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Impinging axisymmetric turbulent fountains

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The behavior of a turbulent fountain that impinges perpendicularly on a horizontal plate a distance H from the fountain origin in a quiescent environment of uniform density is investigated. Images from light induced fluorescence visualization of the flow provide a clear picture of the internal structure of the vertical fountain, impinging radial outflow and the subsequent plumelike flow. For source-plate separations $H/L_{m0} \leq 1.5$, where L_{m0} is the source jet length, and source Froude number $Fr_0 > 10$, the impingement of the fountain results in a buoyant radial wall jet that spreads horizontally before separating from the plate at a radius R_{sp} . The re-entrainment into the fountain and wall jet of buoyant fluid released on separation leads to the formation of a toroidal vortex of outer radius $\sim R_{sp}$. The correlation $R_{sp}/H = 0.03 Ri_{rad}^{-0.75}$, deduced from theoretical scalings and the results of our experiments, successfully relates the maximum nondimensional radial spread to the Richardson number Ri_{rad} that characterizes the source of the buoyant radial wall jet. The transient development of the flow and influence of the buoyant plume above the impingement zone are discussed. © 2007 American Institute of Physics. [DOI: 10.1063/1.2798214]

I. INTRODUCTION

Flows that develop from localized high Reynolds number sources of buoyancy flux B_0 and momentum flux M_0 that act in opposite senses are known as turbulent fountains. In many cases of industrial and geophysical interest, the density difference between the source fluid injected and the environment is small compared with the density of the environment, so that the Boussinesq approximation applies. We restrict our attention to Boussinesq fountains herein. The basic flow configuration for a positively buoyant fountain developing in a homogeneous environment is shown schematically in Fig. 1(a). During the initial transients, the turbulent downward injection of fluid entrains denser fluid from the surrounding ambient. The local momentum flux induced by the action of the buoyancy forces increases with increasing distance from the source until it matches the source momentum flux and the downward descent is halted. Buoyant fluid then rises up around this downward-flowing core. The outer, upward-flowing annular stream entrains fluid from the surrounding ambient and exchanges fluid with the core.

The source conditions of a fountain [located at $z=0$, z denoting the vertical coordinate with origin at the fountain's virtual origin, Fig. 1(c)] can be defined in terms of the source fluxes of buoyancy B_0 ($m^4 s^{-3}$), momentum M_0 ($m^4 s^{-2}$), and volume Q_0 ($m^3 s^{-1}$). Two length scales characterize the behavior of a free fountain source; namely, the momentum jet length L_{m0} and the source length L_{q0} , defined as

$$L_{m0} = M_0^{3/4} / B_0^{1/2} \quad (1a)$$

and

$$L_{q0} = Q_0 / M_0^{1/2}, \quad (1b)$$

respectively. The length scale L_{q0} ($= \pi^{1/2} r_0$, assuming a uniform exit velocity from the source of radius r_0) is proportional to the physical scale of the source and to the distance between the actual source and its virtual origin, as discussed by Morton¹ and Hunt and Kaye.² The length scale L_{m0} is proportional to the vertical distance over which the flow is dominated by the source momentum flux; i.e. is jetlike. The ratio of these length scales is proportional to the fountain source Froude number

$$Fr_0 = \pi^{1/4} \frac{L_{m0}}{L_{q0}} = \pi^{1/4} \frac{M_0^{5/4}}{Q_0 B_0^{1/2}} = \frac{1}{Ri_0^{1/2}}, \quad (2)$$

which is the reciprocal of the square root of the source Richardson number Ri_0 . Turner³ reported on experiments and presented an analytical description of a free fountain in a quiescent environment of uniform density. He showed that the maximum rise height (z_m) and subsequent, reduced, steady-state rise height (z_{ss}) scale on L_{m0} . Baines *et al.*⁴ extended this work to cover a wider range of source conditions and fountains within enclosures for which they determined the manner in which a fountain stratifies the environment into which it is released. They expressed the source conditions, for a release of initial vertical velocity w_0 with reduced gravity g'_0 from a source of radius r_0 , in terms of Fr_0 and for free fountains with $Fr_0 \gg 1$ gave

FIG. 1. (Color online) Schematic indicating bulk flow in a turbulent fountain: (a) Free fountain, (b) fountain impinging on a horizontal plate, and (c) nomenclature for present work.

