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Blockage effect on the flow around a cylinder probe in calibration

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Abstract: Flow around a 2-D cylinder pressure probe placed in uniform flow, free jet flow, and wind tunnel flow was analyzed with potential flow theory and simulated with numerical method. Blockage effect was investigated under several typical flow Mach numbers. The result from numerical simulation shows a similar trend to the one from potential flow method while varies in quantity. Wind tunnel walls accelerate the flow near the probe and thus produce a blockage effect; Boundary of free jet flow, however, decelerates the flow and thus produces a “negative” blockage effect. A maximum incoming Mach number exists when the probe is calibrated in wind tunnel in high subsonic condition due to choking caused by shocks and shock induced separation. The critical Mach number varies with blockage ratio, which makes high Mach number impossible to achieve in large blockage ratio condition. The blockage effect itself is unavoidable for calibration or measurement although a sufficiently small blockage ratio brings minor effect. Correction can be implemented based on the numerical simulation result presented in this paper and further works.

Key words: pressure probe; blockage; measurement error; numerical simulation

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Nomenclature

B	blockage ratio
C_p	pressure coefficient
h	half width of wind tunnel or jet flow
Ma_{∞}	incoming flow Mach number
p	local static pressure
p_s	far field static pressure
p_t	far field total pressure
r	probe head radius
u_{θ}	circumferential velocity
v_{err}	relative error of velocity
θ	offset angle
θ_{ps}	static pressure angle
ψ	stream function

Introduction

High accuracy measurement technique needs to be developed and applied to the experiment in turbomachinery to meet the increasing demand in detailed flow information understanding for ad-

vanced aircraft engine design. Owing to the limitation of industrial environment, conventional instruments such as pressure probes are still the dominating measurement technique. Pressure probes are robust and capable of achieving sufficient accuracy, at the same time, however, they are intrusive methods and would distort the measured flow. Conventionally calibration is performed in a free jet flow with known velocity and then relation between flow parameters and probe placement geometry is established. Compressibility must be taken into account when the probe is going to be used in turbomachines since high Mach number is frequently encountered in these facilities. The probe, therefore, requires a calibration with Mach number close or identical to the flow to be measured. Producing a Mach number as high as the one in a turbomachine in calibration is often an expensive task since high

pressure ratio is needed for a high Mach number free jet flow. Calibrating probes in wind tunnels seems preferable thanks to their ability to achieve high speed with relatively low pressure ratio provided by a fan or compressor. Blockage effect becomes a major concern in wind tunnel calibration; actually it is always a problem in circumstances such as inter-stage flow measurement in small sized turbomachines.

Research concerning blockage effect has been concentrating mainly on wind tunnel experiment. Several researchers studied the blockage effect of pressure probes and no quantitative result is available to identify or compensate the effect^[1-2]. Huang et al and Chakraborty et al used numerical method to study the flow past a cylinder^[3-4]; the Reynolds number in these papers is rather low comparing to the condition in turbomachinery.

Theoretical and numerical method was used in this paper to seek a way to quantitatively determine the error to a cylinder probe due to blockage effect when the probe is placed in a wind tunnel or free jet flow. Two dimensional potential solution of a cylinder placed between two walls was investigated with conventional image method. Flow speed along the surface of the cylinder was derived and subsequently surface pressure coefficient acquired. Numerical simulation of a cylinder placed in a free jet or wind tunnel flow as well as uniform incoming flow was then performed, which considers viscous effect in contrast to potential method. The authors expect that compensation for a cylinder pressure probe working in a wind tunnel could be achieved based on these data and further works on 3-D calculation.

1 Theoretical Analysis

A single hole probe is a handy instrument to acquire flow parameters in 2-dimensional (2-D) flow, as shown in Figure 1. It simulates a 3-hole probe by rotating around its axis and taking data at several angular positions. A method to obtain static pressure is to fit a curve to the calibration

data with measured port pressure versus yaw angle and then find the angle where port pressure equals to static pressure of incoming flow. This angle, which is a weak function of Reynolds number and Mach number as well as other flow parameters such as turbulent intensity, is defined as static pressure angle. When measuring, the probe is to be rotated around its axis for several angular positions (usually over 11 positions) and fit a curve to obtain port pressure at any yaw angle. The angle where port pressure reaches maximum is the direction facing the incoming flow and the port pressure represents stagnation pressure of the flow; the pressure at the defined static pressure angle represents static pressure. In a wind tunnel test or calibration, walls influence the flow near the probe and lead to static pressure angle shifting and can introduce errors.

