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Large-Eddy Simulation of Low-Reynolds-Number Flow Around Partially Porous Airfoils

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This paper analyzes the flow around two-dimensional partially porous airfoils with symmetric and flat geometries using the large-eddy simulation framework in OpenFOAM. The effects of a porous medium near the trailing edge are investigated at a chord Reynolds number of 350,000. Two porous media are modeled to investigate how the porous medium influences the flow around the airfoil and aerodynamic performance: one is a normal porous medium, while the other consists of straight holes perpendicular to the airfoil surface, allowing fluid to pass unidirectionally. It is observed that drag and lift forces vary depending on the internal structure of the porous medium. The size of the laminar separation bubbles also varies depending on the parameters of the porous medium, such as the internal structure, length of the porous section, and porosity.

Nomenclature

AoA	=	angle of attack [deg]
c	=	chord length [m]
h	=	thickness of airfoil [m]
L_p	=	length of porous medium part [m]
C_l	=	lift coefficient
C_d	=	drag coefficient
C_f	=	friction coefficient
C_p	=	pressure coefficient
Re	=	chord Reynolds number
U	=	velocity [m/s]
U_∞	=	freestream speed [m/s]
y^+	=	dimensionless wall distance

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p = pressure [Pa]
 ρ = density [kg/m³]
 μ = viscosity [Pa·s]
 ν = kinematic viscosity [m²/s]

I. Introduction

SMALL aircraft such as micro air vehicles and unmanned aerial vehicles (UAVs) have been developed and widely used in recent years. These aircraft are expected to play an active role in a wide range of fields, including observation and reconnaissance at disaster sites where it is unsafe for humans to enter. Most such vehicles fly at low speed, resulting in lower Reynolds numbers (i.e., $Re = U_\infty c / \nu = 10^4 - 10^5$) than typically encountered by conventional aircraft [1, 2]. Previous studies have shown that the aerodynamic characteristics in such low-Reynolds-number regimes are significantly different from those at high Reynolds numbers [1–5]. At high Re , the lift coefficient C_l generally varies almost linearly with the angle of attack (AoA) until the aircraft stalls. However, at low Re , C_l does not vary linearly with AoA , causing difficulties in maneuvering aircraft and decreasing the lift-to-drag ratio C_l/C_d (C_d is the drag coefficient) [6].

Viscous forces are important compared with inertial forces for low-Reynolds-number flows. As a result, the physical properties of the boundary layer, such as flow separation and reattachment, and the transition to turbulent flow over the airfoil change. A typical phenomenon at low Re is the generation of a laminar separation bubble (LSB) [1, 2, 7, 8]. There is no turbulent transition of the boundary layer. Instead, laminar separation occurs near the leading edge. Turbulence is then generated in the separated shear layer. As the separated flow reattaches to the surface of the airfoil, the LSB is formed. The LSB is called a short bubble when its length is only a few percent of the chord length. As the AoA of the airfoil increases, these bubbles can eventually extend over most of the chord, so that the separated boundary layer may not reattach. In this state, the LSB is called a long bubble, and the lift force is drastically reduced. Therefore, the aerodynamic characteristics of the airfoil largely depend on the formation and behavior of the LSB, which affects the streamlines outside the boundary layer.

In developing UAVs, engineers have often focused on the wings of birds. Birds have evolved to fly within a similar Reynolds number regime to that of small aircraft, and to adapt to a variety of similar flight conditions, from stable fixed-wing gliding to high-angle maneuvers, involving unsteady separation flows [9]. A major difference between birds and conventional UAVs is that bird wings have specifically evolved to have permeable feathers. A bird's wing enables transmissivity of the flow from the lower to the upper surface and vice versa [10]. Previous work on bird wings has shown that the permeability of the wing reduces the flow separation [11]. Several studies measuring the aerodynamic forces on the foremost wing of storks have shown that the lift-to-drag ratio increases as air can pass through the wing [12]. This increase is mainly due to a reduction in drag, but the detailed mechanism is unknown. Another experimental study

[13] has shown that the drag force can be reduced by 22% through the introduction of permeability, which effectively increases the base pressure. By imitating bird wings, an airfoil with a porous medium section has been proposed. The porous component has also been introduced in the transonic Mach number range to generate a shockless supercritical flow around an airfoil [14]. A study on a subsonic flow shows that the bubble size decreases in the separation region on the upper surface [15]. Experimental investigations of the aeroacoustic and aerodynamic performance of a slightly modified semi-symmetric SD 7003 airfoil made from a set of 16 homogeneous porous materials have been conducted, and its performance was compared with that of a non-porous reference airfoil of the same intersection [16]. The results show that the porous materials produce a decrease in lift and an increase in drag. Several different experimental studies [17, 18] have reported similar results. However, experimental studies on partially porous airfoils have mainly been conducted by aerodynamic measurements, where it is difficult to investigate the detailed flow field because of the limited accessible data.

Numerical simulations are an effective means of investigating the flow around an airfoil at low Reynolds numbers. An analytical solution has been obtained based on a thin airfoil theory and Darcy's equation [19] for a thin permeable symmetric airfoil. The result indicates that there is a reduction in the slope of the lift curve as the dimensionless permeability increases. Hajian and Jaworski [20] derived the exact solution of the pressure distribution for a porous SD7003 airfoil and obtained closed-form expressions for the aerodynamic coefficients. Another study using a porous NACA0008 airfoil [21] reported an increase in the lift-to-drag ratio due to the reduction in drag. To the best of the authors' knowledge, on the other hand, there have been few numerical studies on the effects of the porous component on the flow around an airfoil, and the relationship between the porous medium and the LSB has not been studied in detail. Moreover, previous studies on the flow in and around porous media [22, 23] have shown that the internal structure of the porous component has a significant effect on the local fluid flow. Therefore, it is naturally expected that the internal structure of the porous media will affect the flow, hence, the aerodynamic performance of a partially porous airfoil. To date, however, there have been no numerical studies on the effects of different porous media in airfoils. The purpose of this study is, therefore, to clarify the characteristics of low-Reynolds-number flow around porous airfoils, including the effect of different structures of the porous medium.

In this paper, the flows around two-dimensional partially porous airfoils with a symmetric and flat geometry are analyzed using OpenFOAM through the large-eddy simulation (LES) framework. Porous airfoils with different lengths of the porous section L_p will be compared. We also evaluate the effect of different porous structures. The effects of the porous section on the fluid are discussed in terms of aerodynamic performance, friction and pressure coefficients, and boundary layer profile.

The remainder of this paper is organized as follows. Section II presents the basic equations and the solution method. We investigate the effect of a porous medium in Section III. Section IV summarizes the main results of this study.

II. Numerical Models

A. Governing equations and numerical methods

The simulations are performed for compressible fluids through the LES framework with the Smagorinsky subgrid-scale (SGS) model. OpenFOAM with the rhoPimpleFoam module is used with the second order upwind scheme for spatial discretization and the first order Euler scheme for temporal integral. The governing equations are the compressible Navier–Stokes equations. The working fluid is air with the assumption of a perfect gas. The constant viscosity coefficient (1.89773e-05) is given to match the Reynolds number with a previous study [17]. The porous medium is modeled based on the Darcy–Forchheimer equation by adding a sink term S_i to the conservation equations of momentum. The sink term S_i is defined as

$$S_i = - \left(\mu D + \frac{1}{2} \rho u_{kk} F \right) u_i, \quad (1)$$

where u_{kk} is the velocity magnitude, D is the Darcy coefficient, and F is the Forchheimer coefficient. For homogeneous porous media, D and F are expressed as

$$D = \frac{r}{\mu}, \quad (2)$$

$$F = \frac{2f}{\rho}, \quad (3)$$

where r is the intrinsic flow resistivity and f is the inertial resistivity. Various studies have suggested expressions for r and f [24–27]. The theoretical forms have been evaluated in [28]. The best empirical expressions for estimating r and f based on the available data are [28]

$$r = 0.003333d^{-1.500403}n^{0.060350}, \quad (4)$$

$$f = 0.194325d^{-1.265175}n^{-1.141417}, \quad (5)$$

where d is the hole diameter and n is the porosity.

To verify the accuracy of the numerical method, simulations of the flow around an SD7003 airfoil and the flow around a cylinder wrapped in a porous layer have been performed with the developed calculation code. The validation results can be found in our previous study [29]. The results are qualitatively consistent with published values [30–33].

B. Calculation Conditions and Models

Following a previous experimental study [17], a symmetric flat airfoil is considered to minimize the effect of airfoil shape on the flow. The shape of the airfoil is the same as that used in [17]. The chord length of the airfoil is $c = 277$ mm

Table 1 Calculation models

Case	L_p/c	n	Model
1	0	0	–
2	0.04	0.9	Normal, Unidirectional
3	0.1		
4	0.2		
5	0.04, 0.1, 0.2	0.3	
6		0.6	
7		0.9	

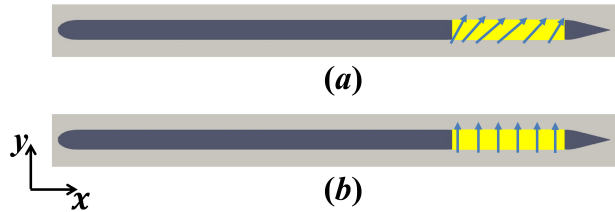


Fig. 1 Schematic of two porous media: (a) normal porous medium; (b) unidirectional porous medium.

and the thickness is $h = 10$ mm. The leading edge is an ellipse with a major axis of 10 mm and a minor axis of 5 mm. The length of the triangular part of the trailing edge is 20 mm. A porous component with different lengths, structures, and porosity is assembled near the trailing edge. The calculation conditions are summarized in Table 1. Two porous media are considered: one is the normal porous medium shown in figure 1(a), and the other consists of straight holes perpendicular to the airfoil surface, as shown in figure 1(b), which allow fluid to pass only unidirectionally. As shown in figure 2, porous medium lengths normalized by c , L_p/c , of 0.04, 0.1, and 0.2 are considered. The porosity n , which indicates the percentage of the void, is set to either 0.3, 0.6, or 0.9 to investigate the effect of the permeability of the porous media. α values of 4, 8, 12, and 16 degrees are considered for all cases.

