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Research on the Resonance-Like Effect in Liquid Columns

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Abstract. Fluid splashing and irregular deformation of liquid columns widely exist in industrial fluid transport and hydraulic component operation. However, most existing studies adopt idealized models with stable liquid columns and regular boundary conditions, while neglecting the dynamic effects of turbulent disturbances on liquid column evolution. This conventional simplification omits numerous practical engineering fluid phenomena, among which the splashing behavior during water dispenser operation serves as a typical representative scenario. Based on turbulent disturbance theories, theoretical derivation and mathematical modeling of the liquid column morphology are carried out. The conclusion is that the optimal disturbance wavelength satisfies a mathematical correlation with the radius which is defined as the resonance-like effect. Furthermore, simplified modeling of practical engineering components is performed. Qualitative regulation methods under prominent turbulent disturbance effects are proposed correspondingly. Meanwhile, structural measurement and optimization approaches for experimental devices are illustrated, aiming to restrain the resonance-like effect between turbulent fluctuation and liquid column geometric characteristics. Experimental tests are implemented on a self-built laboratory platform, and the characteristic disturbance wavelength of the liquid column is measured. The results demonstrate that turbulent disturbance dominates the generation of irregular liquid column structures and fluid splashing. The proposed modeling method and suppression strategy exhibit good feasibility and effectiveness, providing a theoretical reference for the optimal design and safety control of engineering fluid systems.

Keywords: liquid column, turbulent disturbances, mixed flow regime, optimal disturbance wavelength, quasi-resonance

1. Introduction

This paper investigates the physical model of water columns commonly observed in daily life, such as those from water faucets and water dispensers. The traditional water column model is characterized by stability and continuity.

However, several specific physical phenomena will be demonstrated in the following sections, which may contradict conventional understandings.

Preliminary experiments are performed to analyze the physical phenomenon: when hot water flows from a water dispenser into a container, the initially continuous and stable water column frequently results in chaotic and intense splashing. The extent and velocity of such splashing are

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found to vary considerably with environmental conditions. According to experimental observations and Reynolds number estimation, the flow belongs to a laminar–turbulent regime. Combined with literature support, turbulent disturbance is identified as the dominant mechanism responsible for the generation of irregular liquid columns [1, 2].

On the basis of preliminary experimental analysis, combined with existing studies on turbulent disturbances, mathematical modeling and theoretical analysis of the liquid column are conducted.

Combined with practical engineering cases, simplified modeling of engineering components is established. Corresponding analyses are performed to qualitatively and quantitatively eliminate fluid splashing in practical engineering scenarios.

Finally, experimental investigations are carried out based on the self-built experimental system in the laboratory. The disturbance wavelength is measured, which verifies the effectiveness and feasibility of the aforementioned technical strategies.

2. Findings and conjectures

2.1. Unique phenomenon

Using the same water dispenser, a cup filled with a fixed volume of water is employed to receive the water jet. By adjusting the vertical height of the cup, a short audio clip is recorded for each height condition.

