Test-case number 12: Filling of a cubic mould by a viscous jet (PN, PE)

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1 Practical significance and interest of the test-case

The interest of the injection of a viscous fluid in a cubic cavity is to estimate the consistency and the physical meaning of the numerical solutions of multiphase flows modeled by interface tracking methods. The considered problem emphasizes the competition between the inertia of the jet, the viscous effects and the gravity. Even if the surface tension exists and can be taken into account, it is negligible in the filling process with a viscous fluid. Under certain velocity and geometrical conditions, the jet fills the mould regularly whereas it can oscillate in a three dimensional manner under other assumptions. This test is interesting because as it induces strong interface deformations and tests the ability of the numerical method to capture 3D instabilities. The three-dimensional character of the problem makes axisymmetric simulations impossible to be leaded.

2 Definitions and physical model description

A cubic cavity of side L, initially full of air, is filled with a viscous fluid by a cylindrical injector of radius R centered at point (x_c, y_c, z_c) on the upper boundary of the mould. The injection velocity U_0 is considered constant over time and in the jet. The density and the viscosity of the fluids are ρ_l and μ_l for the liquid and ρ_g and μ_g for air. The flow is assumed isothermal with a constant surface tension between the two fluids. The flow is submitted to inertia, gravity and viscous effects. The relevant dimensionless number for the problem are the Reynolds number Re and the Weber number We:

$$\begin{aligned} We &= \frac{\rho_l U_0^2 D}{\sigma} \\ Re &= \frac{\rho_l U_0 D}{\mu_l} \end{aligned} \tag{1}$$

where $D = 2R$.

Following the work of Cruickshank (1988), it is observed that the jet is unstable during the injection for Reynolds numbers in the range $Re < 0.56$ and for cavity over injector aspect ratios $L/D > (2n+1)\pi$, where n is the instability mode of the jet. Depending on the problem configuration (Reynolds number and aspect ratio), the oscillations can be two dimensional (from left to right) or toroidal (three-dimensional rotation), corresponding to instability mode $n = 0$ and $n = 1$ respectively. The first instability which appears is $n = 0$ and it evolves generally towards the $n = 1$ mode.

3 Test-case description

The operating conditions of the filling process for a typical oscillating jet are the following.

$$\begin{gathered} R = 0.08 \text{ m} \\ L = 1 \text{ m} \\ \mathbf{u}_0 = (0, 0, -0.8) \text{ and } U_0 = 0.8 \text{ in m.s}^{-1} \\ 0.0143 \text{ m} \leq \Delta x \leq 0.033 \text{ m} \\ x_c = L/2, y_c = L/2, z_c = L \\ \mathbf{g} = (0, 0, -9.81) \text{ in m.s}^{-2} \end{gathered} \tag{2}$$

where $\mathbf{g}$ is the gravity vector.

The characteristics of the two phases are:

$$\begin{gathered} \rho_l = 1800 \text{ kg m}^{-3} \\ \rho_g = 1.1768 \text{ kg m}^{-3} \\ \mu_l = 5.10^2 \text{ Pa s} \\ \mu_g = 10^{-5} \text{ Pa s} \end{gathered} \tag{3}$$

The surface tension of the liquid-air interface is $\sigma = 0.03$ N.m^{-1}. The dimensionless numbers (1) of the problem have the values:

$$\begin{gathered} We = 6144 \\ Re = 0.4608 \end{gathered} \tag{4}$$

No slip conditions are imposed on all the boundaries of the cavity except on the open upper one which is described by a free outlet boundary condition ($\frac{\partial u_z}{\partial z} = 0$) except on the the injector outlet where a uniform velocity $\mathbf{u_0}$ in set.