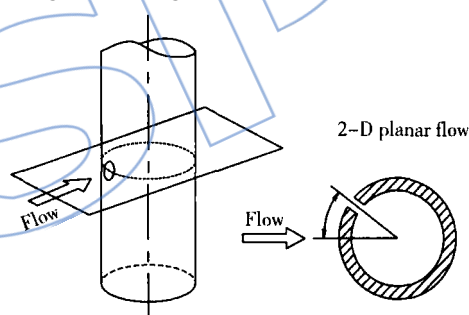


Fig 1 Single hole probe measuring 2-D flow

Assumption of 2-D flow is made when the velocity component along a probe's axis is minimal. A simplification of 2-D flow calculation is therefore feasible to check the relationship between blockage and pressure distribution on the surface of the probe. Calculation of flow around a cylinder based on potential flow theory was performed and the variation of static pressure angle with blockage effect is listed.

Uniform flow passing through a 2-D cylinder is a classical problem in traditional potential theory, by exerting a dipole on a uniform flow a cylinder is simulated and surface pressure distribution is as Equation 1.

$$C_p = \frac{p - p_s}{p_t - p_s} = 1 - 4\sin^2\theta \quad (1)$$

Here p_t , p_s , and p are incoming flow total pres-

sure, static pressure, and cylinder surface pressure respectively. Static pressure angle derived from this solution is 30° and is an invariant to any flow parameter.

Upon calibrating in a wind tunnel, wall effect exists and pressure distribution on a cylinder probe is altered. A calibration wind tunnel usually has a round or square cross section and its axis is perpendicular to the axis of the probe, which forms a complex geometry that cannot be solved with potential flow theory. As a preliminary study a simplified 2-D model is used as shown in Figure 2 where flow can be solved with the so-called image method as has been used in wind tunnel test for decades. An accurate analytical solution for the image method remains unknown, while approximate solutions can be found^[5,6]. C.C. Shih suggested Equation 2:

$$\phi = r \sin \theta - \frac{h \sin(\pi B \sin \theta) \sinh^2\left(\frac{\pi}{2h}\right)}{\pi \left[-\cos^2\left(\frac{\pi B \sin \theta}{2}\right) + \cosh^2\left(\frac{\pi B \cos \theta}{2}\right) \right]} \tag{2}$$

$$B = r/h \tag{3}$$

Here ϕ is stream function, r is radius of the cylinder, h is half wind tunnel width as in Fig 2, and B is blockage ratio as defined.

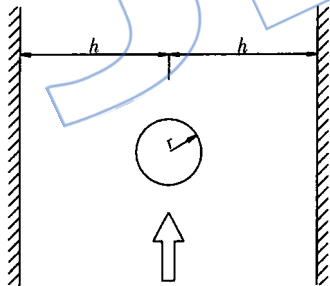


Fig 2 2-D model of a cylinder probe calibrating in wind tunnel

Magnitude of circumferential velocity on the cylinder is just the partial derivative of stream function with respect to radius:

$$u_\theta = \frac{\partial \phi}{\partial r} \tag{4}$$

With assumption of incompressible ideal flow, the angle θ where circumferential velocity equal to the flow speed of incoming undisturbed flow is the static pressure angle θ_{ps} .

In image method, infinite dipoles are placed on both sides of the cylinder to represent the walls, flow near the central dipole that represents the cylinder is “squeezed” and the dipole represents no more a perfect cylinder but more like an ellipse. This is the reason that analytical solutions to image method are extremely difficult to derive. The solution cited above is valid only when blockage ratio remains sufficiently small. Furthermore, viscous effect is not neglectable since boundary layer growth on the cylinder obviously influences the local surface pressure distribution. Wall boundary layer growth also influences the flow markedly in high subsonic flow condition due to compressibility. Nevertheless, Equation 2 and 4 provide a perspective relation between static pressure angle and blockage ratio. As shown in Figure 3, static pressure angle declines with blockage ratio increasing. This is obvious since flow speed near the cylinder rises when wall is approaching, this speed rise causes pressure on the cylinder to drop and surface pressure achieves the value of incoming flow static pressure before the nominal static pressure angle (30°).

