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DNS study of turbulent pipe flow with imposed radial rotation

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(Received xx; revised xx; accepted xx)

1. Introduction

2. The numerical dataset

3. Flow organisation

4. Conclusions

Appendix A.

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Abstract must not spill onto p.2

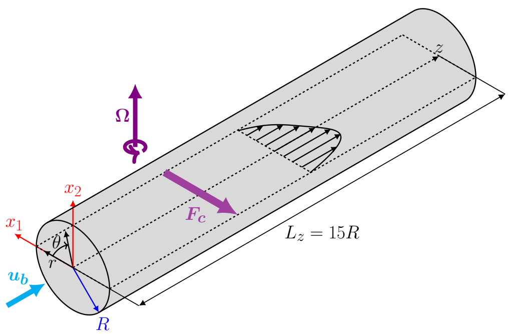

Figure 1: Definition of coordinate system for DNS of rotating pipe flow. z, r, θ are the axial, radial and azimuthal coordinates, respectively. R is the pipe radius, L_z the pipe length, and u_b is the bulk velocity. $\boldsymbol{\Omega}$ is the angular velocity, and $\mathbf{F}_c$ is the resultant mean Coriolis force. The Cartesian coordinates x_1, x_2 define positions in the cross-stream plane.

Re_b	Re_τ	N	$N_z \times N_r \times N_\theta$	$\lambda \times 10^{-2}$	Line
17000	508	0.0078125	$769 \times 97 \times 769$	2.862	-
17000	512	0.015625	$769 \times 97 \times 769$	2.942	-
17000	523	0.03125	$769 \times 97 \times 769$	3.030	
17000	538	0.0625	$769 \times 97 \times 769$	3.212	
17000	566	0.125	$769 \times 97 \times 769$	3.553	
17000	610	0.25	$769 \times 97 \times 769$	4.120	
17000	642	0.375	$769 \times 97 \times 769$	4.576	
17000	669	0.5	$769 \times 97 \times 769$	4.962	
17000	748	1.0	$769 \times 97 \times 769$	6.208	
17000	856	2.0	$769 \times 97 \times 769$	8.117	
44000	1405	0.5	$1793 \times 165 \times 1793$	3.262	-
82500	2379	0.5	$3073 \times 244 \times 3073$	2.662	-
133000	3634	0.5	$4609 \times 328 \times 4609$	2.389	

Table 1: Flow parameters for DNS of rotating pipe flow. The bulk Reynolds number defined as $Re_b = 2Ru_b/\nu$, with R the pipe radius, u_b the bulk velocity and ν the fluid kinematic viscosity. $N = \Omega R/u_b$ is the rotation number and $N_\tau = \Omega R/u_\tau^*$ is the friction rotation number with the global frcition velocity. N_z, N_r, N_θ are respectively the number of grid points in the axial, radial and azimuthal direction. The global friction factor is $\lambda = 8\tau_w^*/\rho u_b^2$, with τ_w^* the azimuthally averaged mean wall shear stress and ρ the fluid density. $Re_\tau = Ru_\tau^*/\nu$ is the friction Reynolds number, with $u_\tau^* = \sqrt{(\tau_w^*/\rho)}$ the mean friction velocity.

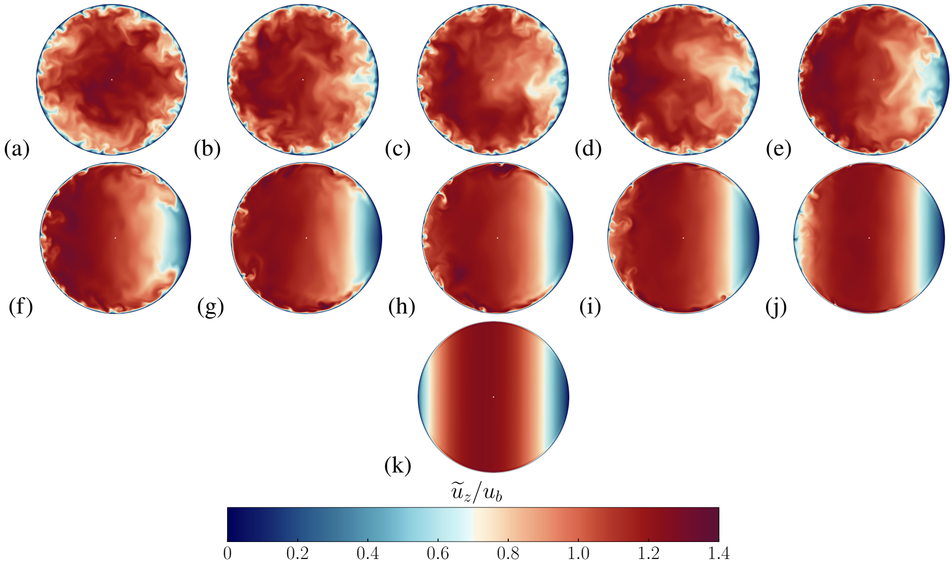

Figure 2: Instantaneous axial velocity contours at Re_b = 17000 in the cross-stream plane. Contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The pressure side of the pipe is on the left, and the suction side is on the right of each sub-panel. Various rotation numbers are considered: (a) N = 0.0, (b) N = 0.0.078125, (c) N = 0.015625, (d) N = 0.0315, (e) N = 0.0625, (f) N = 0.125 (g) N = 0.25, (h) N = 0.375, (i) N = 0.5, (j) N = 1.0, (k) N = 2.0.

