Laser filamentation induced air-flow motion in a diffusion cloud chamber

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Abstract: We numerically simulated the air-flow motion in a diffusion cloud chamber induced by femtosecond laser filaments for different chopping rates. A two dimensional model was employed, where the laser filaments were treated as a heat flux source. The simulated patterns of flow fields and maximum velocity of updraft compare well with the experimental results for the chopping rates of 1, 5, 15 and 150 Hz. A quantitative inconsistency appears between simulated and experimental maximum velocity of updraft for 1 kHz repetition rate although a similar pattern of flow field is obtained, and the possible reasons were analyzed. Based on the present simulated results, the experimental observation of more water condensation/snow at higher chopping rate can be explained. These results indicate that the specific way of laser filament heating plays a significant role in the laser-induced motion of air flow, and at the same time, our previous conclusion of air flow having an important effect on water condensation/snow is confirmed.

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References and links


1. Introduction

The dynamics of femtosecond laser filamentation in bulk media/gas is always an active area of research in nonlinear optics. In recent years, a femtosecond laser beam was found to be able to propagate in air for a long distance as a plasma filament when a dynamic balance between the Kerr focusing and multiphoton/tunnel ionization (MPI) defocusing [1–4] and/or negative higher-order Kerr terms [5,6] is achieved. The self-guided filament has a nearly constant diameter during the propagation, and the intensity clamped in the core of filament can reach ~10^{14} W/cm^2 [3,7], which can explode chemical and biological molecules/agents and cause complicated photo-oxidation reactions [8,9]. A series of interesting optical
phenomena along with laser filamentation can be observed, such as generation of super-continuum spectrum or white-light laser [4,10,11], conical emission and so on [12].

Because of its various applications, femtosecond laser filamentation has attracted lots of attention since several decades, including laser pulse self-compression [13], optical parametrical amplification [14], LIDAR (light detection and ranging) [10], remote sensing [8,15,16], and lightning control [17]. Recently, femtosecond laser-assisted water condensation as a candidate of rain making has been investigated both in a cloud chamber and the atmosphere [9,18–22]. It is found that water condensation around the filaments can be triggered in both saturated and sub-saturated conditions [18,19]. However, due to several complications, including physical, chemical, and thermodynamic processes occurring in the propagation of femtosecond laser pulses in the cloud chamber, the water condensation induced by femtosecond laser filaments has not been fully understood yet. J.-P. Wolf and his collaborators proposed that the photo-oxidative chemistry of nitrogen induces the binary H₂O-HNO₃, which served as nucleation sites of water droplets [9,18–21]. Our recent experimental results show that a continuous and intense updraft of warm moist air also played an important role in this process [22]. In nature, air-flow motion has a significant effect on the microphysical processes in cloud developments. Clouds composed of many tiny water droplets, are formed when air containing water vapor rises, expands under the lower pressures which exist at higher levels in the atmosphere, and thereby cools until some of the vapor condenses. The intense updrafts in clouds will induce vapor deposition onto the growing water/ice particles, and help the formation of large-sized water droplets/ice crystals, while downdrafts make the precipitation particles drift downward and at the same time speed up the coalescence growth of particles [23]. So it is significant to investigate the microscopic processes and mechanisms of air-flow motion in the investigation of water condensation induced by filaments.

In this paper, we numerically simulated the air-flow motion induced by femtosecond laser filaments for different chopping rates in a diffusion cloud chamber. A two dimensional model including energy, mass and momentum transports was used. The laser filaments were treated as a heat flux source. By comparing calculations with experiments, it is found that the specific way of laser filament heating plays an important role in laser-induced air-flow motion, and the related experimental results were explained.

