Thermocapillary Drop Motion on a Horizontal Solid Surface

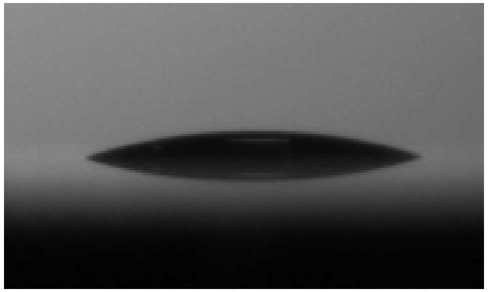
Vikram Pratap

Department of Chemical & Biomolecular Engineering
and Center for Advanced Materials Processing
Clarkson University

Outline

- Background
- Applications
- Literature review
- Objectives
- Experimental setup
- Theoretical work
- Results and Conclusions
- Recommendations

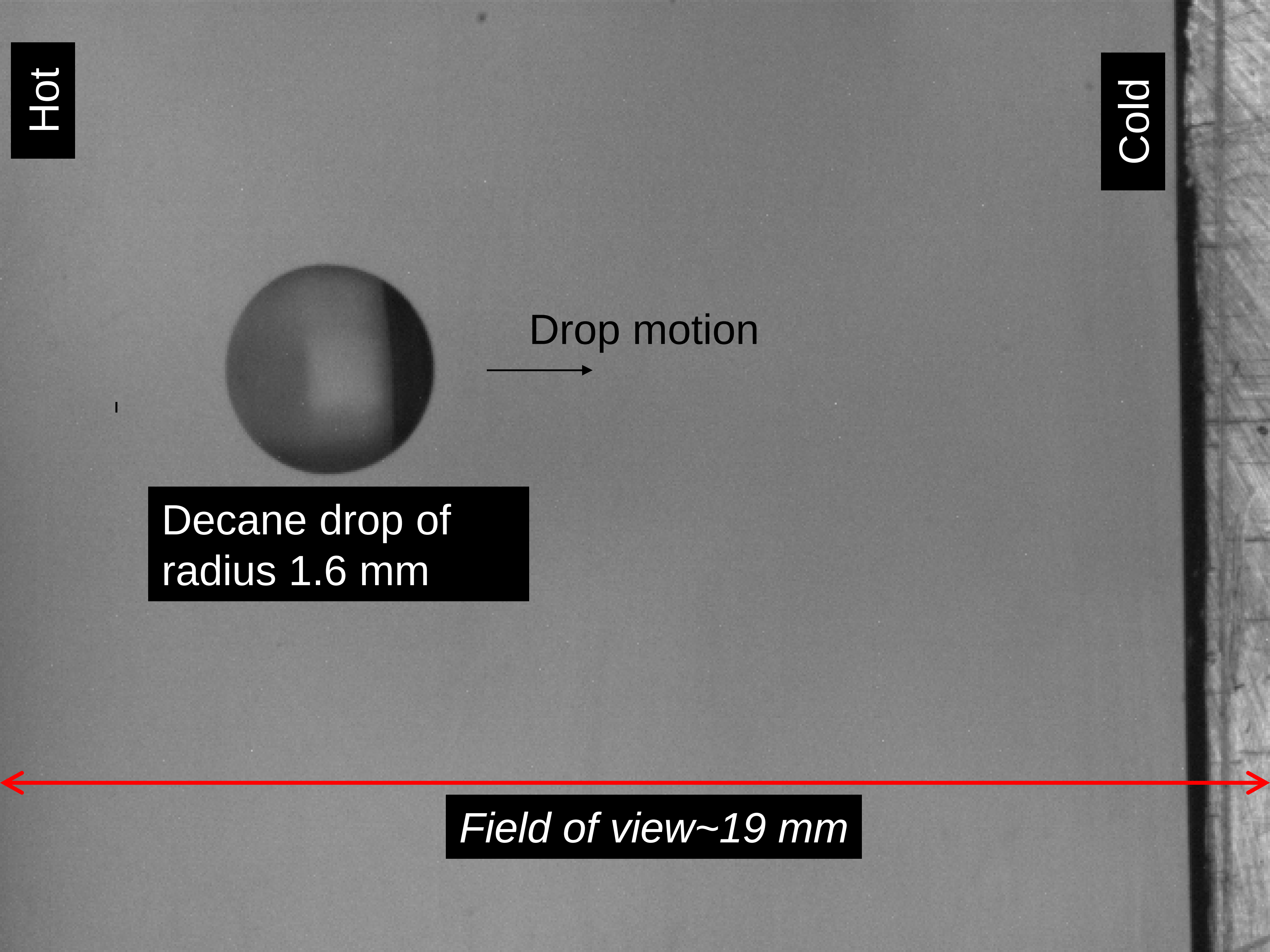
Background

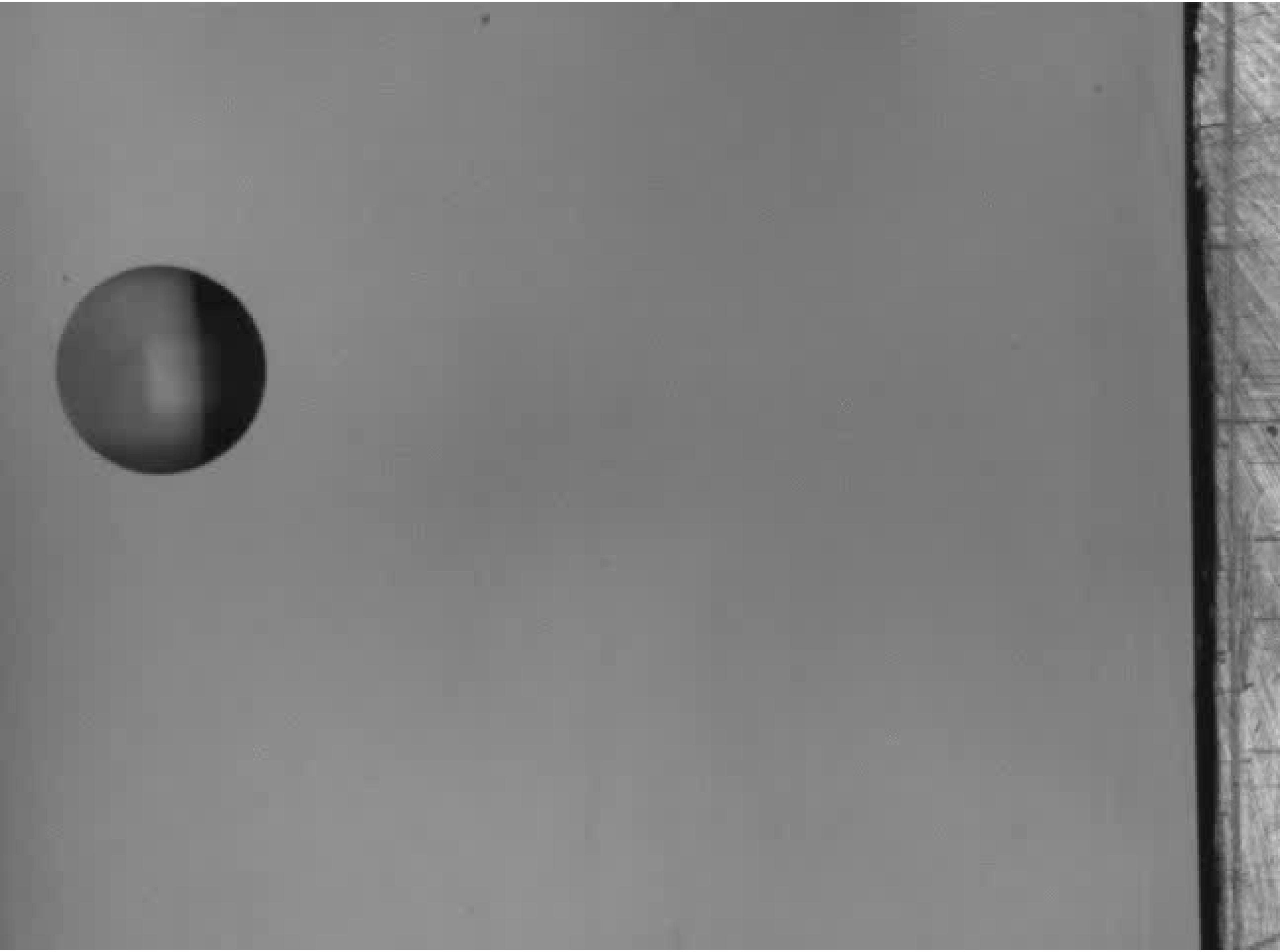


- A drop when introduced on a horizontal solid surface will spread and attain an equilibrium shape.

- A drop on a horizontal surface can be made to move by applying forces to it.

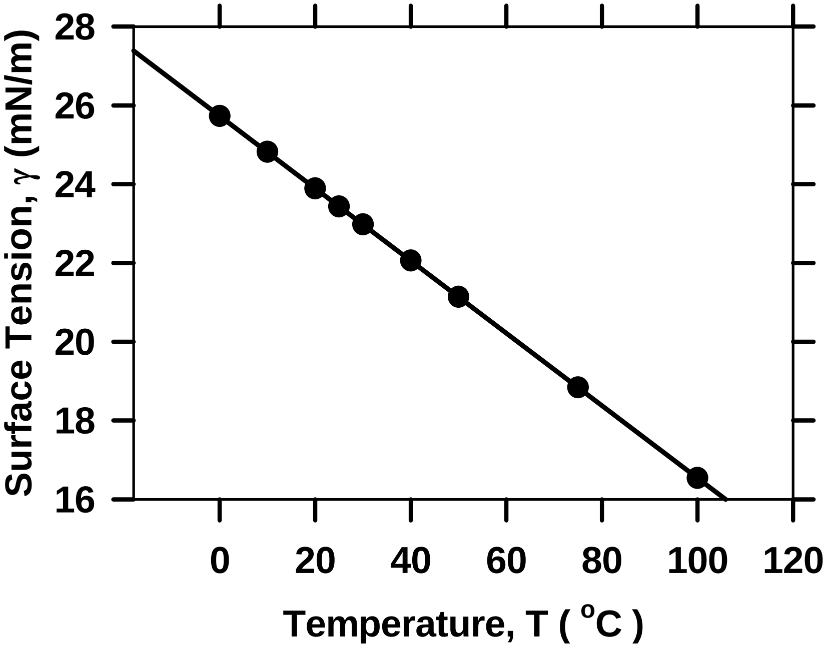
- Forces can be created by two methods:
  - Wettability gradient (contact angle gradient)
  - Thermocapillarity (temperature gradient)

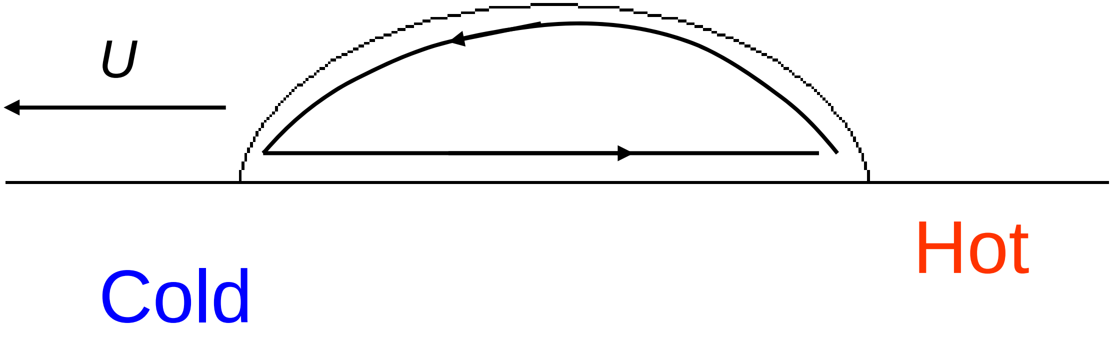

Hot
Cold
Drop motion
Decane drop of radius 1.6 mm
Field of view~19 mm



Why does a drop move in a temperature gradient?

