

Reorientation of Cryogenic Fluids Upon Step Reduction of Gravity

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acknowledged



13.09.2004

Reorientation of a Liquid Surface

Motivation

Experimental Setup

- System overview

- Experiment Conditions

Prediction of Reorientation Behavior

- OHNESORGE Number for a 50 mm Diameter Cylinder

- Center Peak Location

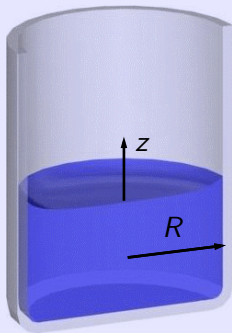
- Center Peak Time

- Wall Peak Location

- Numerics

Outlook

$$k_{zi} \approx 9.81 \text{ m/s}^2$$



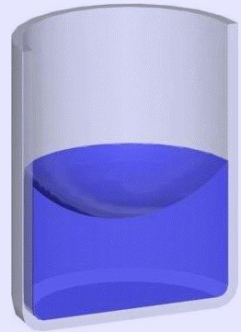
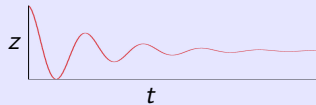
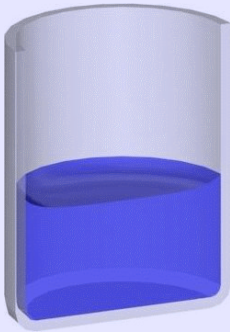
- ▶ Quiescent liquid.
- ▶ High BOND number with $Bo = \rho k_{zi} R^2 / \sigma \gg 1$.
- ▶ Flat liquid surface at the center location.

Initial conditions:

$$\downarrow k_{zi} \approx 9.81 \text{ m/s}^2$$

$$k_z \approx 0 \text{ m/s}^2$$

free surface at the center point (z_{cp}):



Reorientation of the

Investigating the reorientation of cryogenic propellants:

- ▶ Behavior of cryogenic propellants (liquid Hydrogen and Oxygen) upon step reduction of gravity.

* LN_2 at 0.1 MPa; $D = 50$ mm

† Previous Experiments

Investigating the reorientation of cryogenic propellants:

- ▶ Behavior of cryogenic propellants (liquid Hydrogen and Oxygen) upon step reduction of gravity.
- ▶ Small OHNESORGE number: $Oh \approx 3.0 \cdot 10^{-4}$ (*)

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$$Oh = \frac{t_{pv}}{t_{pu}} = \sqrt{\frac{\nu^2 \rho}{\sigma R}} \quad 0.98 \cdot 10^{-3} \leq Oh \leq 20.17 \cdot 10^{-3} \quad (\dagger)$$

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$$Mo = \frac{t_{pvLc}}{t_{puLc}} = \left(\frac{k_{zi} \nu^4 \rho^3}{\sigma^3} \right)^{1/4} \quad 3.63 \cdot 10^{-3} \leq Mo \leq 52.75 \cdot 10^{-3} \quad (\dagger)$$

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- ▶ High initial BOND number: $Bo_i \approx 550$ (*)

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$$Bo = \frac{\rho k_{zi} R^2}{\sigma} \quad 27.7 \leq Mo \leq 194.5 \quad (\dagger)$$

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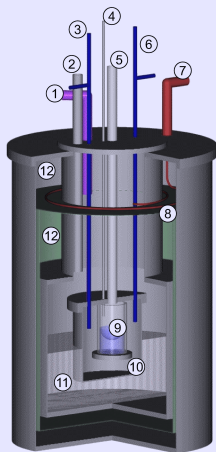
- ▶ Observation of Layer Formation.

* LN_2 at 0.1 MPa; $D = 50$ mm

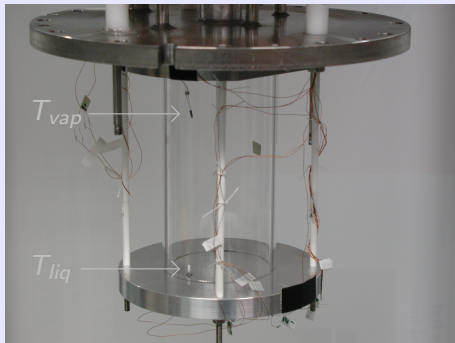
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Experimental Setup

System overview

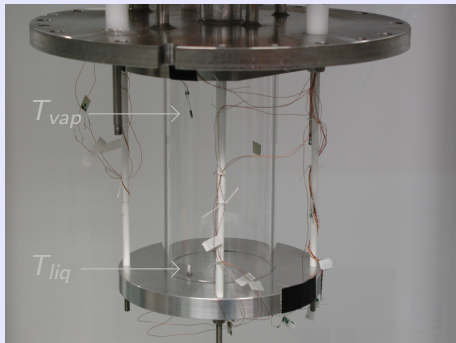


- ① Outer vent line
- ② Outer filling tube
- ③ Endoscope
- ④ Inner filling tube
- ⑤ Inner vent line
- ⑥ Light source
- ⑦ Outer vent line
- ⑧ Heat radiation shield
- ⑨ Fluid test chamber
- ⑩ Vacuum insulation
- ⑪ LN₂ bath
- ⑫ Insulation vacuum



- ▶ Liquid and Vapor of pure Nitrogen.
- ▶ Liquid and Vapor at Saturation state.
- ▶ Pressure range:
 $\approx 0.07 \leq P \leq 0.17$ [MPa]
- ▶ Temperature range
 $\approx 74 \leq T \leq 82$ [K]

Liquid and Vapor conditions:

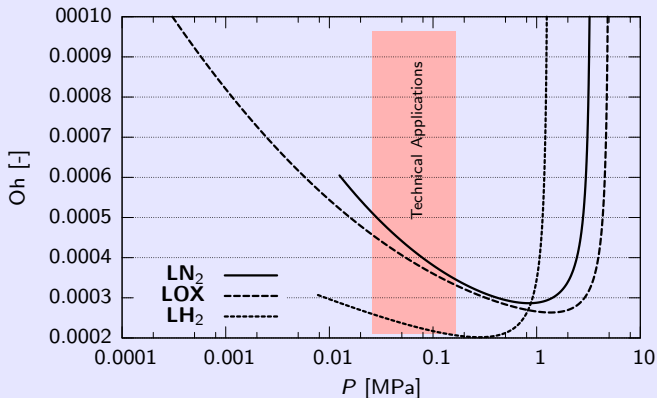


Data acquisition:

- ▶ High speed video recording.
- ▶ Vapor pressure data recording.
- ▶ Liquid and Vapor Temperature data recording.

Prediction of Reorientation Behavior

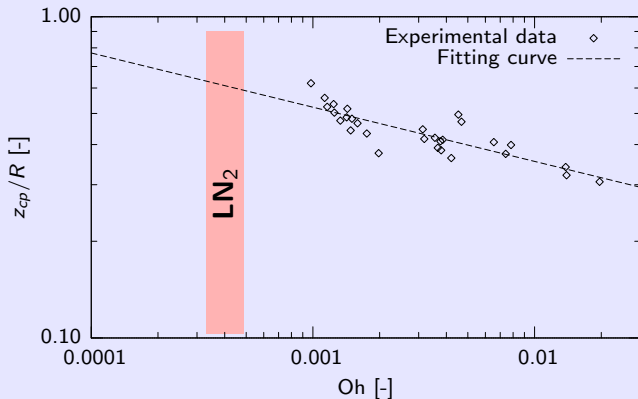
OHNESORGE Number for a 50 mm Diameter Cylinder



OHNESORGE number for LN_2 , LH_2 and LOX in an right circular cylinder with $D = 50$ mm as function of liquid pressure.

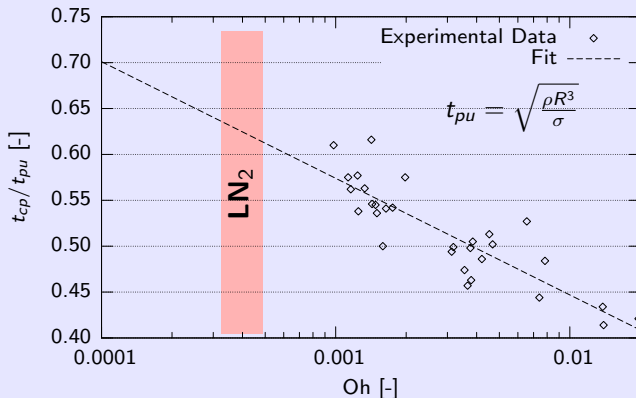
Prediction of Reorientation Behavior

Center Peak Location



Center peak location reaches $z_{cp} \approx 20$ mm for **LN₂** at $P = 0.1$ MPa in a right circular container with $D = 50$ mm.

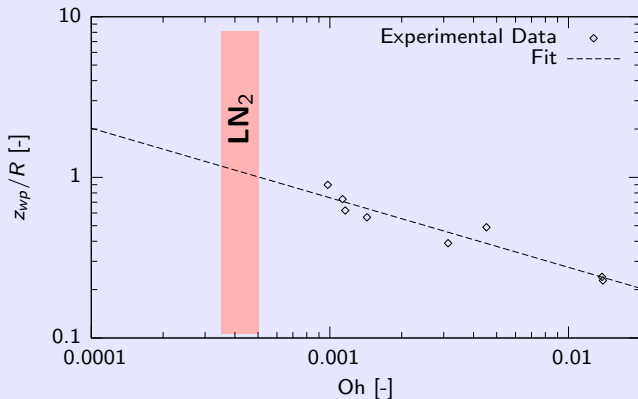




Center peak time is about $t_{cp} \approx 1.5$ s for **LN₂** at $P = 0.1$ MPa in a right circular container with $D = 50$ mm.

Prediction of Reorientation Behavior

Wall Peak Location

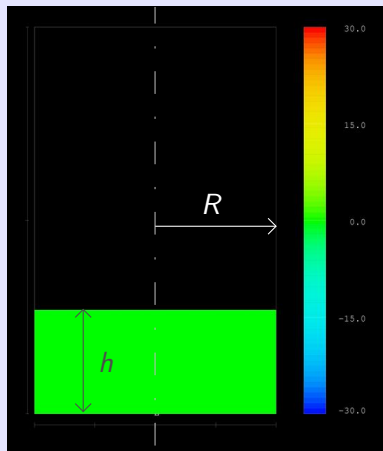


Wall peak location reaches $t_{wp} \approx 26$ mm for **LN₂** at $P = 0.1$ MPa in a right circular container with $D = 50$ mm.



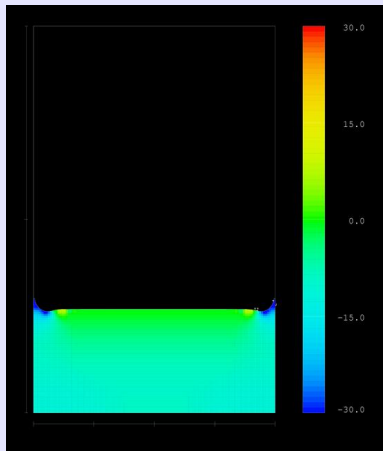
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Reorientation of Cryogenic Fluids Upon Step Reduction of Gravity



Numerical simulation with
FLOW-3D vers. 8.2.5:

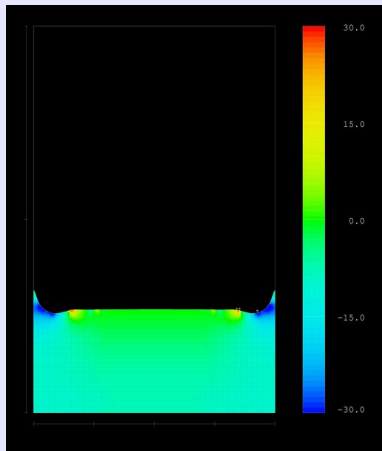
- ▶ $R = 25$ mm
- ▶ $h = 21.5$ mm
- ▶ $P = 0.102$ MPa
- ▶ Grid size: 60×195



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 1 \cdot 0.03$ s

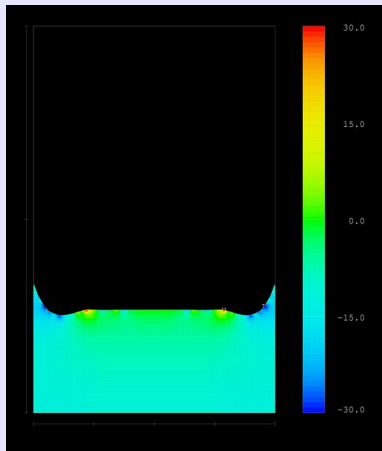
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 2 \cdot 0.03$ s

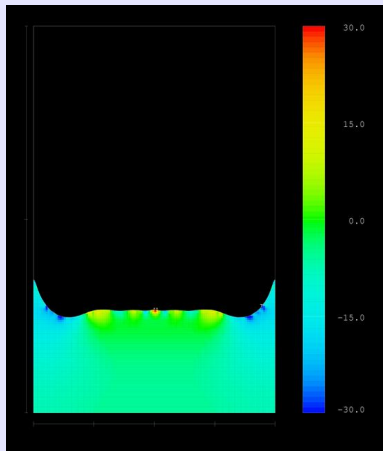
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 3 \cdot 0.03$ s

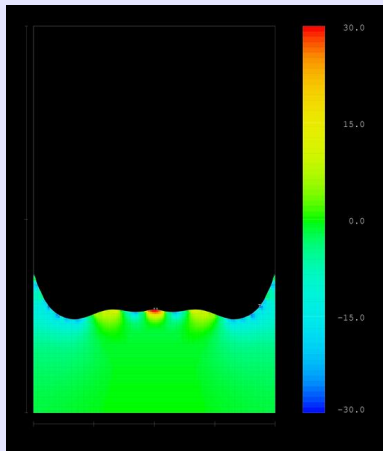
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 4 \cdot 0.03$ s

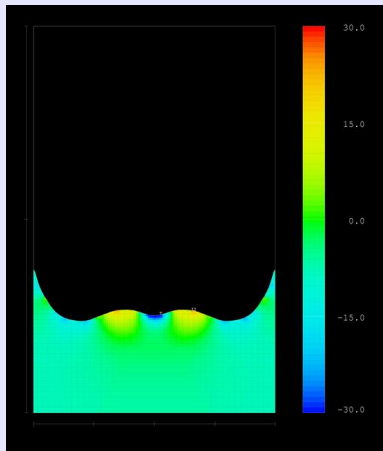
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 5 \cdot 0.03$ s

