Development of the Flow Instabilities and Extrudate Distortions During Extrusion Process

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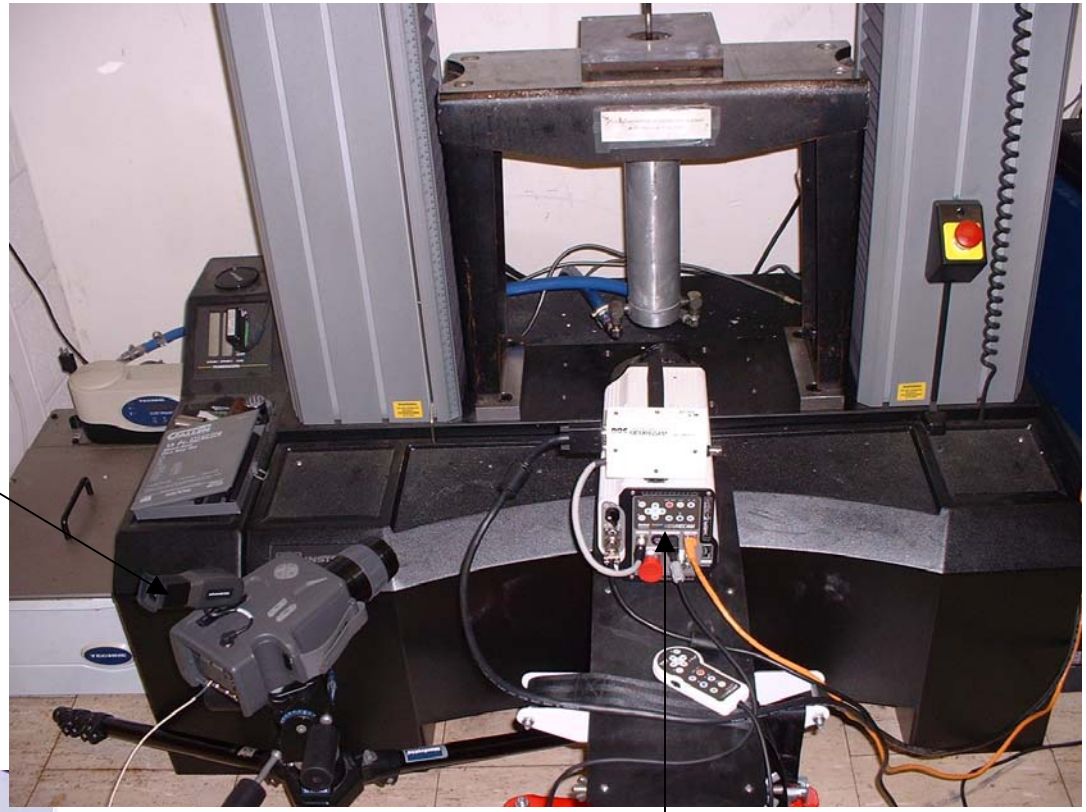
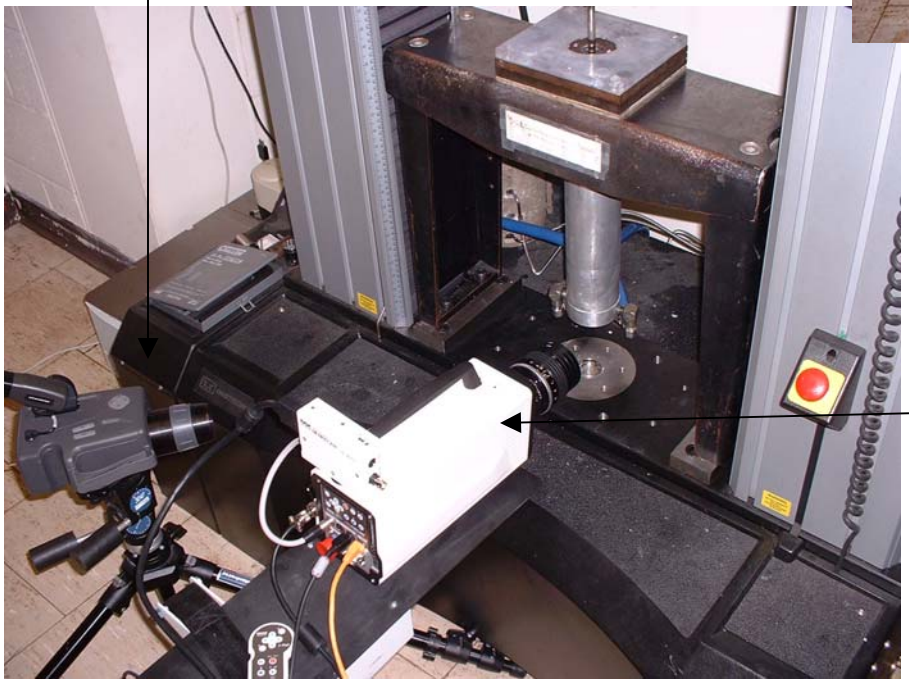
Experimental set-up:
Capillary flow

Thermal Imaging
Camera



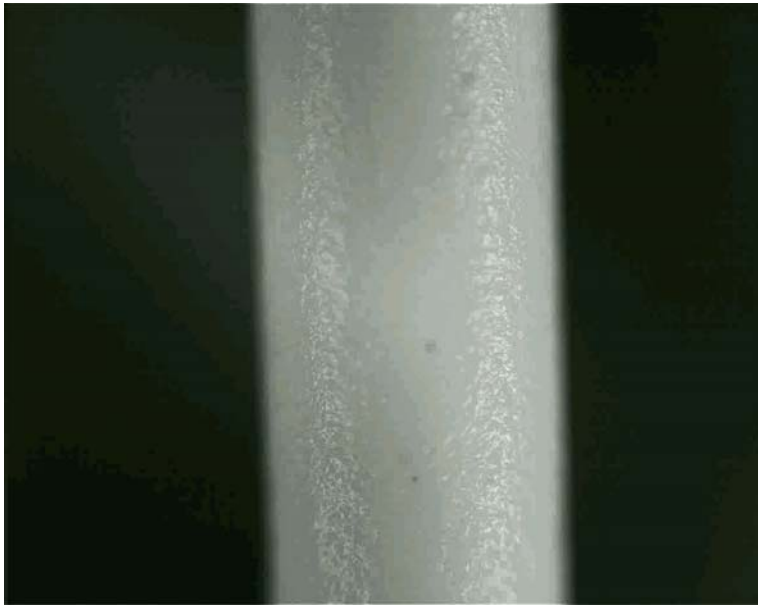


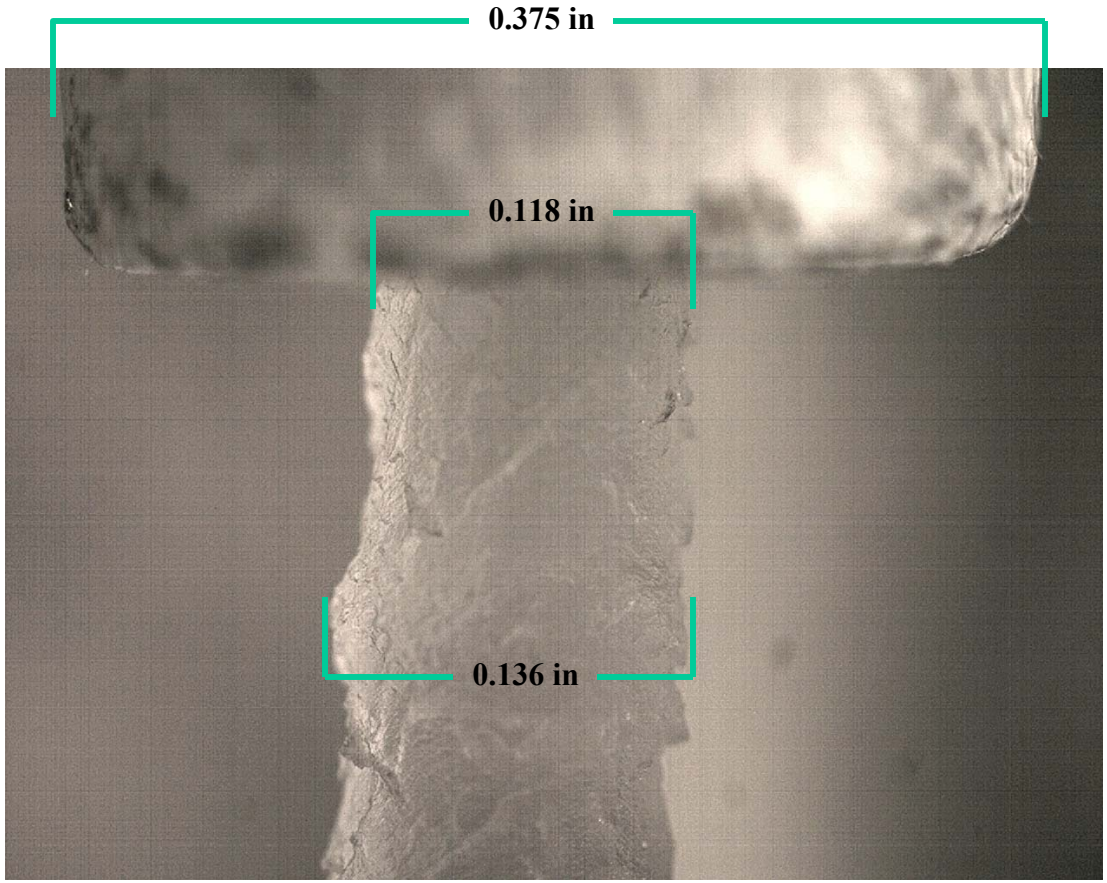
High Speed Camera

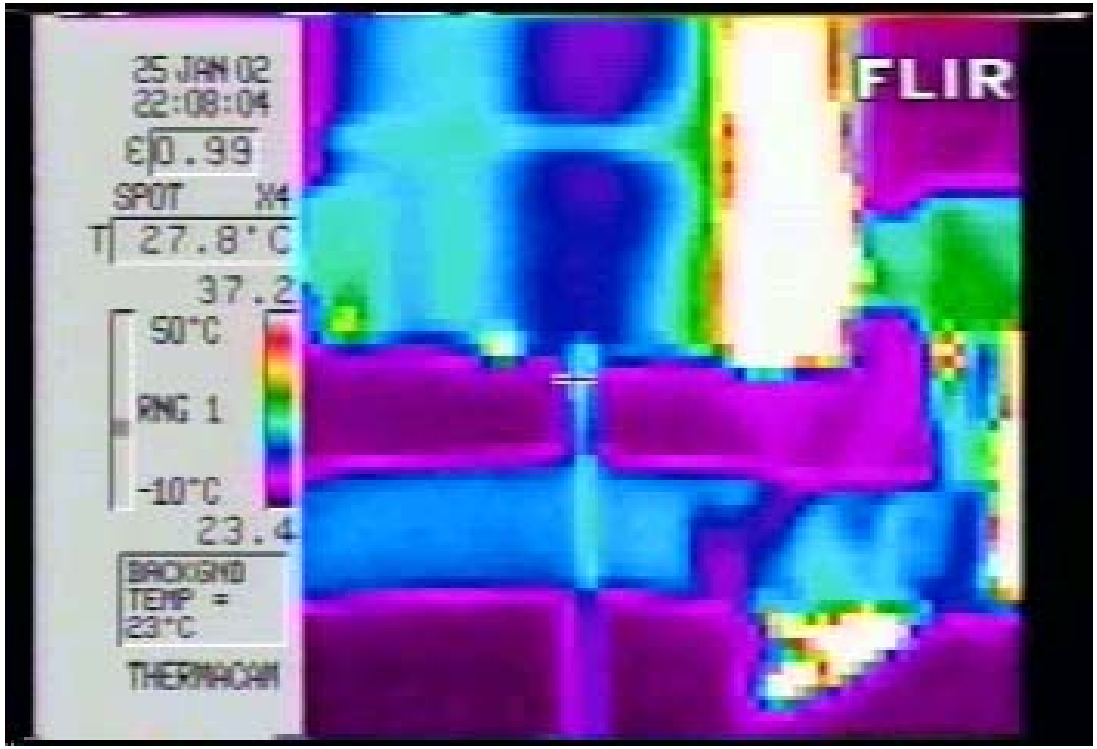
Up to 2000 fps

Study: Poly(dimethyl siloxane) and Suspensions with glass spheres (10 micron) 10-40% by volume

Experimental Materials: Poly(dimethyl siloxane) and suspensions With spherical glass beads (10 micron) in 10 to 40% by volume

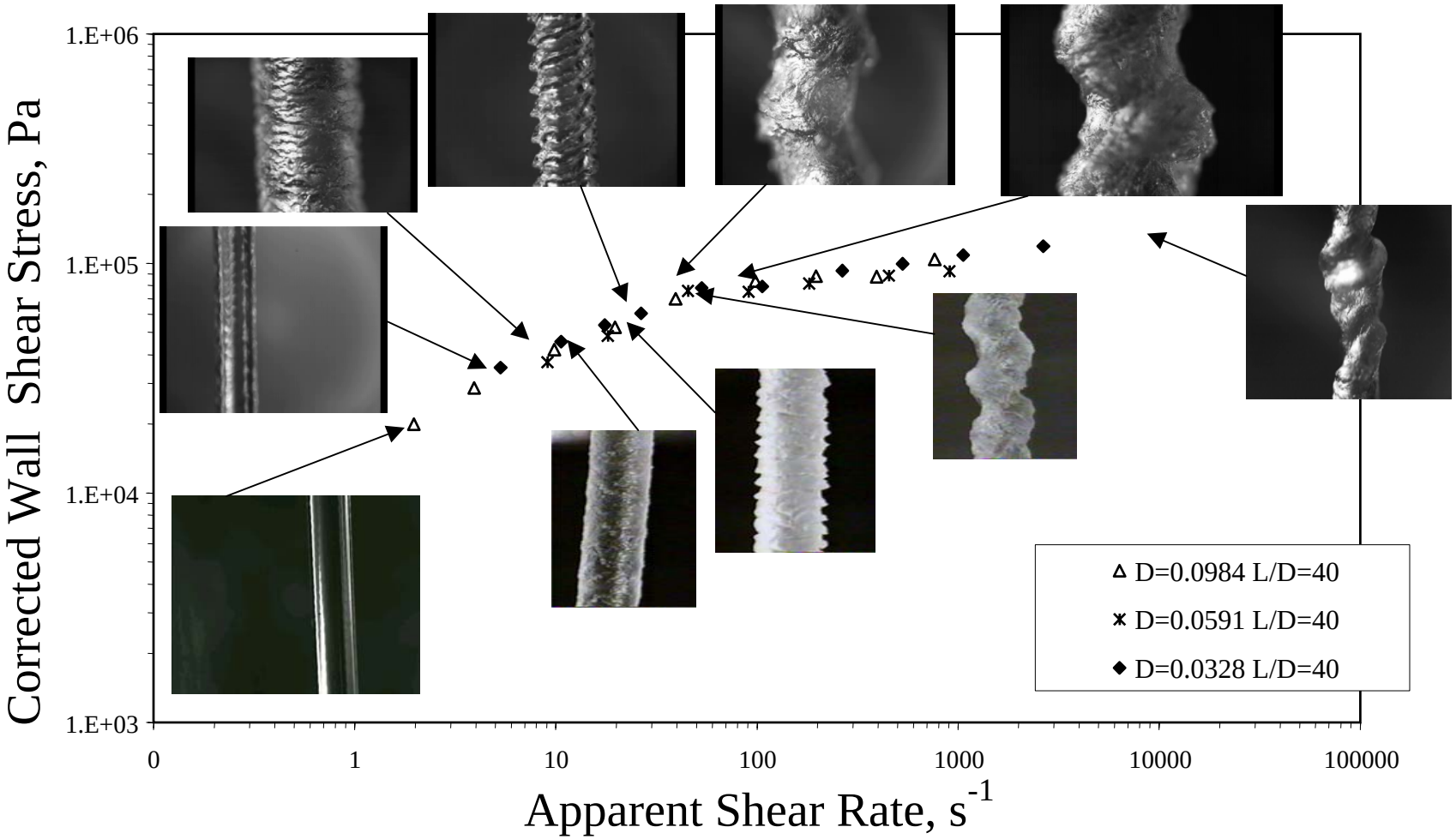






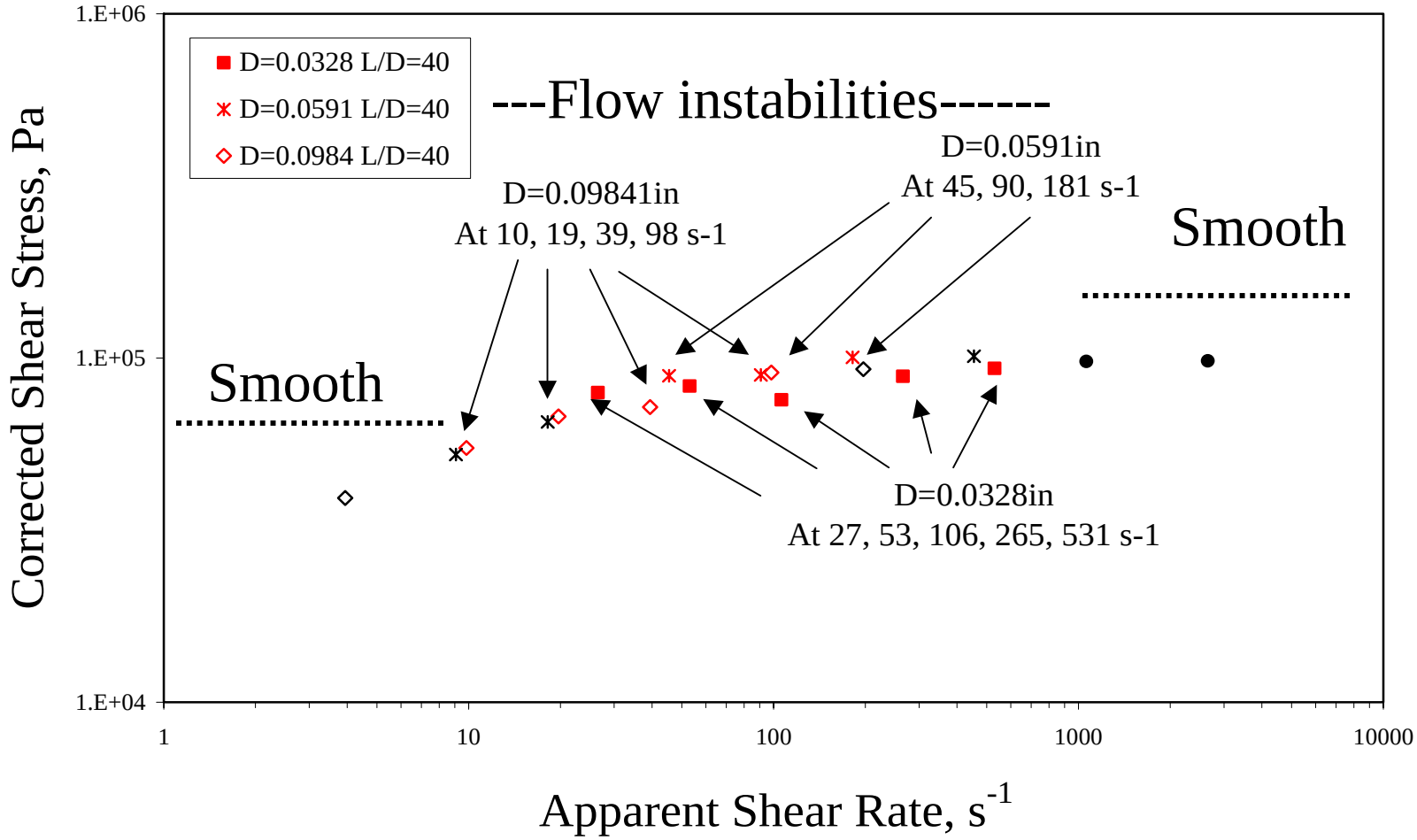
Thermal imaging of the capillary extrusion of PDMS to assure that viscous energy dissipation is not significant

