ENHANCED HEAT TRANSFER RESEARCH IN LIQUID-COOLED CHANNEL BASED ON PIEZOELECTRIC VIBRATING CANTILEVER

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In order to study the variation of vortices and heat transfer enhancement characteristics of piezoelectric vibrating cantilever in liquid-cooled channels, the effects of fluid density and viscosity, mainstream velocity and excitation voltage on vortices were analyzed. The theoretical and numerical simulation of piezoelectric vortices was carried out by using fluid-solid coupling method. On the basis of hydrodynamic function considering the additional effect of liquid viscosity and density on piezoelectric vibrator, the vortex structure of piezoelectric vibrator was analyzed by panel method free-wake model. It is found that the larger the density of the liquid, the smaller the vortex shedding strength and the radius of the core; the larger the viscosity of the liquid, the easier to fully develop the vortex generated by the excitation; the increase of the mainstream flow velocity is beneficial to the development of the vortex structure and the increase of the vorticity intensity; compared with the increase of the mainstream flow velocity, the excitation voltage is more conducive to the enhancement of the vorticity structure, then make it easier to mix hot and cold fluids, thus enhancing heat transfer.

Key words*: Enhanced heat transfer; Piezoelectric vibrating cantilever; Fluid-solid Interaction; Vortex analysis;*

1. Introduction

Piezoelectric vibrating cantilever is widely used in air cooling of electronic equipment because of its simple mechanism, concentrated wind, low noise and low energy consumption, hence it is called piezoelectric fan [1, 2]. The influence of fluid on piezoelectric fans can be neglected because of the low density of air, the small viscosity effect and the low or the static velocity. At this time, researchers usually give the vibration mode of piezoelectric vibrator beforehand, and then study the flow pattern produced by vibration in air and its effect on heat transfer enhancement [3, 4]. In a certain range, the heat transfer enhancement rule of piezoelectric vibrating cantilever obtained by this method has certain universality [5, 6]. However, with the application of piezoelectric vibrator expanding to the field of liquid cooling [7], the fluid-solid interaction between piezoelectric vibrator and fluid cannot be ignored any more [8]. This is because even if the liquid is stationary or its velocity is low, the vibration of piezoelectric cantilever will drive the surrounding fluid to move along with it, which adds a certain mass to the structure. At the same time, when the fluid viscosity is more significant, the fluid will hinder the vibration of the cantilever beam, which is equivalent to increasing the damping of the structure. Therefore, the dynamic response of piezoelectric vibrator will inevitably change, which will lead to the change of piezoelectric vortex and further affect the enhanced heat transfer characteristics of piezoelectric cantilever.

However, at present, there is no unified study and discussion on the influence of density and viscous effect of different kinds of liquids on piezoelectric vortices. Especially in the case of mainstream and the influence of fluid viscous on the structural deformation of piezoelectric vibrating cantilever, the corresponding changes are more complex, which deserves further study [9, 10]. Therefore, a piezoelectric vortex analysis model suitable for liquids was proposed in this paper. Firstly, the hydrodynamic function was used to consider the additional effect of liquid viscosity and density on piezoelectric vibrator. Then, the dynamic response of the vibrator under excitation voltage was solved based on modal expansion method. Finally, the vortex structure generated by vibration excitation of piezoelectric vibrator was analyzed by unsteady panel free-wake model. Thus the mechanism of flow regulation and heat transfer enhancement of piezoelectric vibrator in liquid environment have been detectived by analyzing the law of piezoelectric vortices under different kinds of liquids, mainstream velocity and excitation voltage.

2. Computational investigation

The additional mass and viscous effect of fluid on the cantilever beam can be calculated by the corresponding hydrodynamic function [11].

The piezoelectric vibrator in liquid environment is simplified to a two-dimensional cantilever beam. According to Euler-Bernoulli beam model [12], the transverse vibration equation of the piezoelectric cantilever beam in liquid can be expressed as follows:

$$\rho A u'' + cbu' + YI\frac{\partial^4 u}{\partial x^4} = F \tag{1}$$

Where *u* represents the transverse displacement of the cantilever beam; ρ represents the density of the cantilever beam; *A* represents the cross-sectional area of the cantilever beam; *b* represents the width of the cantilever beam; *c* represents the structural damping coefficient of the elastic beam; *Y* represents the Young's modulus of the elastic beam; *I* represents the cross-sectional inertia moment of the elastic beam; *F* represents the external force on the unit length of the cantilever beam.

