# THE PHENOMENON OF JET BUCKLING: EXPERIMENTAL RESULTS AND NUMERICAL PREDICTIONS

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Abstract - In this work, a new experimental device to visualize the filling of containers, under controlled and reproducible conditions, is described and employed to study the various phenomena that occur during container filling with Newtonian fluids. The experimental results displayed a variety of flow patterns, including the phenomenon of jet buckling. The results obtained experimentally were compared with the predictions given by the CFD code Freeflow3D. This code is based on the Marker-and-Cell technique and was able to handle properly all the issues of the system under study. The numerical results are in accordance with the movies recorded during the experimental runs and showed that the Freeflow3D code was able to predict the most relevant phenomena observed.

## Introduction

In industries like food, chemistry, medical, among others, the phenomenon of jet buckling has a large relevance in tasks involving the filling of containers with liquid like substances. This flow instability is related to the occurrence of some problems like splashing, sloshing and void formation [1, 2] and therefore is undesirable. Despite its obvious importance, the literature on this subject is scarce, especially in what concerns to experimental work with fluids of complex rheology.

The jet buckling phenomenon has been studied since the late fifties, when the work entitled "Liquid rope coiling" by Barnes and Woodcock [3] led the way to several experimental studies, that have been performed until the present time [4-8]. Concerning the theoretical understanding of this phenomenon, the work of Taylor [9] was the pioneer. He noticed that the jet buckling was similar to the buckling instability that occurs in slender beams and concluded that this phenomenon was related to longitudinal compressive stresses in the 'liquid rope'. Zak [10], based in the investigations performed by Cruickshank [4], studied this problem with analytical models and established criteria for the onset of this instability. In the review performed by Bejan [6], in contradiction with the Cruickshank studies [4], it was concluded that this phenomenon can also occur for high Reynolds numbers. Later, Mahadevan et al. [11] showed that the buckling instabilities are an outcome from a competition between compression and bending stresses in slender objects. More recently, Ribe [12] proved that there are other variables involved and demonstrated theoretically that coiling can appear in three distinct dynamical regimes: viscous, gravitational and inertial. The experimental observance of these three regimes was afterwards performed by Maleki et al. [8].

This work reports initial investigations aiming to a deeper understanding of the jet buckling phenomenon. For this purpose an experimental device to visualize the filling of a container under controlled conditions was designed and built. This experimental device was employed to study the filling of a cubic container with a corn syrup based fluid, under different filling regimes, ranging from regions with evident jet buckling to regimes where it does not take place. In order to achieve a deeper understanding of the phenomena involved, the Freeflow3D code, developed by some of the authors, was used to simulate the process using the same conditions employed in the experimental runs. The filling regimes obtained and the comparison of the experimental work with the numerical predictions obtained are discussed.

This paper is organized as follows: in the next section the experimental device is presented and the numerical code employed is briefly described. Then the experimental work and the numerical results are presented and analyzed. Finally, the conclusions of the work done are drawn.

### Experimental Visualization System

The experimental system was built to visualize the filling of containers under controlled and reproducible conditions. Basically, the visualization device, which is illustrated in Figure 1, consists of: (1) a **reservoir** to store the fluid; (2) a **piston** that can be displaced at a controlled velocity, defining a specific flow rate; (3) an **extrusion die** with a specific cross section through which the fluid is injected into the container; (4) two moving **gates** that enable to close the container. These gates allow starting the experiments using two different modes: opened and closed. The gates should be in the opened mode and then be closed when the jet achieves the desired state if the objective is to start the experiment when the impinging jet is fully developed. Alternatively, to record the jet formation right from the beginning of the flow, the gates should start in the closed mode; (5) a **transparent container** that allows the visualization of the filling process.

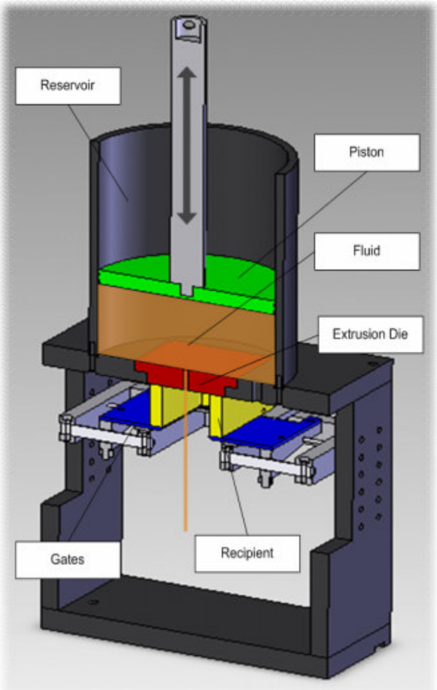



**Figure 1** – Schematic view of the experimental visualization device.

Besides the visualization device, the overall experimental setup consists of a Universal Testing Machine INSTRON 4505, used to control the piston velocity, and thus the fluid flow-rate, and a video camera to record the experimental runs. A photo of the new apparatus coupled to the Universal testing machine is shown in Figure 2.