Critical shear stress: 0.07 MPa



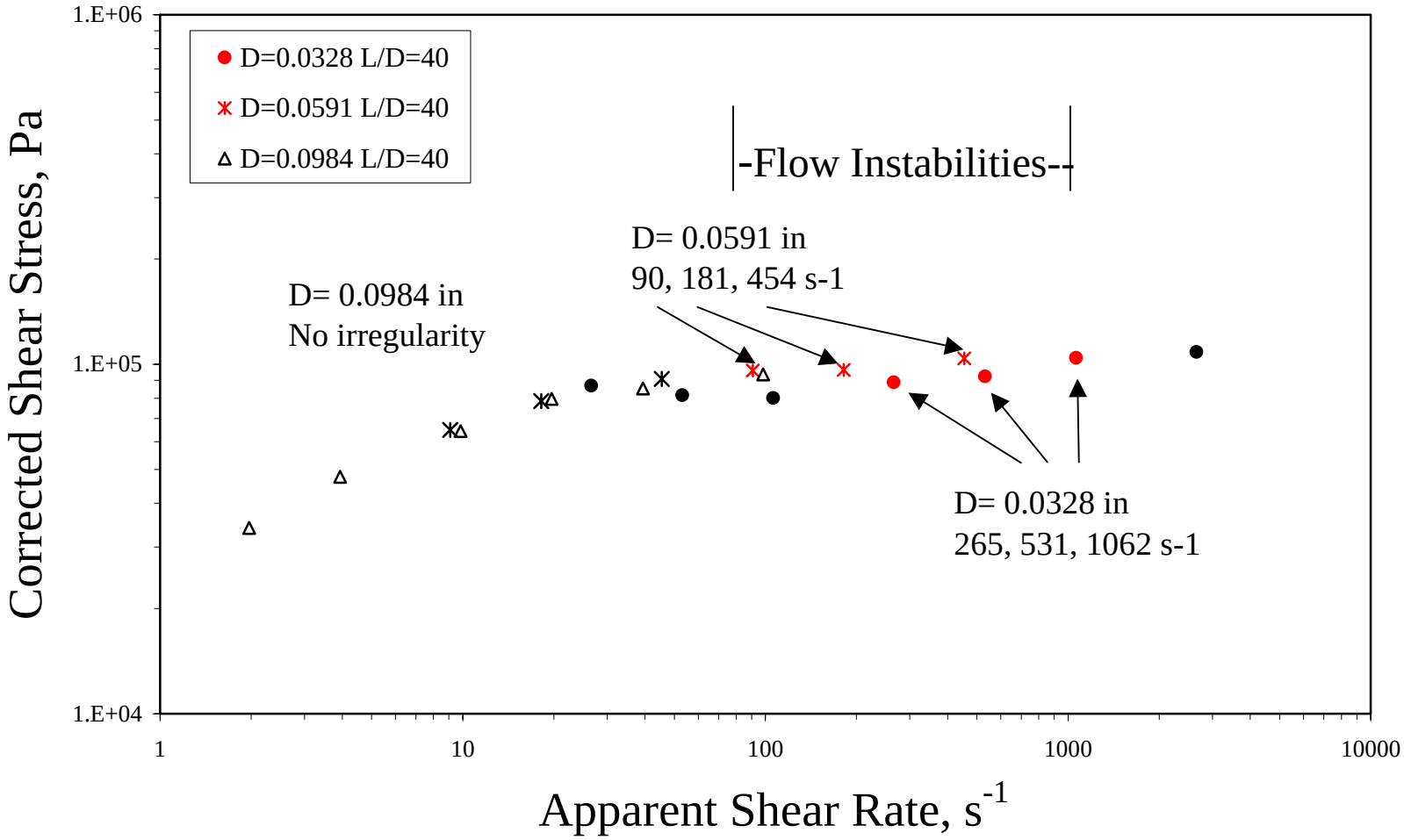
Unfilled poly(dimethyl siloxane)

Arrows indicate that surface/bulk irregularities are observed at those shear rates

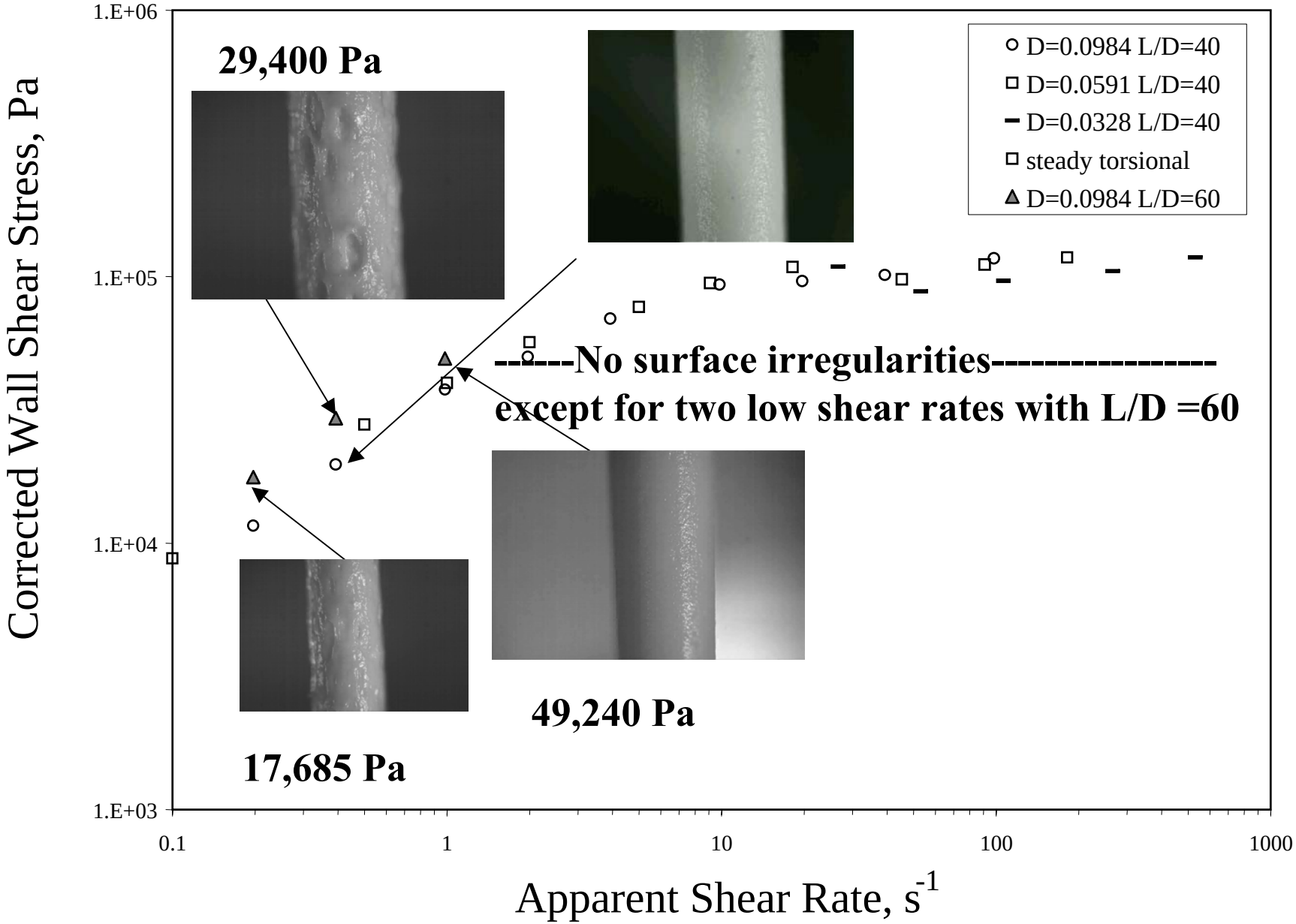


PDMS + Glass Spheres **(10% by vol.)**

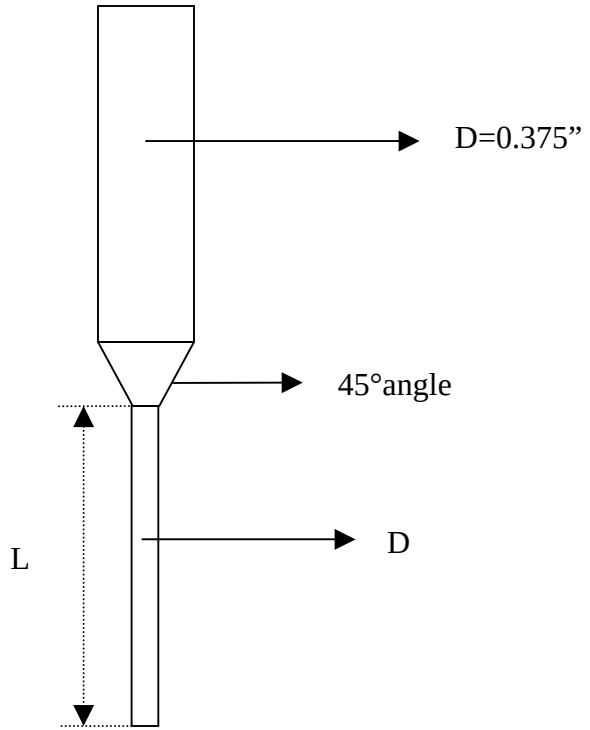
Arrows indicate that surface/bulk irregularities are observed at those shear rates



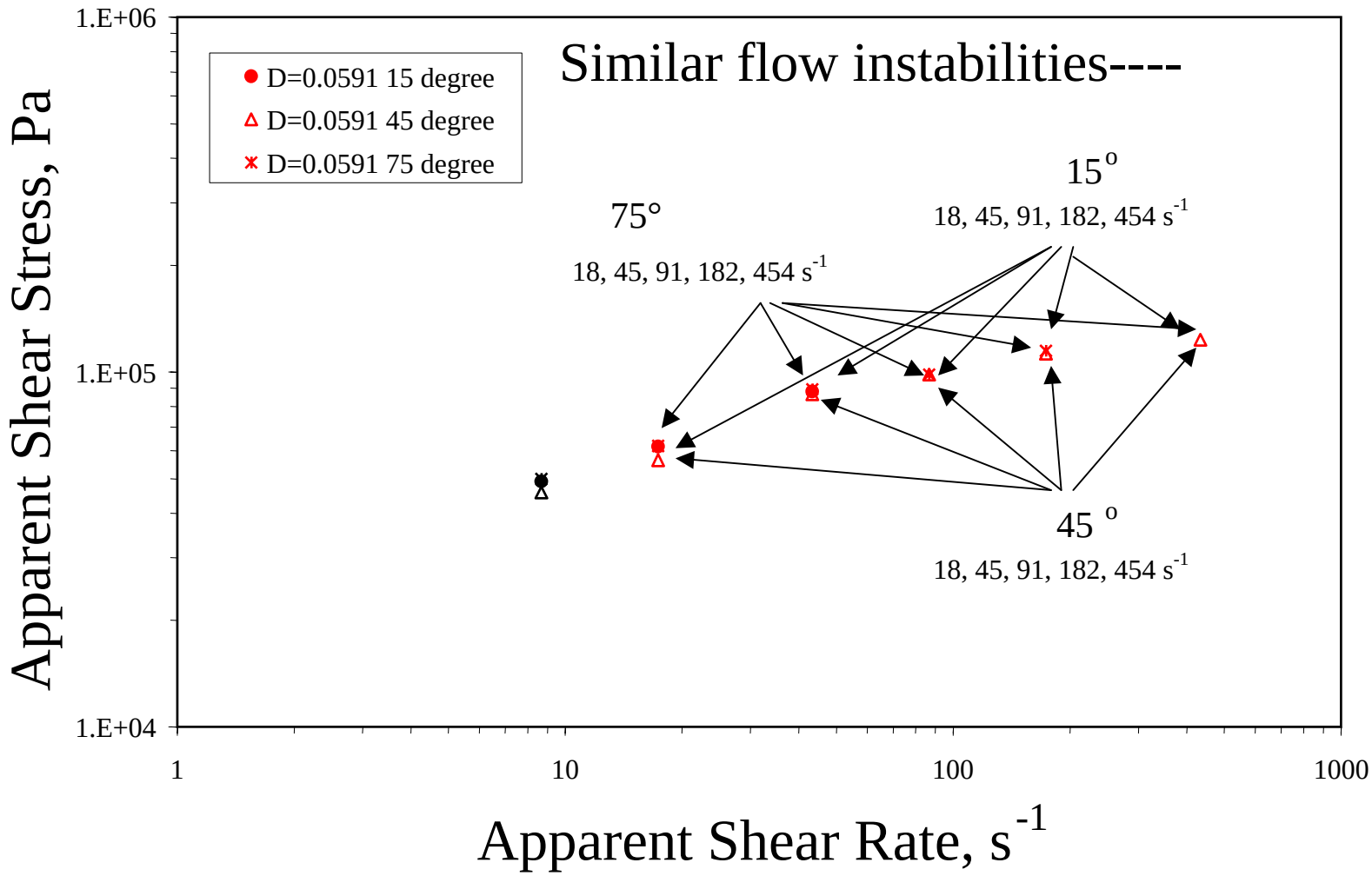
PDMS + Glass Sphere **(20% by vol.)**



Poly(dimethyl siloxane) incorporated with **40% by volume of glass spheres**



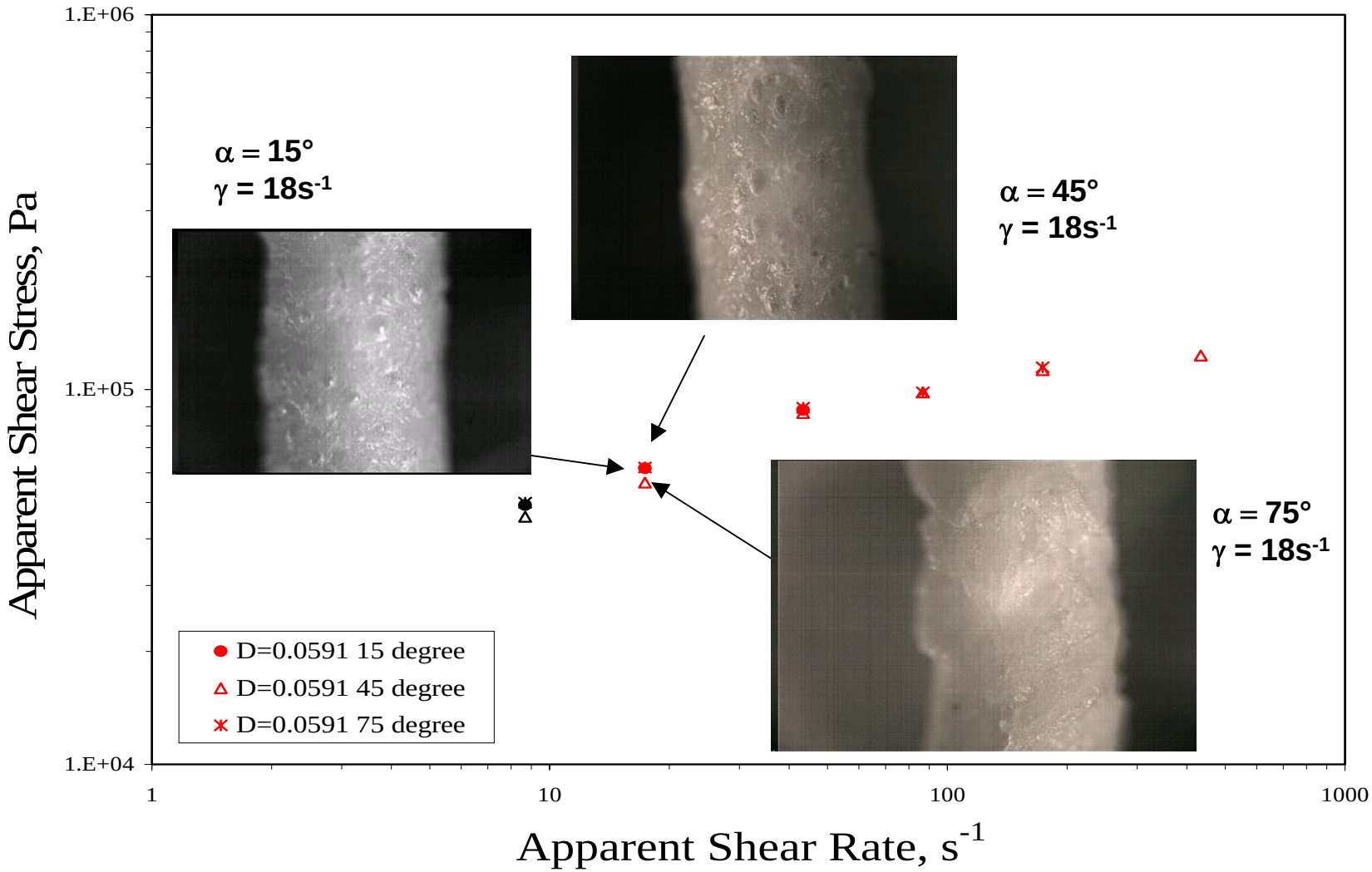
The angle of convergence was varied between 15, 45 and 75 degrees.