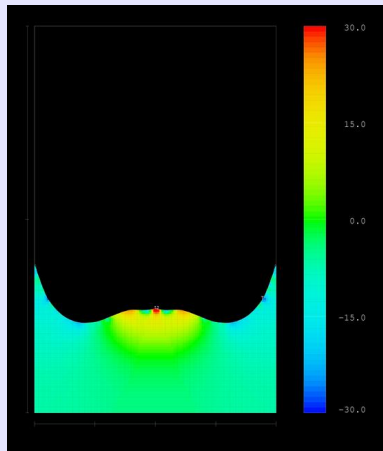
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 6 \cdot 0.03$ s

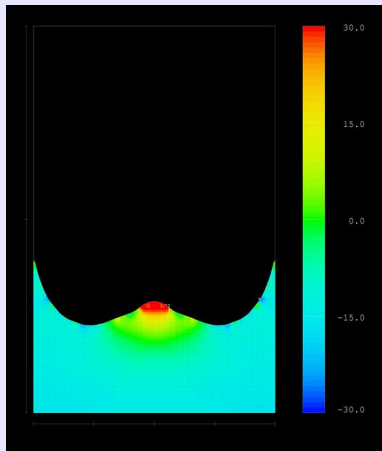
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 7 \cdot 0.03$ s

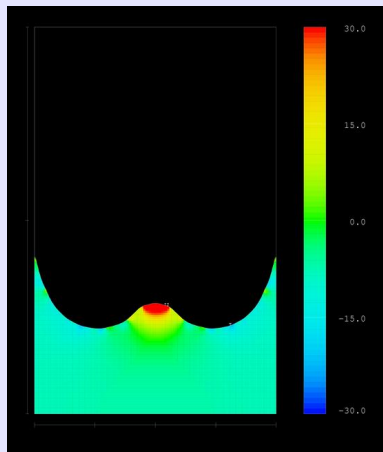
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 8 \cdot 0.03$ s

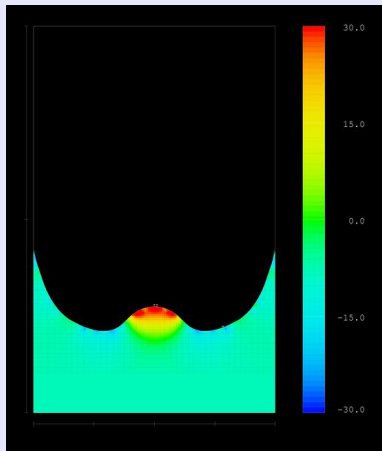
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 9 \cdot 0.03$ s

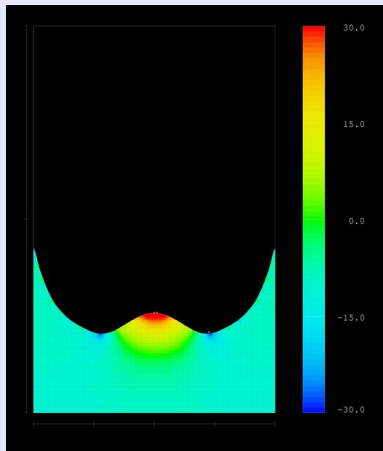
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 10 \cdot 0.03$ s

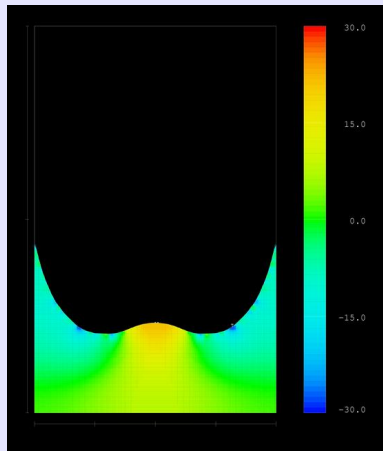
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 11 \cdot 0.03$ s

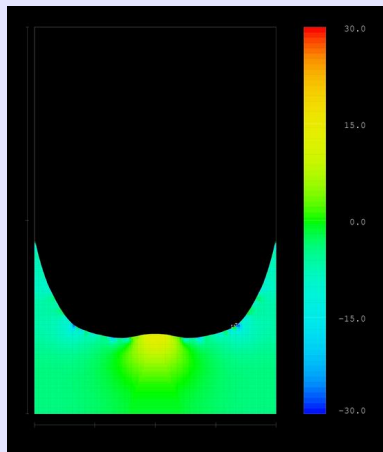
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 12 \cdot 0.03$ s

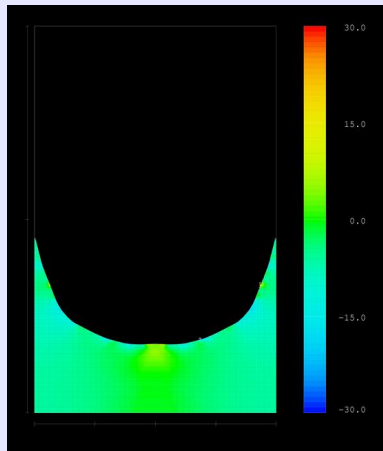
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 13 \cdot 0.03$ s

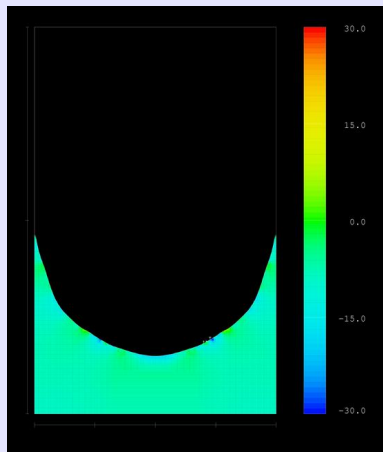
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 14 \cdot 0.03$ s

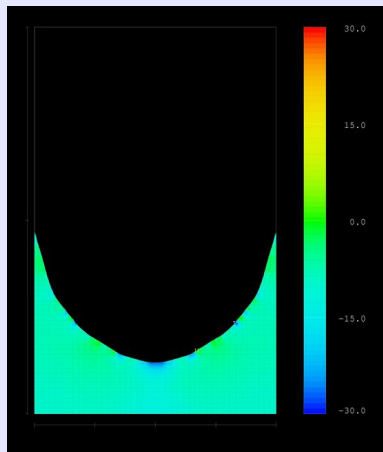
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 15 \cdot 0.03$ s

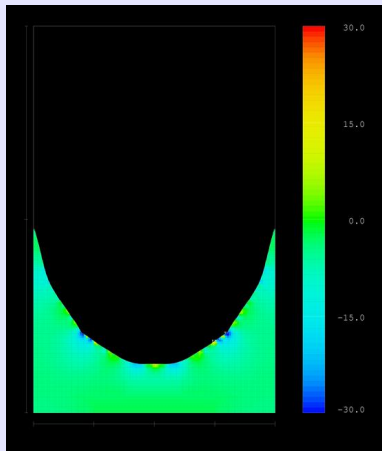
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 16 \cdot 0.03$ s

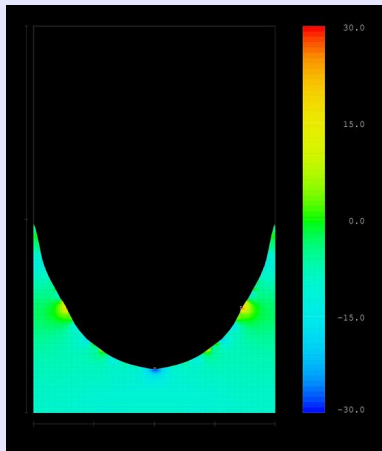
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 17 \cdot 0.03$ s

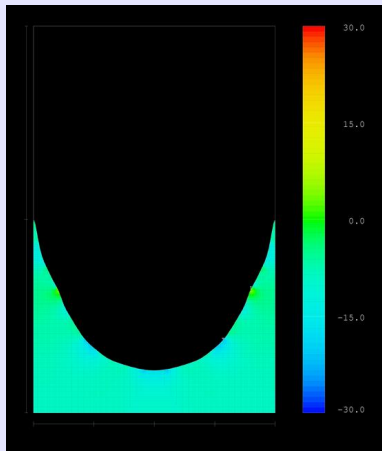
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 18 \cdot 0.03$ s

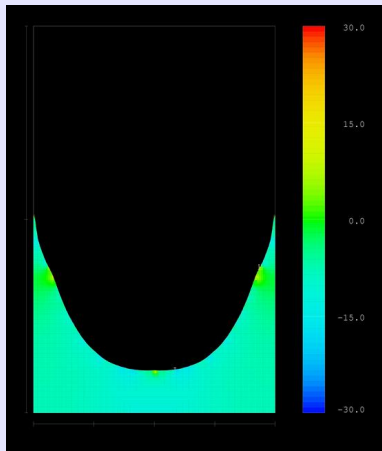
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 19 \cdot 0.03$ s

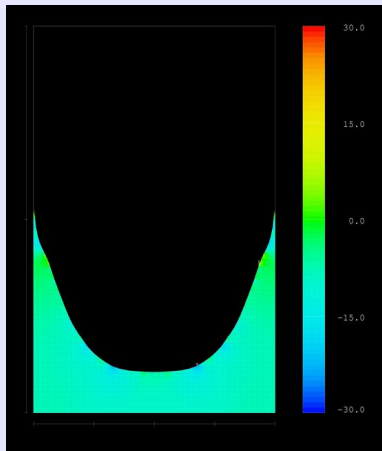
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 20 \cdot 0.03$ s

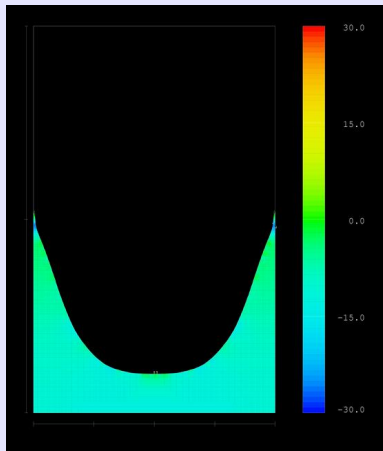
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 21 \cdot 0.03$ s

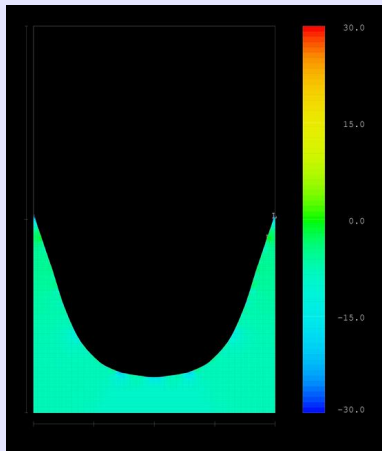
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 22 \cdot 0.03$ s

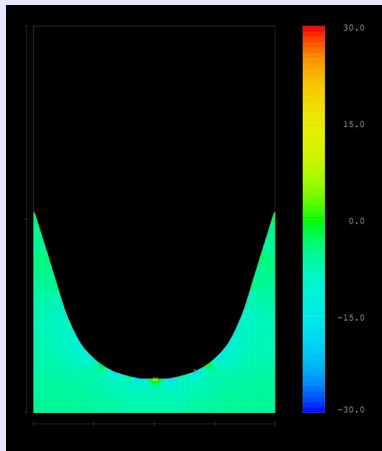
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 23 \cdot 0.03$ s

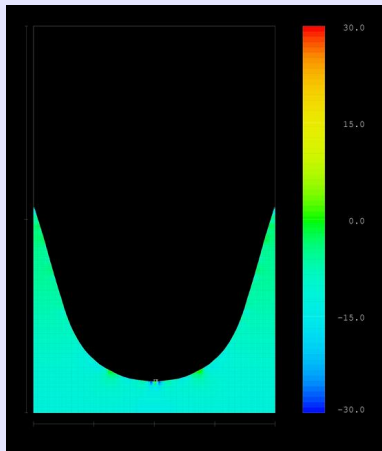
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 24 \cdot 0.03$ s

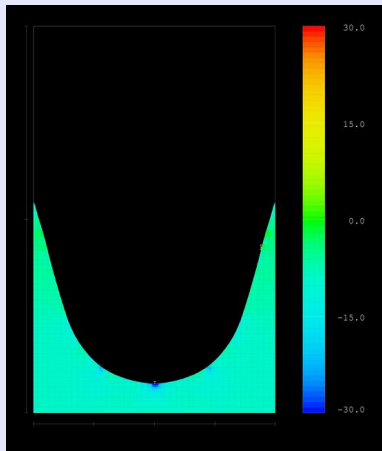
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 25 \cdot 0.03$ s

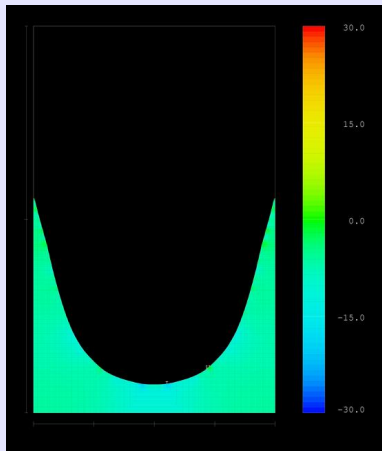
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 26 \cdot 0.03$ s

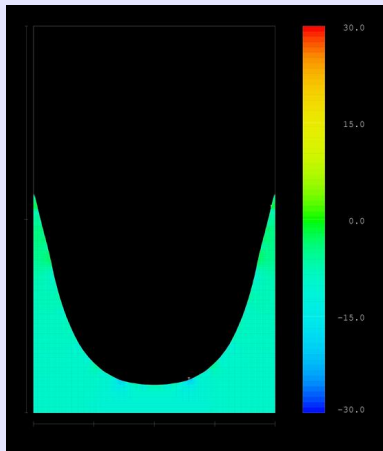
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 27 \cdot 0.03$ s

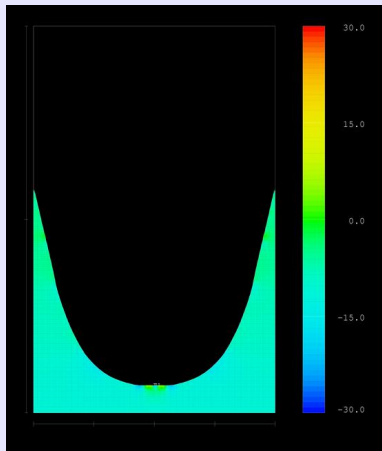
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 28 \cdot 0.03$ s