4 Figures, tables, captions and references

The numerical simulations are leaded with the VOF-PLIC method of Youngs (1982) using the CSF method of Brackbill *et al.* (1992) for the treatment of the surface tension. Following the works of Vincent (1999) and Vincent & Caltagirone (1999), a regular Cartesian 70 x 70 x 70 grid is implemented to illustrate a possible numerical simulation (see figure 1). This grid was prooved sufficient to obtain a converged numerical solution for an unstable jet assuming $H/D = 8.33$ and $Re = 0.4608$.

With respect to several values of the aspect ratrio, H/D, and the Reynolds number, Re, (see figure 2), the numerical stability of the jet is compared to the reference experimental and theoretical results of Cruickshank (1988). The transition limit on Re is well described by the numerical solutions. However, the calculated transitional aspect ratio H/D is found to be in the range of $2n\pi$ whereas the asymptotic analysis of Cruickshank (1988) on an axisymetric jet shows $H/D = (2n + 1)\pi$. The gap between the numerical and theoretical results can be explained by the three-dimensional character of the instability in the numerical simulation.

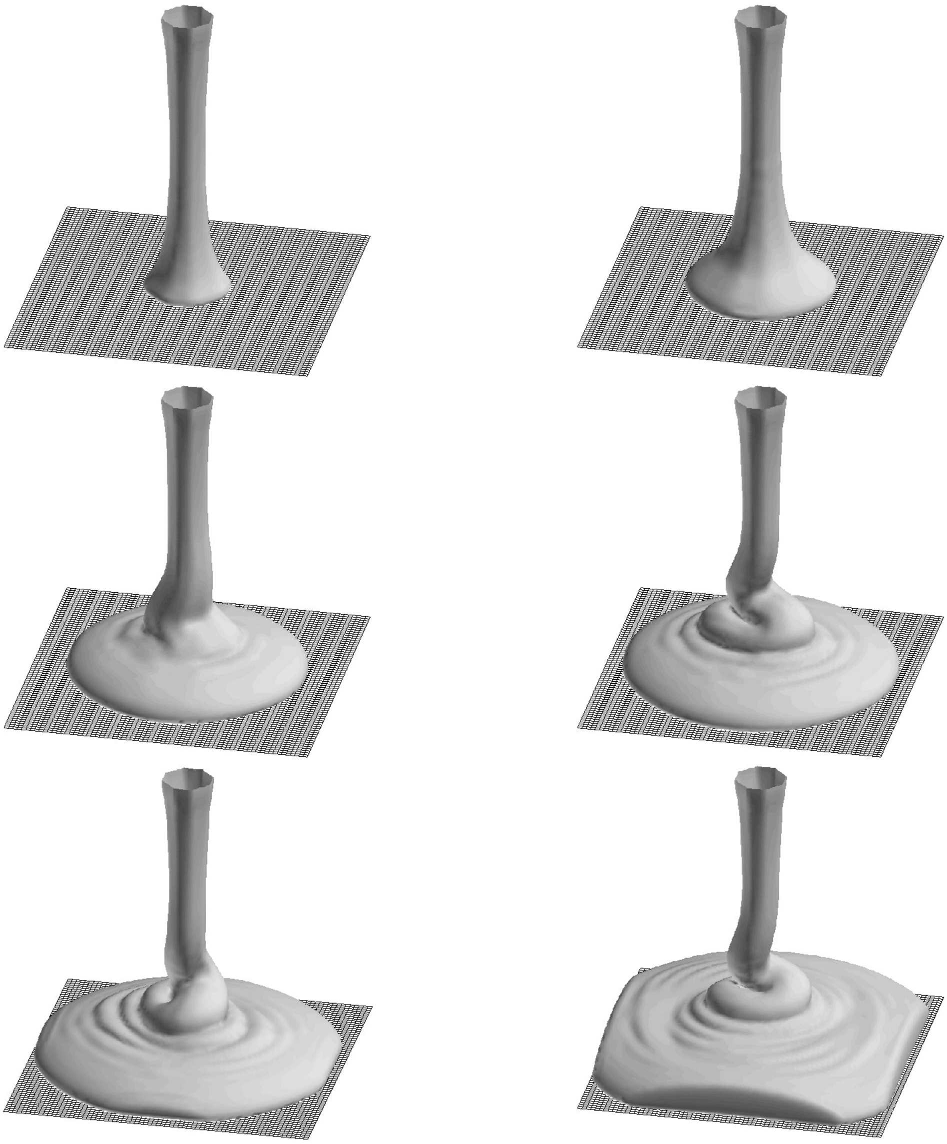

Figure 1: Three-dimensional numerical simulation of the filling of a square cavity by a viscous jet. The results correspond to a space scale $\Delta x = 0.0143$ m and time $t = 1, 2, 4, 5, 6$ et 8 s (from left to right and from top to bottom).

References

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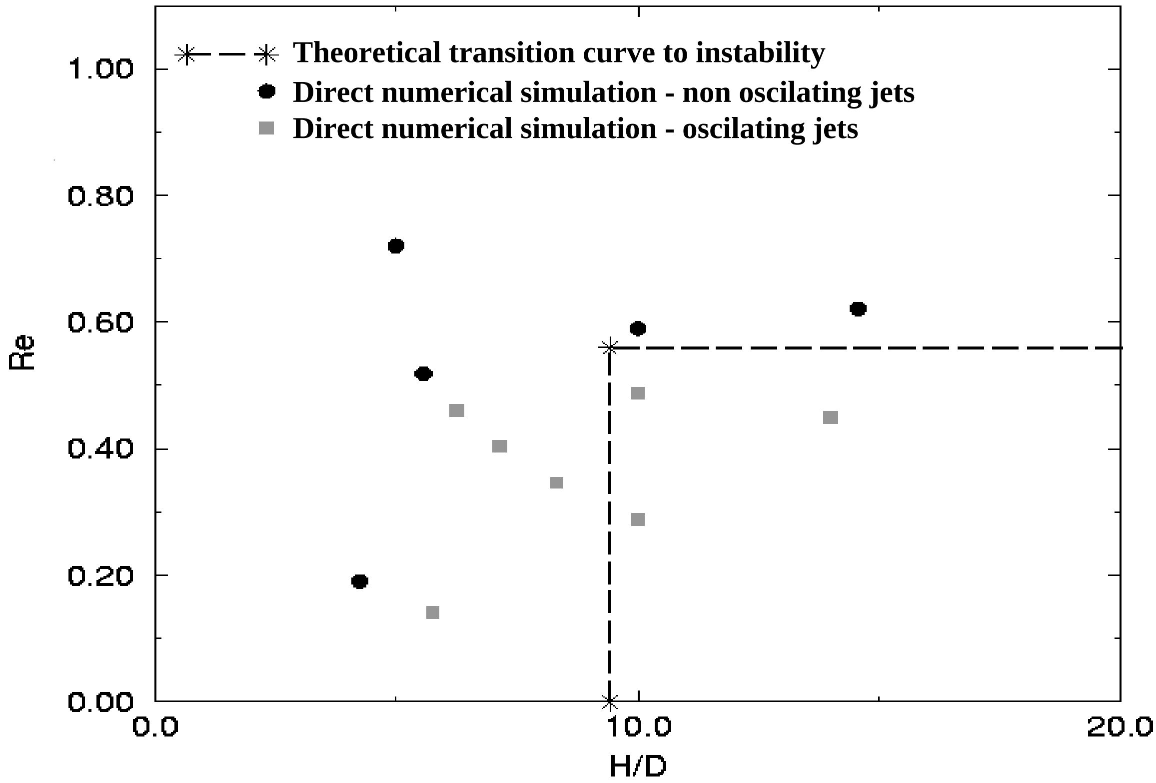

Figure 2: Instability transition diagram for a stagnating viscous jet in a square mould. Comparisons between theoretical and experimental results of Cruickshank (1988) and numerical simulations.