Numerical analysis on local acceleration of liquid film spreading on smooth substrate induced by interaction with a single short pillar

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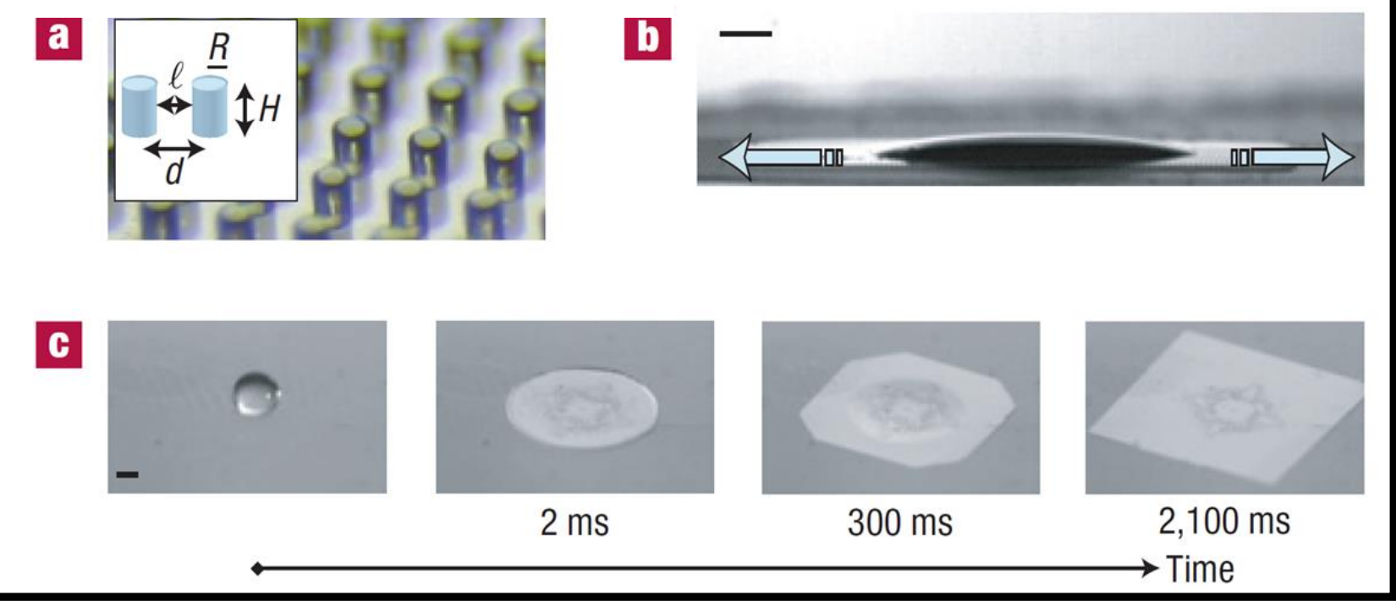
Background

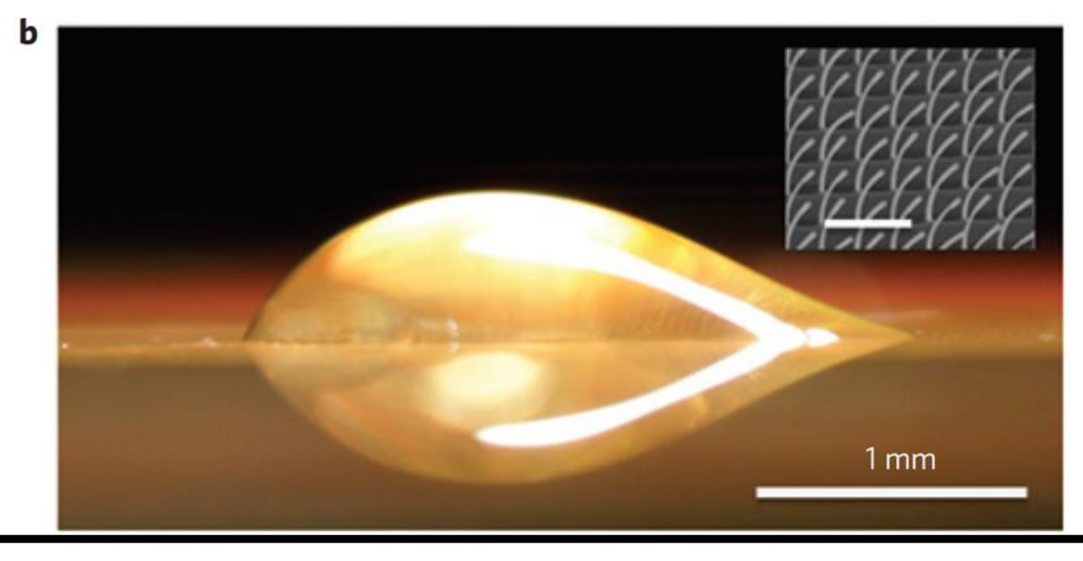
Control of dynamic wetting is indispensable for environmental control under micro/low gravity conditions[1-4]. Liquid spreading can be characterized by the behavior of a macroscopic contact line (M-CL). In previous study, Mu et al.[5,6] experimentally found that the interaction between spreading liquid film and a single spherical particle or a pillar on a substrate induce rapid acceleration of the M-CL. Nakamura et al.[7] revealed that the acceleration is caused the pressure difference between the upstream and the downstream side inside the meniscus around the particles.