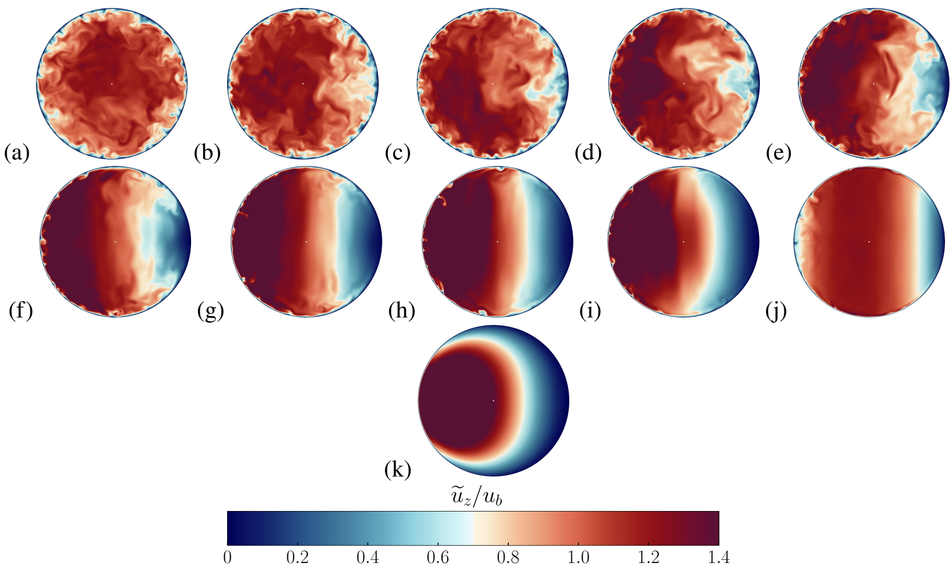

Figure 3: Instantaneous temperature contours at Re_b = 17000 in the cross-stream plane. Contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The pressure side of the pipe is on the left, and the suction side is on the right of each sub-panel. Various rotation numbers are considered: (a) N = 0.0, (b) N = 0.0.078125, (c) N = 0.015625, (d) N = 0.0315, (e) N = 0.0625, (f) N = 0.125 (g) N = 0.25, (h) N = 0.375, (i) N = 0.5, (j) N = 1.0, (k) N = 2.0.

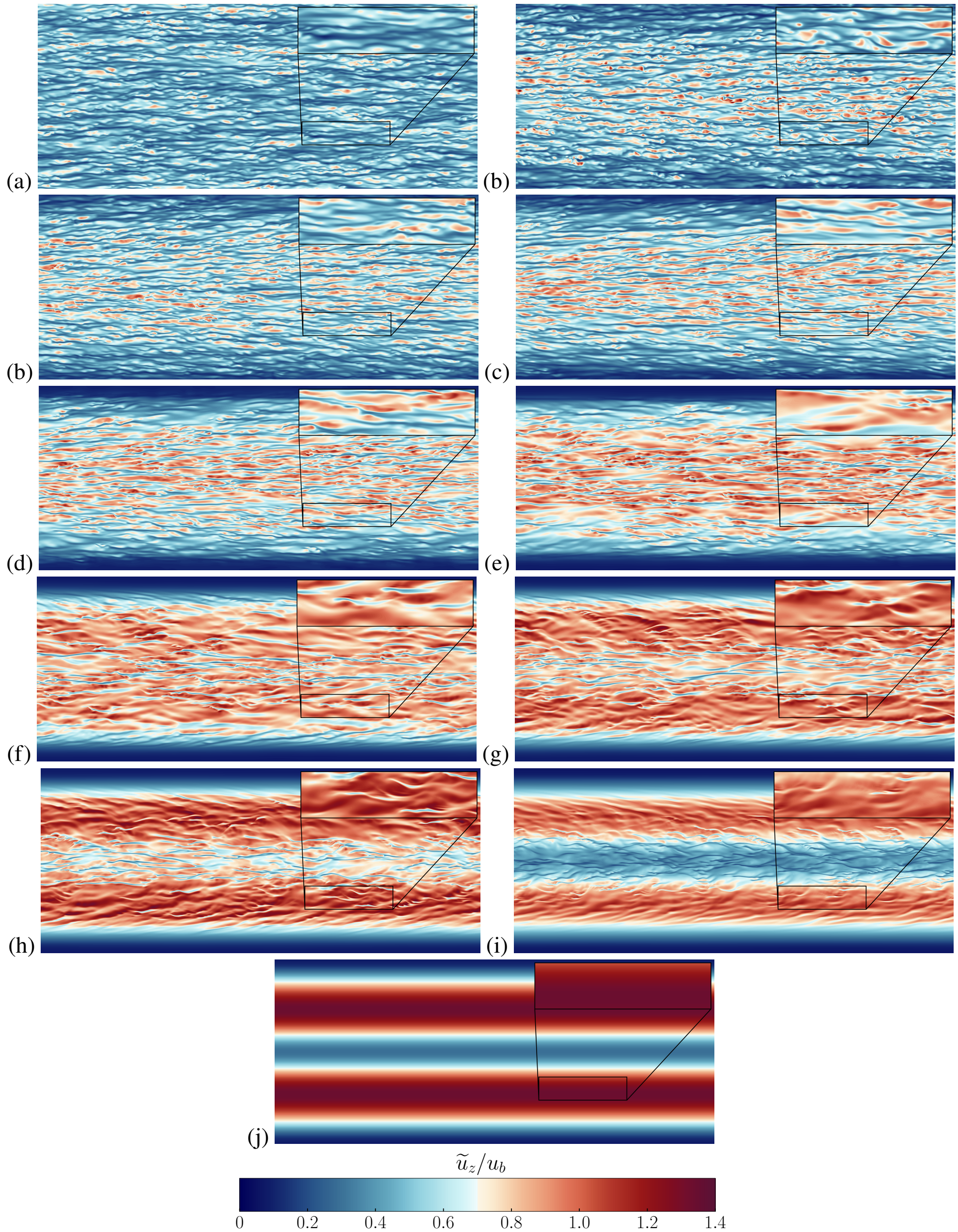

Figure 4: Instantaneous axial velocity (u_z/u_b) contours at Re_b = 17000 in an unrolled cylindrical shell at a distance y^* = 15 from the wall (evaluated in the non-rotating case). Contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The insets in the top-right corner of each panel report magnified views of a small portion of the shell. Various rotation numbers are considered: (a) N = 0.0, (b) N = 0.078125, (c) N = 0.015625, (d) N = 0.0315, (e) N = 0.0625, (f) N = 0.125, (g) N = 0.1875, (h) N = 0.25, (i) N = 0.5, (j) N = 2.0.

