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Reynolds number effects on the coherent dynamics of the turbulent horseshoe vortex system. (English) Zbl 1295.76013

Flow Turbul. Combust. 86, No. 2, 231-262 (2011).

Summary: The adverse pressure gradient induced by a surface-mounted obstacle in a turbulent boundary layer causes the approaching flow to separate and form a dynamically rich horseshoe vortex system (HSV) in the junction of the obstacle with the wall. The Reynolds number of the flow (Re) is one of the important parameters that control the rich coherent dynamics of the vortex, which are known to give rise to low-frequency, bimodal fluctuations of the velocity field (*W. J. Devenport* and *R. L. Simpson* [J. Fluid Mech. 210, 23–55 (1990)]; *J. Paik* et al. [Phys. Fluids 19, No. 4, 045107, 20 p. (2007; Zbl 1146.76499)]). We carry out detached eddy simulations (DES) of the flow past a circular cylinder mounted on a rectangular channel for $Re = 2.0 \times 10^4$ and 3.9×10^4 [*B. Dargahi*, Exp. in Fluids 8, 1–12 (1989)] in order to systematically investigate the effect of the Reynolds number on the HSV dynamics. The computed results are compared with each other and with previous experimental and computational results for a related junction flow at a much higher Reynolds number ($Re = 1.15 \times 10^5$) [Devenport and Simpson (loc. cit.); Paik et al.,(loc. cit.)]. The computed results reveal significant variations with Re in terms of the mean-flow quantities, turbulence statistics, and the coherent dynamics of the turbulent HSV. For $Re = 2.0 \times 10^4$ the HSV system consists of a large number of necklace-type vortices that are shed periodically at higher frequencies than those observed in the $Re = 3.9 \times 10^4$ case. For this latter case the number of large-scale vortical structures that comprise the instantaneous HSV system is reduced significantly and the flow dynamics becomes quasi-periodic. For both cases, we show that the instantaneous flowfields are dominated by eruptions of wall-generated vorticity associated with the growth of hairpin vortices that wrap around and disorganize the primary HSV system. The intensity and frequency of these eruptions, however, appears to diminish rapidly with decreasing Re. In the high Re case the HSV system consists of a single, highly energetic, large-scale necklace vortex that is aperiodically disorganized by the growth of the hairpin mode. Regardless of the Re, we find pockets in the junction region within which the histograms of velocity fluctuations are bimodal as has also been observed in several previous experimental studies.

MSC:

76F65 Direct numerical and large eddy simulation of turbulence
76F40 Turbulent boundary layers

Keywords:

coherent structures; horseshoe vortex; detached-eddy simulations; Reynolds number effects; junction flows

Full Text: DOI

References:

[1] Agui, J.H., Andreopoulos, J.: Experimental investigation of a three dimensional boundary layer flow in the vicinity of an upright wall mounted cylinder. J. Fluids Eng. 114, 566–576 (1992) · doi:10.1115/1.2910069

[2] Allen, J.J., Naitoh, T.: Scaling and instability of a junction vortex. J. Fluid Mech. 574, 1–23 (2007) · Zbl 1108.76301 · doi:10.1017/S0022112006003879

[3] Apsley, D.D., Leschziner, M.A.: Investigation of advanced turbulence models for the flow in a generic wing-body junction. Flow Turbul. Combust. 67, 25–55 (2001) · Zbl 1094.76517 · doi:10.1023/A:1013598401276

[4] Baker, C.J.: The turbulent horseshoe vortex. J. Wind Eng. Ind. Aerodyn. 6, 9–23 (1980) · doi:10.1016/0167-6105(80)90018-5

[5] Chen, H.C.: Assessment of a Reynolds stress closure model for appendage hull junction flows. J. Fluids Eng. 117, 557–563 (1995) · doi:10.1115/1.2817301

[6] Chrisohoides, A., Sotiropoulos, F., Sturm, T.W.: Coherent structures in flat-bed abutment flow: computational fluid dynamics simulations and experiments. J. Hydraul. Eng. 129, 177–186 (2003) · doi:10.1061/(ASCE)0733-9429(2003)129:3(177)

[7] Dargahi, B.: The turbulent flow field around a circular cylinder. Exp. Fluids 8, 1–12 (1989) · doi:10.1007/BF00203058

[8] Devenport, W.J., Simpson, R.L.: Time-dependent and time-averaged turbulence structure near the nose of a wing-body junction. J. Fluid Mech. 210, 23–55 (1990) · doi:10.1017/S0022112090001215

[9] Doligalski, T.L., Smith, C.R., Walker, J.D.A.: Vortex interactions with walls. Annu. Rev. Fluid Mech. 26, 573–616 (1994) · Zbl 0808.76023 · doi:10.1146/annurev.fl.26.010194.003041

[10] Hunt, J.C.R., Wray, A.A., Moin, P.: Eddies, stream, and convergence zones in turbulent flows. In: Proceedings of the Summer Program. Center for Turbulence Research, pp. 193–208. NASA Ames/Stanford University (1988)

[11] Hussein, H., Martinuzzi, R.: Energy balance for turbulent flow around a surface mounted cube placed in a channel. Phys. Fluids 8, 764–780 (1996) · doi:10.1063/1.868860