In this study we focus on the effect of the height of the tiny structure on the acceleration phenomenon.

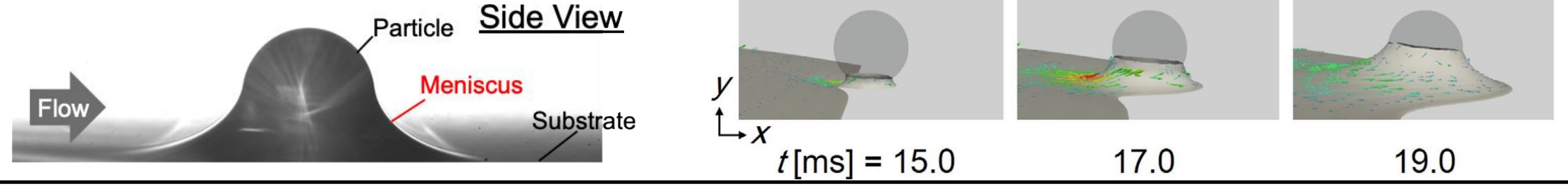
Courbin et al. (2007)



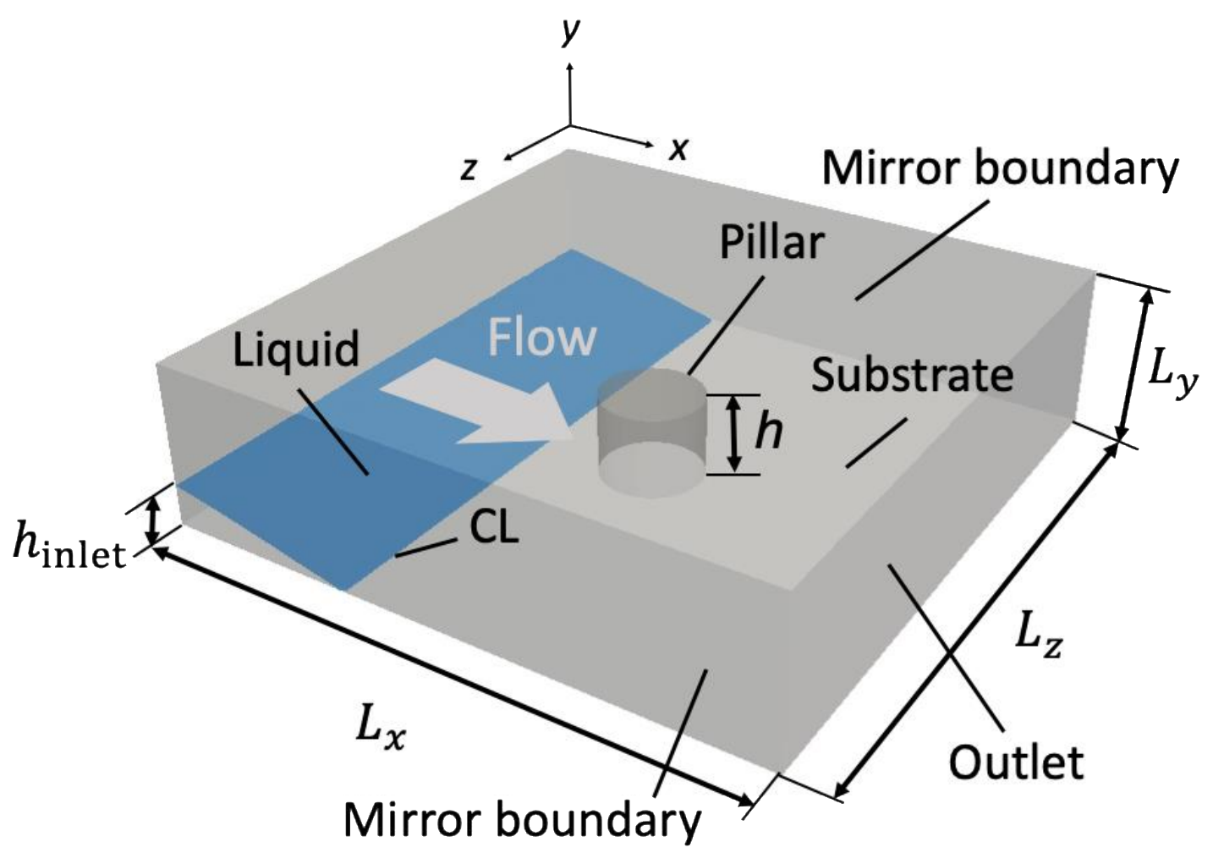
Chu et al. (2010)



Nakamura et al. (2020)



Method



- Continuity equation

$$\nabla \cdot \boldsymbol{U} = 0$$

- Navier-Stokes equation

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{U}\boldsymbol{U} \right) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \boldsymbol{g} + \boldsymbol{F}_{\text{SV}}$$

- Advection equation of α

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot \left(\alpha \boldsymbol{U} \right) + \nabla \cdot \left[\alpha \left(1-\alpha \right) \boldsymbol{U}_r \right] = 0$$