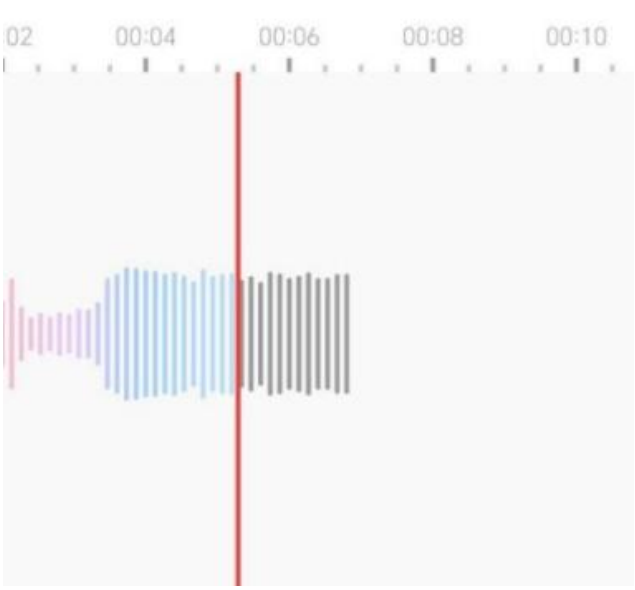


Figure 1. 4cm, water column diagram

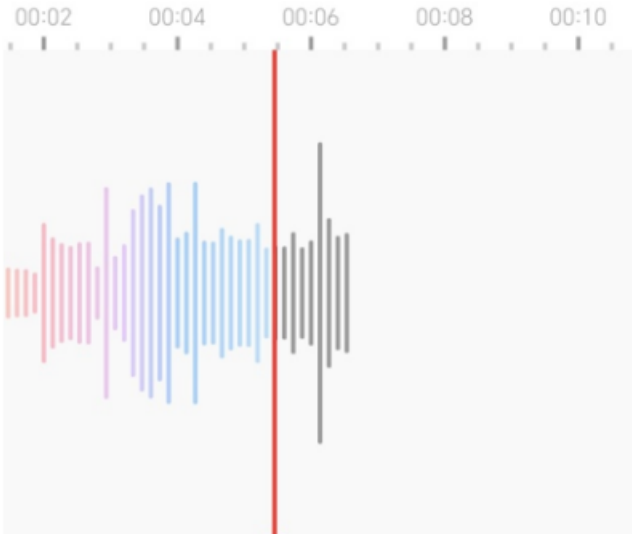


Figure 2. 10cm, water column diagram

As illustrated in Figures 1 and 2, after excluding the initial transient stage where the water jet has not yet contacted the cup, the acoustic signal generated by the falling water column at 4 cm is relatively continuous and stable. In contrast, the corresponding signal at 10 cm shows significant and irregular oscillations.

To more intuitively reflect the non-uniform physical properties of the liquid column, high-speed camera footage of water flow is shown.

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Figure 3. Water column in high-speed camera



Figure 4. Water column in high-speed camera

It is clearly visible from the high-speed images that the water-air interface is irregular and evolves continuously over time, as illustrated in Figures 3 and 4.

All these phenomena indicate that the liquid column is subjected to certain disturbances during its flow, resulting in random and unstable flow as well as an irregular gas-liquid interfaces.

2.2. Conjectures and verification

To investigate the origin of flow disturbance, we performed fundamental Reynolds number calculations because the turbulent flow regime formed at relatively high flow velocities exerts an influence on the liquid column.

$$\mathrm{Re} = \frac{\mathrm{uL}}{\mathrm{v}} \tag{1}$$

For general water dispensers, L can be taken as the diameter of the jet, u is the velocity of the water at the jet. Assume that $\mathrm{u} = 0.2\mathrm{m/s}$ $\mathrm{L} = 0.01\mathrm{m}$.

$$\mathrm{Re} = \frac{\mathrm{uL}}{\mathrm{v}} \approx 2000 \tag{2}$$

According to the Reynolds number calculation, it can be observed that the flow regime lies between conventional laminar flow and turbulent flow. Consequently, the unstable flow and irregular interface of the liquid column result from the combined effects of various disturbances, among which turbulent effects and external aerodynamic effects play dominant roles.

The present experimental results suggest the following for breakup of turbulent round liquid jets in quiescent gases at conditions where aerodynamic effects are small compared to liquid turbulence effects [3-6]: These disturbances grow as they convect along the jet, leading to the formation of a rough, highly disturbed jet surface [7-10]. Disturbance growth is dominated by the effects of liquid turbulence rather than aerodynamic forces [1].

By combining the initial experimental waveform recordings of the falling liquid column with turbulent flow analysis, corresponding hypotheses can be proposed.

As the height of the liquid column decreases and the water flow velocity increases, the Reynolds number rises, indicating an intensification of turbulent effects in the model. This results in stronger disturbances acting on the liquid column, which in turn generate the corresponding acoustic waveform patterns of the falling water.

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However, in practice, velocity variation with height only constitutes a partial characteristic of liquid flow. Alternatively, variations in the geometric characteristics of the liquid column are also closely correlated with disturbance effects. In the subsequent theoretical analysis, the coupled model of liquid column modes and disturbances such as turbulence is quantitatively analyzed, and corresponding conclusions are presented.