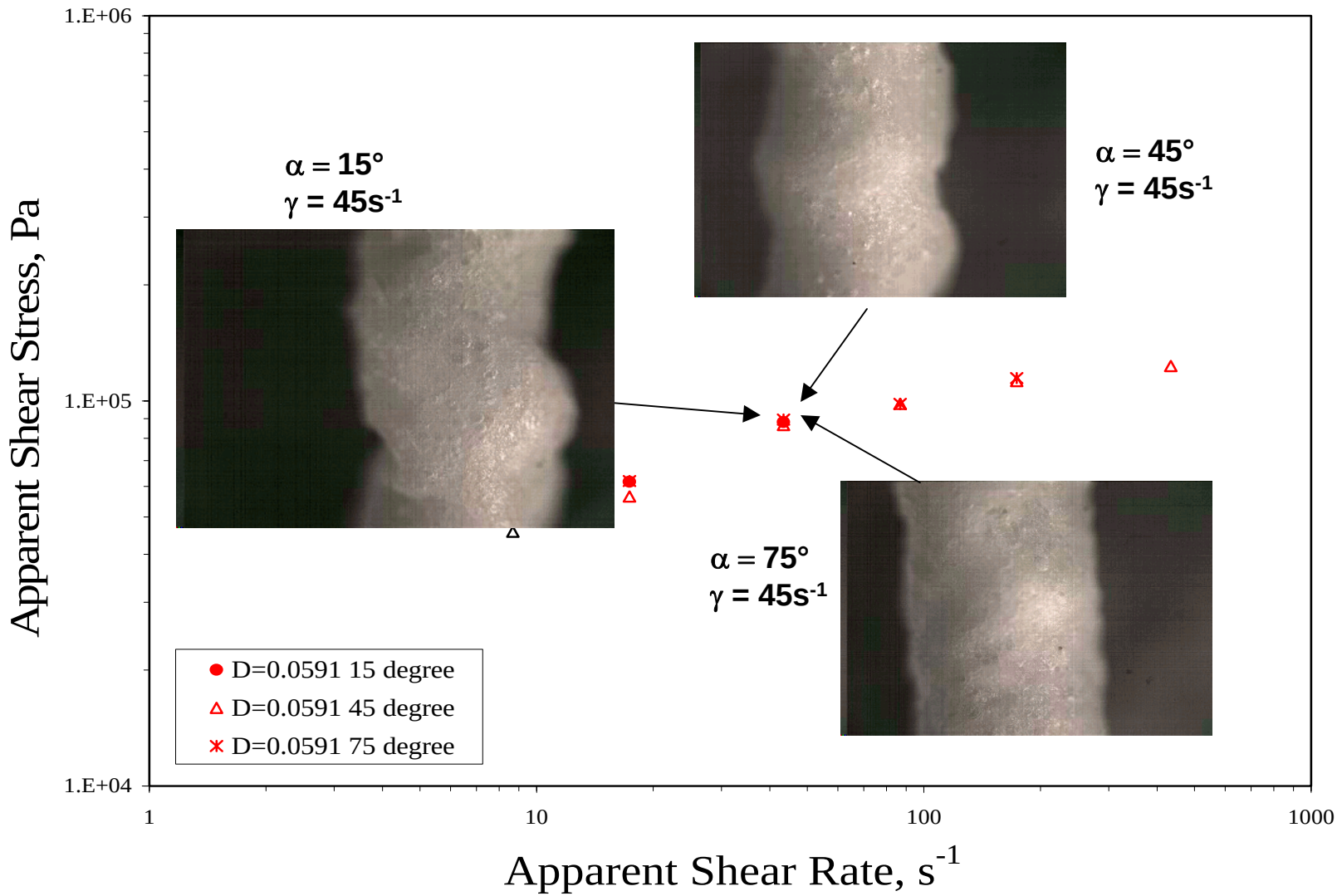
PDMS + Glass Sphere(10% by vol.)

Apparent Shear Stress vs. Apparent Shear Rate Behavior

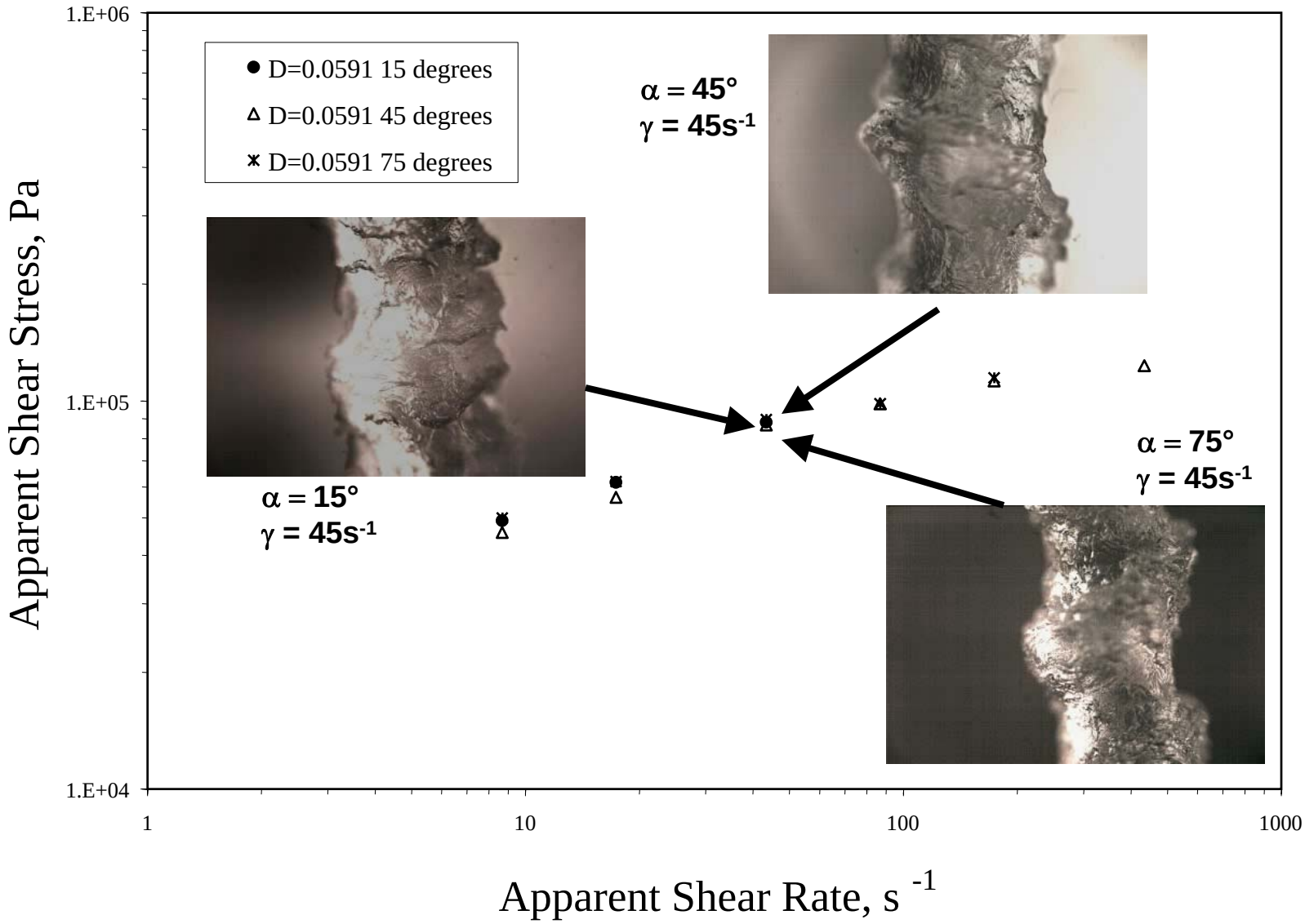
Comparison of Different Convergence Angles



PDMS + Glass Sphere(10% by vol.) Mixture
Apparent Shear Stress vs. Apparent Shear Rate Behavior
Comparison of Different Angle



PDMS + Glass Sphere(10% by vol.) Mixture
Apparent Shear Stress vs. Apparent Shear Rate Behavior
Comparison of Different Angle



Pure PDMS

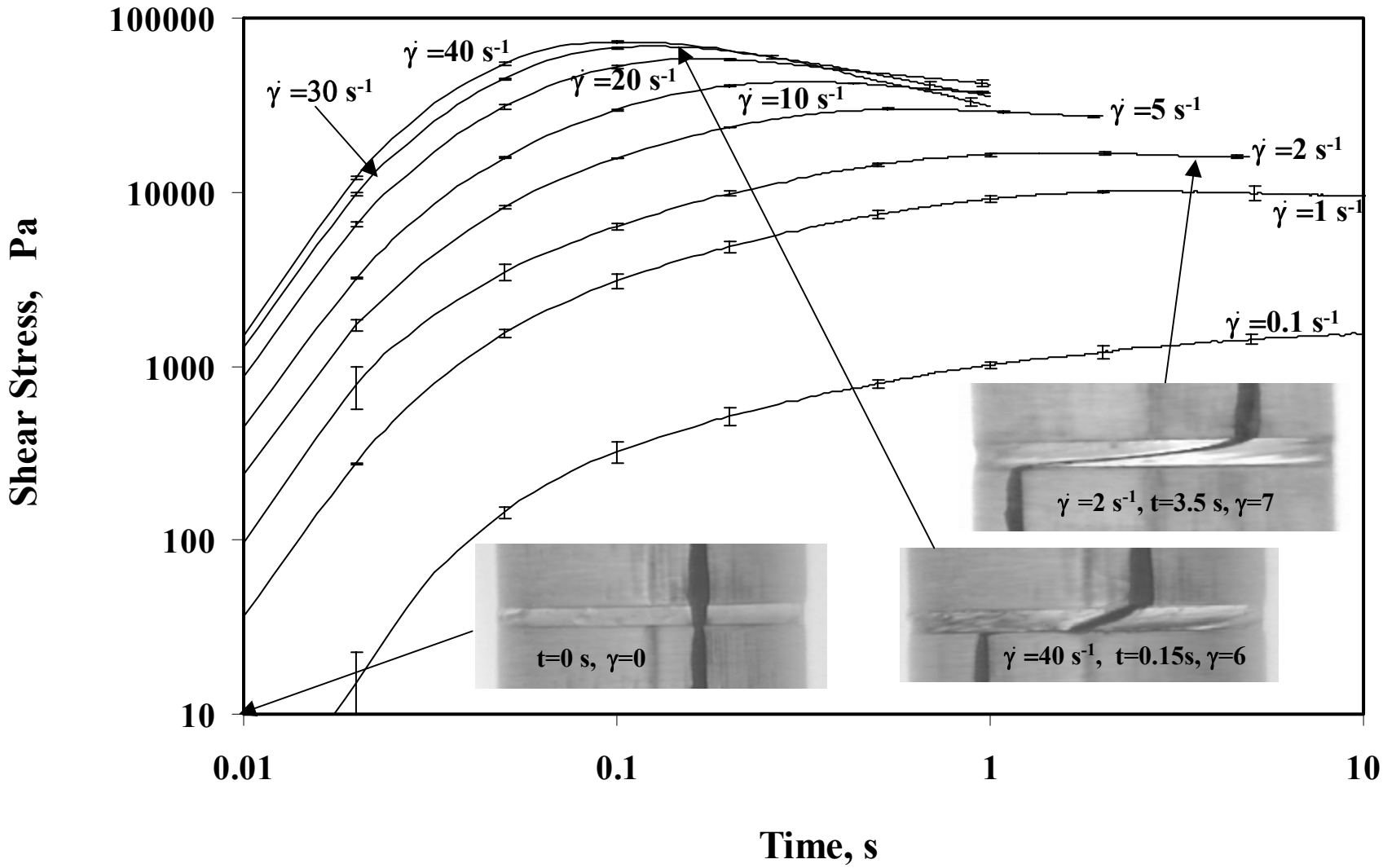
Apparent Shear Stress vs. Apparent Shear Rate Behavior: Comparison of Different Converging Entry Angles

FOCUS

- PDMS unfilled
- PDMS filled with 40% of glass spheres

Investigate:

- Tools: Wall slip analysis for the determination of the critical wall shear stress at which strong slip is observed
- Simulation: Time-dependent analysis of flow in a capillary considering compressibility of the melt/suspensions