When a cantilever beam in a fluid receives piezoelectric excitation, the external force on its unit length can be expressed as:

$$F = F_L + F_E \tag{2}$$

Where F_L represents the interaction force between the fluid and the beam, F_{E} represents the equivalent piezoelectric driving force and the additional mass force and the damping force can be expressed as follows:

$$F_L = -\frac{\pi}{4}\rho_f b^2\left(\theta_r u'' + \omega\theta_i u'\right) \tag{3}$$

Where ρ_f represents the fluid density; ω represents the vibration frequency of the beam; the real and imaginary parts of the hydrodynamic function of the rectangular cross-section beam are respectively represented by θ_r and θ_{i} . Detailed settings are given in reference [13].

The mode superposition method is used to solve the Eq. (1) -(3). The dynamic response of the cantilever beam under the action of fluid can be obtained. Then it can be substituted into the panel free-wake model to analyze the flow pattern changes under the excitation of piezoelectric vibration.

The panel method divides the structure into corresponding panels, and assumes that the flow field satisfies the potential flow theory. The wake model adopts Lamb-Oseen viscous vorticity model, in which the strength of the attached vorticity in *i*-th panel is γ_i , and the angle between the panel and the x-axis is β_i . The calculation process is shown in Fig. 1.

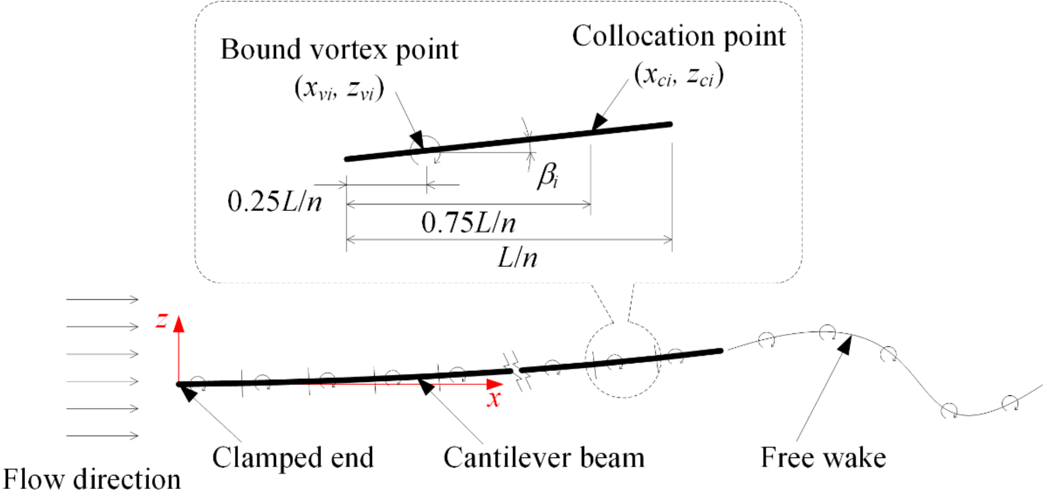


Fig. 1 Panel method free-wake model

Assuming that the fluid velocity at each collocation point is equal to the normal velocity of the cantilever beam, it can be obtained from Kelvin's theorem [14]:

$$\mathbf{a}_{i,j} \cdot \boldsymbol{\gamma}_i = \mathbf{rhs}_i \tag{4}$$

Where, $\boldsymbol{\gamma}_i$ indicates the strength of the attached vortices, $\mathbf{a}_{i,j}$ means the normal velocity of the *j*-th attachment vortices induced by the *i*-th configuration point in unit strength, $\mathbf{rhs}_i$ represents the normal velocity caused by the discrete vortices removed from the wake and the uniform incoming flow at the *i*-th configuration point of the cantilever beam.