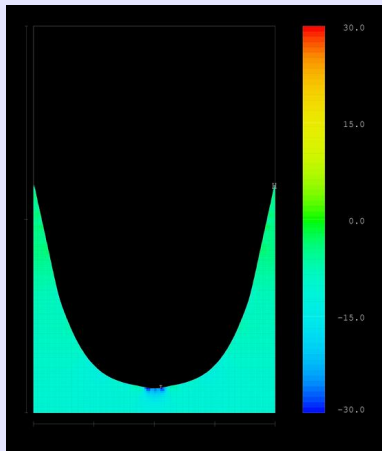
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 29 \cdot 0.03$ s

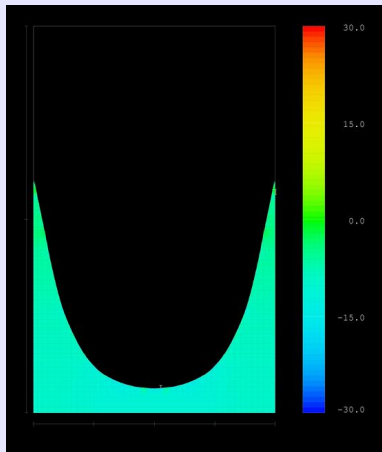
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 30 \cdot 0.03$ s

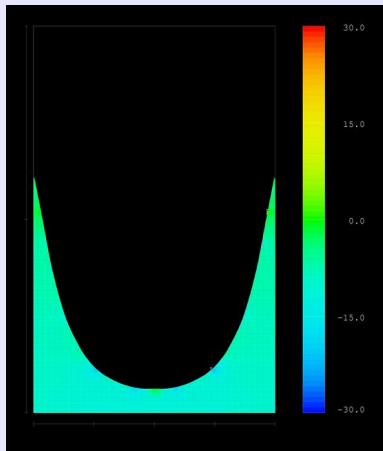
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 31 \cdot 0.03$ s

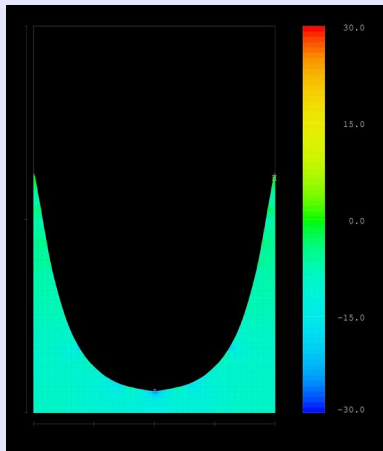
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 32 \cdot 0.03$ s

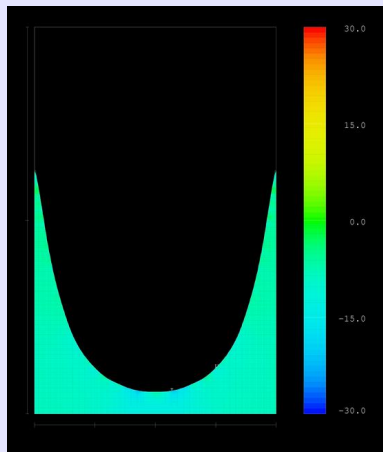
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 33 \cdot 0.03$ s

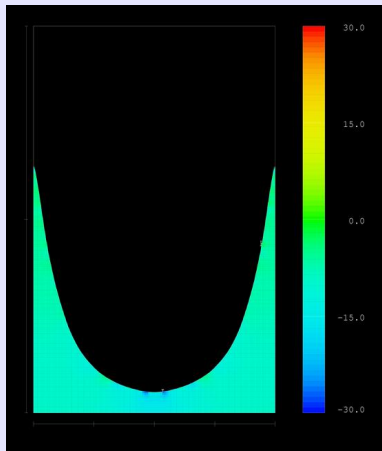
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 34 \cdot 0.03$ s

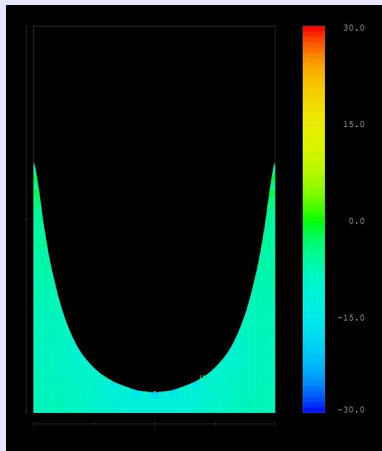
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 35 \cdot 0.03$ s

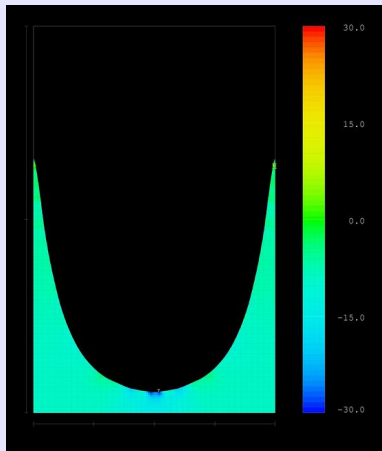
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 36 \cdot 0.03$ s

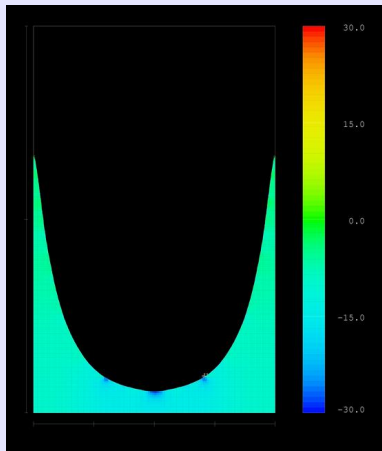
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 37 \cdot 0.03$ s

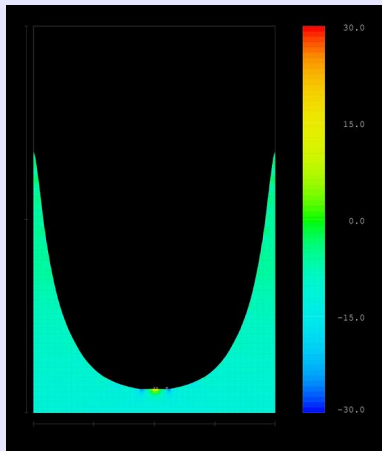
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 38 \cdot 0.03$ s

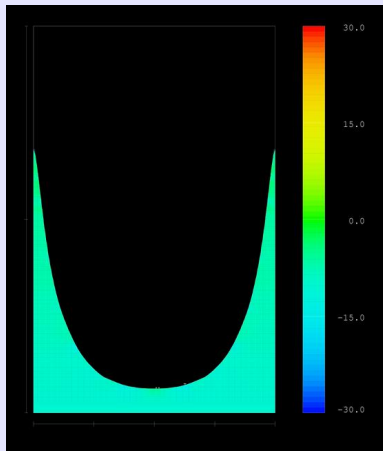
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 39 \cdot 0.03$ s

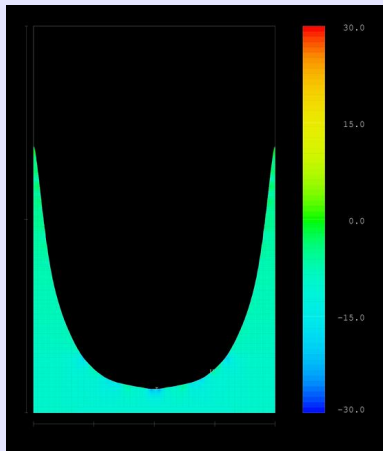
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 40 \cdot 0.03$ s

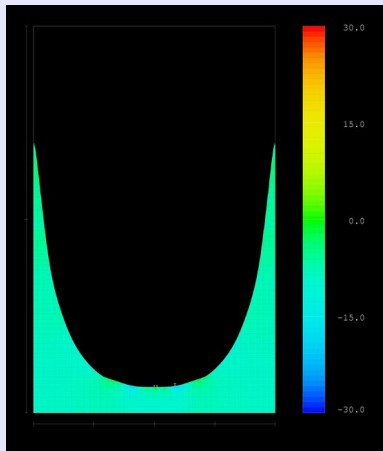
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 41 \cdot 0.03$ s

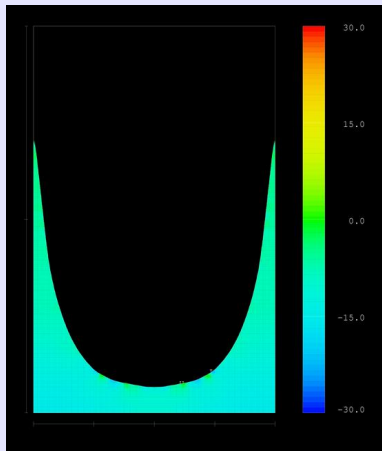
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 42 \cdot 0.03$ s

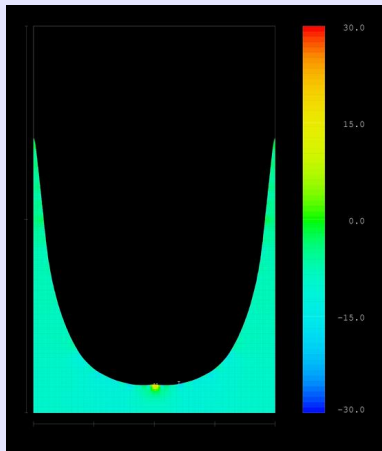
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 43 \cdot 0.03$ s

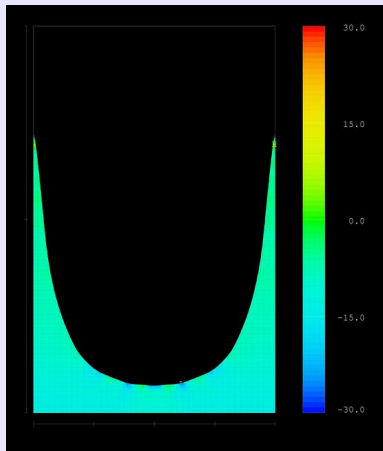
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 44 \cdot 0.03$ s

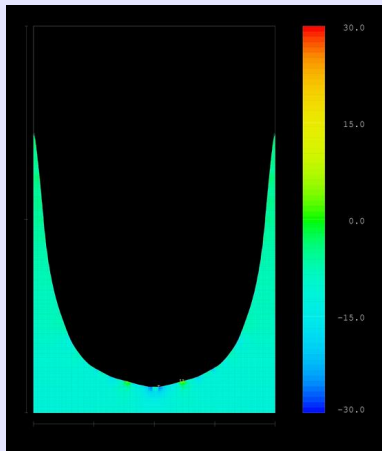
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 45 \cdot 0.03$ s

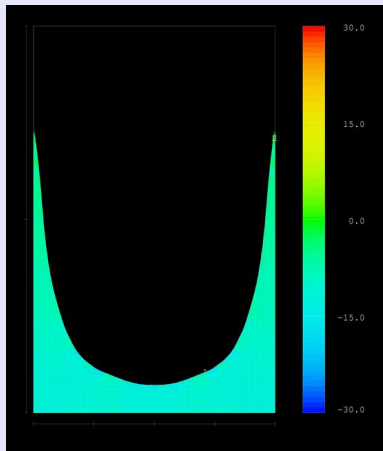
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 46 \cdot 0.03$ s

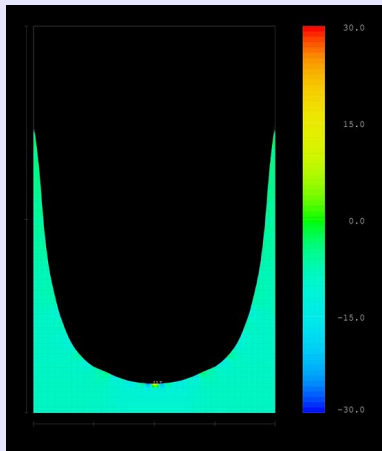
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 47 \cdot 0.03$ s

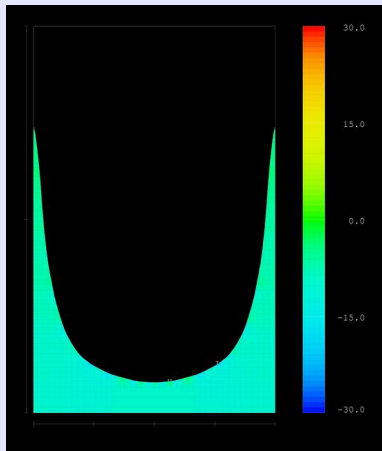
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 48 \cdot 0.03$ s

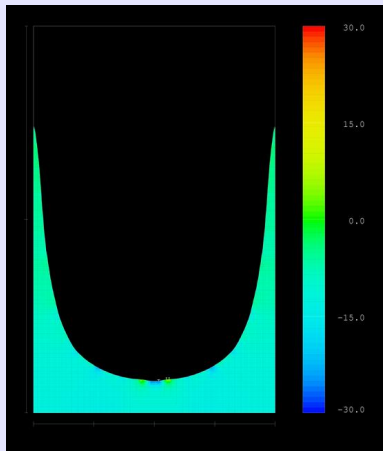
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 49 \cdot 0.03$ s

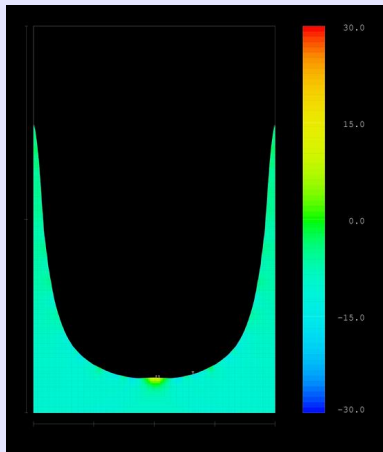
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 50 \cdot 0.03$ s

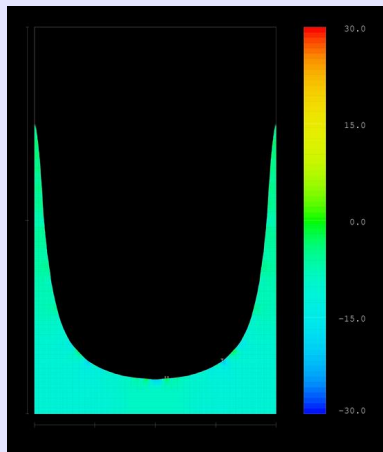
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 51 \cdot 0.03$ s