Computational conditions

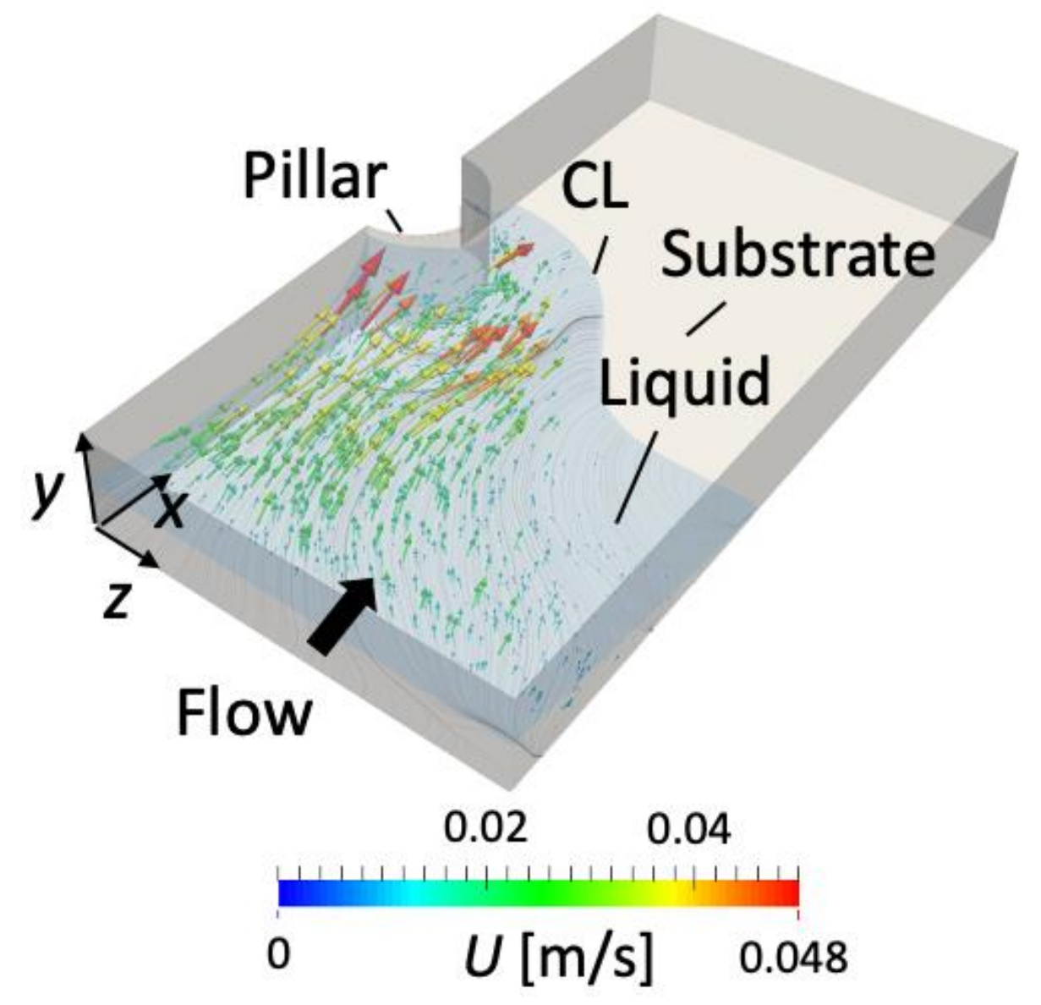
$L_x \times L_y \times L_z$ [μm]	300 × 80 × 300
$N_x \times N_y \times N_z$	$L_x / 2 \times L_y / 2 \times L_z / 2$
D_p [μm]	50
h [μm]	10, 20, 30, 40, 70
g [m/s^2]	9.81
h_{inlet} [μm]	20

Properties of fluids
(2cSt silicone oil & Air)

θ_p [◦]	20
θ_s [◦]	5
σ [N/m]	1.83×10^{-2}
ρ_l [kg/m^3]	873
ρ_g [kg/m^3]	1
ν_l [m^2/s]	2.0×10^{-6}
ν_g [m^2/s]	1.48×10^{-5}

