Buoyancy-driven instability in plumes

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The instability dynamics of plumes are a result of buoyancy- and shear-related mechanisms acting simultaneously [1, 2]. We investigate the interplay between these two in various settings, and we describe how buoyancy leads to the growth of axisymmetric and helical perturbations. A linear stability analysis of a forced round plume (with nonzero momentum at the inlet) is performed for $Pr = 1$, $Re = 100$ and $Ri = 1$ for various azimuthal modes m, and regions of absolute/convective instability in the flow are mapped out. Only the helical mode m = 1 is observed to transition to absolute instability under the Boussinesq assumption, owing to buoyancy effects that interact constructively with the common shear instability. This dominance of the helical mode is found to persist throughout the self-similar flow region, for a very large range of Grashof and Prandtl numbers. Figure 1a shows perturbation streamlines over temperature perturbation contours for a helical instability mode, and figure 1b displays corresponding contours of vertical velocity. The positive feedback mechanism resulting from buoyant acceleration and temperature convection can be inferred.

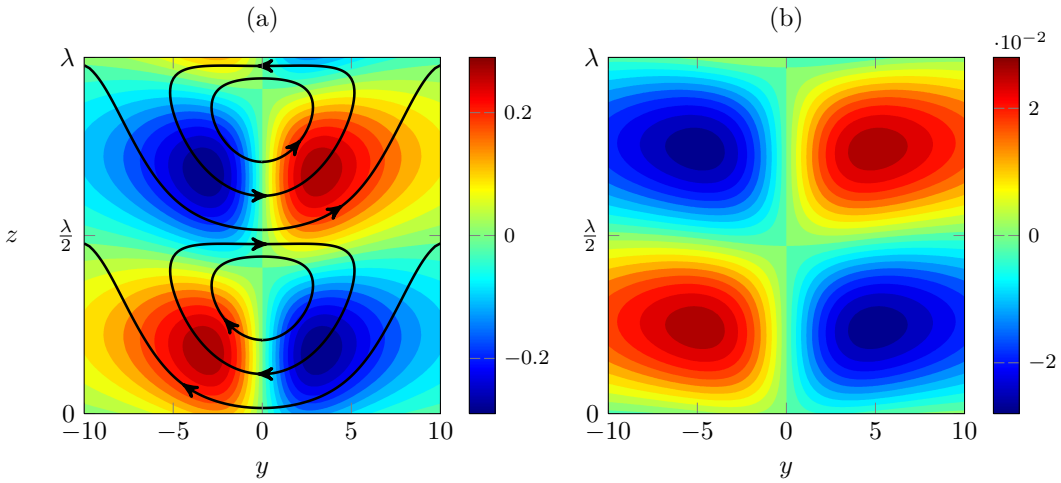

Fig. 1: Helical $m = 1$ eigenmode for parameters $Pr = 1$, $Gr = 5$ and $k = 0.01$. All quantities are shown in a Cartesian plane, with the centerline of the plume at $y = 0$. a) Perturbation isotherms and perturbation streamlines; b) perturbation axial velocity.

In a non-Boussinesq situation, however, the dynamics seem to be different. It is established experimentally [3] and numerically [4, 5] that Helium jets injected into air and strongly heated jets with small momentum at the inlet exhibit axisymmetric puffing. This axisymmetric puffing behaviour has been attributed to a baroclinic torque, which is absent in the Boussinesq approximation. The importance of the baroclinic torque for plume instability is currently under investigation.

References

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