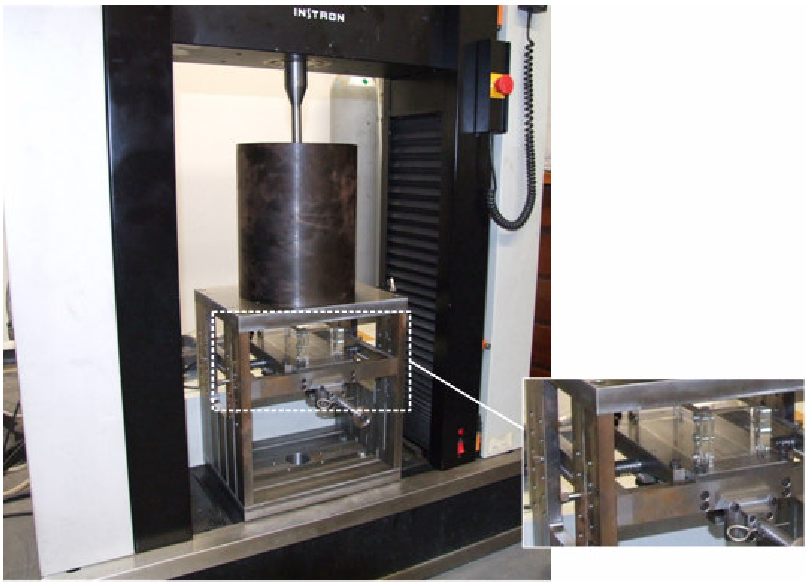



**Figure 2** – Visualization device coupled to the Universal Testing Machine.

**Brief description of the Freeflow3D code**

Freeflow3D [13] is a system designed specifically to simulate three-dimensional free surface flows. It embodies the GENSMAC3D method [14] and solves the governing equations using the finite difference method on a staggered grid. GENSMAC3D approximates curved boundaries and free surfaces in such a way that the discrete Poisson equation, resulting from the velocity update and pressure correction, requires the solution of a symmetric positive definite linear system at each time step. This linear system can be large, attaining 1 million unknowns, and is solved by the conjugate gradient method both robustly and efficiently. Details of the methodology and of the equations involved can be found in Tomé et. al. [14]. In addition, Freeflow3D contains an interface with solid modelling technology so that a video sequence of the numerical simulation produces a flow pattern which is very close to reality. The Freeflow3D system is composed of three distinct modular parts:

**Modflow3D** - An interactive system for the specification of fluid flow models which includes the definition of elements in the fluid domain such as containers, nozzles, fluid properties, etc.

**Simflow3D -** This system is the central part of Freeflow3D as it implements the discrete governing equations and the boundary conditions. It uses de GENSMAC3D [14] method which is a modification of the GENSMAC method [15] employing marker particles on the free surface only.

**VisFlow3D -** An interactive system for the visualization of the output generated by the Simflow3D module.

The three modules were written using the programming language C under the operating system UNIX (LINUX). The graphic interfaces of Modflow3D and VisFlow3D use the windowing system Xview under X-Windows. The data structure was designed to permit easy access and data interdependency in order to simplify software maintenance and extensions. The modules communicate with each other through files.

The Freeflow3D code can deal with three-dimensional incompressible free surface flows. The Freeflow3D system has the following features:

- It can simulate flows at high Reynolds numbers: a high order upwind scheme for approximating the advective terms of the momentum equations has been implemented into the code;
- It can solve 3D free surface tension dominated flows: an efficient numerical method for computing the curvature has been included into Freeflow3D;
- It can deal with three-dimensional multi-fluid flows: a numerical technique for dealing with 3D multi-phase flows has been developed and added to the code;
- It can simulate 3D free surface flows of Generalized Newtonian fluids: recently a constitutive equation for Generalized Newtonian fluids described by the Cross model has been included into the code;
- It can deal with 3D viscoelastic free surface flows: Freeflow3D has been extended to viscoelastic free surface flows governed by the Oldroyd-B and PTT (Phan-Thien-Tanner) constitutive equations.