$$\frac{z_{ss}}{r_0} = 2.46 Fr_0 = \frac{2.46 w_0}{\sqrt{g_0' r_0}}. \quad (3)$$

Bloomfield and Kerr⁵ reported on the behavior of axisymmetric and line fountains in a stratified environment. Bloomfield and Kerr⁶ modified the plume conservation equations of Morton *et al.*⁷ to account for the dependence of the annular flow around the central core of the fountain on the steady-state rise height. Detailed laser Doppler anemometry measurements of the structure of a miscible water fountain at one particular set of source conditions have been reported by Cresswell and Szczepura,⁸ who provided detailed information on the mean velocity field, turbulence intensity, and intermittency within the fountain.

The focus of our study is on a turbulent fountain impinging energetically on a horizontal plate as shown schematically in Fig. 1(b); i.e., when the local Froude number in the fountain at the plate is large compared with unity ($Fr_H \gg 1$); thus, the vertical flow is jetlike on impingement. These impinging flows are of interest as a fundamental problem in fluid mechanics and in a number of practical applications. The latter include the heating of large building spaces by warm jets of air directed downward from the ceiling, e.g., air curtains, flow from the jets of vertical takeoff aircraft, and in gas metal arc welding (GMAW), which is used extensively in manufacturing industries. In GMAW, a shielding gas, used to protect the weld from contaminants, is ejected downwards from the welding torch nozzle and impinges on the welding work piece (Godbole *et al.*⁹). The ejected gas is subject to intense heating by the electric arc and a buoyant mixture of air, shielding gas, and contaminants rises into the breathing zone of the welder. Recent international research has highlighted the risks of human exposure to this welding fume, which may include neurodegenerative and respiratory disease (McMillan¹⁰). The work presented herein represents part of a wider research effort to understand welding fume dispersion and improve welding fume capture systems.

Impingement with a free surface by vertically rising plume flows from localized sources of buoyancy flux and momentum flux acting in the same sense were examined by Lawrence and MacLachy.¹¹ They investigated the radial spread of the resulting positively buoyant plume. However, unlike the present case, the stratification established by the plume impinging and spreading along the free surface was intrinsically stable [Fig. 1(c)]. Holstein and Lemckert¹² and Lemckert¹³ reported experiments on saline fountains

impinging on rigid and free surfaces, respectively. Their work focused on assessing how the radius of spread R_{sp} [Fig. 1(c)] was related to the source fluxes and source-plate separation H .

Holstein and Lemckert¹² argued that the total length traveled by the buoyant fluid prior to separation from the plate ($H + R_{sp}$) must be related to the fountain source conditions according to $(H + R_{sp})/r_0 = c Fr_0^k$, where the constant c and the exponent k were to be found by experiment. However, this relationship does not account for variations in H , and they subsequently suggested that $c = 2.7(H/r_0)^{1/2}$, and determined that $k = 0.4$. We present a more detailed analysis that successfully correlates the radius of spread of the impinging fountain for fountain source conditions that yield energetic impacts.

The major objective of the present work is to determine how the horizontal plate changes the nature of the free fountain and to investigate the near field flow close to the plate.

II. LENGTH SCALES AND GOVERNING PARAMETERS

The source-plate separation H provides a third length scale in addition to L_{m0} and L_{q0} . The behavior of the impinging fountain might, therefore, be expected to be determined by these three length scales and the fountain source Reynolds number $Re_0 = 2r_0 w_0 / \nu$, where ν denotes the kinematic viscosity of the release. We restrict our attention to fully turbulent fountains for which the flow is independent of Re_0 , and shall not consider further the effects of viscous forces.

For sufficiently large separation distances the fountain will not impinge on the plate. From Eq. (3), impingement is not expected to occur, other than perhaps during an initial transient, for $H \geq 2.5 r_0 Fr_0$ (approximately). For smaller separations the action of the buoyancy forces will not have reduced the momentum flux of the descending flow to zero at $z = H$, and impingement will occur. If the separation is sufficiently small, one might expect the radial outflow to behave as a buoyant turbulent radial wall jet. The behavior of neutrally buoyant impinging jets has been discussed by many authors; e.g., Rajaratnam.¹⁴ However, for a fountain, the radial outflow is positively buoyant and will, therefore, separate from the plate when the Coanda effect has diminished sufficiently. Etheridge and Sandberg¹⁵ reported briefly on the case of a plane two-dimensional geometry where a buoyant jet issued from a rectangular slot of height h parallel and adjacent to a horizontal surface. The nondimensional horizontal distance x_{sp}/h between the source of the positively buoyant fluid and the point of detachment was found to be a function of the jet source Richardson number.