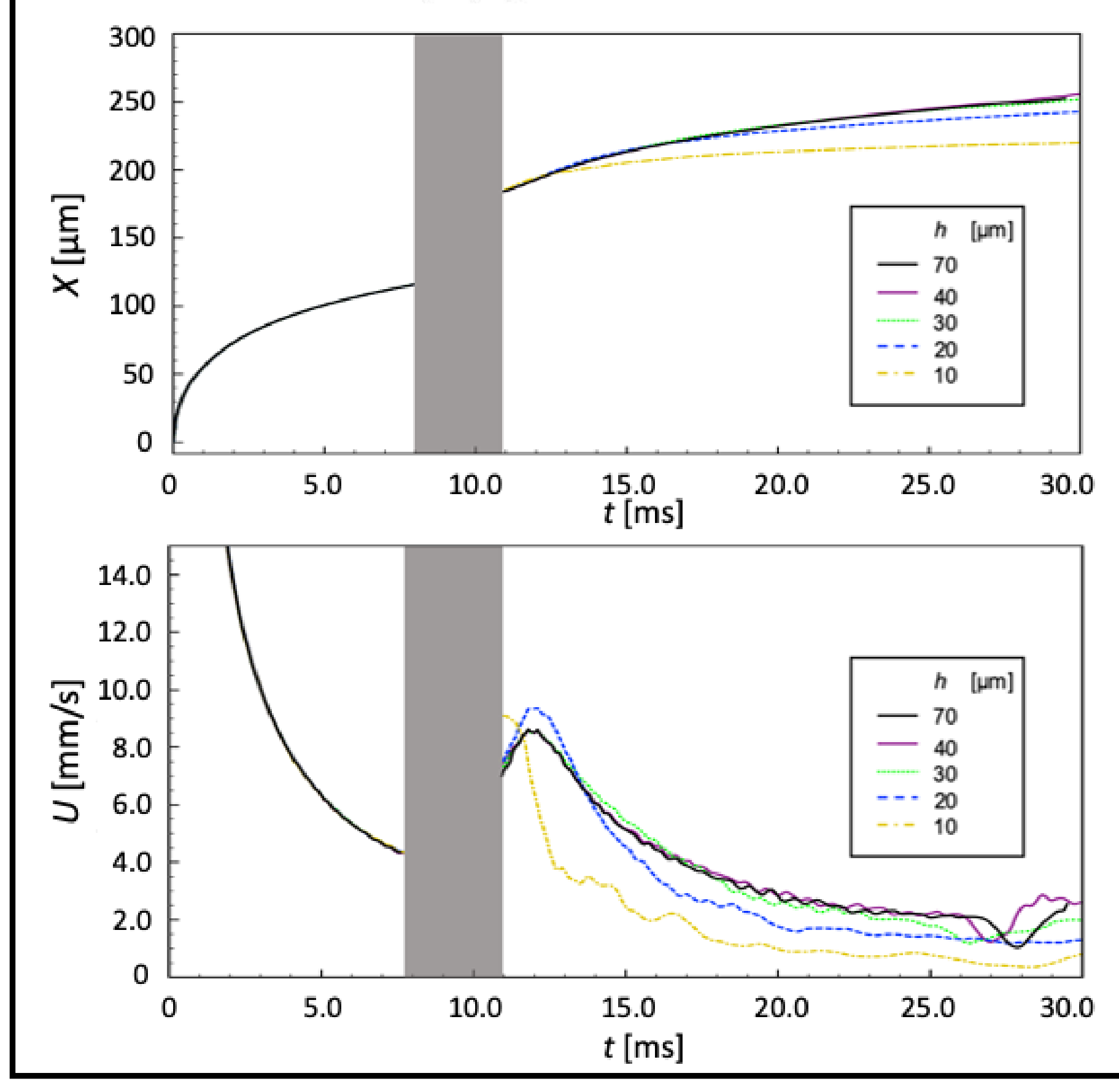
Results

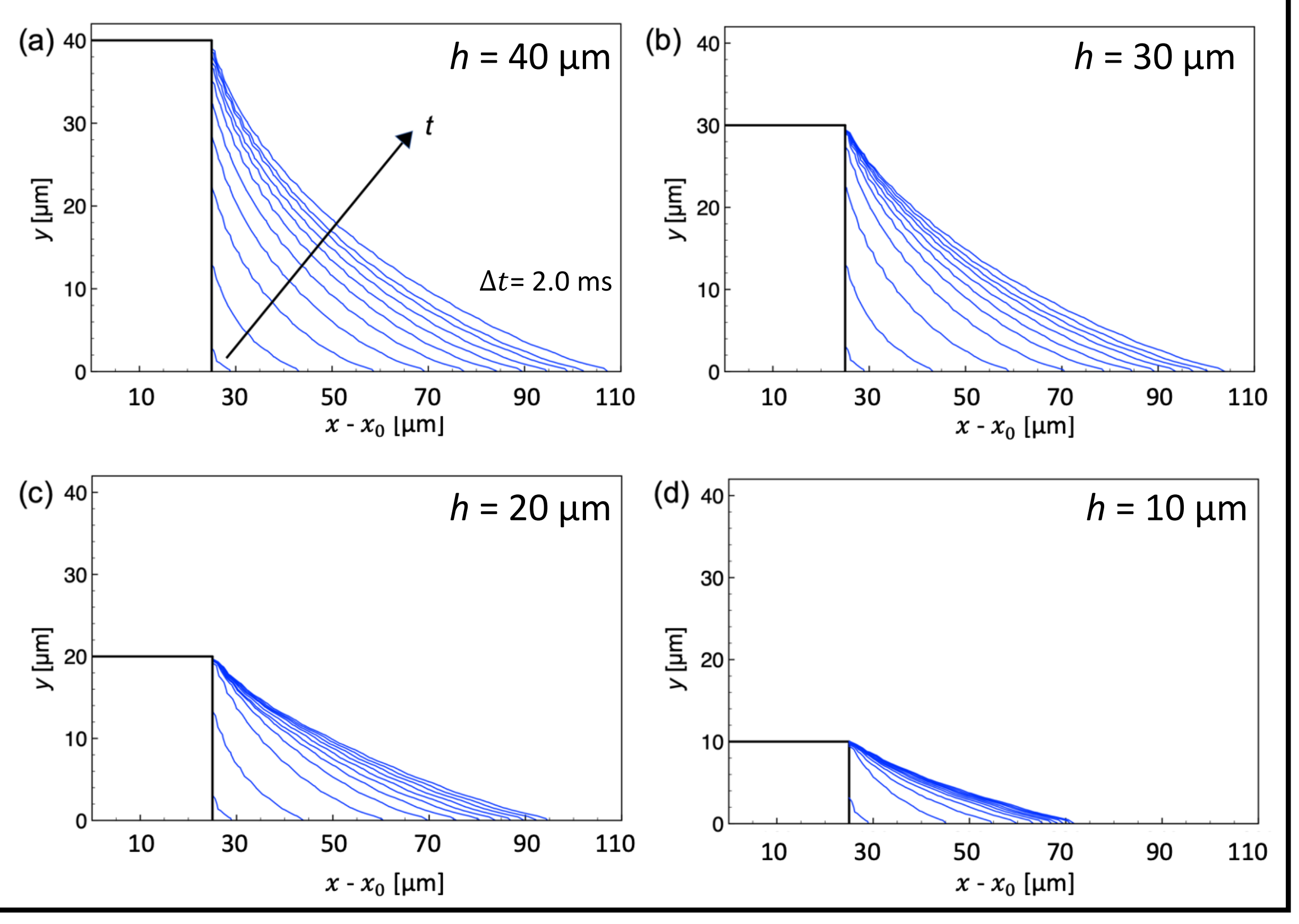
Spreading distance & velocity



The left figure shows the acceleration phenomenon of the contact line (CL) after liquid film contacts with a pillar.

The figure on the lower left shows the time change of position and velocity of CL, and the figure on the lower right shows the time change of shape of the meniscus. The higher the pillar, the longer the spreading distance, but there is little difference when the pillar is taller than 40 μm. The maximum velocity is greater when the pillar is short, however, the velocity damping also becomes faster.