**Case study**

In this study a Corn Syrup based fluid was used in the experimental work. Corn syrup is a common laboratory fluid adequate for this type of work. It behaves approximately as a Newtonian Fluid, it can be easily obtained in the market and it is not expensive when compared to other fluids. The results presented in this work were obtained with a dilute solution of Corn Syrup (97%) with water (3%), which allowed achieving a suitable viscosity level. Viscosity measurements were performed using a ROSAND RH7-2 capillary rheometer equipped with a special device to characterize low viscosity fluids. The density of the fluid was also measured. The results obtained in the characterization were the following: viscosity of 3.5 Pa.s and density of 1,380 kg/m3. The geometry employed in the experiments was the following: circular extrusion die with 6 mm diameter; cubic recipient 60 mm height; bottom of the recipient located at a distance of 110 mm from the extrusion die exit (for details, see Figure 3).

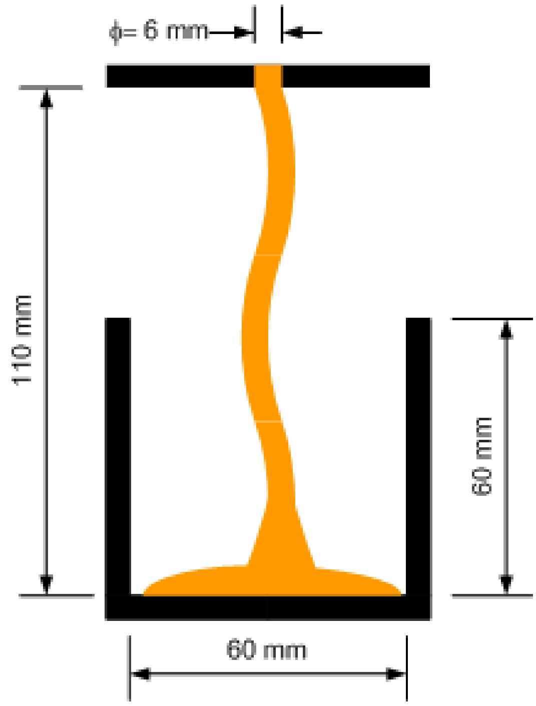



**Figure 3** – Geometry employed in the experiments.

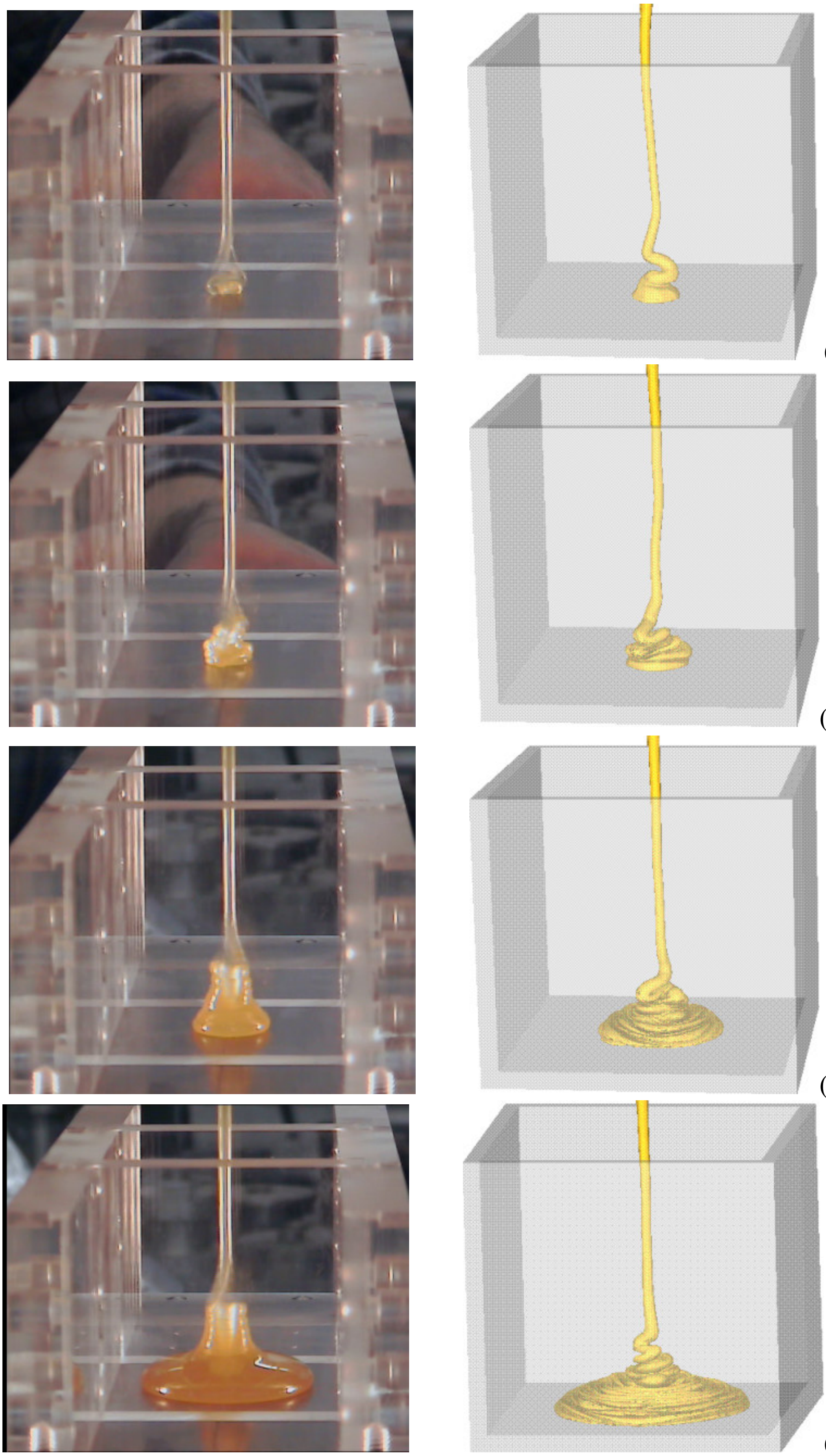
During the experiments several different conditions were tested. However, the comparisons with the numerical predictions are only presented for three selected conditions, listed in Table 1.