Our focus is on energetic impingements for which the vertical flow is jetlike at the level of the plate; i.e., when the local Froude number at the plate is large compared with unity. Based on a local value of the Froude number $Fr(z) = w(z)/\sqrt{g'(z)z}$, the Froude number at impingement ($z = H$) may be estimated as

$$\text{Fr}_H = \lambda \frac{w_0}{\sqrt{g'_0 r_0}} \frac{r_0}{H} = \lambda \text{Fr}_0 \frac{r_0}{H}, \quad (4)$$

where $\lambda = c_1 c_2^{1/2} \pi^{1/4} (\approx 4.6)$ and the constants $c_1 \approx 6.9$ and $c_2 \approx 0.25$ (see Ref. 16) relate to the classical scalings in an axisymmetric turbulent jet; i.e., $w(z) = c_1 M_0^{1/2} z^{-1}$, $Q(z) = c_2 M_0^{1/2} z$. In other words, for highly forced (energetic) fountains at impingement, the fountain source conditions must satisfy

$$\text{Fr}_0 \gg \frac{1}{\lambda} \frac{H}{r_0}. \quad (5)$$

This constraint has implications for the radial outflow source conditions following impingement [see Eq. (17)]. The same basic scaling as in Eqs. (4) and (5) may be deduced from plume theory (Morton *et al.*⁷), from which the rate of change of momentum flux in the core of the fountain in a uniform environment is given by

$$\frac{dM}{dz} = - \frac{QB}{M}. \quad (6)$$

This holds for the downward descending core prior to flow reversal and the subsequent exchange of momentum between upflow and downflow. Thus,

$$\frac{dM^2}{dz} \approx \frac{M_0^2 - M_H^2}{H} \approx -2Q_H B_0 \quad (7)$$

and

$$M_0^2 - M_H^2 \approx -2Q_H B_0 H. \quad (8)$$

If the momentum flux at the plate is relatively unchanged from the fountain source momentum flux, then on dimensional grounds, $Q_H = c_2 M_0^{1/2} H$, and from Eq. (8), we require

$$G \ll 1, \quad \text{where } G = \left| \frac{2c_2}{\pi^{1/2}} \left(\frac{H}{r_0} \right)^2 \frac{1}{\text{Fr}_0^2} \right|. \quad (9)$$

Thus, from Eq. (9), the parameter G combines the geometric ratio H/r_0 and the relative importance of momentum fluxes, buoyancy fluxes, and volume fluxes at the fountain source via Fr_0 . Comparing Eqs. (9) and (5) confirms the same basic scaling. With $G \approx 0$, the flow is dominated by its momentum flux as it strikes the plate; i.e., it is jetlike on impingement. As G increases, for example, by increasing H and with fixed source geometry and source fluxes, the momentum flux at the plate decreases. Exceeding a critical value of G will result in the momentum flux being reduced to zero for $z < H$, and impingement will not occur. For fixed H/r_0 , small G corresponds to large Fr at impingement.

III. RADIUS OF SPREAD

The impinging fountain forms the “source” of the buoyant radial wall jet. In the analysis that follows we identify quantities at this source using the subscript “rad.” We assume that at the plate the fountain properties are similar to those of a free jet (in principle, the analysis may be extended beyond this case by integrating the plume equations for conservation of volume, momentum, and buoyancy fluxes). In particular,

the momentum flux at the plate (M_H), is taken to be equal to that at the fountain source, and the volume flux (Q_H) and radius (b_H) are then

$$Q_H = c_2 (H/L_{q0}) Q_0 \quad (10)$$

and

$$b_H = 2\alpha H, \quad (11)$$

where $\alpha = 0.0535$ is the entrainment coefficient applicable to jets.¹⁷ To estimate a source Froude number for the radial outflow, namely,

$$\text{Fr}_{\text{rad}} = \frac{u_{\text{rad}}}{\sqrt{g'_{\text{rad}} \delta_{\text{rad}}}}, \quad (12)$$