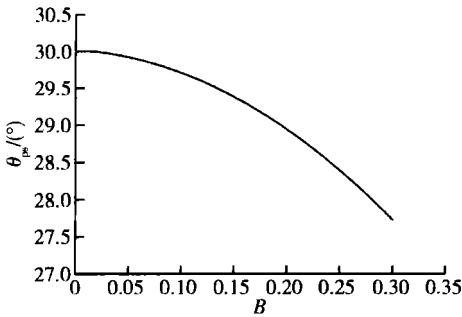


Fig 3 Static pressure angle versus blockage ratio

If blockage effect is not considered in calibration, static pressure angle is always regarded as 30 degree, therefore, the recorded port pressure as well as resulted velocity will vary with blockage ratio. As shown in Fig. 4, velocity error is approximately 1% for blockage ratio of 0.15.

For free jet flow calibration, potential theory is invalid since the flow is essentially rotation-

al. An observational analysis indicates that the free jet calibration has a “negative” blockage effect, which is to say that the presence of the shear flow boundary slows the flow near the probe. Static pressure at any point of the free boundary of a jet flow equals to the static pressure of incoming undisturbed flow, while at the same point under uniform flow condition, static pressure is lower because of the presence of the probe, which explains the reduction of the flow speed near the probe by jet flow free boundary.

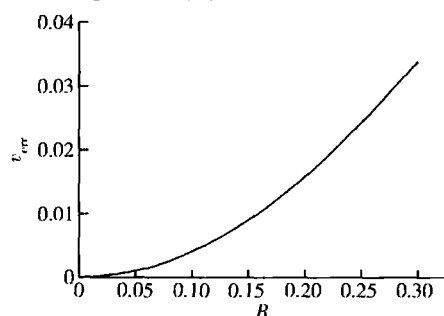


Fig 4 Velocity error due to blockage effect

2 Numerical Simulation

2.1 Model and grid generation

A comprehensive numerical simulation was performed to investigate the blockage effect of the walls of wind tunnel or free boundary of jet flow to a 2-D cylinder in order to acquire a relation between blockage ratio and static pressure angle under various incoming Mach number.

Computational models used to simulate a cylinder probe in uniform flow, wind tunnel flow, and free jet flow were built. A fixed diameter of 6 mm was chosen to have an invariant Reynolds number with different blockage ratios. Five blockage ratios of 0.06, 0.1, 0.15, 0.2, and 0.3 were set by changing the width of the wind tunnel. Three widths of free jet flow were set with “negative” blockage ratios of 0.06, 0.12, and 0.5 (defined as ratio of the diameter of the cylinder to the width of the jet flow). Uniform flow condition was calculated for comparison by having a sufficient large distance of side boundaries and setting them as pressure far field. Six Mach numbers (0.2~ 0.7, with inter-

val of 0.1) was calculated for the above blockage ratios. Mach number was altered by changing inlet flow total pressure; Reynolds number, therefore, varies with Mach number as well. Based on diameter of the cylinder, Reynolds number ranges from 3×10^4 to 1×10^5 corresponding to the six Mach numbers.

Commercial software *Fluent* was used with unsteady Reynolds averaging method (URANS), second order upwind scheme, and Reynolds Stress turbulence model with enhanced wall treatment. Structured grid was used for all the cases and two typical ones of them are presented in Figure 5 and Figure 6. Grid dependency was investigated and a grid with 150 nodes on the surface of the cylinder is proved sufficient to have a fine resolution of surface pressure distribution. In high subsonic incoming flow cases shocks may exist and special grids must be built. Adaptive mixed grid is employed to capture the shocks and a fine structured grid with sectional refinement is then created based on the adaptive result, as in Fig 6. Grid in boundary layer is carefully refined since the thickness of boundary layer on the cylinder plays an important role in the surface pressure distribution, and the boundary layer on the sidewalls plays an important role in flow discharge capacity. y^+ of the first grid to the walls is kept close to 1 for all the computational cases.

