Micro-force drag measurement of a fixed air bubble at low Re numbers using flexible micro-pillars

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A new concept to measure drag forces acting on particles fixed in the close-wall region with detectable forces down to even pico-Newton is presented. A feasibility study was carried out using a MOMS-based sensor consisting of a flexible micro-pillar (Fig. 1). Such a cylindrical pillar with a diameter of a few microns and a height of 390µm is manufactured from an elastomer (PDMS) such that it is very flexible and easily deflected by the fluid forces or supplementary forces acting on flow obstacles attached to the tip. The pillar tip bending is detected optically using highly magnifying optics (Fig. 2).

The experiments were carried out in a plate-cone rheometer with an air bubble of a diameter of 140µm attached to the pillar's tip. The Reynolds number based on the bubble diameter was varied in the range of 0.1 to 15.

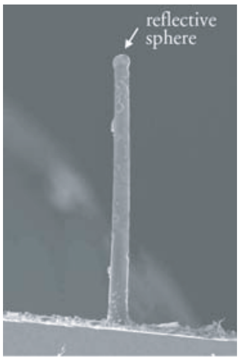

Fig. 1 SEM of a single pillar sensor with reflective tip (height 470µm, diameter 25µm)

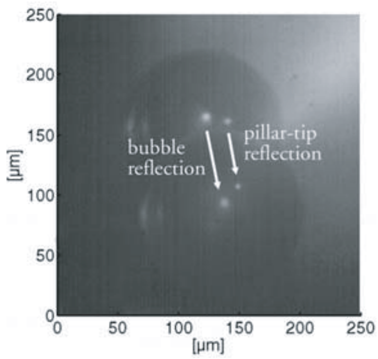

Fig. 2 Comparison of the non-deflected and deflected bubble position and the reflections in detail. Arrows evidence the trajectories of the reflective spots.

The theoretical deflection of the pillar tip was calculated using the Oseen approximation for the drag coefficient of a cylinder and linear bending theory. It can be described as a function of the uniform shear stress τ in the rheometer, assuming the pillar as a one-sided clamped cylinder bend by the viscous forces of the flow.

A calibration of the pure sensor geometry was performed in the plane shear flow of the plate-cone rheometer using water/water-glycerin. The calibration of the sensor confirmed a linear relation between the pillar-tip bending and the applied shear forces in plane shear flow. Although linear bending theory is only applicable at small deflections, the linear behavior reaches up to high deflection rates. In the case of the sensor used this was up to values of ~80px (88µm).

Assuming the bubble drag as a force acting concentrated in the center of the bubble, the resulting pillar-tip deflection can be calculated by using formulae from linear bending theory.

Besides the pillar-tip deflection also the reflection from the bubble was evaluated (Fig. 2) to ensure the no-slip of the bubble on the pillar tip such that a plane shear flow around the bubble could be assumed.

Fig. 3 shows the result from the theoretical calculation compared to the measured deflection of the pillar tip. It can be clearly seen that the measured pillar bending corresponds well with the theoretical prediction. The bubble deflection is also shown in Fig. 3, indicating a constant ratio to the pillar bending confirming that the bubble stays on the pillar tip without rotation.

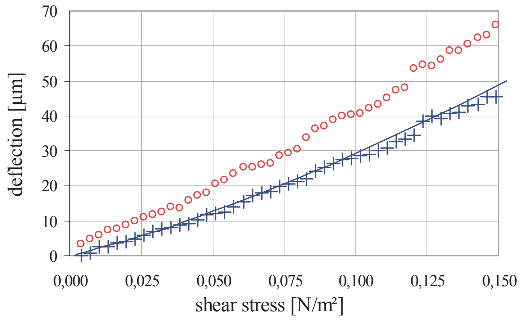

Fig. 3 Comparison of theoretical and measured deflection. The rheometer speed was continuously increased. The fluid is water at 25°C. Solid line: theoretical pillar deflection, + measured pillar tip deflection, o: measured pillar plus bubble deflection

The measured drag forces reached down to a few nano-Newtons. Since the resolution of the sensor is determined by the magnification of the optics an even higher resolution can be achieved using microscopic optics making pico-Newton measurements possible.

The sensor concept achieves a minimum of interference between sensor and particle. The forces existing on the pure sensor structure are in the order of 10% of the flow forces acting on both, the sensor structure and the particles.

Another advantage of the sensor is the two-dimensional sensitivity of the pillar structure. Common micro-cantilevers are normally one-directional devices, such that only one force direction can be detected with such sensors. The pillar technology and the optics used allow a temporal resolution of up to 1825Hz, enabling measurements of time-dependent two-dimensional turbulent wall shear stress distributions and drag forces.

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