Visualization of Mass Transport and Heat Transfer in the FAPA Ambient Ionization Source

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Electronic Supplementary Material

Schlieren Imaging Theory

Schlieren imaging is a diagnostic tool that produces an image based on spatial gradients in refractive index. Schlieren imaging has existed for over 300 years [1] and was originally described by Hooke. The name schlieren comes from the German word “Schliere” which roughly translates to “streak” or “striation. The basic principles of schlieren imaging are presented in Figure 1. A point, or slit source of light fully illuminates a focusing optical element at exactly its focal length, creating a perfectly collimated beam of light. The collimated beam is then focused to a point by a second optical element and the light at the focal point is partially blocked by a knife edge. Any disturbance in refractive index within the collimated beam, the schlieren working area (SWA), causes light to miss the knife edge and produce either an attenuation or enhancement in the resulting image. Whatever is in the schlieren working area can then be brought to a focus at the image plane by the second (focusing) lens. Schlieren imaging has been utilized for a variety of diagnostics during its long history, ballistics, plasmas/arcs[2, 3], flames[4], laser-ablation[5, 6], aerodynamics, sound waves[7] electrophoresis[8] heat transfer[9] this is by no means a comprehensive list, just an example of the far reaching applications schlieren imaging offers for a more complete listing see Settles[1].

A schlieren-setup utilizing lenses has the benefit of being straightforward to set up and troubleshoot; however, it has several shortcomings. First, lenses cause chromatic aberrations with the use of a white light source because of the wavelength dependence of refractive index. This dependence causes different wavelengths of light to focus at different points, which causes unwanted coloring. Additionally, it is difficult to find quality lenses large enough to provide a suitable working area without significant cost. Conveniently, replacing the lenses with concave mirrors removes the chromatic aberration and allows a larger working area for a reasonable price. As long as the angle between the arc lamp, the first mirror, and the working area is the same as the angle between the knife edge, the second mirror, and the working area, the optical aberration known as coma will be eliminated.

Due to the necessity of using spherical mirrors, spherical aberration can be a concern; however, this problem can be lessened by the use of a horizontal or vertical slit after the arc lamp and subsequently placing the knife edge at either the saggital or tangential focal point. This modification lessens spherical aberration at the cost of losing the orthogonal schliere information.