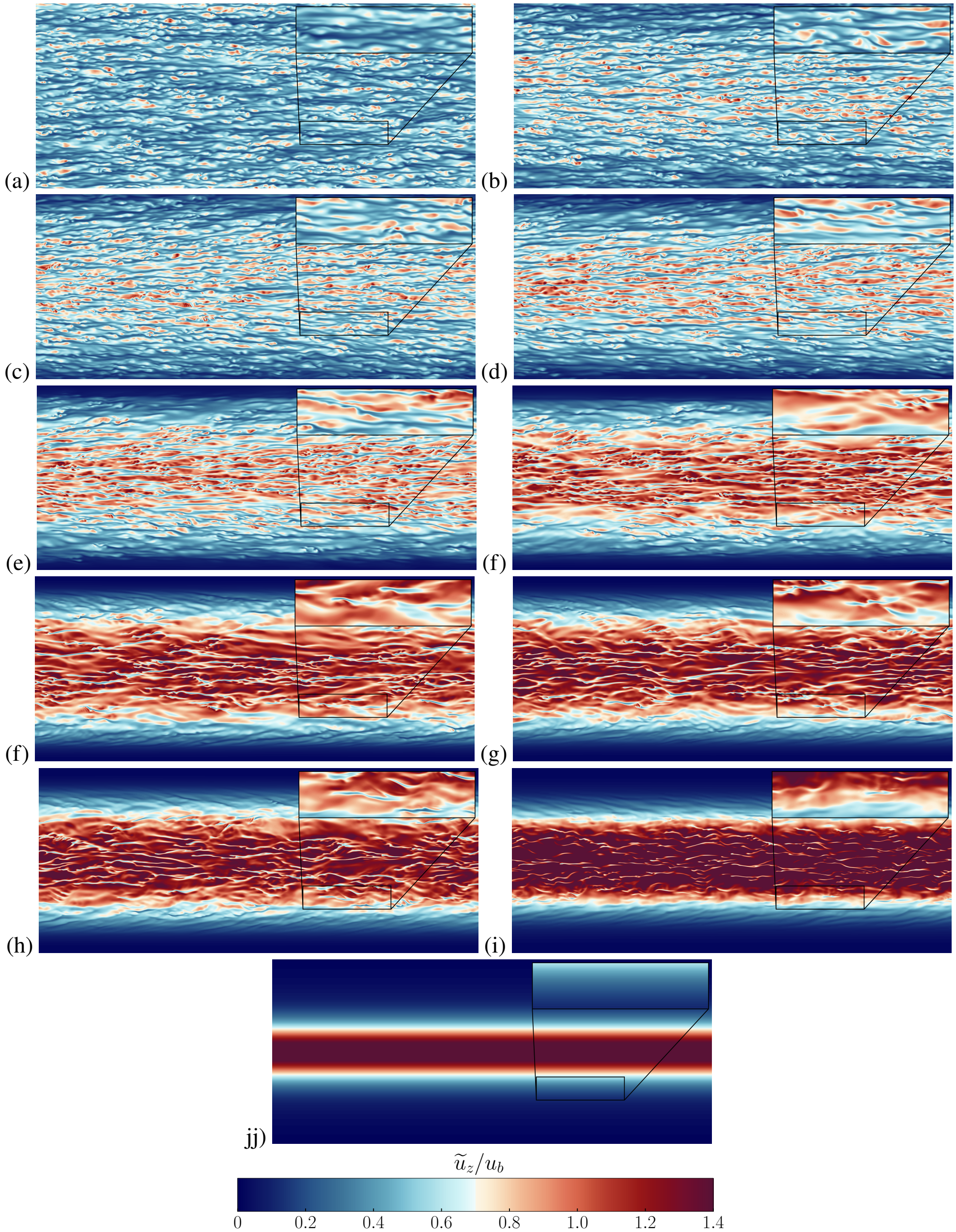

Figure 5: Instantaneous temperature (t_z/t_b) at $Re_b = 17000$ in an unrolled cylindrical shell at a distance $y^* = 15$ from the wall (evaluated in the non-rotating case). Contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The insets in the top-right corner of each panel report magnified views of a small portion of the shell. Various rotation numbers are considered: (a) $N = 0.0$, (b) $N = 0.078125$, (c) $N = 0.015625$, (d) $N = 0.0315$, (e) $N = 0.0625$, (f) $N = 0.125$, (g) $N = 0.1875$, (h) $N = 0.25$, (i) $N = 0.5$, (j) $N = 2.0$.

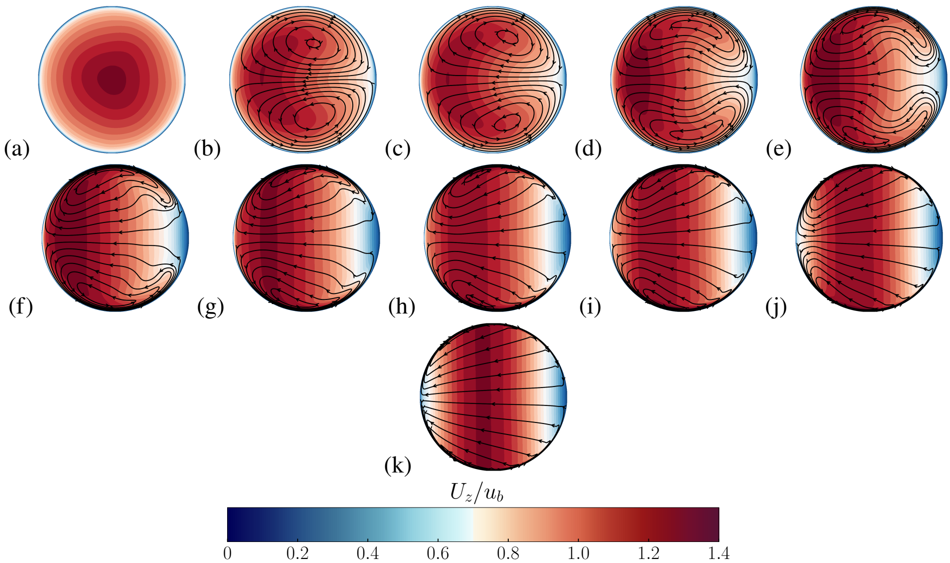

Figure 6: Mean axial velocity contours with superposed cross-flow streamlines, at Re_b = 17000. Twenty-four contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The pressure side of the pipe is on the left, and the suction side is on the right of each sub-panel. Various rotation numbers are considered: (a) $N = 0.0$, (b) $N = 0.0.078125$, (c) $N = 0.015625$, (d) $N = 0.0315$, (e) $N = 0.0625$, (f) $N = 0.125$ (g) $N = 0.25$, (h) $N = 0.375$, (i) $N = 0.5$, (j) $N = 1.0$, (k) $N = 2.0$.

