Computers & Fluids 90 (2014) 172–185

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical and experimental investigations of three-dimensional container filling with Newtonian viscous fluids

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A R T I C L E   I N F O

Article history:
Received 4 April 2013
Received in revised form 12 September 2013
Accepted 11 November 2013
Available online 25 November 2013

Keywords:
Container filling
Jet buckling
Three-dimensional free surface flows
Experimental assessment
Finite differences

A B S T R A C T

This work employs numerical and experimental approaches to investigate three-dimensional container filling with Newtonian viscous fluids. For this purpose, a computer code developed for simulating three-dimensional free surface flows has been used. The CFD Freeflow3D code was specifically designed to deal with unsteady three-dimensional flows possessing multiple moving free surfaces. An experimental apparatus that allows the visualization of the various phenomena that can occur during the filling of containers has been constructed and employed. Experiments on container filling were carried out by varying the fluid velocity at the injection nozzle. This paper presents a computational study on container filling with Newtonian viscous fluids and employs the experimental results to validate the software. The experimental observations were compared with the predictions from the Freeflow3D code and good agreement between the two sets of results is observed. Moreover, the code predictions showed that it is capable of capturing the most relevant phenomena observed in the experiments.

1. Introduction

Industries like food, cosmetic, chemical, among others, usually employ automatic filling of containers in their production lines. In these processes, it is important to fill the containers as fast as possible to achieve high production rates and, at the same time, assure that the product characteristics are not affected negatively. The filling process is usually carried out by a moving nozzle that injects the product, in a fluid form, into a container. During the filling stage, several problems can arise like jet buckling, splashing, doming, air entrapment, among others [11]. Therefore, an understanding of the filling process can be helpful to avoid these undesirable flow regimes. Indeed, many researchers (e.g. [2,4,6,7,11,13]) have been working on the development of tools that are capable of simulating the filling of containers with viscous fluids. In particular, a study on the filling of two-dimensional containers was presented by Tomé et al. [13]. In their work, they considered the filling of rectangular and trapezoidal 2D containers with a Newtonian viscous fluid. This study presented numerical predictions obtained by the GENSMAC code [15], which were compared with experimental observations obtained by varying the size of the nozzle and the issuing fluid velocity at the nozzle. Good agreement between the numerical predictions and the experimental results was reported.

In this work, we consider the application of the Freeflow3D code [2] in the simulation of a three-dimensional cubic container filling with Newtonian viscous fluids. To verify the correctness of the code predictions, an experimental system developed to visualize the instantaneous filling of containers, under controlled flow conditions, was designed and built. This device was employed to study the filling of a cubic container with a corn syrup based fluid, under different filling regimes, ranging from the occurrence of evident jet buckling to situations where splashing takes place. The Freeflow3D code was then used to simulate the filling process using the same conditions employed on the experimental runs. The filling regimes obtained and the comparison of the experimental results with the numerical predictions obtained by the Freeflow3D code are discussed.

The main contributions of this work are the experimental assessment of the Freeflow3D code and to provide numerical as well as experimental results on three-dimensional container filling. These results might be useful to researchers working on this topic, as they can use both the experimental and numerical results to benchmark the correctness of their codes.

This paper is organized as follows: in the next section a description of Freeflow3D code is presented, while Section 3 deals with the illustration of the capabilities of the Freeflow3D in simulating time-dependent three-dimensional flows, that can be found during

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http://dx.doi.org/10.1016/j.compfluid.2013.11.015

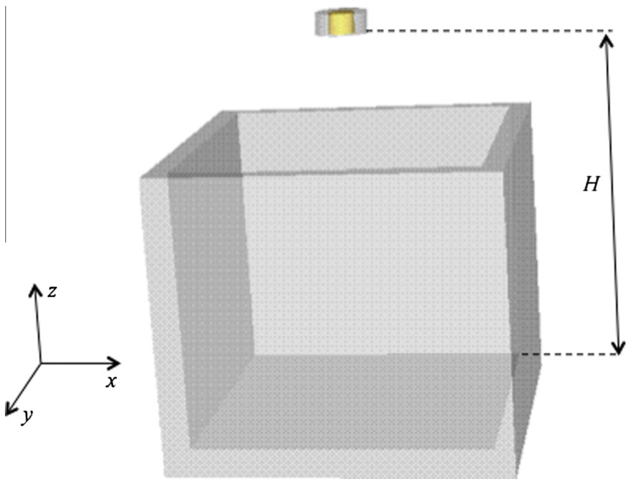

Fig. 1. Schematic view of the flow domain employed to simulate the container filling problem. The yellow surface identifies the location of the nozzle from where fluid is injected into the container. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the filling of a cubic container. Section 4 describes the system employed in the experiments performed on the filling of a cubic container. The experimental and the numerical results are presented, compared and analyzed in Section 5. Finally, the conclusions are summarized in Section 6.

