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Displacement flows in periodically moving pipe: Understanding multiphase flows hosted in oscillating geometry

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HIGHLIGHTS

- Experimental study of buoyant miscible displacement flows in an oscillating pipe.
- Experiments covering a wide range of the most relevant dimensionless groups.
- Quantifying displacement front velocities and macroscopic diffusion coefficients.

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ABSTRACT

In the present work, we experimentally study displacement flows of two Newtonian, miscible fluids in a long, vertical moving pipe while comparing the results with the corresponding displacement flows in a stationary pipe. When in motion, the pipe slowly oscillates like an inverted pendulum. The two fluids have a small density difference and a nearly-identical viscosity. The denser displacing fluid is placed above the displaced fluid. Overall, our buoyant displacement flows in a moving pipe are at least controlled by three dimensionless groups, namely the Reynolds number, the densimetric Froude number, and the Rossby number. Experimental images of the penetrating front of the heavy displacing fluid into the light displaced one have been analyzed for a wide range of the dimensionless groups. In particular, three different flow regimes are observed for displacement flows in a moving pipe: a stable flow that is non-diffusive (for $Re/Ro \lesssim O\left(10^2\right)$ & $Re/Fr^2 < 35$), a stable-diffusive flow (for $Re/Ro \gtrsim O\left(10^2\right)$ & $Re/Fr^2 < 35$) and an unstable-diffusive flow (for $Re/Fr^2 > 35$). In addition, penetration front velocities as well as macroscopic diffusion coefficients have been quantified. The results show in detail that depending on the value of the density difference and the mean imposed displacement flow velocity, the geometrical movement can have different and even opposite effects, e.g., slightly increase or decrease the front velocity. The pipe motion seems to also slightly increase the macroscopic diffusion coefficient. While the findings of this study can help understand the leading order effects associated with a flow geometry movement on displacement flows, they can be of great importance for industrial applications and for development of relevant fluid mechanics theories.

1. Introduction

In simple words, displacement flows occur when a fluid is imposed to push another fluid of different properties in a flow geometry that is usually confined. Displacement fluid flows are among the most widespread phenomena in nature (Elrick et al., 1966; Grotberg and Jensen, 2004), as well as in industry, e.g., in oil and gas industry (Dake, 1983; Nelson and Guillot, 2006) and other applications (Schweizer and Kistler, 2012). In the present work, we experimentally study high-Péclet-number miscible displacement flows of Newtonian fluids in a long, vertical, moving pipe. The two fluids have the same viscosity. The density difference between the two fluids is small, implying that the Boussinesq approximation is applicable. However, as the heavy fluid is placed on the top of the light fluid, buoyancy is still significant in driving fluid flow motion. At the same time, there is a downward laminar imposed flow, with a mean velocity, $\widehat{V}_0$. [1] In addition, during the displacement flow process the test pipe slowly oscillates like an inverted pendulum (see Fig. 1). Buoyant displacement flows in stationary geometries have been studied in depth recently (see

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[1] In this paper we adopt the convention of denoting dimensional quantities with the ∧ symbol and dimensionless quantities without.

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Nomenclature

At	Atwood number
c	dimensionless fluid concentration
C	dimensionless concentration
$\overline{C}_x$	averaged concentration with respect to x
$\overline{C}_{xy}$	averaged concentration with respect to x & y
$\overline{C}_{xyz}$	averaged concentration with respect to x, y & z
$\hat{D}$	pipe diameter, m
$\hat{D}_m$	molecular diffusivity, m^2/s
$\hat{D}_M$	macroscopic diffusion coefficient, m^2/s
$\hat{D}^s_M$	pseudo macroscopic diffusion coefficient, m^2/s
$\hat{f}$	pipe motion angular frequency, 1/s
Fr	densimetric Froude number
$\hat{g}$	acceleration due to gravity, m/s^2
$\hat{L}$	length of the pipe, m
m	viscosity ratio
p	dimensionless pressure
Pe	Péclet number
Re	Reynolds number
Ro	Rossby number
$\mathbf{u}$	dimensionless fluid velocity
V_f	dimensionless front velocity
$\widehat{V}_f$	front velocity, m/s
$\widehat{V}_0$	mean imposed flow velocity, m/s
$(\hat{x}, \hat{y}, \hat{z})$	Cartesian coordinates, m/s
$(\hat{r}, \hat{\theta}, \hat{z})$	cylindrical coordinates, m/s
$\hat{z}_0$	radial distance between the gate valve & the rotation center
Z_0	characteristic dimensionless radial distance between the gate valve & rotation center

