Inertial instability in Newtonian cross-slot flow – A comparison against the viscoelastic bifurcation

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A cross-slot geometry is formed by an “horizontal” planar channel along which two incoming fluid streams are made to impinge on each other, and an intersecting “vertical” channel which carries the outlet flow, with other two streams now moving away from the central section and leaving through the vertical channel ends. A stagnation point is formed right at the geometrical center of the cross-slot, at least under conditions of low inertia.

The flow configuration in a cross-slot device offers some interesting features for non-Newtonian fluid mechanics due to the presence of the internal, standing, stagnation point that enables the development of very high elongational strains when compared to other flow configurations.

One such feature is the formation of bi-refringent strands (Harlen et al [1]), very long narrow regions of concentrated extensional stresses emanating along the outlet arms of the cross-slot, which have been the focus of many studies in the non-Newtonian literature. Another is the tendency for the natural development of an asymmetric flow pattern, even at very low Reynolds numbers, which has been recently discovered, first experimentally with polyacrylamide solutions flowing in micro fabricated devices (Arratia et al 2006 [2]), and then numerically with the simplest of the viscoelastic constitutive equations, the upper convected Maxwell model (UCM, Poole et al. 2007 [3]). At a critical Deborah number the flow bifurcates and forms an antisymmetric flow pattern (symmetry about the diagonal planes), with unequal flow distribution of the incoming streams among the two cross-slot outlet arms. Existence of this flow bifurcation at Re=0, as revealed by numerical simulations, is not conditioned by the singular nature of the extensional behavior of the constitutive equation, since for finite extensibility models the same kind of phenomenon occurs (Rocha et al [4]), neither it is conditioned by the geometric singularity imposed by the four sharp corners, since by rounding the corners the effect remains [4]. In addition, more complex 3D cross-slot geometries exhibit the asymmetry as well, as recently shown in Afonso et al [5].

A natural question one might ask is whether, even for a Newtonian fluid, there will be similar bifurcation and asymmetries at high Reynolds number, when inertial effects start dominating the dynamics of the flow. As far as we are aware such question in the

context of the cross-slot geometry has never posed and has not been explored with help of numerical simulations. That is the purpose of the investigation reported in this talk. We found indeed a transition at a critical Reynolds number of (Re)cr=1500 (based on the average inlet velocity and the channels width), above which the flow becomes asymmetric but the asymmetry being different from the inertialess viscoelastic case. While this shows symmetry about the cross-slot diagonals (y=+x or y=-x), the inertial Newtonian flow is symmetric about the horizontal plane (y=0). For increasing Re, four identical standing recirculating bubbles are formed starting at the 4 corners of the geometry; when Re>(Re)cr, the 2 bubbles on one side (say, x>0) become larger than the 2 bubbles at the other side (x<0). The flow remains steady. The asymmetry found is reminiscent of that occurring in flow through planar expansions (Coanda effect) but occurs at higher Re. A difference compared to the viscoelastic case is that the stagnation point does not stay at the center of the geometry; this is due to the fact that the two larger vortices stay on the same side of the vertical axis.

Another difference found from the results of the present simulations is that the excess pressure drop for the bifurcated flow is larger than the pressure drop for a corresponding totally symmetric situation. In the viscoelastic counterpart at Re=0 the fact that the energy loss was smaller for a bifurcated solution compared to the symmetric solution was used as a justification for “nature” to prefer the former. Here, for a flow with significant inertial contribution (Re above about 1500), with a Newtonian fluid, we have the opposite scenario, thus implying that the previous argument was not credible as an explanation for the cross-slot viscoelastic bifurcation (in fact, this was pointed out by a referee in one of our papers).

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