ONSET OF ASYMMETY AND THREE-DIMENSIONALITY IN TRANSITIONAL ROUND FOUNTAINS IN A HOMOGENEOUS FLUID

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Summary The onset of entrainment and asymmetry, which occurs in transitional fountains with intermediate Fr and Re ($1 < Fr < 10$, $100 < Re < 1000$), is the key to shed light on the turbulence generation mechanism in fountains. In this study, a series of direct numerical simulations (DNS) are carried out for transitional fountains in the ranges of $0.1 \le Fr \le 8$, $10 \le Re \le 2000$ to study the onset of asymmetry and three-dimensionality of these fountains. The results show that fountains at a specific Fr values with $Re > 150$ and at a specific Re value with $Fr > 0.5$ are asymmetric and three-dimensional and the extents of their asymmetry and three-dimensionality strongly depends on Re and Fr respectively.

INTRODUCTION

Fountains are common both in nature and in industrial and environmental settings. These are jet flows with a negative buoyancy force acting in the direction opposite to the jet direction. When a fluid is injected upward into a miscible lighter ambient fluid, or a fluid is directed downwards into a miscible denser ambient fluid, a fountain occurs.

In a quiescent homogeneous ambient fluid, the fountain behavior is predominantly governed by the Reynolds number Re, and the Froude number Fr. When $Re > 1000$ and $Fr >> 1$, fountains are turbulent, with strong entrainment and mixing occurring between the fountain fluid and the ambient fluid. The behavior of these turbulent fountains has been well understood. On the other hand, when $Fr < 1$ and $Re < 500$, fountains are weak and laminar, with little entrainment and mixing occurring between the fountain and the ambient fluids. The behavior of such fountains has also been understood reasonably well after enormous recent studies initiated and led by us [1, 2].

The onset of entrainment and asymmetry, which occurs in transitional fountains with intermediate Fr and Re ($1 < Fr < 10$, $100 < Re < 1000$), is the key to shed light on the turbulence generation mechanism in fountains. Nevertheless, only quite recently the research on fountains in this transitional regime was initiated by us [3, 4], and the understanding of their behavior is very limited, which motivates us to continue the investigation in this study.

NUMERICAL METHODOLOGY

A series of direct numerical simulations (DNS) are carried out for transitional fountains in the ranges of $0.1 \le Fr \le 8$, $10 \le Re \le 2000$. The physical system under consideration is a vertical circular container containing a Newtonian fluid initially at rest and at a uniform temperature of T_a, the sidewall is non-slip and insulated and the top is open. On the bottom center, an orifice with radius R_0 is used as the fountain discharge source. The remaining bottom region is a rigid non-slip and insulated boundary. At time $t = 0$, a stream of fluid at T_0 ($T_0 < T_a$) is injected upward into the container from the source to initiate the fountain flow and this discharge is maintained thereafter.

The flow is described by the Navier–Stokes and temperature equations, which are discretized on a non-uniform mesh using finite volumes, with standard 2nd-order central difference schemes used for the viscous and divergence terms. The QUICK 3rd-order upwind scheme is used for the advective terms. The 2nd-order Adams-Bashforth scheme and Crank-Nicolson scheme are used for the time integration of the advective terms and the diffusive terms. The PRESTO (PREssure STaggering Option) scheme is used for the pressure gradient. The ICEM technique is used to create O-Type Multiblock Hexahedron meshes. The minimal number of grids used is 944636 and the maximum is 2069965.

RESULTS

A typical DNS result showing the evolution of the temperature field of a $Fr = 2$ transitional fountain with increasing Re at a specific height is presented in figure 1. It is found that at small Re ($Re = 100$), the fountain is axisymmetric; however, when $Re > 100$, asymmetry occurs and the flows become three-dimensional. Similar phenomena are also observed for other Fr values, although at different critical Re numbers and the extent of these phenomena are different. To detect the occurrence and the extent of asymmetry and three-dimensionality in transitional fountains, R_c and ΔR are introduced. R_c is defined in figure 2, where the interface between the fountain fluid and the ambient fluid on a sectional plane at a specific height and the equivalent circular sectional area of the fountain fluid are sketched. R_c is the distance between the center of the fountain source and the center of the equivalent circular sectional area of the fountain fluid, which represents the extent of asymmetry. ΔR is the root mean square of (R_i - R_a), where R_a is the

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radius of the equivalent circular sectional area of the fountain fluid and R_i is the distance of point i (totally N points) on the interface from the center of the equivalent circular sectional area of the fountain fluid. Apparently, ΔR is a parameter quantifying the extent of three-dimensionality of the fountain. It is appropriate to assume that $R_c/R_0 > 1\%$ and $\Delta R/R_0 > 1\%$ are the criteria for the occurrence of asymmetry and three-dimensionality, respectively.