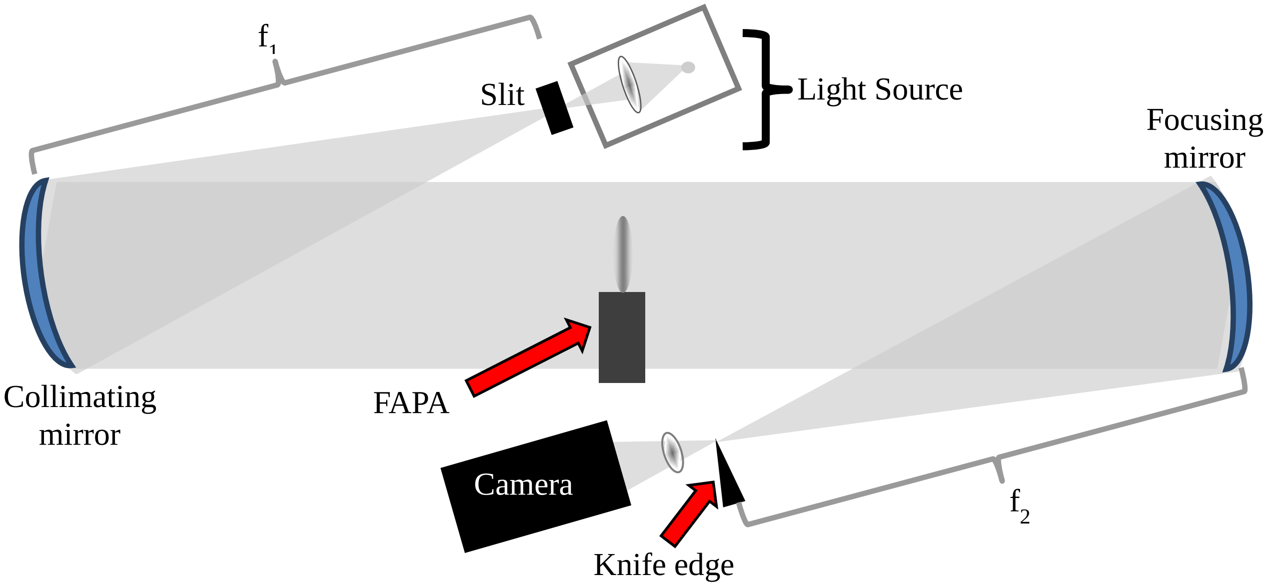

Fig. 1 Schematic diagram of “Z” or Toepler schlieren instrument that utilizes mirrors, a Xe-arc lamp and a camera for image capture. Light from the Xe-arc lamp passed through a microscope objective used as a condensing lens, before it passed through a 2-mm slit, which fully illuminated a collimating mirror. Collimated light then passed through the schlieren working area, where the FAPA source was positioned, before it impinged on a focusing mirror

which recreated the slit image on a knife edge (razor blade) before it was focused by an image optic and captured by a digital camera.

Essentially, with a horizontal slit and horizontal razor blade, the schlieren setup is sensitive only to vertical changes in refractive index and vice versa for a vertical slit and razor blade. This phenomenon can be readily explained by examining the knife edge in greater detail. Only a change in refractive index that causes light to hit or miss the blade will be imaged. Therefore, only changes in refractive index parallel to this edge, which create perpendicular changes in light, will be seen.

The angle of refracted light with respect to parallel, ε, is proportional to the first spatial (*x* and *y*) derivative of refractive index[1].

$$\varepsilon_x = \frac{L}{n_o}\frac{\partial n}{\partial x}, \quad \varepsilon_y = \frac{L}{n_o}\frac{\partial n}{\partial y} \tag{1}$$

Where L is the length of the schliere in the direction specified, n_o is the refractive index of the surrounding media, x and y are the dimensions perpendicular to the optical axis and n is the refractive index of the schlieren. Another property of the schlieren system, sensitivity; can be shown to be equal to

$$S = \frac{dC}{d\varepsilon} = \frac{f_2}{a} \tag{2}$$

Where S is the sensitivity, C is the contrast of the image, ε is the angle of refracted light, f_2 is the focal length of the second image optic, and a is the height of unblocked light. This equation shows that the sensitivity of the system can be readily changed by simply moving the razor blade. There is a cost associated with this ease of adjustment, as the value a approaches 0 (blocking all light), or blocking no light, the spatial resolution of the system suffers as refractive index gradients are no longer represented symmetrically. More detailed theory can be found in a variety of texts [1,10,11].