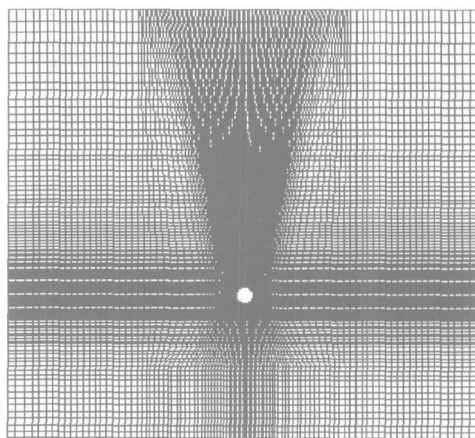


Fig 5 Grid for free jet or uniform flow

2.2 Results and discussion

Unsteady vortex shedding is a typical char-

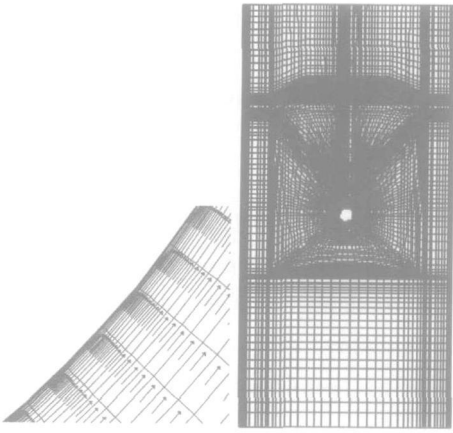


Fig 6 Grid and caculated velocity vector for wind tunnel flow with $Ma_{in} = 0.7$

acteristic of flow passing a cylinder, which is the reason that unsteady computation was performed instead of RANS. Nevertheless, data reduction technique of a cylinder probe is based on steady state flow; the unsteady result must be averaged. An averaging over two periods of flow rate variation yields the “steady state” solution. The reason that two periods was used is based on the knowledge of symmetric vortices shedding from both side of the cylinder results in two periods of flow rate variation corresponding to one period of cylinder surface pressure fluctuation. For the conditions in this paper, a corresponding Strouhal number of 0.2 is suggested in literatures. Strouhal number was checked over all the computation cases and a range of 0.15~0.19 was found, which demonstrates that the calculated unsteady phenomenon is of the flow nature instead of numerical oscillation.

Figure 7 gives averaged pressure coefficient (C_p , as defined in equation 1) distribution at the surface of the cylinder with blockage ratio of 0.06. In the figure, 0 degree offset angle corresponds to stagnation point. The angle where C_p equals to 0 is the defined as static pressure angle.

As a comprehensive comparison, Figure 8 presents static pressure angle variation with blockage ratio and incoming flow Mach number for wind tunnel calibration. Maximum incoming flow Mach number was encountered for high

blockage ratio cases because of choking, therefore not all the Mach numbers can be calculated for all the blockage cases. The phenomenon of choking and maximum incoming flow Mach number will be discussed later.

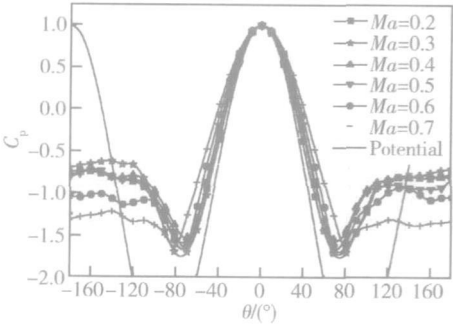


Fig 7 Surface pressure coefficient distribution

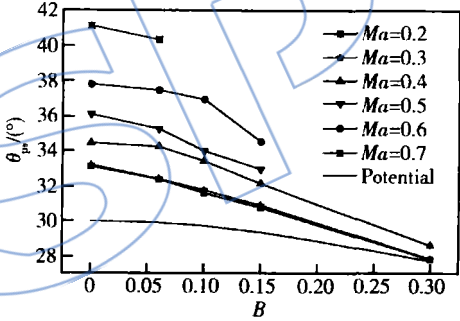


Fig 8 Static pressure variation with Blockage ratio for wind tunnel calibration

In Figure 9, relation between static pressure angle and incoming flow Mach number is plotted for different blockage ratio. Data from Fig 7 as well as data from free jet flow and uniform flow are plotted. As shown, free jet flow has a “negative” blockage effect, a jet flow with $B= 0.12$ has a similar effect as a wind tunnel flow with $B= 0.06$ but with a negative shift.