3. Theoretical derivation

3.1. The flow and geometric governing equations

In this part, rigorous physical and mathematical formulations will be employed to elucidate the working mechanism between the liquid jet and the disturbances, and corresponding quantitative conclusions will be derived to facilitate the solution of subsequent engineering problems.

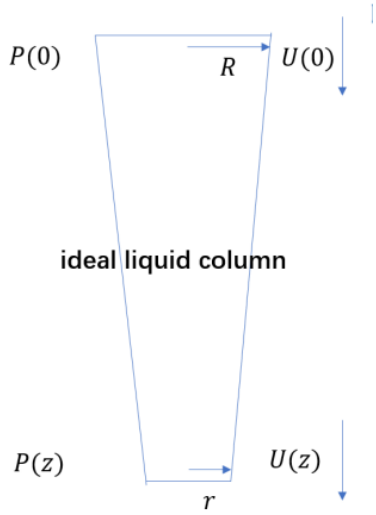


Figure 5. Ideal liquid column

As shown in Figure 5, the Bernoulli equation is employed to construct a physical model for an ideal two-dimensional liquid column and the only conservative body force field is the gravitational field.

$$\frac{1}{2}\rho U(0)^2 + \rho gz + P(0) = \frac{1}{2}\rho U(z)^2 + P(z) \tag{3}$$

Under steady inflow conditions, the problem is evidently steady-state. Nevertheless, it is difficult to verify that the water flow is irrotational throughout the entire liquid column; hence, the application of the Bernoulli equation must be confined to specific streamlines. Since an ideal liquid column exhibits rotational symmetry, the streamline is selected on the sidewall of the liquid column as illustrated in Figure 6.

DOI: 10.54254/2755-2721/2026.BA35659

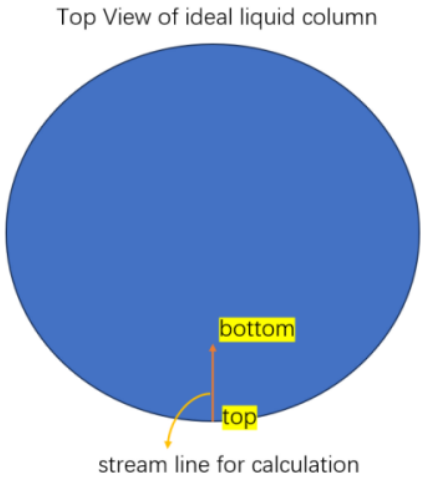


Figure 6. Top view of ideal liquid column

Subsequently, the Young-Laplace equation is applied to express the pressure relationships at different positions:

$$\mathrm{P}\left(\mathrm{z}\right)-\mathrm{P}\left(0\right)=\frac{\gamma}{\mathrm{r}}-\frac{\gamma}{\mathrm{R}} \tag{4}$$

Mass conservation holds between different cross-sections:

$$\pi r^2 U(z)=\pi R^2 U(0) \tag{5}$$

Combining Equations (3), (4) and (5) yields the geometric and hydrodynamic characteristics of the liquid column:

$$\frac{\mathrm{r}}{\mathrm{R}}=\left(1+\frac{2\mathrm{gz}}{\mathrm{U}_0^2}\right)^{-\frac{1}{4}} \tag{6}$$

$$\frac{\mathrm{U}_0}{\mathrm{U}_z}=\left(1+\frac{2\mathrm{gz}}{\mathrm{U}_0^2}\right)^{-\frac{1}{2}} \tag{7}$$

From Equations (6) and (7), several fundamental qualitative conclusions can be drawn:First, as the falling height z increases, the flow velocity at the edge of the liquid column rises, and the flow radius gradually decreases. Furthermore, a higher outlet velocity intensifies the contraction of the liquid column radius and simultaneously reduces the changing rate of flow velocity.

3.2. Disturbance analysis

Next, a differential flow segment is selected on the liquid column for theoretical analysis, to investigate the variations in its geometric and dynamic characteristics under disturbances.