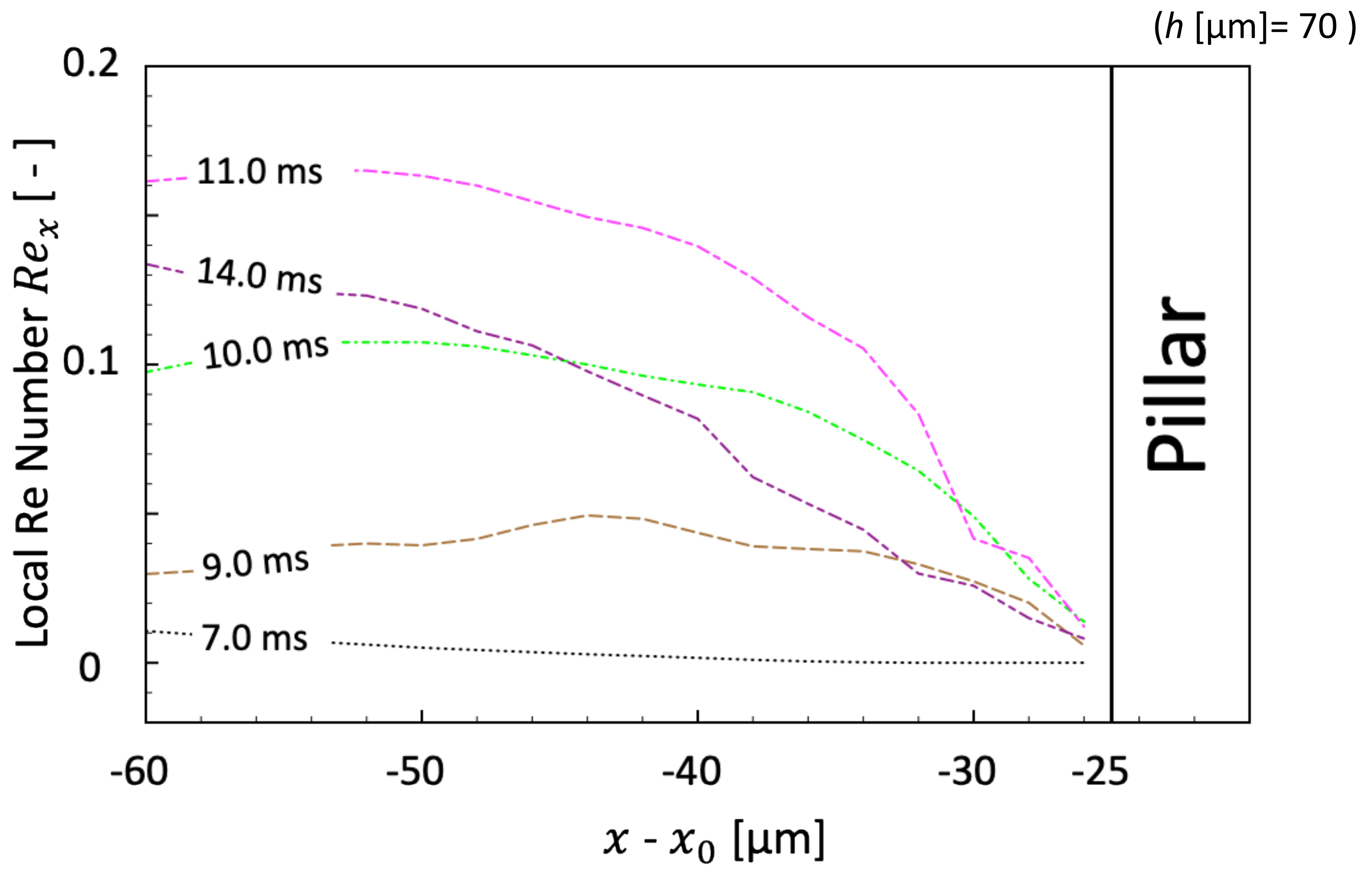




Local Reynolds number

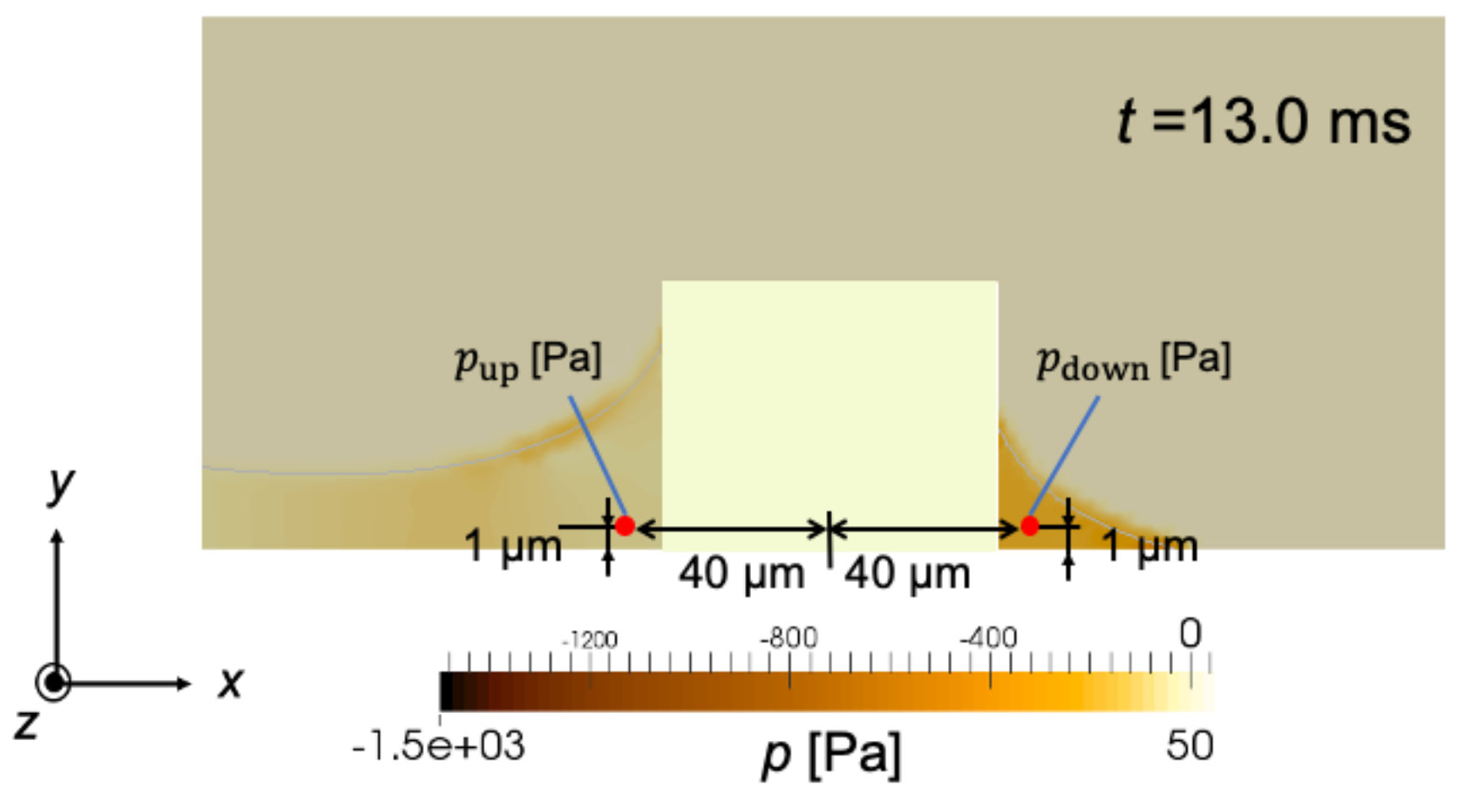
$$Re_x = \frac{\int_0^{\delta} u_x \, dy}{\nu}$$