- Surface tension decreases with increase in temperature.





Applications

It is basically a transport mechanism for liquids without the need for a conventional mechanism

- Lab-on-a-chip.
  - Chemistry
  - Biotechnology

- Reduced gravity
  (or space) experiments.

Literature Review

Theory

- Brochard (1989)
  - Developed a 2D model for small contact angles using lubrication theory, for both wettability and temperature gradients
- Ford and Nadim (1993)
  - Developed a 2D model for an arbitrarily-shaped drop using lubrication theory
  - The model allowed for the possibility of change in the contact angles due to a temperature gradient
- Subramanian *et al.* (2005)
  - Developed a 3D model using lubrication theory
  - The model was developed and used for wettability gradients

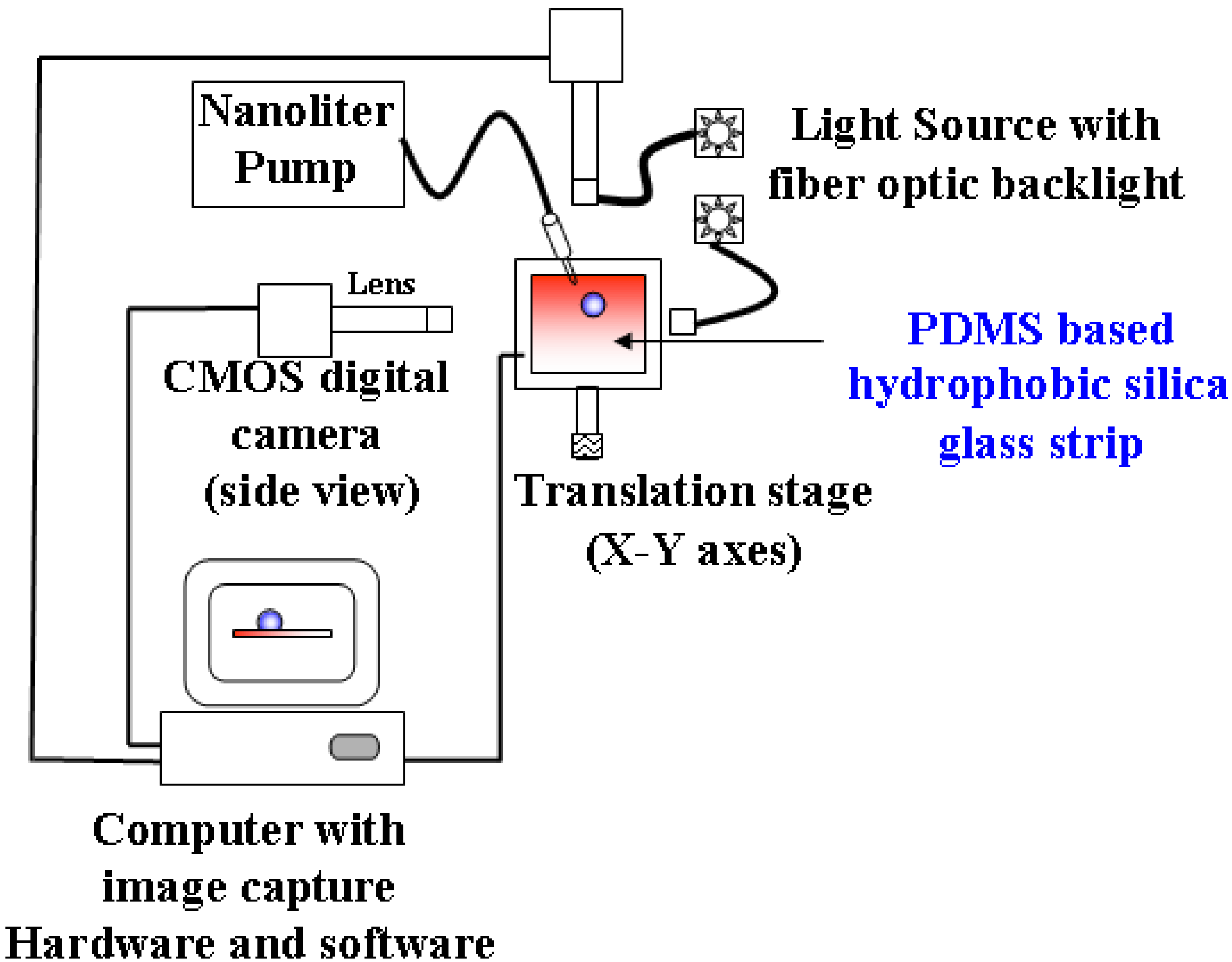
Experiments employing temperature gradients

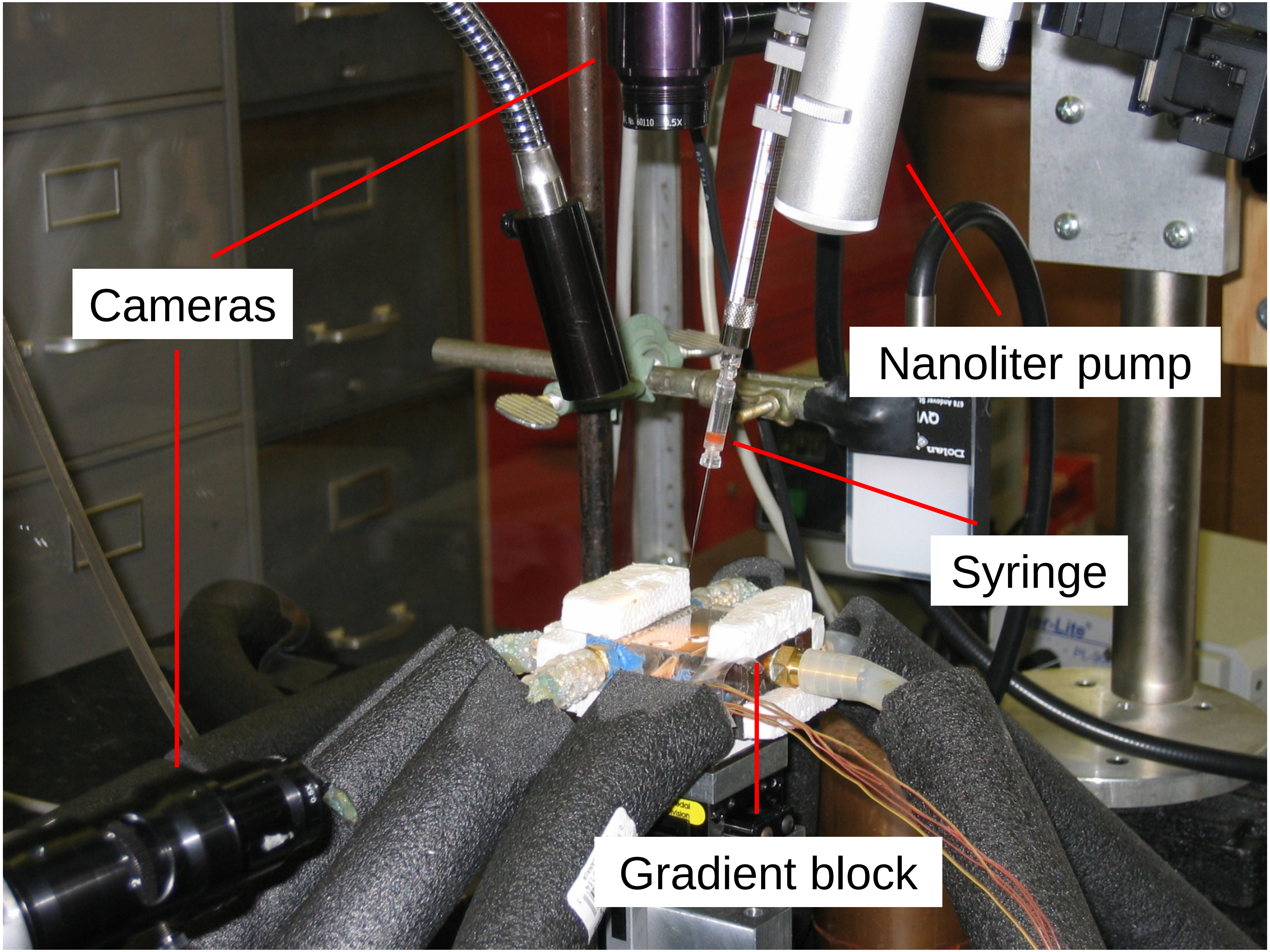
- Bouasse (1924) performed experiments with an oil drop on a slightly tilted metal wire. The drop moved up when the lower end of the wire was heated.
- Brzoska et al. (1993) studied the motion of silicone oil drops on silanized surfaces.
- Yarin *et al.* (2002) studied the motion of drops of different alkanes along a glass fiber.
- Chen *et al.* (2005) performed experiments with various alkanes on silanized surfaces.