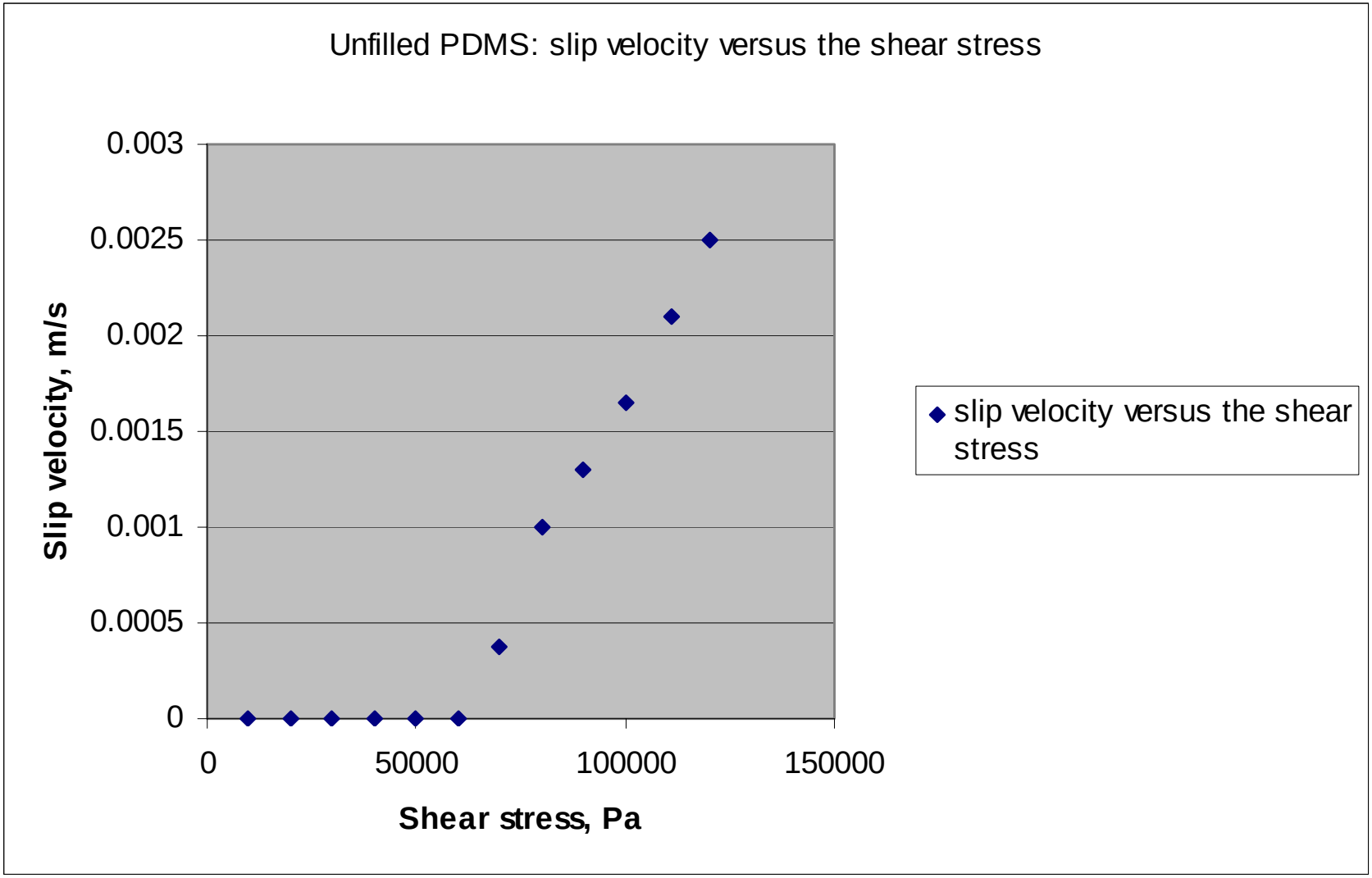
Unfilled PDMS steady torsional flow

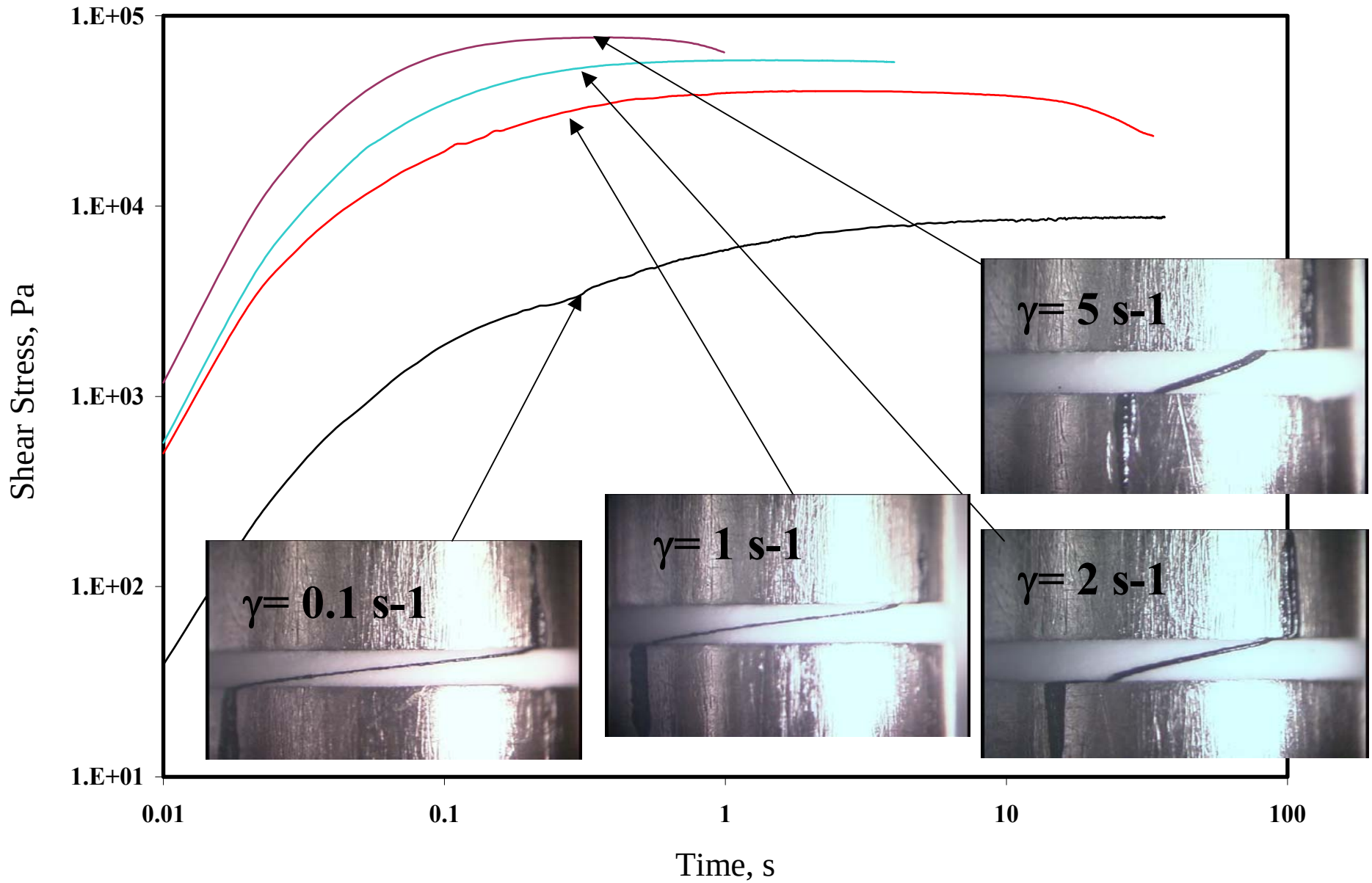
Critical wall shear stress values at which strong wall slip is initiated in steady torsional flow

- Unfilled PDMS:
  - @ 10°C .067 MPa
  - @ 30°C .069 MPa
  - @ 50°C .068 Mpa

Unfilled PDMS

$$u_s = \beta \tau_w^{sb} \left(1 + \tanh\left(\alpha(\tau_w - \tau_a)\right)\right)$$

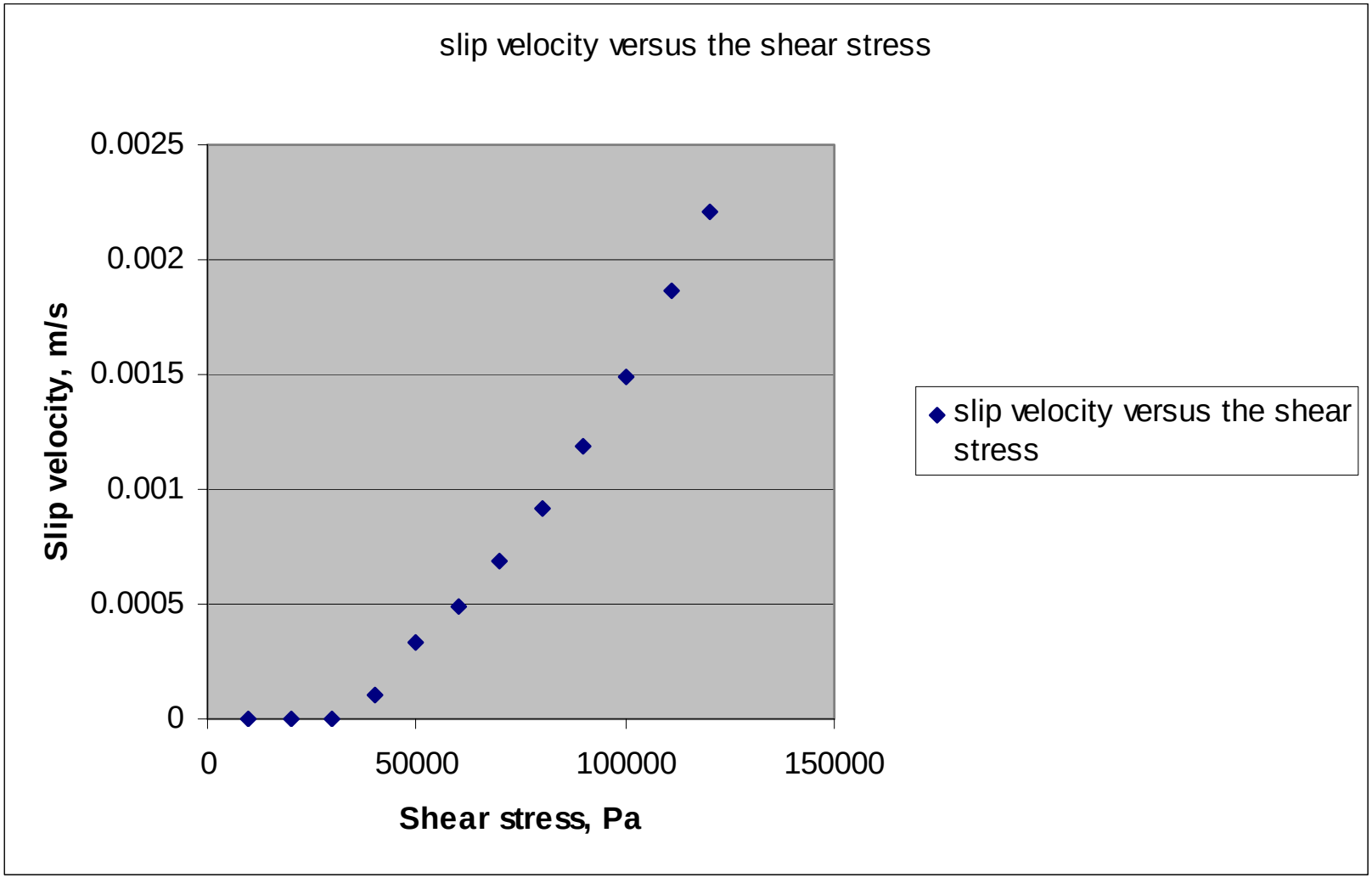




40% filled PDMS: Critical shear stress for onset of strong wall slip: 35,000 Pa

PDMS with 40% glass spheres:
Slip velocity, Us vs wall shear stress τ_w :

$$u_s = \beta \tau_w^{sb} \left(1 + \tanh\left(\alpha(\tau_w - \tau_a)\right)\right)$$



Simulation (straight land section):

- **Compressibility**
- **Wall slip, f(P, Wall shear stress)**
- **Time-dependence**
- **Generalized Newtonian fluid**

Compressibility: **Density, ρ varies with pressure P: constants γ and γ_1:**

$$\rho = \gamma p + \gamma_1$$

PDMS: $\gamma_1 = 958.0 kg \cdot m^{-3}$ $\gamma = 1.4 \times 10^{-6} m \cdot s^{-2}$

PDMS with 40% glass: $\gamma_1 = 1073.4 kg \cdot m^{-3}$ $\gamma = 1.6 \times 10^{-6} m \cdot s^{-2}$

$$u_s = \beta \tau_w^{sb} \left(1 + \tanh\left(\alpha(\tau_w - \tau_a)\right)\right)$$

$$\beta = \beta_0 (p_a / p)^{\kappa}$$

Time-dependent equations of continuity and motion:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial z}\left[\left(p + \frac{\gamma_1}{\gamma}\right)V\right] = 0$$

$$\frac{\partial V}{\partial t} + \frac{2\tau_w}{(\gamma p + \gamma_1)R} + \frac{1}{\gamma p + \gamma_1}\frac{\partial p}{\partial z} = 0$$

V is the mean velocity in the channel in z-direction, t is time, P is pressure, τ_w is the wall shear stress.

Solve numerically using finite differences (Predictor-Corrector):

$$\frac{\hat{p}_{i+1/2} - p^{l}_{i+1/2}}{\Delta t} + \frac{\left((p^{l}_{i+3/2} + p^{l}_{i+1/2})/2 + \gamma_1/\gamma\right)V^{l}_{i+1} - \left((p^{l}_{i+1/2} + p^{l}_{i-1/2})/2 + \gamma_1/\gamma\right)V^{l}_{i}}{\Delta z} = 0$$

$$\frac{\hat{V}_i - V^{l}_{i}}{\Delta t} + \frac{2\tau_{wi}^{\ l}}{\left(\gamma(p^{l}_{i-1/2} + p^{l}_{i+1/2})/2 + \gamma_1\right)R} + \frac{1}{\left(\gamma(p^{l}_{i-1/2} + p^{l}_{i+1/2})/2 + \gamma_1\right)}\frac{p^{l}_{i+1/2} - p^{l}_{i-1/2}}{\Delta z} = 0$$

$$\tau_{wi}^{\ l} = -\frac{R}{2}\left(\frac{\partial p}{\partial z}\right)_{si}^{l} \qquad V_i^{\ l} = F\left[\left(\frac{\partial p}{\partial z}\right)_{si}^{l}\right]$$

Δt time step, Δz grid spacing, *l* is the time step index, and
F is the function to obtain steady state value of mean velocity V

Under steady state conditions there is an analytical solution for local mean velocity V:

$$
V = \begin{cases}
-\dfrac{16\tau_y}{R^2 m^{1/n}(1+1/n)(3+1/n)}\left[-\tau_y - \dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s\right]^{2+1/n}\left(-\dfrac{\partial p}{\partial z}\right)_s^{-3} \\
\quad -\dfrac{16}{R^2 m^{1/n}(1+1/n)(2+1/n)}\left[-\tau_y - \dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s\right]^{3+1/n}\left(-\dfrac{\partial p}{\partial z}\right)_s^{-3} \\
\quad +\dfrac{16\tau_y}{m^{1/n}(1+1/n)}\left[-\tau_y - \dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s\right]^{1+1/n}\left(-\dfrac{\partial p}{\partial z}\right)_s^{-1} \\
\quad +\beta\left[-\dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s\right]^{sb}\left[1+1\tanh\left(\alpha\left(-\dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s - \tau_a\right)\right)\right], & \dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s > \tau_y, \\
\\
\beta\left[-\dfrac{R}{2}\left(\dfrac{dp}{dz}\right)_s\right]^{sb}\left[1+1\tanh\left(\alpha\left(-\dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s - \tau_a\right)\right)\right], & \dfrac{R}{2}\left(\dfrac{\partial p}{\partial z}\right)_s \le \tau_y.
\end{cases}
$$

Mean velocity, V set at entrance:

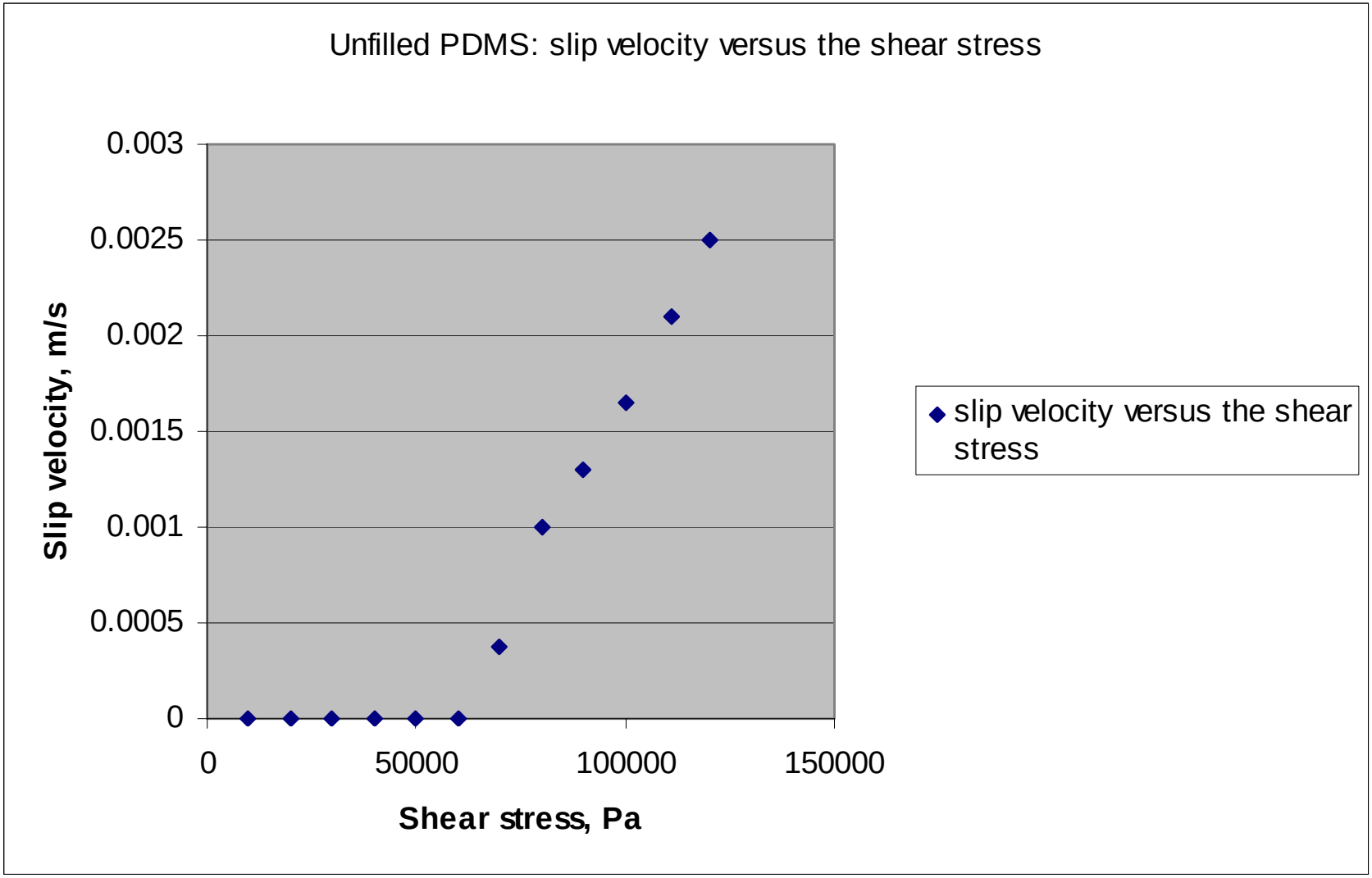
$$V = V_0, \qquad z = 0$$

Pressure ambient, Pa at length L

$$p = p_a, \qquad z = L$$

Unfilled PDMS

$$u_s = \beta \tau_w^{sb} \left(1 + \tanh\left(\alpha(\tau_w - \tau_a)\right)\right)$$

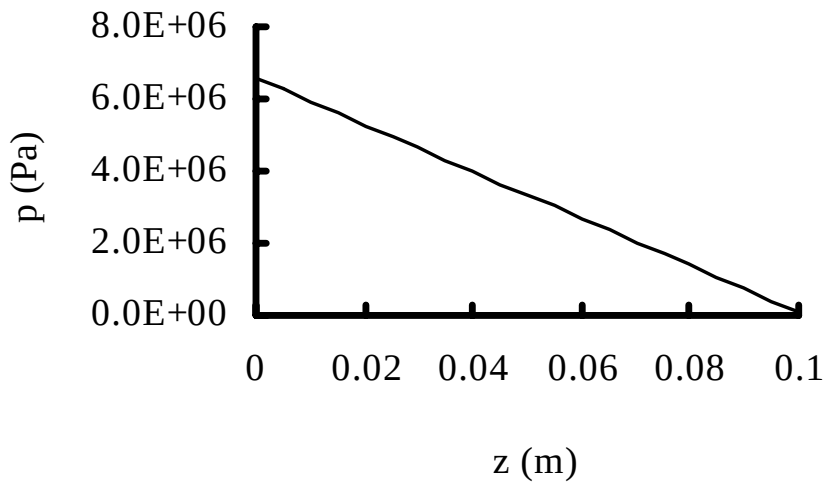


Unfilled PDMS

At low shear rate

$$m = 17200\, Pa \cdot s^{0.39} \qquad n = 0.39$$

$$\beta_0 = 1.8 \times 10^{-11}\, m \cdot s^{-1} \cdot Pa^{-2.26} \qquad \kappa = 1$$