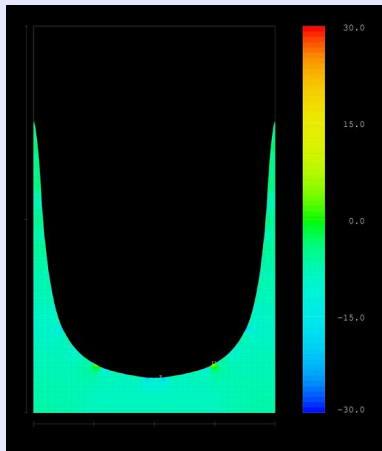
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 52 \cdot 0.03$ s

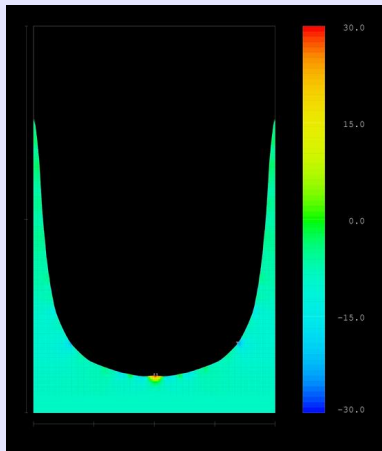
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 53 \cdot 0.03$ s

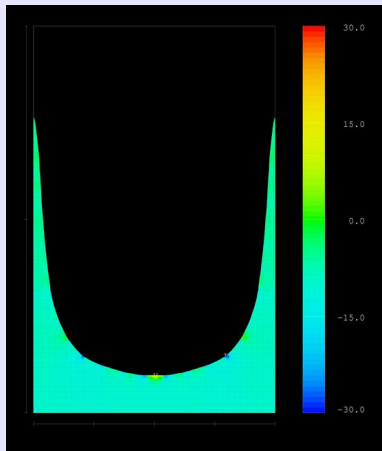
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 54 \cdot 0.03$ s

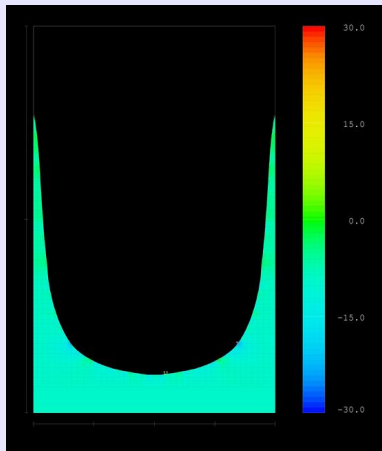
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 55 \cdot 0.03$ s

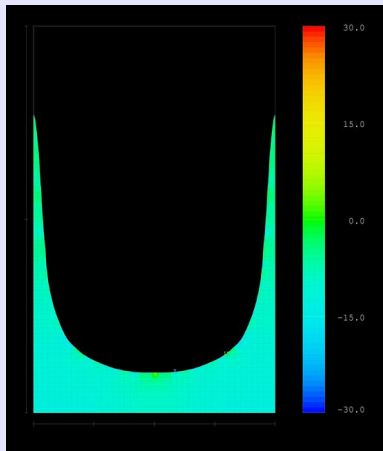
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 56 \cdot 0.03$ s

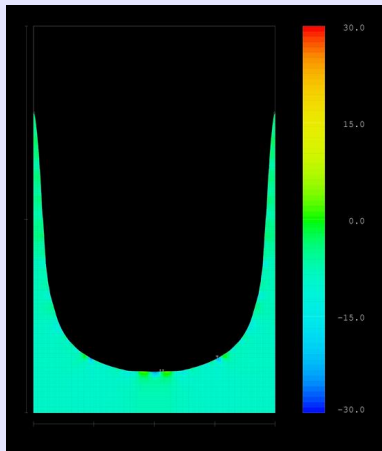
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 57 \cdot 0.03$ s

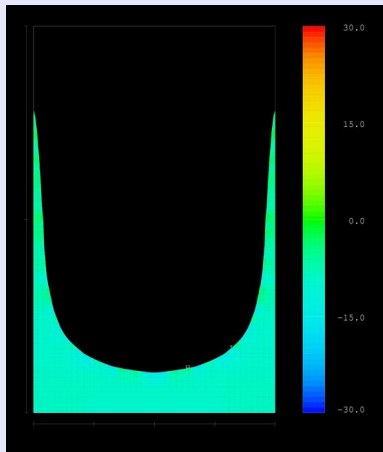
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 58 \cdot 0.03$ s

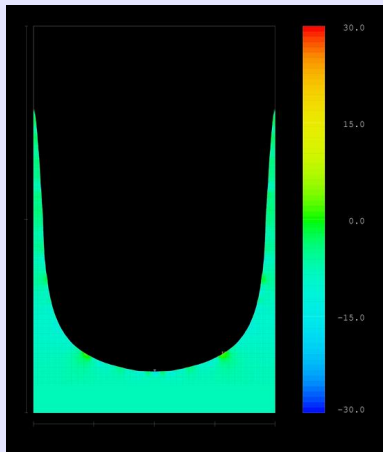
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 59 \cdot 0.03$ s

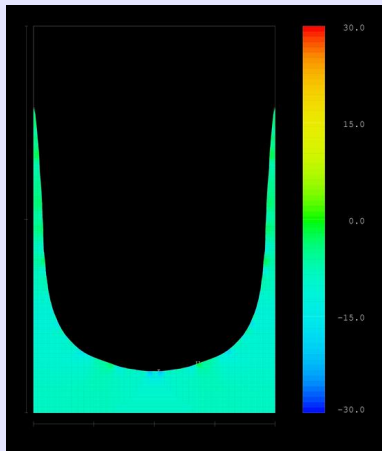
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 60 \cdot 0.03$ s

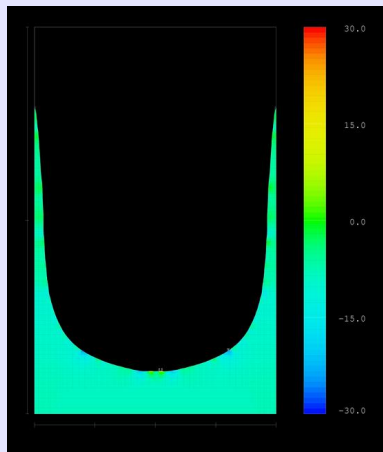
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 61 \cdot 0.03$ s

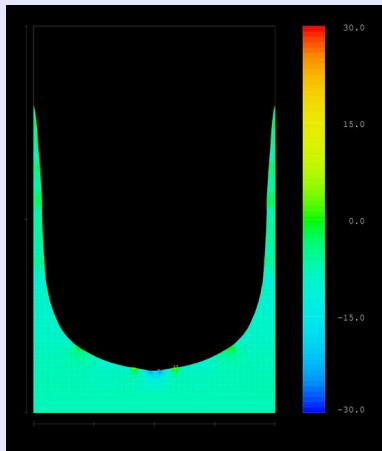
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 62 \cdot 0.03$ s

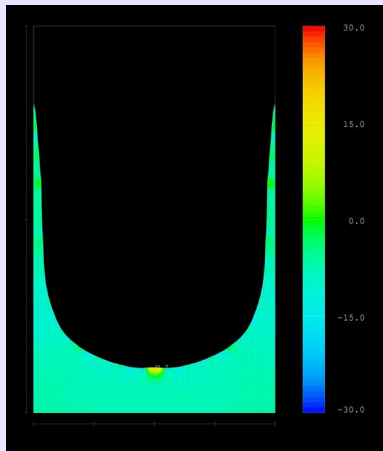
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 63 \cdot 0.03$ s

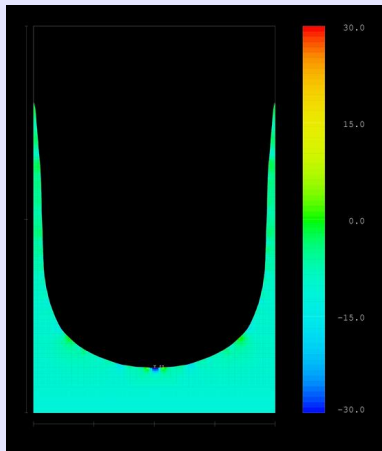
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 64 \cdot 0.03$ s

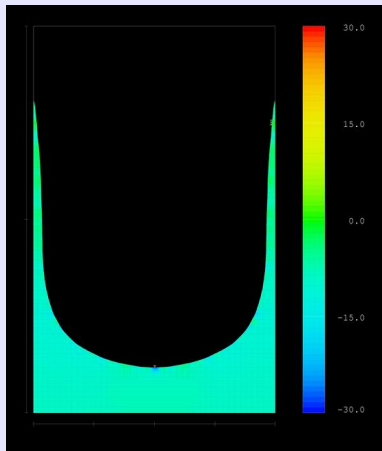
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 65 \cdot 0.03$ s

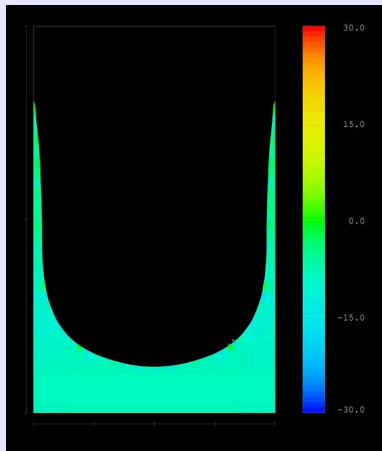
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 66 \cdot 0.03$ s

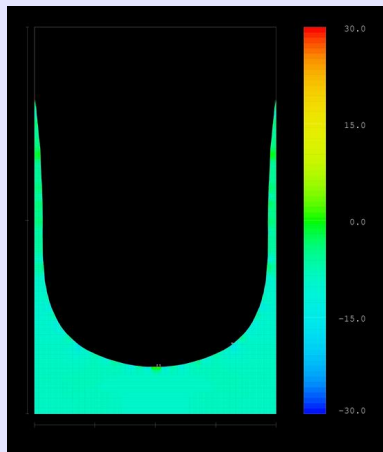
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 67 \cdot 0.03$ s

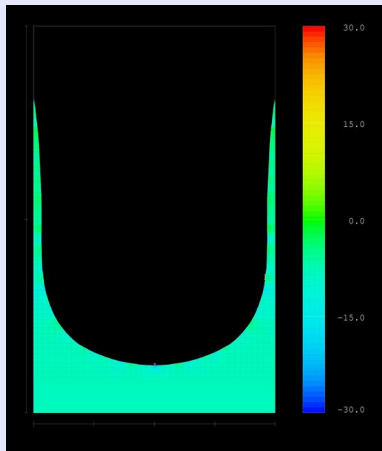
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 68 \cdot 0.03$ s

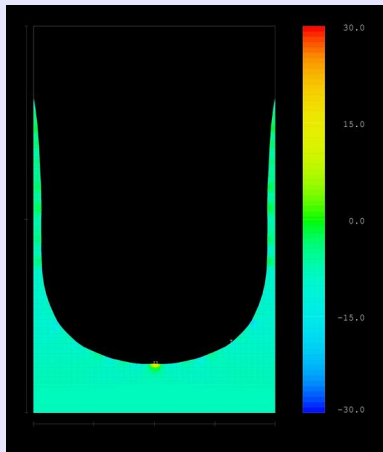
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 69 \cdot 0.03$ s

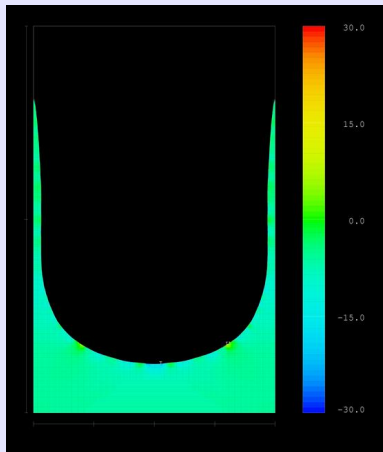
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 70 \cdot 0.03$ s

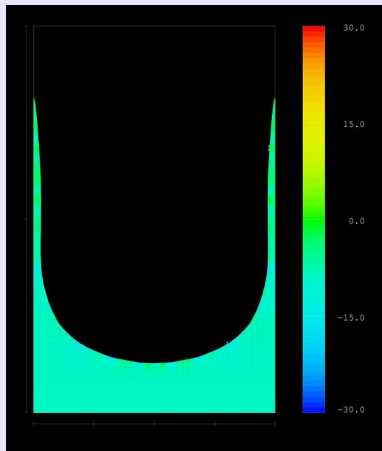
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 71 \cdot 0.03$ s

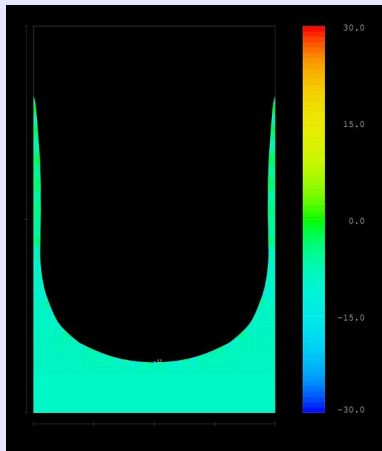
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 72 \cdot 0.03$ s

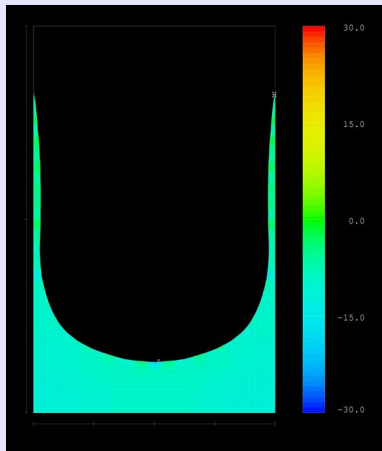
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 73 \cdot 0.03$ s

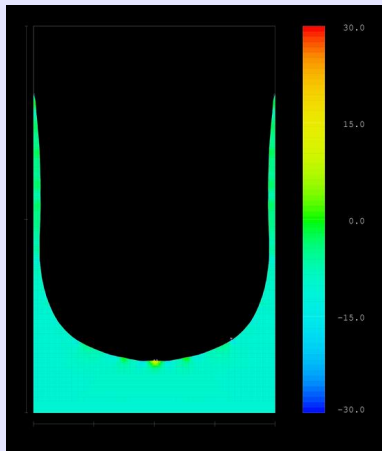
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 74 \cdot 0.03$ s

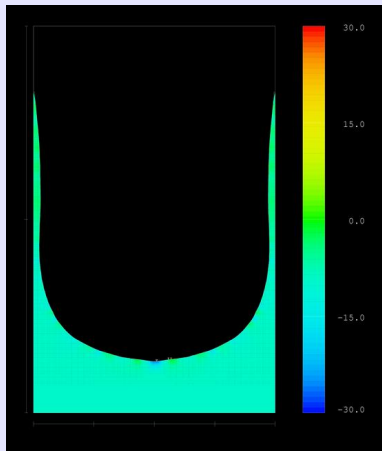
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 75 \cdot 0.03$ s