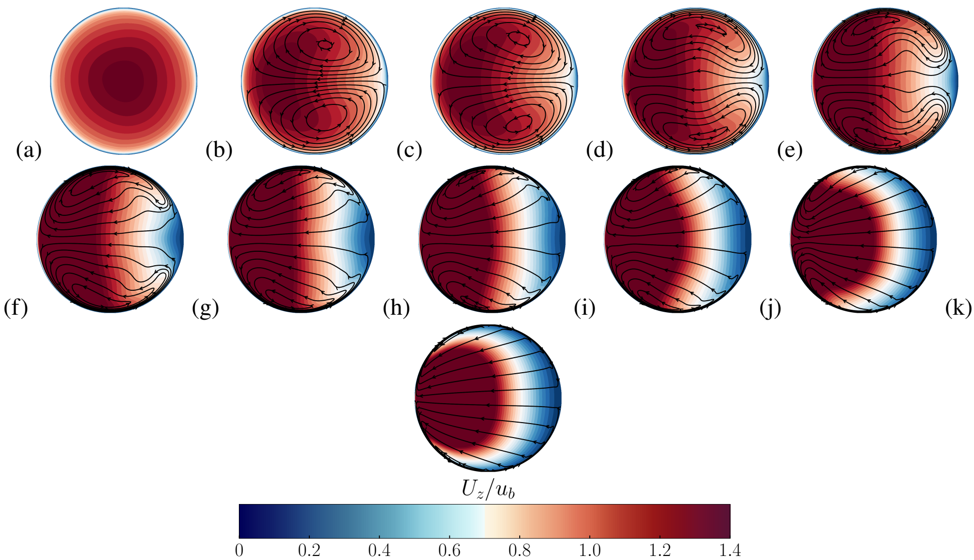

Figure 7: Mean temperature contours with superposed cross-flow streamlines, at Re_b = 17000. Twenty-four contour levels ranging from 0 to 1.4 are shown, in colour scale from blue to red. The pressure side of the pipe is on the left, and the suction side is on the right of each sub-panel. Various rotation numbers are considered: (a) $N = 0.0$, (b) $N = 0.0.078125$, (c) $N = 0.015625$, (d) $N = 0.0315$, (e) $N = 0.0625$, (f) $N = 0.125$ (g) $N = 0.25$, (h) $N = 0.375$, (i) $N = 0.5$, (j) $N = 1.0$, (k) $N = 2.0$.

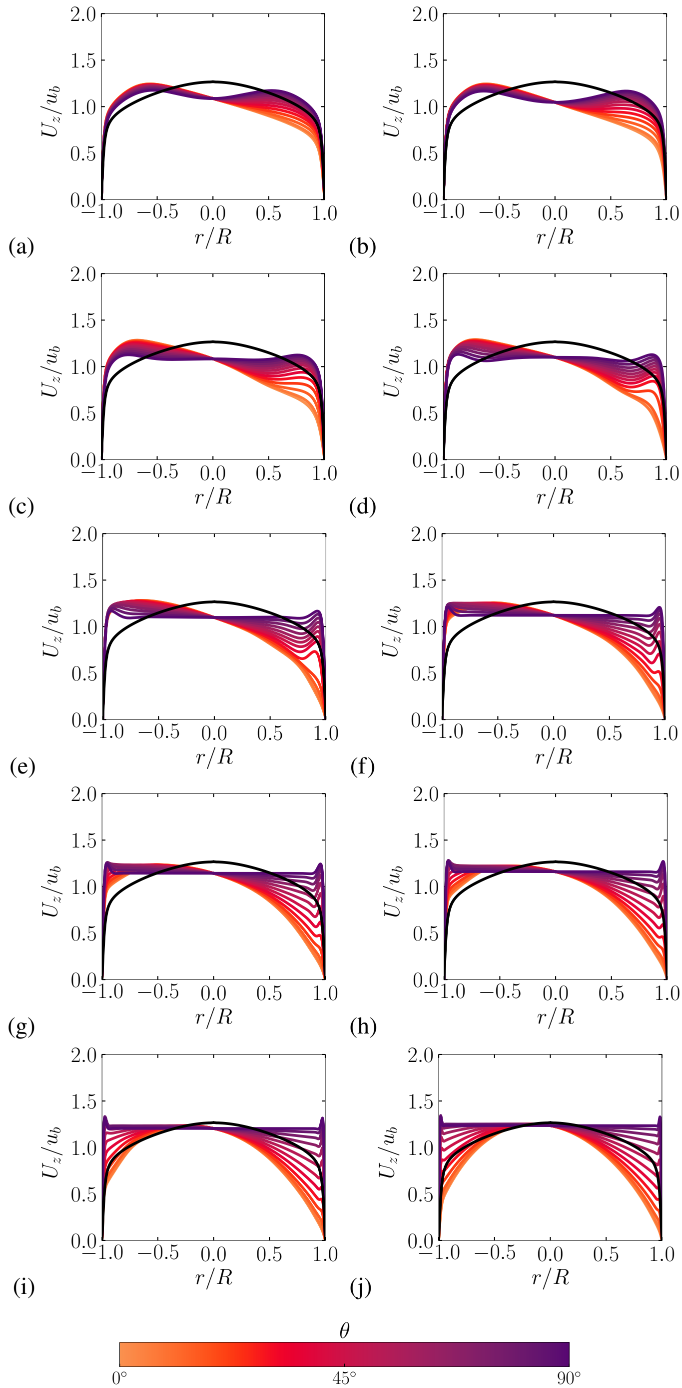

Figure 8: Radial profiles of outer-scaled axial velocity at various azimuthal positions, for flow cases at $Re_b = 17000$. Only the interval $\theta = [0°, 90°]$ is shown, at stations spaced 7.5° apart, with negative values of r signifying profiles taken at $\theta + 180°$. (a) $N = 0.0.078125$, (b) $N = 0.015625$, (c) $N = 0.0315$, (d) $N = 0.0625$, (e) $N = 0.125$ (f) $N = 0.25$, (g) $N = 0.375$, (h) $N = 0.5$, (i) $N = 1.0$, (j) $N = 2.0$. The black solid line denotes the mean axial velocity profile in the non-rotating case.