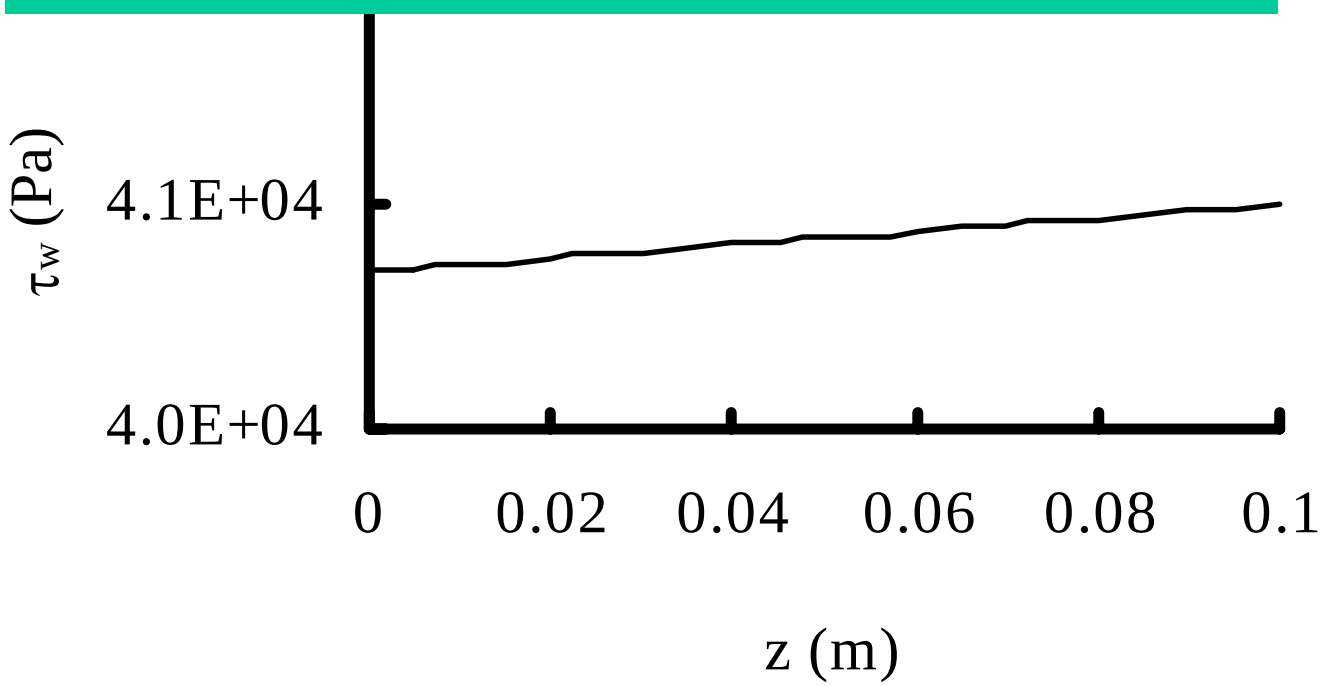


Solution of a pure PDMS flow: 2R=0.0025m, L/2R=40, V_0=0.0002m/s **(<u>shear rate: 0.6 s^{-1}</u>).**

Unfilled PDMS

At low shear rate

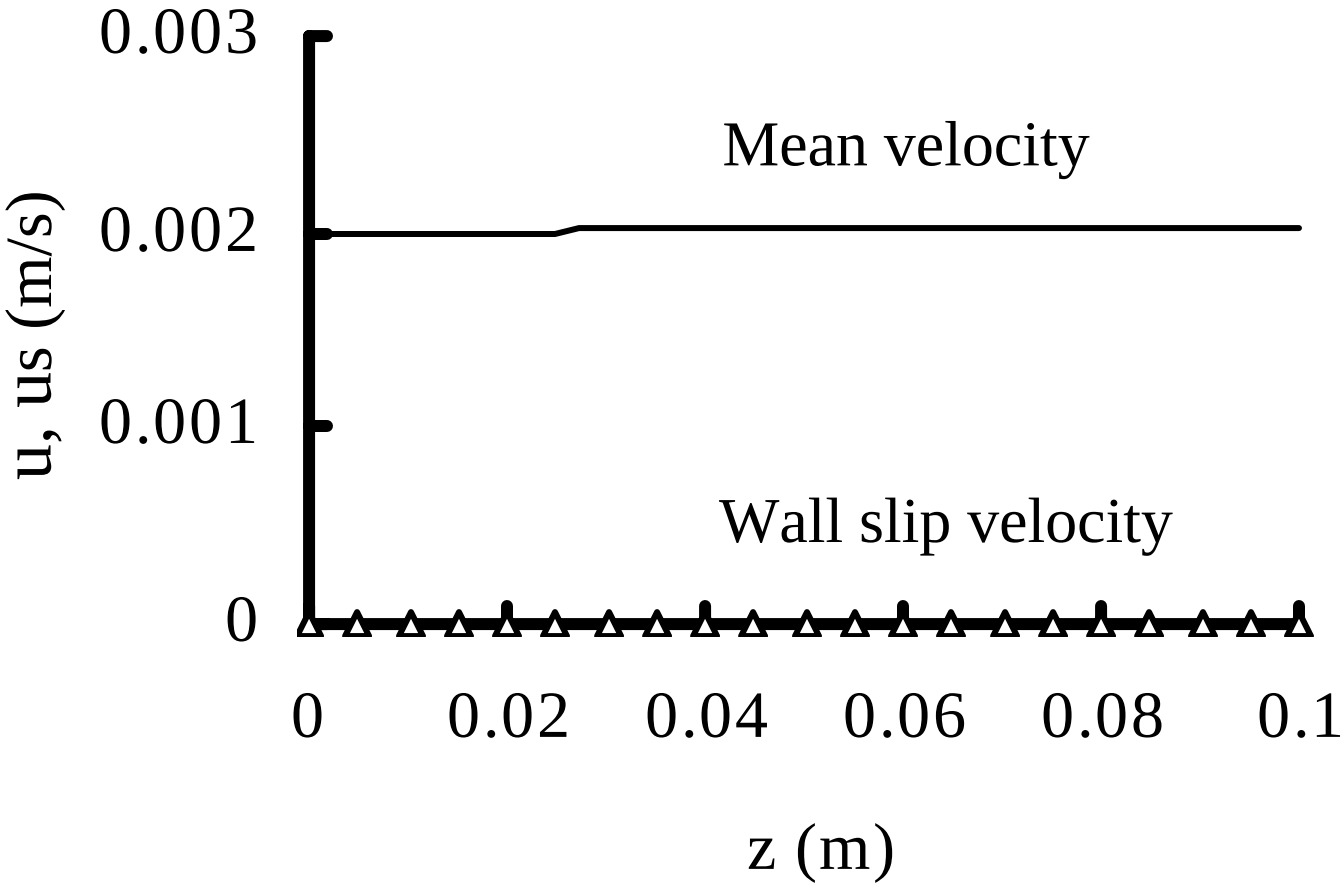
Remember the critical shear stress of 70, 000 Pa



Solution of a pure PDMS flow: 2R=0.0025m, L/2R=40, V_0=0.0002m/s (shear rate: 0.6 s-1).

Unfilled PDMS

At low shear rate

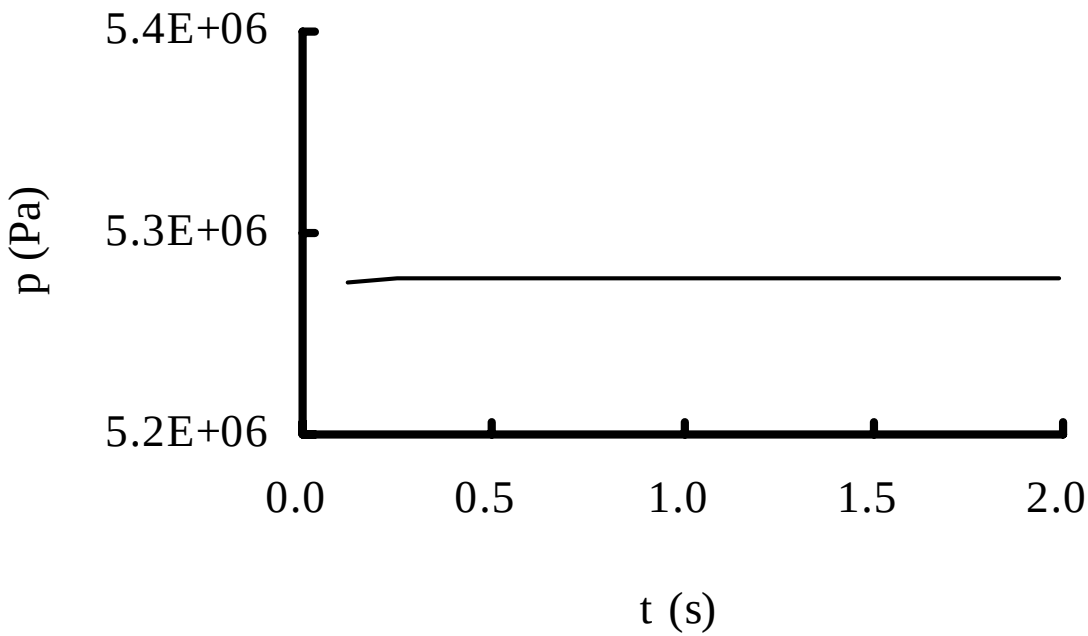


2R=0.0025m, L/2R=40,V_0=0.0002m/s: **<u>shear rate: 0.6 s^{-1}</u>**
(triangles: slip velocity)

Unfilled PDMS

At low shear rate

Time dependence



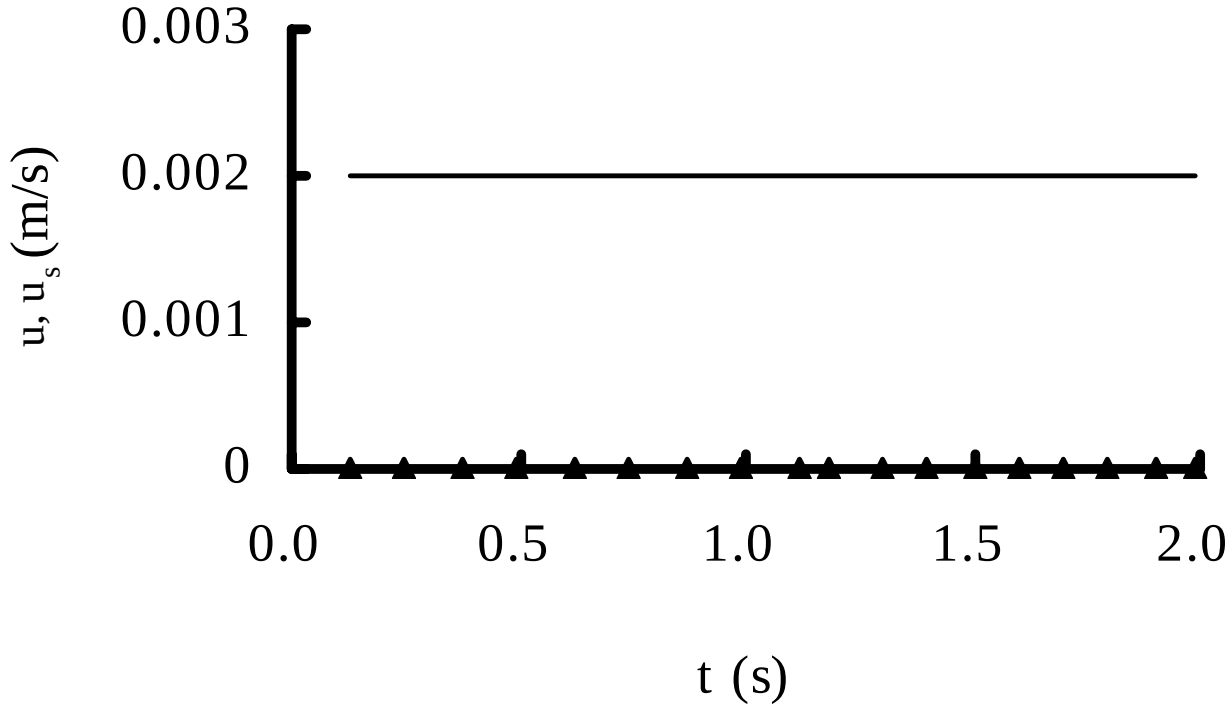
2R=0.0025m, L/2R=40, V_0=0.0002m/s

(shear rate: 0.6 s^{-1}).

Time dependence

Unfilled PDMS

At low shear rate



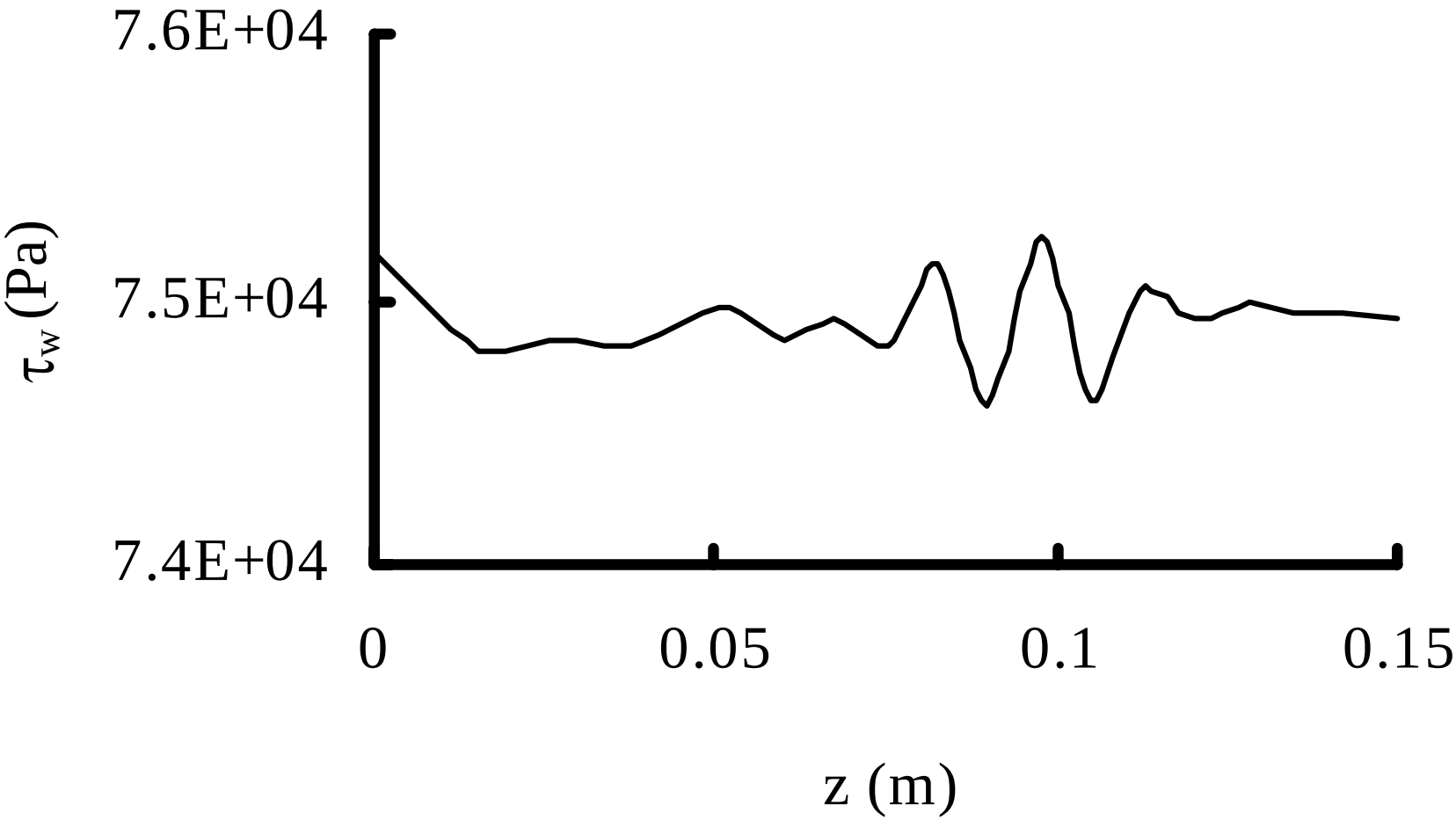
2R=0.0025m, L/2R=40, V_0=0.0002m/s

(shear rate: 0.6 s^{-1}).