Objectives

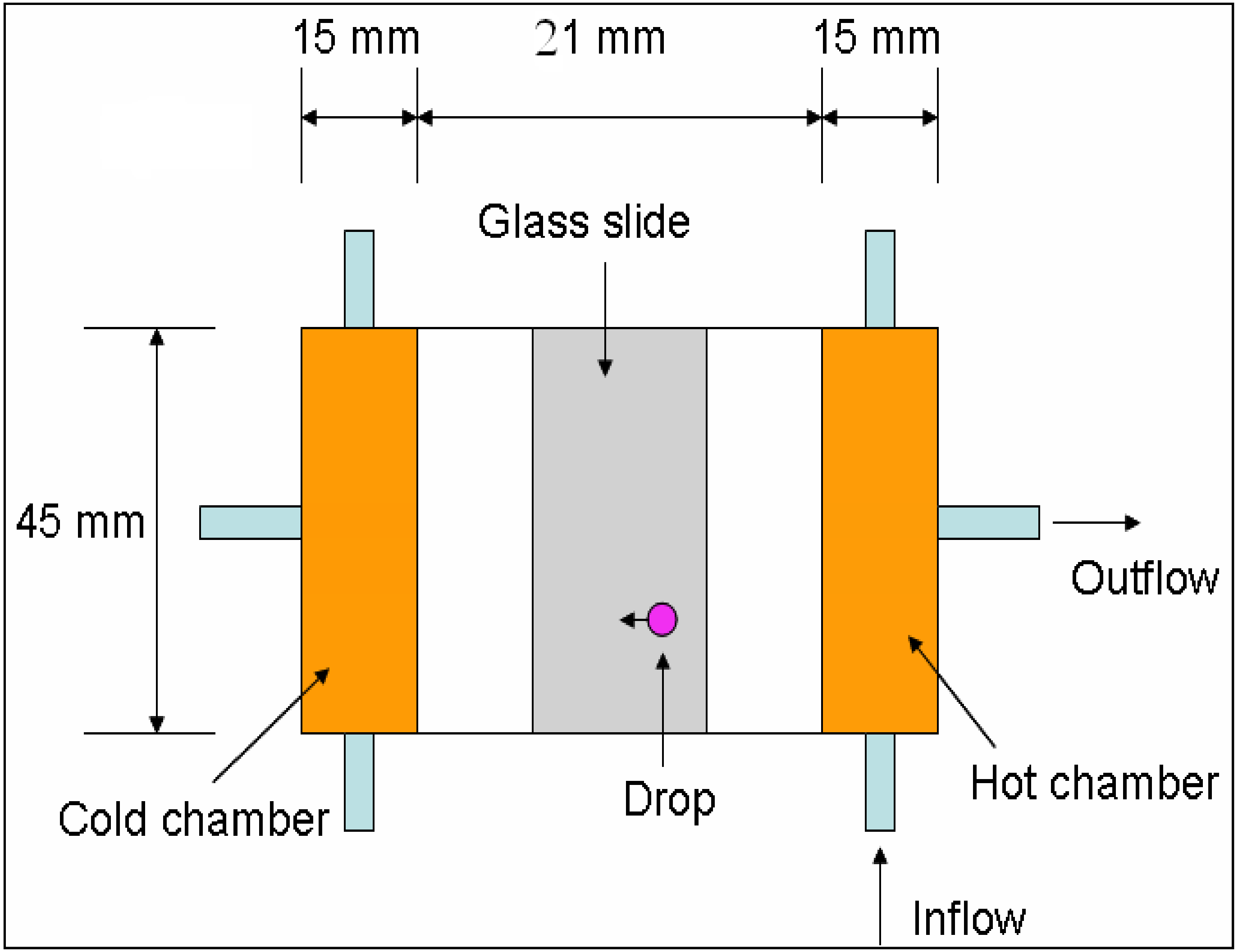
- To measure the velocities of liquid drops of various sizes at different gradients.
- To measure the contact angle as a function of temperature .
- To extend the theoretical model developed by Subramanian *et al.* (2005) for temperature gradients.
- To compare the measured velocities with predictions from theory.

Schematic of the experimental apparatus




Cameras
Nanoliter pump
Syringe
Gradient block

Thermal gradient block



Surface Preparation

- A glass surface is cleaned with deionized water, acetone and methanol.

- The surface is then washed with base Piranha (30:70; NH_4OH :H_2O_2) solution.

- Next the surface is coated with PGMA using a spin coating method.

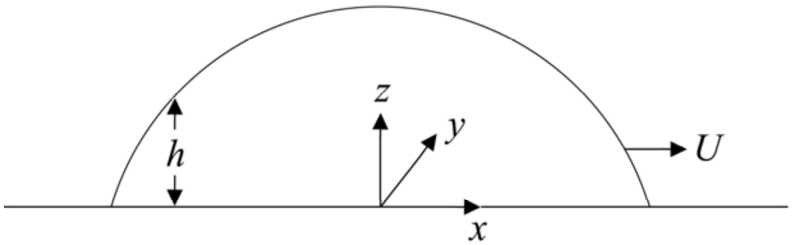
- Then a PDMS layer is adhered onto the PGMA layer on the glass surface.

Experimental procedure

- A steady state temperature gradient is established using circulating fluid from constant temperature baths
- The coated glass slide is then placed on the block surface and sufficient time is allowed for a steady gradient to be established on the surface
- Next, decane drops of different sizes are introduced on different tracks on the surface and their motion is monitored using video cameras.
- The captured images are then tracked using SPOTLIGHT which yields position vs. time data.
- The instantaneous velocity is deduced by finding the slope of the position vs. time curve.

Theoretical model

$$\boxed{\frac{\partial p}{\partial x} = \mu \frac{\partial^2 v_x}{\partial z^2}}$$



$$v_x(z=0) = -U$$

$$\mu \frac{\partial v_x}{\partial z}\bigg|_{z=h} = \frac{\partial \gamma}{\partial x}$$

$$v_x = -U + \frac{1}{2\mu}\frac{\partial p}{\partial x}\left(z^2 - 2hz\right) + \frac{z}{\mu}\frac{\partial \gamma}{\partial x}$$

$$\int_0^h v_x dz = 0$$ Volumetric flow condition

$$\tau_w = -\mu \frac{\partial v_x}{\partial z}\bigg|_{z=0} = -\frac{3\mu U}{h} + \frac{1}{2}\frac{\partial \gamma}{\partial x}$$

$$h = \sqrt{R^2 cosec^2\theta - r^2} - R\cot\theta$$

$$F_h = \int_\Omega \tau_w \, dA$$

$$F_h = -6\pi\mu UR\left[g\left(\theta, 1-\varepsilon\right) - g\left(\theta, 0\right)\right] + \frac{\pi R^2 G\gamma_T}{2}$$

where

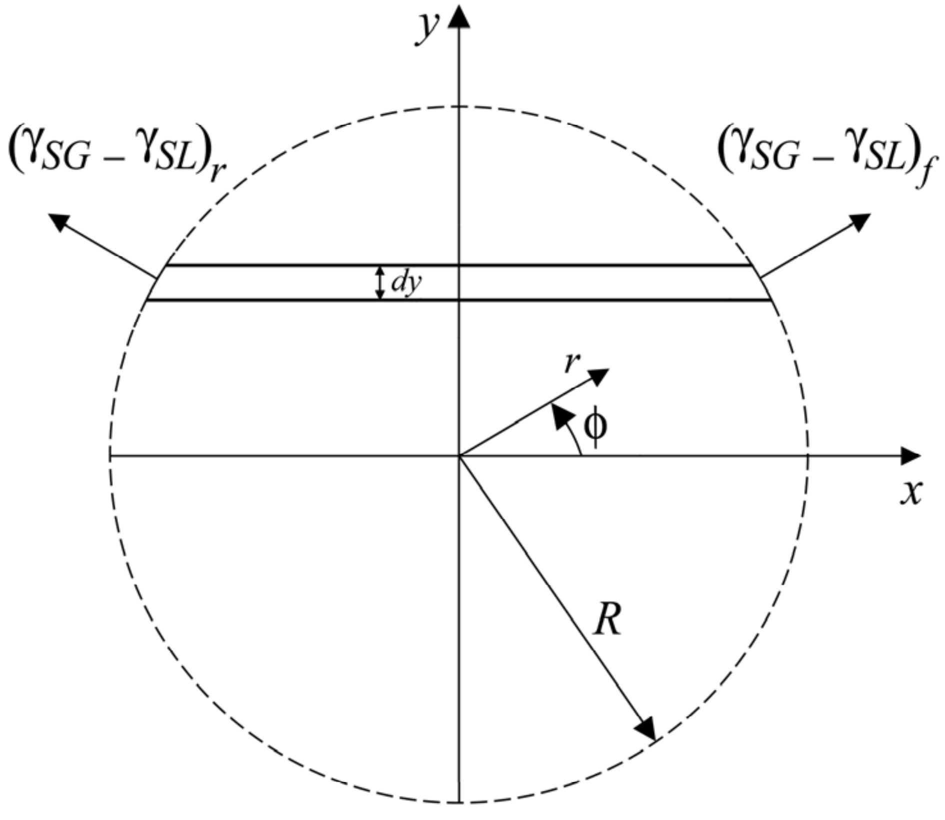
$$g = \int \frac{rdr}{\sqrt{cosec^2\theta - r^2} - \cot\theta} = -\left[\cot\theta \ln\left(\sqrt{cosec^2\theta - r^2} - \cot\theta\right)\right.$$

$$\left. + \sqrt{cosec^2\theta - r^2} - \cot\theta \right]$$

and

$$\varepsilon = L_s / R$$

Force at the contact line



$$dF_{cl} = \left[\left(\gamma_{SG} - \gamma_{SL} \right)_f - \left(\gamma_{SG} - \gamma_{SL} \right)_r \right] \cos\phi \, dl$$

$$F_{cl} = 2R\int_0^{\frac{\pi}{2}} \left\{\left(\gamma_{SG} - \gamma_{SL}\right)_f - \left(\gamma_{SG} - \gamma_{SL}\right)_r\right\}\cos\phi\, d\phi$$

$$\gamma_{SG} - \gamma_{SL} = \gamma \cos\theta_e$$

$$\gamma = \gamma_0 + \gamma_T G\, x$$

where G is the temperature gradient

$$F_{cl} = 4R^2 G\gamma_T \cos\theta_e \int_0^{\frac{\pi}{2}} \cos^2\phi \, d\phi = \pi R^2 G\gamma_T \cos\theta_e$$