[12] Kalitzin, G., Medic, G., Iaccarino, G., Durbin, P.: Near-wall behavior of RANS turbulence models and implications for wall functions. J. Comput. Phys. 204, 265–291 (2005) · Zbl 1143.76459 · doi:10.1016/j.jcp.2004.10.018

[13] Kirkil, G., Constantinescu, S.G., Ettema, R.: Coherent structures in the flow field around a circular cylinder with scour hole. J. Hydraul. Eng. 134, 572–587 (2008) · doi:10.1061/(ASCE)0733-9429(2008)134:5(572)

[14] Krajnović, S., Davidson, L.: Large-eddy simulation of the flow around a bluff body. AIAA J. 40, 927–936 (2002) · doi:10.2514/2.1729

[15] Martinuzzi, R., Tropea, C.: The flow around surface-mounted, prismatic obstacles placed in a fully developed channel J. Fluids Eng. 115, 85–92 (1993) · doi:10.1115/1.2910118

[16] Paik, J., Sotiropoulos, F.: Coherent structure dynamics upstream of a long rectangular block at the side of a large aspect ratio channel. Phys. Fluids 17, 115104 (2005) · Zbl 1188.76118 · doi:10.1063/1.2130743

[17] Paik, J., Sotiropoulos, F., Sale, M.J.: Numerical simulation of swirling flow in complex hydroturbine draft tube using unsteady statistical turbulence models. J. Hydraul. Eng. 131, 441–456 (2005) · doi:10.1061/(ASCE)0733-9429(2005)131:6(441)

[18] Paik, J., Escauriaza, C., Sotiropoulos, F.: On the bimodal dynamics of the turbulent horseshoe vortex system in a wing-body junction. Phys. Fluids 19, 045107 (2007) · Zbl 1146.76499 · doi:10.1063/1.2716813

[19] Rodi, W.: Comparison of LES and RANS calculations of the flow around bluff bodies. J. Wind Eng. Ind. Aerodyn. 69–71, 55–75 (1997) · doi:10.1016/S0167-6105(97)00147-5

[20] Rodi, W., Ferziger, J., Breuer, M., Pourquié, M.: Status of large eddy simulation: results of a workshop. J. Fluids Eng. 119, 248–262 (1997) · doi:10.1115/1.2819128

[21] Roulund, A., Sumer, B.M., Fredsøe, J., Michelsen, J.: Numerical and experimental investigation of flow and scour around a circular pile. J. Fluid Mech. 534, 351–401 (2005) · Zbl 1134.76370 · doi:10.1017/S0022112005004507

[22] Seal, C.V., Smith, C.R., Rockwell, D.: Dynamics of the vorticity distribution in endwall junctions. AIAA J. 35, 1041–1047 (1997) · doi:10.2514/2.192

[23] Seal, C.V., Smith, C.R.: Visualization of a mechanism for three-dimensional interaction and near-wall eruption. J. Fluid Mech. 394, 193–203 (1999) · Zbl 0944.76521 · doi:10.1017/S0022112099005571

[24] Shur, M., Spalart, P.R., Strelets, M., Travin, A.: Detached-eddy simulation of an airfoil at high angle of attack. In: Rodi, W., Laurence, D. (eds.) Turbulent Shear Flows, pp. 669–678. Elsevier, Amsterdam (1999)

[25] Simpson, R.L.: Junction flows. Annu. Rev. Fluid Mech. 33, 415–443 (2001) · Zbl 0988.76025 · doi:10.1146/annurev.fluid.33.1.415

[26] Sotiropoulos, F., Abdallah, S.: The discrete continuity equation in primitive variable solutions of incompressible flow. J. Comput. Phys. 95, 212–227 (1991) · Zbl 0725.76058 · doi:10.1016/0021-9991(91)90260-R

[27] Sotiropoulos, F., Constantinescu, G.: Pressure-based residual smoothing operators for multistage pseudocompressibility algorithms. J. Comput. Phys. 133, 129–145 (1997) · Zbl 0883.76062 · doi:10.1006/jcph.1997.5662

[28] Spalart, P.R., Allmaras, S.R.: A one-equation turbulence model for aerodynamic flows. Rech. Aerosp. 1, 5–21 (1994)

[29] Spalart, P.R., Jou, W.H., Strelets, M., Allmaras, S.R.: Comments on the feasibility of LES for wings and on a hybrid RANS/LES approach. In: Liu, C., Liu, Z. (eds.) Advances in DNS/LES. Greyden Press, Columbus (1997)

[30] Tang, H.S., Jones, S.C., Sotiropoulos, F.: An overset grid method for 3D unsteady incompressible flows. J. Comput. Phys. 191, 567–600 (2003) · Zbl 1134.76435 · doi:10.1016/S0021-9991(03)00331-0

[31] Tseng, M., Yen, C., Song, C.C.S.: Computation of three-dimensional flow around square and circular piers. Int. J. Numer. Methods Fluids 34, 207–227 (2000) · Zbl 0994.76056 · doi:10.1002/1097-0363(20001015)34:3<207::AID-FLD31>3.0.CO;2-R