PIV Study on the Interaction of Triple Transitional Round Fountains in a Homogeneous Fluid

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Abstract
This paper investigates experimentally the transient behavior of the interaction of triple transitional fountains injected from three round sources into a homogeneous fluid using the PIV technique over the Reynolds and Froude numbers in the ranges $100 \leq Re \leq 1000$ and $1 \leq Fr \leq 10$. The results show that the behavior of the interaction can be categorized into several distinct regimes: (a) Flapping steady regime, where the flow in the interaction region sways horizontally initially but soon becomes stable with no fluctuation in the interaction height and negligibly small horizontal sway; (b) Bobbing-flapping steady regime, where the interaction region bobs initially with a repeated up-and-down motion, which then reduces in amplitude and duration and three-dimensional horizontal swaying behaviour, but at full development, the interaction becomes steady; (c) Flapping unsteady and bobbing-flapping unsteady regimes, where the behaviors of steady and unsteady interactions are quite similar with the exception that, in the unsteady regime, the interaction remains unsteady even at full development, with fluctuating maximum interaction height and continual swaying; and (d) Transitional/turbulent unsteady regime, where the interaction demonstrates strong unsteadiness and oscillating behavior starting from the beginning. All these observed characteristics are also mapped into a $Re-Fr$ diagram.

Introduction
Negatively buoyant jets, commonly called fountains, are very common phenomenon in industry, geophysics and environments. Whenever any denser fluid is steadily injected upwards into a less dense fluid or in the opposite case when any lighter fluid is injected downwards into a denser fluid a fountain like flow structure forms. The fountain flow behavior can be fully characterized by the dimensionless parameters the Reynolds number $Re$ and the densimetric Froude number $Fr$, which are defined as follows,

$$Re = \frac{V_0 R_0}{\nu}, \quad Fr = \frac{V_0}{[R_0 g (\rho_a - \rho)]^{1/2}},$$

where $V_0$ is the mean inlet velocity of the jet fluid at the source, $R_0$ is the radius of the source, $\nu$ is the kinematic viscosity of fluid, $g = (\rho_a - \rho_b) / \rho_a$ is the reduced gravity between the fluid at the source and the ambient fluid, $g$ is the acceleration due to gravity, $\rho_a$ and $\rho_b$ are the densities of the jet fluid and the ambient fluid at the source, respectively.

There are numerous situations where fountain type structure arises, such as the heating, ventilation and air conditioning of a large building structure, forced cooling of turbines, replenishment of magma chambers in the earth crust, disposal and management of brines, municipality sewerage and industrial waste into ocean, water quality management in reservoir or small lakes, evolution of volcanoes, replenishing of cold salt water at the bottom of a solar pond.

Kaye and Hunt [2] classified a round fountain as either “very week” ($0 < Fr < 1$), “weak” ($1 < Fr < 3$), or “forced” ($Fr > 3$). The major features of forced fountain flows include the buoyancy forces are weak compared with the source momentum flux (thus also called “strong” fountains); the inner upflow of the fountain fluid behaves like a turbulent jet with strong mixing and entrainment of the ambient fluid (thus also called “turbulent” fountains) while the outer downflow of the fountain fluid behaves more like a dense plume; both the upflow and downflow continue to develop along their trajectories so the flow never attains self-similarity and the flow statistics vary with the axial location and the Froude number; and the fountain penetrates a large distance into the ambient fluid. On the other hand, in very weak or weak fountains, the discharge momentum flux of a fountain flow plays a less important role than the negative buoyancy flux and the flow is in the laminar or transitional regime (thus also called “laminar” or “transition” fountains). For these weak fountains, it has been shown that their flow behavior is considerably different from that of forced fountains [1, 2, 3, 10]. For example, it has been shown that $Z_m$ is smaller than $R_0$ for weak fountains while for forced fountains $Z_m$ is much larger than $R_0$, where $Z_m$ is the maximum fountain penetration height; there are no distinguishable upward and downward flows in weak fountains, instead, the streamlines curve and spread from the fountain sources, while in forced fountains, the upward and downward flows are clearly distinguished; there is usually little entrainment of the ambient fluid into the fountain fluid in weak fountains while such an entrainment is one of the major activities occurring in forced fountains; the Reynolds number affects the penetration height in laminar fountains whereas in forced fountains it does not.

So far the studies on fountains have focused on fountains injected from a single source, in particular the single forced fountains. The most common parameter used in characterizing these fountain flow behaviour is $Z_m$, which is normally made dimensionless as $Z_m = Z_m / R_0$. For a single forced fountain ejected from a round source into a homogeneous fluid, it has been found that $Z_m = C F r$, where $C$ is a constant of proportionality. $C = 2.46$ was found by many studies [1, 2, 9], although other values of $C$ have also been reported. The readers are referred to some recent studies, such as Williamson et al. [10] and Burridge and Hunt [1] for the details.