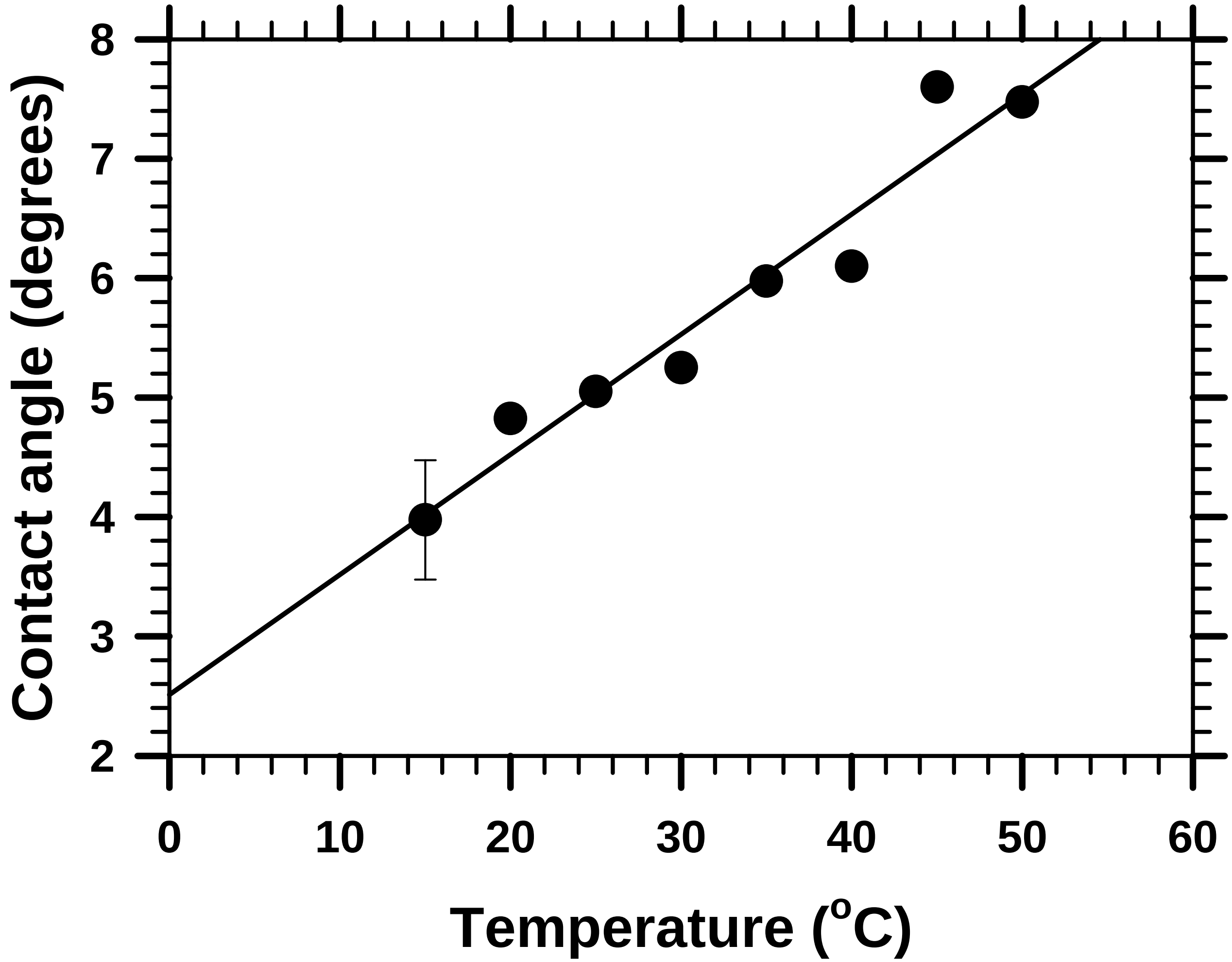
$$F_h + F_{cl} = -6\pi\mu UR\left[g\left(\theta, 1-\varepsilon\right) - g\left(\theta, 0\right)\right]$$

$$+ \frac{\pi R^2 G\gamma_T}{2} + \pi R^2 G\gamma_T \cos\theta_e = 0$$

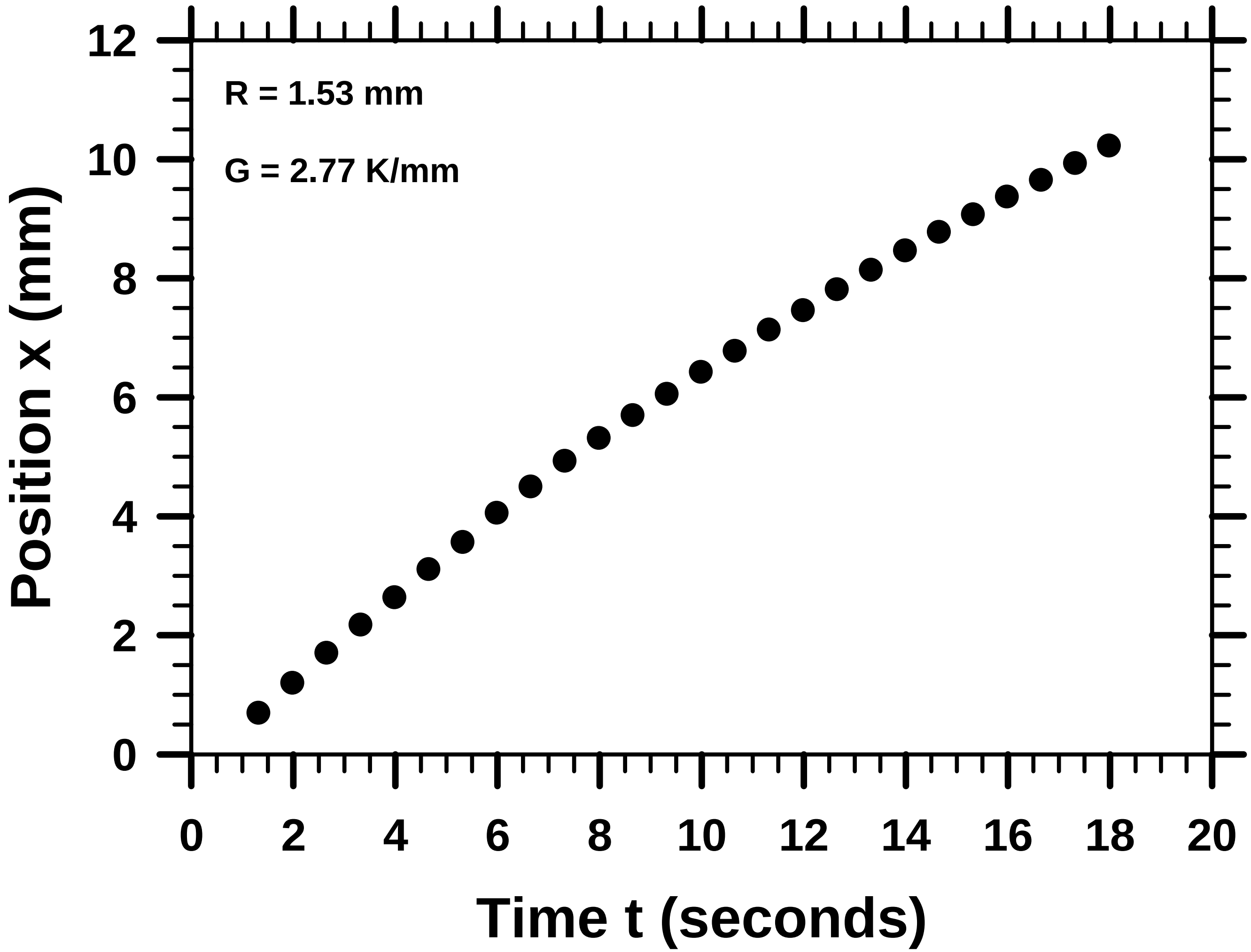
$$\boxed{U = \frac{RG\gamma_T\left(1 + 2\cos\theta_e\right)}{12\mu\left[g\left(\theta, 1-\varepsilon\right) - g\left(\theta, 0\right)\right]}} \qquad (5.51)$$