Figure 3 shows the c-type structured grid used in this study. The spanwise length of the computational domain is very thin (0.001 mm) compared with $C = 277$ mm and the flow is considered to be two-dimensional. The far-field boundary is located 20 chords forward of the airfoil to reduce its effect on the solution near the airfoil. The time step is set to 6×10^{-7} s. The maximum Courant number is approximately 0.310 and the average Courant number is approximately 8.62×10^{-4} . Time integrations are performed until 1 second and the statistics are calculated using data from 0.05 to 1 second to eliminate early transitions. The chord Reynolds number Re based on the freestream speed $U_\infty = 20$ m/s is 350,000, which is the same as in a previous study [17]. The initial temperature and density of air are given as 298 K and 1.1818534 kg/m³, respectively.

A grid-dependence study of the airfoil mesh was performed and the results are presented in Table 2. We compared

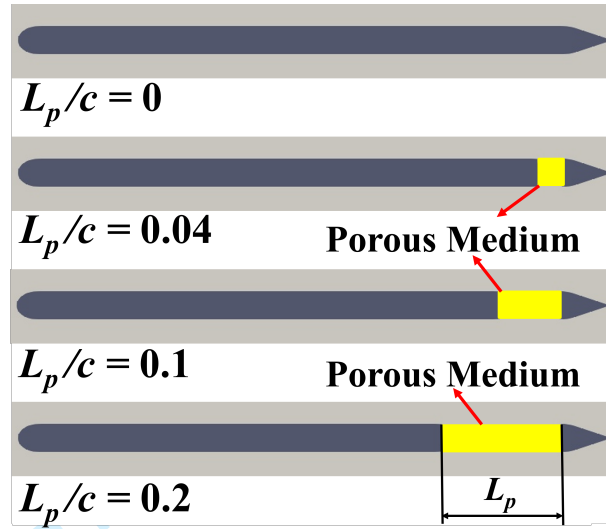


Fig. 2 Length of the porous media.

Table 2 Grid-dependence study ($AoA = 12^\circ$)

Case	grid number	y^+	Wraparound mesh points on the airfoil	C_l	C_d
1	250,000	6.0	660	1.0002	0.1899
	300,000	1.0	740	1.0122	0.1946
	350,000	0.6	780	1.0139	0.1990
	400,000	0.6	870	1.0141	0.2003
3 (Unidirectional)	250,000	6.0	680	1.0067	0.1996
	300,000	1.0	750	1.0261	0.2038
	350,000	0.6	800	1.0584	0.2098
	400,000	0.6	880	1.0692	0.2132

C_l and C_d for a non-porous airfoil (Case 1) and a porous airfoil (Case 3 for the unidirectional model) with different grid numbers. The grid resolution was varied by changing the wraparound mesh points on the airfoil and the dimensionless wall distance y^+ , where y^+ is the length from the wall normalized by the viscous unit, defined as

$$y^+ = \frac{u_\tau y}{\nu}. \quad (6)$$

Here, y is the distance to the nearest wall and u_τ is the friction velocity at the nearest wall, defined as

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}, \quad (7)$$

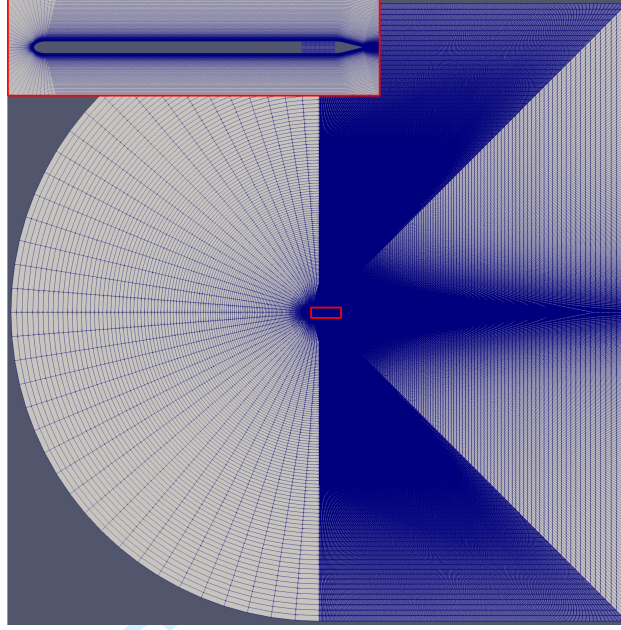


Fig. 3 C-type structured mesh.

where the wall shear stress τ_w is calculated by

$$\tau_w = C_f \frac{1}{2} \rho U_\infty^2. \quad (8)$$

The skin friction C_f is estimated by the Schlichting skin-friction correlation

$$C_f = (2 \log_{10} Re - 0.65)^{-2.3}. \quad (9)$$

For Case 1, the differences in C_l and C_d between grid numbers of 300,000 and 350,000 are about 0.17% and 2.20%, and those of 350,000 and 400,000 are about 0.01% and 0.65%, respectively. For Case 3, the differences in C_l and C_d between grid numbers of 300,000 and 350,000 are about 3.15% and 2.94%, and those of 350,000 and 400,000 are about 1.02% and 1.62%. The grid size for LES requires the smallest large-scale eddies to be captured. The dimensionless wall distance $y^+ = 0.6$ meets this requirement. Thus, the mesh with about 350,000 nodes best balances the accuracy and calculation cost.

III. Results and Discussion

A. Lift and Drag Forces for $n = 0.9$

The effects of porous media with a porosity of $n = 0.9$ (Cases 2, 3, and 4) are considered in this section. This value of n is close to that of a honeycomb plate used in a previous study [17], i.e., $n = 0.96$. A slightly lower value