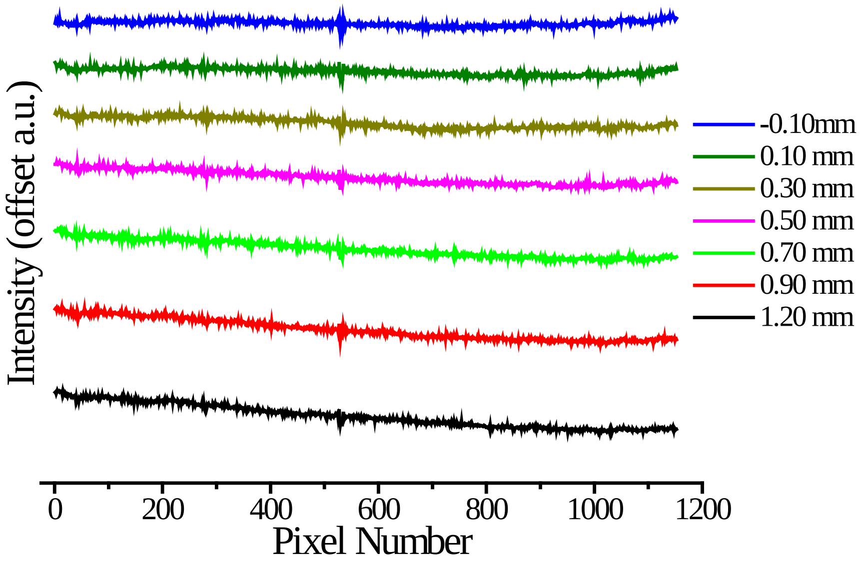

Fig. 2 Effect of moving the razor blade along the light axis, illustrating the sensitivity of adjustment along the z axis for background evenness, which is indicative of finding the true focal point of the focusing mirror.

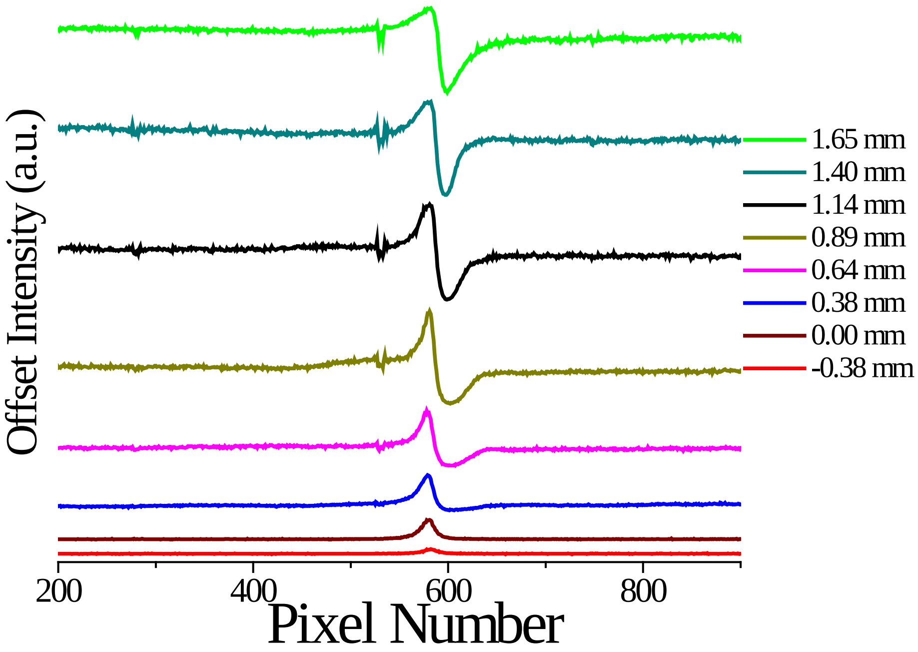

Fig. 3 Line profiles extracted from several schlieren images illustrating the effect of moving the blade along the x axis (changing the *a* value)

FAPA ignition movie.mpg

Fig. 4 Video of FAPA igniting, 0.250 mm I.D. capillary, 1.50 L/min helium, 25 mA and 500 V.

