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# TIME-DEPENDENT INSTABILITIES IN FLOWS OF VISCOUS AND VISCOELASTIC FLUIDS IN CURVED DUCTS OF SQUARE CROSS-SECTION

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Since the early work of Dean [1,2], flows in curved ducts have been of great interest because of their wide applications in chemical, mechanical and biological engineering. The complexity of the flow in curved ducts lays on the secondary flow, transverse to the main flow. In steady flows, the secondary flow may show multiple patterns, ranging from 1-pair of vortices to multiple-pairs, also called Dean instabilities, and from a symmetric structure to asymmetric [3,4]. Besides, many bifurcation studies [5-7] have shown that multiple solutions may arise, which can be stable or unstable. The complexity of the secondary flow is also increased when unsteady flows are considered [8-10]. In those cases, the time-dependent solutions, in general, undergo a series of transitions between flow regimes going from steady-state to periodic, to multi-periodic and ending in a chaotic state, as the Dean number is increased, thus adding more complexities to the flow. However, most of the unsteady flow studies have only considered viscous incompressible fluids, but for fluids of complex nature, such as viscoelastic fluids, there are significant changes in flow dynamics as has also been observed under steady state flow conditions [11].
The aim of this numerical study is to describe in detail the development of time-dependent instabilities in the three-dimensional developing flow along an 180○ curved duct of square cross-section, for both viscous and viscoelastic incompressible fluids. The duct geometry is the same considered in [3, 4, 11]. The governing equations are numerically solved using a finite-volume method on a collocated mesh arrangement. Non-slip condition at walls and a fully developed velocity profile at the entrance are assumed, and the whole geometrical domain is considered to allow the possible appearance of asymmetries in the flow. The problem is solved for Newtonian viscous fluids and for the viscoelastic FENE-CR fluid model, which describes accurately the behaviour of dilute polymer solutions. Numerical simulations were carried out for different Dean numbers and, in the case of the viscoelastic

fluid, also for different Weissenberg numbers and fluid extensibilities. The development along time of the Dean instabilities is depicted for the different parameters along the curve through flow patterns (velocity fields) and vorticity contours. Velocity and stress profiles are also analysed in both space and time. Our results reveal stationary and time-dependent instabilities when inertia, elasticity and extensibility are increased, and show significant variations in the distributions of stress and velocity together with complex secondary flow patterns.

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## REFERENCES

[1] W.R. Dean, Note on the notion of fluid in a curved pipe, Philosophical Magazine, 4(20): 208-223, 1927

[2] W. R. Dean, The stream-line motion of fluid in a curved pipe, Philosophical Magazine, 5(30): 673-695, 1928.

[3] B. Bara, K. Nandakumar, J.H. Masliyah, An experimental and numerical study of the Dean problem: flow development towards two-dimensional multiple solutions, J. Fluid Mech., 244: 339-376, 1992.

[4] P.A.J. Mees, K. Nandakumar, J.H. Masliyah, Instabilities and transitions of flow in a curved square duct: the development of two pairs of dean vortices, J. Fluid Mech., 314: 227-246, 1996.

[5] Cheng, K.C., Lin, R.C., Ou, J.W., Graetz problem in curved square channels. J. *Heat Transfer*, Vol. **97**, pp. 244–248, 1975.

[6] Winters, K.H., A bifurcation study of laminar flow in a curved tube of rectangular cross-section. *J. Fluid Mech.*, Vol. **180**, pp. 343–369, 1987.

[7] Yanase, S., Kaga, Y., Daikai, R., Laminar flows through a curved rectangular duct over a wide range of the aspect ratio. *Fluid Dyn. Res.*, Vol. **31**, pp. 151–183, 2002.

[8] Yanase, S., Nishiyama, K., On the bifurcation of laminar flows through a curved rectangular tube. *J. Phys. Soc. Japan*, Vol. **57**, pp. 3790–3795, 1988.

[9] Mondala, R.N., Kagab, Y., Hyakutake, T., Yanase, S., Bifurcation diagram for two-dimensional steady flow and unsteady solutions in a curved square duct. *Fluid Dynamics Research*, Vol. **39**, pp. 413–446, 2007.

[10] Islama, Md.S., Mondal, R.N., Effects of curvature on unsteady solutions through a curved square duct flow. *Procedia Engineering*, Vol. **56**, pp. 217 – 224, 2013.

[11] Malheiro, J.M., Oliveira, P.J, Pinho, F.T., Parametric study on the three-dimensional distribution of velocity of a FENE-CR fluid flow through a curved channel. Journal of Non-Newtonian Fluid Mechanics, Vol. **200**, pp. 88-102, 2013.