3. Model Validation

The validity of the free-tail process of the panel method is verified by comparing with the results of the existing literature. In the simulation process, a two-dimensional cantilever beam model was adopted. The windward point of the cantilever beam at its initial position is defined as the coordinate origin, and the x-axis direction is parallel to the length direction of the plate. The length of the plate is *L*, the velocity of the main stream is *v*, and the lateral displacement is $d = d\sin(\omega t)$, where *d* is the amplitude and ω is the frequency. The vortex of a cantilever beam is calculated by adding point vorticity process (increases critical distance $L_{cr} = 5v\Delta t$, Δt is time step) on the basis of fixed viscous vorticity core (radius of vorticity core $r_{core} = 0.03L$) and compared with reference [15]. The visual experimental results are shown in Fig. 2 and the theoretical results are shown in Fig. 3.

From the comparison it can be seen that except the farthest vortex from the free end of the piezoelectric vibrator is not photographed by the experimental results, the other vortices are basically in agreement with the calculated results, which verifies the validity of the vortex calculation and analysis program in this paper.

Fig. 2 Results of experiment

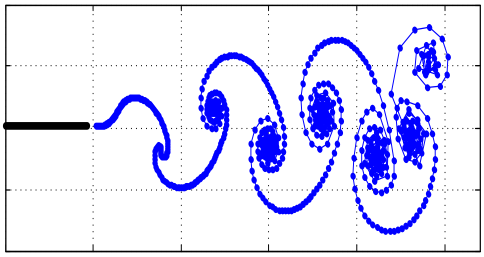


Fig. 3 Results of calculation

4. Results and Discussion

According to Wang, Qi and Zhong's previous research results [16-18], the longitudinal vortices in the mainstream direction are positively correlated with the degree of heat transfer enhancement. Therefore, higher vortices intensity often corresponds to higher convective heat transfer coefficient. In this paper, the influence of different fluid types, mainstream velocity and driving voltage on the strength of piezoelectric vortex is indirectly explained.

Resin glass was chosen as the basic elastic material of piezoelectric vibrator and polyvinylidene fluoride (PVDF) as the piezoelectric thin film material. The length and width of the piezoelectric vibrator were 0.1m and 0.01m respectively.

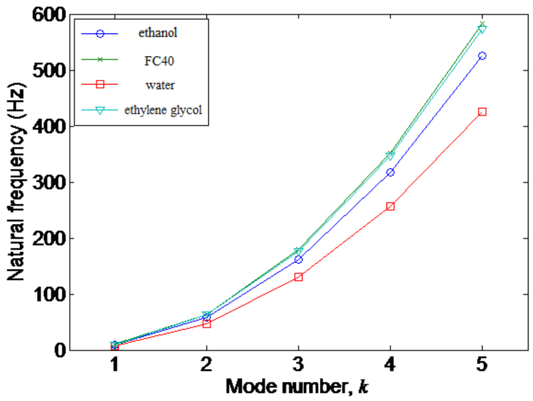
4.1. The law of piezoelectric vortices under different type of liquids

The effects of density and viscosity of four coolants: ethanol, FC40, cooling water and ethylene glycol, on the influence of piezoelectric vortices are studied. The density and viscosity parameters at 20℃ are shown in Tab. 1.

Tab. 1 Densities and dynamic viscosities of four different kinds of fluids

Name	Density/[kgm-3]	Viscosity[Pas-1]
ethanol	789	0.0012
FC40	1850	0.0037
water	997	0.0009
ethylene glycol	1115.5	0.0157

Firstly, the natural frequencies and damping ratios of piezoelectric vibrators in different fluids are calculated by modal analysis method. The results are shown in Fig. 4 and Fig. 5.