Decane Results

Contact angle measurements

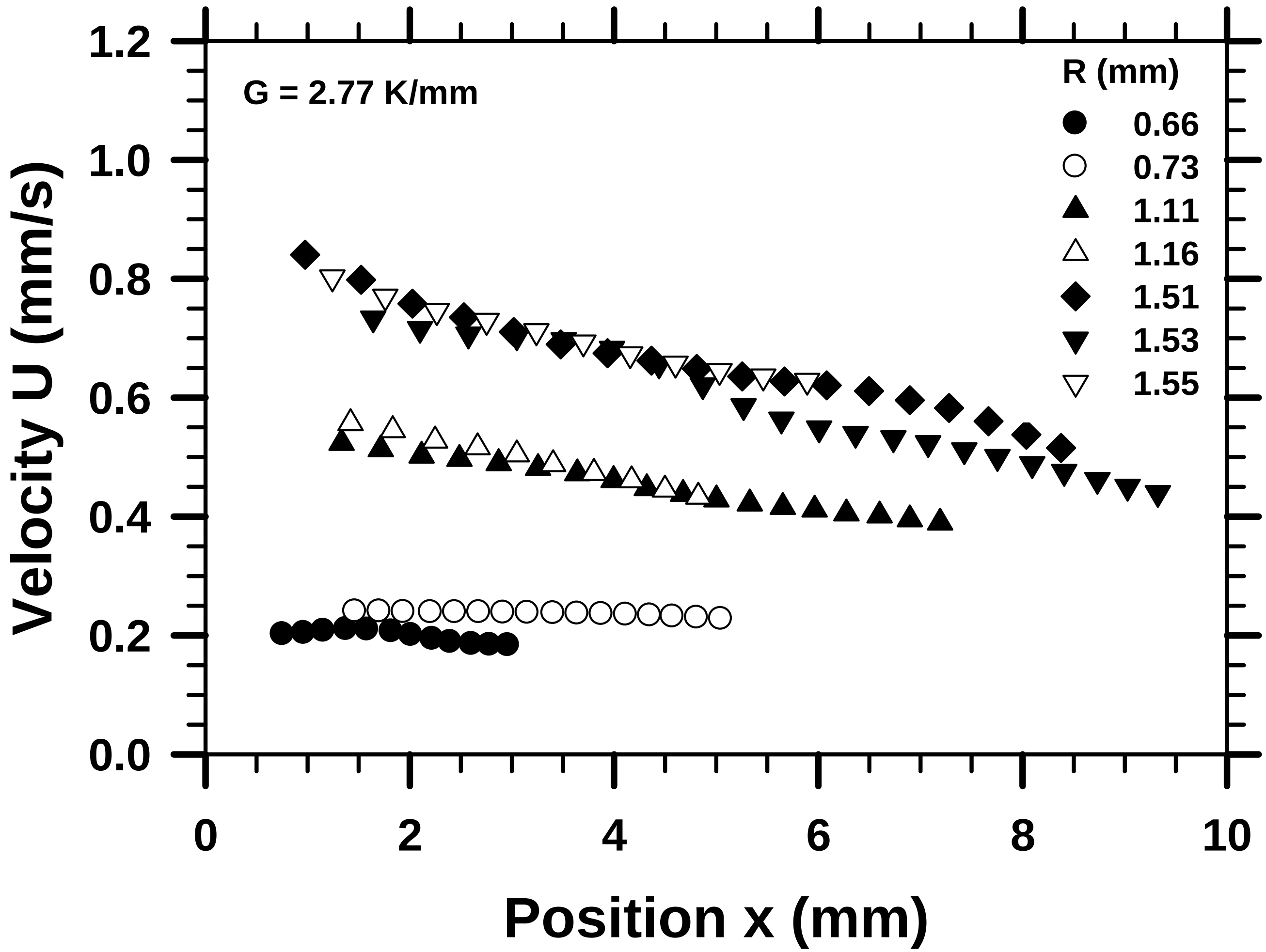


High Gradient

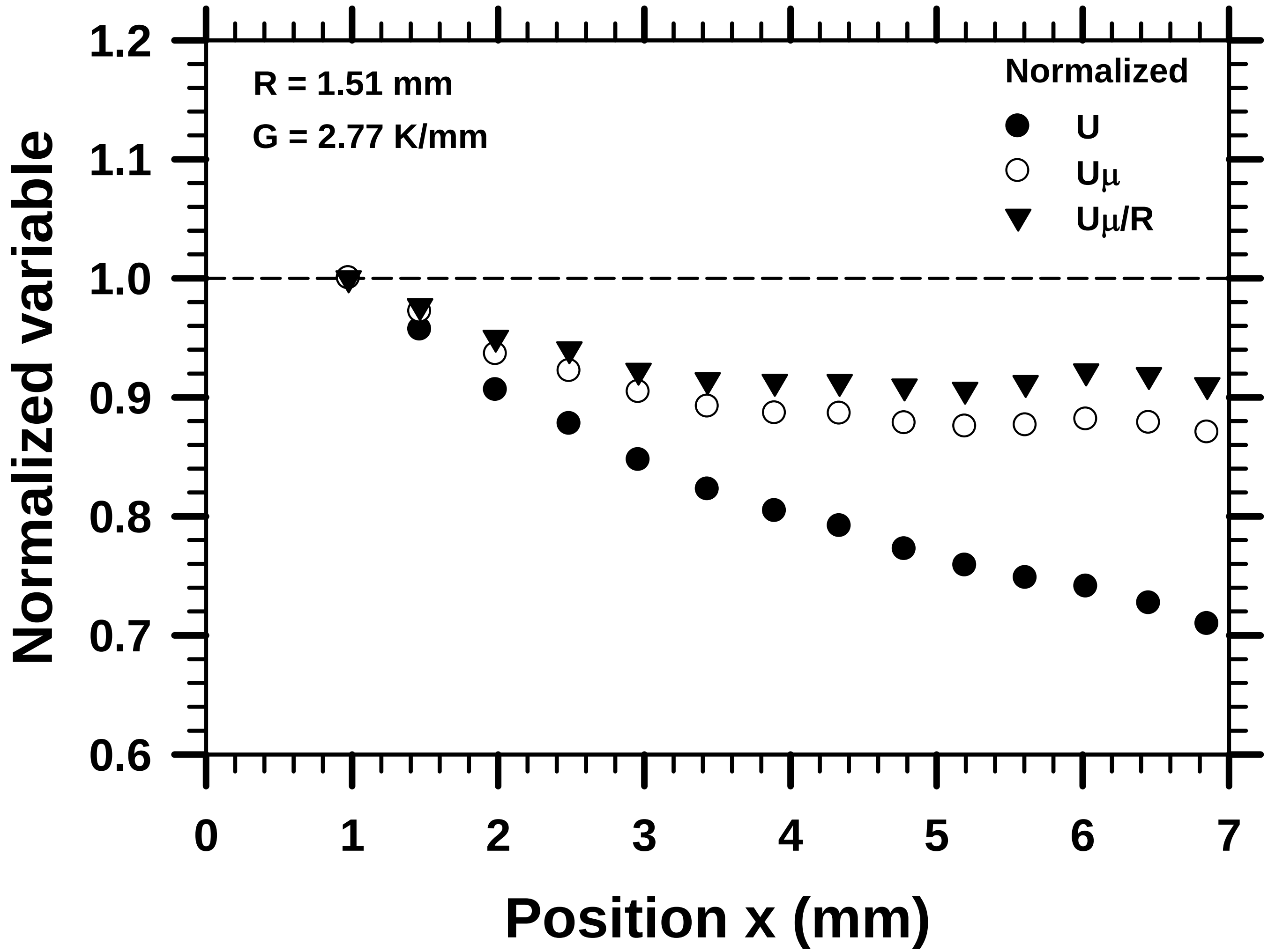


Velocity vs position

High gradient

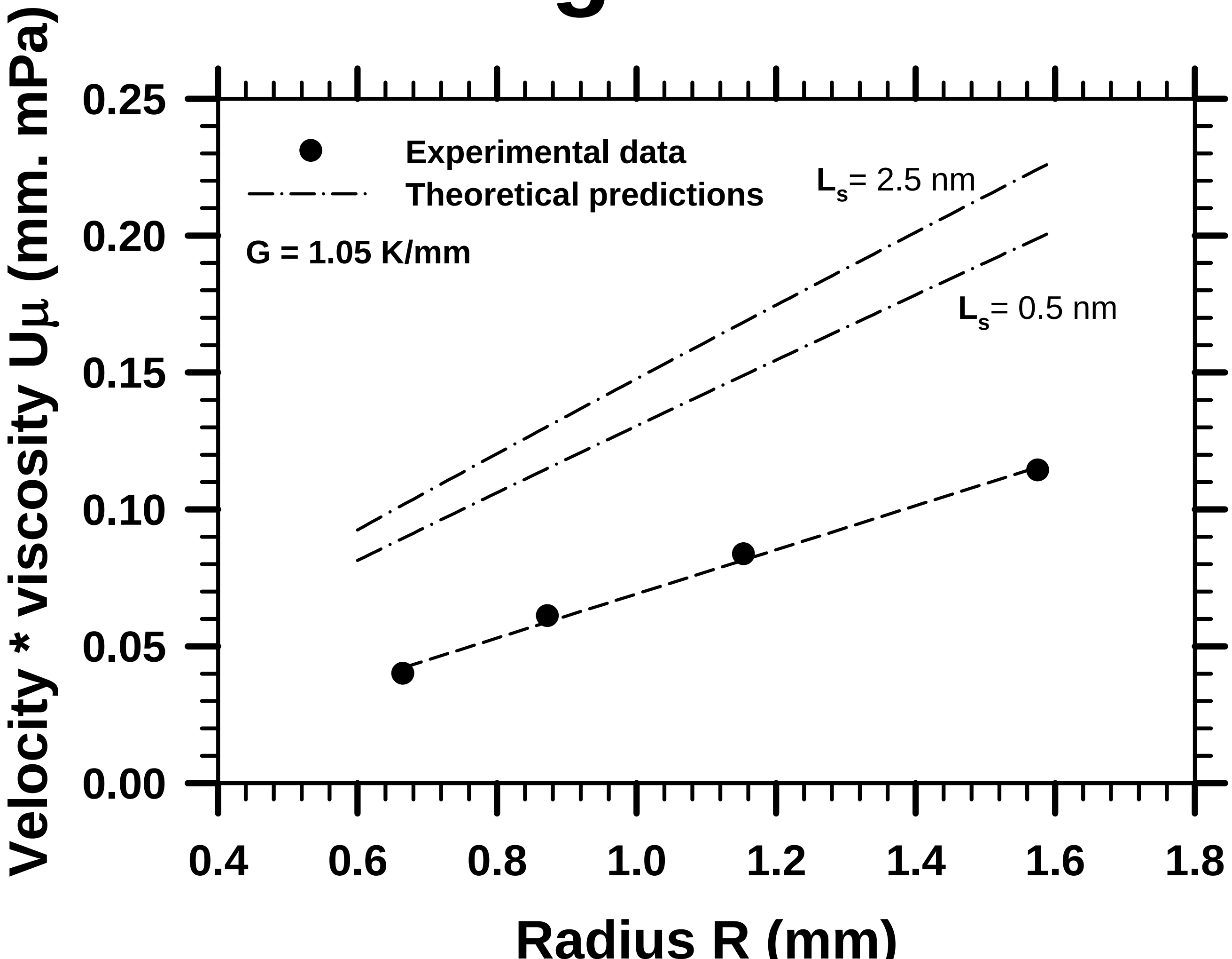


Corrected velocity of a drop



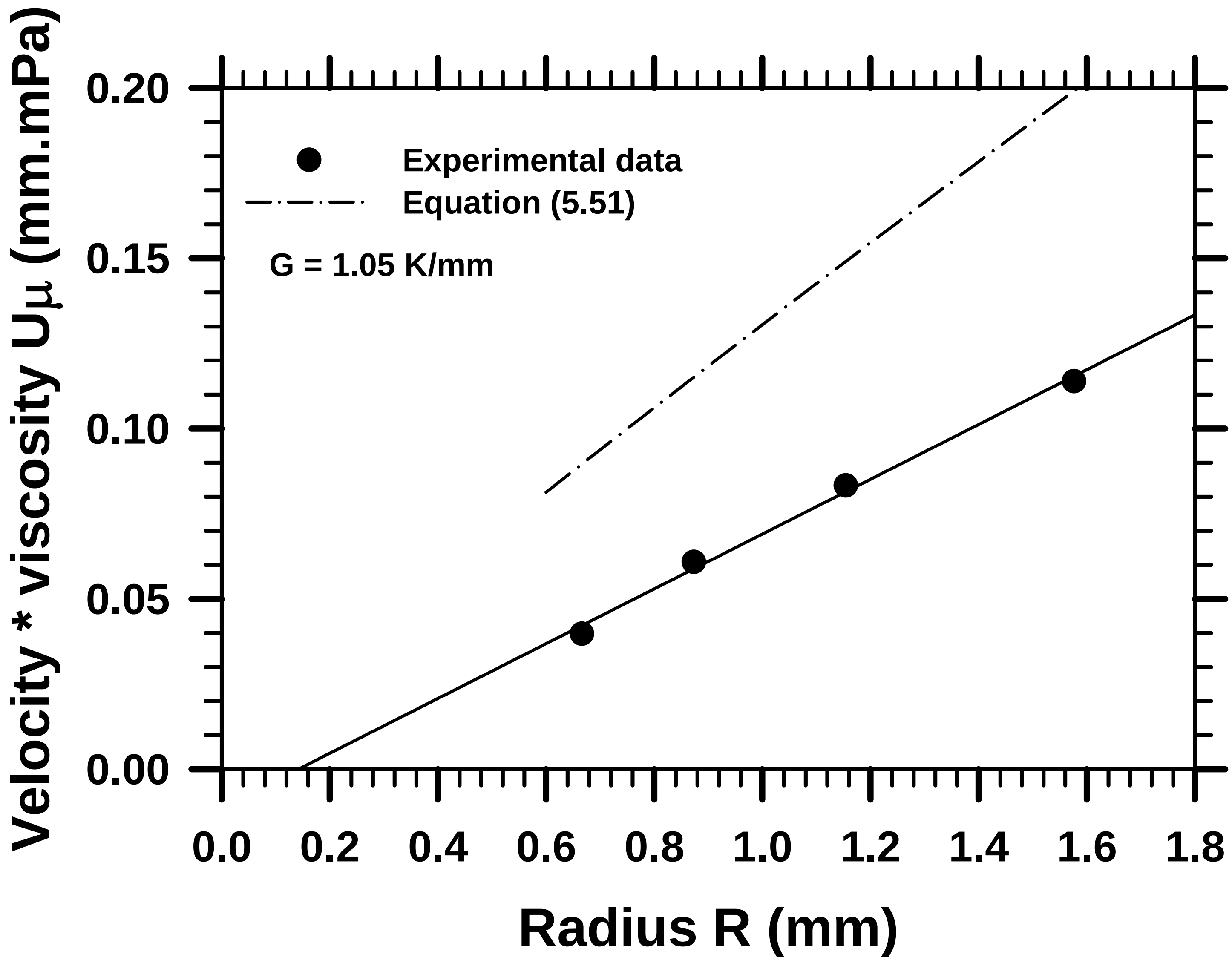
Comparison with predictions

Low gradient



Predicted vs observed slopes

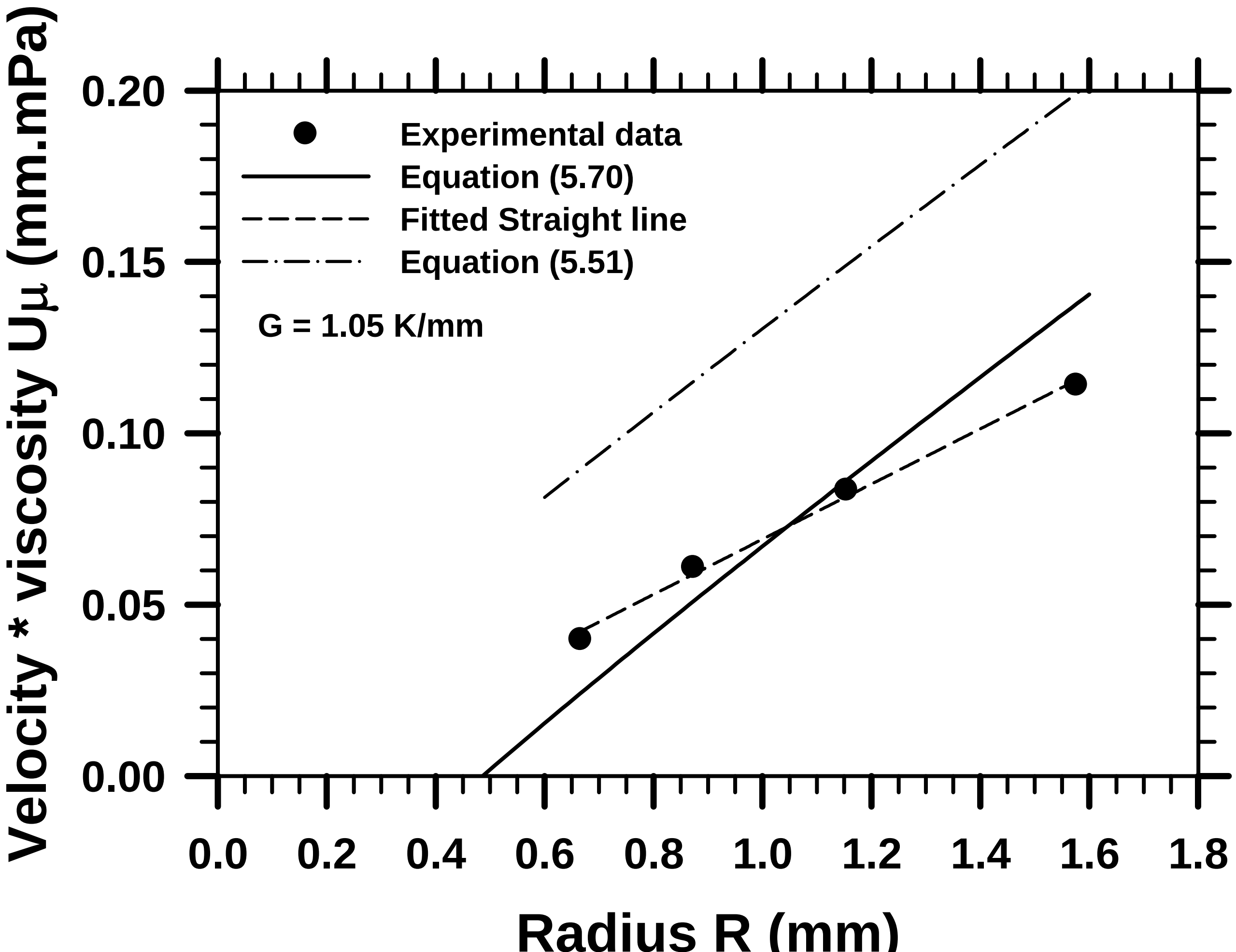
