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Optimal contract wall for desired orientation of fibers and its effect on flow behavior*

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Abstract: The orientation of suspended fibers in the turbulent contraction is strongly related to the contraction ratio, which in some cases may be detrimental to the actual production. Here for a certain contraction ratio, the contraction geometry shape is optimized to obtain the desired fiber orientation. In view of the nonlinearity and the complexity of the turbulent flow equations, the parameterized shape curve, the dynamic mesh and a quasi-static assumption are used to model the contraction with the variable boundary and to search the optimal solution. Furthermore the Reynolds stress model and the fiber orientation distribution function are solved for various wall shapes. The fiber orientation alignment at the outlet is taken as the optimization objective. Finally the effect of the wall shape on the flow mechanism is discussed in detail.

Key words: Fibers orientation, wall shape, turbulent contraction, dynamic mesh, nonlinear optimization

Introduction

The fiber filling can effectively improve the stiffness and the strength of manufactured goods, whose performances depend largely on the fiber orientation distribution. The contraction is one of common internal flows, mainly used for the speedup flow, such as the pulp flow box in the paper industry and the jet nozzle of the extrusion die. It is shown that the flow behaviors inside the contraction are more complex than in the channel due to the acceleration effect, which leads to a higher alignment of the fiber orientation under the same entrance conditions. And what's more, the fiber orientation might very likely to follow the flow direction for a large contraction ratio C because the strong streamwise strain rate, rather than the stochastic turbulence effect, would play a major role in the vector field at this moment. As the fiber orientation alignment may affect the overall properties of the industrial products significantly, it is very important to investigate how to control the fiber orientation under a given large contraction ratio.

The dynamics of the fiber suspension and the orientation behavior of the fibers suspended in the planar contraction were much studied. Batchelor and Proudman[1] and Ribner and Tucker[2] considered the cases when C is very large and the time scale of the flow is much smaller than that of the vortex, and suggested that the development of the turbulent kinetic energy is dependent on the local flow strain rate which is related to the geometry of the flow field. Hussain and Ramjee[3] concluded that the flow shape and the Reynolds number in the axial symmetric contraction flow have little effect on the turbulent characteristics, but the inlet condition is the most important parameter. A series of studies by Lin et al.[4-8] show that with the increase of the Reynolds number more fibers will be aligned with the flow direction in the laminar flow regime while the fiber orientation distributions become more homogeneous in the turbulent regime. For the fibers with a high aspect ratio the mean velocity distribution has a more significant effect on the fiber orientation distribution than the fluctuating velocity. Olson

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et al.[9,10] calculated the fiber orientation distribution with a constant diffusion coefficient in the contraction and it is shown that the influence of the contraction ratio on the fiber orientation is more significant than the entrance velocity. Parsheh et al.[11,12] employed a model with the rotational diffusion rate depending heavily on the turbulence of the entrance and decaying exponentially with the contraction ratio. Then four contraction wall shapes, including the constant mean rate of strain, the linear rate of strain, the quadratic rate of strain and the flat walls, were considered to analyze the influence of the contraction geometry on the orientation anisotropy. It is shown that the anisotropic orientation of fibers is dependent on the contraction wall shape while both the turbulence intensity and the rotational diffusion coefficient have little to do with the contraction shape. And what's more, the rotational Peclet number, defined as the streamwise velocity gradient divided by the rotational diffusion coefficient, is shown to be the crucial quantity to determine whether the turbulent effect on the fiber orientation is dominant or not.

Although the optimal shape is not given finally by Parsheh et al.[11], the importance of the flow morphology for the motion and orientation of fibers is shown by the fact that the contraction with flat walls has the smallest orientation anisotropy and the contraction with the constant rate of strain has the largest anisotropy at the outlet . Thus the optimization of the wall shape is the way to deal with the anisotropic distribution of fibers under a constant contraction ratio, just as did by Mäkinen and Hämäläinen[13], Nazemi and Farahi[14] and Farhadinia[15]. Mäkenin and Hämäläinen[13] discretized the contaction shape with the Bezier function and solved the diffusion–convection equation with the streamline upwind Petrov-Galerkin (SUPG) finite element method. Nazemi and Farahi[14] and Farhadinia[15] turned the shape optimization problem into the coefficient optimization of the state equation, which is related to the average flow velocity gradient and the fiber orientation angle. By using an embedding method, the optimal measure representing the optimal shape is approximated by the solution of a linear programming problem. But the assumption of the quasi one dimensional potential flow was made and the effect of turbulence was neglected in their optimization solutions.

For the nonlinear and multi-variable coupling trait of the turbulence control equation, the latest optimization methods for the wall shape are mainly divided into two major categories. One is the reverse design method with the design variables obtained to meet a given objective function value by solving the control equations or by a progressive approach. But this method brings about many technical problems in practical applications: (1) It is difficult to obtain the relationship directly between the variables and the objective function, because a variable is often coupled with other variables in a group of turbulence dynamics equations. (2) The solution of the turbulent dynamics equation would be very sensitive to the mutative flow state or the boundary. Therefore, the inverse design method faces problems of sensitivity and uncertainty of the solution. (3) The method requires some relevant experience or parameters to initialize, which would make the solutions fall into a small range and make the whole optimization system lack of robustness.

The other is the optimal design method. The optimal solution with respect to the objective function can be obtained by combining the direct solution with the optimization searching of the solution space with a good performance in the practice[16,17]. But this method often uses a deputy model or an approximate calculation model, associated with the number of parameters, the sample size, the variable range and the approximate precision, and the method still needs to be adjusted and tested repeatedly for the optimization accuracy and reliability.

In order to achieve the accuracy of the dynamics solution, the deputy model is not used here. The dynamic mesh technology is adopted to model the variable flow boundary and to obtain directly the solution of the fiber orientation distribution in the turbulence. Then a parametric curve equation of the wall shape as Fig.1 is constructed at first. Based on the dynamic mesh model and the quasi-static assumption, the optimal parameters of the wall geometry can be obtained for the desired fiber orientation distribution. The effects of the wall shape parameters of the contraction, such as the inlet tangential angle α , the outlet tangential angle β and the ratio R_L of the length L to the height h_0 , on the flow behavior are studied in detail.

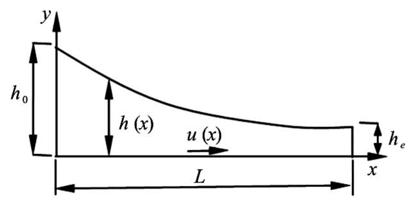

Fig.1 The 2-D model of plannar contraction

1. Parametric optimal model

1.1 *Parametric equation of wall shape*

Based on the bicubic parametric curves, the quintic curve, and the Vyshinsky curve for the contraction section of the wind tunnel, the parametric cubic curve for the wall shape function is constructed as follows

$$\frac{h-h_e}{h_0-h_e}=a\left(\frac{x}{L}\right)^3+b\left(\frac{x}{L}\right)^2+c\frac{x}{L}+d \tag{1}$$