

DNS ANALYISIS OF INTERACTIONS BETWEEN TURBULENT FLOW AND ELASTIC FIBERS IMPLANTED ON A FLAT PLATE

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ABSTRACT

The interaction between turbulent flow and elastic fibers implanted on a flat wall is numerically investigated. The influence of the collective motion of the fibers on the large scale vortices above them is focused on. The vortices increase the momentum transfer between inside and outside of the canopy layer. They are characterized by the strong sweep and weak ejection. The turbulent flow is reproduced by the direct numerical simulation of the Navier-Stokes equation of incompressible fluid. Each flexible fiber is modeled to be a one-dimensional object connected by Lagrangian markers, and geometric non-linearity is taken into account. The interaction between fluid flow and fibers is solved by an immersed-boundary method. In this research, a parameter study is conducted for investigating the effect of the properties of fibers such as length, elasticity and number density on the turbulent flow. The results of the spectral analysis imply that the fibers oscillate not at the frequency of the characteristic vibration but at the frequency of the velocity fluctuation when the Young's modulus of the fibers is low. The profiles of Reynolds stress for different fiber lengths show that the momentum is transferred more extensively between inside and outside of the canopy layer when the fibers show an in-phase motion.

1 Introduction

The large scale vortices near the top of a canopy draw attention because of its contribution to reduction and enhancement in heat and mass exchange between inside and outside of the canopy layer. The large scale vortices are characterized by its strong sweep and weak ejection (Ikeda,1996). The flow structure in the canopy layer is affected by the properties of the fibers such as length, elasticity and number density. The oscillation amplitude of the fibers increases in the case of the appropriate fiber properties and flow condition (Murakami,1990). This implies that a canopy can be used to control the flow over it, and in turn, the exchange of heat and the mass transfer.

In the present study, the interaction between the flow and a layer of fibers clamped at a flat plate is numerically studied. To investigate the effects of the fiber properties, we compared the canopy flows of different lengths, Young's moduli and number densities of the fibers. By varying these parameters, we study the relationship between the canopy flow and the oscillation of the fibers.

Table 1. Cases of fiber properties

	N_f	h/H	$E \times 10^4$
Case A	16×8	1/3	2
Case RB1	16 imes 8	1/4	~
Case RB2	16 imes 8	1/2	∞
Case B1	16 imes 8	1/4	2
Case B2	16 imes 8	1/2	2
Case C1	16 imes 8	1/3	4
Case C2	16×8	1/3	0.8

In this paper, we show the outline of the numerical method, results of computation and discussion on the spectral analysis of the velocity fluctuation and the tip amplitude of the fiber oscillation, followed by discussion on the profiles of the main stream velocity and the Reynolds stress.

2 Governing Equations and Numerical Methods



In the present study, a plane channel containing the fibers implanted on the bottom is dealt with. Figure(1) shows a schematic of the computational domain and the fibers. A slip condition is imposed at the top $(x_2 = H)$ of the channel and a no-slip condition at the bottom $(x_2 = 0)$. The flow is driven by a constant pressure gradient in x_1 (streamwise) direction. A fully-developed flow is obtained by the periodic boundary condition in x_1 and x_3 (spanwise) directions. The fibers are clamped uniformly at 90 degrees on the

bottom wall. The fiber properties of the respective cases are summarized in Table 1. We define the Case A as the "base" case. To see the difference caused by the length and Young's modulus of the fibers, we set out Case B series and Case C series respectively. Case R series employ rigid fibers.

2.1 Governing Equations

The flow of the incompressible Newtonian fluid is governed by the continuity equations and the Navier-Stokes (N-S) equations,

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$
$$\rho_l \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} \right) = -\nabla p' + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{f}_f - \frac{d\bar{p}}{dx_1} \boldsymbol{e}_1, \tag{2}$$

where \boldsymbol{u} is the velocity, ρ the density of the fluid, p' the differential pressure from the mean pressure \bar{p} , \boldsymbol{f}_f is the interaction force between the fluid and the fibers. Note that $d\bar{p}/dx$ is set to be unity. The Reynolds number based on the channel height *H* and the mean friction velocity at the bottom wall u_{τ} is fixed throughout the present study.