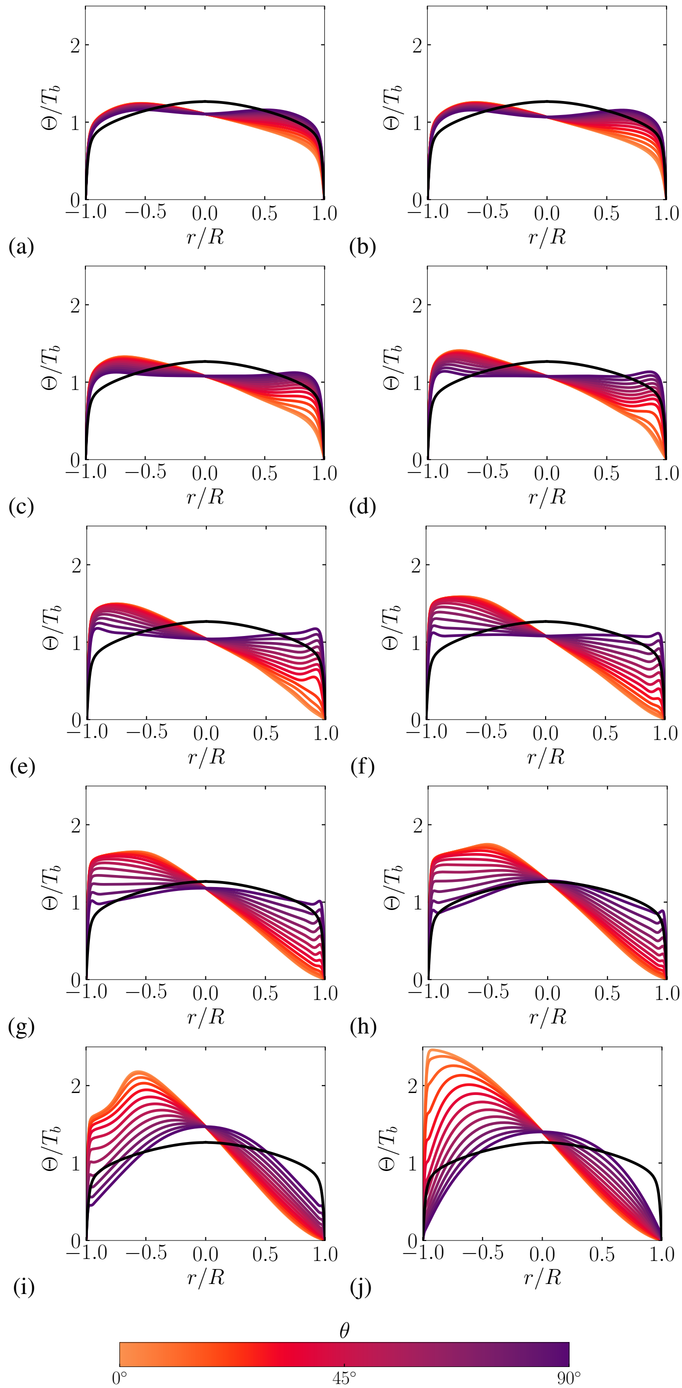

Figure 9: Radial profiles of outer-scaled temperature at various azimuthal positions, for flow cases at Re_b = 17000. Only the interval $\theta = [0°, 90°]$ is shown, at stations spaced 7.5° apart, with negative values of r signifying profiles taken at $\theta + 180°$. (a) N = 0.0.078125, (b) N = 0.015625, (c) N = 0.0315, (d) N = 0.0625, (e) N = 0.125 (f) N = 0.25, (g) N = 0.375, (h) N = 0.5, (i) N = 1.0, (j) N = 2.0. The black solid line denotes the mean axial velocity profile in the non-rotating case.

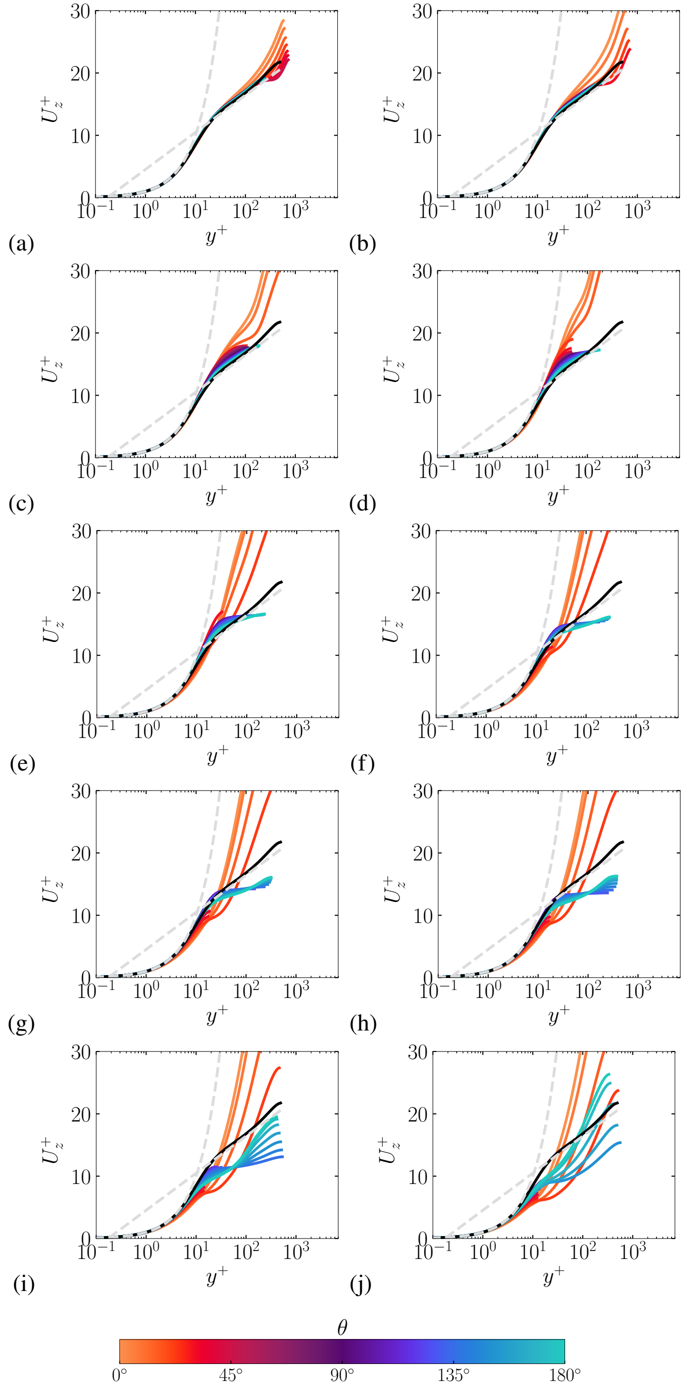

Figure 10: Wall-normal profiles of inner-scaled axial velocity, at various azimuthal positions spaced 7.5° apart, for flow cases at $Re_b = 17000$. Only the interval $\theta = [0°, 180°]$ is shown. (a) $N = 0.0.078125$, (b) $N = 0.015625$, (c) $N = 0.0315$, (d) $N = 0.0625$, (e) $N = 0.125$ (f) $N = 0.25$, (g) $N = 0.375$, (h) $N = 0.5$, (i) $N = 1.0$, (j) $N = 2.0$. The black solid line denotes the mean axial velocity profile in the non-rotating case. The dashed gray lines depict the compound law-of-the wall $U^+ = y^+$, $U^+ = \log y^+/0.387 + 4.53$.