Wall shear stress: distance dependence

Unfilled PDMS

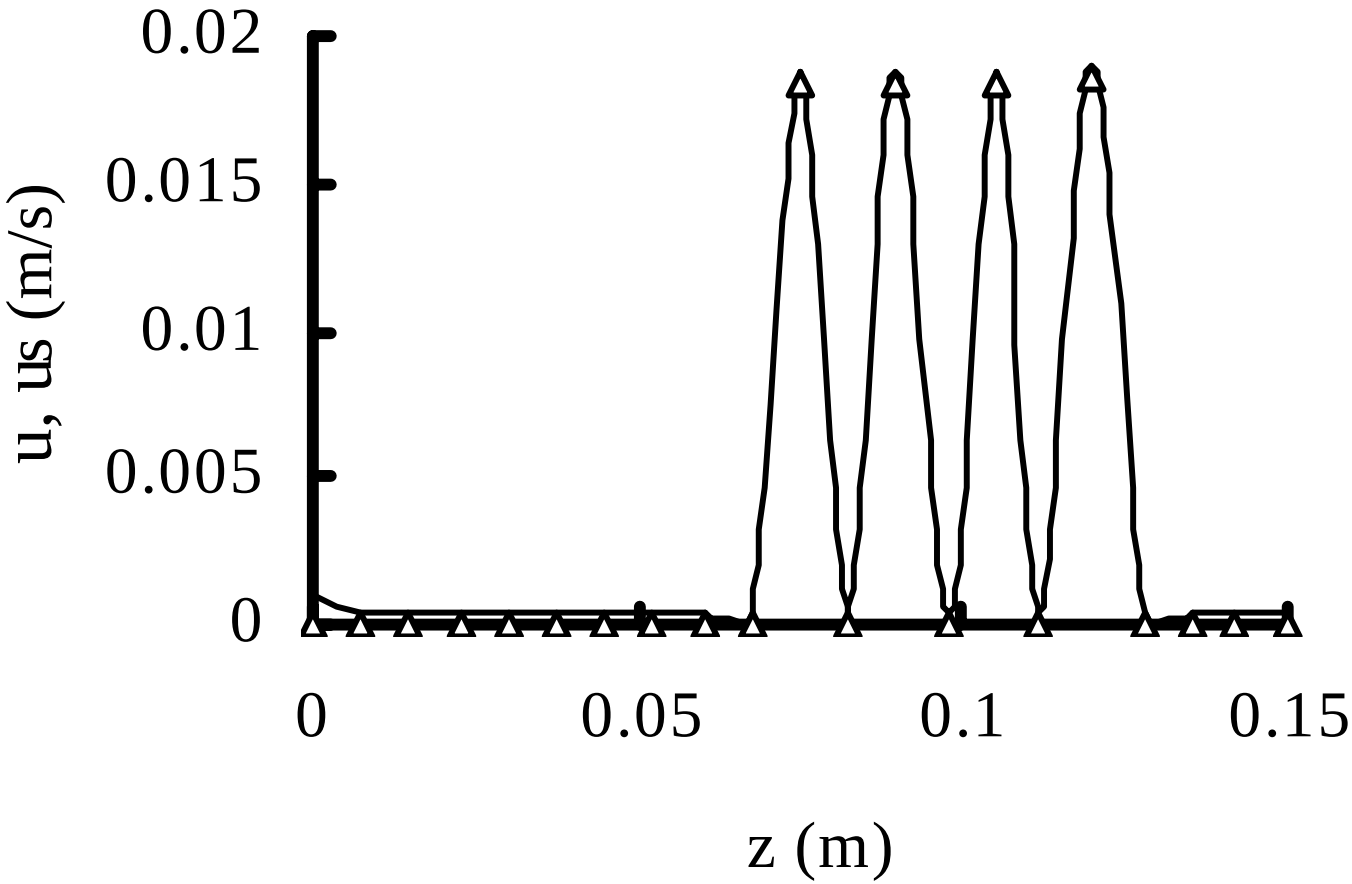
Higher shear rate



<u>Shear rate: 3 s^{-1}</u>

Mean and wall slip velocity versus distance

Unfilled PDMS

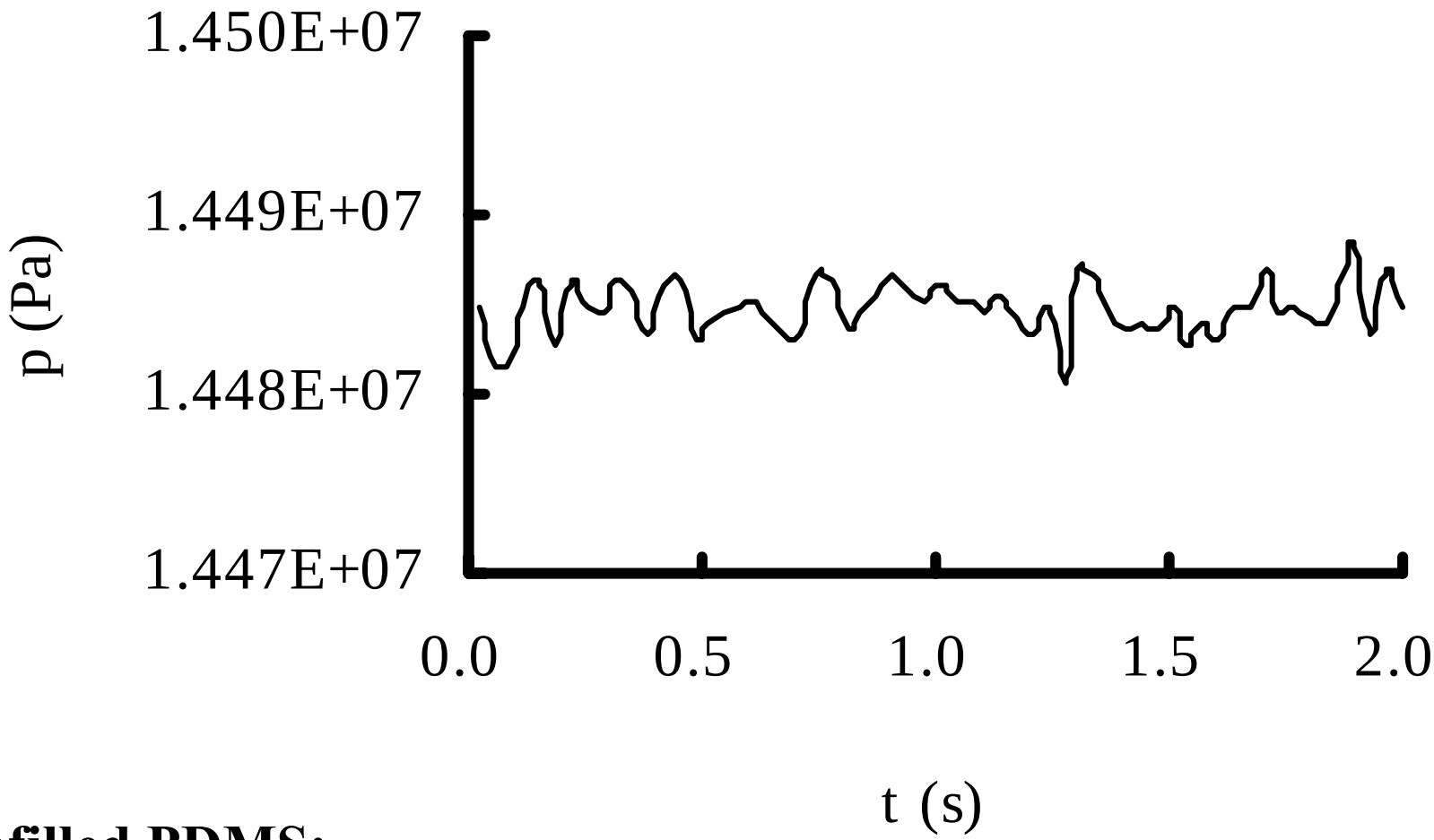


<u>Shear rate: 3 s^{-1}</u>

In the figure, triangles represent slip velocity.

Pressure: time dependence

Unfilled PDMS

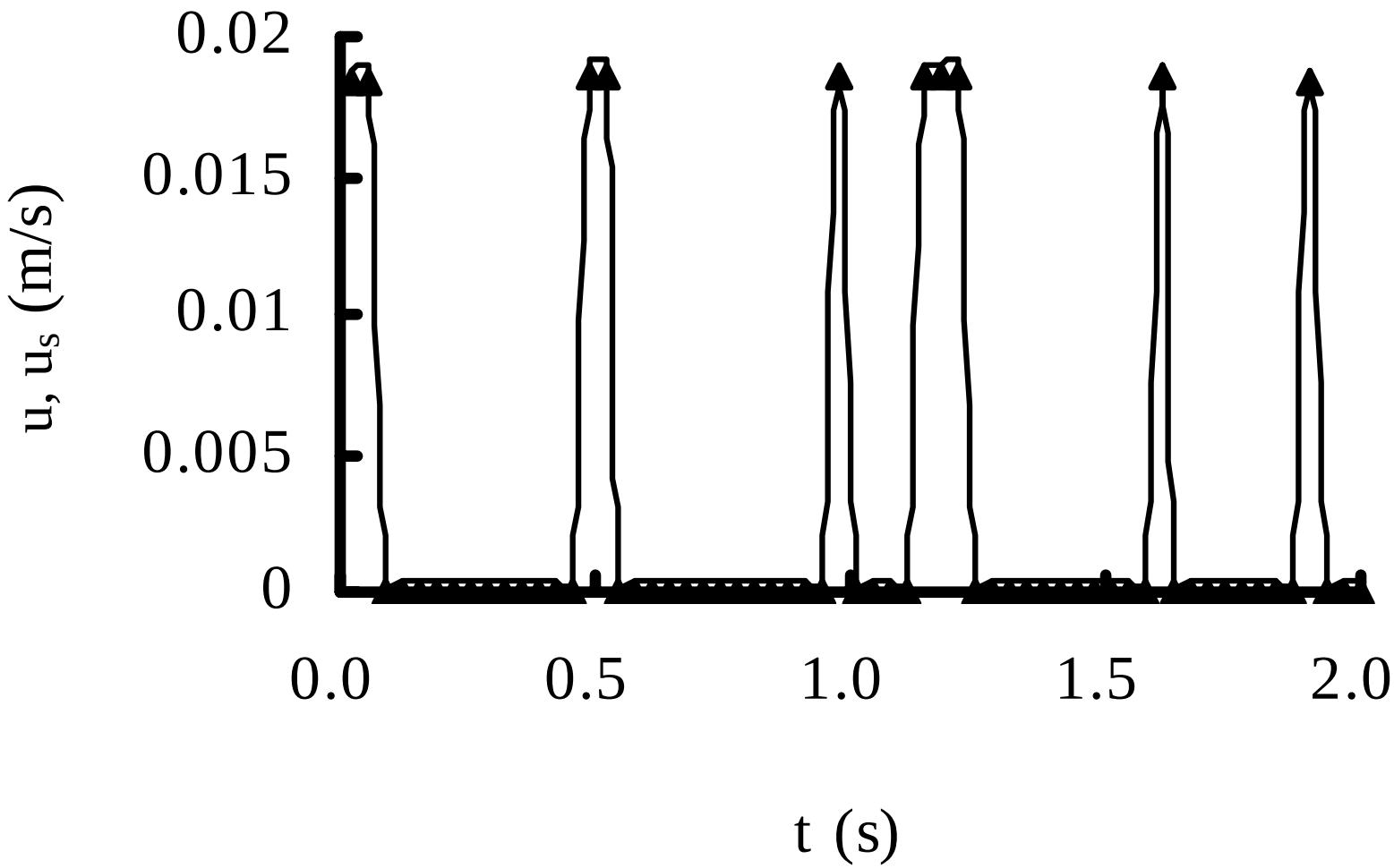


Unfilled PDMS:

<u>Shear rate: 3 s^{-1}</u>

Mean and wall slip velocity: Time dependence

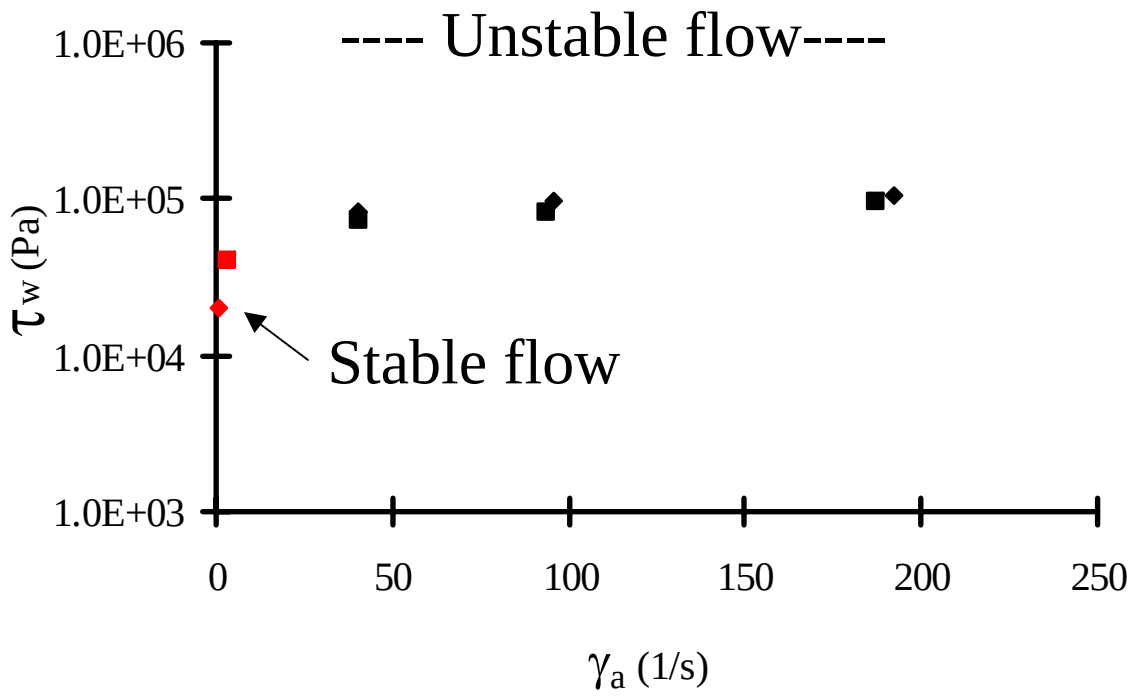
Unfilled PDMS

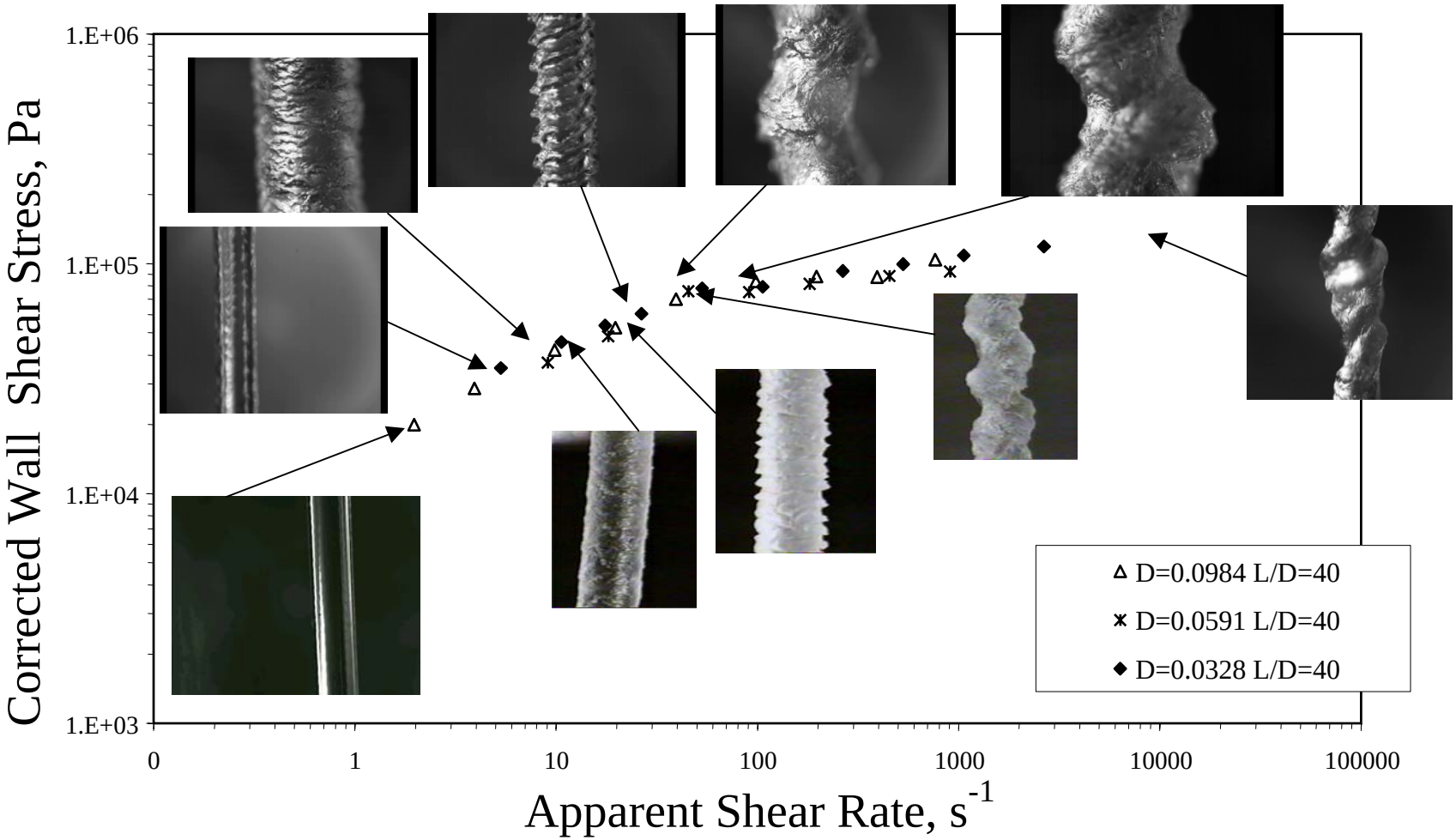


<u>Shear rate: 3 s^{-1}</u>

In the figure, triangles represent slip velocity.