we require expressions for the radial velocity u_{rad} , buoyancy g'_{rad} , and a characteristic length scale; namely, the flow depth δ_{rad} [Fig. 1(c)]. By continuity, the volume flux $Q_{\text{rad}} = 2\pi b_H \delta_{\text{rad}} u_{\text{rad}} = Q_H$; hence,

$$u_{\text{rad}} = \frac{Q_H}{2\pi b_H \delta_{\text{rad}}}. \quad (13)$$

The source-plate separation is the dominant length scale in the problem and, hence, we would expect the radial flow depth to scale on this length just as, for example, the fountain width at the plate or the outflow depth from a buoyant plume;^{18,19} i.e., for some constant c_3 ,

$$\delta_{\text{rad}} = c_3 H. \quad (14)$$

The radial source velocity may now be written

$$u_{\text{rad}} = \frac{c_2}{2^2 \pi^{1/2} c_3 \alpha} \frac{r_0 w_0}{H}. \quad (15)$$

The radial source buoyancy is given by the buoyancy in the fountain at $z = H$. As the environment is unstratified, the buoyancy flux from the fountain is conserved, i.e., $B_0 = Q_0 g'_0 = Q_{\text{rad}} g'_{\text{rad}}$; hence,

$$g'_{\text{rad}} = g'_0 \frac{Q_0}{Q_H} = \left(\frac{\pi^{1/2}}{c_2} \right) g'_0 \frac{r_0}{H}. \quad (16)$$

Substituting Eqs. (13)–(15) into Eq. (12) yields

$$\text{Fr}_{\text{rad}} = \frac{1}{2^2 \pi^{3/4} \alpha} \left(\frac{c_2}{c_3} \right)^{3/2} \frac{r_0}{H} \frac{w_0}{\sqrt{g'_0 r_0}} \propto \frac{r_0}{H} \text{Fr}_0. \quad (17)$$

Equation (17) indicates that the source conditions for the radial outflow Fr_{rad} are related to those of the fountain source via the inverse of the dimensionless source-plate separation. As expected, Fr_{rad} decreases with increasing H . Comparing Eqs. (17) and (5), we have $\text{Fr}_{\text{rad}} \gg 1/\lambda$. We note that the basic relationship (17) can also be obtained following other approaches which, however, are more difficult to justify on physical grounds. Herein, we made the assumption that the outflow thickness scales on H , alternatively invoking that a constant fraction of the kinetic energy flux (or quantity with the dimensions of momentum flux) in the descending flow is imparted to the radial outflow the same basic scaling is obtained.

The quantity Fr_{rad} gives the relative magnitudes of inertia and buoyancy in the outflow and hence, we expect the radius at which the flow separates from the plate R_{sp} to be a function of Fr_{rad} ; i.e., scaling R_{sp} on δ_{rad} , we have $R_{sp}/\delta_{rad} = f(Fr_{rad})$. In terms of the Richardson number $Ri_{rad} = 1/Fr_{rad}^2$,

$$\frac{R_{sp}}{\delta_{rad}} = f(Ri_{rad}) \quad (18)$$

for some function f , where, from Eq. (17),

$$Ri_{rad} \propto \left(\frac{H}{r_0}\right)^2 Ri_0. \quad (19)$$

Assuming a power-law dependence and using Eqs. (14) and (18), this becomes

$$\frac{R_{sp}}{H} = m Ri_{rad}^n \quad (20)$$

for constant m and exponent n . In the following sections, we investigate whether such a power-law dependence holds.

IV. EXPERIMENTS

Laboratory experiments were carried out to measure the radius of separation [R_{sp} , Fig. 1(c)] of the radial outflow and determine the overall structure of the impinging fountain. Experiments focused on fountain source conditions and plate separations that gave $G \ll 1$ [see Eq. (9)], although some experiments were run for a broader range of G . Preliminary experiments to determine R_{sp} were visualized using the shadowgraph technique. Further light induced fluorescence (LIF) experiments were then conducted with sodium fluorescein dye added to the source fluid and the tank lit from below with a thin vertical light sheet. This facilitated clear visualization of the internal flow structure of the impinging fountains for the first time.