Temperature gradient (K/mm)	Observed slope (Pa x 10^{-4})	Predicted slope (Pa x 10^{-4})	Percentage discrepancy in slope	Contact angle decreased by 1°
1.05	0.805 ± 0.175	1.19 ± 0.14	48.4	13.9
1.85	1.90 ± 0.10	2.57 ± 0.23	35.4	9.4
2.77	4.25 ± 0.4	5.01 ± 0.40	17.9	0.6



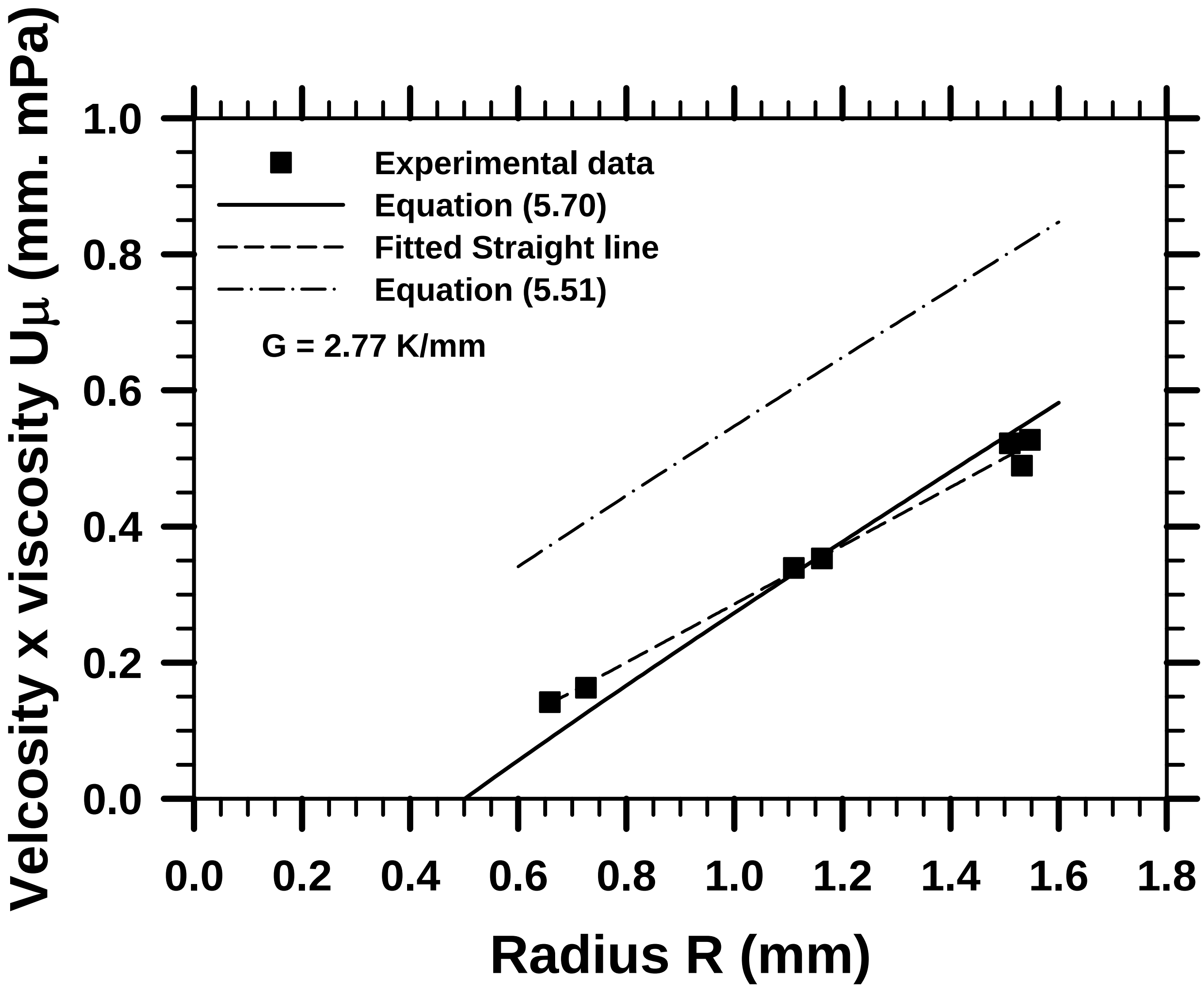
Experimental data
Equation (5.51)
G = 1.05 K/mm
0.00
0.05
0.10
0.15
0.20
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Radius R (mm)
Velocity * viscosity Uμ (mm.mPa)