Figure 3 shows the DNS results for R_c/R_0 and $\Delta R/R_0$ when $Fr = 2$ with $10 \le Re \le 2000$. It demonstrates that when $Re \le 150$, both R_c/R_0 and $\Delta R/R_0$ are smaller than 1%, indicating that these fountains are axisymmetric; when $200 \le Re \le 500$, both parameters are larger than 1% and increase with Re, clearly showing that these fountains are asymmetric and three-dimensional and the extents of asymmetry and three-dimensionality increase dramatically with Re; when $Re > 500$, although the fountains are asymmetric and three-dimensional, however, the extents of these phenomena do not change with Re. Similar trends are also observed for other Fr values.

Figure 4 shows the DNS results for R_c/R_0 and $\Delta R/R_0$ when $Re = 200$ with $0.5 \le Fr \le 8$. It is found that only the $Fr = 0.5$ fountain keeps axisymmetry and all others are asymmetric and three-dimensional and the extents of asymmetry and three-dimensionality increase significantly with Fr. Similar trends are also observed for other Re values.

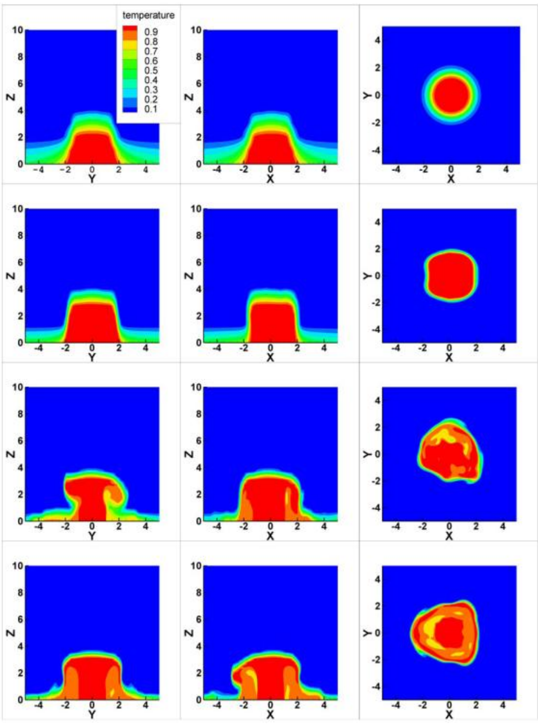
Figure 1. Temperature fields of $Fr = 2$ fountain at Y-Z, X-Z and X-Y planes with Re =100, 200, 500 and 1000 (from top to bottom).

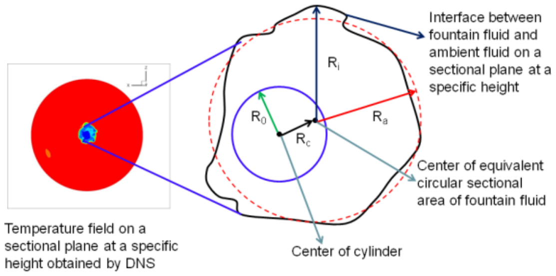

Figure 2. Sketch of the definition of R_c.

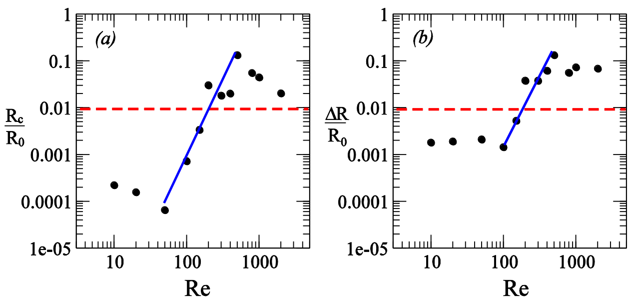
Figure 3. Results for R_c/R_0 and $\Delta R/R_0$ when $Fr = 2$ with $10 \le Re \le 2000$.

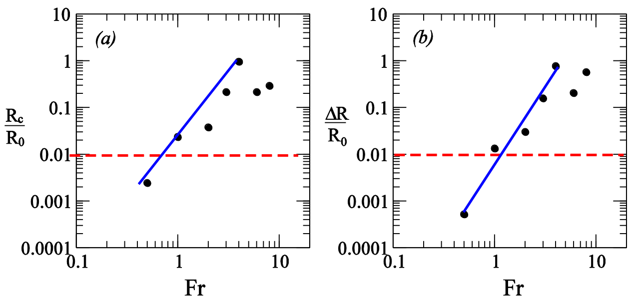
Figure 4. Results for R_c/R_0 and $\Delta R/R_0$ when $Re = 200$ with $0.5 \le Fr \le 8$.

CONCLUSIONS

DNS results show that for a specific Fr value fountains are asymmetric and three-dimensional when $Re > 150$ and the extents of asymmetry and three-dimensionality increase with Re; for a specific Re value fountains with $Fr > 0.5$ are asymmetric and three-dimensional and the extents of asymmetry and three-dimensionality increase with Fr.

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