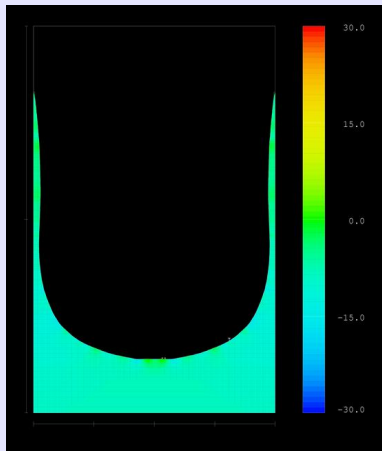
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 76 \cdot 0.03$ s

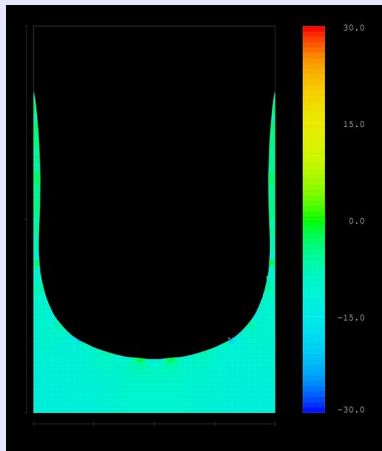
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 77 \cdot 0.03$ s

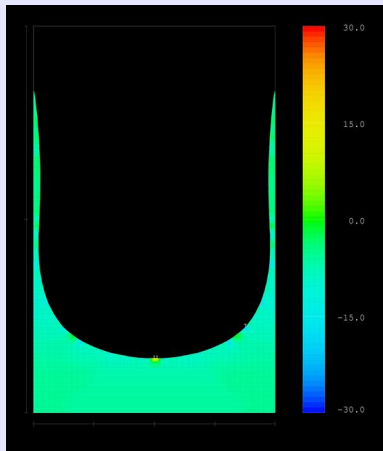
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 78 \cdot 0.03$ s

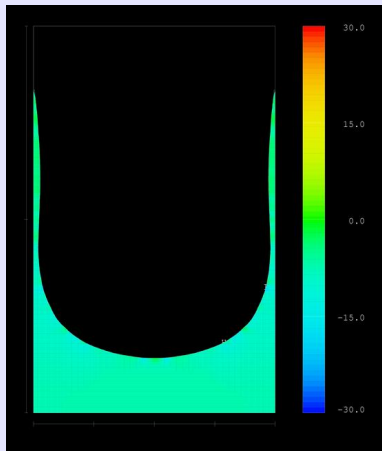
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 79 \cdot 0.03$ s

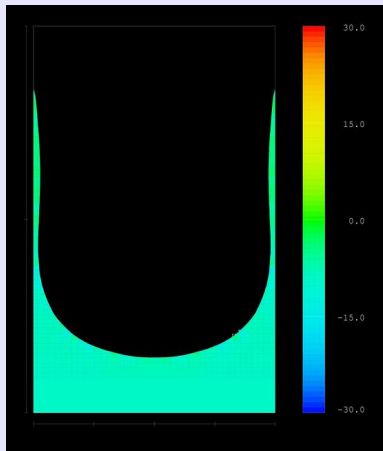
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 80 \cdot 0.03$ s

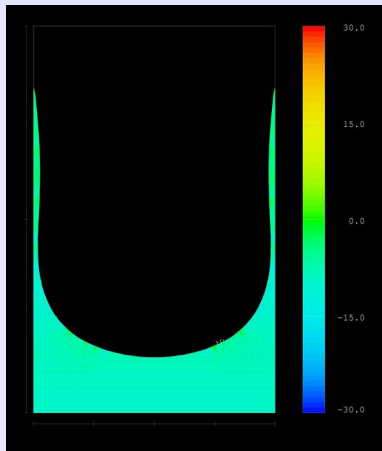
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 81 \cdot 0.03$ s

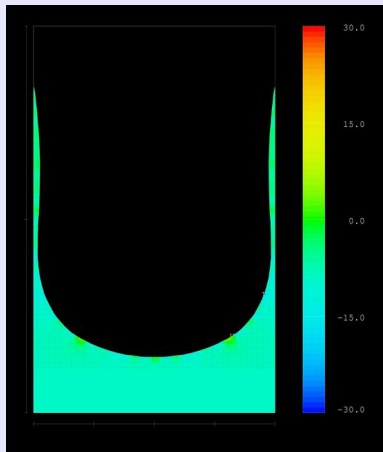
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 82 \cdot 0.03$ s

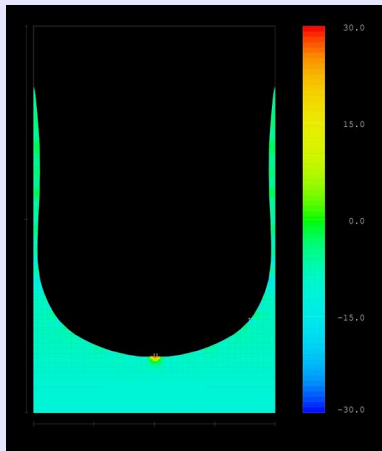
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 83 \cdot 0.03$ s

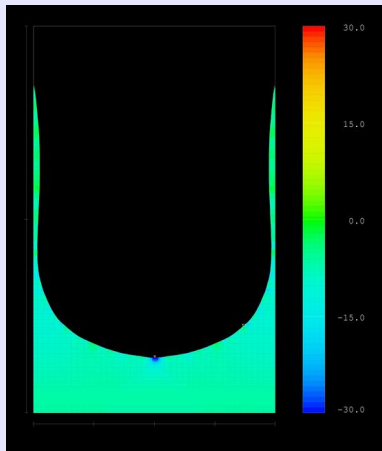
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 84 \cdot 0.03$ s

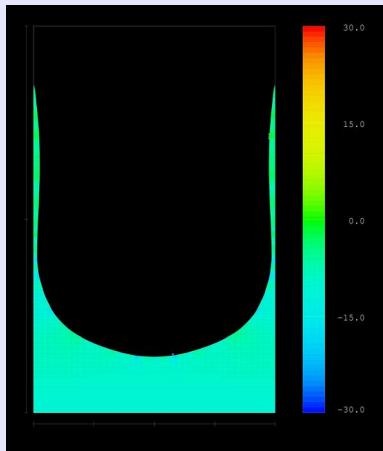
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 85 \cdot 0.03$ s

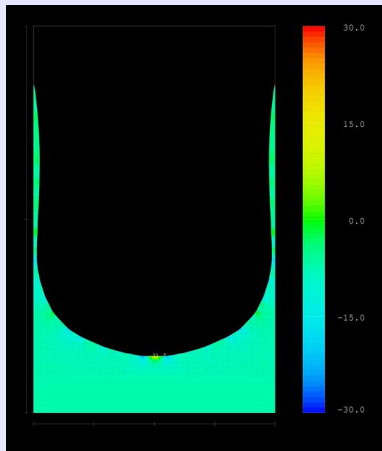
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 86 \cdot 0.03$ s

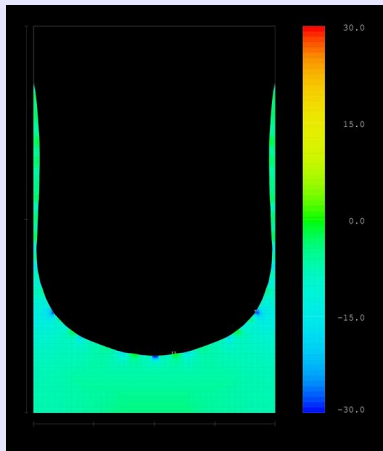
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 87 \cdot 0.03$ s

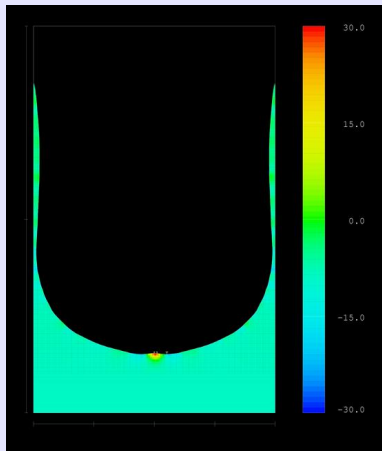
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 88 \cdot 0.03$ s

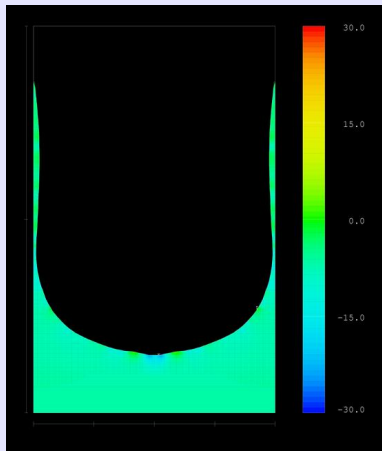
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 89 \cdot 0.03$ s

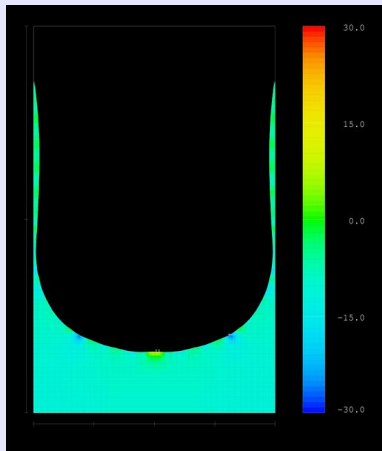
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 90 \cdot 0.03$ s

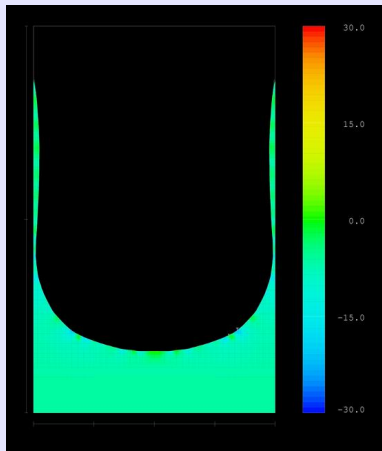
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 91 \cdot 0.03$ s

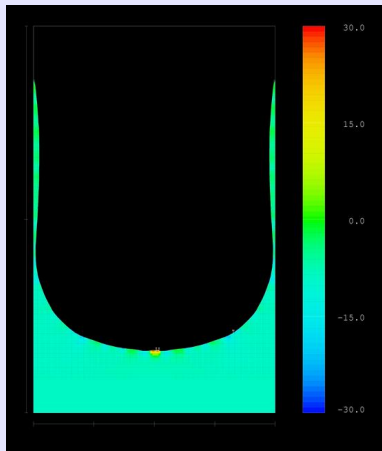
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 92 \cdot 0.03$ s

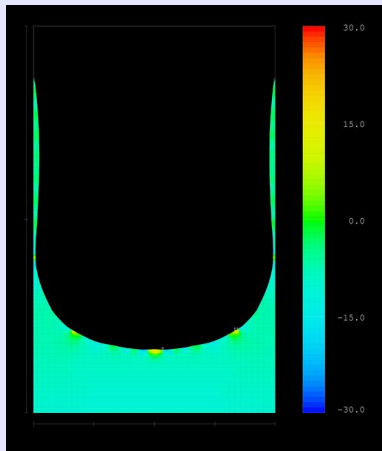
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 93 \cdot 0.03$ s

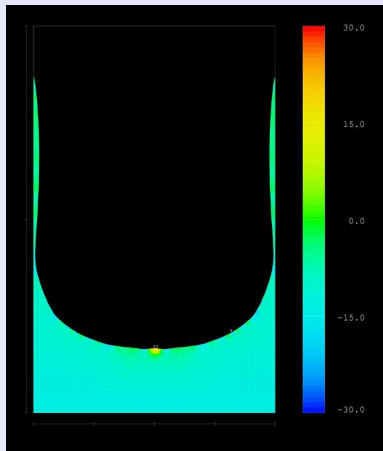
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 94 \cdot 0.03$ s

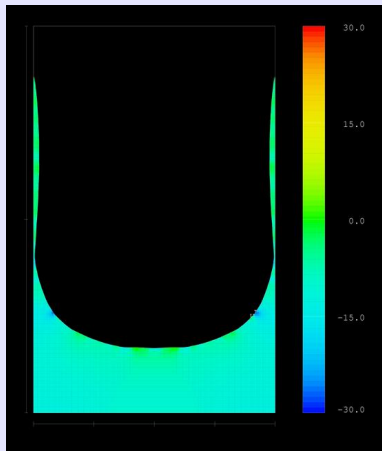
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 95 \cdot 0.03$ s

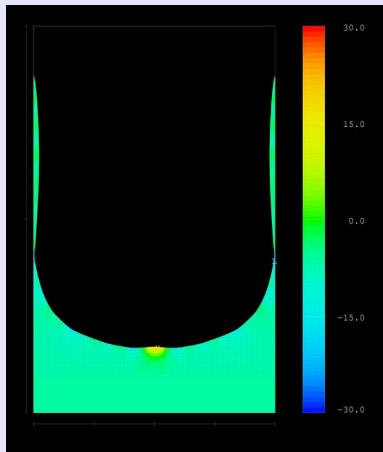
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 96 \cdot 0.03 \text{ s}$

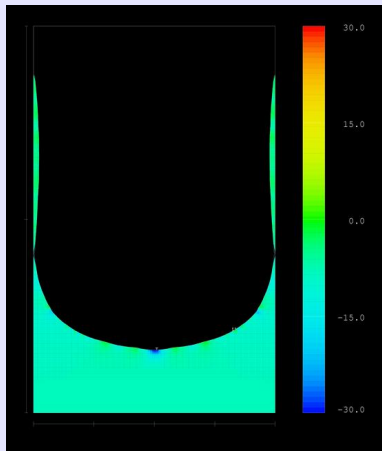
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 97 \cdot 0.03$ s

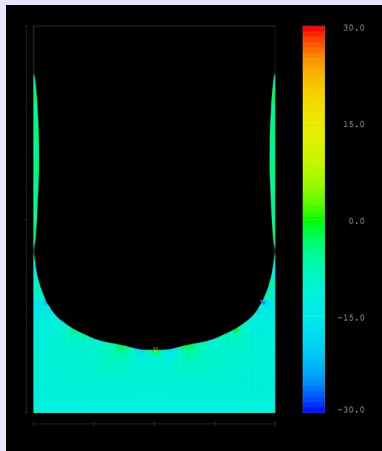
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 98 \cdot 0.03$ s