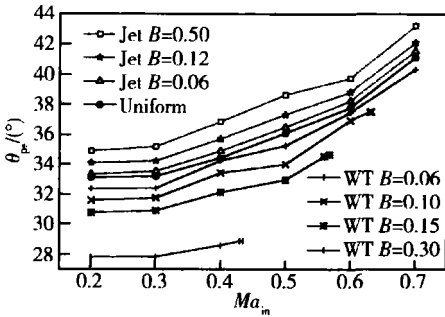


Fig 9 Static pressure variation with Mach number

In the theoretical analysis above, we had the conclusion that static pressure angle does not vary with any flow parameter. That conclusion, however, was reached for irrotational inviscid flow. With viscosity presence, boundary layer exists and grows from the stagnation point on. The outside irrotational flow “feels” a smaller curvature near the cylinder thereby static pressure angle is larger comparing to potential flow solution. Furthermore, separation is unavoidable for a flow around a cylinder, which may have an influence on the static pressure angle. Since Reynolds number rises with the increasing of Mach number, both viscosity and compressibility are account for the variation of the static pressure angle. Mach number, however, should be the major factor since Reynolds number is relatively high and is in a relatively small range. From the abundant calibration data of different sized cylinder probe in the Laboratory in BUAA that works in the same range of Reynolds number, static pressure angle was found to be from 33 to 46 degree and the static pressure angle increases with Mach number. These experimental results agree with the current computation result well.

For a flow passing a cylinder, a critical incoming flow Mach number of 0.466 can be derived which results a maximum Mach number near the cylinder of 1.0. That is to say, for an incoming flow Mach number of 0.5 or higher, the flow may contain shocks. This critical Mach number decrease with the increasing of blockage ratio since flow near the cylinder is accelerated with the approaching of the walls. Continue to increase the incoming flow Mach number will result in a second critical Mach number. Fig 10 is the case of incoming flow Mach number of 0.7. Maximum Mach number in the flow field achieves 1.85 somewhere after offset angle of 90° . Shocks arise between wake and walls, and the reflected shocks form a normal shock. Shocks interact with boundary layer on the walls of wind tunnel and induce separation. The separated boundary layers together with the wake

narrow the flow passage and choke the flow; consequently a second critical Mach number of the incoming flow is decided. The second critical Mach number is the highest incoming flow Mach number that a wind tunnel can have in probe calibration. This second critical Mach number decreases with the increasing of blockage ratio with apparent reason. As shown in Fig. 8, a wind tunnel calibration with blockage ratio of 0.15 has a maximum incoming Mach number of 0.57; a higher Mach number calibration is impossible in this case.

In Fig 10, the oblique shocks join the wake at a distance of two diameters of the cylinder, which phenomenon had been observed by Zheng et. al.^[7]. In that paper, a sphere instead of a cylinder was placed in a supersonic flow, still 2-D flow after the body is comparable to the case in this paper. As has been stated in potential theoretical analysis, free jet flow has a “negative” blockage effect on the probe. As shown in Fig 11, the free boundary of the jet has an influence to the flow near the cylinder by a constant pressure boundary, which is different from the case of uniform flow. An observation can be made by careful observing of velocity vector graph (not shown here) that the flow curves at the boundary both sides of the cylinder and provides a “larger” passage, which slows down the flow near the cylinder. It is suggested therefore that even though a free jet flow has a smaller blockage effect, care still need to be taken to retain a much larger jet flow dimension over the size of the probe.

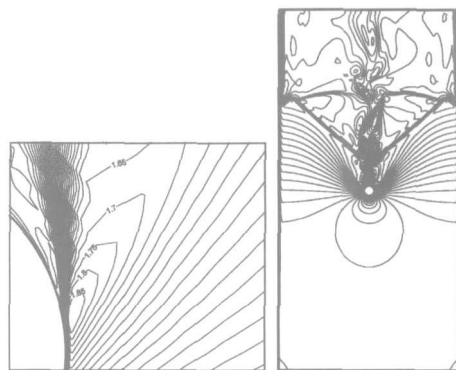


Fig. 10 Mach number distribution for $Ma_\infty = 0.7$ in wind tunnel flow with $B = 0.06$



Fig. 11 Mach number distribution for $Ma_{in} = 0.4$ in free jet flow with $B = 0.06$

Correction of blockage effect in conventional test had been studied for years; an effective method is wall signature method. By registering static pressure along the sidewall, flow distortion near the model can be derived with some simplifications. Sidewall pressure distributions for blockage ratio of 0.06 are shown in Fig. 12. Unit of the abscissa is normalized by the diameter of the cylinder, cylinder is located at $l/d = 0$. Not only cylinder itself but also the wake from it have blockage effect on the flow. For $Ma_{in} = 0.6$, shocks emerge near the cylinder and influence the recovery of pressure although no shock is found near the sidewalls. As shown in Fig. 10, strong shocks presence at $Ma_{in} = 0.7$, which is also shown in Fig. 12 with a sudden pressure rise at a location 7 times cylinder diameter after the cylinder.