For laminar and transitional round fountains the consensus seems to be that in addition to the momentum flux and buoyancy flux the fluid viscosity also plays an important role [2, 4, 10], leading to the conclusion that $Z_m$ is also under the influence of $Re$ and several scalings have been developed. For example, Lin and Armfield [4] showed that for transitional round fountains dimensional consistency requires $Z_m = C_1 F r / Re^n$, where $n$ is a constant which is found to be dependent on $Fr$ and $Re$ and $C_1$ is a constant of proportionality. However, a wide range of $n$ values...
have been obtained for different values of $Fr$ and $Re$, again as
summarized by Williamson et al. [10] and Burridge and Hunt
[1].

The onset of instability and unsteadiness in fountains is the key
to elucidate the mechanism for the generation of turbulence and
entrainment in fountains but is not well understood, although
some attempts have been made recently, such as that by [5] and
[10].

The interaction of multiple source jets/plumes is very common
and important phenomenon in many applications such as
cooling and heating in food industry, computers and elec-
tronic instruments, flow rising from industrial and households
smokestacks, displacement ventilation and air conditioning of
large building spaces. Despite these numerous application, this
is an area that the studies are scarce and lacking [6, 7, 8]. To
the authors best knowledge, no study has been found to inves-
tigate the interaction among multiple fountains, which motivate
us to conduct this study to examine the behavior of interaction
of triple transitional fountains by using flow visualization and
non-invasive PIV technique.

**Experimental Apparatus and Setup**

Experiments have been conducted over the ranges of $100 \leq Re \leq 1000$ and $1 \leq Fr \leq 10$ by using a High-Framing-Rate
Stereo PIV (HFR-SPIV) system, from Dantec Dynamics. In
these experiments, triple round fountains were produced by in-
jecting, through three identical round orifices, saline water ver-
thetical upwards into fresh water contained in a 24 cm diameter
tank. In order to avoid clogging of seeded particles inside the flow meter, a water filter was installed be-
tween the fountain sources. The volumetric rates were
maintained between 0.0451 l/min to 0.451 l/min. The density
ratio $(\rho_0 - \rho_a)/\rho_a$ for saline water and $\rho_a$ for fresh water,
both at the fountain sources) was varied between 0.00059763
and 0.05976289.

The FlowManager of the Dantec PIV device controls the du-
ration of the PIV experiment, the image capturing of the high
speed camera (a Redlake HG-100K camera with a maximum
resolution of $1504 \times 1128$ pixels and at a high framing rate of 30
fps), and the operation of the double pulsed laser (a Lee LDP-
100MQG Nd: YAG laser emitting 0.532 $\mu$m radiations). The
saline water inlet pipe was aligned flush with the floor of the
fresh water tank and the saline water pipe was kept long enough
to ensure that the flow entering the test tank was fully devel-
oped. A small amount of food dye was used for visualizing
fountain flows.

Experimental ranges of $Fr$ and $Re$ are varied by adjusting salin-
ity of saline water and inlet flow rate for a constant inlet nozzle
size $R_0 = 2.5$ mm. One jet source is placed at the centre of the
test tank and the two other sources are located on the left and
right side of the central fountain. The centre-to-centre distance
between the central and the adjacent fountains is 10 mm, which
is kept fixed for all of the conducted experiments.

**Experimental Results and Discussion**

The observed behavior of the interaction of triple fountains ob-
tained from the current experiments can be categorized broadly
into a steady and an unsteady regime. A demarcation line can
be found to distinguish these two regimes. However, the exact
location of the line cannot be determined in this study due to
the restrictions on the experiments. Nevertheless, the experi-
mental results show that the regime with $Re \leq 100$ and $Fr \leq 5$
and $100 \leq Re \leq 300$ at $Fr = 1$ can be roughly considered as in
the steady regime and the remaining are in the unsteady regime,
as summarized in the $Re – Fr$ regime mapping plot shown in
figure 2, where a part of the results shown were obtained from
another ongoing study on the interactions of triple round foun-
tains by direct numerical simulation (DNS).

![Figure 1: Schematic of the experimental setup:](image)

Prior to the commencement of each experiment, the salt water
tank was filled with fresh water. High quality salt and almost
neutral buoyant Nylon 12 Polyamide polymer spherical tracer
particles (density 1030 kg/m$^3$, mean diameter 50 $\mu$m) were
added into the salt water tank and well mixed using a Davey
D15A submersible sump pump to achieve the desired uniform
density of the saline water for the specific Froude umber of the
experiment. The Perspex-sided test tank was filled with fresh
water from the mains up to the desired height, and Nylon 12
Polyamide polymer spherical tracer particles were also added
and well mixed. After the saline water in the saline water tank
and the fresh water in the test tank became stationary, their indi-
vidual densities were measured by a hand-held Mettler Toledo
Densito 30PX density meter which had an accuracy of 0.001
g/cm$^3$.

