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Correlations for maximum penetration heights of transitional plane fountains in linearly stratified fluids☆

Mohammad Ilias Inam [a], Wenxian Lin [a,b,*], S.W. Armfield [c], Yinghe He [a]

[a] College of Science & Engineering, James Cook University, Townsville, QLD, 4811, Australia
[b] Solar Energy Research Institute, Yunnan Normal University, Kunming, Yunnan 650092, PR China
[c] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

In this study, a series of three-dimensional direct numerical simulations (DNS) were carried out using ANSYS Fluent for transitional plane fountains in linearly stratified fluids with the Reynolds number (*Re*), Froude number (*Fr*) and dimensionless temperature stratification parameter (*s*) over $28 \le Re \le 300$, $3 \le Fr \le 10$, and $0.1 \le s \le 0.5$, to study and quantify the effects of these governing parameters on the maximum fountain penetration height, including the initial one during the early developing stage and the time-averaged one at the quasi-steady state, as well as the time to reach the initial maximum penetration height. The results show that both the initial and time-averaged maximum fountain heights as well as the time to attain the initial maximum fountain height increase with *Fr* but decrease with *s*, whereas the effect of *Re* is negligible, and the fluctuations of the maximum fountain penetration height at some specific locations at the quasi-steady state also follow the similar trends. Empirical correlations to quantify the effects of *Fr*, *s* and *Re* on these bulk fountain behavior parameters were obtained from the DNS results over the ranges of *Fr*, *s* and *Re* considered.

1. Introduction

This paper is a continuation of our recent study [1] in which the asymmetric transition and the maximum fountain penetration heights of transitional plane fountains in linearly stratified fluids were investigated using a series of three-dimensional direct numerical simulations (DNS) obtained by ANSYS Fluent over $25 \le Re \le 300$ and $0 \le s \le 0.5$, all at $Fr = 10$. The Reynolds number, *Re*, the Froude number, *Fr*, and the dimensionless temperature stratification parameter, *s*, which are the major governing parameters for fountains in linearly stratified fluids, are defined as follows,

$$Re = \frac{W_0 X_0}{\nu}, \quad \mathrm{Fr} = \frac{W_0}{[g\beta X_0 (T_{a,0} - T_0)]^{1/2}}, \mathrm{s} = \frac{X_0}{(T_{a,0} - T_0)} \frac{dT_{a,Z}}{dZ}, \qquad (1)$$

where X_0 is the half-width of the slot at the source of plane fountain, W_0 is the mean inlet velocity of the jet fluid at the source, *g* is the acceleration due to gravity, T_0 is the temperature of the jet fluid, $T_{a,0}$ and $T_{a,Z}$ are the initial temperatures of the ambient fluid at the source (*i.e.*, at $Z = 0$) and at height *Z*, and ν and β are the kinematic viscosity and coefficient of volumetric expansion of fluid, respectively. It is assumed in these definitions that the density difference of the jet fluid and the ambient fluid is due to their difference in temperatures and the Oberbeck-Boussinesq approximation is applicable. In [1], empirical correlations were developed using the numerical results to quantify the effects of *Re* and *s* on the initial and time-averaged maximum fountain penetration heights (*i.e.*, $z_{m,i}$ and $z_{m,a}$, respectively, which are made dimensionless by X_0), and the time to attain $z_{m,i}$. The results show that both $z_{m,i}$ and $z_{m,a}$ increase with *Re*, but decrease with *s*, and the effect of *s* on $z_{m,i}$ and $z_{m,a}$ is much stronger than that of *Re*. However, the effect of *Fr* was not examined in [1] as all DNS runs were carried out at a fixed *Fr* value (*i.e.*, $Fr = 10$). This motivates the current study.

In the current study, the effect of *Fr* on the maximum penetration heights of transitional plane fountains is examined using DNS results with *Fr* varying over $3 \le Fr \le 10$, but *Re* and *s* varying essentially over the same ranges as those in [1], *i.e.*, $28 \le Re \le 300$ and $0.1 \le s \le 0.5$. The effects of *Re* and *s* are also re-examined with DNS results with these varying *Fr* values. Empirical correlations to quantify the overall effects of *Fr*, *Re* and *s* are also developed with the DNS results over these ranges. As an introduction to fountains and a brief review on some previous work on the topic was detailed in [1] and can also be readily available elsewhere (see, *e.g.*, [2–24]), these will not be repeated here.

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* Corresponding author at: College of Science & Engineering, James Cook University, Townsville, QLD, 4811, Australia.
E-mail address: wenxian.lin@jcu.edu.au (W. Lin).

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2. Problem addressed and methodology

The physical system under consideration is a rectangular container of the dimensions $H\times B\times L$ (Height $\times$ Width $\times$ Length), containing a Newtonian fluid initially at rest and with a constant temperature gradient $dT_{a,z}/dZ$, as sketched in Fig. 1 of [1]. At the center of the container bottom, a narrow slot with a half-width of X_0 in the Y direction functions as the source for plane fountain, with the remainder of the bottom being a rigid non-slip and adiabatic boundary. The two vertical surfaces in the $X-Z$ plane, at $Y=\pm B/2$, are assumed to be periodic whereas the two vertical surfaces in the $Y-Z$ plane, at $X=\pm L/2$, are assumed to be outflows. The top surface in the $X-Y$ plane, at $Y=H$, is assumed to be a wall. The origin of the Cartesian coordinate systems is at the center of the bottom. The gravity is acting in the negative Z-direction. At time $t=0$, a stream of fluid at T_0 ($T_0<T_{a,0}$) is injected upward from the slot with a uniform velocity W_0 into the container to initiate the plane fountain flow and this discharge is maintained over the whole course of a specific DNS run.