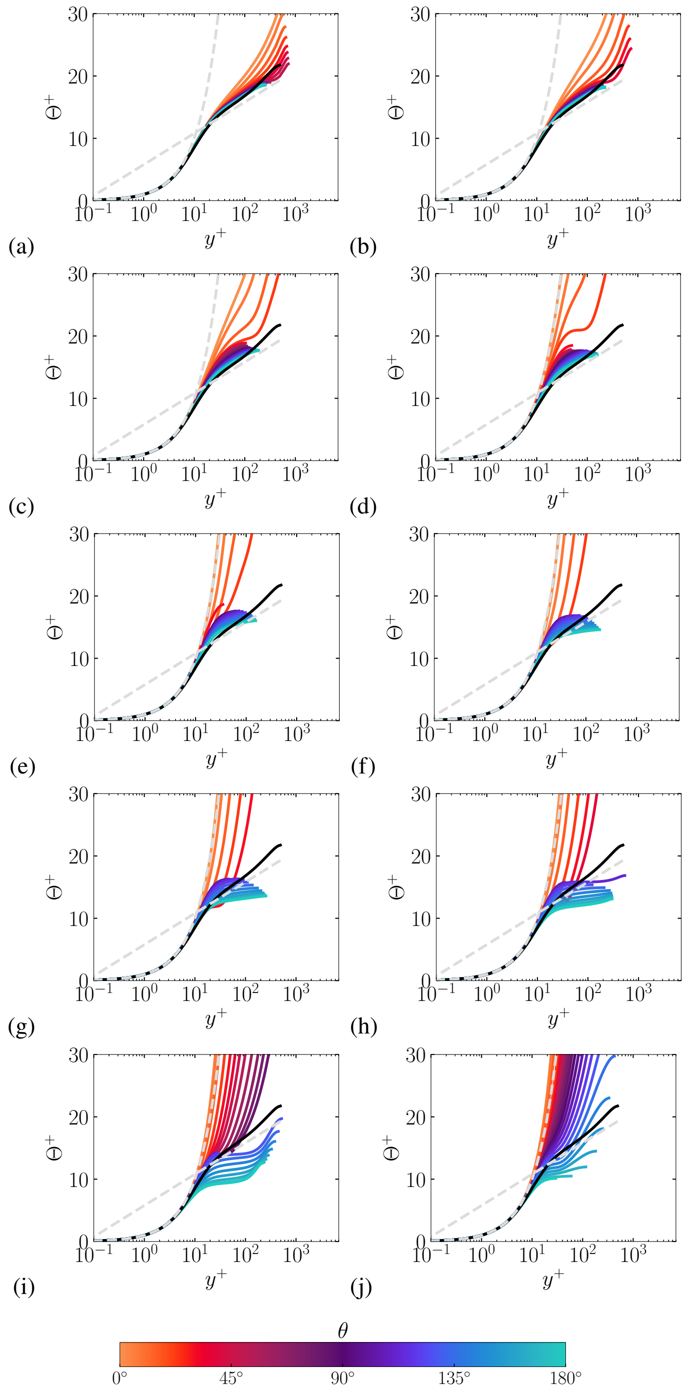

Figure 11: Wall-normal profiles of inner-scaled temperature, at various azimuthal positions spaced 7.5° apart, for flow cases at $Re_b = 17000$. Only the interval $\theta = [0°, 180°]$ is shown. (a) $N = 0.0.078125$, (b) $N = 0.015625$, (c) $N = 0.0315$, (d) $N = 0.0625$, (e) $N = 0.125$ (f) $N = 0.25$, (g) $N = 0.375$, (h) $N = 0.5$, (i) $N = 1.0$, (j) $N = 2.0$. The black solid line denotes the mean temperature profile in the non-rotating case. The dashed gray lines depict the compound law-of-the wall $\theta^+ = y^+$, $\theta^+ = \log y^+/0.387 + 4.53$.