2. Experiment

The experimental setup was similar to that in our previous published paper [22]. A regenerative amplified Ti: sapphire laser at wavelength of 800 nm that delivers 50 fs, 1 kHz, mode-locked pulses was used in our study. The laser energy before the incident window of the cloud chamber was 8 mJ. The length of the generated filaments was about 10 cm with a diameter of about 100 μm. The different chopping rates were obtained by using a mechanical chopper. A CW 532-nm laser beam with 10 W output power, was used to probe the air-flow motion after being expanded to 45 mm in diameter and truncated by a 28 mm (height) × 5 mm (width) slit. The cloud chamber had a size of 0.5 (length) × 0.5 (width) × 0.2 (height) m³, and a vertical temperature gradient was maintained in the chamber by using a refrigerating machine to cool the bottom base plate at a temperature of −46 °C, while the top plate of the chamber was kept at room temperature. A water reservoir was mounted at a height of 17 cm relative to the cold bottom base plate inside the chamber. The reservoir was in a 45 cm × 45 cm square frame with a cross-section of 5 cm × 2 cm in a downward-pointing triangle. It held distilled water pumped from a water tank under the bottom base plate. The quantity of water vapor inside the chamber was controlled by adjusting the electric current of a heating wire submerged in the water. The height of the laser axis relative to the bottom base plate of the cloud chamber was set at 10 mm.

The effect of laser-induced updraft on snow formation was investigated by chopping the 1 kHz laser pulses at different frequencies. A chopper was used to divide the 1 kHz beam into equal temporal sections. An n-Hz chopped beam except 1 kHz means that the total number of pulses reaching the target in each second = (1000/2n) × n = 1000/2 = 500 and is independent...
of n. The dynamic motion of the updraft induced by laser filaments at different chopping rates was also recorded relative to the 1 kHz laser filamentation (Figs. 1(a)–1(c)). The intensity of the updraft decreased rapidly with decreasing chopping rate. When the chopping rate was adjusted to 1 Hz, instead of intense updraft/convections, only intermittent updraft was observed and hardly any snow was formed on the bottom plate. On the other hand, lots of particles/ice crystals can be recognized in the filament active volume even with naked eyes, especially when irradiated by 1 kHz laser pulses. The velocity of the updraft at different chopping rates was also estimated by calculating the velocities of air flow or particles with sizes of ~30 μm (red line with square symbols in Fig. 3 of [22]). We found that the maximum velocity of updraft increases with increasing chopping rate, and the most intense updraft tends to exist above the center of laser filaments. Correspondingly, a heap of snow was produced and confined in the center area just below the laser filaments except for the case of 1 Hz chopping rate where no snow was collected. These results indicate that air-flow effect plays an important role in triggering water condensation and snowfall, so it is significant to investigate the mechanisms of air-flow formation in a cloud chamber.

3. Theory and numerical model

In order to get an insight into the mechanism of air flow near the laser filaments, we simulated numerically the flow fields in the cloud chamber using a two dimensional model. Figure 2 shows the sketched map of the calculated cross section, and the 10-cm long red line with a width of 100 μm above the bottom of the chamber represents the heat flux source induced by the laser filament. The spatial distribution of air-flow velocity is the result of the coupled mass-heat transfer and flow processes, which are mathematically described by (a) the continuity, (b) the energy, (c) momentum equations of the gas.
The continuity equation is described by the equation [24–26]

$$\frac{\partial}{\partial t}(\rho) + \nabla \cdot (\rho \vec{u}) = 0,$$

where $\rho$ is the density, and $\vec{u}$ is the velocity of air flow.

Accounting for the heat transport due to conduction and air transport, the energy equations are given by [25–27]

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \vec{u} h) = -\nabla \cdot q$$
$$\nabla \cdot q = \nabla \cdot (\lambda \nabla T) + S$$
$$h = c_p T,$$

where $h$ is the specific enthalpy, $q$ is the heat flux, and $c_p$ is the specific heat capacity. $T$ is the temperature, and $S$ is the internal heat source. $\lambda = \rho \alpha c_p$ is the thermal conductivity, and $\alpha$ is the thermal diffusivity. As boundary conditions, setting the temperatures $T_0$ at $Y = 0$ (the bottom of the chamber) as $-46 \degree C$, and $T_L$ at $Y = L$ (the top of the chamber) as the room temperature, respectively, the corresponding specific enthalpy can be calculated. Two side walls were assumed to be adiabatic. In this model, the laser filament zone was treated as a heat flux source, and air was assumed as an ideal gas, room-temperature values of specific heat and thermal diffusivity were used.

