PHYSICAL REVIEW E VOLUME 62, NUMBER 3 SEPTEMBER 2000

Laser wipers

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(Received 1 May 2000)

We present a novel application of lasers for removing particle deposits on inaccessible optical windows. The particular example arises with respect to cryostats filled with liquid helium. We explain the observation in terms of the radiation force acting on the adhering particles. We estimate the radiation forces to be much larger than all other forces acting on the particle.

PACS number(s): 47.70.−n, 66.90.+r

It is now well known [1] that lasers can be used to manipulate microscopic objects, as in ''laser tweezers'' or ''laser scalpels.'' Here, we present another use of lasers, namely, the cleaning of optical windows that are otherwise inaccessible. As far as we know, this application (''laser wipers'') is entirely new, and the technique is the only means of cleaning the optical windows during hydrodynamic experiments that require both optical access and solid particles in the flow.

The particular application arose in the case of optical Dewers filled with cryogenic helium. The use of cryogenic helium allows the generation of turbulent flows at very high Reynolds numbers [2]. In this experiment liquid helium at 4.2 K is kept in a chamber of the type shown in Fig. 1(a). Surrounding this inner chamber is another chamber kept at liquid nitrogen temperature (77 K), as well as an external chamber at the ambient temperature (the latter two are not shown in the figure). Each chamber is fitted with a set of four windows, marked (b), that provide optical access. The space between the chambers is kept under vacuum ($\approx 1\ \mu$Torr) to diminish heat transfer by conduction.

Turbulence is generated by pulling a grid of bars through an otherwise stagnant column of liquid helium. We are interested in mapping the turbulent flow field by using particle image velocimetry (PIV). For this purpose, polydispersed hollow glass spheres with a mean size of approximately 7 μm are used as tracers of the fluid flow and laser scatterers for PIV. The scattered light is captured at two successive instants of time using the optical arrangement shown schematically in (c) and (d) of Fig. 1 (consisting of a plano-convex lens and a cylindrical lens, operating at the sagittal focus), and a color digital camera. The low density of liquid helium (0.12 g/cm^3) restricts the choice of tracer particles to thin-walled hollow spheres, which have the smallest possible density. In practice, most of the particles are denser than liquid helium. So, to carry out the experiment we introduce a relatively large volume (e.g., 100 cm^3) of particles into the helium column and allow most of them to settle to the bottom, leaving after a few minutes only a small fraction of approximately neutrally buoyant particles to remain suspended in the liquid. However, in the process, many of the sedimenting particles practically coat the inside of the optical windows, as shown in Fig. 1(e). This will make it impossible to measure the fluid motion inside.

The fluid shear imparted by the grid movement next to the windows is ineffective in shaking the particles off the surface. However, a sheet of a pulsed Nd:YAG laser, incident on the chamber, shakes the particles loose, as shown for a vertical slit marked by the arrow in Fig. 1(f). The laser sheet is produced by the optical arrangement already mentioned. The actual focus of the sheet is along the axis of the chamber, where the PIV images are taken. In this way, the thickness of the laser sheet incident on the innermost window of the cryostat is approximately 500 μm. By sweeping the laser sheet across the window, as denoted by the arrows in Fig. 1(d), the cleaning effect of this laser wiping is complete, as shown in Fig. 1(g). The effect can be observed for an unfocused laser beam as well, but laser intensity correlates with the effectiveness of cleaning.

To explain this observation, we estimate the magnitude of the forces acting on a typical adhering particle—which we take to be 7 μm in size, this being the mean particle size in the present experiments. Neglecting electrostatic forces, the adhesive force on a sphere of radius r onto a wall (the inside of the optically flat window) is due to the liquid surface tension γ, and can be calculated [3] to be $4\rho\gamma r$; this is about 4 pN in this case. The shearing force due to the grid motion can be calculated by combining the particle area seen by the flow (πr^2) with the shear $\mu du/dy$, where μ is the dynamic viscosity of liquid helium, u is the grid velocity, and the characteristic shear is calculated over the radius of the particle r. This force is approximately 0.06 pN in magnitude and cannot overcome the adhesive force. When the particle intercepts a focused beam of large intensity, it experiences a radiation force given by

$$F_p = E_p r^2 Q_r / Ac, \tag{1}$$

where E_p is the pulse energy, Q_r is the radiation pressure scattering coefficient ($\approx$0.7 in geometric optics for a solid glass sphere with index of refraction 1.5), A the area of laser focus, and c the speed of light [4]. The magnitude of F_p is quite large ($\approx 1.3\ \mu$N), leading to the observed effect on the particles. The use of the steady-state formula to calculate F_p is justified (even though the duration of the laser pulse is