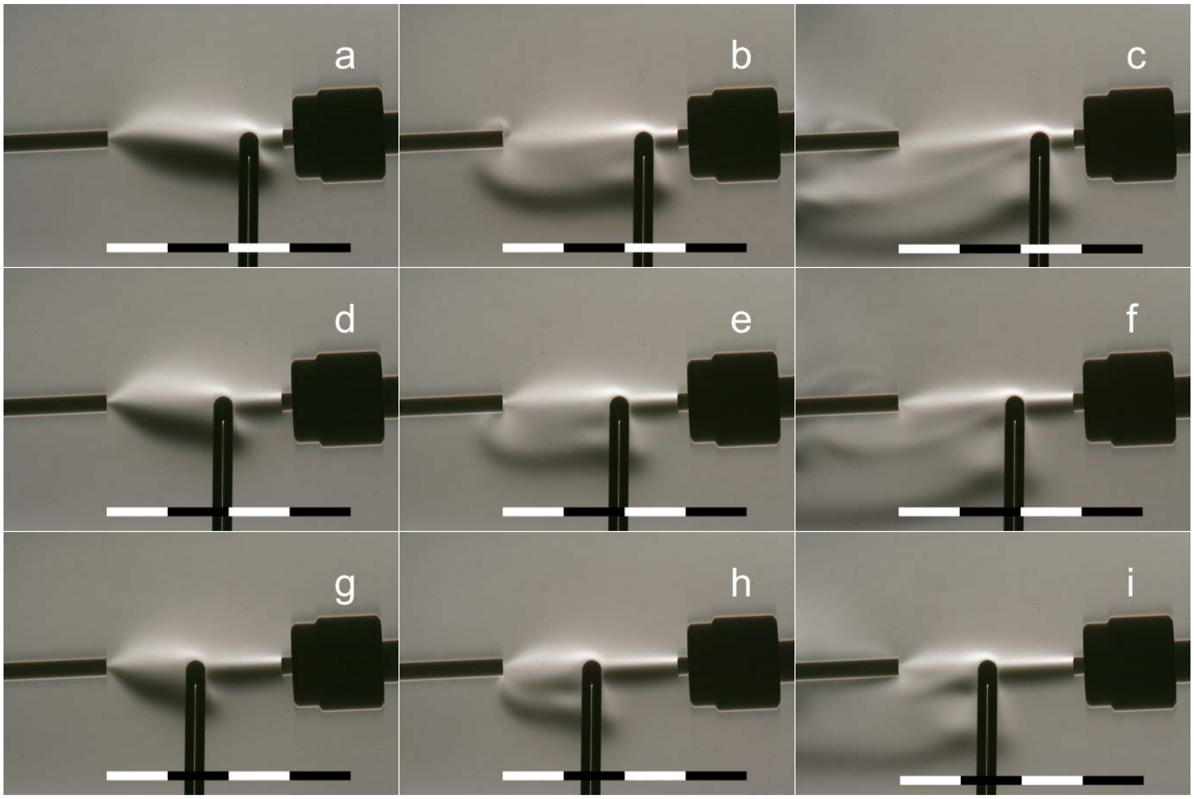

Fig. 5 Schlieren images of a FAPA plasma gas flow interacting with a melting point capillary at source to capillary distances of 2 (a,b,c) 4 (d,e,f) and 6 (g,h,i) mm. Gas flow rates of 0.50 (a,d,g), 1.00 (b,e,h), and 1.50 (c,f,i) L/min of He.