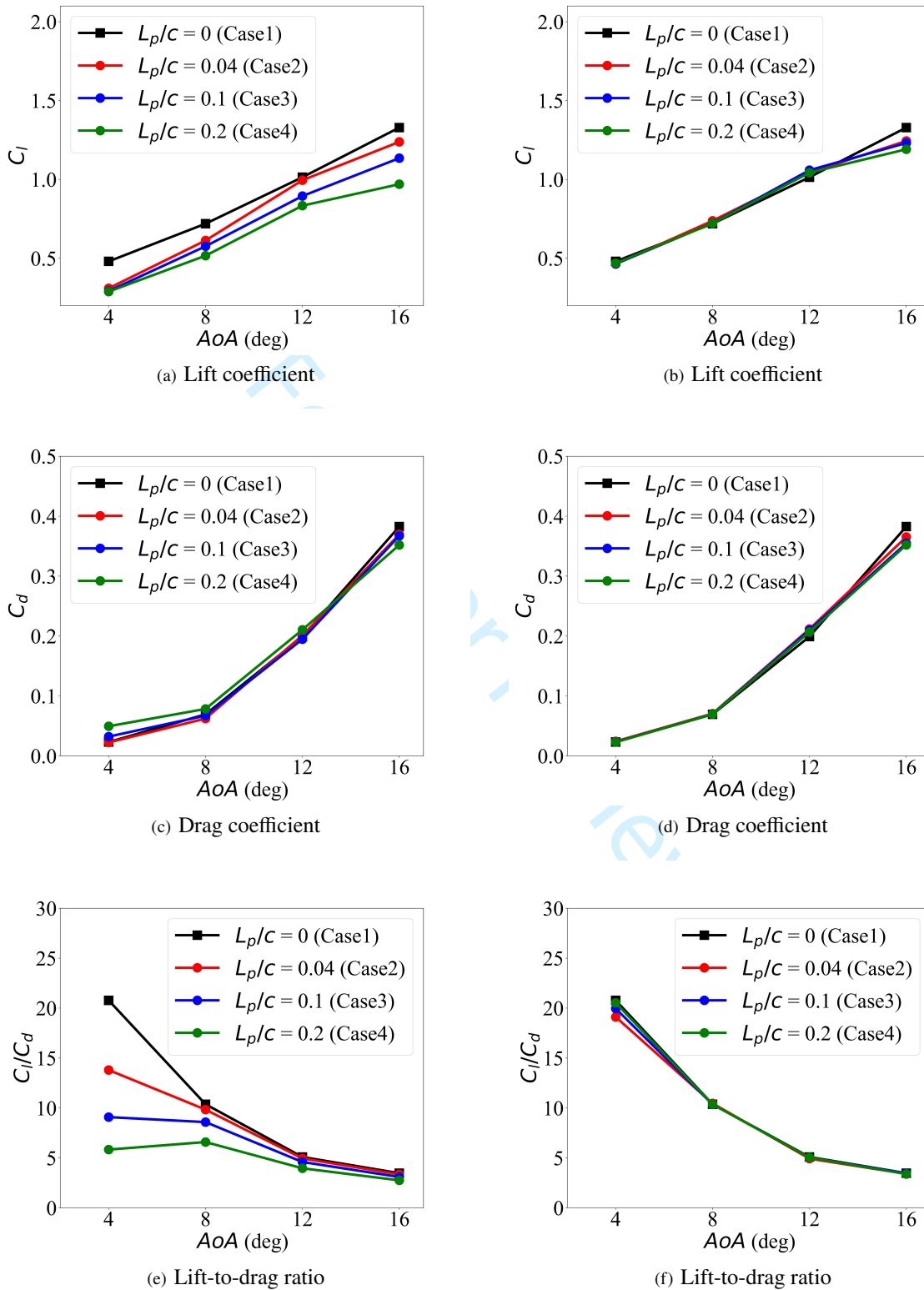
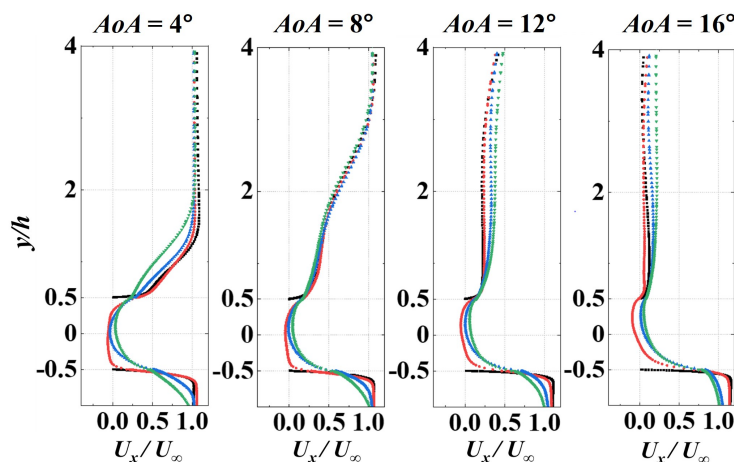
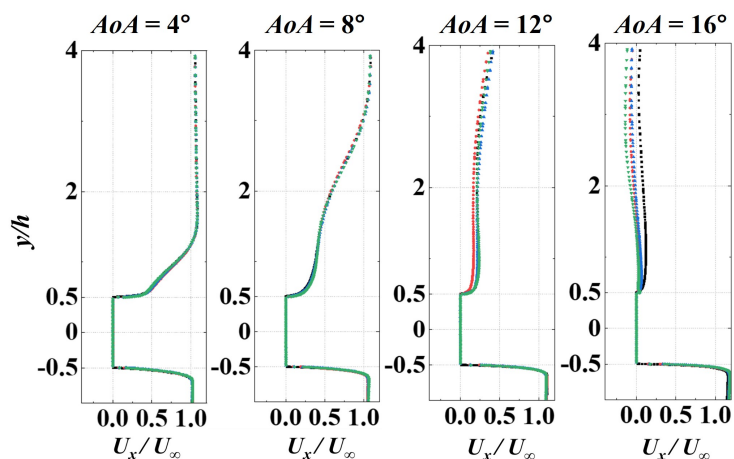


Fig. 4 The lift and drag coefficients and the lift-to-drag ratio: (a), (c), (e) are for the normal porous model; (b), (d), (f) are for the unidirectional porous model.

- $L_p/c = 0$ (Case1) • $L_p/c = 0.04$ (Case2) ▲ $L_p/c = 0.1$ (Case3) ▼ $L_p/c = 0.2$ (Case4)



(a) Normal porous medium



(b) Unidirectional porous medium

Fig. 5 Mean streamwise velocity profiles at $x/c = 0.894$.

of $n = 0.9$ is considered in this study because the airfoil used in the experiment has a solid mounting plate to hold a honeycomb plate. The lift and drag coefficients, $C_l = F_l / \frac{1}{2} \rho A U_\infty^2$ and $C_d = F_d / \frac{1}{2} \rho A U_\infty^2$, and the lift-to-drag ratio C_l/C_d with respect to AoA are shown in figure 4. Here, A is the projected area and F_l and F_d are the normal and parallel components of the total force to the air stream and they are calculated as the sum of the friction and pressure forces acting on the whole airfoil including the porous section. Figures 4(a), (c), (e) and figures 4(b), (d), (f) are for the normal and unidirectional porous media, respectively. As shown in figure 4(a), C_l decreases as the length of the porous section L_p/c increases for all AoA considered. The effects of the porous medium on C_l for all L_p/c are similar at $AoA = 4^\circ$, and the dependence of L_p/c on C_l rises as AoA increases. Figure 4(c) shows that C_d increases as the porous section becomes longer at $AoA = 4^\circ$, but the opposite is true at $AoA = 16^\circ$. At $AoA = 8^\circ$ and 12° , C_d decreases

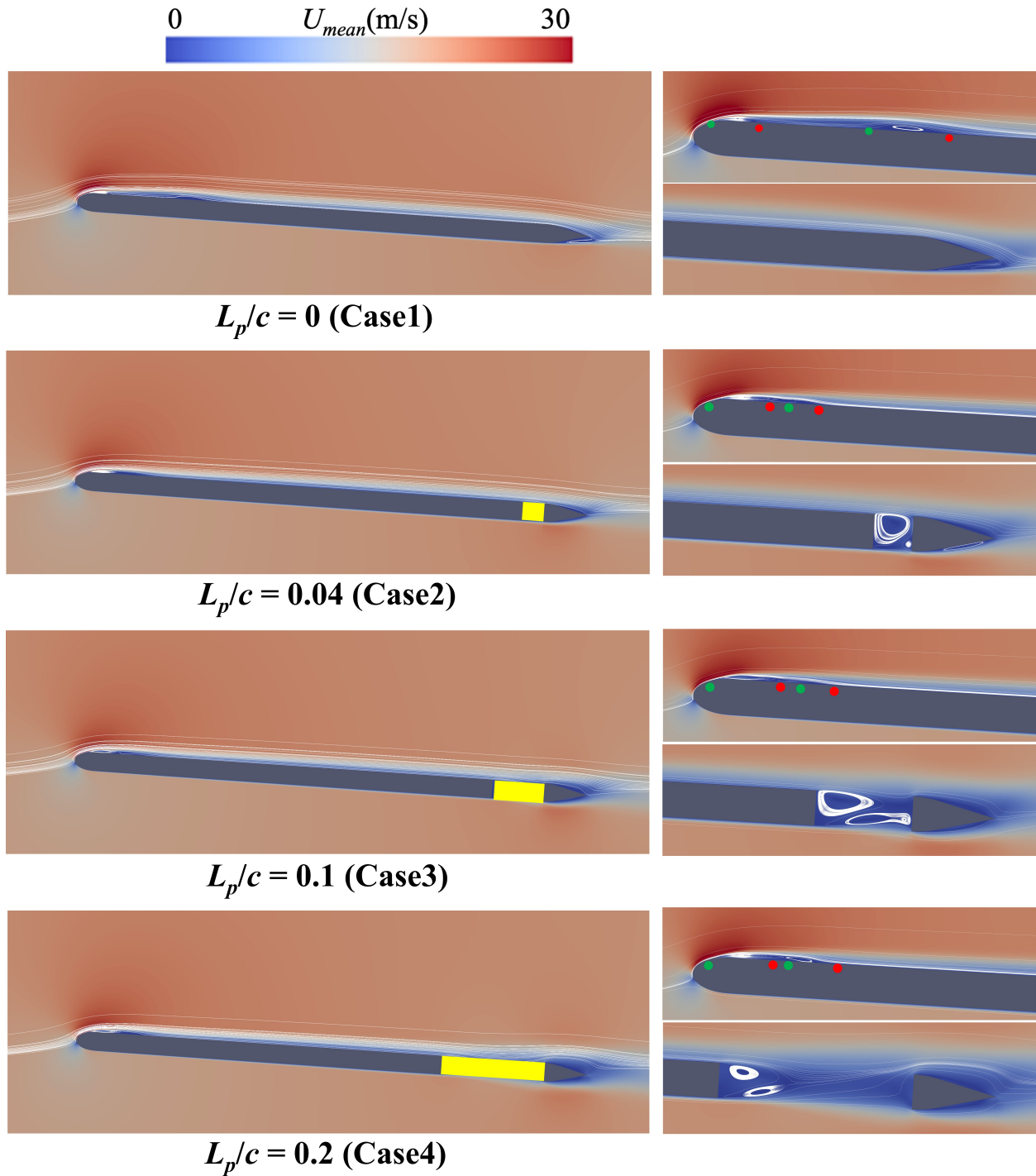


Fig. 6 Contours of the mean velocity and streamlines with different lengths of the porous section (yellow) at $AoA = 4^\circ$ for the normal porous model.