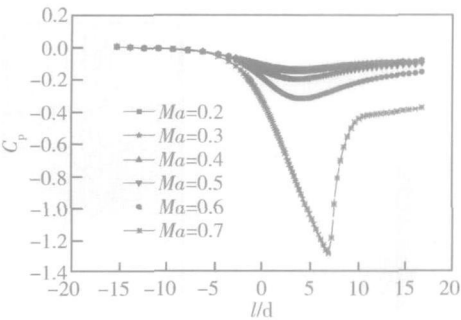


Fig. 12 Sidewall pressure variation

Pressure distribution along the sidewall

should be monitored in a wind tunnel calibration to ensure that no such strong shocks presents in the flow field. This kind of flow is not going to be meet in a test with identical structure and therefore can result in an invalid calibration.

Curve fitting is performed to the data from Fig 8, and a relationship between the static pressure angle and blockage ratio under different Mach number is acquired. By compensating the blockage effect, θ_{ps} - Ma_{in} relations nearly independent to blockage ratio can be obtained, as shown in Fig. 13.

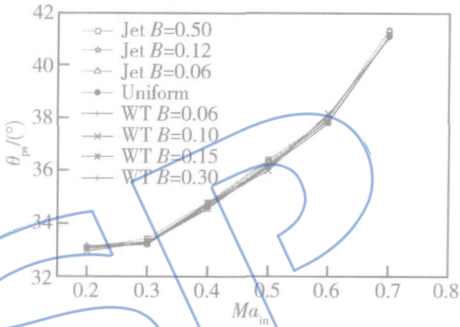


Fig. 13 Static pressure variation with Mach number with blockage effect corrected

3 Concluding Remarks

Blockage effect is investigated in this paper through potential flow theory and numerical simulation. Image method based on potential flow theory that had been used in wind tunnel test is inappropriate in the case in this paper since boundary layers on the probe and sidewall play a major role. Following conclusions can be drawn from above results.

Firstly, Numerical simulation is capable of revealing the complex flow phenomenon in a wind tunnel calibration and therefore a powerful tool for error correction.

Secondly, Blockage effect needs to be considered for blockage ratio larger than 0.06, which causes a static pressure angle error of 10 in scale. Jet flow is with a “negative” blockage effect and the effect is smaller than the one from wind tunnel walls; still correction is needed for a blockage ratio of 0.12 or more.

Furthermore, blockage effect limits the in-

coming flow Mach number upon calibrating a probe in a wind tunnel. Since high subsonic Mach number is often met in turbomachines, a large enough wind tunnel should be used in calibration.

The 2-D computation in this paper is just a preliminary study, 3-D effect might be strong for an actual wind tunnel calibration and a 3-D computation is under way.

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References:

- [1] Bubeck H, Heneka A. Measuring errors of pneumatic multihole probes [C] // 7th Symposium on Measuring Techniques in Transonic and Supersonic Flows in Carscades and Turbomachines. Aachen: September 1983.
- [2] Ma H, Jiang H. Velocity gradient and wall effect on the measurement error of pressure probes[J]. Gas Turbine Experiment and Research, 1997, 10(4): 42-46. (In Chinese)
- [3] Huang P, Feng J. Wall effects on the flow of viscoelastic fluids around a circular cylinder[J]. Journal of Non-Newtonian Fluid Mechanics, 1995, 60: 179-198.
- [4] Chakraborty J, Verma N, Chhabra R P. Wall effects in flow past a circular cylinder in a plane channel: a numerical study [J]. Chemical Engineering and Processing, 2004, 43: 1529-1537.
- [5] Yuan Y. Approximate solution of incompressible ideal potential flow past a cylinder between two parallel walls [J]. Applied mathematics and Mechanics, 1988, 9(1): 63-71 (In Chinese).
- [6] Lin C. Incompressible ideal flow past a cylinder between two walls[J]. Journal of Northwestern Polytechnical University, 1984, 2: 143-150 (In Chinese).
- [7] Zheng Z, Lin T. Drag on a sphere in transonic flow field [J]. Chinese Journal of Theoretical and Applied Mechanics, 1984, 16: 207-212 (In Chinese).