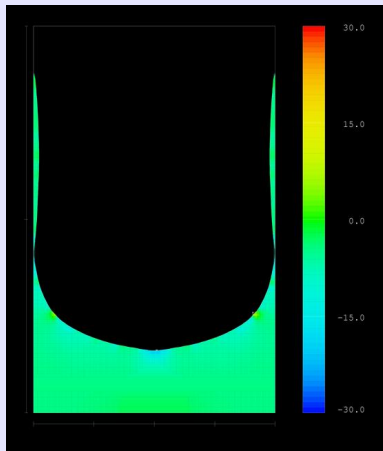
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 99 \cdot 0.03$ s

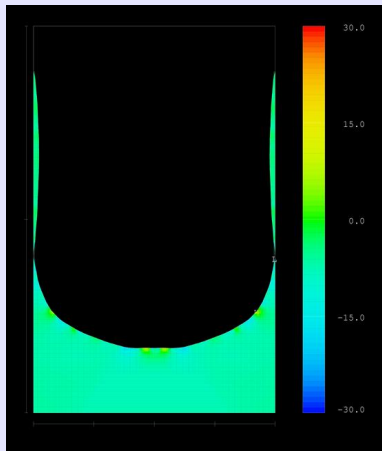
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 100 \cdot 0.03$ s

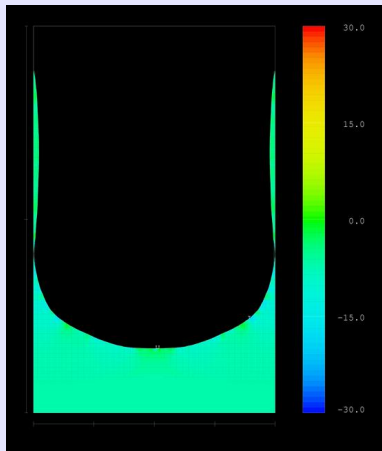
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 101 \cdot 0.03$ s

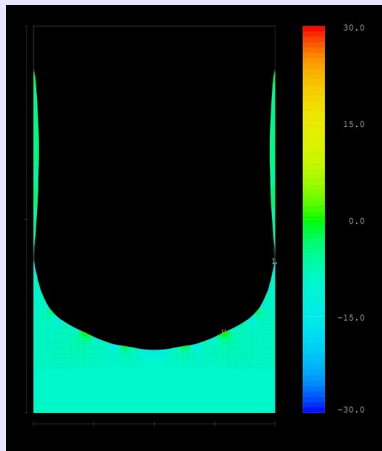
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 102 \cdot 0.03$ s

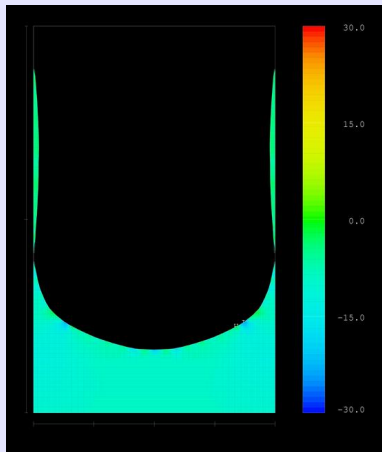
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 103 \cdot 0.03$ s

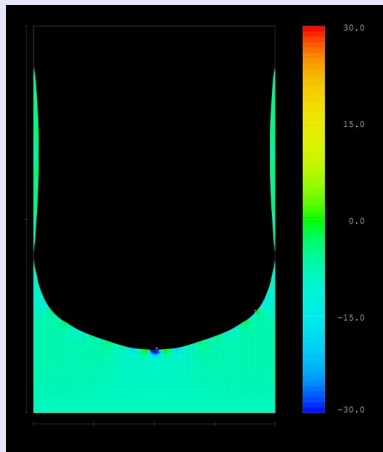
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 104 \cdot 0.03$ s

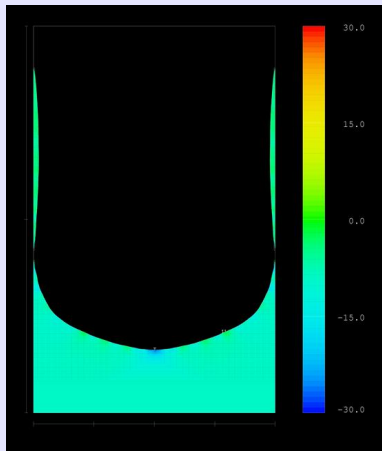
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 105 \cdot 0.03$ s

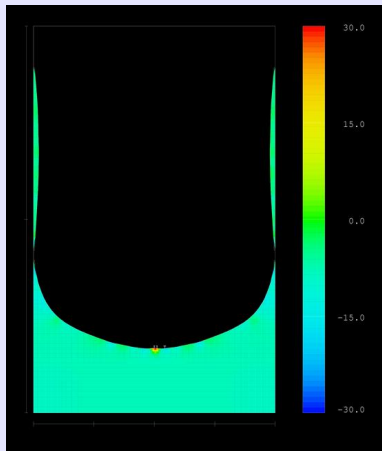
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 106 \cdot 0.03$ s

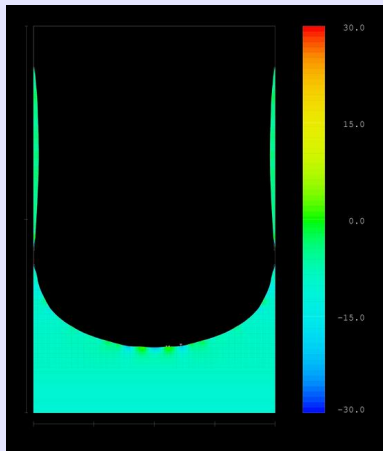
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 107 \cdot 0.03$ s

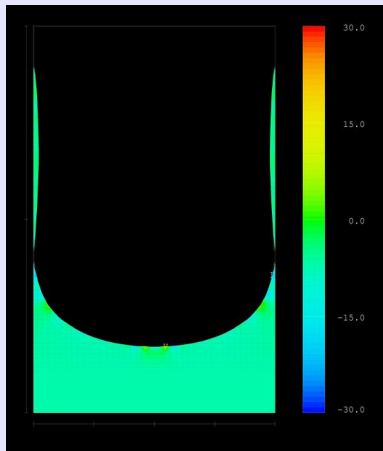
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 108 \cdot 0.03$ s

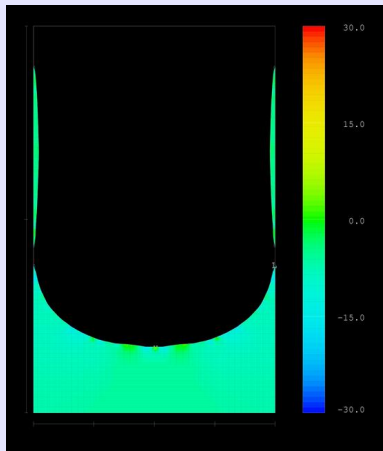
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 109 \cdot 0.03$ s

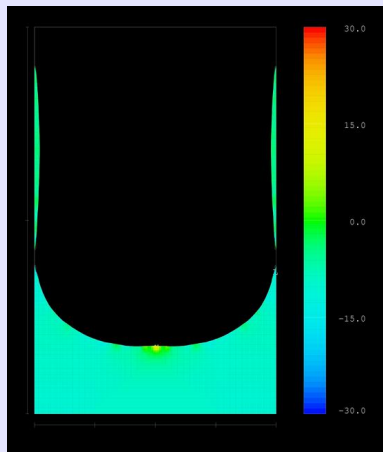
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 110 \cdot 0.03$ s

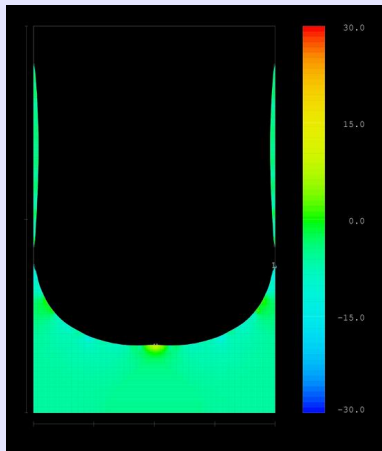
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 111 \cdot 0.03$ s

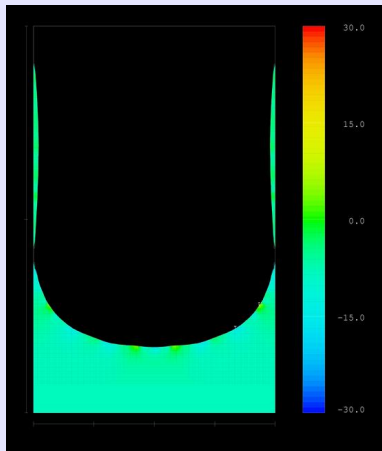
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 112 \cdot 0.03$ s

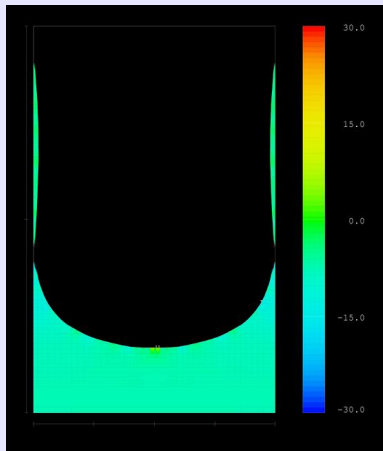
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 113 \cdot 0.03$ s

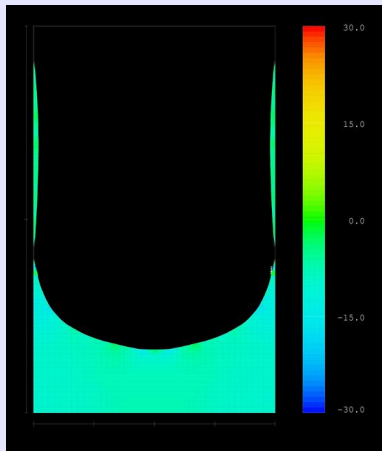
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 114 \cdot 0.03$ s

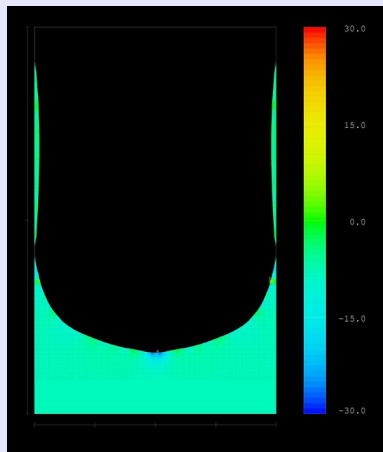
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 115 \cdot 0.03$ s

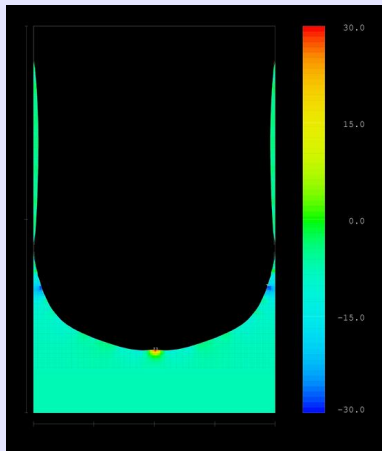
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 116 \cdot 0.03$ s

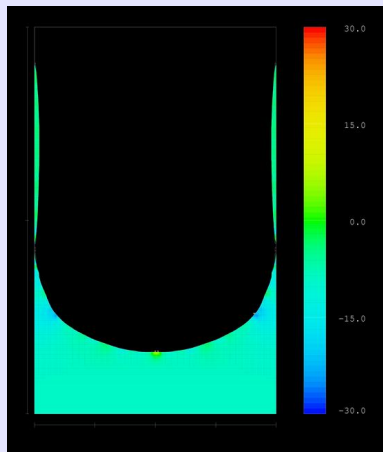
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 117 \cdot 0.03$ s

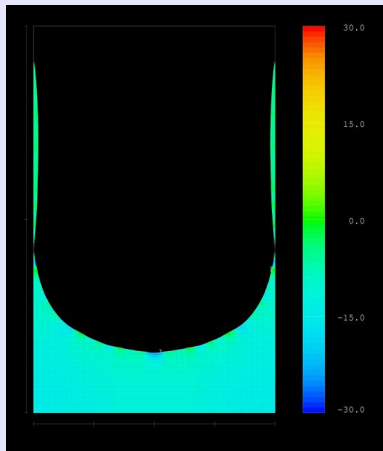
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 118 \cdot 0.03$ s

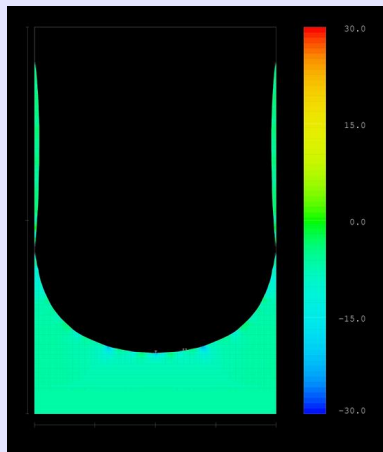
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 119 \cdot 0.03$ s

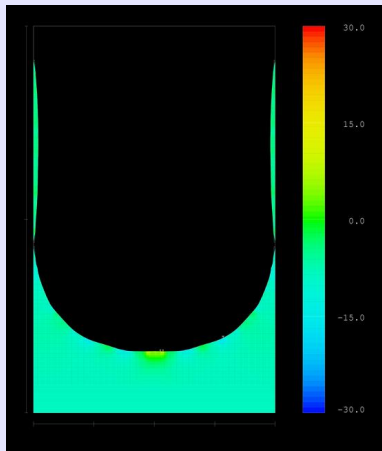
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 120 \cdot 0.03$ s

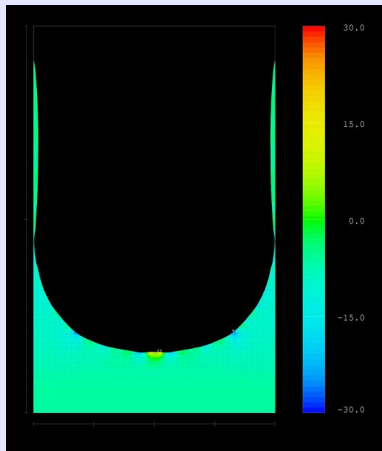
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 121 \cdot 0.03$ s