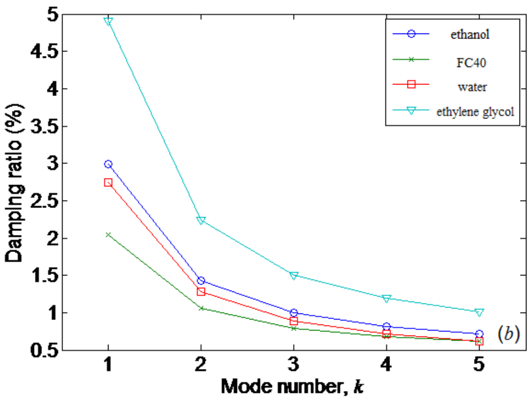
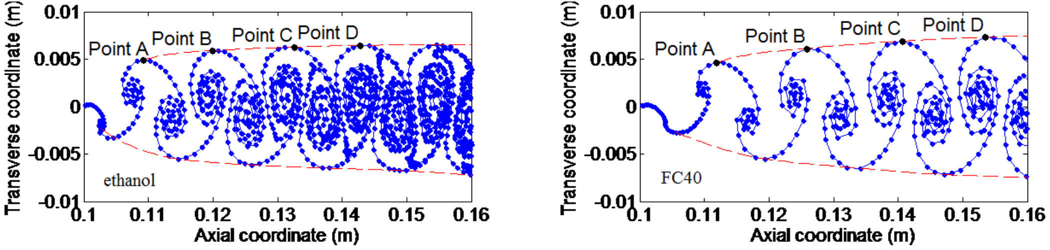


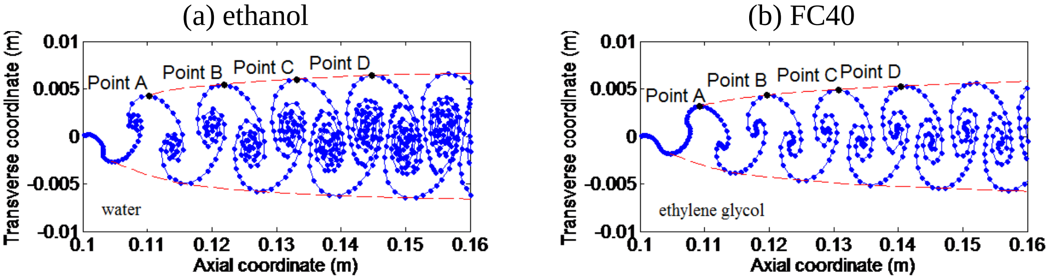
Fig. 4 Natural frequencies **Fig. 5 Damping ratio**

As can be seen from Fig. 4, the natural frequencies of piezoelectric vibrators are the highest in ethanol and the lowest in FC40. This is because the natural frequencies are mainly affected by the added mass, consequently they gradually decrease with the increase of fluid density. From Fig. 5, it can be found that the damping ratio in ethylene glycol is the highest, while that in ethanol is the lowest. It can be seen that the damping ratio is mainly related to the dynamic viscosity of the fluid. The higher the dynamic viscosity, the greater the damping, but also affected by the density of the fluid. Therefore, under the combined action of the two modes, the damping in cooling water is increased, and higher than ethanol.

The additional mass and viscous effect of the fluid make the dynamic response of the piezoelectric vibrator change accordingly, and also cause the dissipation of the midpoint vorticity intensity of the longitudinal wake, leading to the change of the vorticity intensity. When the excitation voltage is 50 Vac, the excitation frequency is the first natural frequency of the piezoelectric vibrator, and the main flow velocity is 0.1 m/s. The variation of the piezoelectric vortex is shown in Fig. 6.



(a) ethanol (b) FC40



(c) water (d) ethylene glycol

Fig. 6 Vortex structure in different kinds of fluids

As can be seen from Fig. 6, although the same piezoelectric excitation produces vortex streets in different fluids, it presents completely different shapes. Affected by the density, the vortex in ethanol is the most concentrated, while the vortex in ethylene glycol is the sparsest. The vortex width of each point in each fluid is selected, as shown in Fig. 7.