Considering natural convection, the momentum equations take the following form [25–27]

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho \vec{u} u) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} - V_x$$
$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho \vec{u} v) = \nabla \cdot (\mu \nabla v) - \frac{\partial p}{\partial y} - V_y + \rho g.$$

Here $\mu$ is the dynamic viscosity of air, $p$ is the total pressure, $V_x$ and $V_y$ are additional viscosity terms not included in $\nabla \cdot (\mu \nabla u)$ and $\nabla \cdot (\mu \nabla v)$, and $g$ is the gravitational acceleration.

In this work, Eqs. (1)–(6) were solved by a commercial program Fluent 6.3, in which, the control volume method was used to discretize the transport equations. The solution of the
density, energy and momentum equations was approximated by the second order up-wind differencing scheme in order to improve the precision of the calculation. The pressure-implicit with splitting of operators (PISO), part of the SIMPLE family of algorithms, was employed for the pressure–velocity coupling scheme [24]. The final calculated results were obtained when the monitored residuals including continuity, energy, and velocities were less than $10^{-4}$.

In our experiments, the 50-fs laser pulse with the energy of 8 mJ was self-focused to thin filaments with a diameter of about 100 μm and a length of 10 cm, therefore, the average power of laser filaments per unit of area is $\sim 2 \times 10^4$ W/m² assuming the total energy conversion efficiency of the incident fs laser pulse into the filament was 5% [3,11,28]. This value was set as the specific heat flux induced by each laser pulse in the model. The heating time of each laser pulse was assumed to be 1 μs, after which the deposited energy began to thermal diffuse outward. The used time steps in the model are 0.01 μs and 0.001 ms during the time of laser heating and interval between two adjacent pulses, respectively. This approximation was validated by observation of nearly identical air-flow velocities in the simulation. The heat flux source was set by user-defined functions (UDF) programmed with C language, which was then interpreted and compiled by Fluent 6.3.

4. Results and analysis

We simulated the flow fields in the cloud chamber induced by the fs laser at different chopping rates. In our cloud chamber, due to the periodic heating of laser filament, a relative heat balance can be obtained between the laser filament and its surroundings through heat transfer for a period of time, therefore, the final velocities and patterns of air flow can reach a relative stable state. In the model, we obtained the simulated flow fields (Fig. 3) at the time moment of $\sim 2$ s, at this time, the simulated flow fields reached a relative stable state (velocities and patterns of air flow changed very small compared with the results obtained in the next period of laser-filament heating, that is, converged solutions were obtained), which was decided by the monitored residuals including continuity, energy, and velocities which were set less than $10^{-4}$ in our model. Before this moment, the simulated flow fields had great change in the two neighboring period of laser-filament heating (not converged solutions), and after this moment, the simulated flow fields were similar to those at the time of $\sim 2$ s since converged solutions had been obtained. Figure 3(a) indicates the calculated flow field for the chopping rate of 1 Hz, and the corresponding experiment results are shown in Figs. 1(a) and 4. In the experiments, it was observed that the updraft rose from the center of the filament first, then went up to a certain height, finally began to fall and formed a weak air-flow cycle. This motion direction of air flow agrees with the simulated results. Additionally, the area with larger air-flow velocities, that is, darker colors (red and green) in the inset of Fig. 3(a) can correspond roughly to that with the intense scattering/updraft in the experiments (close to the red arrow line in (Fig. 1(a)). On the other hand, the areas with the smallest air-flow velocities (blue areas in the inset of Fig. 3(a)) agree with those with the weakest scattering/updraft in Fig. 1(a) (yellow elliptic-like area). One can see that the calculated maximum velocity of air flow locates at the updraft above the middle of the laser filament, which is consistent with the experimental observation. Moreover, the calculated value of the maximum velocity of updraft is 1.47-2.46 cm/s (red and green velocities in Fig. 3(a)), which is close to the experimental value 3.62 cm/s (Figs. 1(a) and 4). The difference is in that the air-flow motion in the experiments was not as symmetric as that in the simulated results. However, their patterns are similar if we compare the left half of the Figs. 1(a) and 3(a) only. The asymmetry of air flow in the experiment was probably caused by the fact that, in spite of intensity clamping, the distribution of power inside a laser filament is non-uniform along the filament because of self-pulse shortening (compression).