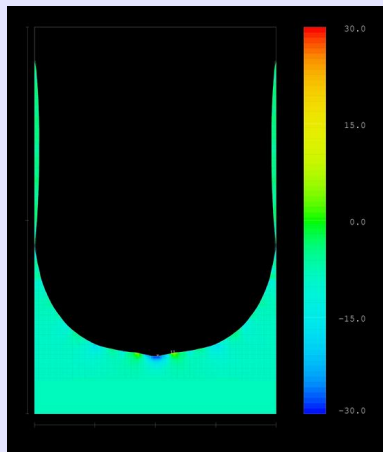
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 122 \cdot 0.03$ s

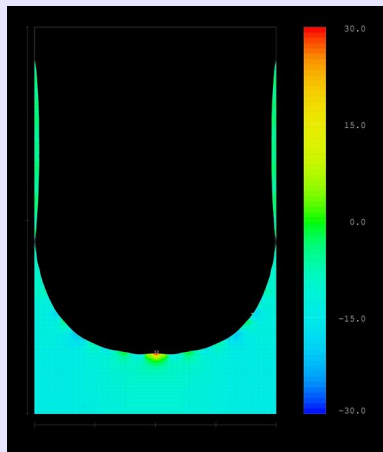
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 123 \cdot 0.03$ s

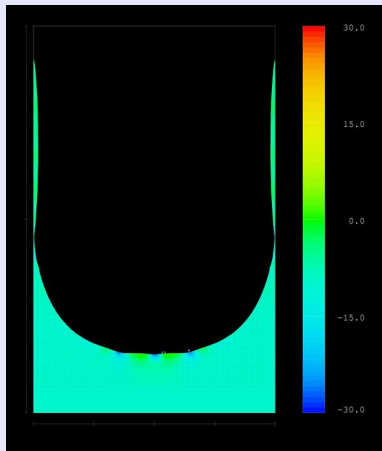
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 124 \cdot 0.03$ s

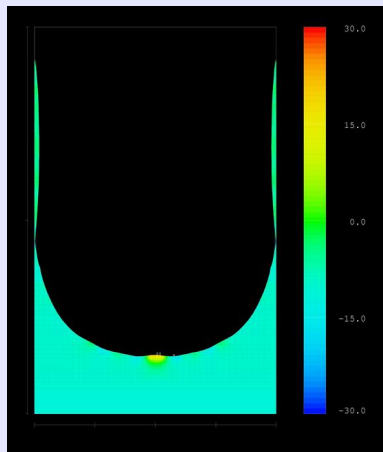
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 125 \cdot 0.03$ s

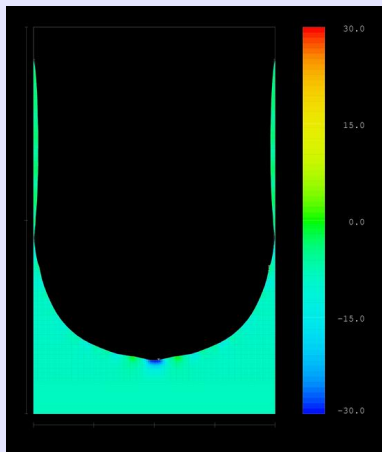
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 126 \cdot 0.03$ s

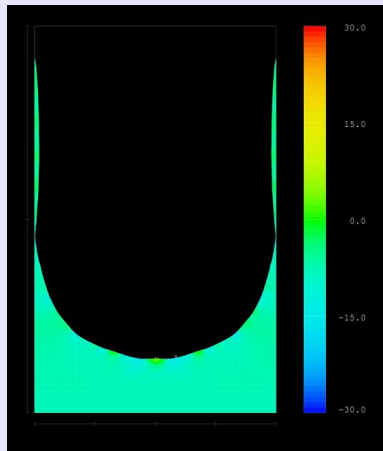
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 127 \cdot 0.03$ s

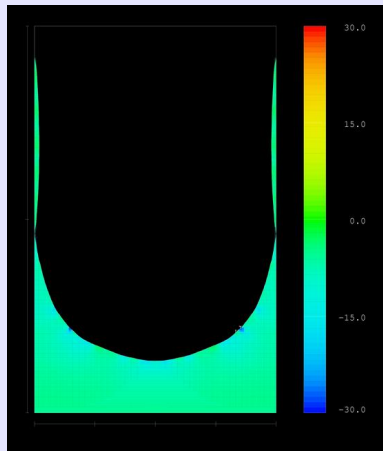
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 128 \cdot 0.03$ s

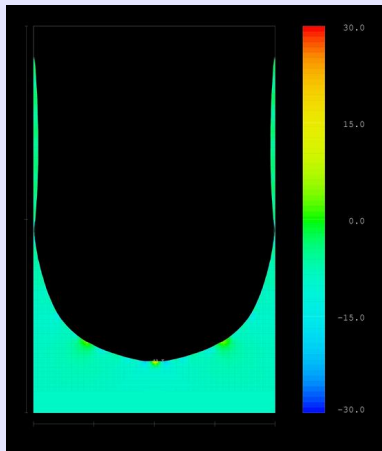
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 129 \cdot 0.03$ s

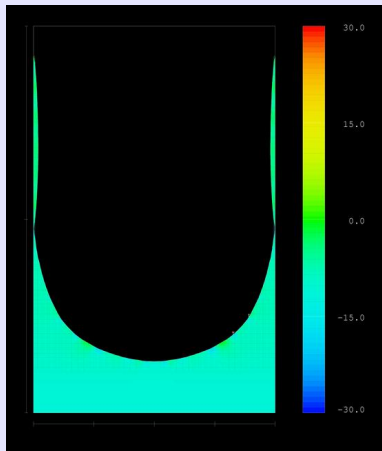
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 130 \cdot 0.03$ s

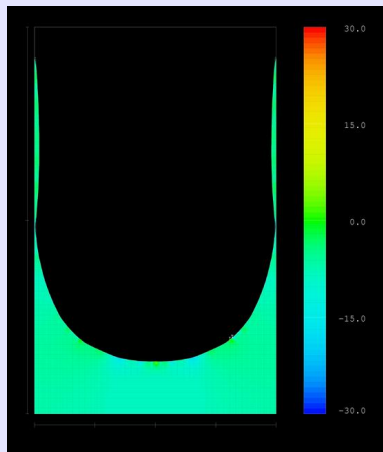
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 131 \cdot 0.03$ s

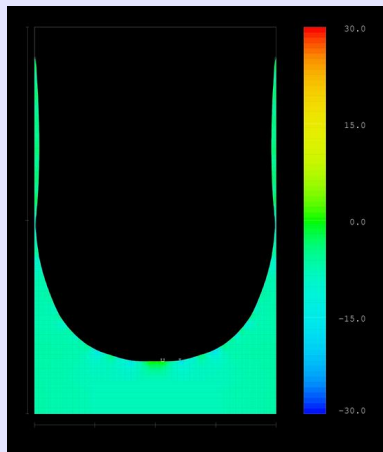
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 132 \cdot 0.03$ s

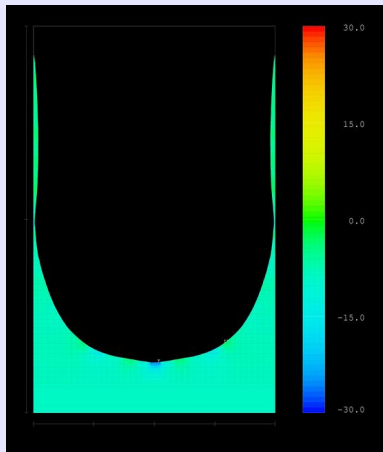
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 133 \cdot 0.03$ s

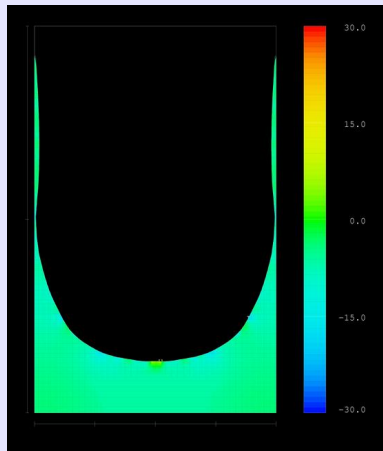
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 134 \cdot 0.03$ s

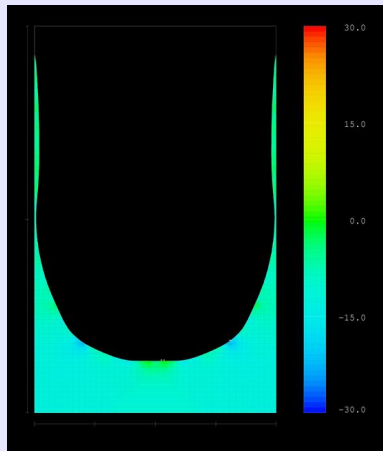
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 135 \cdot 0.03$ s

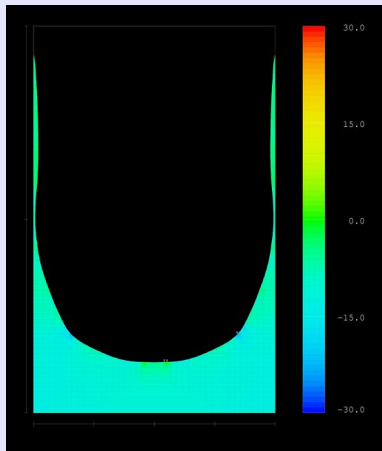
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 136 \cdot 0.03 \text{ s}$

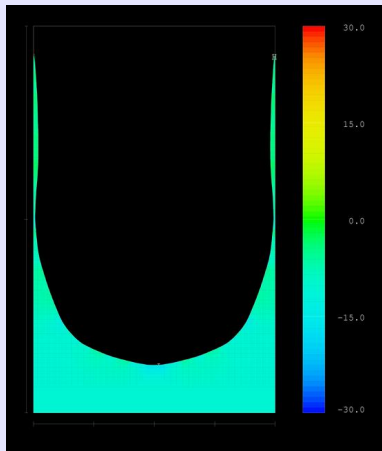
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 137 \cdot 0.03$ s

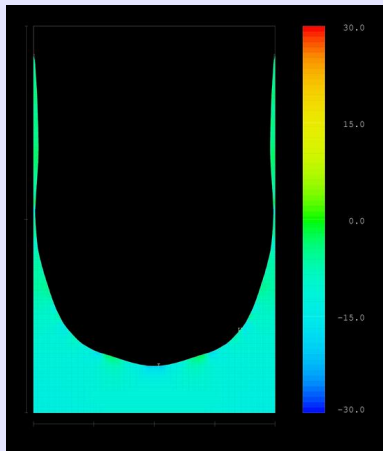
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 138 \cdot 0.03$ s

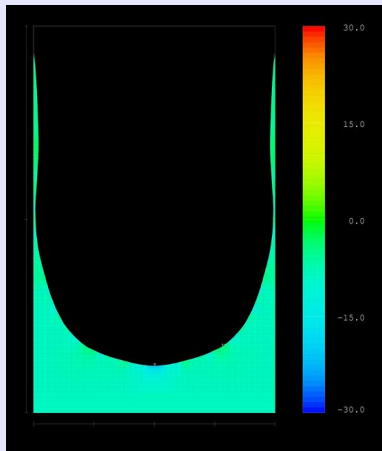
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 139 \cdot 0.03$ s

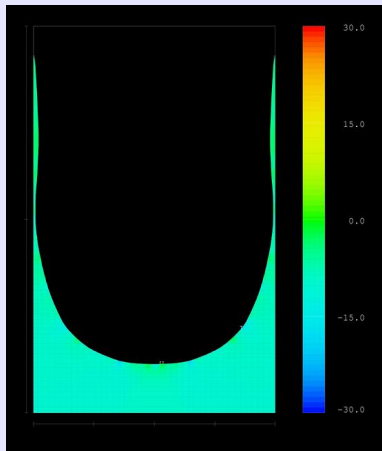
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 140 \cdot 0.03$ s

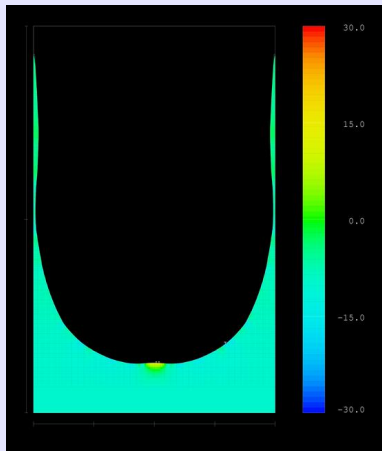
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 141 \cdot 0.03$ s

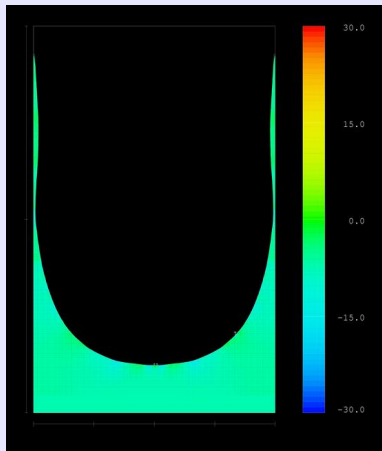
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 142 \cdot 0.03$ s

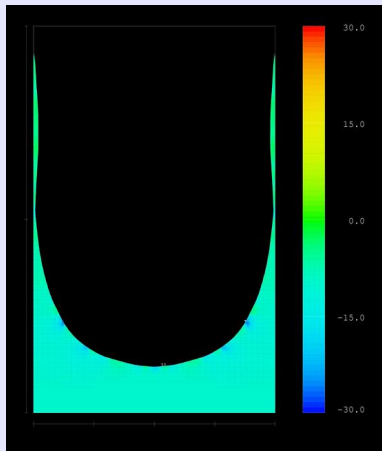
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 143 \cdot 0.03$ s

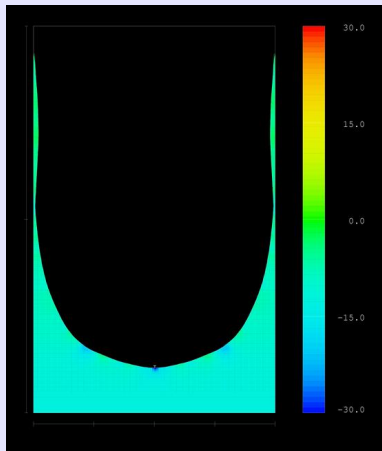
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 144 \cdot 0.03$ s