The governing equations for the flow, which are three-dimensional incompressible Navier-Stokes and temperature equations with the Oberbeck-Boussinesq approximation, and the initial and boundary conditions are the same as those presented in [1] and hence not repeated here. The reader is also referred to [1] for the details about the numerical methodology used in the DNS runs, including the schemes used for the discretization of the governing equations and the construction and testing of the non-uniform computational meshes.

DNS runs were carried out using ANSYS Fluent 13 with Fr, Re and s over $3\le Fr\le 10$, $28\le Re\le 300$ and $0.1\le s\le 0.5$. In addition, the DNS runs with $s=0$, which corresponds to a homogeneous fluid case, were also carried out for the purpose of comparison.

3. Qualitative observation of transient behavior

The evolution of transient behavior of a typical transitional plane fountain in stratified fluid was illustrated, as an example, by the snapshots of temperature field on three individual planes as presented in Fig. 3 of [1] for the case of $Fr=10$, $Re=100$ and $s=0.1$. It was observed from the figure that at the early development stage, the fountain flow maintains symmetry in the horizontal directions, but becomes asymmetric and unstable subsequently which is dominated by a flapping motion (*i.e.*, the horizontal oscillations), until it eventually becomes fully developed and attains a quasi-steady state. At the quasi-steady state, the instantaneous fountain behavior still changes with time, however, the time-averaged behavior essentially becomes steady.

The effects of Re and s on the transient fountain behavior, in particular at the quasi-steady state, were examined in [1] using the representative temperature contours at the quasi-steady state with Re varying over $25\le Re\le 300$ at $Fr=10$ and $s=0.1$ and with s varying over $0\le s\le 0.5$ at $Fr=10$ and $Re=100$, respectively, as shown in Figs. 5 and 8 in [1]. The results show that all these fountains become asymmetric and unsteady at the quasi-steady state; the fountain penetration height in the $X-Z$ plane is essentially independent of Re at higher Re values

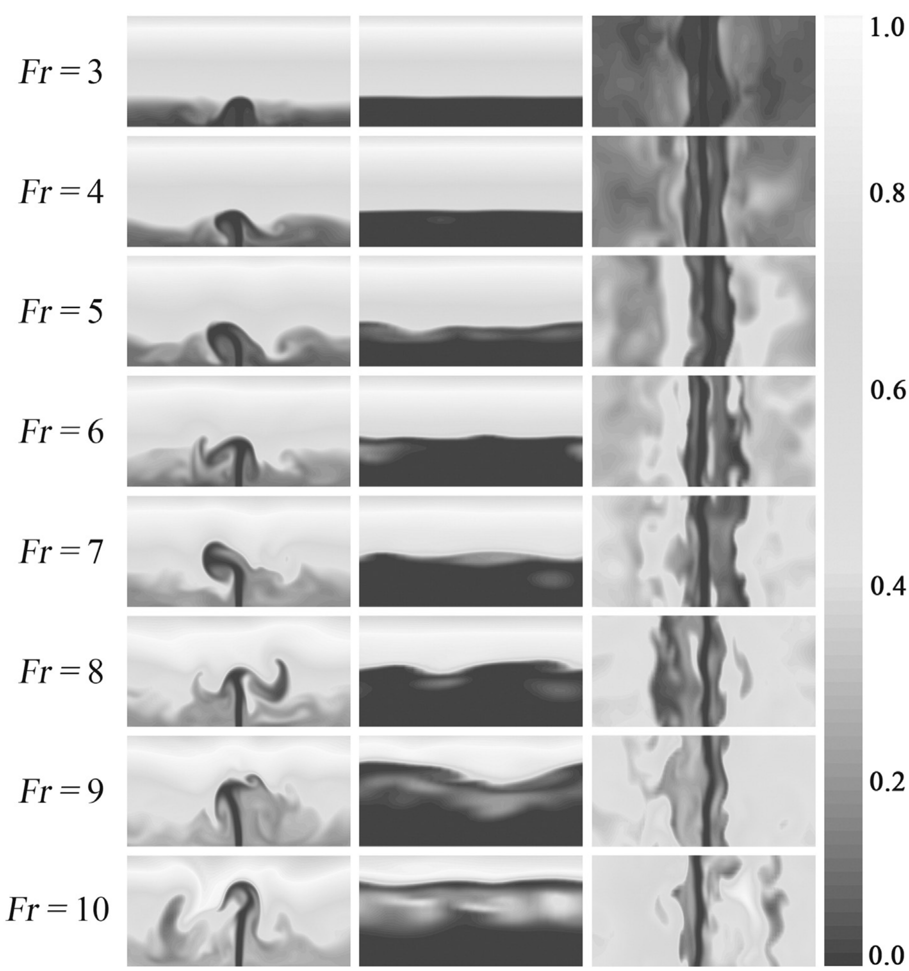

Fig. 1. Snapshots of temperature contours at the quasi-steady state for Fr over $3\le Fr\le 10$ at $Re=100$ and $s=0.1$, at $Y=0$ in the $X-Z$ plane (first column), $X=0$ in the $Y-Z$ plane (second column), and $Z=0.5Z_{m,i}$ in the $X-Y$ plane (third column), respectively, where $Z_{m,i}$ is the initial maximum fountain penetration height. The temperature contours are normalized with $[T(Z)-T_0]/(T_{a,Z=100X_0}-T_0)$.