Figure 3(b) shows the simulated flow fields for the chopping rate of 15 Hz. It is found that the areas with larger air-flow velocities (areas with higher density light blue and yellow colors in the inset of Fig. 3(b)) are broadly in line with those with the intense scattering/updraft in the experiments (areas in the red ellipse and near the red arrow lines in Fig. 1(b)) although the
simulated positions of air flow are a little higher. Also, the areas with the smaller air-flow velocities (blue areas in the inset of Fig. 3(b)) compare well with those with the weakest scattering/updraft in Fig. 1(b) (yellow triangular-like areas). The simulated maximum velocity of updraft is 5.06-7.23 cm/s (red and yellow velocities in Fig. 3(b)), which is close to the experimental average value 9.3 cm/s (Fig. 4).

The simulated flow field for 1 kHz repetition rate is shown in Fig. 3(c). One can see that the velocities of air flow in the center area in the simulated result (inset of Fig. 3(c)) are smaller, which disagrees with the experimental result that the center scattering/updraft is the most intense (red elliptical area in Fig. 1(c)). This is probably caused by the strong scattering of the large accumulation of snow right below the center of the filament (see discussion later). However, the areas with the larger air-flow velocities (areas with green and yellow colors in the inset of Fig. 3(c)) can compare well with those with the intense scattering/updraft on the two sides (red rectangular areas in Fig. 1(c)). A quantitative discrepancy appears between the maximum velocities of updrafts in spite of the large error bars (Fig. 4). The possible reasons will be analyzed below.

The flow fields for the other two chopping rates of 5 and 150 Hz have also been numerically simulated, and the obtained patterns of air flow and maximum velocities of updraft (Fig. 4) agree with the experimental results. For the chopping rate of 150 Hz, the difference between the simulated and experimental maximum velocities of updraft is a little larger than that for the smaller chopping rates; nevertheless, it still falls within the reasonable bound of error. The corresponding flow fields have not been given here because the patterns of air flow for 5 Hz and 150 Hz are similar to those for 1 Hz and 1 kHz, respectively. It needs to be emphasized here that, for all the chopped beams (1, 5, 15, 150 Hz), although the chopping rates are different, the number of laser pulses (500/second) is the same for all chopped beams, that is, the total heat flux is the same, indicating that the specific way of laser filament heating plays an important role in the laser-induced motion of air flow.
Fig. 3. Simulated flow fields for chopping rate of 1 Hz (a), 15 Hz (b) and 1 kHz (c), respectively. The velocity vectors are colored by velocity magnitude (m/s). The rectangular areas in (a)–(c) have the same size as the experimentally captured images as shown in Figs. 1(a)–1(c), respectively, and the insets on the top are their corresponding enlarged figures.
Now, we can give a simple physical picture about the laser-filament induced water condensation/snow formation based on our experimental and simulated results. It has been generally accepted that the initial condensation nucleus causing water condensation is H$_2$O-HNO$_3$. The fundamental chemical substance HNO$_3$ is generated by femtosecond laser-filament induced photoionization and photo oxidation reaction [9]. The existence of HNO$_3$ was also confirmed in our experiments [22]. The air-flow motion played an important role after the formation of condensation nucleus H$_2$O-HNO$_3$, which moved with the strong updraft resulted from laser filament heating, and simultaneously became bigger and bigger through continuous collision. In nature, a strong updraft favors a lot of water condensation because air flow rises to a cooler/colder zone at higher altitude. This is similar to the cloud chamber in our experiments, where the laser filament zone was hot, but the volume around the laser filament was cold. Although the updraft pushed the vapor very far away from the filament zone, cold zone favoring water condensation only existed in a small volume around the laser filament (the experimentally measured temperature was 0-1.4°C in the vertical distance of 5 mm-20 mm above the laser filament). Therefore, when laser filament induced moist air flow with lots of condensation nuclei arrived at the colder zone around the laser filament, effective water/ice condensation would occur. Higher chopping rates would induce faster and stronger (higher velocity) updraft of air. The faster or stronger updraft would carry more condensation seeds (nano-size water or ice particles containing HNO$_3$) from the filament zone into the central draft current where the temperature was low. The higher collision rate inside the central draft current resulted in condensation into heavier particles (snow, water droplets and ice) that fell down below the filament zone to form a snow pile on the cold plate. Slower chopping rate would not induce a strong updraft (Fig. 3(a)) and hence much less condensation seeds would be carried upward. Our experimental observation showed that under such a weak updraft condition, very little snow or ice below the filament zone was formed [22]. This would imply that the majority of snow and ice were created in the updraft outside the filament zone. The filament zone served as a source of small condensation seeds.