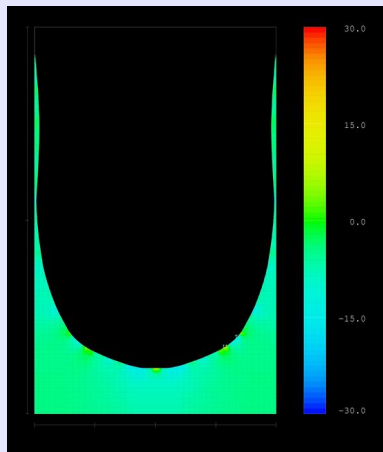
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 145 \cdot 0.03$ s

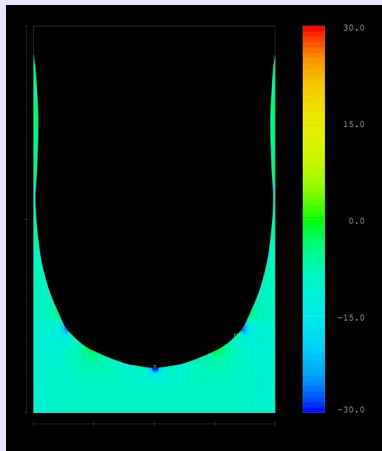
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 146 \cdot 0.03$ s

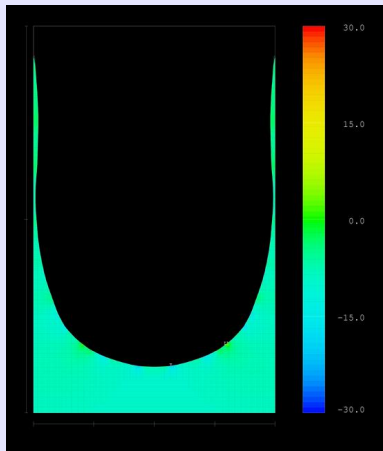
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 147 \cdot 0.03$ s

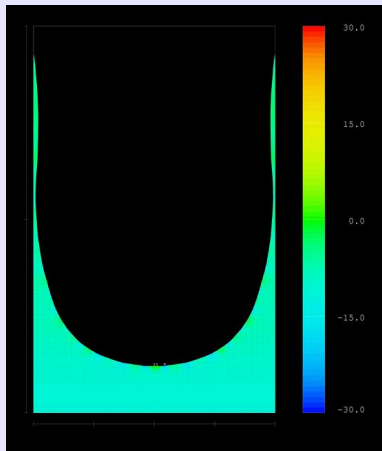
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 148 \cdot 0.03$ s

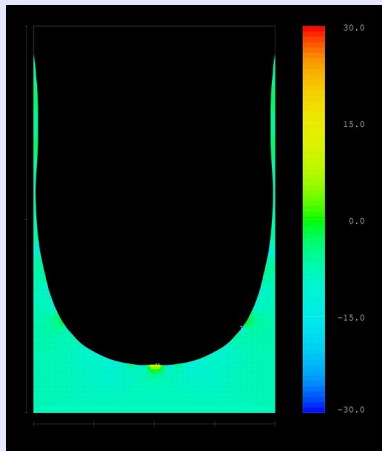
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 149 \cdot 0.03$ s

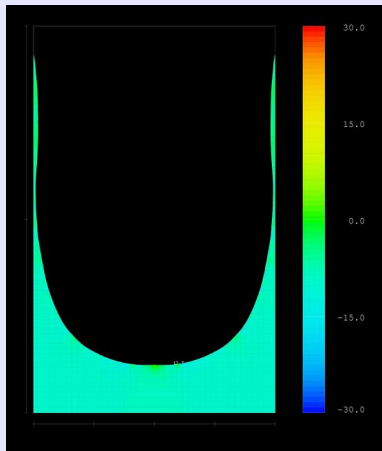
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 150 \cdot 0.03$ s

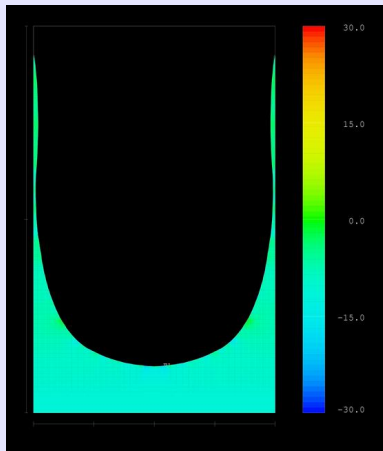
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 151 \cdot 0.03$ s

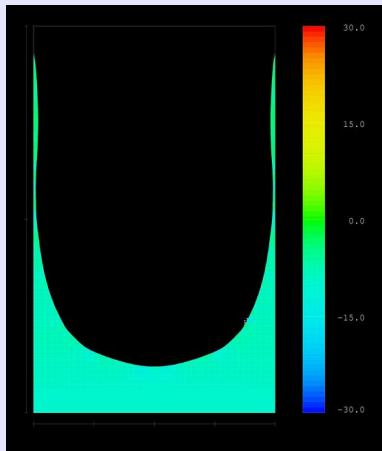
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 152 \cdot 0.03$ s

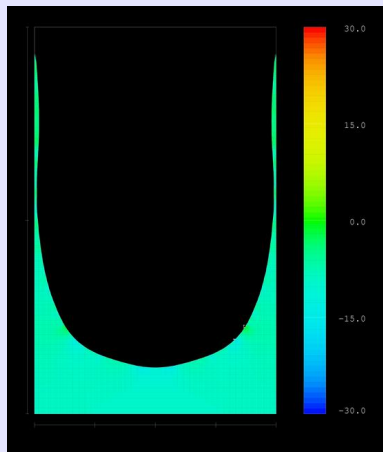
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 153 \cdot 0.03$ s

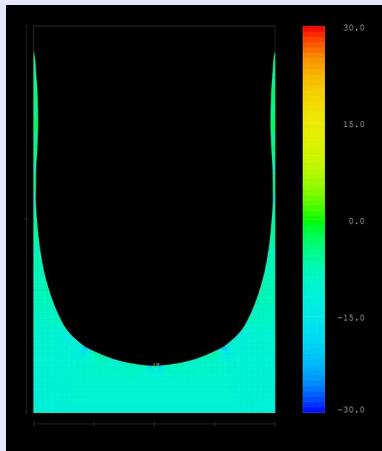
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 154 \cdot 0.03$ s

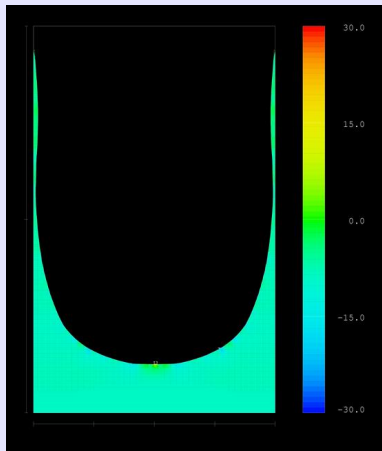
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 155 \cdot 0.03$ s

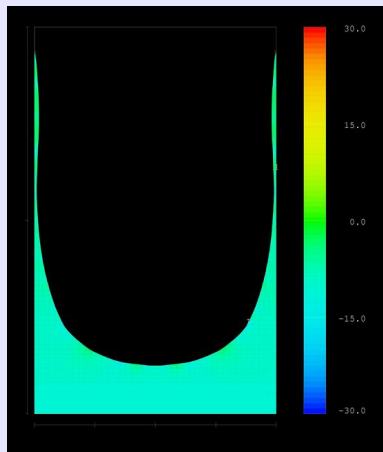
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 156 \cdot 0.03$ s

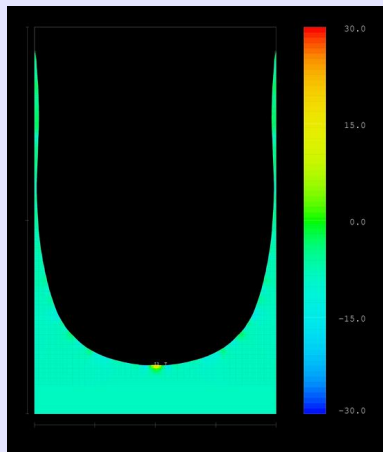
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 157 \cdot 0.03$ s

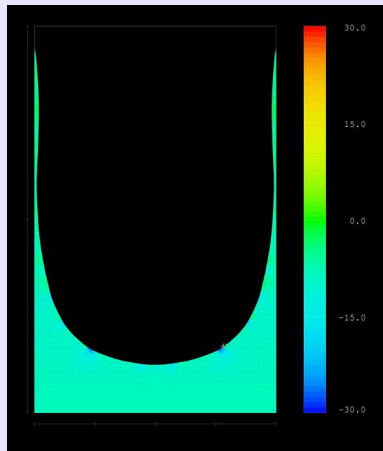
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 158 \cdot 0.03$ s

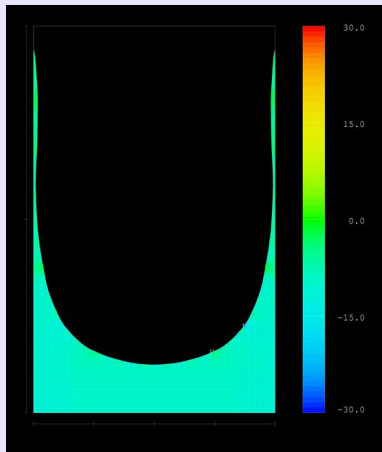
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 159 \cdot 0.03$ s

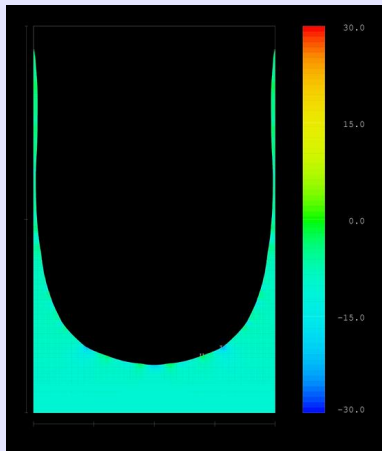
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 160 \cdot 0.03$ s

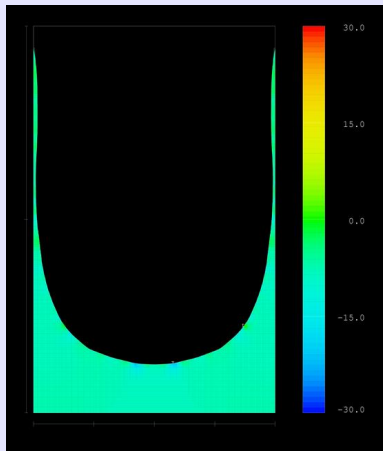
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 161 \cdot 0.03$ s

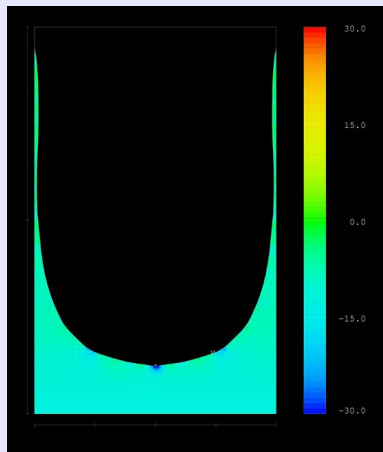
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 162 \cdot 0.03$ s

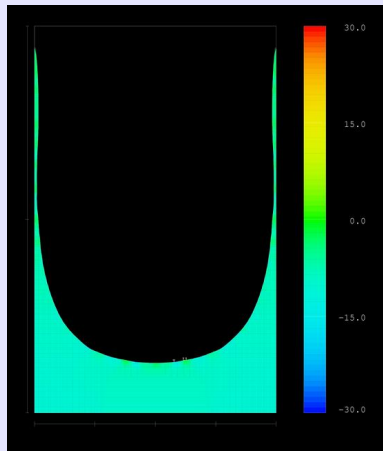
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 163 \cdot 0.03$ s

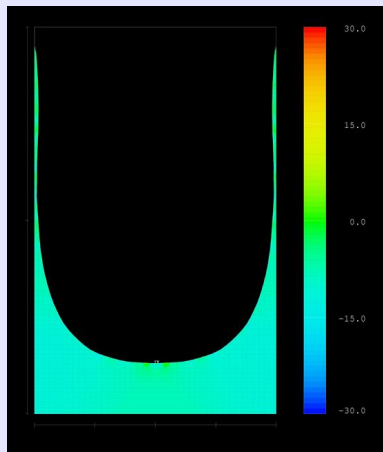
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 164 \cdot 0.03$ s

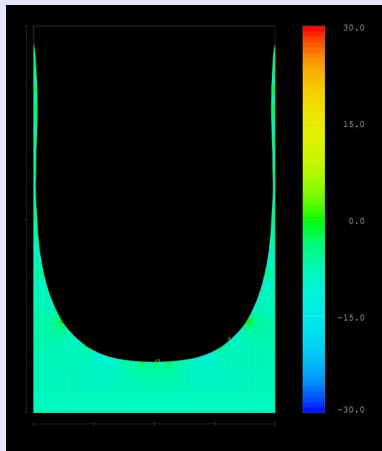
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 165 \cdot 0.03$ s

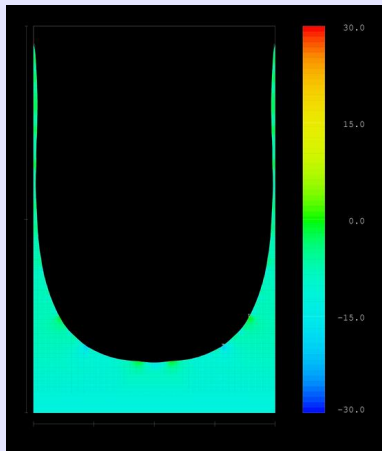
▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$t = 166 \cdot 0.03$ s

▶ restart



Numerical simulation with
FLOW-3D vers. 8.2.5:
Color bar indicating relative
pressure; $-3 \leq \Delta P \leq 3$ [Pa]

$$t = 167 \cdot 0.03 \text{ s} = 5.01 \text{ s}$$

▶ restart

Drop tower experiments are scheduled for December 2004.

For Further Reading:

[1] Mark Michaelis.

Kapillarinduzierte Schwingungen freier Flüssigkeitsoberflächen,
volume Nr. 454 of *Reihe 7 Strömungstechnik.*

VDI Verlag, Düsseldorf, fortschritt-berichte edition, 2003.

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