Calculations: Unfilled PDMS





Flow curves and extrudates of poly(dimethyl siloxane) collected with capillaries with different diameters and development of extrudate surface irregularities

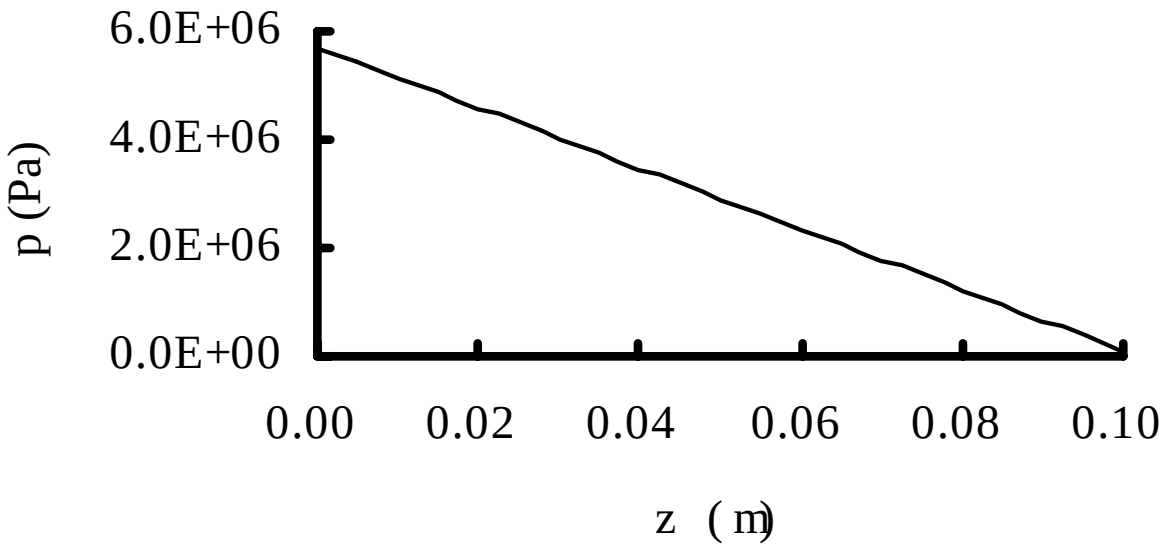
PDMS with 40% glass

(Shear rate: 0.6 s^{-1})

$$\beta_0 = 7 \times 10^{-13} m \cdot s^{-1} \cdot Pa^{-2.17} \qquad \kappa = 0.3$$

$$n = 0.5 \qquad m = 50000 Pa \cdot s^{0.5}$$

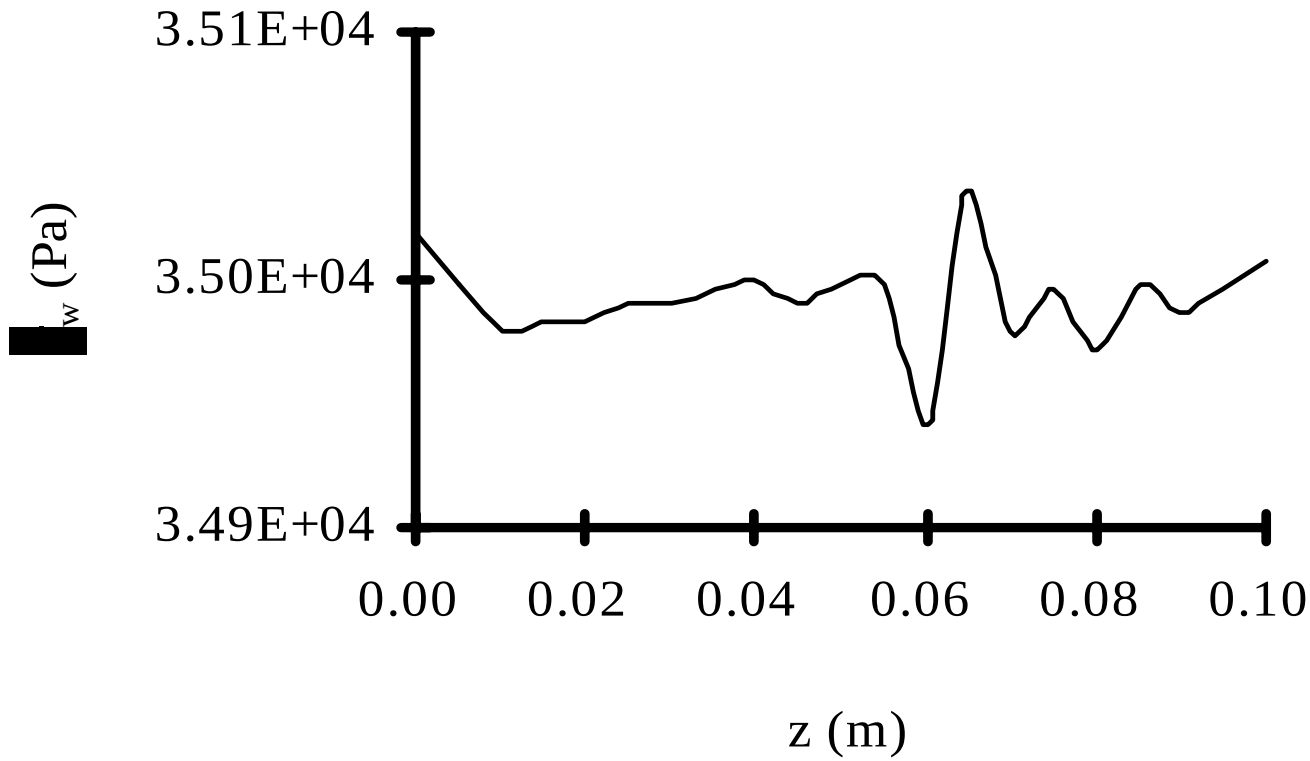
$$\beta = \beta_0 (p_a / p)^{\kappa} \qquad \tau_y = 403 Pa$$



40% PDMS

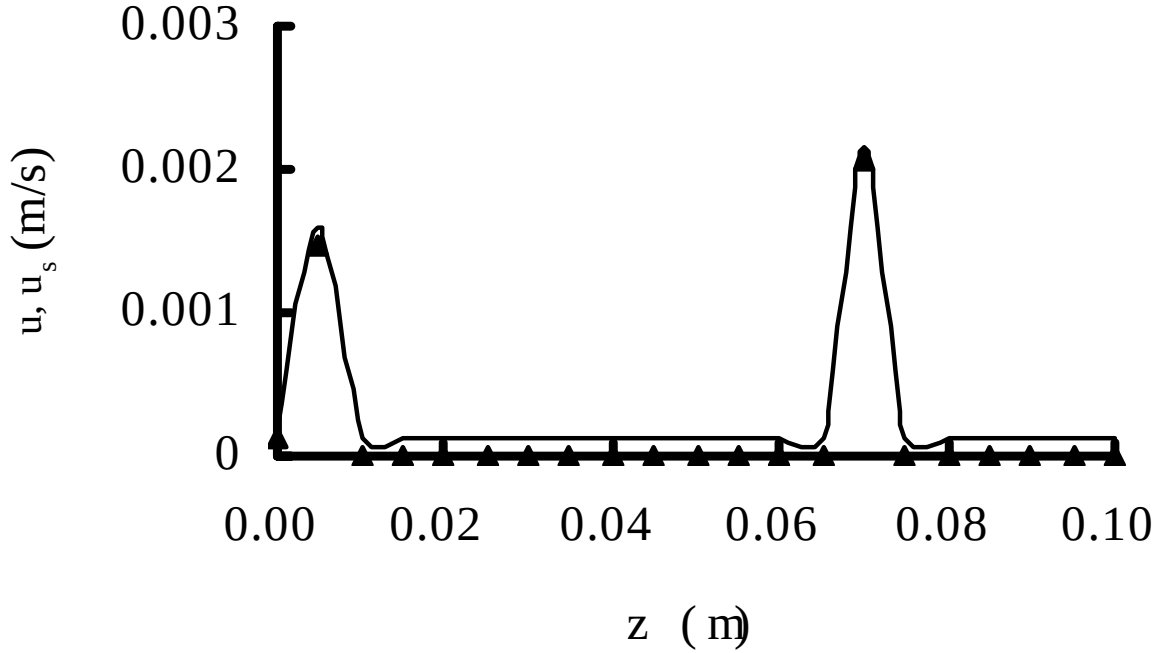
(Shear rate: 0.6 s^{-1})

Wall shear stress versus distance



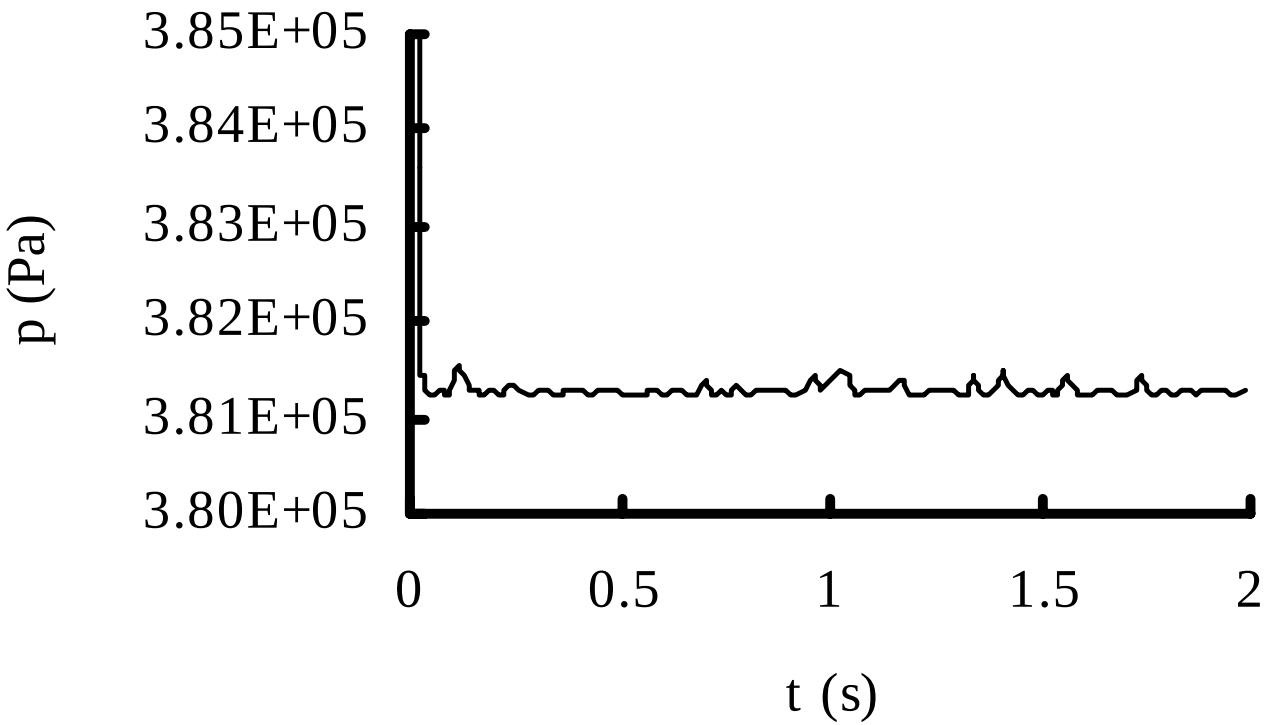
40% PDMS

(Shear rate: 0.6 s^{-1})



Triangles represent slip velocity.

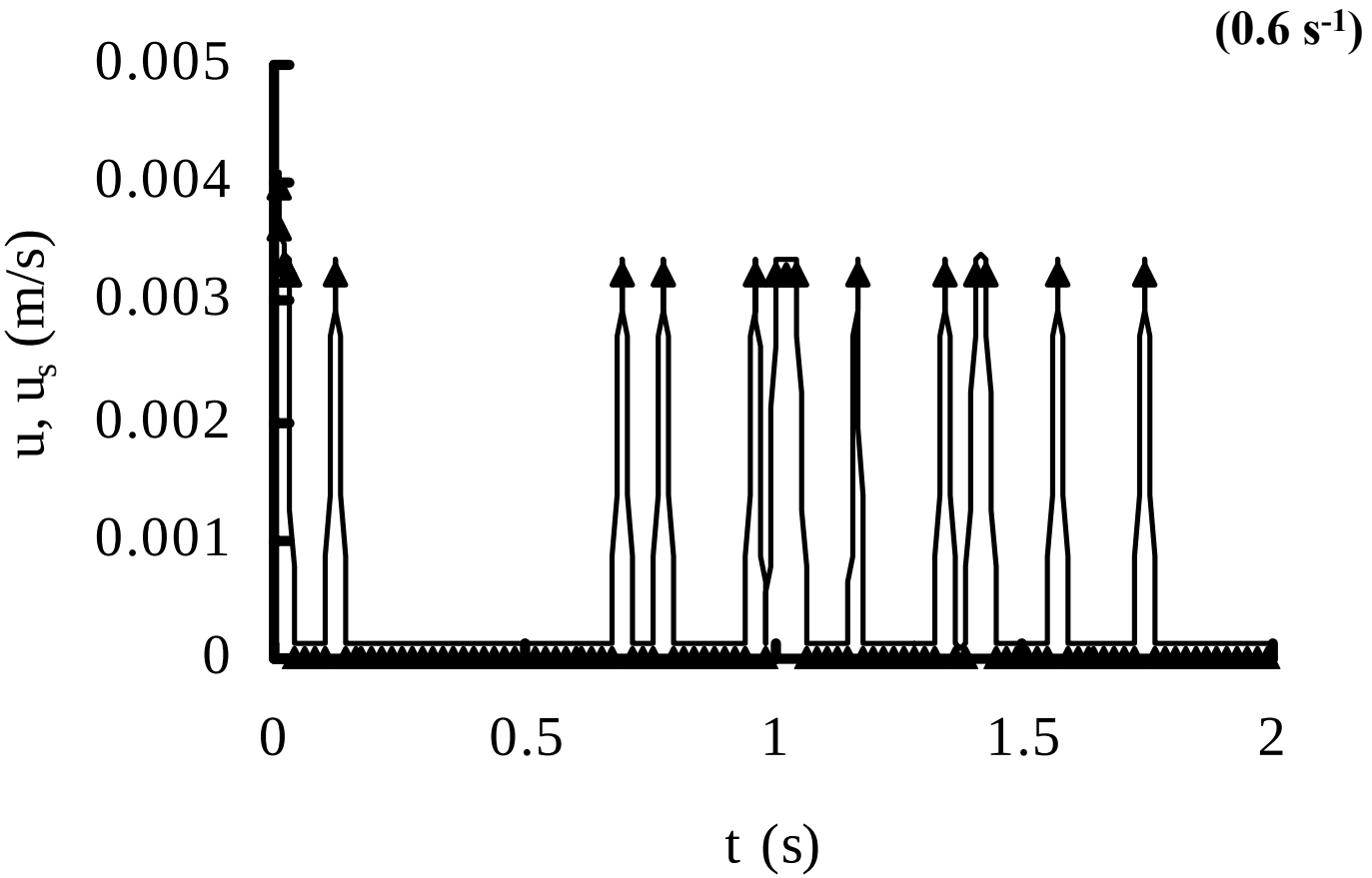
40% PDMS
(0.6 s^{-1})



z/L=0.4

Mean and slip velocity versus time

40% PDMS

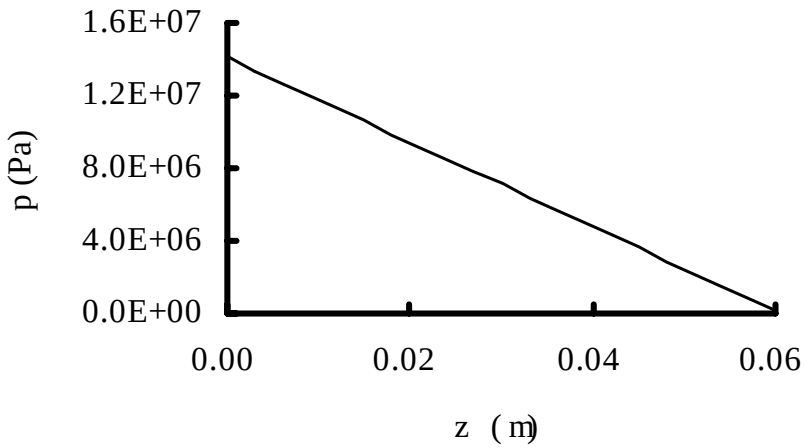


z/L=0.4

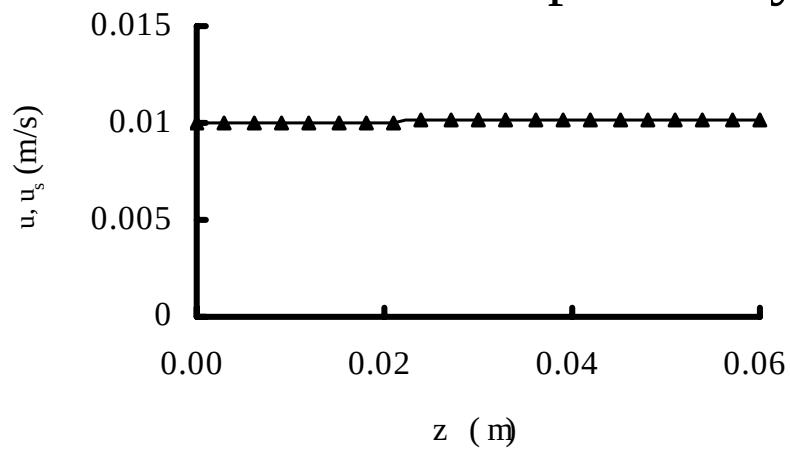
PDMS 40% glass

Typical behavior at higher hear rates: (Exp: 50 s^{-1}).

