m long 1 cm diameter hose. Only one inlet diameter was chosen for this study, as past investigations of jets have shown that the behaviour can be readily characterised using non-dimensional expressions such as Eq. [1]. Fountain fluid inflow rates were monitored using a calibrated rotometer, with the flow rates adjusted so that the fountain always impinged on the free upper surface. A total of 33 experiments were completed with $6 < Fr_o < 54$, 5 < H < 25 cm and $756 < Re < 3182$, where $Re = 2w_o r_o/n$ is the source Reynolds number and n is viscosity.

The radius at which the impinging fluid plunged below the surface, which was always significantly less than the width of the tank, was determined from data collected 5 mm below the water surface by horizontally traversing a calibrated in situ microscale conductivity and temperature probe across the tank. Transects were always conducted using the same azimuthal and radial angles and commenced shortly after pumping commenced when it appeared a steady state developed (which usually took only about 30 sec). The microscale probe (Precision Measurement Engineering, USA, Model 125) has sensor resolutions of 1×10^{-3} °C and 2×10^{-5} Sm^{-1}, spatial resolution of +/- 2 mm, and time responses of approximately 0.02 and 0.004 s respectively, with the traversing mechanism having a spatial resolution < 1 mm. Signals from the probe were recorded electronically and stored for analysis. A number of traverses (typically 6 at 4 cms^{-1}) were made for each experiment and the average width value determined. Traverses were performed at intermittent steps to avoid adding significantly to mixing across the fountain and within the tank. The amount of fountain fluid injected into the tank was small in relation to the initial tank volume; meaning changes in total water depth during an experiment were negligible. Further the water within the tank was changed and monitored on a regular basis to ensure the water surface was not contaminated.

Results and Discussion

Figure 2 presents an example of a vertical impinging fountain striking a free surface (ie $z_m > H$). The dyed rising jetting water was issuing upwards from the nozzle before striking the surface and spreading radially outwards (along the free surface). At some radial distance (R) the spreading fountain water detached from the free surface and plunged downwards into the ambient as an annular plume that had some degree of unsteadiness. That is, the water did not fall as a simple stream, but instead it had a blobby type nature (as typically found in any annular plume type flows – eg. [9]). Visual observations of the plunging point indicated that it experienced some wondering, but that the mean radius appeared to remain constant with time.

Figure 3 presents an example of the conductivity signal recorded as the microscale probe was traversed across the tank. For clarity, the conductivity signal recorded during each traverse has been displaced sequentially by 0.05 Sm^{-1}. The region of highest conductivity marks the central core of the fountain, while adjacent to this is the zone of lower conductivity marking the plunging annular ring. The conductivity is lower because the fluid has had more time to entrain the surrounding ambient fluid Adjacent to the plunging fluid is the ambient region having the lowest constant conductivity values. In keeping with general unsteady nature of jet/plume behaviour, the central region was found to wander from one traverse to another. The outer radius of the falling fluid is clearly marked by a conductivity signal (the radius for traverse 5 is shown). While the probe sensors were positioned 5 mm below the water surface, it is expected that there would be little change in diameter of the plunging radius was observed from when it initially falls below the free surface. In this study, the constant C from Eq [1] had to exceed 3 in order for the development of impinging fountains. As discussed earlier, this is in keeping with previously published works.

If the properties of submerged fountains impinging on a free surface are governed by r_o, Fr_o and H then dimensional reasoning and Eq. [1] suggest that the average radius to which the fluid can spread out across the surface ($\overline{R}$) for a given set of initial conditions would be given by:

$$C_1 Fr_o{}^n = f\left(\frac{\overline{R}}{r_o}, \frac{H}{r_o}\right) \tag{2}$$

where C_1 and n are constants.

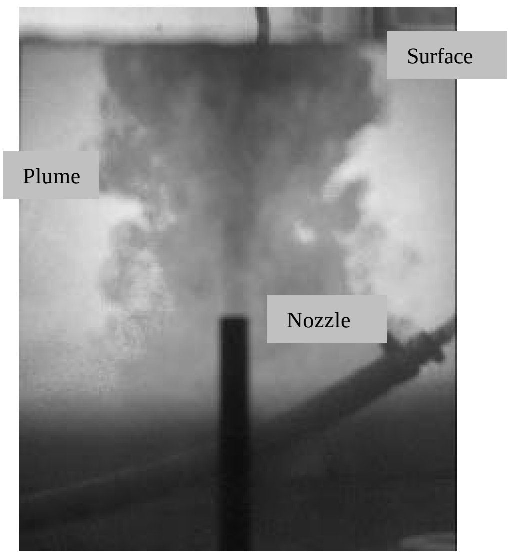

Figure 2. Example of a negatively buoyant fountain impinging of a free surface. For clarity the fountain fluid is dyed.