A glass-walled tank measuring $1.4 \times 1.4 \text{ m}^2$ in plan was filled with salt water to a depth of approximately 1.2 m. Fresh water was injected into this saline ambient through nozzles of radius in the range $1.5 \leq r_0 \leq 5 \text{ mm}$, held rigidly using a stainless steel support at distances of $25 \leq H \leq 200 \text{ mm}$ above a horizontal clear acrylic plate. These nozzles were similar in construction to those described by Hunt and Linden²⁰ and were designed to provide a fully turbulent and uniform velocity profile at the nozzle exit. The Reynolds number at the outlet of the fountain source varied between 500 and 4000 depending on the particular source conditions. The light sheet was generated by means of a line of ten closely spaced dichroic incandescent 12 V bulbs that were directed at a 1 mm wide slit in black cardboard sheeting attached to the lower glass surface of the tank. The light sheet varied in thickness between 2 and 3 mm over the field of view. Images were captured by a digital charge coupled device video camera [a JAI CV-M4 CL+ monochrome, 1380×1030 pixel resolution] and processed using the *DigiFlow* image acquisition and analysis software system developed by Dalziel.²¹

V. RESULTS AND DISCUSSION

The structure of the impinging fountain flow observed was somewhat different from that which might be surmised from the observations of previous research using the shadowgraph technique or using basic dyed fluid methods. The LIF experiments reported here allowed a vertical section through the impinging fountain to be clearly visualized. The images presented in this section have been enhanced primarily by correcting for the background variation in lighting intensity using the *DigiFlow* software but have not been adjusted to take account of the progressive attenuation of the light sheet (projected from below the horizontal plate) by sodium fluorescein dye.

A. Steady-state impingement

The basic flow structure of the impinging fountain was found to depend primarily on the nondimensional nozzle-plate separation and fountain source Froude number. Results are presented for experiments with $H/r_0 > 5$ and $Fr_0 > 10$, for which an energetic impingement occurred. We refer, hereinafter, to the (quasi-) steady state as the flow realized once the vertically rising plume flow is well established and the separation radius attains a (quasi-) steady value.

Figure 2 is an enhanced image of a typical impinging flow taken once a quasisteady state was reached. The image is annotated to highlight the main features of the flow. The radius of the descending jet of fluid from the source of the fountain increased linearly with increasing distance from the source. Before rising, the buoyant fluid was forced radially outwards as it impacted on the plate and, thus, the rising flow was wider than would have been the case from a free fountain. A wall jet was generated by the impinging fountain. This jet spread radially across the horizontal surface, entrained fluid from above and increased in depth at an approximately constant rate (Fig. 2). The velocity of the radial wall jet decreased with increasing radius and hence the Coanda effect (whereby the buoyant jet was held to the surface) diminished progressively until, at a critical radius ($r = R_{sp}$), the flow detached from the boundary and rose upwards.

One of the most striking features of the flow, as observed for highly forced conditions at impingement, was that as the buoyant radial outflow separated and lifted from the plate it did not form a line plume (circular in plan). Rather, the separated flow was re-entrained into both the radial outflow and the descending fountain, and a toroidal vortex was formed (indicated by the dashed arrow in Fig. 2; see also Fig. 4). After the initial transients, a relatively steady turbulent plume formed above the toroidal vortex. The presence of the toroidal vortex may have an important effect on heat transfer in nonisothermal situations as stationary vortices may “trap” fluid and inhibit heat transfer (e.g., in impinging jets used for cooling applications), as pointed out by Geers *et al.*²²

For $H/L_{m0} \ll 1$, the steady-state flow along the plate behaved similarly to an energetic, nonbuoyant, turbulent jet impinging on a plate. Beyond the (near field) impingement zone, the thickness δ of the radial jet appeared to increase linearly with radius, as highlighted in Fig. 2. However, one

FIG. 2. Digitally enhanced and annotated image illustrating the main characteristics of the flow field (only left of fountain centerline is shown). $G=0.0061$, $Fr_0=113$, $H/L_{m0}=0.10$, and $H/r_0=16.6$ ($g'_0=0.092$ m/s², $r_0=1.5$ mm, and $Q_0=9.44$ cm³/s).

might expect the radial growth rate ($d\delta/dr$) to be greater for impinging fountains than jets since the radial outflow of the fountain is statically unstable. Vortices aligned circumferentially were generated in the impingement zone and swept outward; these are clearly visible in Fig. 2. The presence of these vortices is believed to be the primary cause of the locally high turbulence intensities reported by Cooper *et al.*²³ and other researchers investigating isothermal impinging jets. The point of separation, at R_{sp} , fluctuated about a mean location as successive vortices reached the zone of separation.