Greek letters

$\mathcal{A}$	pipe oscillation (rotation) maximum amplitude
β	pipe inclination angle (deg)
δ	ratio of pipe diameter to pipe length
$\hat{\mu}$	fluid dynamic viscosity, Pa.s
$\hat{\nu}$	kinematic viscosity, mm^2/s
$\hat{\rho}$	fluid density, kg/m^3
$\hat{\bar{\rho}}$	mean density, kg/m^3
$\hat{\omega}_0$	pipe motion angular speed, rad/s
Ω	dimensionless rotation vector
$\Re$	normalized dimensionless position vector
ϕ	linear interpolation function

Subscripts

H	heavy displacing fluid
L	light displaced fluid
t	derivative with respect to time

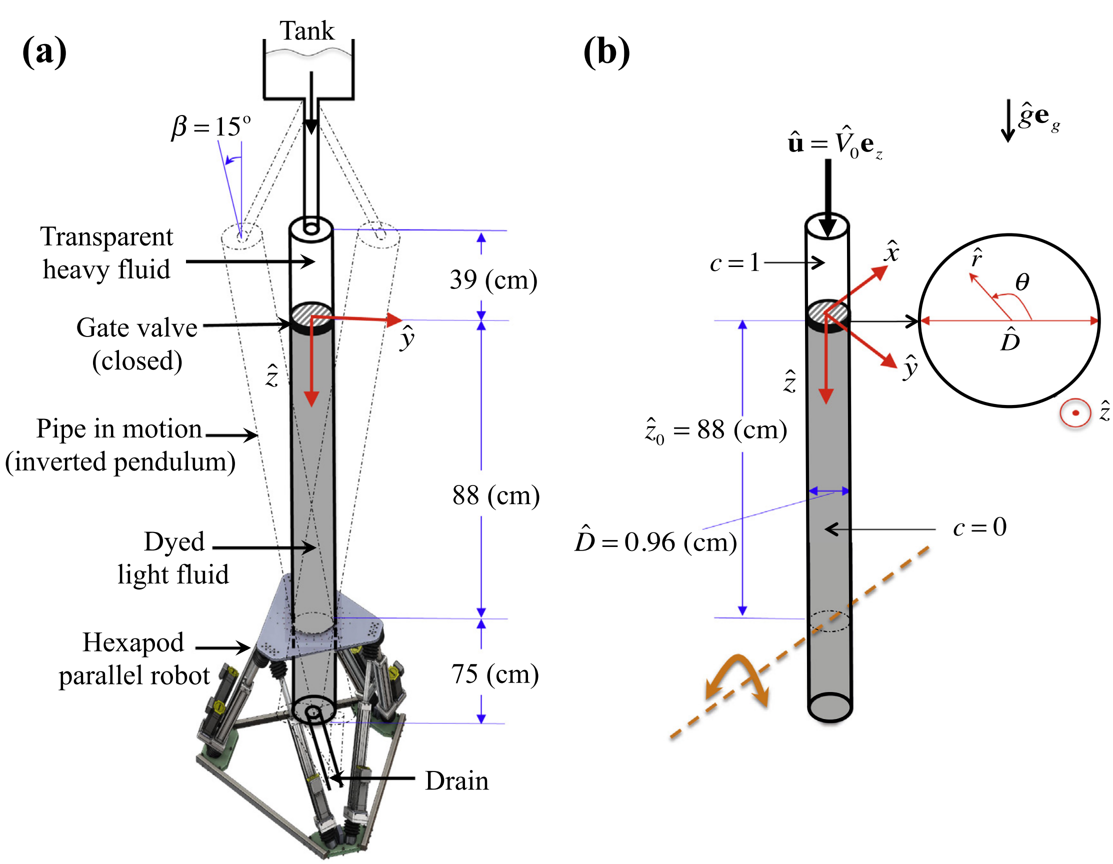

Fig. 1. Schematic view of the experimental displacement flow setup: (a) the pipe in motion and (b) coordinates, dimensions and other details.

e.g., Taghavi et al., 2012; Alba et al., 2013; Amiri et al., 2016) but the literature on buoyant displacement flows in moving geometries is almost non-existent. The focus of our study is to draw a comparison between buoyant miscible displacement flows in moving and stationary pipes, through studying a number of key and leading order features of these flows.