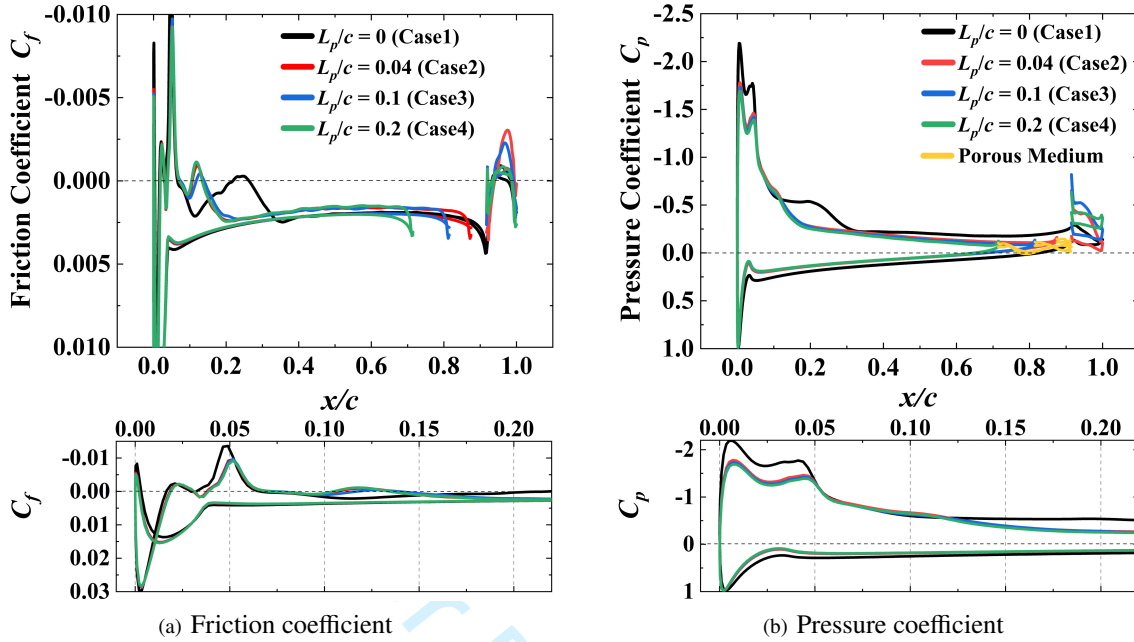


Fig. 7 Friction and pressure coefficients at $AoA = 4^\circ$ for the normal porous model.

slightly compared with the non-porous airfoil (Case 1) for $L_p/c = 0.04$ and 0.1 , and increases for $L_p/c = 0.2$. The results also show that the greatest increase in C_d for the porous airfoils occurs at $AoA = 4^\circ$. Figure 4(e) shows that the porous medium causes a decrease in C_l/C_d for all cases, and the decrease is significant for lower values of AoA and longer porous sections. These results are in qualitative agreement with previous experiments [17].

The unidirectional porous condition in figures 4(b), (d), (f) shows the different effects that porous materials can impart. Compared with the normal porous model, C_l and C_d vary little and the variations with respect to $AoAs$ are irregular. The lift and drag coefficients hardly vary at $AoA = 4^\circ$ and 8° , and slightly larger values of C_l and C_d are attained with the porous medium at $AoA = 12^\circ$. However, C_l and C_d become small at $AoA = 16^\circ$ when the porous section is introduced. Figure 4(f) shows that C_l/C_d decreases at $AoA = 4^\circ$, whereas it remains unchanged at $AoA = 8^\circ$, 12° , and 16° . This is due to the cancellation of the effects of the porous medium on C_l and C_d .

B. Mean Flow Field for $n = 0.9$

The mean flow field for $n = 0.9$ (Cases 2, 3, and 4) is now discussed. First, to explore the effects of the different internal structures on the mean flow field, figure 5 shows the streamwise velocity profiles inside and around the porous media. All results were obtained at $x/c = 0.894$, where the porous component is introduced to the airfoil. The upper and lower figures are for the normal and unidirectional porous media, respectively. The vertical coordinates of $y/h = 0.5$ and -0.5 correspond to the upper and lower surfaces of the airfoil, respectively, and the space between them is the porous media. With the normal porous medium, the variation in the velocity distribution of the boundary layer differs

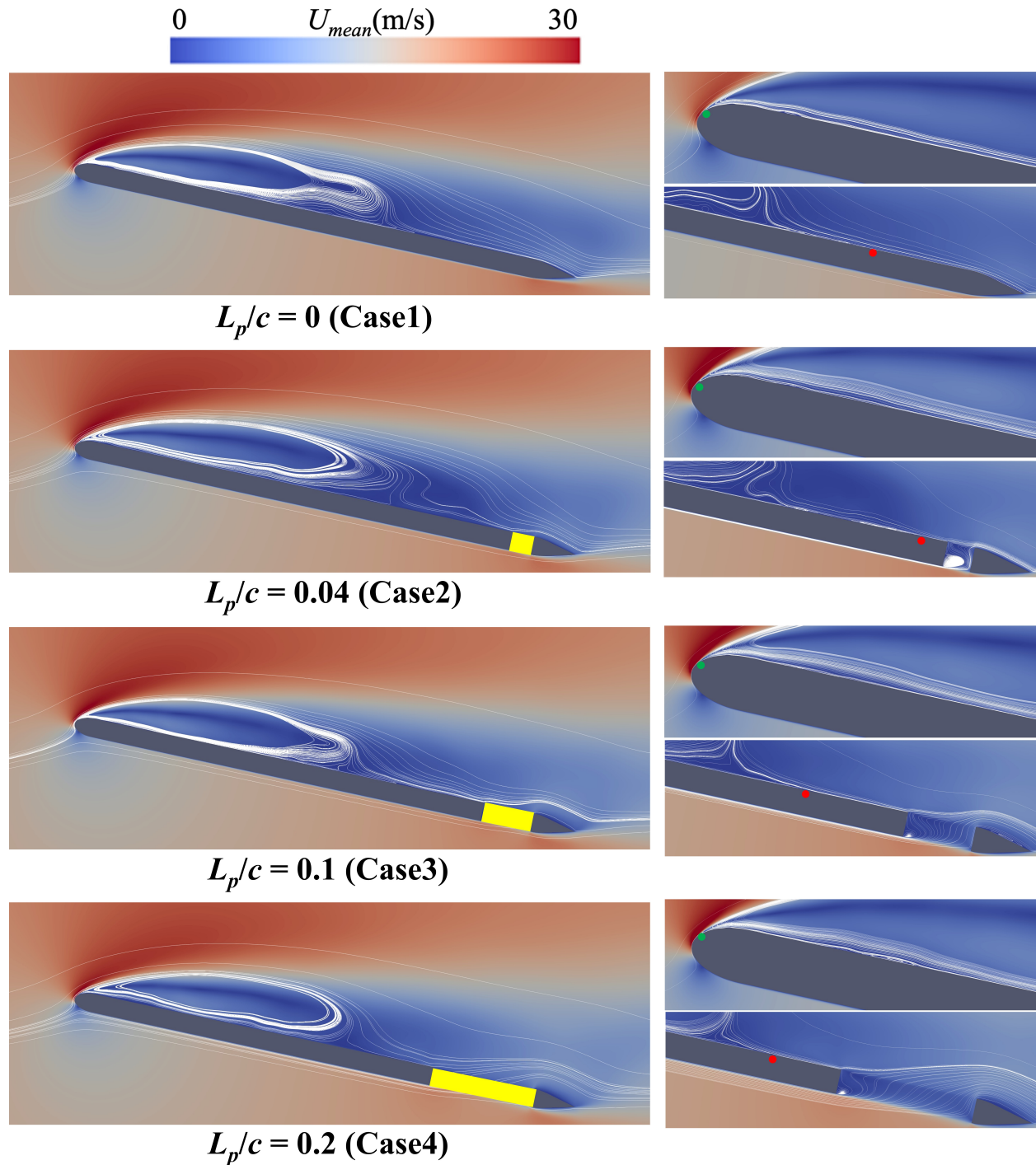


Fig. 8 Contours of the mean velocity and streamlines with different lengths of the porous section (yellow) at $AoA = 12^\circ$ for the normal porous model.

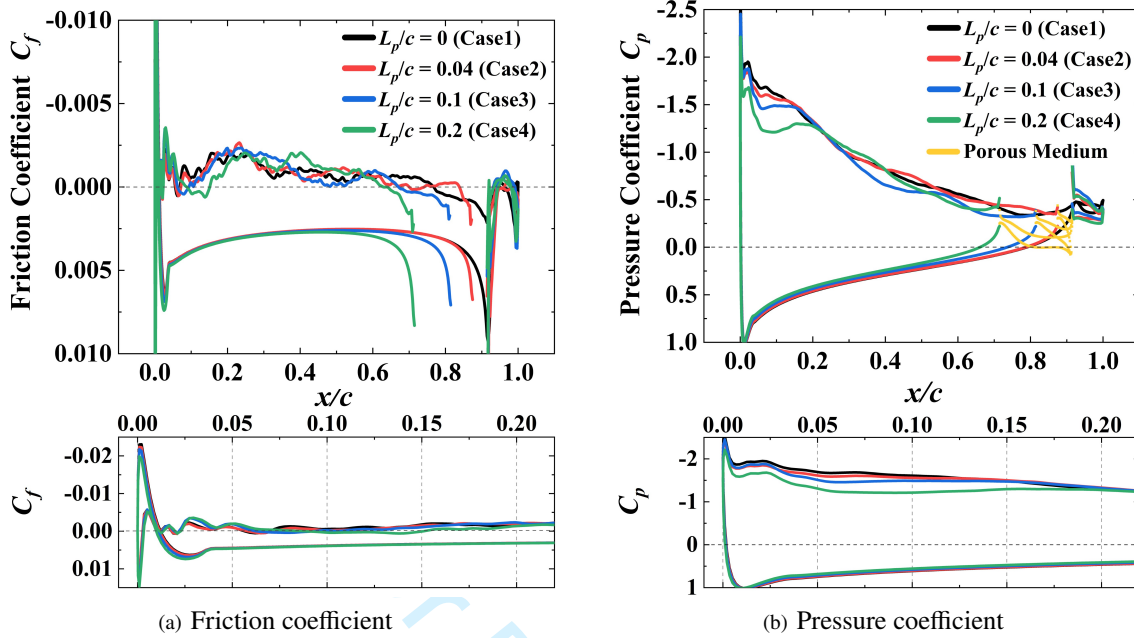


Fig. 9 Friction and pressure coefficients at $AoA = 12^\circ$ for the normal porous model.

depending on AoA . On the upper surface, as the length of the porous section L_p/c increases, the velocity decreases at low AoA and increases at high AoA . On the lower surface, the velocity decreases as L_p/c increases. The velocity inside the porous media increases as L_p/c increases. Figure 5(b) shows that the velocity profiles inside and on the lower surface are almost independent of L_p/c for the unidirectional porous medium. On the other hand, the velocity profile on the upper surface varies slightly depending on L_p/c at AoA values of 12° and 16° .