Combining the momentum conservation equation, the mass continuity equation and the surface pressure balance equation yields the following result [2]:

$$\omega^2=\frac{\gamma}{\rho \mathrm{R}_{\mathrm{o}}^3}\mathrm{kR}_0\frac{\mathrm{I}_1(\mathrm{kR}_0)}{\mathrm{I}_0(\mathrm{kR}_0)}\left(1-\mathrm{k}^2\mathrm{R}_0^2\right) \tag{8}$$

DOI: 10.54254/2755-2721/2026.BA35659

* I_0, I_1 are the zero-order and first-order modified Bessel functions.

An unstable mode can only exist when $kR_0 < 1$

Therefore, such disturbances only exert effective effects on the column segments whose perimeter is smaller than the wavelength.

When $\lambda_{max} \approx 1.3 \bullet 2\pi R_0$,the growth rate of disturbances reaches its maximum.

The characteristic breakup time can be estimated according to the maximum growth rate:

$$t = 2.91\sqrt{\frac{\rho R_0^3}{\gamma}} \tag{9}$$

3.3. Theoretical summary: quasi-resonance effect

Combining the static and dynamic characteristics of the liquid flow derived in the first part with the conclusions regarding the disturbance effect on the flow obtained in the second part, namely by coupling Equations (6), (7) and (8),

We obtain the following results:

The optimal disturbance wavelength satisfies the following relationship with the radius at any position of the liquid column.

$$\lambda \cong 2\pi r = 2\pi\left(1 + \frac{2gz}{U_0^2}\right)^{-\frac{1}{4}} * R_0 \tag{10}$$

This phenomenon whereby the wavelength of disturbance matches the geometric dimension of liquid column is defined as resonance-like effect

4. Engineering modeling and analysis

4.1. Modeling

To apply the physical theoretical model to the structural design of water dispensers in engineering, we first conduct physical modeling for the general structure of a water dispenser (Figure 7).

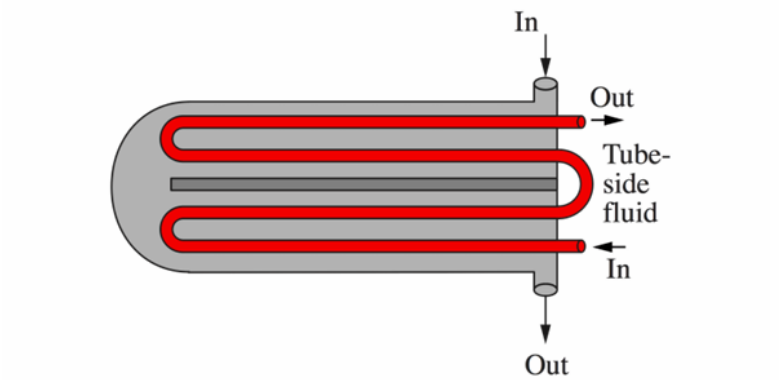


Figure 7. Ideal pipeline structure

On the basis of equivalence and approximation, to reduce unnecessary theoretical calculations and corrections, the model is simplified as Figure 8.

DOI: 10.54254/2755-2721/2026.BA35659

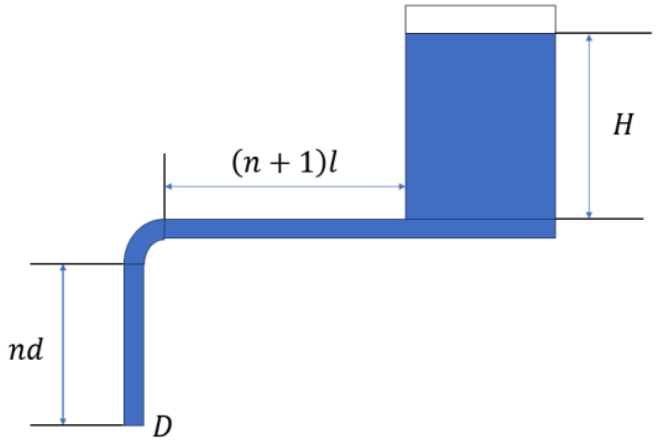


Figure 8. Simplified version of water dispense model

The relevant parameters in the figure are defined as follows:
H denotes the real-time water level height in the water tank;
n represents the number of repeated bent pipe units;
l is the horizontal length of a single bent pipe unit;
d is the vertical height of a single bent pipe unit;
D stands for the inner diameter of the bent pipe.