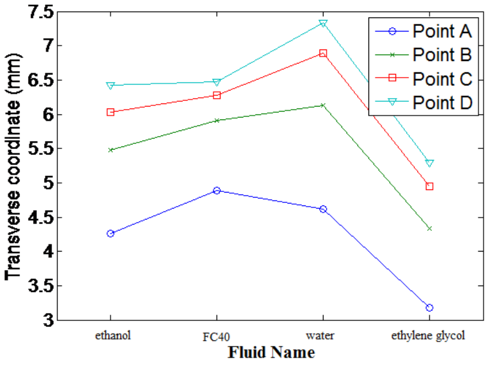


Fig. 7 Vortex width in different fluids

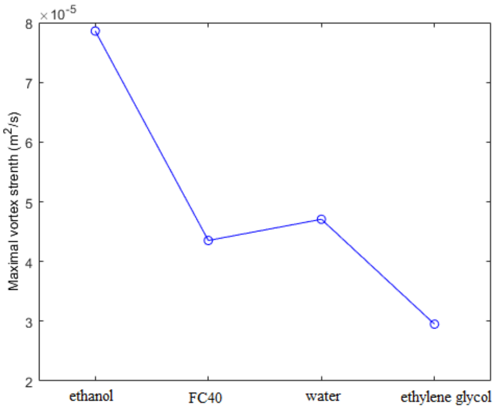


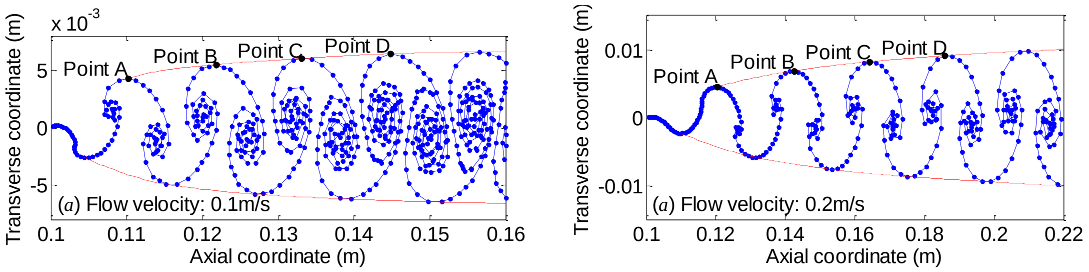
Fig. 8 Vortex strength in different fluids

According to Fig. 7, the radius of the vortex nucleus increases with the wake shedding away from the viscous dissipation. At point A nearest to the piezoelectric vibrator, the radius of the vortex nucleus of FC40 is the largest; at other locations, the radius of the vortex nucleus produced by water is the largest; and at all locations, the radius of the vortex nucleus produced by ethylene glycol is the smallest. The reason is that the viscous and density of FC40 are relatively small, thus the vibration displacement of ethanol is the largest, and the radius of vortex nucleus is the largest when it falls off. However, as time goes on, under the combined effect of density and viscous, the interaction between vortices begins to be remarkable; and because of its high density, the transverse effect of water is initially induced. The velocity is small, but the interaction between vortices and vortices is small and can develop steadily, hence the radius of vortices core is the largest. Ethylene glycol has a high damping ratio because of its maximum viscosity, which makes the vortex unable to fully develop. The maximum vorticity intensity of the four media in a period is compared in Fig. 8.

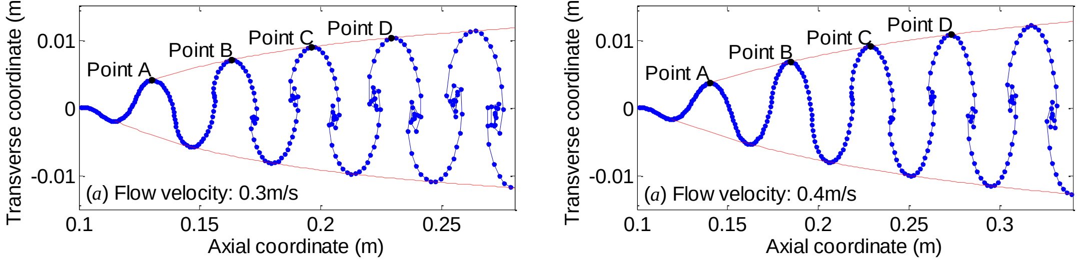
Fig. 8 indicates that the vortex strength is the largest among the ethanol with the lowest viscosity, because the viscous dissipation of the fluid with the lowest viscous effect is also smaller under the same external input, therefore the vortex strength of the fluid with the lowest viscous effect is the largest. From the point of view of heat transfer enhancement, the difference of density and viscosity of different fluids often leads to the difference of vortex strength and radius of vortex core. Therefore, it is necessary to determine the type of coolant according to heat transfer requirements, and then determine the installation location of piezoelectric vibrating cantilever.