**Table 1** – Experimental conditions employed for comparison between numerical and experimental results

| **Experimental Run** | **Piston Velocity** [m/min] | **Flow Rate** [$mm^3/s$] | **Die Exit Velocity** [m/s] | **Re** |
|---|---|---|---|---|
| 1 | 5.0 | 3284 | 0.12 | 0.28 |
| 2 | 50.0 | 32840 | 1.16 | 2.75 |
| 3 | 250.0 | 164200 | 5.81 | 13.74 |

**Results and Discussion**

The results obtained experimentally and the numerical predictions for the three filling conditions are illustrated in Figures 6 to 8. We can observe in those figures that three different filling regimes were obtained: (1) evident occurrence of jet buckling (Figure 6); (2) smooth filling of the container (Figure 8); (3) transition between the two former situations (Figure 7). In the Experimental Run 1 (see Table 1), the Reynolds number was 0.27 and the ratio H/D = 18.33. The results clearly show the formation of jet buckling during all the filling process. In addition, due to the low injection velocity, we can see that the jet narrows due to gravity. Both these phenomena were predicted by the numerical modelling code, being also in agreement with the experimental observations published by Cruickshank and Munson [4], who reported that an axisymmetric jet buckles if both conditions Re < 1.2 and H/D > 7.2 are satisfied. However, there are some small discrepancies related to the geometry of the fluid pool. Initially, the experimental results show a jet that, when reaching the bottom of the container, buckles and the phenomenon of coiling takes place. The numerical results also show that the jet buckles but the effect of coiling starts later. We believe that these differences may be related to surface tension effects that have been omitted in the numerical runs.
For the Experimental Run 3 (see Figure 8), corresponding to the highest Re tested, the jet does not buckle and, due the inertia effects, the fluid climbs up the walls before filling the inner part of the container, leaving a space between the impinging jet and the fluid close to the walls, thus hiding the place where the jet reaches the fluid pool. Again, the numerical predictions are close to the experimental results. Finally, in the Experimental Run 2 (see figure 9), there is a transition regime between the former situations. The experimental results show that in the beginning there is a slightly jet bucking that disappears at the final stages. In this case, close to the place where the jet hits the fluid pool, the jet surface forms a cone that lasts all the filling process. With the exception of the initial filling stages, the numerical predictions are well correlated with the experimental measurements.