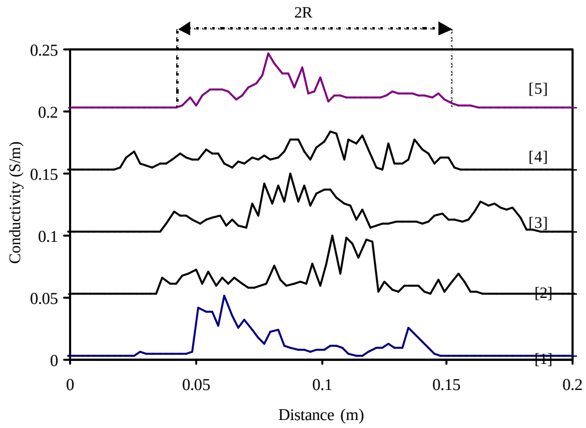

Figure 3. Surface conductivity as a function of distance traversed by the microscale probe as it moved backwards and forwards through a fountain impinging on the free surface. Each line represents one traverse (traverse number is shown in square brackets) with each line sequentially displaced vertically by 0.05 S. In this experiment Fr_o= 22, H = 11.8 cm and Re = 3200.

Now, in the first instance if it is considered that the fluid elements within the fountain travels a distance R+H (= z_m in a vertically unbounded system when R = 0) before negative buoyancy dominates, causing the fluid to plunge downwards, than Eq. [3] becomes:

$$\frac{H+\overline{R}}{r_o} = C_1 Fr_o^{\ n} \ , \qquad (3)$$

Figure 4 presents the experimentally derived data. The line of best fit to the data shows how that Eq [3] can be used to predict the spreading radius with C_1= 4.8 and n = 0.74, and a squared correlation coefficient of 0.921. That is:

$$\frac{H+\overline{R}}{r_o} = 4.8 Fr_o^{\ 0.74} \ , \qquad (4)$$

Eq [4] will have an upper limit of application, which are yet to be determined. This limit is reached when the fountains have sufficient momentum to break through the free surface and exit the ambient. Recently, [9] found a similar formulation for submerged fountains impinging on a rigid surface. However in their study n (=0.4) was different and C_1 was found to be dependant upon the ratio H/r_o, such that they found for a rigid surface $(H+R)/r_0 = 2.7(H/r_0)Fr_0^{\ 0.4}$. In this study the extra dependence on H/r_o was not observed, suggesting the type of surface on which the fountain impinges plays a significant role in the spreading dynamics. Further studies are required to quantify this.

Conclusions

Detailed laboratory experiments and simple dimensional considerations have been used to investigate the spreading radius of water fountains when they impinge on the free surface of the receiving ambient. It was observed that as the fountains struck the free surface the fountain fluid spread out radially before plunging below the surface. The plunging distance was found to be a function of the source radius, the ambient fluid depth and the source Froude number.

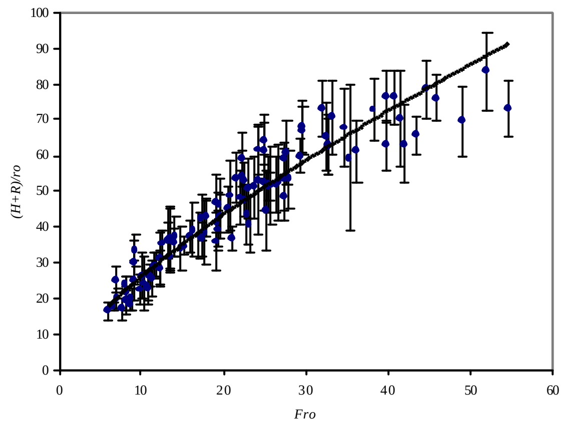

Figure 2. Normalised radius of fountain as a function of Fr_o. The solid line is the line of best fit $(H+R)/r_o = 4.8Fr_o^{\ 0.74}$ with a squared correlation coefficient of 0.921. The vertical error bars indicate one standard deviation.

This investigation indicates that a number of important aspects of fountains striking a free surface warrant further investigation. Yet to be determined is the amount of energy lost in the formation of surface motions generated by impinging fountains, the dilution rates within the fountain flow and a formulation to describe the behaviour of the observed plume wondering. The influence of viscosity and diffusion rates (which are different for air and water systems) on the spreading distance also warrants further investigation, so that universally applicable relations can be derived.

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