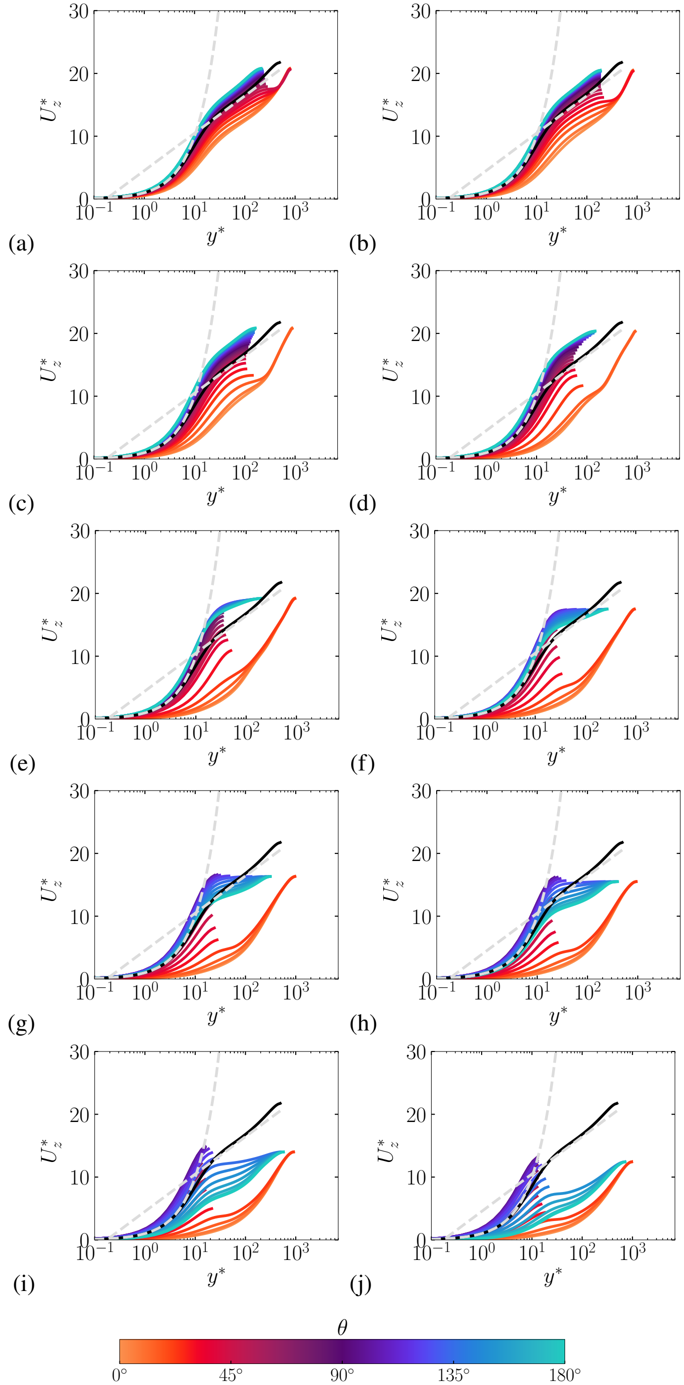

Figure 12: Wall-normal profiles of outer-scaled axial velocity, at various azimuthal positions spaced 7.5° apart, for flow cases at Re_b = 17000. Only the interval $\theta = [0°, 180°]$ is shown. (a) N = 0.0.078125, (b) N = 0.015625, (c) N = 0.0315, (d) N = 0.0625, (e) N = 0.125 (f) N = 0.25, (g) N = 0.375, (h) N = 0.5, (i) N = 1.0, (j) N = 2.0. The black solid line denotes the mean axial velocity profile in the non-rotating case. The dashed gray lines depict the compound law-of-the wall $U^+ = y^+$, $U^+ = \log y^+/0.387 + 4.53$.

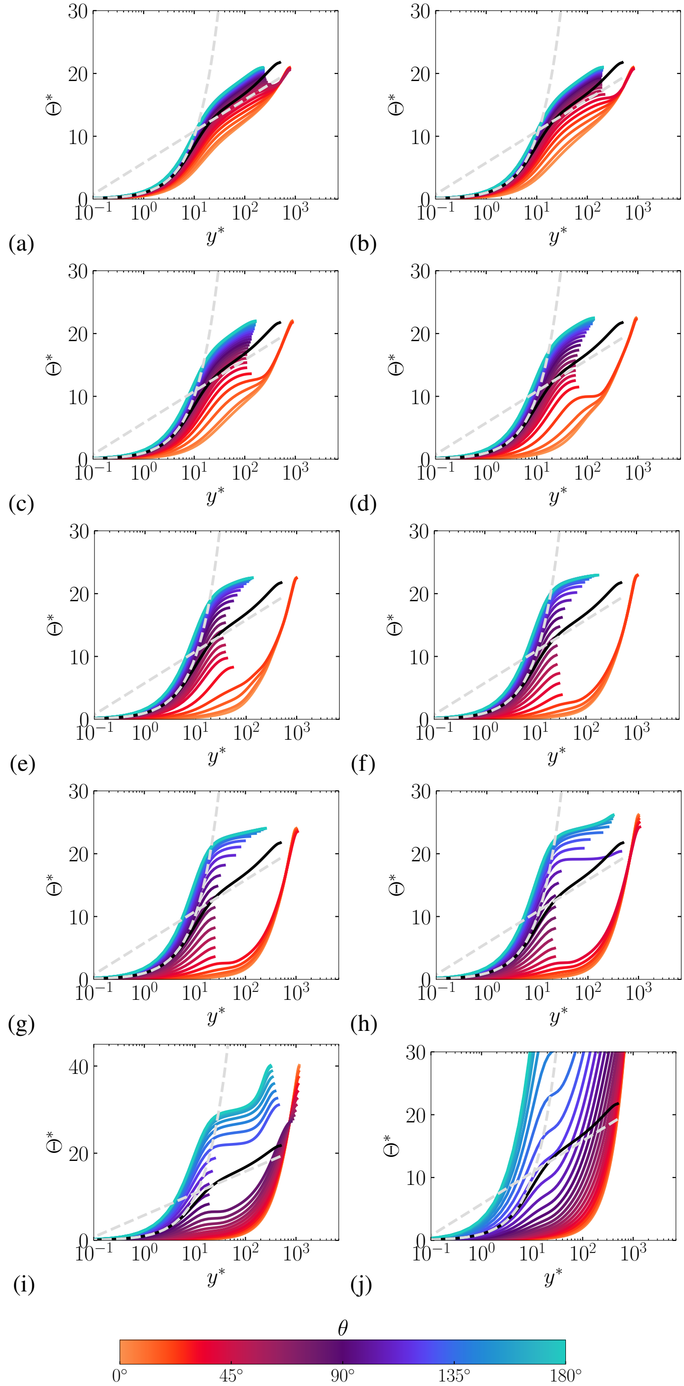

Figure 13: Wall-normal profiles of outer-scaled temperature, at various azimuthal positions spaced 7.5° apart, for flow cases at $Re_b = 17000$. Only the interval $\theta = [0°, 180°]$ is shown. (a) $N = 0.0.078125$, (b) $N = 0.015625$, (c) $N = 0.0315$, (d) $N = 0.0625$, (e) $N = 0.125$ (f) $N = 0.25$, (g) $N = 0.375$, (h) $N = 0.5$, (i) $N = 1.0$, (j) $N = 2.0$. The black solid line denotes the mean temperature profile in the non-rotating case. The dashed gray lines depict the compound law-of-the wall $\theta^+ = y^+$, $\theta^+ = \log y^+/0.387 + 4.53$.