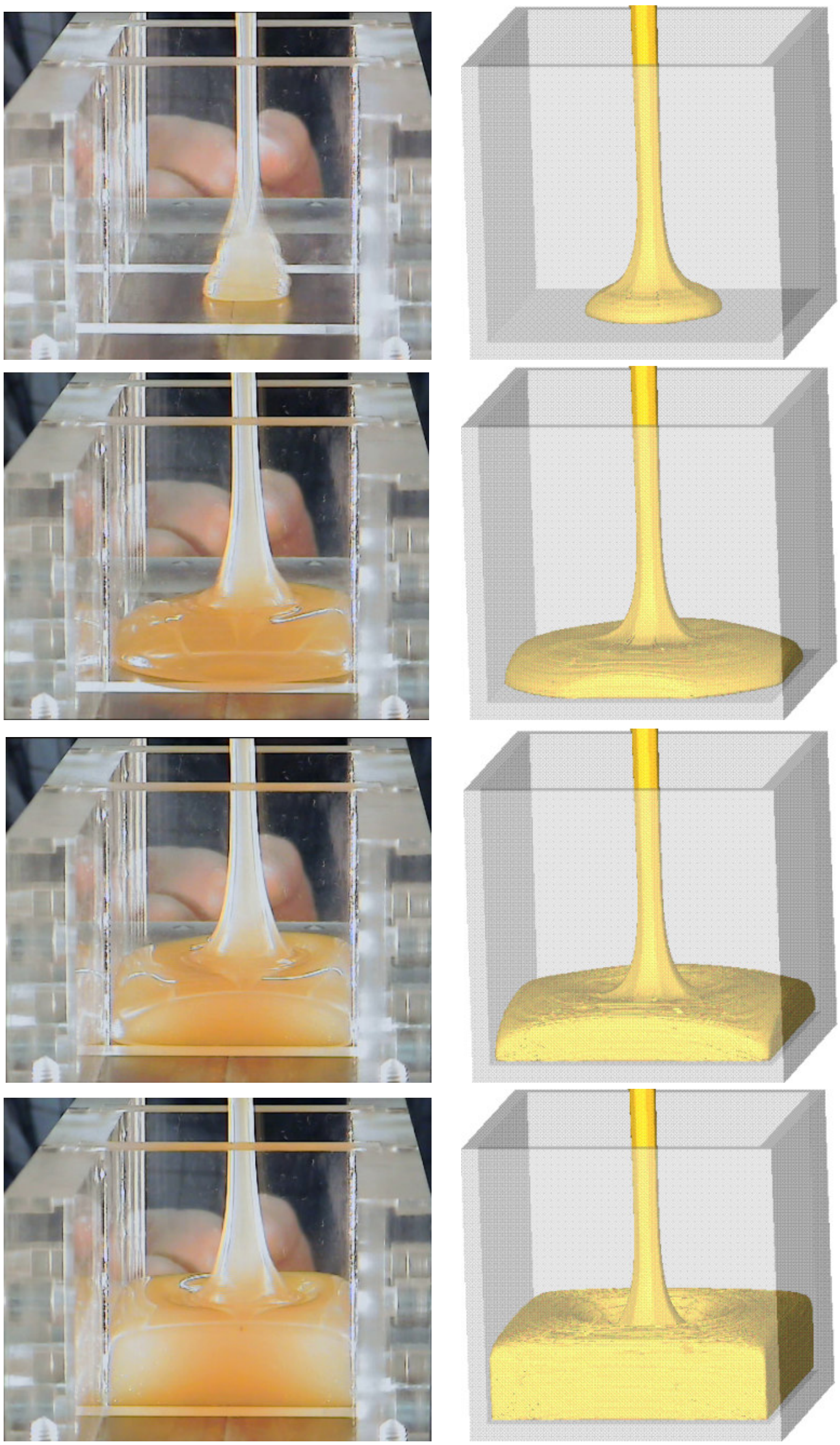
(a)

(b)

(c)

(d)

**Figure 6** – Experimental results and Numerical predictions for Run 1: (a) 32 s; (b) 40 s; (c) 80 s; (d) 148 s.



(a)
(b)
(c)
(d)

