Vortices in the wake of a femtosecond laser filament

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Abstract: We report on the experimental observation of fluid flow caused by propagation of femtosecond filaments in dry air. We find that the ionization of the medium deposits a non-negligible amount of heat, which creates vortices in a semi-confined glass cylinder. We confirm the influence of thermal gradients on vortex formation by the use of a heated wire in a similar configuration.

OCIS codes: (320.7090) Ultrafast lasers; (350.5400) Plasmas; (120.6810) Thermal effects; (280.7060) Turbulence.

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#220361 - $15.00 USD Received 6 Aug 2014; revised 5 Sep 2014; accepted 6 Oct 2014; published 16 Oct 2014

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1. Introduction

Femtosecond filamentation - whereby self-focusing caused by the optical Kerr effect and defocusing caused by plasma formation are in balance - was discovered approximately twenty years ago [1]. Since then, a significant body of work on this subject has accumulated with excellent reviews available [2, 3]. The unusual properties of femtosecond filaments have led to the suggestion of numerous applications such as LIDAR [4, 5], lightning protection [6], generation of single cycle pulses [7], laser induced breakdown spectroscopy [8], and fluid dynamics measurements [9, 10].

The observation of laser-induced water vapor condensation in the atmosphere and in cloud chambers using the 220 mJ Teramobile laser [11], has inspired field and cloud chamber experiments in which charged species, formed by the laser, were identified as the nucleation agents [12,13]. Cloud chamber experiments with a 1kHz 2mJ laser source identified an updraft of warm moist air creating vortices perpendicular to the filament ~5mm below the laser; the laser-induced flow having a significant effect on water condensation and snow formation [14–16]. Here we explore the fluid flow dynamics that ensue in dry air as a result of filamentation with 0.7 mJ pulses at 1kHz. Taking advantage of light-sheet illumination to obtain a cross-section of the fluid flow, we find the formation of pairs of counter-rotating vortices in the wake of the laser filament, which could affect fluid dynamics measurements involving filamentation [9, 10]. Our observation is made in the absence of a complicated thermofluids environment involving humid air, an imposed temperature stratification (bottom plate temperature at −19.5°C while the temperature in the top was + 19°C), and in the absence of phase changes (condensation) [14–16].

2. Experimental setup

A schematic of the experimental setup is presented in Fig. 1. The output from a 1 kHz regenerative amplifier with 800 nm central wavelength, is focused with a long focal length concave mirror (f = 500 mm). The laser pulses are first characterized and their spectral phase is corrected to near transform limited by using multiphoton intrapulse interference phase scan (MIIPS) [17, 18]. The transform limited pulse duration at full-width half-maximum (FWHM) is 40 fs. For all the measurements presented here the average power is set to 700 mW. The beam is focused in air. Glass tubes of two different diameters (4mm and 14mm) and lengths are used to keep room air currents to a minimum. The glass tubes are intersected by a laser sheet, which is created by a CW green laser diode (532 nm) focused by a cylindrical lens. In order to visualize the fluid flow, a small amount of butanol is sprayed in the air near the tube; the butanol mist enters the tube and scattering allows us to see the fluid flow dynamics surrounding the filament taking advantage of Mie scattering. Pictures and video of the fluid dynamics were acquired using a digital single-lens reflex (DSLR) camera set at a 30° angle from the laser direction of propagation.

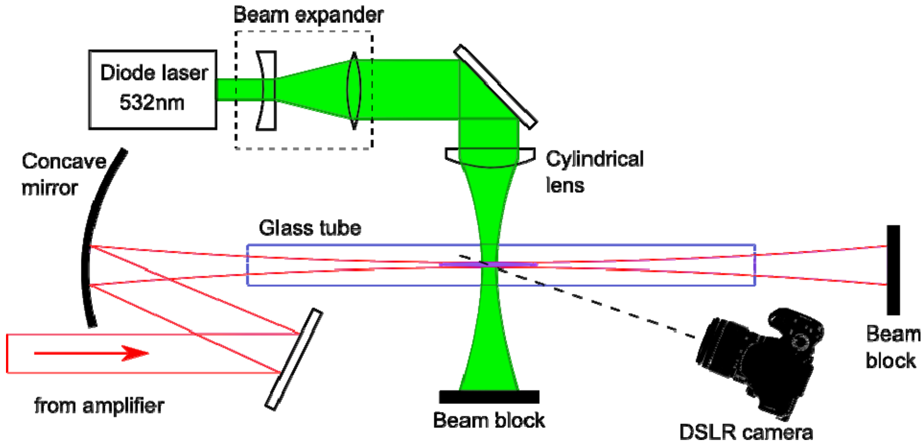

Fig. 1. Experimental setup. Green diode laser is used to create a laser sheet in the vertical plane. DSLR camera images green scattered light from seed particles, unveiling the fluid flow resulting from filamentation in a narrow glass tube.