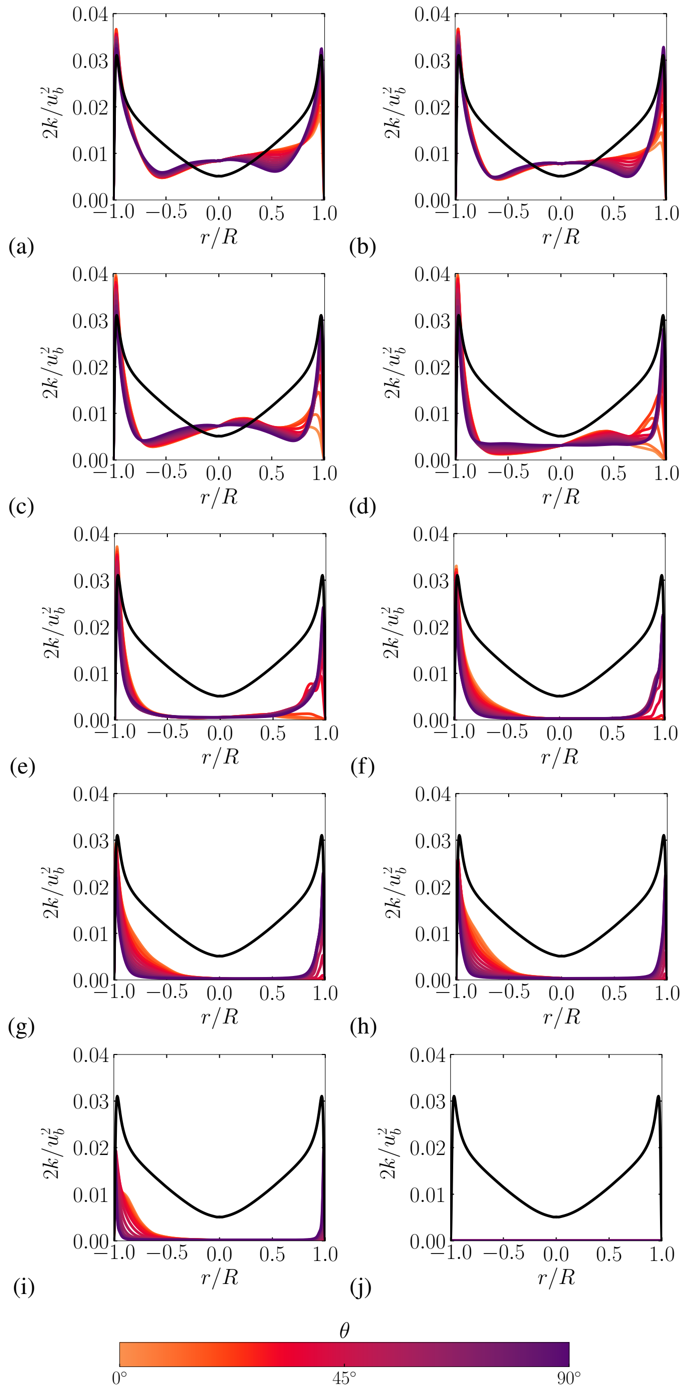

Figure 14: Radial profiles of outer-scaled turbulence kinetic energy at various azimuthal positions, for flow cases at Re_b = 17000. Only the interval $\theta = [0°, 90°]$ is shown, at stations spaced 7.5° apart, with negative values of r signifying profiles taken at $\theta + 180°$. (a) $N = 0.03125$, (b) $N = 0.5$, (c) $N = 2.0$, (d) $N = 8.0$. (e) $N = 0.1$, (f) $N = 0.5$, (g) $N = 2.0$, (h) $N = 16.0$. The black solid line denotes the mean turbulence kinetic energy profile in the non-rotating case.

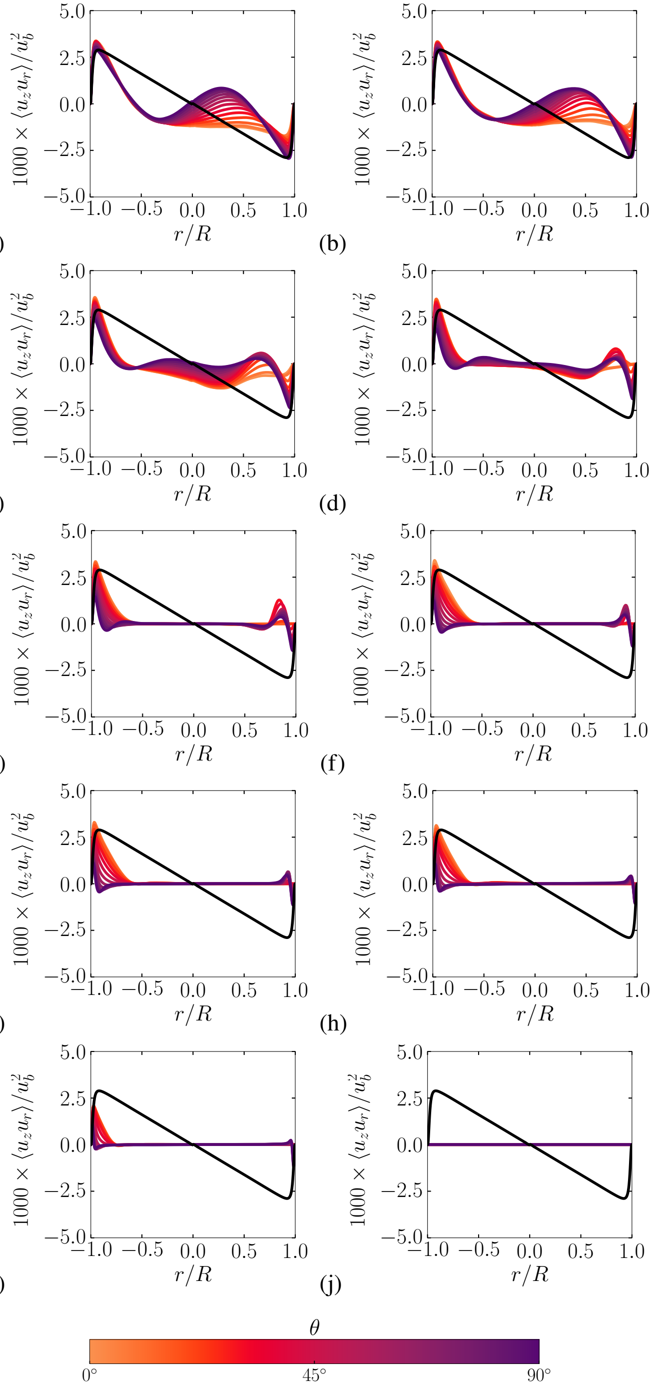

Figure 15: Radial profiles of outer-scaled Reynolds shear stress at various azimuthal positions, for flow cases at $Re_b = 17000$. Only the interval $\theta = [0°, 90°]$ is shown, at stations spaced 7.5° apart, with negative values of r signifying profiles taken at $\theta + 180°$. (a) $N = 0.03125$, (b) $N = 0.5$, (c) $N = 2.0$, (d) $N = 8.0$. (e) $N = 0.1$, (f) $N = 0.5$, (g) $N = 2.0$, (h) $N = 16.0$. The black solid line denotes the Reynolds shear stress profile in the non-rotating case.