Figure 3 shows the dependence of the flow structure on the parameter G once steady state had been reached. The toroidal vortex was formed, as discussed above, in all cases where $H/L_{m0} \leq 1.5$. The dynamics of the vortex are difficult to show clearly in still images such as those of Fig. 3. Thus, a quantitative analysis of the internal structure of the flow was carried out and is illustrated in Fig. 4, where the particle imaging velocimetry analysis facility in *DigiFlow* was used to determine the local velocity field from a LIF movie of the experiments shown in Fig. 2. The sense and scale of the vortical structure are clear. The impingement of the fountain on the plate became less strong with increasing plate separation H/L_{m0} and the re-entrainment of buoyant fluid by the wall jet became progressively weaker. As a result of the weakening of this re-entrainment the toroidal vortex was not observed to exist for larger plate separations; i.e., for $H/L_{m0} > 1.5$. Moreover, for $H/L_{m0} \approx 2$, the fountain made initial contact with the plate but was then observed to repeatedly separate from and then attach to the plate, as shown in

Fig. 3(d). This behavior is discussed further in Sec. V B 2.

Figure 5 shows a plot of the data from all the shadow-graph experiments that were carried out over a wide range of source conditions and nozzle-plate separations. The solid line plotted in this figure is $R_{sp}/H=0.03Ri_{rad}^{-0.75}$. Thus, the nondimensional spread of the radial jet is successfully correlated by the power-law scaling (see Sec. III). It is interesting to note that the exponent of $n=-0.75$ is identical to that reported in Etheridge and Sandberg¹⁵ for a two-dimensional geometry where a plane buoyant jet was introduced with horizontal momentum flux parallel to and immediately above a horizontal surface.

B. Transient development of an impinging turbulent fountain

The transient development of the impinging fountain for $H/L_{m0} < 1.5$ showed three distinct stages (I–III). These stages are illustrated in the sequence of images in Fig. 6.

Stage I. First, the starting fountain impacted with the plate and a horizontal radial flow was established [Figs. 6(a) and 6(b)]. The front of the radial jetlike flow formed a vortex ring, the major radius of which increased with time. The front was quite different from that of a gravity current resulting from an impinging, *negatively* buoyant plume as in the case of the classic “filling box” situation (see, for example, Baines and Turner¹⁸ and Kaye and Hunt¹⁹). During the initial transient, relatively little buoyant fluid escaped re-entrainment into the fountain and the wall jet.

Stage II. The separation radius increased with time be-

FIG. 3. Instantaneous LIF images showing the structure of the impinging fountain flow for a range of nondimensional plate-nozzle separations under quasisteady conditions.

fore reaching a maximum. At approximately this point in time, a bulk upward motion of buoyant fluid occurred above the zone $r < R_{sp}$ and a starting plume developed with the radial outflow effectively acting as a horizontally distributed source of buoyancy for the developing plume.

Stage III. Finally, the bulk plume flow above the nozzle ($z < 0$) acted to reduce, and sometimes reverse, the direction

of flow induced in the ambient and the re-entrained buoyant fluid adjacent to the fountain. Thus, the momentum flux of the fountain when it reached the plate reduced and, as a consequence, the separation radius decreased and settled to a quasisteady value.

1. Characteristic timescale

A timescale appropriate to the development of the toroidal vortex may be defined as the time taken by the buoyant fluid arriving at the plate to occupy a volume equal to that of the vortex. The volume of the vortex scales as L_{m0}^3 and the volume flow rate at the plate as $M_0^{1/2} L_{m0}$. Thus, the timescale for the development of the large toroidal structure is $\tau = M_0/B_0$. The change in the separation radius R_{sp} with time for a typical experiment is shown in the time-series of Fig. 7. This image was generated by processing the digital movie recording so that a horizontal line of pixels just above the flat plate was extracted from each movie frame. These lines of pixels were then placed one above the other to give time on the vertical axis and a measure of the radius of the separation point R_{sp} on the horizontal axis. The separation radius R_{sp} can be seen to have grown rapidly during the very early transient as the out-flowing front propagated across the plate. A maximum value of R_{sp} was then attained (at $\tau \approx 2$) as the toroidal vortex was formed. The radius of spread then decreased to a quasisteady value (at $\tau \approx 4$) as the buoyant plume rising above the impingement zone led to a horizontal influx of ambient fluid across the plate.