In order to investigate the mechanism of laser-induced air flow at different chopping rates, we calculated the temperature distribution across the filament zone which was given in the form of a matrix/mesh of facets in the model. In Fig. 5(a), we show the area weighted average temperature as a function of time for repetition rates of 1 kHz, and as a comparison 2 kHz was also given. The area weighted average temperature was calculated by multiplying the temperature of each facet by its area, summing everything up, and divided by the total area of the mesh. For the other chopping rates, we can estimate roughly the heat accumulation by the decay of recorded area weighted average temperature of laser filament zone on time after a...
pulse irradiation as shown in Fig. 5(b). This single pulse decay is very slow. If the repetition rate of heating is much faster than the decay rate, heat accumulation is expected. Thus, even though peaks are seen in Fig. 5(a), heat accumulation is obvious because the temperature can reach a relatively stable state when the repetition rate increases to a certain number; at this time, air-flow motion also reaches a relative stable state. At 1 kHz repetition rate, heat accumulation is evident, which increases with time, and heat flux of each laser pulse. The velocities of updraft will increase when the laser repetition rate or heat flux of each laser pulse increases further, which can reach 45.5 cm/s at 2 kHz with $2 \times 10^4$ W/m$^2$ heat flux of each laser pulse. The red dashed line in Fig. 5(b) indicates the ambient temperature (~244 K) without laser irradiation (data are from [29]), which crosses the decay line at the time of ~12 ms. This means that the temperature of laser filament zone relaxes to below the ambient temperature before the next pulse arrives if the chopping rates are less than ~40 Hz. Therefore, at 1 kHz, 2 kHz and 150 Hz, heat accumulation induced by laser filament heating is large enough and would not decay below the ambient temperature during the interval between two neighboring pulses, so near continuous air-flow motion was observed. But at 1 Hz, 5 Hz and 15 Hz, heat accumulation induced by laser filament heating is little and will decay to below/near ambient temperature during the interval between two neighboring pulse trains, so intermittent air-flow motion was observed.

![Fig. 5](https://example.com/fig5.png)

**Fig. 5.** (a) Dependences of area weighted average temperature of laser filament zone on time. Red, blue and black lines show the calculated results with the heat fluxes of each laser pulse: $2 \times 10^4$ W/m$^2$ at 1 kHz repetition rate, $2 \times 10^4$ W/m$^2$ at 2 kHz repetition rate, and $1 \times 10^4$ W/m$^2$ at 2 kHz repetition rate, respectively. (b) Decay of area weighted average temperature of laser filament zone on time after one pulse irradiation with the heat flux of $2 \times 10^4$ W/m$^2$. The horizontal dashed line indicates the ambient temperature of ~244 K without laser irradiation which is from [29].

The latent heat released by water vapor condensing onto droplets/ice crystals plays a very important role on the continuous rising of air in natural cloud [23,25]. This effect was not considered in our model, which is a possible reason why the simulated maximum velocity of
updraft is a little smaller than the experimental data and is particularly evident at higher chopping rates. For the higher chopping rates from several hundred to 1 kHz, more latent heat is generated due to more water condensation events [22], which makes the velocity of updraft increase significantly. For the lower chopping rates of 1, 5, 15 and 150 Hz, less latent heat will be generated due to less water condensation event, therefore air-flow motion is less enhanced.