The flow fields and aerodynamic forces are now investigated in more detail for both porous media at $AoA = 4^\circ$ and 12° . Figure 6 shows the mean velocity field with different lengths of the porous section (yellow) at $AoA = 4^\circ$ for the normal porous model. The green and red symbols in the mean velocity profiles mark the separation and reattachment points, respectively. It is shown that a small LSB is generated at the leading edge for all cases. This is due to the shape of the leading edge of the airfoil. Twin vortices form inside the porous media. Figure 7 shows the friction and pressure coefficients for these cases. In figure 7 [as well as figures 9, 11, and 13], the upper panels show the distribution of the whole airfoil and the lower panels show the profile near the leading edge (up to $x/c \approx 0.2$). The separation and reattachment points can be seen in the friction coefficient distribution in figure 7(a). The length of the LSB at the leading edge is approximately $0.046c$ between the separation point at $x/c = 0.018$ and the reattachment point at $x/c = 0.064$, and is hardly affected by the porous section. This short LSB near the leading edge may be caused by the change in the shape from the curved leading edge to the flat airfoil section ($x/c = 0.033$). For the non-porous airfoil ($L_p/c = 0$), another LSB is generated from the separation point at $x/c = 0.21$ and reattachment point at $x/c = 0.26$, and the length of this LSB is approximately $0.05c$. However, for the porous airfoils, the second LSB is generated between

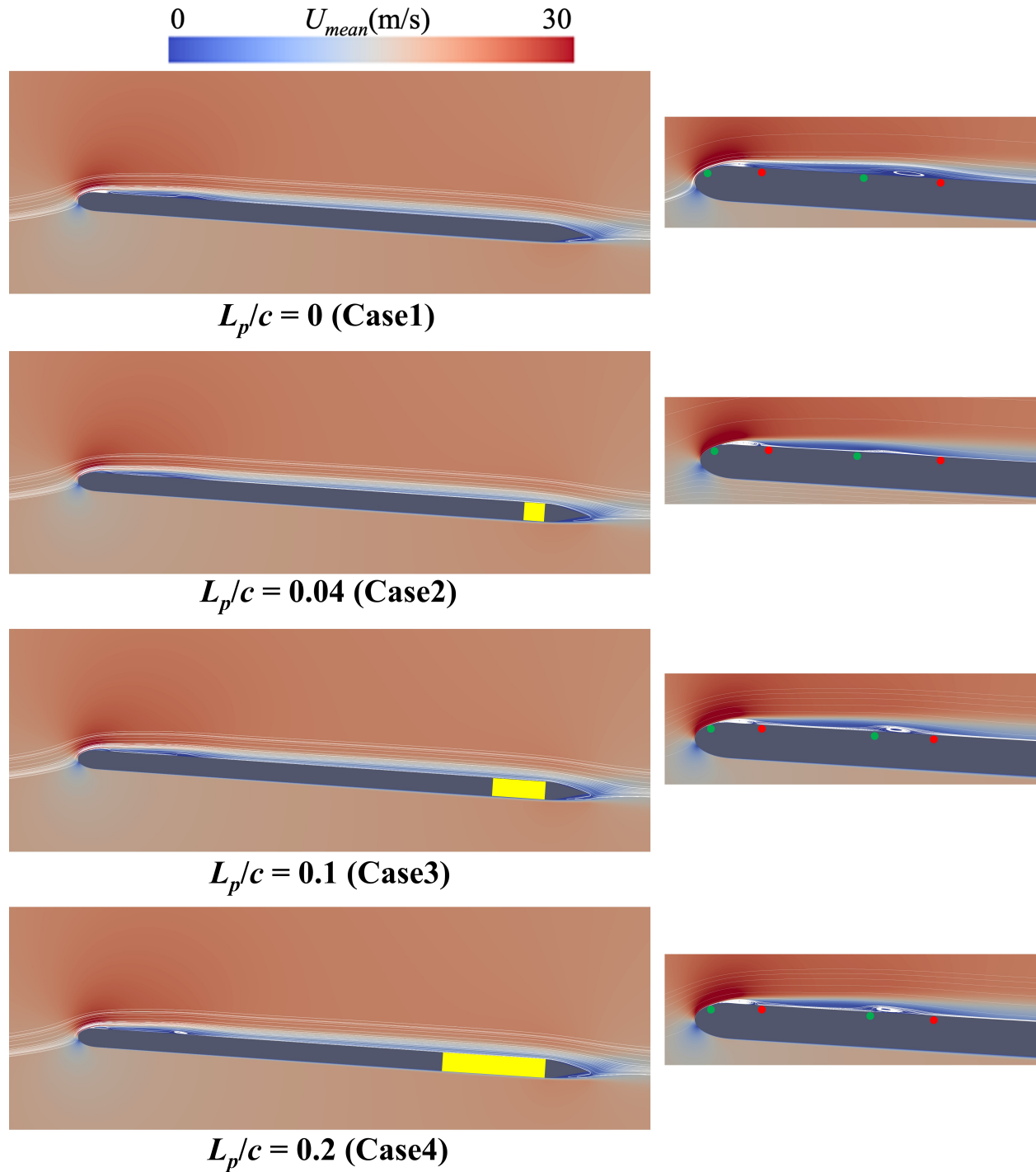


Fig. 10 Contours of the mean velocity and streamlines with different lengths of the porous section (yellow) at $AoA = 4^\circ$ for the unidirectional porous model.

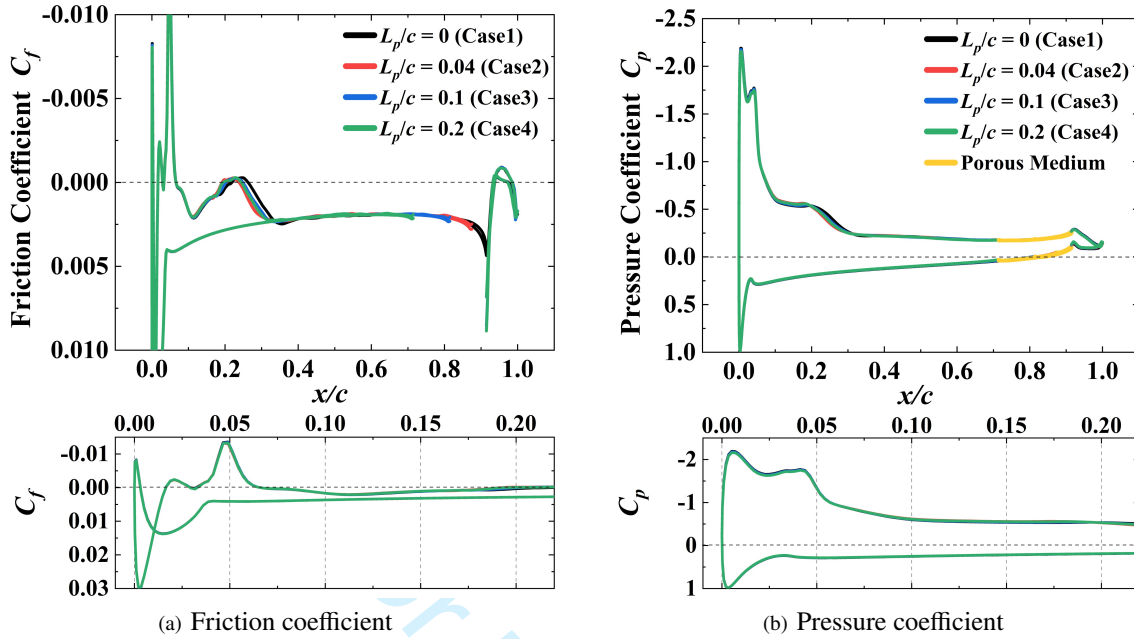


Fig. 11 Friction and pressure coefficients at $AoA = 4^\circ$ for the unidirectional porous model.

the separation point at $x/c = 0.1$ and the reattachment point at $x/c = 0.13$, and so its length is approximately $0.03c$. Compared with the non-porous airfoil, both the separation and reattachment points move towards the front and the size of the second LSB is small for the porous airfoil. For the porous airfoils with different porous component lengths, the size and location of the first and second LSBs are similar. The friction coefficient increases rapidly immediately upstream of the porous component, which is one of the reasons for the increase in drag. Near the trailing edge, the absolute value of C_f increases as L_p/c decreases. Suction peaks appear at the leading edge in the pressure coefficient profiles in figure 7(b); this is consistent with the friction coefficient profiles. Compared with the non-porous airfoil, the suction peaks for the porous airfoils are reduced by similar amounts. The distribution of C_p indicates that at $x/c \approx 0.1-0.2$, the non-porous airfoil result shows a pressure plateau on the upper surface. However, this pressure plateau does not appear for the porous airfoils, leading to a reduction in C_p . The pressure difference between the upper and lower surfaces of the airfoil decreases at the porous section. Moreover, a reduction in the pressure difference can be seen in the whole region of the airfoil when the porous medium exists near the trailing edge.