FIG. 4. (Color online) Velocity field averaged over 0.4 s for the flow shown in Fig. 2. Vectors were deduced from an analysis of ten successive LIF images and are shown overlaid on an enhanced, instantaneous image of the flow.

FIG. 5. (Color online) Steady separation radius of the buoyant radial wall jet as a function of the Richardson number at the radial jet source. Symbols are experimental data and the solid line is Eq. (20) with $m=0.03$ and $n=-0.75$.

2. Intermittency of fountain attachment

When the nozzle-plate separation $H/L_{m0} \approx 2$, the fountain initially made contact with the plate but subsequently detached and made intermittent contact in the quasisteady state. Figure 8 is a time-series image showing this transient

behavior. The figure was generated by extracting a vertical line of pixels on the centerline of the fountain, extending from the nozzle outlet to the plate, from each frame of the digital movie of the experiment shown in Fig. 3(d). Figure 8 shows that the starting fountain descended to the plate and

FIG. 6. Snapshots of the initial development of the impinging fountain flow field for source conditions ($g'_0=0.058$ m/s², $r_0=1.5$ mm, and $Q_0=9.4$ cm³/s): $G=0.283$, $Fr_0=40$, $H/L_{m0}=0.69$, $H/r_0=40.0$, and $\tau=8.3$ s.

FIG. 7. (Color online) Typical time-series showing the variation of R_{sp} . A series of horizontal rows of pixels (just above the plate) have been assembled from a digitally enhanced movie. Source conditions $G=0.068$, $Fr_0=136$, $H/L_{m0}=0.34$, $H/r_0=66.6$, and $\tau=8.3$ s ($g'_0=0.041$ m/s², $r_0=1.5$ mm, and $Q_0=7.6$ cm³/s).

remained attached thereto for ~ 15 s before detaching and then reattaching intermittently. This observation is similar to the unsteadiness previously found in the vertical rise height of a notionally steady free fountain in a uniform ambient.⁸

VI. CONCLUSIONS

The flow structure within a turbulent fountain impinging on a horizontal plate is complex and is primarily dependent on the fountain source Froude number and the nondimensional separation H/r_0 of the nozzle and plate. Our focus has been on situations where fountains are energetic when impinging on the plate, so that at the plate the local value of the

Froude number is large compared with unity. Under these conditions the impinging fountain generates a buoyant radial wall jet that spreads out across the plate until buoyancy forces overcome the Coanda effect and the flow separates from the plate at a radius R_{sp} . In all cases where $H/L_{m0} \leq 1.5$, a toroidal vortex was formed by the mechanism of re-entrainment of a substantial fraction of the fluid released at R_{sp} back into the downward axial jet and radial wall jet.

The transient development of the impinging fountain has been investigated and it is found that the fountain reaches the quasisteady separation radius after an initial period where the plume rising from the impingement zone is not fully developed. Thus, the separation radius is initially larger than in the steady state since the ambient fluid is coflowing with, rather than counterflowing against, the vertical fountain flow. For small values of the Froude number, at impingement the fountain weakly impinged on the plate and contact with the plate was intermittent.

The results of light induced fluorescence experiments indicate that modeling the upward flow from the impinging fountain as a line plume arising from a ring of radius R_{sp} is unrealistic owing to re-entrainment of the separating fluid by the fountain and radial jet. Finally, the authors have developed a theoretical framework whereby the steady-state spreading radius (R_{sp}) of an energetic impinging fountain may be predicted from the fountain source Richardson number and the dimensionless source-plate separation.

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FIG. 8. (Color online) Time-series showing initial attachment of fountain to plate (at $z=100$ mm) and subsequent intermittent detachment/reattachment events. A series of vertical columns of pixels (from the nozzle outlet to the plate) have been assembled from a digitally enhanced movie of the experiment shown in Fig. 3(d) ($\tau=25.9$ s).