Using Poiseuille straight pipe equation to establish the relationship between flow velocity and other pipeline parameters.

$$Q = \frac{\Delta P \pi D^4}{128 \mu L} \left(\Delta P = P_1 - P_2\right) \tag{11}$$

$$\Delta P = \rho g \left(H + nd\right) \tag{12}$$

$$L = (n + 1)l + nd \tag{13}$$

$$U_0 = v = \frac{Q}{A} = \frac{\Delta P D^2}{32 \mu L} = \frac{\rho g (H+nd) D^2}{32 \mu ((n+1)l+nd)} \tag{14}$$

It should be noted that v denotes the flow velocity at the outlet of the water dispenser.

Reviewing the theoretical analysis of the liquid column in Part II, we can derive the velocity and radius of the water dispenser liquid column at the falling height z.

$$\frac{U_0}{U_z} = \left(1 + \frac{2gz}{U_0^2}\right)^{-\frac{1}{2}} \tag{15}$$

$$U_z = \left(1 + \frac{2gz}{U_0^2}\right)^{\frac{1}{2}} * U_0 \tag{16}$$

Similarly, the geometric radius of the liquid column at height z can also be derived:

$$\frac{r}{R} = \left(1 + \frac{2gz}{U_0^2}\right)^{-\frac{1}{4}} \tag{17}$$

DOI: 10.54254/2755-2721/2026.BA35659

$$r = \left(1 + \frac{2gz}{U_0^2}\right)^{-\frac{1}{4}} * R \tag{18}$$

*Given that the expression after substituting U_0 is overly cumbersome, the velocity U_z is presented in the form of coupled governing equations here.

4.2. Analysis in resonance-like effect

Combined with the characteristic breakup time derived from the foregoing disturbance theory, the momentum impact of broken droplets (generated by optimal disturbance) on the water surface can be calculated, which serves as the key index to evaluate the splashing phenomenon of the water dispenser(since it can be considered that the momentum of the impinging water flow is converted into the momentum of splashing droplets at a fixed ratio, while the remaining part is absorbed by the internal water due to friction and other factors. This ratio is denoted as α

$$\dot{M} = \pi r^2 \rho * \left(1 + \frac{2gz}{U_0^2}\right)^{\frac{1}{2}} * U_0 \tag{19}$$

$$t = 2.91\sqrt{\frac{\rho R_0^3}{\gamma}} \tag{20}$$

$$I = 2.91\sqrt{\frac{\rho R_0^3}{\gamma}} * \pi\rho * \left(1 + \frac{2gz}{U_0^2}\right)^{\frac{1}{2}} * {U_0}^2 * R_0^2 \tag{21}$$

$$I' = 2.91\alpha\sqrt{\frac{\rho R_0^3}{\gamma}} * \pi\rho * \left(1 + \frac{2gz}{U_0^2}\right)^{\frac{1}{2}} * {U_0}^2 * R_0^2 \tag{22}$$

The U_0 is controlled by this expression

$$U_0 = v = \frac{Q}{A} = \frac{\Delta P D^2}{32\mu L} = \frac{\rho g(H+nd)D^2}{32\mu((n+1)l+nd)} \tag{23}$$

It can be clearly observed from the calculation results that when external conditions such as temperature and atmospheric pressure remain unchanged, the dominant variables are the outlet radius, outlet flow velocity and falling height of the liquid column. With the increase of these parameters, the splashing intensity all rises accordingly. However, from a quantitative perspective, their degrees of influence differ significantly.

$$I' \propto \sqrt{z} \propto R_0^{3.5} \propto {U_0}^2 \tag{24}$$

Therefore, from an engineering perspective, to solve the hot water splashing problem of water dispensers, the outlet radius should be taken as the primary consideration. Reducing the outlet radius can effectively lower both the velocity and mass of splashing droplets.