4.2. The law of piezoelectric vortices under mainstream

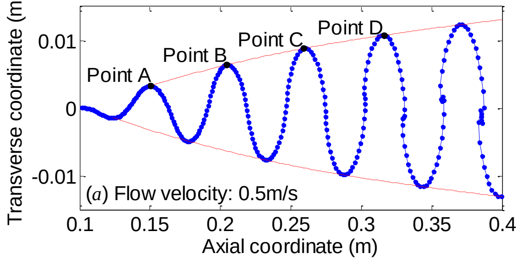
Usually, the liquid in the liquid environment in which the piezoelectric vibrating piece is located already has a certain flow velocity, and it is necessary to analyze the influence of the flow velocity of the main flow on the piezoelectric vortex. Therefore, the coolant is studied as water, and the excitation voltage is 50Vac, the frequency remains unchanged as the first-order natural frequency, and the flow rate of the main flow is changed between 0.1-0.5m/s. The obtained piezoelectric vortices are shown in Fig. 9.



(a) flow velocity=0.1m/s (b) flow velocity=0.2m/s



(c) flow velocity=0.3m/s (d) flow velocity=0.4m/s



(e) flow velocity=0.4m/s

Fig. 9 Vortex structure at different mainstream

It can be seen from Fig. 9 that as the flow velocity increases, the vortex structure in the vortex street gradually weakens, because the viscous effect between the vortex and the vortex is correspondingly weakened as the flow velocity increases. At the same time, the weakening of the vortex viscous effect makes the vortex structure more easily develop, therefore the width of the vortex gradually increases with the vortex shedding, and the higher the flow velocity, the more obvious the phenomenon, as shown in Fig.10.