**Figure 7** – Experimental results and Numerical predictions for Run 2: (a) 20 s; (b) 80 s; (c) 120 s; (d) 200 s.

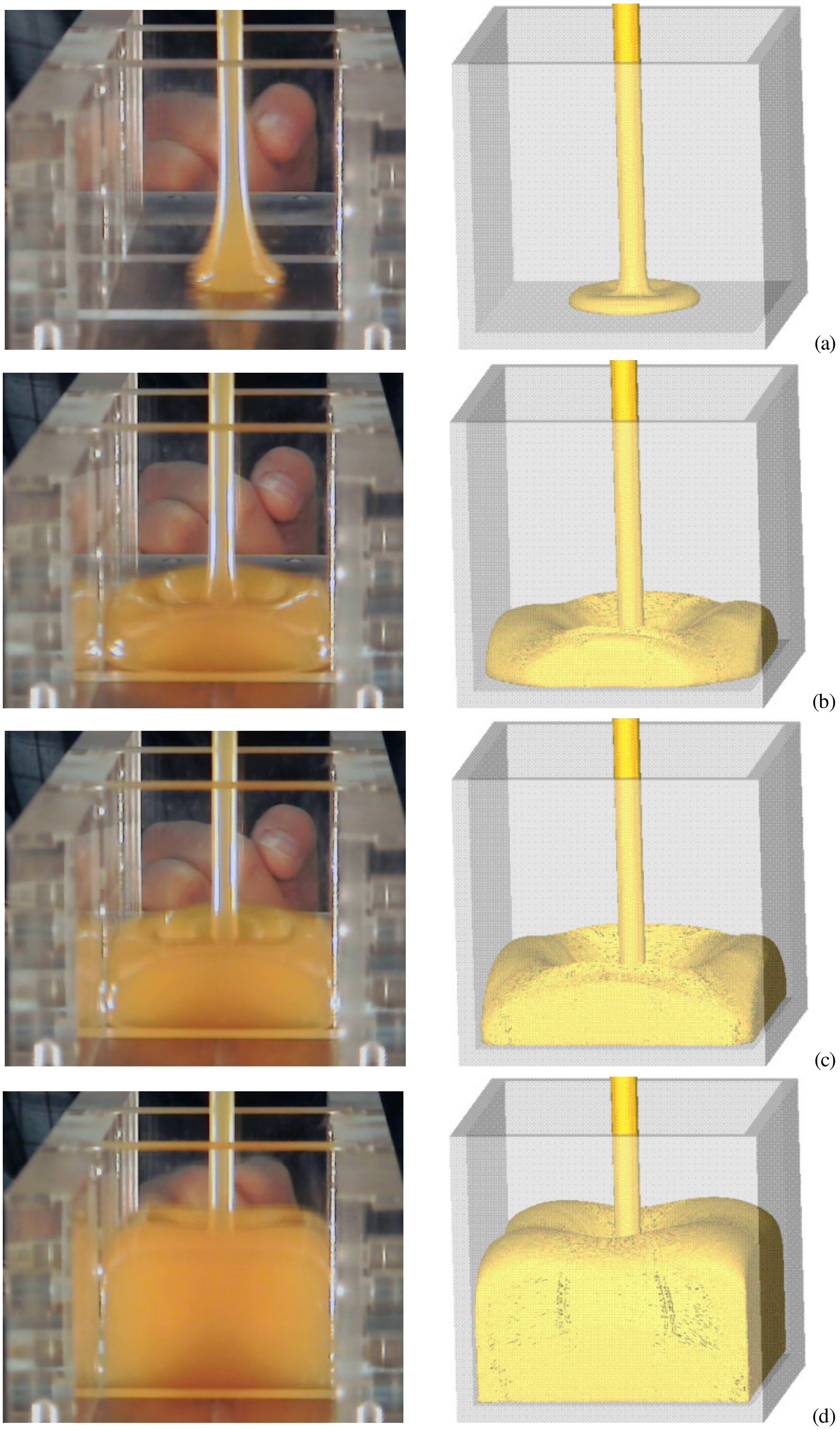



**Figure 8** – Experimental results and Numerical predictions for Run 3: (a) 3 s; (b) 20 s; (c) 30 s; (d) 68 s.

## Conclusion

A new testing device was built specially for this study; it was capable of perform the filling of containers under controlled and reproducible conditions. Numerical and experimental studies of the filling of a cubic container through a circular die were performed. During the filling process three different situations were identified: (1) evident occurrence of jet buckling; (2) smooth filling of the container; (3) transition between the two former situations. The qualitative comparison between the pictures recorded during the experimental work and the numerical predictions showed to very good. We conclude that the Freeflow3D code was able to predict almost all the phenomena observed experimentally. However, a more detailed and systematic work, both experimental and numerical, must be carried out in order to get answers to some pendent questions: Which process parameters are relevant for the jet buckling? What are the onset conditions? What is the influence of a more complex rheology on the jet buckling phenomenon?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