Additionally, there is no way to avoid plasma generation since the ultrashort characteristic of fs pulses makes the intensity of laser filaments reach \(-10^{14}\) W/cm\(^2\) (assuming total energy conversion efficiency 5%) in our experiments, which is followed by intense white-light emission, especially for 1 kHz irradiation. The generated plasma containing different kinds of energetic particles (electrons, ions and atoms), will expand toward the background gas driven by the energy locally deposited on the target by the laser pulses. The plasma plume pushes away and compresses the background gas with the propagation of a shockwave at a supersonic speed ahead of the plasma to form a denser layer in front of the wave [30–32]. A typical timescale of plasma expansion and shock wave is ns to \(~100\) ns [32], while the minimum interval between the two adjacent laser pulses is 1 ms in our experiments, which is much longer than the timescale of plasma expansion and shock wave. This means that plasma expansion and shock wave effect on air-flow motion induced by laser pulse has no influence on the next laser pulse (no accumulation effect in the air-flow motion). Therefore, the plasma expansion and shock wave effect can be ignored in the air-flow motion induced by different chopping rates.

The good consistency between the numerical and experimental data was obtained for a 1 \(\mu\)s laser heating time of each pulse. At constant heating energy of each pulse (heat flux: \(2 \times 10^4\) W/m\(^2\)), if the heating time of each laser pulse is reduced from 1 \(\mu\)s to 0.1 \(\mu\)s or increases from 1 \(\mu\)s to 10 \(\mu\)s, the simulated maximum velocities of updraft are nearly invariable, indicating the heating time of laser pulse has a very small impact on numerical results. Additionally, the parameter of thermal diffusivity has a greater effect on the simulated results than other thermodynamical parameters. Although no data are available for higher temperatures, it has been indicated that the thermal diffusivity of air varies from 0.23 to 0.4 \((\text{cm}^2\cdot\text{s}^{-1})\) (0.23 was used in our model) when heated from 300 K to 365 K [33]. However, in our experiments air is mixed with lots of water droplets or ice crystals, the thermal diffusivity will decrease dramatically because the thermal diffusivity of ice and water is \(~10\)% and \(~1\)% of that of air, respectively [34], leading to the result that the present model probably overestimates the heat accumulation/temperature and the thermal diffusive area, especially for higher chopping rates. This plays an opposite role on the velocities of air flow compared with the effect induced by latent heat release by water/ice particles condensation.

Our present model can explain the mechanism of generation of the intense laser filament-induced air flow. This could give a qualitative explanation of water condensation in the cloud chamber induced by fs laser filaments. Since the detailed mechanism involves complex physical, chemical and thermodynamic processes, more studies need to be made in future work. 1) In the real experiment, there are many water droplets in the filament zone before the laser pulse arrives. The explosion of water droplets need to be considered. 2) The role of chemistry in nucleation and water condensation, i.e. the role of HNO\(_3\), etc., need to be studied in detail. For example, what is the role of pure water vapor as compared to nm size water droplets in the condensation mechanism through collision with HNO\(_3\) molecules?

5. Summary and conclusion

Our previous experiments have indicated that updraft will speed up the particle-particle collisions and help them to form large-sized ice crystals in a diffusion cloud chamber [22]. However, the detailed mechanisms of updraft have not been investigated there. In this paper, we simulated air-flow motion in the diffusion cloud chamber for different chopping rates. A two dimensional model, including couple energy, mass and momentum transports was used and calculated by a commercial program Fluent 6.3. In this model, the laser filament was treated as a heat flux resource, and the heating time and heat flux of each laser pulse is set as
1 μs and $2 \times 10^4$ W/m$^2$, respectively. The simulated patterns of flow fields and maximum velocity of updraft agrees well with the experimental measurements for the chopping rates of 1, 5, 15 and 150 Hz. For chopping rate of 1 kHz, there is a quantitative inconsistency between the simulated and experimental maximum velocities of updraft although a similar pattern of flow field is obtained. The latent heat released by water vapor condensing into droplets/ice crystals may be another mechanism to accelerate the air-flow motion, especially for the higher chopping rates from several hundreds Hz to 1 kHz. The velocities of updraft will increase with increasing chopping rates under the same heat flux of each laser pulse. Based on the present simulated results, the experimental observation of more water condensation/snow at higher chopping rate can be explained. It is concluded that the specific way of laser filament heating plays an important role in the laser-induced air-flow motion, and at the same time, our previous conclusion of air flow having an important effect on water condensation/snow is confirmed. These results will be helpful for further development and optimized use of the technique of laser-induced water condensation. Further investigations will focus on the more complex processes in the numerical simulation, such as condensation of water vapor, nucleation and so on.

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