- ¹B. R. Morton, "Forced plumes," *J. Fluid Mech.* **5**, 151 (1959).
- ²G. R. Hunt and N. G. Kaye, "Virtual origin correction for lazy turbulent plumes," *J. Fluid Mech.* **435**, 377 (2001).
- ³J. S. Turner, "Jets and plumes with negative or reversing buoyancy," *J. Fluid Mech.* **26**, 779 (1966).
- ⁴W. D. Baines, J. S. Turner, and I. H. Campbell, "Turbulent fountains in an open chamber," *J. Fluid Mech.* **212**, 557 (1990).
- ⁵L. J. Bloomfield and R. C. Kerr, "Turbulent fountains in a stratified fluid," *J. Fluid Mech.* **358**, 335 (1998).
- ⁶L. J. Bloomfield and R. C. Kerr, "A theoretical model of a turbulent fountain," *J. Fluid Mech.* **424**, 197 (2000).
- ⁷B. R. Morton, G. I. Taylor, and J. S. Turner, "Turbulent gravitational convection from maintained and instantaneous sources," *Proc. R. Soc. London, Ser. A* **234**, 1 (1956).
- ⁸R. W. Cresswell and R. T. Szczepura, "Experimental investigation into a turbulent jet with negative buoyancy," *Phys. Fluids A* **5**, 2865 (1993).
- ⁹A. Godbole, P. Cooper, and J. Norrish, "Computational fluid dynamics analysis of on torch welding fume extraction," *Australasian Welding J.* **52**, 35 (2007).
- ¹⁰G. McMillan, "Is electric arc welding linked to manganism or Parkinson's disease?" *Toxicological Reviews* **24**, 237 (2005).
- ¹¹G. A. Lawrence and M. R. MacLachy, "Radially spreading buoyant flows," *J. Hydraul. Res.* **39**, 583 (2001).
- ¹²D. M. Holstein and C. J. Lemckert, "Spreading of energetic submerged fountains impinging on a rigid surface," in *Proceedings of the 14th Australasian Fluid Mechanics Conference*, Adelaide, Australia (Causaul Pro-

- ductions, Adelaide, 2001), p. 749. Available from Department of Mechanical Engineering, Adelaide University, S.A. 5005, Australia (<http://www.mecheng.adelaide.edu.au/14afmc>).
- ¹³C. J. Lemckert, "Spreading radius of fountains after impinging on a free surface," in *Proceedings of the 15th Australasian Fluid Mechanics Conference*, Sydney, Australia (University of Sydney, Sydney, 2004). Available at <http://www.aeromech.usyd.edu.au/15afmc/proceedings>.
- ¹⁴N. Rajaratnam, *Turbulent Jets* (Elsevier, Amsterdam, 1976).
- ¹⁵D. Etheridge and M. Sandberg, *Building Ventilation: Theory and Measurement* (John Wiley, Chichester, 1996), p. 445.
- ¹⁶E. J. List, "Turbulent jets and plumes," *Annu. Rev. Fluid Mech.* **14**, 189 (1982).
- ¹⁷P. N. Papanicolaou and E. J. List, "Investigations of vertical turbulent buoyant jets," *J. Fluid Mech.* **195**, 341 (1998).
- ¹⁸W. D. Baines and J. S. Turner, "Turbulent buoyant convection from a source in a confined region," *J. Fluid Mech.* **37**, 51 (1968).
- ¹⁹N. B. Kaye and G. R. Hunt, "Overturning in a filling box," *J. Fluid Mech.* **576**, 297 (2007).
- ²⁰G. R. Hunt and P. F. Linden, "Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind," *J. Fluid Mech.* **426**, 355 (2001).
- ²¹S. B. Dalziel, "Rayleigh–Taylor instability: Experiments with image analysis," *Dyn. Atmos. Oceans* **20**, 127 (1993).
- ²²L. F. G. Geers, M. J. Tummers, and K. Hanjalić, "Particle imaging velocimetry-based identification of coherent structures in normally impinging multiple jets," *Phys. Fluids* **17**, 055105 (2005).
- ²³D. Cooper, D. C. Jackson, B. E. Launder, and G. X. Liao, "Impinging jet studies for turbulence model assessment—I. Flow-field experiments," *Int. J. Heat Mass Transfer* **36**, 2675 (1993).