A fountain flow was initiated by opening the ball valve to eject
saline water into the test tank at a fixed flow rate for the spe-
cific Reynolds number using the sump pump, and this flow was
maintained in the course of the experiment. The volumetric flow
rate was measured and controlled by an Aalborg high precision
needle valve flow meter. In order to avoid clogging of seeded
particles inside the flow meter, a water filter was installed be-
tween the flow meter and other results are from DNS.

![Figure 2: $Re – Fr$ regime map for the interactions of triple round fountains, where experimental results are located within dotted area and other results are from DNS](image)
From the experimental results, it is found that the steady regime can be further divided into two sub-regimes: flapping and bobbing-flapping. Due to insufficient experimental data, the exact ranges of \( Re \) and \( Fr \) for the flapping steady interaction cannot be determined. Among all experimental cases, only one case, that is, when \( Re = 100 \) and \( Fr = 1 \), the interaction is in the flapping steady regime. However, it is speculated that the interaction of some other triple round fountains with smaller \( Fr \) and \( Re \) values should also be in this sub-regime. In this sub-regime, the initial flow in the interaction region between two adjacent fountain sources moves horizontally around the middle plane of these two fountain sources with gradually increasing maximum interaction height for a very short period of time and then becomes stable with no fluctuation in the interaction height and negligible horizontal sways when the interactions attain full development. The evolution of a flapping steady interaction is captured in figure 3 for \( Re = 100 \) and \( Fr = 1 \). Figure 3(a-f) shows that the steady flapping interaction sways left and right and attains nearly maximum interaction height stages in figure 3(f). After that, it gradually comes to steady state without any fluctuation in height. It is also observed from the PIV images that the time-averaged maximum interaction height in the flapping steady regime stay on the middle plane between the adjacent fountain sources at the steady state.

The bobbing-flapping steady regime is observed for \( 2 \leq Fr \leq 5 \) at \( Re = 100 \) and \( 200 \leq Re \leq 300 \) at \( Fr = 1 \), as shown in figure 2. In this sub-regime, the peak of the interaction region initially moves upwards, comes to rest at a finite height and then collapses around the next rising peaks. This phenomenon repeats for a short period of time, demonstrating a bobbing behavior. At the same time, the interaction region sways horizontally, not limited on the plane passing through the fountain sources, showing a three-dimensional feature. After this, the interaction eventually becomes steady with no change of the maximum interaction height, which is located on the middle plane between the adjacent fountain sources, and again no further horizontal sway. The PIV images showing the time evolution of the bobbing-flapping steady interaction is shown in figure 4 for \( Re = 100 \) and \( Fr = 3 \). It is observed that the formation of interactions of fountains, the development of the penetration heights and the movement of interaction region are demonstrated in figure 4(a-n). After that, the interaction becomes stable with negligible change of its height for a long period of time, as shown in figure 4(o-p). It is also observed from the PIV images that the time-averaged maximum interaction height in the bobbing-flapping steady regime stay on the middle plane between the adjacent fountain sources at the steady state.

The unsteady interaction regime can be divided into three sub-regimes: flapping, bobbing-flapping and transitional/turbulent. The unsteady flapping regime is observed for \( 200 \leq Re \leq 300 \) with \( 2 \leq Fr \leq 5 \); the unsteady bobbing-flapping regime is in the ranges of \( 100 \leq Re \leq 300 \) with \( 6 \leq Fr \leq 10 \); and the unsteady transitional/turbulent regime is found for \( 400 \leq Re \leq 1000 \) with \( 1 \leq Fr \leq 10 \), as shown in figure 2.
interaction remains unsteady even at full development, with fluctuating maximum interaction height and continual sway.

The unsteady flapping interaction is presented in figure 5 for $Re=300$ and $Fr=4$, where the formation of unsteady interaction and the flapping behavior are clearly seen. The time average maximum interaction height in the flapping unsteady regimes stay away from the middle plane between the adjacent fountain sources as shown in figure 5(b).

Figure 6 presents the typical PIV images showing the time evolution of the bobbing-flapping-unsteady interaction with $Re = 200$ and $Fr = 7$. It exhibits the formation of unsteady bobbing-flapping interaction. After the initiation of interaction, initially its front rises up to a certain height, comes to rest, collapses flapping interaction. After the initiation of interaction, initially using flow visualization and noninvasive PIV technique.

Figure 7: Typical PIV images showing the time evolution of the transitional/turbulent-unsteady interaction in triple round fountains with $Re = 600$ and $Fr = 8$ at (a) $\tau = 15.27$; (b) $\tau = 22.91$; (c) $\tau = 30.54$; (d) $\tau = 45.82$; (e) $\tau = 61.09$; (f) $\tau = 91.64$; (g) $\tau = 114.55$; and (h) $\tau = 183.29$.

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