Theory vs Experiments

Low gradient



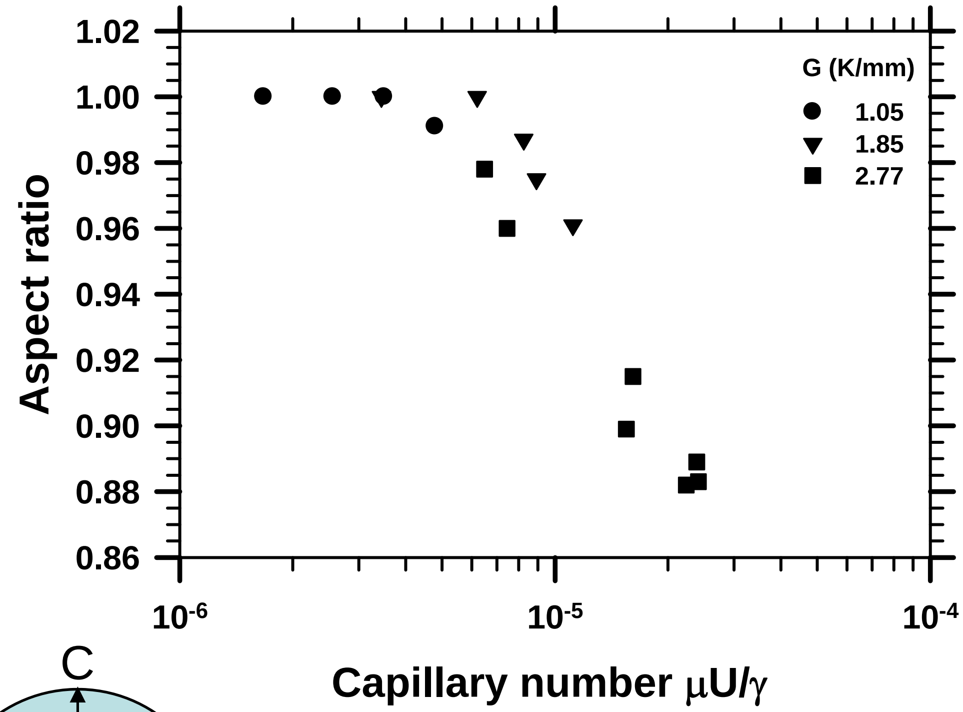
High gradient



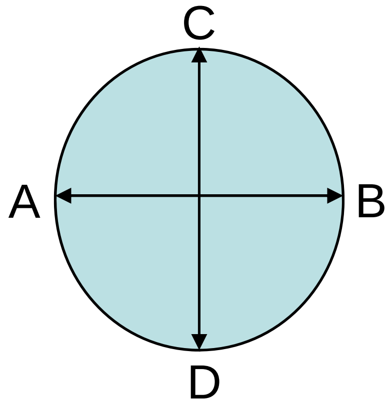
Aspect ratio

Capillary number is a dimensionless quantity that represents the relative effect of viscous forces to surface tension forces, and is written as