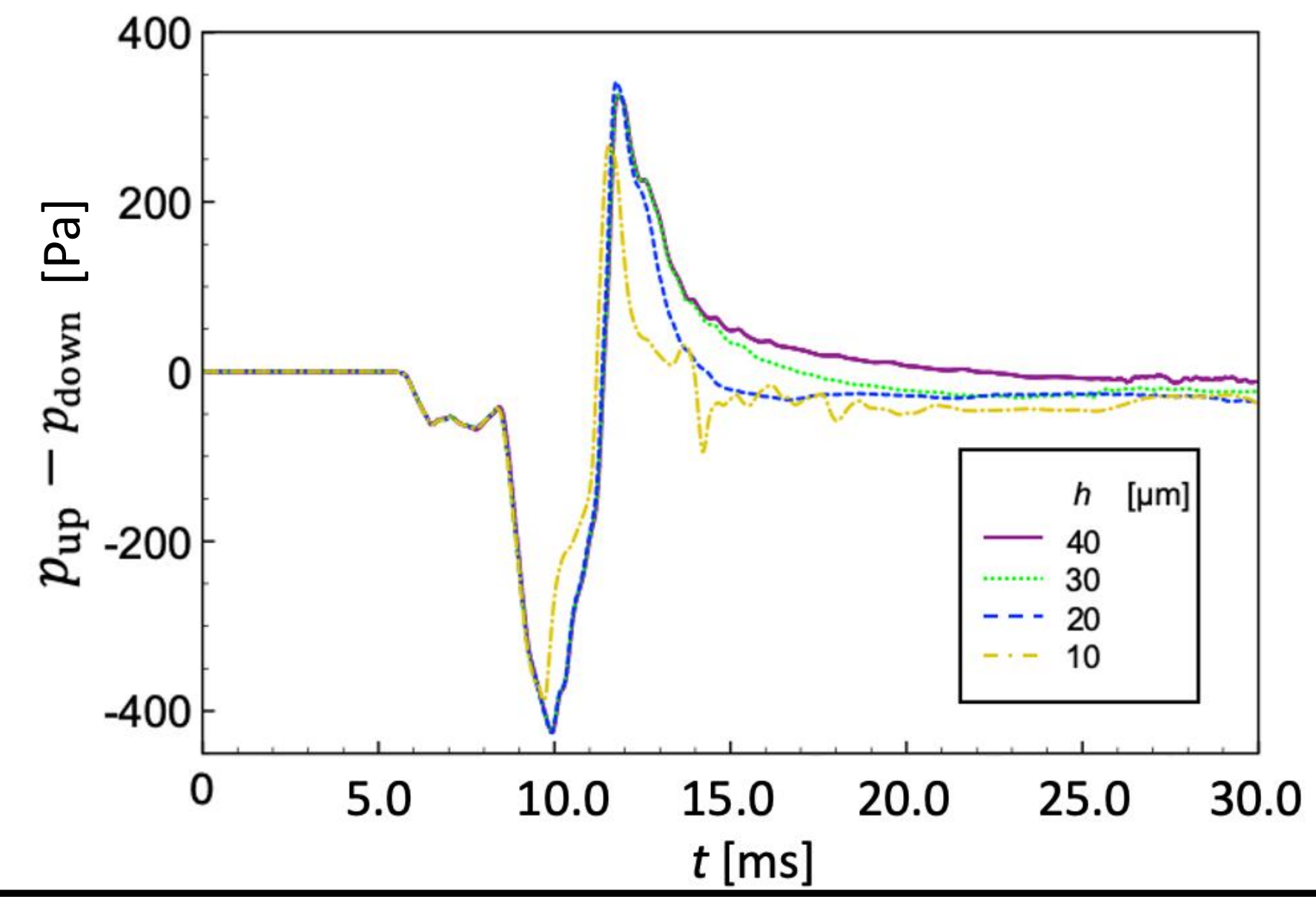
u_x [m/s]: Velocity of the liquid film
δ [m] : Thickness of the liquid film
ν [m^2/s] : Kinetic viscosity



This figure shows the time change of local Reynolds number Re_x when the pillar is 70 μm. After the liquid film contacts with the pillar, Re_x becomes more than 10 times larger than that at 7.0 ms. Hence, the formation of the meniscus causes the intense acceleration phenomenon of liquid film.