4.3. Avoidance of the resonance-like phenomenon

Nevertheless, theoretical analysis indicates that there exists a more effective approach to mitigate the splashing problem optimizing the pipeline system to detune the geometric radius of the liquid

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column from the disturbance wavelength radius since detuning the perturbation wavelength and liquid column radius is the fundamental method to suppress quasi-resonance

The effective disturbance wavelength:

$$\lambda \cong 2\pi r = 2\pi\left(1+\frac{2gz}{U_0^2}\right)^{-\frac{1}{4}} * R_0 \tag{25}$$

Therefore, to decouple the disturbance radius from the geometric radius of the liquid column (In other words, to suppress the occurrence of the resonance-like phenomenon), adjusting the radius of the falling liquid column at any position according to Equation (18) and comparing it with the disturbance radius is an essential control measure.

However, the disturbance radius in an arbitrary system cannot be obtained merely by theoretical solutions at present, so it needs to be determined experimentally.

5. Experiment

Relevant experimental equipment:

1: Water bucket (used to simulate the upstream pipeline system)

2: Lifting platform(used to adjust the height of the beaker)

3: Straight ruler (used to measure the falling height of the liquid column)

4: Beaker and thermometer (serve as the water-receiving platform, measure the water temperature, and maintain the water temperature at approximately 30 ℃ by the hot water mixing method)

5: Adapter tube (used to change the outlet radius)

We change the outlet condition by adopting adapter tubes of different specifications, since the length of the No.4 adapter tube does not meet the matching requirement, only the first three types are selected for the experiment(as shown in the table), and the outlet flow velocity is adjusted by varying the height of the upstream water surface (U_0 ***is calculated by expression*** 3).

The characteristic breakup position is identified from the sound waveform diagram, and the corresponding height z is recorded.

Wavelength is calculated by:

$$\lambda \cong 2\pi r = 2\pi\left(1+\frac{2gz}{U_0^2}\right)^{-\frac{1}{4}} * R_0 \tag{26}$$

Each group of operating conditions was repeated 5 times, and the final measurement results were averaged to reduce random experimental errors (see Table 1).

Table 1. Experiment data

Adapter tube	U_0 / ms^{-1}	z / cm	λ / mm
number 1(2.3mm)	0.92	1.9	7.58
number 1(2.3mm)	1.04	2.3	8.61
number 2(3.2mm)	0.97	6.4	8.10

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Table 1. (continued)

number 2(3.2mm)	1.08	9.0	7.95
number 3(3.9mm)	0.95	13.5	8.58
number 3(3.9mm)	1.05	17.0	8.57

Finally, the disturbance radius of the experimental system was measured to be around 8 mm.

This experiment possesses great practical significance for engineering applications. It indicates that by measuring the disturbance wavelength of different water dispenser systems and further adjusting relevant structural parameters, the splashing problem can be effectively controlled.

6. Conclusion

This study aims at exploring the resonance-like effect between turbulent disturbances and geometric characteristics of falling liquid columns, and revealing the formation mechanism of liquid splashing in typical engineering scenarios such as water dispensers. The findings indicate that the flow state of the liquid column presents a mixed laminar-turbulent transition feature, and turbulent disturbances dominate the generation of irregular interface morphology and splashing behavior. The analysis revealed that the optimal disturbance wavelength has an evident mathematical correlation with the liquid column radius at certain falling heights, which supports the initial hypothesis that wavelength-size matching induces the resonance-like effect.

This research contributes to the existing body of knowledge by establishing a coupled theoretical model of liquid column contraction, flow velocity evolution and disturbance instability, filling the research gap in the quasi-resonance mechanism of turbulent liquid jets. The findings extend previous liquid jet breakup theories by quantifying the critical wavelength and breakup time of disturbance growth. This study has important guiding significance for the optimal structural design and splashing suppression of fluid delivery components, providing feasible theoretical and experimental references for the safety control of practical engineering fluid systems.

Nevertheless, there are still inherent limitations in this work that require further improvement and in-depth exploration.

This study has several limitations that need to be further improved in future work. First, with the increase of flow velocity and turbulence intensity, the simplified model based on Bernoulli's equation will produce certain calculation errors. Since the Navier-Stokes equations for turbulent flow have no general analytical solution, this study adopts a simplified physical model for theoretical derivation. Second, the established simplified model of the water dispenser reduces computational complexity but cannot fully reproduce the real flow characteristics inside the pipeline. Subsequent research can combine numerical simulation and experimental tests to optimize the model.

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