Figure 8 shows the mean velocity field at $AoA = 12^\circ$ for the normal porous model. It is shown that a longer LSB is generated near the leading edge. The length and shape of the LSB vary with L_p/c . Compared with $AoA = 4^\circ$, separation occurs closer to the leading edge. Inside the porous medium, only a small vortex is formed. As shown in the friction coefficient distribution in figure 9(a), for the non-porous airfoil, the separation point and the reattachment point are located at $x/c = 0.07$ and 0.76 , respectively. For porous airfoils with $L_p/c = 0.04, 0.1$ and 0.2 , the reattachment points are located at $x/c = 0.70, 0.67$, and 0.62 , respectively. However, the separation points are consistently located at

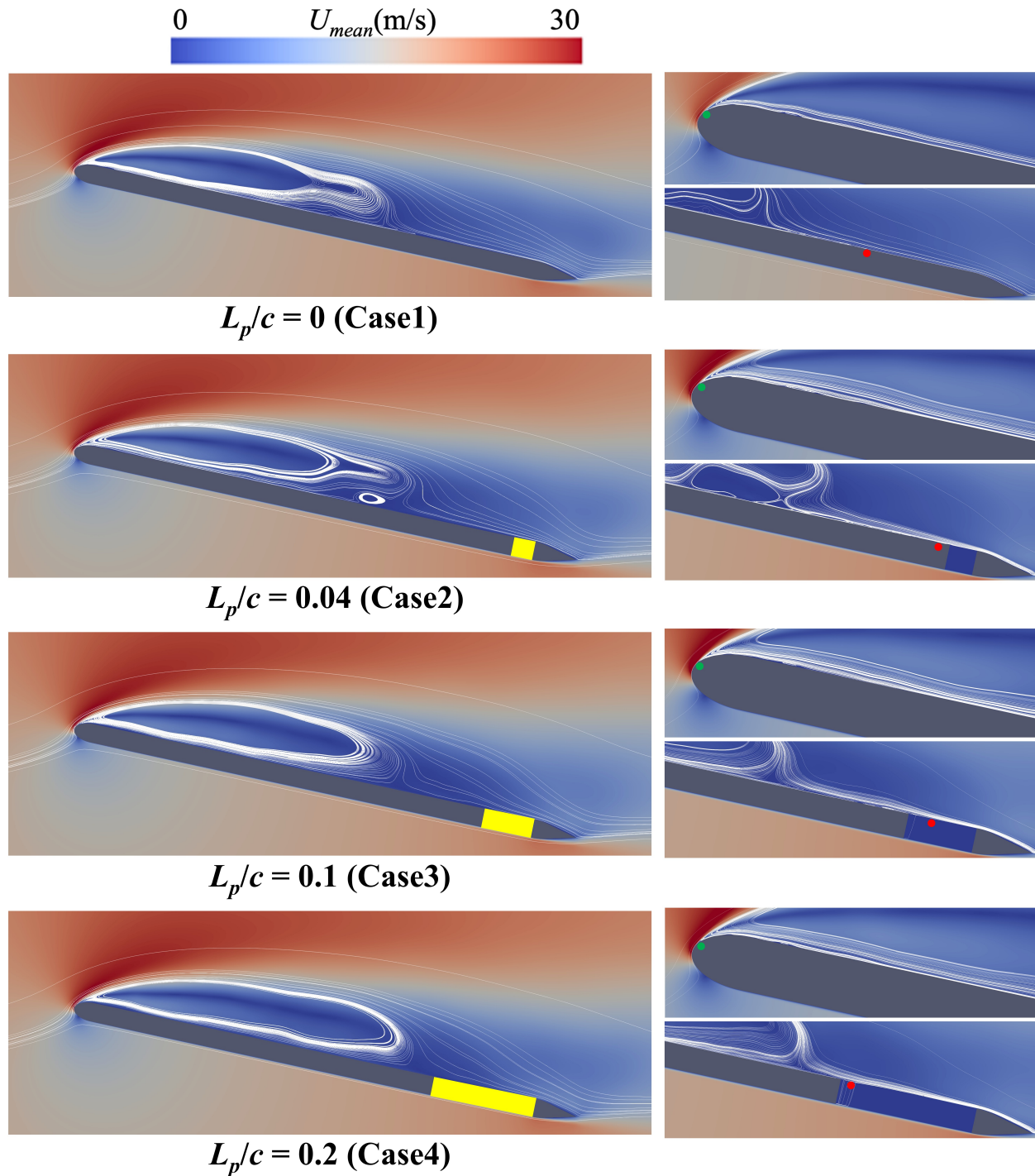


Fig. 12 Contours of the mean velocity and streamlines with different lengths of the porous section (yellow) at $AoA = 12^\circ$ for the unidirectional porous model.

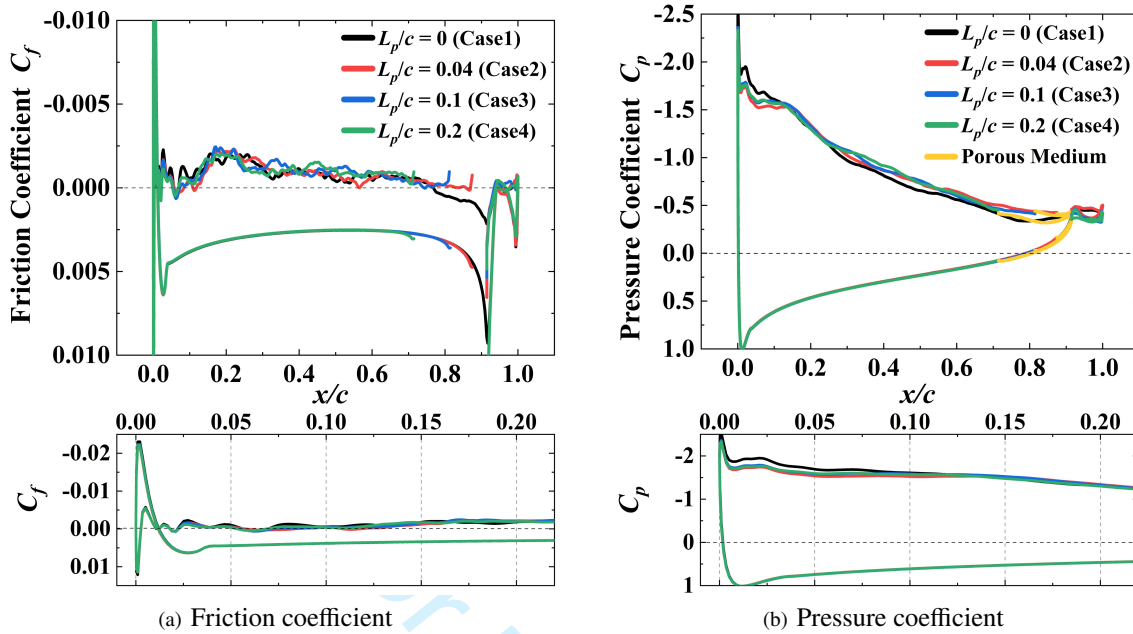


Fig. 13 Friction and pressure coefficients at $AoA = 12^\circ$ for the unidirectional porous model.

$x/c = 0.07$. Thus, the length of the LSB decreases with increasing L_p/c as the reattachment point moves forward. As can be seen from the visualization results for the non-porous airfoil, the separated flow does not immediately reattach but forms a very thin reverse-flow region beneath the bubble. For $L_p/c = 0.04$, several small vortices form after the separated flow approaches the wall so that C_f exhibits several separations and reattachment points. For larger L_p/c , the reattachment points move upstream. Near the leading edge, a small secondary vortical structure forms inside the LSB for all cases. As L_p/c increases, the length of the vortex increases and its position moves downstream. The pressure coefficient distribution in figure 9(b) indicates that, near the leading edge, the suction peak becomes smaller with increasing L_p/c . After the suction peak, a sharp adverse pressure gradient appears, and an increase in L_p/c enhances the magnitude of pressure recovery (at $x/c \approx 0.05$). Moreover, the results for the porous airfoils exhibit unique characteristics, i.e., a region of favorable pressure gradient appears at $x/c \approx 0.1$, where the secondary vortical structure is formed, and this region is wider for the longer porous section. This region of favorable pressure gradient accelerates the fluid and pushes the vortex downward. A long adverse pressure gradient can be seen behind the separation point, where the separation bubble is generated. Downstream of the LSB, the C_p distribution exhibits a favorable pressure gradient between the reattachment point and the porous component. This favorable pressure gradient is thought to be due to the fluid's acceleration on the porous surface, allowing the flow to reattach upstream of the porous medium. For larger values of L_p/c , this favorable pressure gradient lies further upstream, so the reattachment point also moves upstream. Then, at the porous section, the pressure difference between the upper and lower surface decreases. In general, we can see a decrease in the pressure difference over the whole of the porous airfoils, causing a significant reduction in C_l .