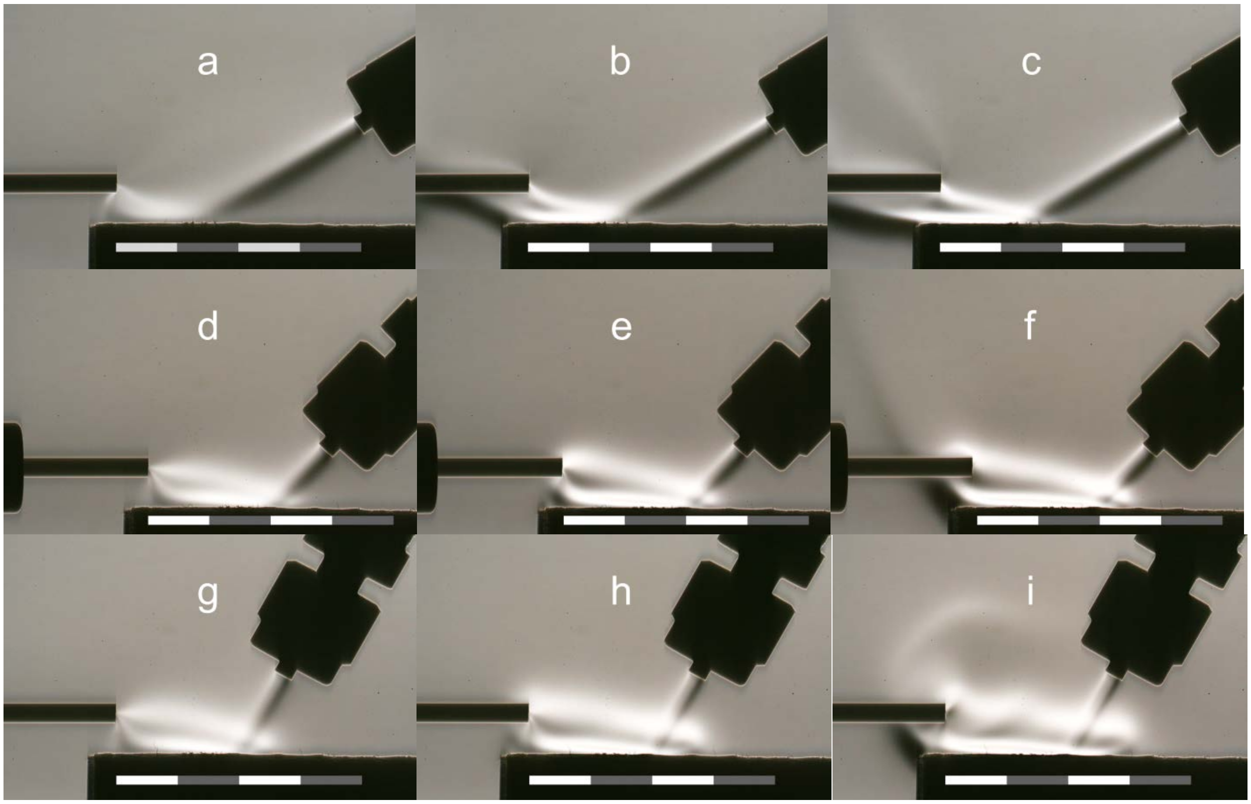

Fig. 6 Schlieren images of FAPA plasma gas impinging on a surface before capture by an interface. Source-to-surface angles of 30° (a,b,c), 45° (d,e,f) and 60° (g,h,i) and flow rates of 0.50 (a,d,g), 1.00 (b,e,h,) and 1.50 (c,f,i) L/min.

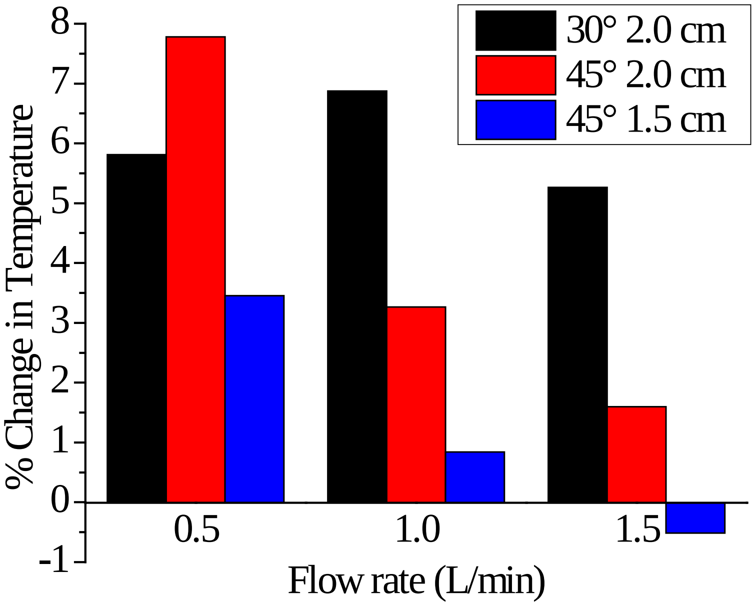

Fig. 7 Percentage change in peak temperature on a glass slide caused by applying vacuum to a mock mass spectrometer interface, all bars represent a decrease in temperature except 45° 1.5 cm where the temperature increased. This graph illustrates the modest effect that a vacuum interface has on surface temperature.

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