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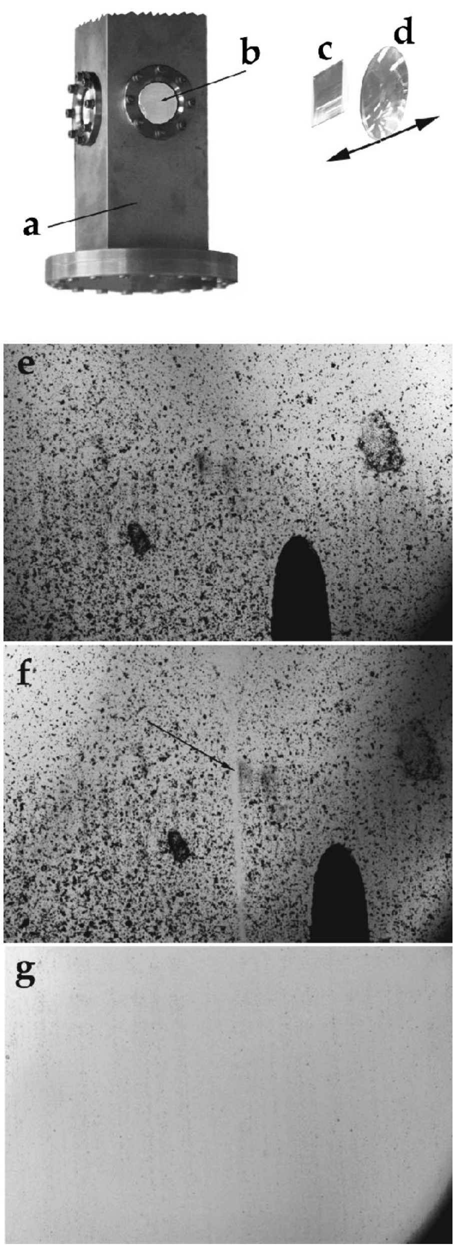

FIG. 1. (a) The innermost chamber, filled with liquid helium at 4.2 K. (b) One of the four optical windows on the inside chamber to allow optical access. (c) and (d) are, respectively, the cylindrical lens and the plano-convex lens used to form the laser sheet which traverses the optical windows and propagates through the cryostat. (e) Photograph of an inner-chamber optical window, showing the deposit of particles on its side that is in contact with liquid helium. The height of the field shown is 1 cm. The large dark structures seen in the photograph are due to particle aggregation. (f) Photograph of the same window after ten laser pulses, each of 100 mJ energy and 10 ns duration, have been fired through. The arrow shows that the area where the laser sheet was incident is free of particles. (g) Photograph of the clean window after sweeping the laser sheet across the window surface.

short), because the time scale characteristic of the van der Waals forces responsible for surface tension in the liquid [5] is very small (on the order of 1 ps). It is worth noting that the radiation force is much larger than the particle weight (approximately 4 pN for a solid glass sphere).

In the above calculation we have neglected the countergradient force that is normally associated with particle confinement in optical tweezers. The radiation force from Eq. (1) above should be much larger than the countergradient force for a relatively uniform beam far from diffraction-limited focus. We have also neglected light absorption by the glass shell of the particles, which is the predominant mechanism operating in the case of optical scalpels, namely laser ablation.

While the present example of laser wipers arose in the context of optical surfaces in cryogenic helium, various other experiments with inaccessible optical windows may be good candidates for this application. For example, one may think of cleaning the soot off windows in firing optical engines (e.g., Ref. [6]). A more exotic application may be in the cleaning of solar panels in spacecraft. Environments such as the Martian atmosphere are laden with dust particles that are a potential hazard to the smooth operation of solar panels over the span of months or years [7]. Even though a pulsed laser is a somewhat bulky device, it may be useful to incorporate one in a large space installation.

The work was supported by the National Science Foundation under Grant No. DMR-95-29609.

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