3. Results

Results of laser-induced fluid flow are illustrated in Fig. 2, obtained with the smaller diameter tube. In these cases two almost identical vortices (a vortex pair of opposite rotation) are created with symmetry in vertical and horizontal planes. Vortex rotation direction is opposite for right-left or top-bottom. The circular motion with gradually increasing rotational frequency starts when the laser filament is formed. The speed of the rotation is stabilized within a very short period of time (about 1 second) and stays constant while the filament is present. When the filament is not formed or the laser is blocked, the motion stops completely.

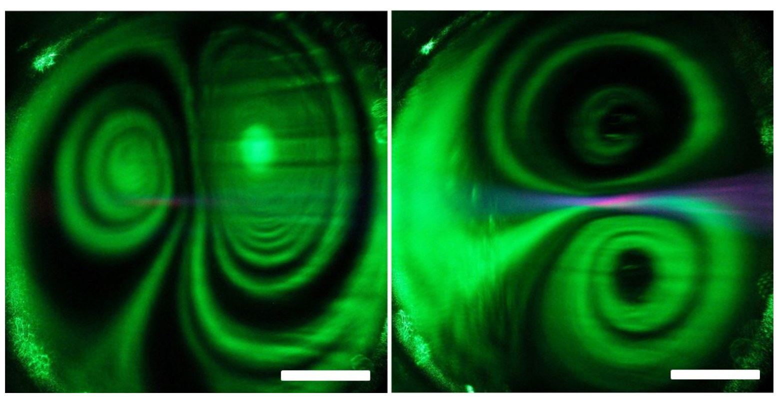

Fig. 2. Two different vortex pairs observed in the 4 mm diameter glass tube induced by laser filamentation. The laser filament is observed as a purple hue in the middle of each image. Scale bars are 1 mm. The number of vortices as well as their relative orientation depends on the position of the laser filament relative to the center of the tube. Video uploaded as (Media 1).

The orientation of vortices (Fig. 2 left image versus right image) is found to depend on the position of the filament relative to center of the tube. With a slight offset from the central position inside the tube vortices have a preference to form in a certain configuration. For instance, the difference between the two cases illustrated in Fig. 2 is that the filament is displaced in the vertical direction relative to center of the tube (left) or in the horizontal direction (right). When the filamentation is closest to the symmetry axis of the tube other flow arrangements are possible such as – three- and four-vortices.

#220361 - $15.00 USD Received 6 Aug 2014; revised 5 Sep 2014; accepted 6 Oct 2014; published 16 Oct 2014

To study the influence of the tube on the fluid flow dynamics in the wake of laser filamentation we used a tube with a larger inner diameter – 14 mm. All other experimental parameters were kept the same. The result is presented in Fig. 3. In this arrangement we observed two counter-rotating vortices with much slower rotation speed, counterclockwise for the left vortex and clockwise for the one on the right. Real-time videos were recorded for conditions similar to those in Figs. 2 and 3, and can be found under (Media 1) and (Media 2).

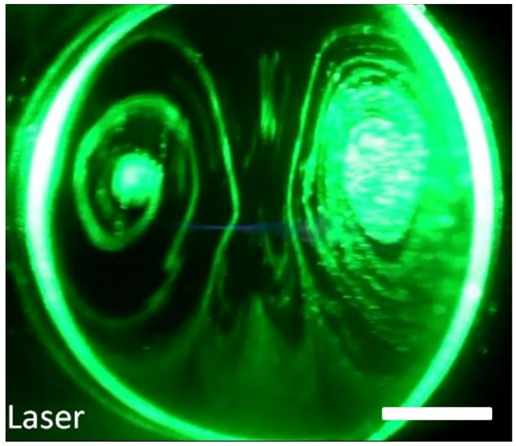

Fig. 3. Vortex pair formed in the glass tube with 14 mm in diameter created by laser filamentation. The filament can be observed as a faint purple hue in the middle of the image. The scale bar is 3mm. Video uploaded as (Media 2).