Pressure



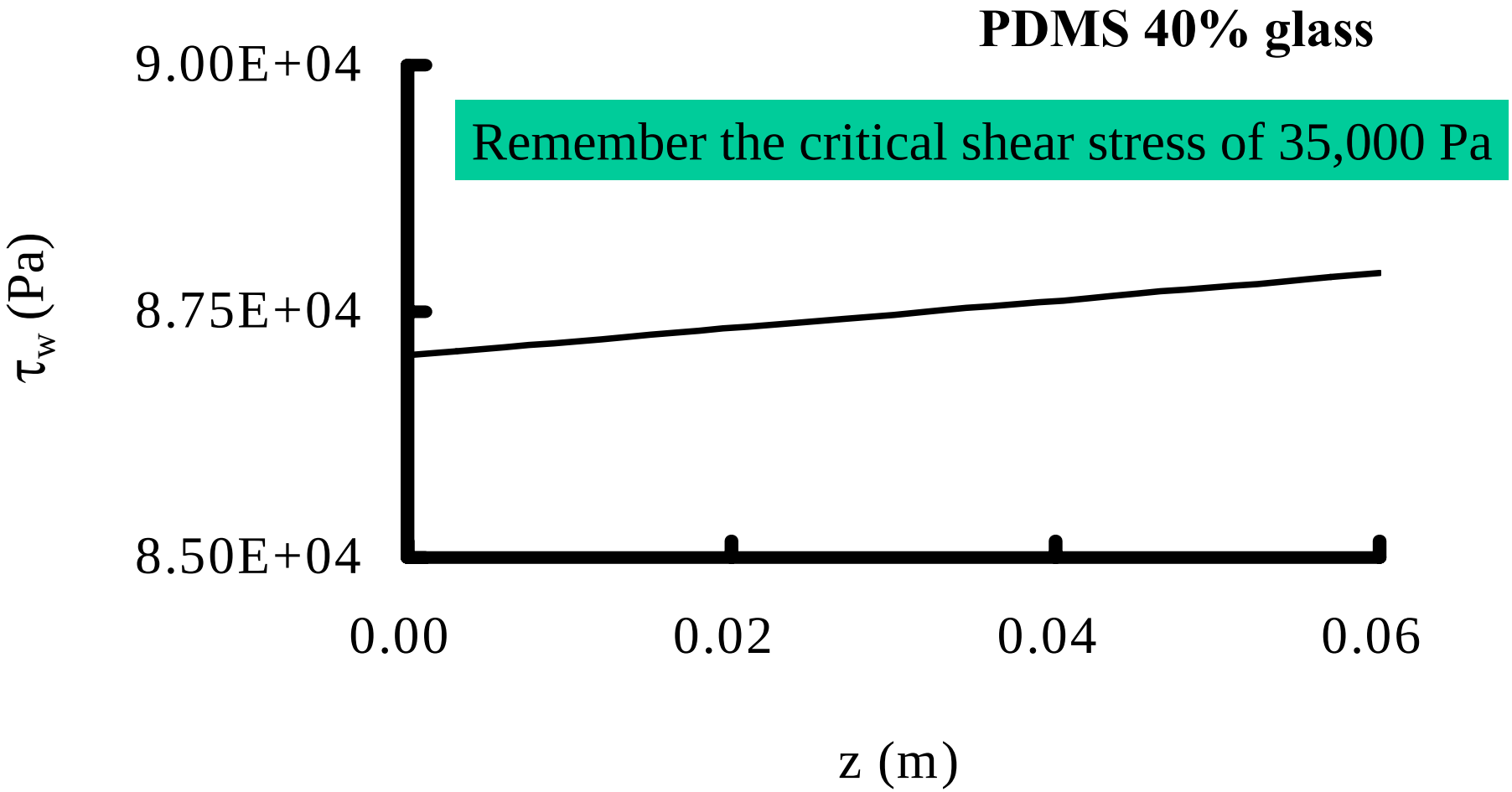
Mean and slip velocity



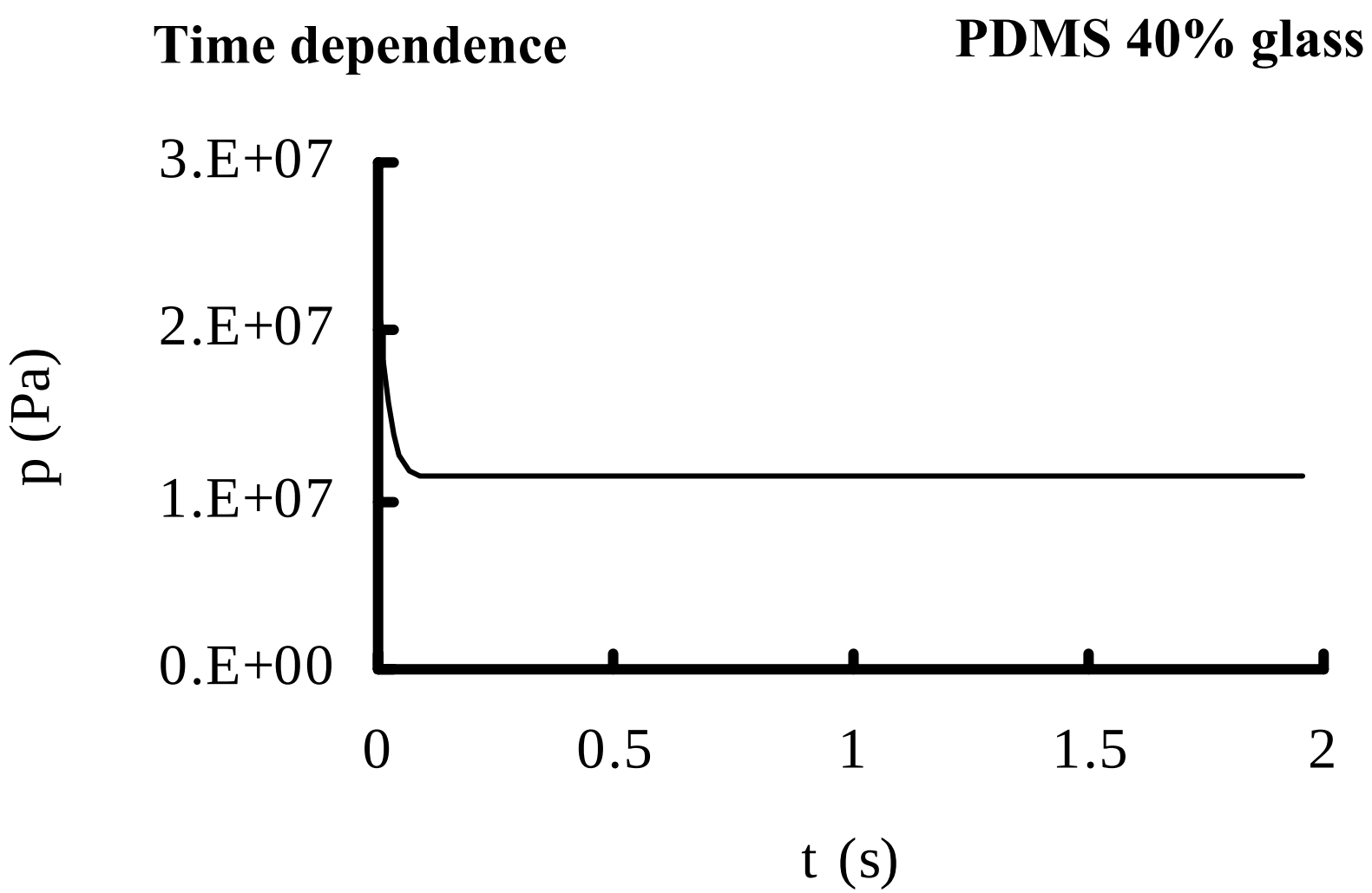
Plug flow U=Us

Triangles represent slip velocity

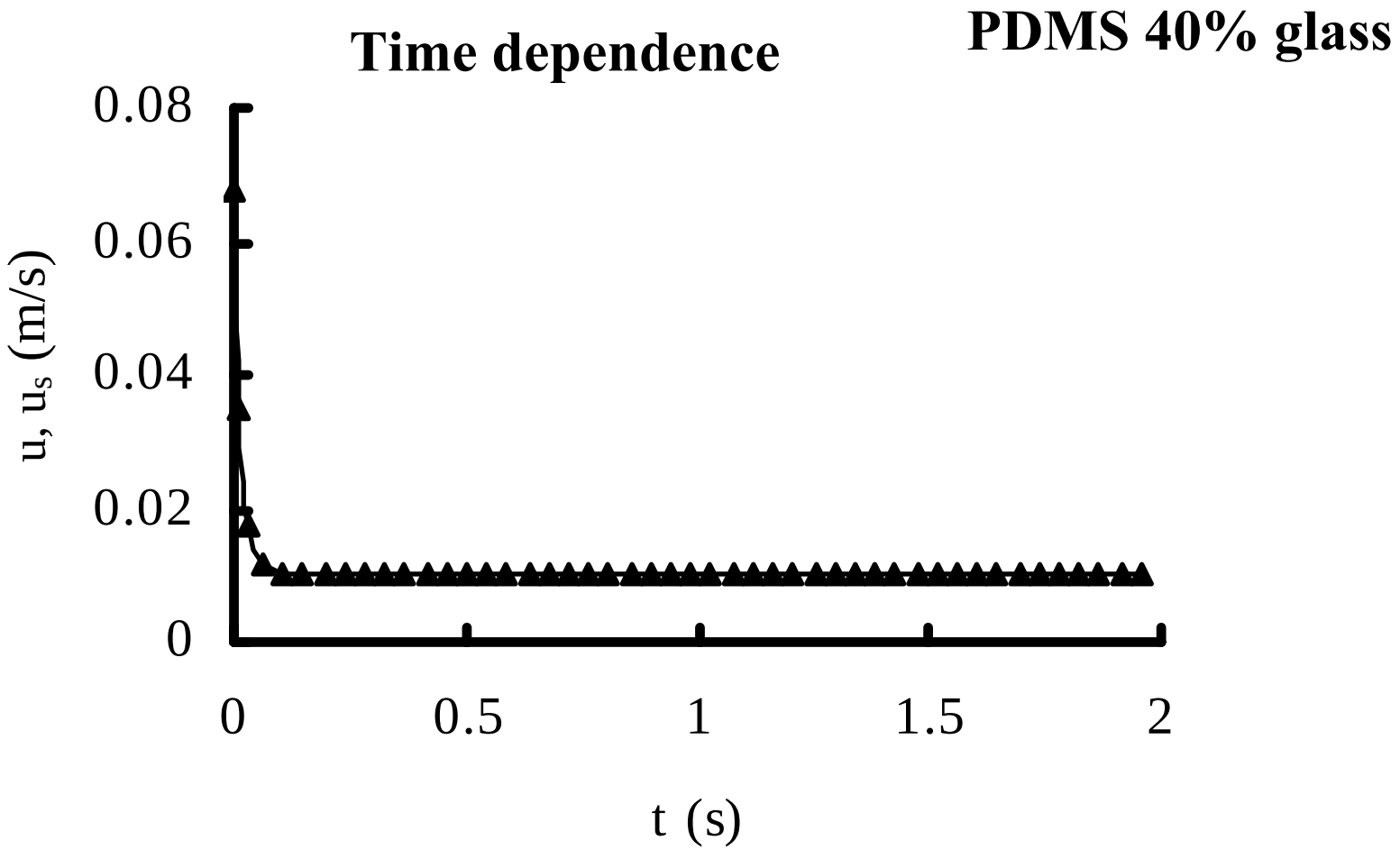
2R=0.0015m, L/2R=40, V_0=0.01m/s



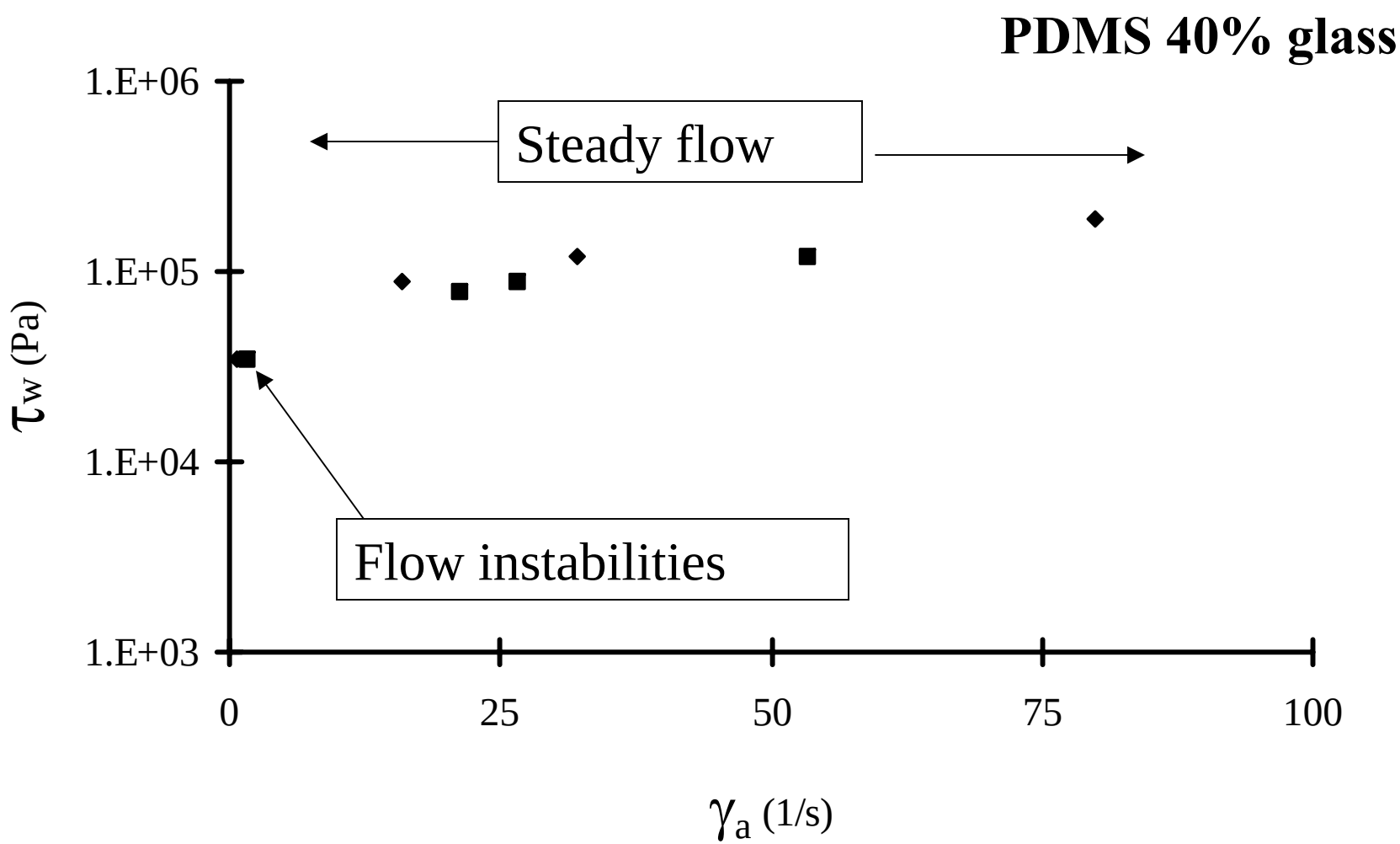
2R=0.0015m, L/2R=40, V_0=0.01m/s (50 1/s).



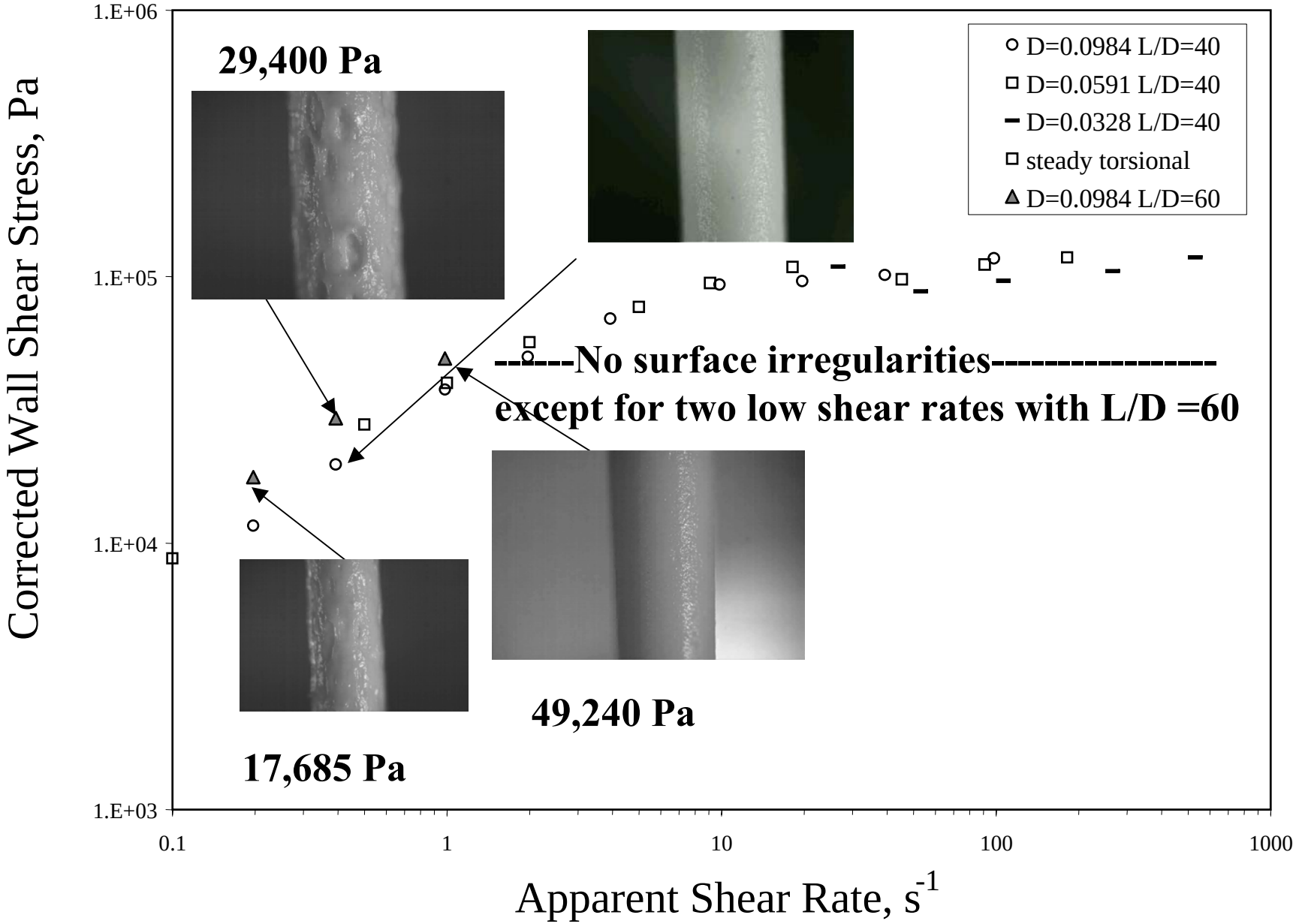
Solution for flow of PDMS suspension
2R=0.0015m, L/2R=40, V_0=0.01m/s
(50 1/s).



2R=0.0015m, L/2R=40, V_0=0.01m/s.
In the figure, triangles represent slip velocity (plug flow is observed).



–Squares – 2R=0.0015m, L/2R=40, diamonds – 2R=0.0025m, L/2R=60.



Poly(dimethyl siloxane) incorporated with **40% by volume of glass spheres**

Conclusions

It appears that the stability of stick or slip at the wall during extrusion governs the occurrence of surface irregularities.

Conditions which give rise to wall shear stress values at the wall, which are in the vicinity of the critical wall shear stress at which strong wall slip is onset give rise to flow instabilities.

Conditions which give rise to wall shear stress values which are significantly lower or higher than the critical wall shear stress generate a stable stick or stable slip condition, which are both free from flow instabilities.