2. Brief description of the Freeflow3D code

The basic equations governing incompressible unsteady moving free surface flows of Newtonian fluids are the mass conservation and the Navier–Stokes equations that can be written in non-dimensional form as

$$\nabla \cdot \mathbf{v} = 0, \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla)\mathbf{v} - \nabla p + \frac{1}{\mathrm{Re}}\nabla^2 \mathbf{v} + \frac{1}{\mathrm{Fr}^2}\mathbf{g}, \tag{2}$$

where t is the time, $\mathbf{v}$ is the fluid velocity, p is the pressure, $\mathbf{g}$ is the unit gravitational field vector, $\mathrm{Re} = (\rho V D)/\mu$ is the Reynolds number and $\mathrm{Fr} = V/\sqrt{Dg}$ is the Froude number. V and D are appropriate scalings for velocity and length, ρ is the density, μ is the viscosity and $g = 9.81\ \mathrm{ms}^{-2}$ is the gravitational constant.

Eqs. (1) and (2) are solved subjected to the no-slip boundary condition ($\mathbf{v} = \mathbf{0}$) on rigid walls and a prescribed velocity on inflows ($\boldsymbol{V}_{\mathrm{inf}}$). If surface tension is not important, the boundary conditions on the moving free-surfaces can be written as (see Batchelor [1])

$$\mathbf{n} \cdot \boldsymbol{\sigma} \cdot \mathbf{n} = 0 \quad \text{and} \quad \mathbf{m} \cdot \boldsymbol{\sigma} \cdot \mathbf{n} = 0, \tag{3}$$

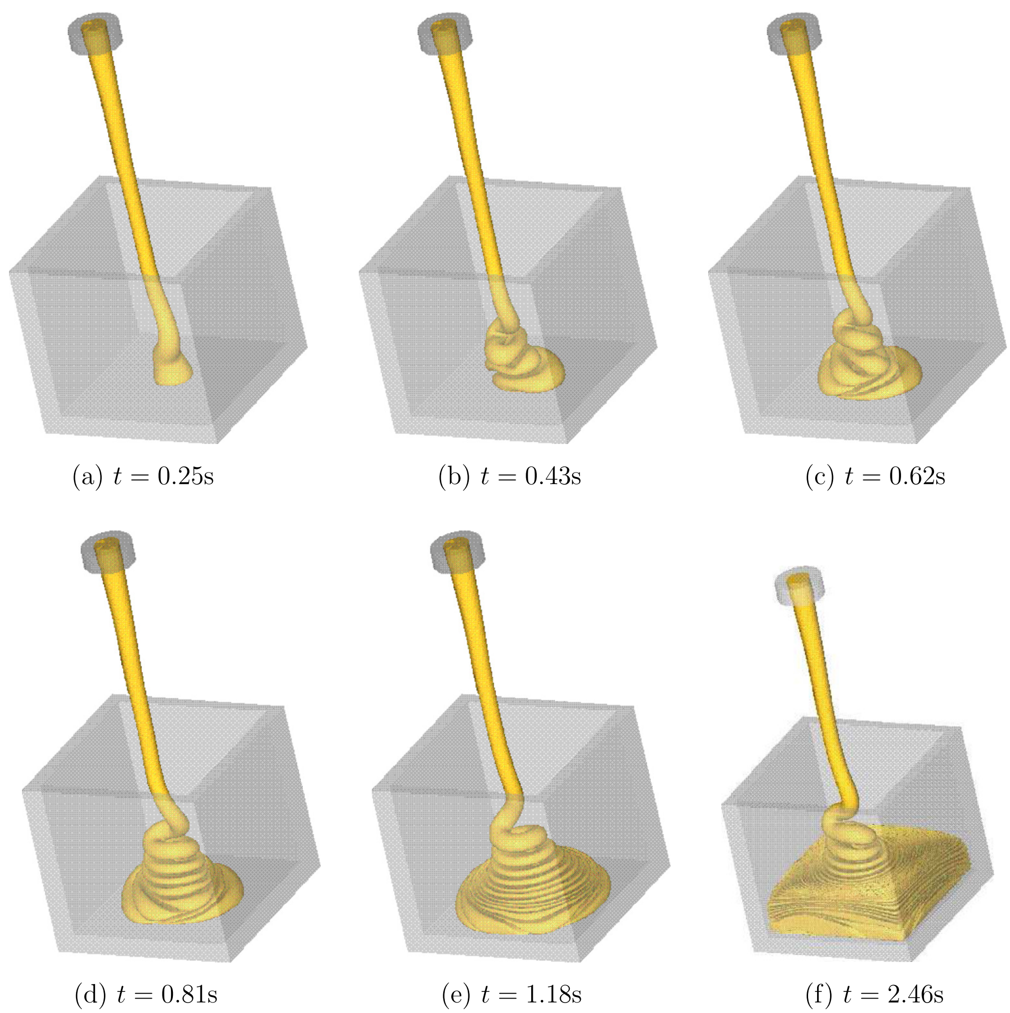

Fig. 2. Numerical simulation of the filling of a cubic container with $V = 0.25\,\mathrm{m\,s}^{-1}$. Fluid flow visualizations at selected times. Jet buckling is displayed.