4. Discussion and implications

Ionization associated with the filament suggests the laser deposits sufficient energy to cause local heating, which then causes convective fluid flow within the confined cylindrical volume. The heat deposited by the laser plasma with estimated local temperature of 3000-5000 K [19] is transferred to gas molecules surrounding the filament, thereby causing gas expansion and creating fluid motion by several possible mechanisms, including radially expanding shock waves and an upward motion for these molecules due to gravity. When the expanding gas reaches the cylindrical wall of a tube it forms counter-rotating vortices. Despite the high temperatures, the overall heating effect from laser filaments may be neglected when using low repetition rate sources [11–13], but becomes significant when using kHz laser sources [14–16].

To test the buoyancy-generated flow hypothesis, we replaced the laser filament by a resistance wire diameter of 0.45 mm at the center of a 14-mm tube. When the wire is heated the temperature gradient in the gas creates vortices identical to those created by laser, see Fig. 4. When the temperature of the wire reaches 150°C, the rate of rotation in the vortices matches that of the laser induced vortices. This measurement gives us a sense of the local macroscopic heating caused by the laser filament. In some cases we see more complex vortex arrangements (not shown) that are not explained by the simple buoyancy hypothesis. We plan to evaluate if those cases are related to multi-filament formation.

Our findings are complementary to cloud-chamber measurements of laser-filamentation-induced condensation and snow formation [11, 14]. Condensation was found to result from the creation of plasma generated nucleating agents [11], and particle growth is enhanced by laser-induced motion of air flow [14, 16]. Cloud chamber measurements and associated simulations under high humidity and near a cold plate visualized the formation of a vortex formed a few millimeters below the filament [16]. The light-sheet illumination experiments presented here on dry air capture the formation of vortex pairs along the filament. These findings support the fact that heating by the filament cannot be neglected and affects fluid flow, even in the absence of temperature stratification and condensation.

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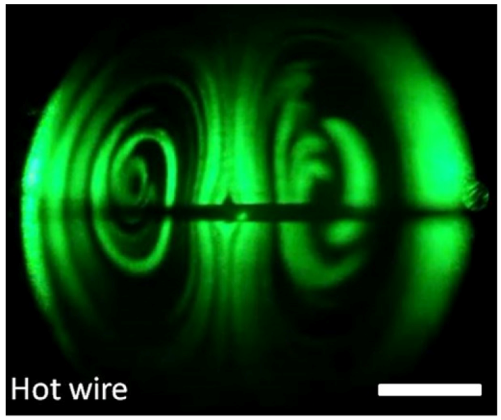

Fig. 4. Vortex pair formed in the glass tube with 14 mm in diameter created by a hot resistance wire, which casts a horizontal shadow. The temperature of the wire was adjusted to match the period of rotation of the laser-induced vortices. The scale bar is 3mm.

The measurements presented here are useful for implementation of applications based on laser filaments. For single pulse applications, the laser experiences no distortion from local heating as it propagates. However, the fluid flow dynamics in the wake of the pulse are disturbed by local heating. We are aware of one type of measurement whereby a femtosecond laser excites the excited B-state of nitrogen, and the emission is used to achieve molecular tagging velocimetry (MTV) [20] for fluid dynamics studies in air [9]. Findings of local heating introduced by a filament and the changes in fluid dynamics surrounding the filament suggest that MTV experiments need to take these effects into account and care must be exercised in the interpretation of results. Conversely, the findings reported here indicate filaments can be used to affect fluid flow dynamics remotely.

5. Conclusion

We report on the experimental observation of fluid flow caused by propagation of femtosecond filaments in dry air. Significant flow disturbance comprising multiple vortices has been observed. We hypothesize that the nature of this fluid flow arises from gas expanding from the heated region created by the plasma associated with filamentation. Convection processes and the constrained volume force the gas to form vortices. This hypothesis has been tested with a heated wire placed in the tube instead of laser beam, and the observed vortex formation was very similar to the laser-induced one. These findings confirm the importance of heat flux from filaments and the resulting fluid flow, a result relevant to applications of filaments for molecular tagging velocimetry, condensation and in general for the use of high-repetition rate sources where the medium does not renew fast enough and subsequent pulses travel in areas with increasing thermal energy. The analysis presented explains the simplest case of a single pair of vortices induced by an updraft caused by thermal buoyancy. Under certain conditions of intense laser excitation and confinement more complicated fluid flow is observed. We plan to explore the higher energy regime, and different chamber configurations using axial as well as transverse light sheet illumination.

Acknowledgments

The work was funded by Air Force Office of Scientific Research (AFOSR) FA9550-13-1-0034 (Drs. Enrique Parra and Douglas Smith, Program Managers). The authors gratefully acknowledge seed funding for this work from the Michigan State University Office of the Vice President of Research and Graduate Studies, Prof. Steven Hsu.