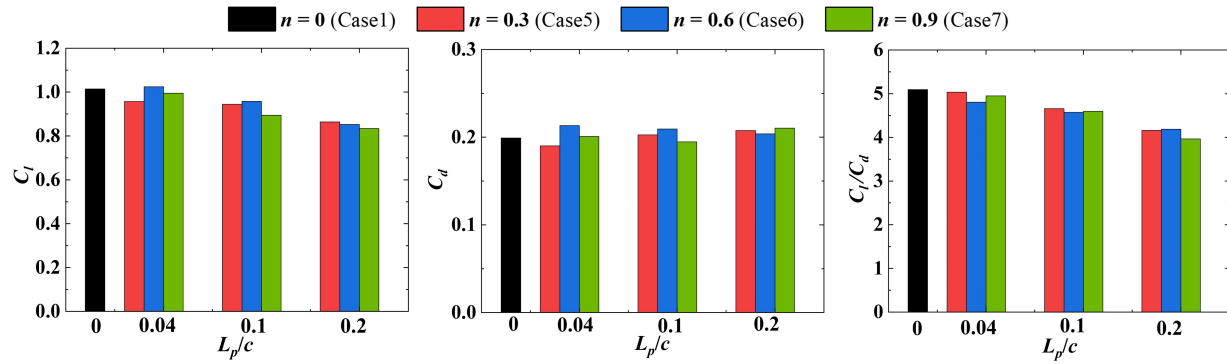


Fig. 14 Variation of the aerodynamic performance of partially porous airfoils with respect to the porosity: normal porous model.

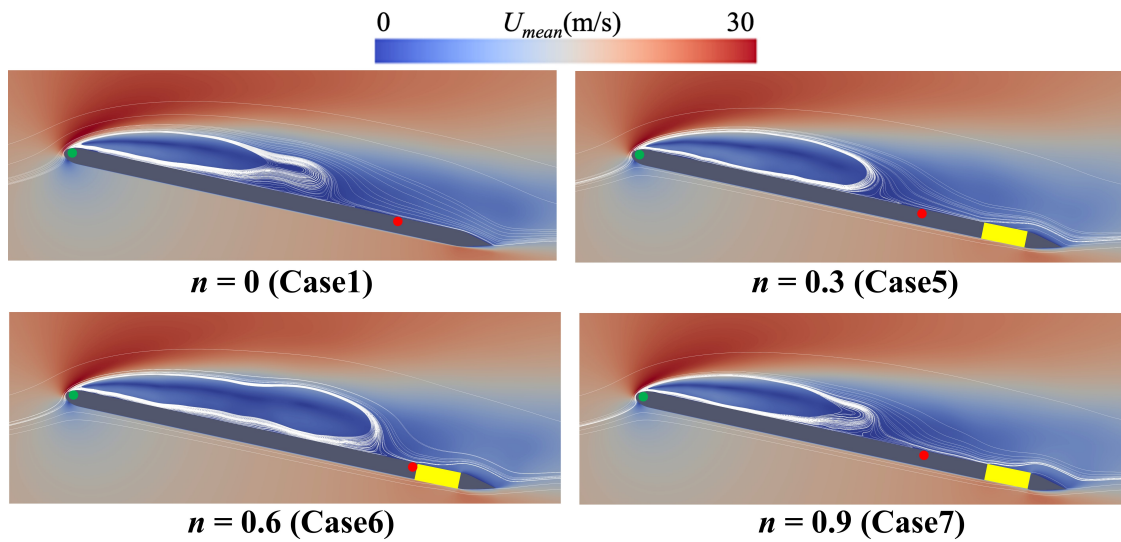


Fig. 15 Contours of the mean velocity and streamlines with different porosity of the porous component (yellow) for $L_p/c = 0.1$.

The mean flow field around the airfoils with the unidirectional porous medium is now discussed. Figures 10 and 11 show the mean velocity field and the friction and pressure coefficients at $AoA = 4^\circ$, respectively. As shown by the C_f distribution in figure 11, at $AoA = 4^\circ$, the size of the LSB for the porous airfoil is slightly reduced. However, the mean flow around the airfoil, the location of the LSB, and the distributions of C_p and C_f show no significant differences between the porous and non-porous airfoils. The pressure coefficient on the upper surface varies only slightly compared with the normal porous case, and the large pressure difference between the upper and lower surfaces persists when the unidirectional porous component is introduced. These small variations can be explained by the boundary conditions on the unidirectional porous surface, where the velocity in the x direction is zero. Thus, the mean velocity is zero both on the porous surface and inside the porous medium. The non-porous airfoil also imposes a zero-velocity condition on the surface, which results in similar mean velocity profiles on the porous and non-porous airfoils.

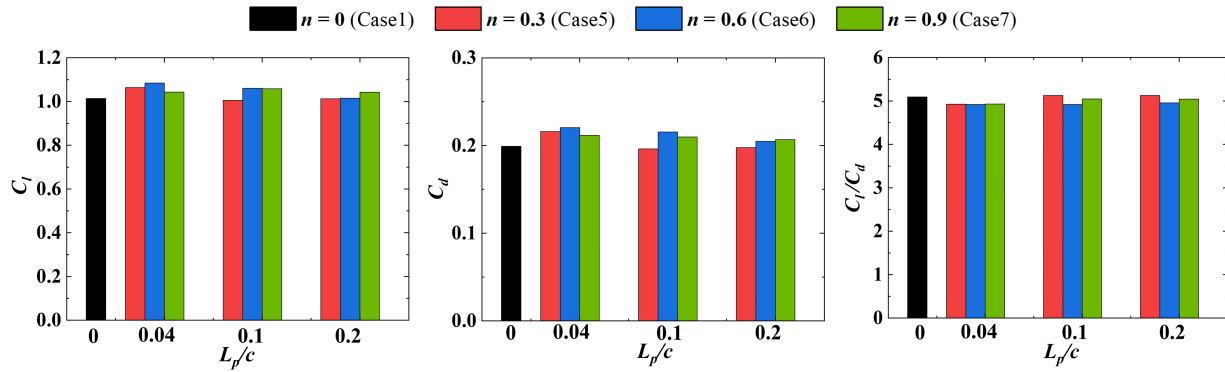


Fig. 16 Variation of the aerodynamic performance of partially porous airfoils with respect to porosity: unidirectional porous model.

The effects of the unidirectional porous medium are not significant even at high AoA as shown in figures 12 and 13. At $AoA = 12^\circ$, C_f in figure 13(a) exhibits a slight decrease upstream of the porous component, causing the flow to reattach to the upper surface of the porous medium. From the flow visualization in figure 12, the positions of the large-scale separated flows close to the wall are all similar. However, the location of the reattachment point moves downstream in the case of porous airfoils. This is because the unidirectional porous medium causes the surface vortices to roll up from the surface. As shown in the C_p distribution in figure 13(b), the suction peak on the upper surface of the porous airfoils becomes smaller near the leading edge. In the field of the LSB, the C_p distribution shows an adverse pressure gradient with a similar trend. However, the pressure on the upper side is lower for the porous airfoils, which may act to increase the lift coefficient. As for $AoA = 4^\circ$, the pressure difference between the upper and lower surfaces remains large, even on the porous section.

C. Effects of Porosity n of Porous Media

In this section, the aerodynamic forces and the flow around the porous airfoils are described for various values of the porosity n (Cases 5, 6, and 7). The variations of C_l , C_d , and C_l/C_d with n and L_p/c at $AoA = 12^\circ$ for the normal porous airfoil are shown in figure 14. The effect of porosity on C_l and C_d is similar for $L_p/c = 0.04$ and 0.1 . Both C_l and C_d increase as n increases from 0.3 to 0.6. However, because C_d increases by more, C_l/C_d is smaller for $n = 0.6$. The reason for these variations can be seen in the mean velocity profiles in figure 15. For $n = 0.6$, the size of the LSB increases significantly. For the long porous section $L_p/c = 0.2$, the maximum of C_l/C_d occurs for $n = 0.6$. Generally, C_l/C_d decreases with increasing L_p/c compared with the non-porous airfoil for all porosities considered, and the effect of n on C_l/C_d is not significant.

The variations in C_l , C_d , and C_l/C_d with n and L_p/c at $AoA = 12^\circ$ for the unidirectional porous airfoil are shown in figure 16. Compared with the non-porous airfoil, C_l increases slightly, especially for larger porosities of $n = 0.6$ and 0.9 . The drag coefficient C_d also increases, except for the porous medium with $n = 0.3$ and $L_p/c = 0.1$ and 0.2 .