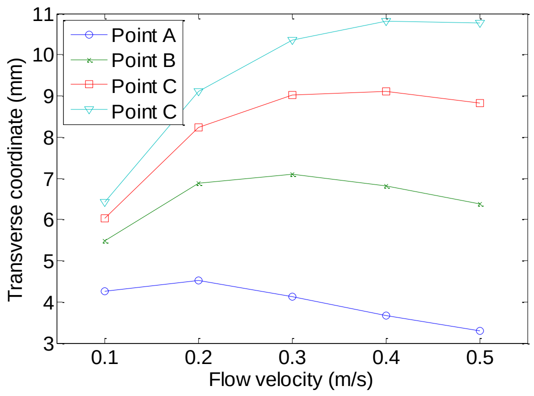


Fig. 10 Vortex width at different mainstream

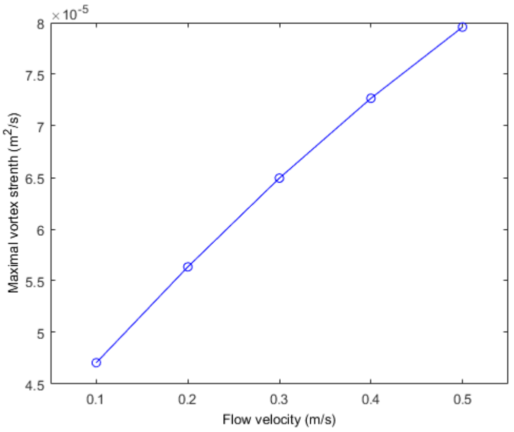


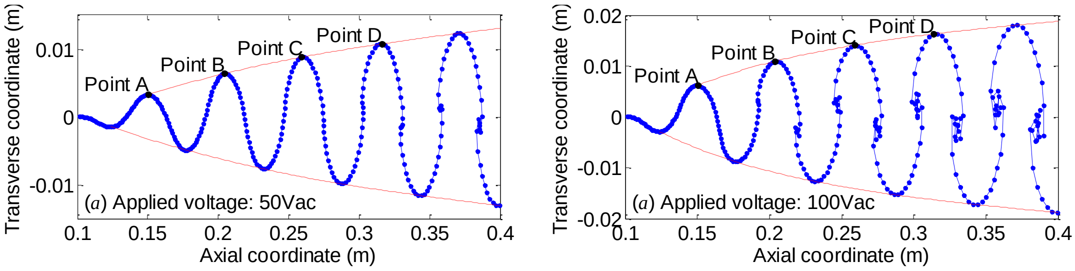
Fig. 11 Vortex strength at different mainstream

The vortex strength at different main flow rates is shown in Fig. 11. According to Fig. 11, as the flow rate increases, the vortex intensity at the same position increases accordingly, because the flow rate increases while a part of the fluid. The kinetic energy is transmitted to the eddy current, thus the strength of the new vortex which is detached from the free end of the piezoelectric vibrating piece is improved.

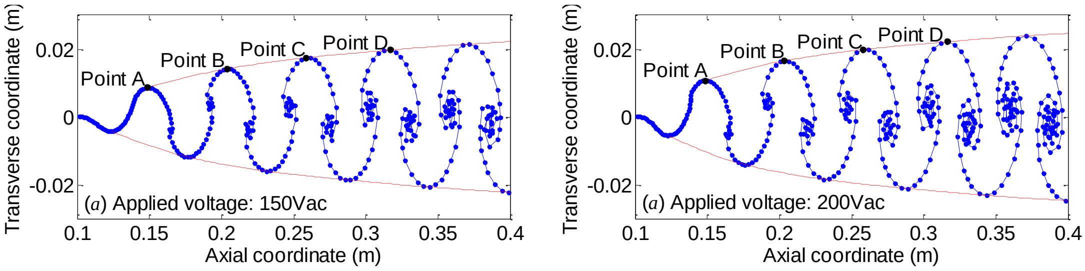
From the perspective of heat transfer, the vortex intensity increases with the increase of the width of the piezoelectric vortex, which is more conducive to the exchange and mixing between the hot and cold fluids, and strengthens the convective heat transfer process. It can be seen that under the premise of the flow resistance, the increase of the mainstream flow rate can make the piezoelectric vortex more orderly generation and development, thereby increasing the strength of the piezoelectric vortex and enhancing the heat transfer, and the conclusion is equally applicable to the other fluids.

4.3. The law of piezoelectric vortices under excitation voltage

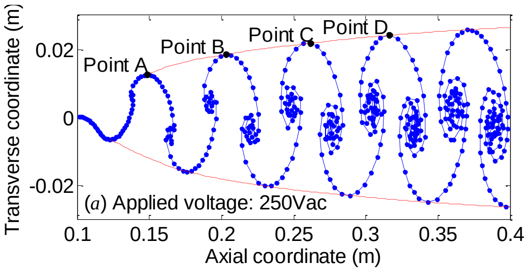
In addition to coolant and mainstream velocity, the amplitude and frequency of excitation voltage can also change the dynamic response of piezoelectric vibrator, but the effect of amplitude is more direct than that of frequency. Therefore, the coolant is studied as water, and the excitation frequency is the first-order natural frequency, the excitation voltage is 50Vac~250Vac, and the mainstream velocity is 0.5m/s. The variation of the vortex at each voltage is shown in Fig. 12.



(a) applied voltage = 50 Vac (b) applied voltage = 100 Vac



(c) applied voltage = 150 Vac (d) applied voltage = 200 Vac



(e) applied voltage = 250 Vac

Fig. 12 Piezoelectric vortex structure at different excitation voltages

It can be seen from Fig. 12 that as the excitation voltage increases, the point vortex in the vortex street and the width of the vortex and the internal vortex structure are fully developed. When the excitation voltage is 250Vac, the internal vortex it can be observed clearly. This is because as the voltage increases, the vibrational displacement of the piezoelectric sheet increases, resulting in an increase in the lateral induced velocity, which causes the vortex to widen and the vortex intensity to increase, as shown in Fig. 13 and Fig. 14.