For the modeling of elastic fibers, one dimensional St.Venent-Kirchhoff material is employed, and the motion of the individual fibers is solved considering the geometric non-linearity. The equation of motion of a fiber is expressed as

$$\rho_f \frac{\partial^2 \mathbf{X}}{\partial t^2} = \nabla_X \cdot \left(\mathbf{S} \cdot \mathbf{F}^T \right) + \mathbf{F}_f, \tag{3}$$

where **X** is the position of the Lagrangian markers set on the fiber, **S** is the second Piola-Kirchhoff stress tensor, **F** is the deformation gradient tensor and F_f denotes the Lagrangian force exerted on the structure by the surrounding fluid. Young's modulus is nondimensionalized by the reference pressure as $E^* = E/\rho u_{\tau}^2$.

2.2 Numerical Methods

The whole computational domain is divided into fixed uniform rectangular cells. The velocity components are arranged on the cell faces and the pressure is on the cell center. Equations (1) and (2) are discretized by the 2nd order central finite difference method. A fractional step method is used for coupling the velocity and the pressure. For the time advancement, the backward Euler method is applied for the pressure term and the 2nd order Adams-Bashforth method is for the connective and viscous terms. The SOR method is applied for Poisson's equation of pressure.

Lagrangian markers are arranged along the fibers, and a finite element method with beam elements is used for discretizing Equation (3). The Newmark- β method is applied for the time marching.

The interactions between the fluid and the fibers are treated by a following immersed boundary method proposed by Huang et al $^{3)}$. The interaction force acting on the fibers from the fluid is modeled by the following equation:

$$\boldsymbol{F}_{f} = -\kappa \left(\tilde{\boldsymbol{X}}_{ib}^{p} - 2\boldsymbol{X}^{n} + \boldsymbol{X}^{n-1} \right), \qquad (4)$$

where κ is a penalty parameter of a sufficiently large value to enforce the no-slip condition and \tilde{X}_{ib}^{P} is the predicted po-



Figure 2. Instantaneous velocity in an *x*-*y* cross section : Case C1 (hard)



Figure 3. Instantaneous velocity in an *x*-*y* cross section : Case C2 (soft)

sition of the markers obteinbed as

$$\tilde{\boldsymbol{X}}_{ib}^{p} = \boldsymbol{X}_{ib}^{n} + \boldsymbol{U}_{ib}^{n} \Delta t, \qquad (5)$$

$$\boldsymbol{U}_{ib}(\boldsymbol{Y},t) = \int_{\Omega} \boldsymbol{u}(\boldsymbol{x},t) \delta\left[\boldsymbol{X}(\boldsymbol{Y},t) - \boldsymbol{x}\right] d\boldsymbol{x}, \quad (6)$$

where Ω is the Eulerian flame for fluid flow and δ an approximate delta function introduced by Peskin⁴). The same approximate delta function is also applied for the projection of the internal force from a Lagrangian marker on a fiber to the Eulerian flame for fluid flow as follows:

$$\boldsymbol{f}_{f} = \int_{\Gamma} \boldsymbol{F}_{f}(\Gamma, t) \boldsymbol{\delta}[\boldsymbol{x} - \boldsymbol{X}(\Gamma, t)] d\Gamma.$$
(7)

Here Γ is the surface of the fiber.

3 Results and Discussions3.1 The Effect of the Fiber Elasticity

Figures 2 and 3 show the instantaneous flow field visualized by the vectors in an x-y cross-section. In both cases, large-scale spanwise vortices are observed .The fibers of the lower Young's modulus cases are deformed largely than those of the higher Young's modulus cases. The larger deformations are expected to cause the stronger turbulence intensity. Therefore, the fiber oscillations inducted by the flow are focused on. In the following, the spectrums of the tip amplitude of the fiber oscillation and the main stream fluctuation in the cases of different fiber elasticities are dealt with.