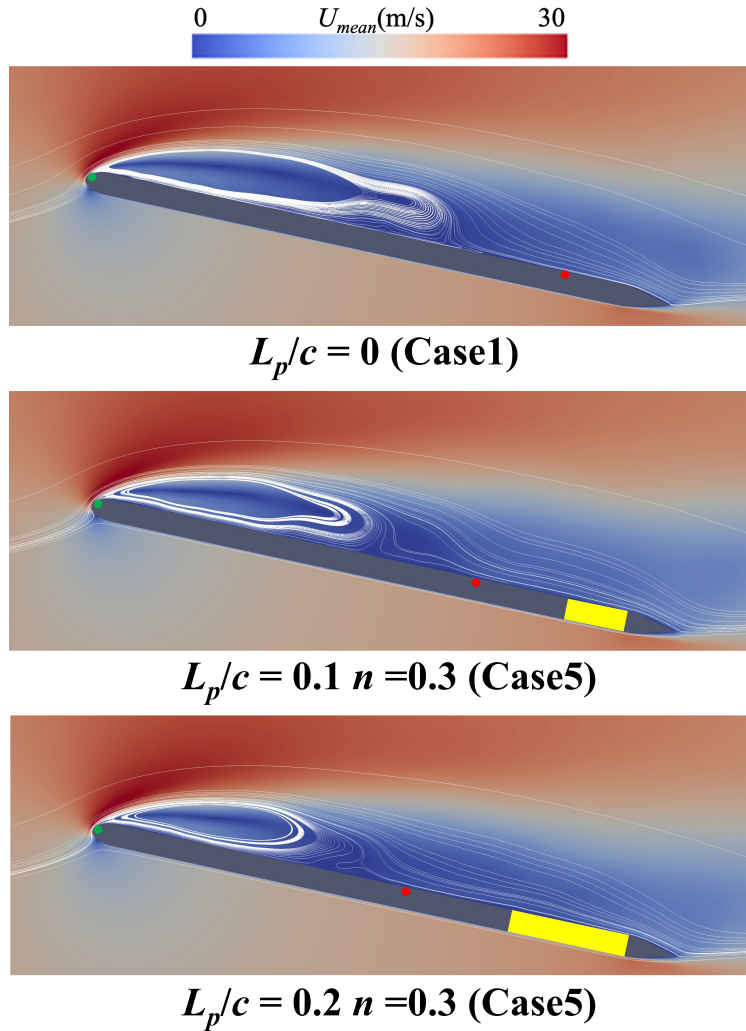


Fig. 17 Contours of the mean velocity and streamlines with different porosity of the porous component (yellow) for the increasing lift-to-drag ratio conditions.

Because of the decrease in C_d for these two cases, C_l/C_d increases. Figure 17 visualizes these two conditions. We can see that the size of the LSB decreases significantly with the introduction of the porous section. Figures 18 and 19 show the distributions of C_f and C_p for these two conditions (red lines). It can be seen from the C_f distribution for $n = 0.3$ in figure 18 that the large-scale separated flow reattaches at $x/c \approx 0.68$ for $L_p/c = 0.1$ and at $x/c \approx 0.54$ for $L_p/c = 0.2$. Although the LSB becomes smaller with the introduction of the porous section, the recirculating flows (i.e., negative C_f) are locally strengthened. This is one reason for the decrease in C_d for $n = 0.3$ with $L_p/c = 0.1$ and 0.2 . The C_p result in figure 19 shows that, near the leading edge, the suction peak becomes smaller with increasing n for $L_p/c = 0.1$ and 0.2 . Then, due to the larger LSB, the pressure on the upper surface decreases for $n = 0.6$ and 0.9 . Thus, the pressure difference between the upper and lower surfaces becomes larger, resulting in larger pressure drag. In

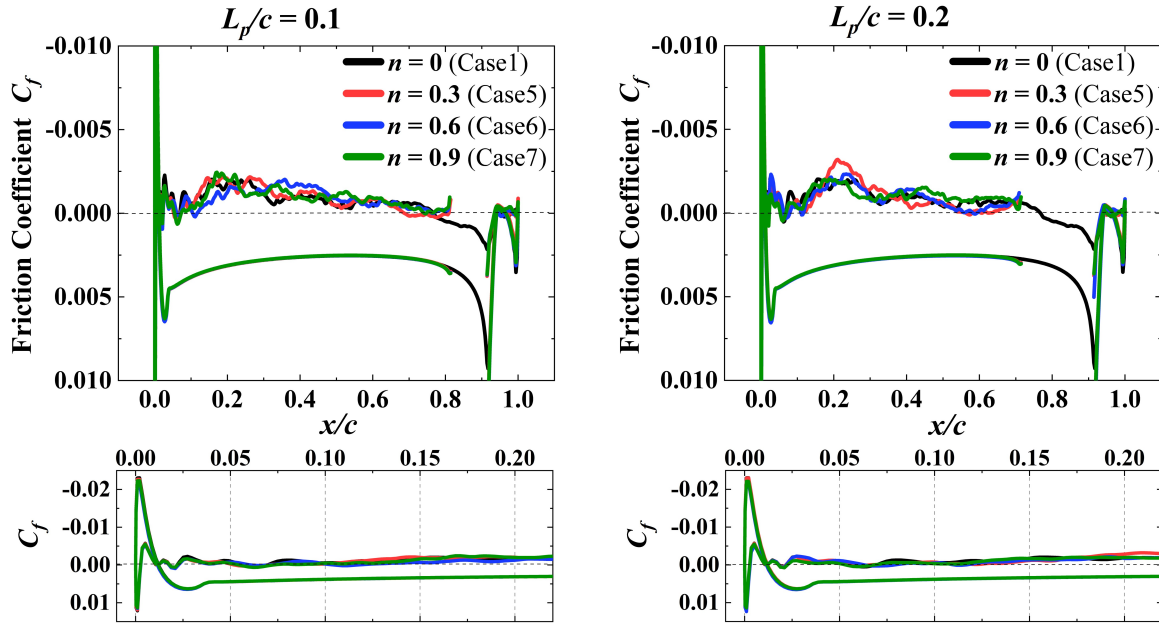


Fig. 18 Distribution of friction coefficient for Cases 1, 5, 6, and 7.

contrast, due to the smaller LSB for $n = 0.3$, the pressure drag is reduced. The smaller LSB for $n = 0.3$ suggests that C_l is not as large as for $n = 0.6$ and 0.9 . However, the decrease in C_d for $n = 0.3$ due to the reductions of friction and pressure drags results in a slight increase in C_l/C_d for $n = 0.3$ with $L_p/c = 0.1$ and 0.2 at a high AoA of 12° .

IV. Conclusions

The flow around airfoils with a porous-medium section has been investigated through the LES framework under low-Reynolds-number conditions. The LES was performed with the code developed for partially porous symmetric and flat airfoils. The main results of this study are as follows.

The size of the LSB varies when the porous medium is installed. As a result, the aerodynamic performance varies, and the variations depend on the internal structure of the porous medium. This study has identified that, for a normal porous medium, the lift and the lift-to-drag ratio decrease more as the length of the porous section increases. However, for the unidirectional porous condition, the flow around the airfoil is not significantly affected by the porous component. The variations in the flow around the airfoil due to the porous medium are mainly caused by the variations in the pressure difference around the porous component. For the normal porous medium, the pressure difference decreases significantly. However, the pressure difference is large in the case of the unidirectional porous medium. A lower porosity for the unidirectional porous component significantly reduces the size of the LSB. As a result, with a low-porosity porous medium, the lift-to-drag ratio increases at a high AoA .

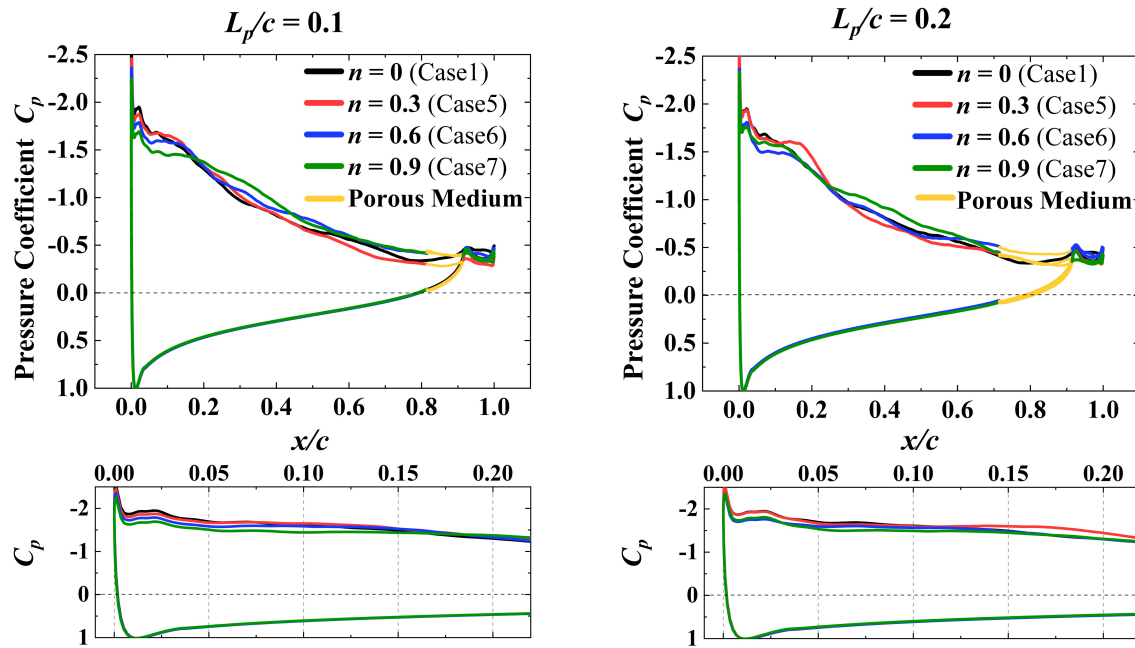


Fig. 19 Distribution of pressure coefficient for Cases 1, 5, 6, and 7.

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