$$\mathrm{Ca} = \frac{\mu U}{\gamma}$$

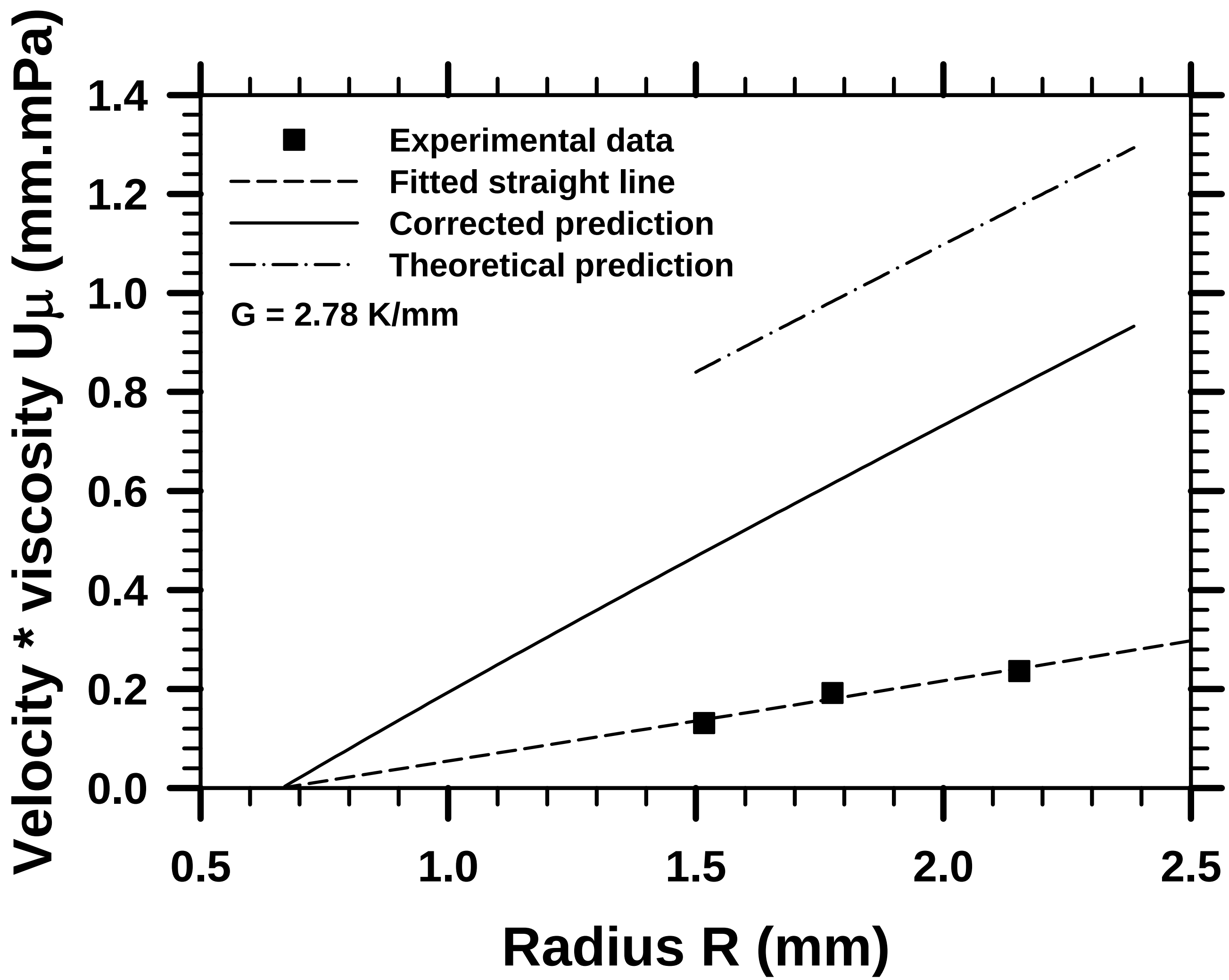


$$\text{Aspect ratio} = \frac{AB}{CD}$$



Hexadecane Results

Theory vs experiments

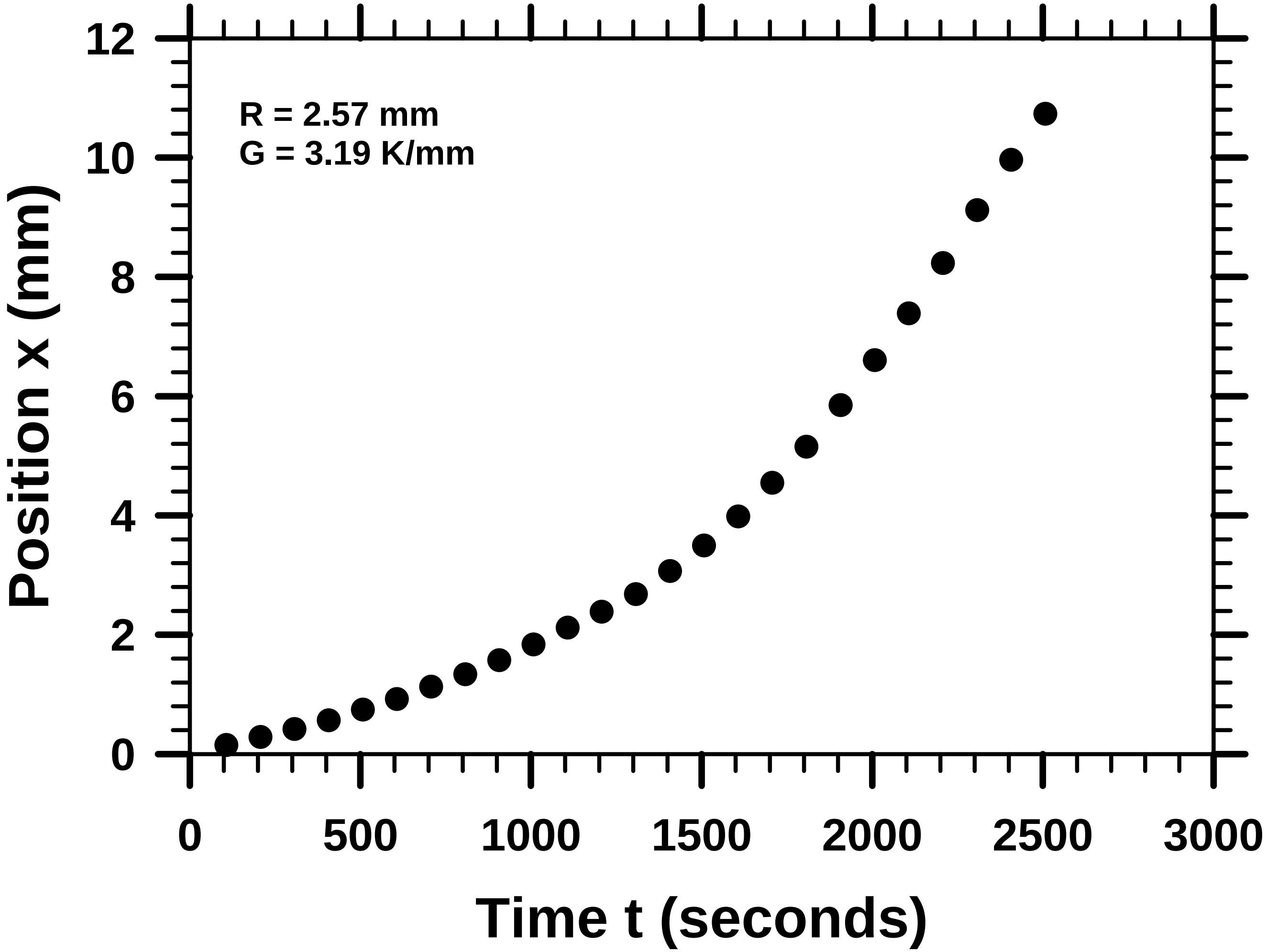


Slopes comparison

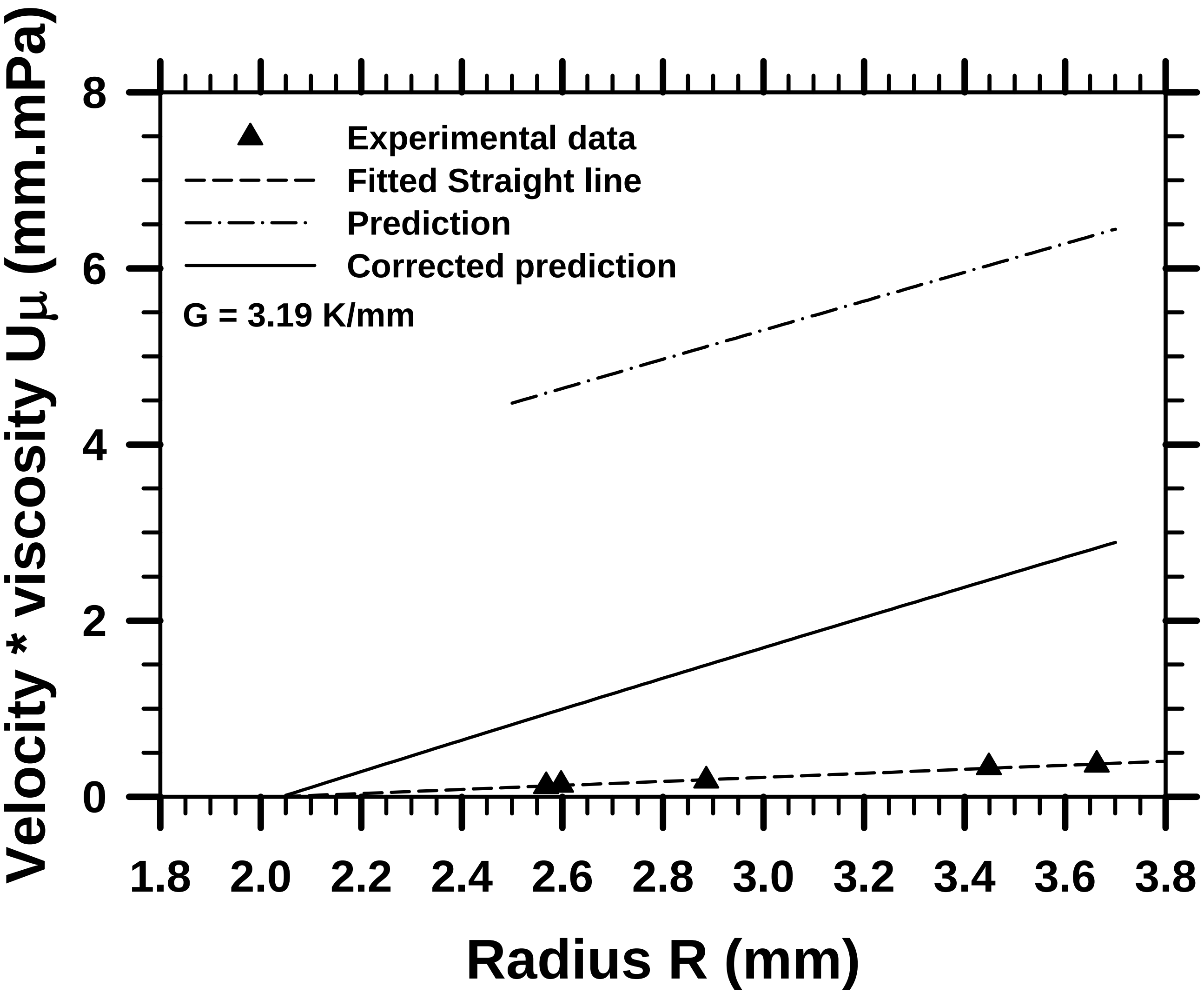
Temperature gradient (K/mm)	Observed slope (Pa x 10^{-4})	Predicted slope (Pa x 10^{-4})	Percentage discrepancy in slope
1.02	0.254 ± 1.046	1.95 ± 0.15	665
1.89	0.83 ± 0.33	3.68 ± 0.37	343
2.78	1.64 ± 4.12	5.12 ± 0.42	212

Squalane Results

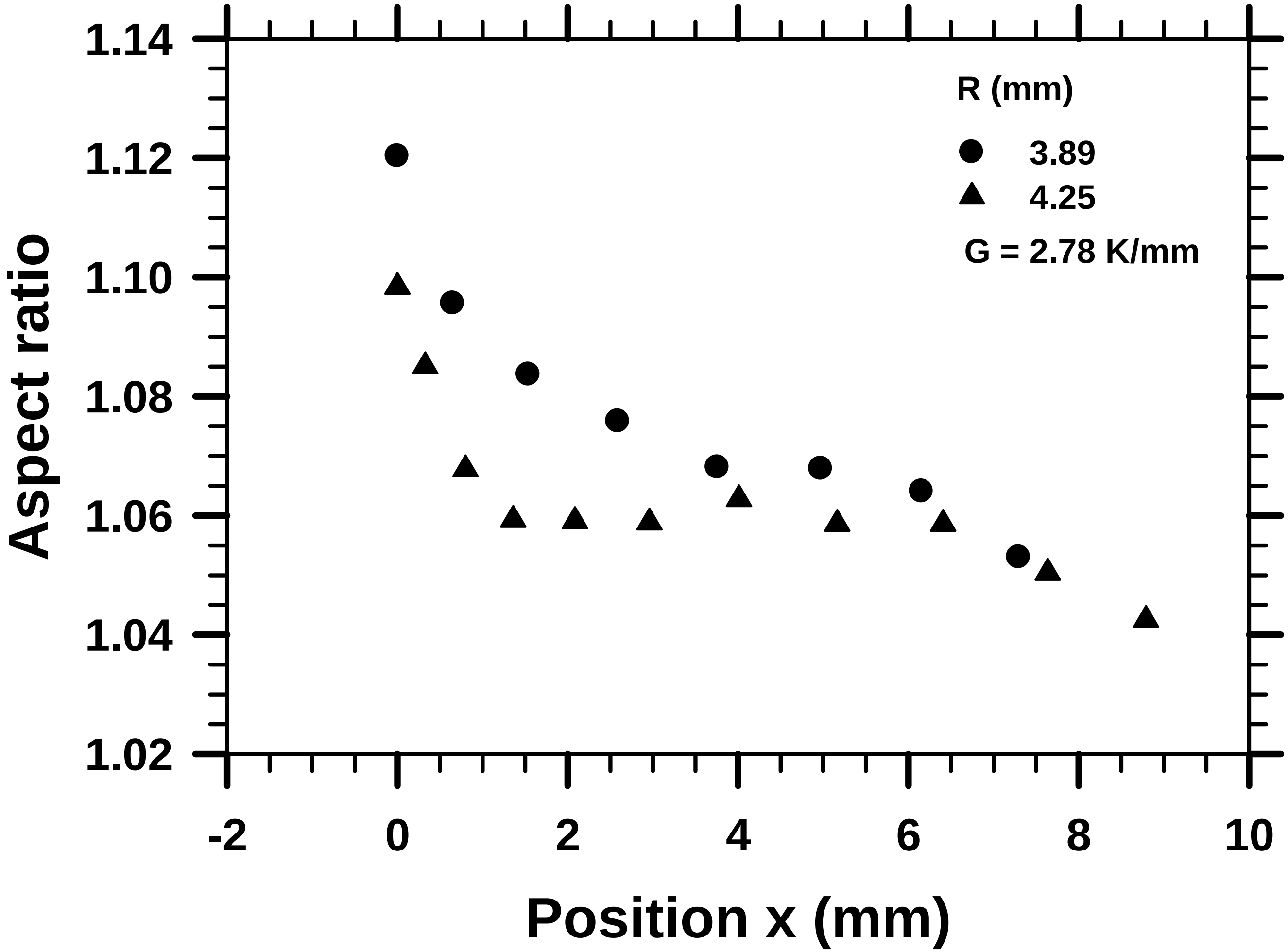
High gradient



Slopes comparison



Aspect ratio of squalane



Conclusions

Decane

- The contact angle of decane increases with increasing temperature.
- The velocity of a drop scales approximately linearly with size in the range of the data collected.
- The velocity appears to decrease with increasing viscosity.
- The slopes of the prediction are reasonable considering the approximations in developing the theory.
- The slopes of the predictions were found to be very sensitive to contact angle.
- Drop below a critical size did not move. This indicates the possible existence of contact angle hysteresis.

Hexadecane

- Hexadecane drops are larger than the decane drops, so that their shape is influenced significantly by gravity.
- The velocity of hexadecane drops also scales approximately linearly with radius.
- Velocity appears to decrease with increasing viscosity.
- Observed velocities are much smaller than those predicted. The reasons are not obvious.
- There is clear evidence of a critical radius below which a drop does not move in a given temperature gradient.

Squalane

- In order to exceed the critical radius, large drops had to be used; gravity plays a significant role in deforming the shapes of these drops

- the footprints of squalane drops are well-deformed from a circle, and the aspect ratio changes during the motion of the drop

- The velocity of squalane drops increases as the viscosity increases

- The velocity of squalane drops scales approximately linearly with the average radius

- The predictions are much worse than in the other cases; this may be connected to the extreme deformation of the footprints of the drops.

Recommendations

- Low contact angles should be measured with a better technique.

- The predictions for hexadecane and squalane were very different from experimental data. It would be interesting to study those liquids, particularly squalane in detail.

Acknowledgement

- Prof. R. Shankar Subramanian – Thesis advisor.
- Prof. Sergiy Minko and his student Roman Sheparovych.
- NASA for financial support.

Thank You

Questions?