Spectral Analysis The spectrum of the velocity fluctuation is shown in Figures 4 and 5 and the spectrum of



Figure 4. Spectrum of the velocity fluctuation: Case C1 (hard)



Figure 5. Spectrum of the velocity fluctuation: Case C2 (soft)



Figure 6. Spectrum of the fiber movement: CaseC1 (hard)

fiber oscillation is shown in Figures 6 and 7. The oscillation amplitude is multiplied by 1000. In the cases of the lower Young's modulus, the spectrum of the fiber oscillation has it's largest peak at the same frequency as that of the velocity fluctuation. The result implies that the fibers oscillate not at the frequency of their characteristic vibration but at the frequency of the velocity fluctuation.



Figure 7. Spectrum of the fiber movement: CaseC2 (soft)



Figure 8. Instantaneous velocity in an *x*-*y* cross section : Case B1 (elastic) and RB1 (rigid), short



Figure 9. Instantaneous velocity in an *x*-*y* cross section : Case B2 (elastic) and RB2 (rigid), long

3.2 The Effect of Fiber Length

Figures 8 and 9 show the instantaneous flow fields visualized by the vectors in an x-y cross-section. In the case of the longer fibers (case B2), the large-scale spanwise vortices are observed and they are probably due to the inflection of the velocity profile near the canopy edge. In the cases of the shorter fibers, the vortices cannot grow much because they are more subject to the effect of the no-slip wall at the bottom. The flow resistance is stronger in Case B2 due to both the resistance of the fibers and the generation of largescale turbulence structure. In the longer case, some fibers show an in-phase motion. On the other hand, the fibers of the shorter case seem to move rather in a random way.

3.2.1 Velocity Profile Figures 10 and 11 show the profiles of the main stream velocity. In the figures, X_2



Figure 10. Main stream velocity: Case B1 (elastic) and RB1 (rigid), short



Figure 11. Main stream velocity: Case B2 (elastic) and RB2 (rigid), long

shows the distance from the bottom wall and U_1 is the main stream velocity. An inflection point of the profile is found near the canopy edge in both cases. The main stream velocity is higher above the rigid canopy than above the elastic canopy. This indicates that the deformations of the fibers increase the resistance to the flow. In the longer fiber cases, velocity is lower in the elastic canopy layer than in the rigid canopy layer. To the contrary, in the shorter cases, the difference between the velocity profiles in the elastic canopy and rigid canopy is little.

3.2.2 Reynolds stress The profiles of the Reynolds shear stress of each case are shown in Figures 12 and 13. While there is little difference between the profiles of Reynolds stress in the elastic canopy and the rigid canopy of the shorter fiber case, Reynolds stress is larger in the elastic canopy than in the rigid canopy in the longer cases. This indicates that the momentum is transferred more effectively in the elastic canopy layer when the fibers show in-phase motions, which tends to generate the large-scale vortices near the canopy edge. Figures 14 and 15 show the four-quadrants mappings of the velocity fluctuation in a zx cross section near the edge of the elastic canopy. In the figures, u' represents the fluctuation of the velocity in x_1 (streamwise) direction and v' in x_2 direction. The results indicate the stronger sweeps and ejections in the longer fiber case. The stronger sweeps and ejections near the edge of



Figure 12. Reynolds stress: CaseB1 (elastic) and RB1 (rigid), short



Figure 13. Reynolds stress: CaseB2 (elastic) and RB2 (rigid), long



Figure 14. Four-quandrants mappings of (u',v'): short

canopy lead to the more extensive momentum transfer.

4 Conclusion

The effects of the fiber properties on the interaction between the turbulent flow and fibers implanted on a flat plate are investigated. By the results of spectral analysis, it is shown that the cause of the fiber oscillation differs due to



Figure 15. Four-quadrants mappings of (u',v'): long

the Young's modulus of the fibers.

By comparing the cases with elastic fibers of different lengths, it is shown that the in-phase motions of the fibers promote the sweeps and ejections and the stronger sweeps and ejections lead to the large Reynolds stress near the edge of elastic canopy.

More detailed analysis on the structure of the large scale vortices near the canopy edge is to be dealt with.

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