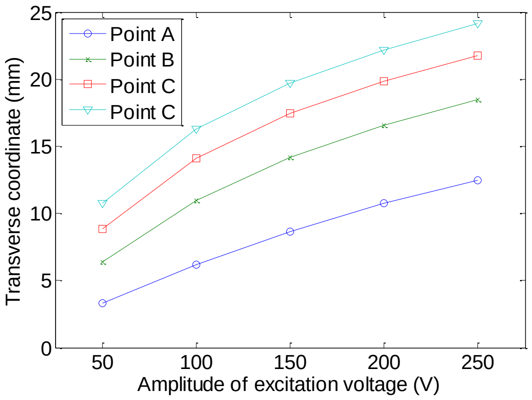


Fig. 13 Vortex width at different excitation voltages

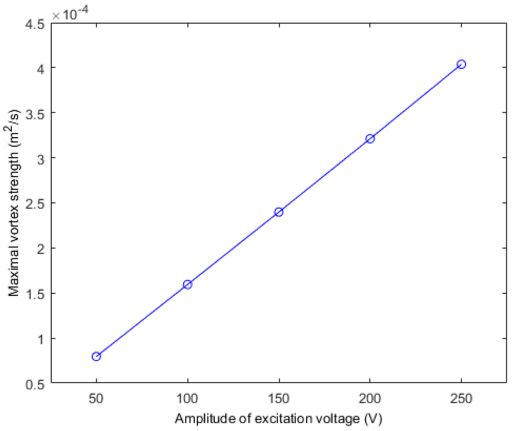


Fig. 14 Vortex strength at different excitation voltages

It can be seen from Fig. 13 and Fig. 14 that, unlike the increase of the velocity of mainstream, when the excitation voltage is increased, the width of the vortex monotonously increases, and the increase amplitude is significantly higher than the increase of the main flow velocity, and the vortex intensity increases as the excitation voltage increases. The improvement is also more obvious. From the perspective of heat transfer, in the case that the main flow rate cannot be further improved, the excitation voltage can be increased as much as possible, thereby increasing the vortex intensity and the radius of the vortex core, thus the convection heat transfer enhancement range is further increased.

5. Conclusions

The amplitude of the vibration displacement of the cantilever beam in the fluid with higher density is smaller, and the intensity of the corresponding tail vortex shedding is smaller, and the width of the corresponding tail vortex is usually smaller.

For fluids with higher viscosity, the radius of the vortex core is larger, and the radius of the vortex core increases faster with time, making the vortex structure easier to develop.

The increase of the mainstream flow velocity reduces the viscous effect between the vortex and the vortex, which is beneficial to the full development of the vortex structure and the increase of the vortex strength, which is beneficial to heat exchange.

Compared with increasing the mainstream flow rate, increasing the excitation voltage is more helpful to increase the vortex core radius and vortex strength of the piezoelectric vortex, consequently the hot and cold fluid in the fluid is more easily mixed and enhances heat transfer.

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Nomenclature

A – cross-sectional area, [mm2]
F – force, [N]
I – inertia moment, [mm4]
L – length of the plate, [mm]
Y – Young's modulus, [Nm2]
a – normal velocity of attachment vortices, [mm/s]
c –damping coefficient, [–]
d – lateral displacement, [mm]
rhs – normal velocity of discrete vortices, [mm/s]
t – time step, [s]
u – transverse displacement, [mm]
v – velocity of the main stream, [mm/s]
r – radius of vorticity core, [mm]

Greek symbols
β – angle between the panel and x-axis, [°]
γ – strength of the vorticity, [m2s-1]
θ – hydrodynamic function, [–]
ρ – density, [kg/m3]
ω – vibration frequency, [Hz]

Subscripts
E – piezoelectric force, [–]
L – fluid force, [–]
cr – critical distance, [mm]
core – vorticity core, [–]
f – fluid, [–]
i – imaginary parts, [–]
r – real parts, [–]

Abbreviations
PVDF – polyvinylidene fluoride

Subscripts
E – piezoelectric force, [–]

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