Pressure distribution around pillar



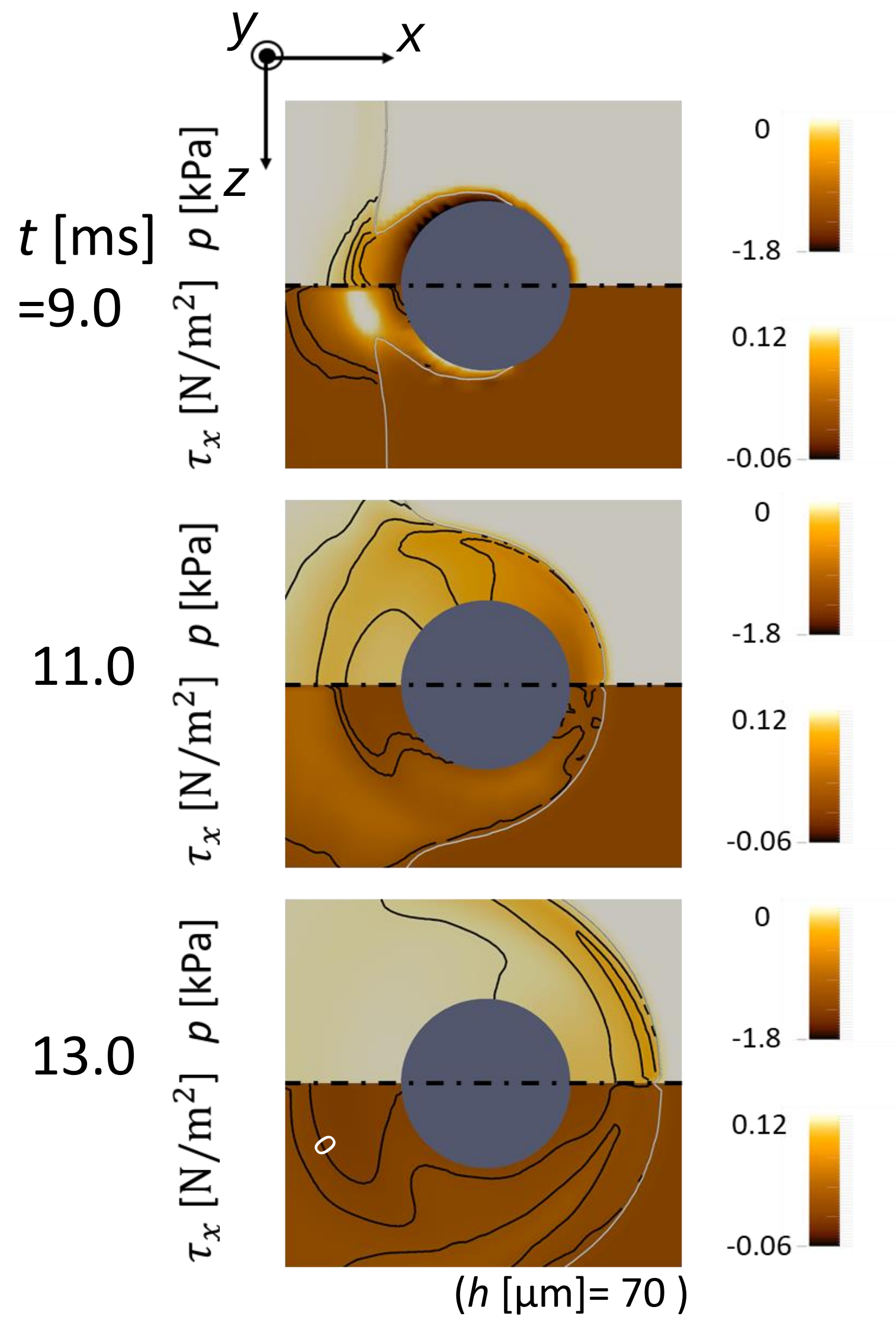


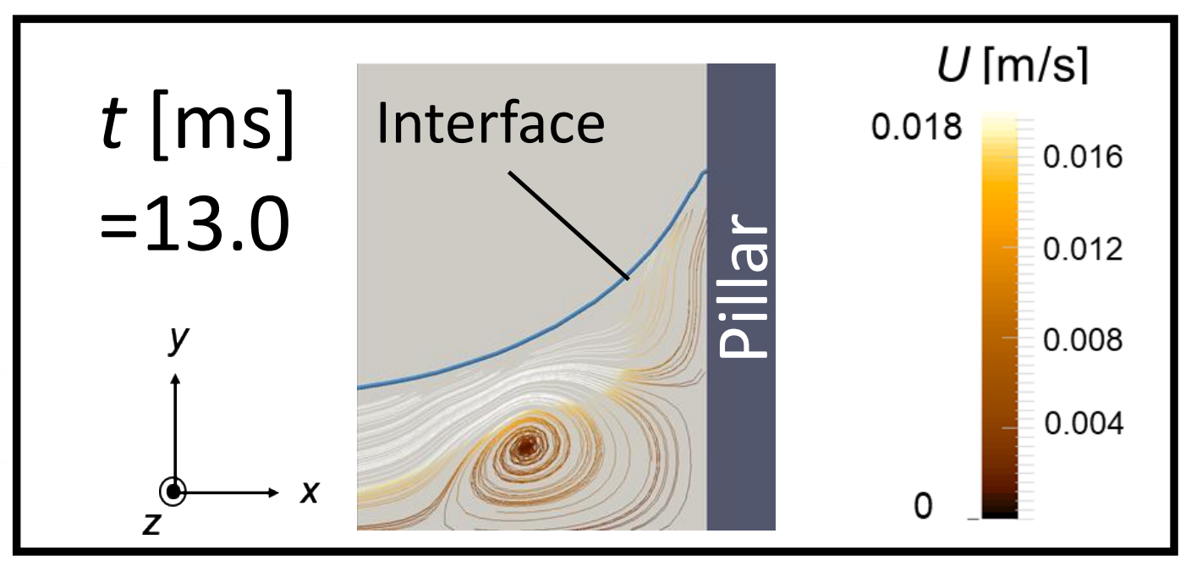
The upper figure shows the measurement points of pressure p_{up} and p_{down} inside the meniscus around the pillar, and the lower figure shows the time change of pressure difference between p_{up} and p_{down}. This pressure difference is mainly caused by the formation of meniscus.

The damping of $p_{up} - p_{down}$ becomes more significant when the pillar is short, and it makes the damping of the velocity more significant.

We find that a meniscus with a small curvature radius cannot be formed for a sufficiently long time to induce the acceleration of the liquid near CL when the pillar is short.

Pressure & wall shear stress on the substrate





Temporal variations of the pressure (top half) and the wall shear stress (bottom half) are illustrated after the interaction between the CL and the pillar. Just after liquid contacts with the pillar, the pressure around the pillar significantly decreases from upstream side to downstream side. Also, the wall shear stress shows negative value around the pillar. It is indicated that there is vortex in this region.

Conclusions

- The liquid film is more likely to be driven when the pillar is higher, but there is a threshold of height. In this case, the threshold is around 40 μm.
- When the pillar is short, the damping of the velocity and $p_{up} - p_{down}$ are significant because a small curvature radius cannot be formed for a sufficiently long time to induce the acceleration of the liquid near the CL.
- Just after liquid contacts with the pillar, the negative τ_x region appears on the substrate, that is, the vortex occurs around the pillar.

References

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