Abstract

This thesis presents a comprehensive direct numerical simulation (DNS) study of three-dimensional transitions in the wake of an infinitely long heated square cylinder, modeled using a spanwise periodic computational domain, subjected to uniform cross-flow of air (Prandtl number, $Pr = 0.7$) in the presence of thermal buoyancy. A non-Oberbeck–Boussinesq (NOB) compressible flow model is employed to account for variations in thermophysical and transport properties under large-scale heating conditions. To solve the governing compressible flow equations, a variant of the flux-based Particle Velocity Upwind-Modified (PVU-M+) scheme is utilized, employing finite difference techniques. A low Mach number of $M = 0.1$ is used to minimize pressure compressibility effects. The amount of heating is controlled by the overheat ratio, expressed as $\varepsilon = (T_w - T_\infty)/T_\infty$, where T_w is the wall temperature and T_∞ is the free-stream temperature.

At a Reynolds number of $Re = 250$, the heated wake exhibits multiple three-dimensional instability modes as heating increases. These modes are characterized by changes in the number of streamwise vortex pairs and the associated spanwise wavelength λ_z/L, where L denotes the side length of the square cylinder. As the heating level increases, the shorter wavelength structure Mode-B ($\lambda_z/L \sim 1.2$), observed in the unheated cylinder wake, transitions to longer wavelength structures: Mode-E ($\lambda_z/L \sim 2$) and Mode-D ($\lambda_z/L \sim 3$). The emergence and suppression of vortex dislocations are closely associated with the heating intensity, thereby influencing the unsteady force characteristics and frequency spectra.

A detailed analysis at $Re = 180$ highlights the role of baroclinic vorticity production and thermophysical property variations in wake behavior. The chaotic wake associated with Mode-A instability in the unheated case transitions into a two-dimensional wake at low heating levels ($\varepsilon = 0.2$), followed by the emergence of periodic and quasi-periodic three-dimensional wakes as the heating level increases. The streamwise baroclinic vorticity production term (Γ_x) is identified as a key contributor to the generation of streamwise vorticity (Ω_x), while the spanwise term (Γ_z) plays an indirect role in redistributing rotational energy among other vorticity components, thereby modulating vortex shedding strength and frequency.

At $Re = 300$, the effect of free-stream orientation on the wake dynamics of the heated cylinder is investigated. Under aiding buoyancy, increasing heat input results in the suppression of vortex shedding and the development of steady or quasi-steady plume-like structures. In contrast, cross-buoyancy induces more complex and asymmetric wake behavior characterized by sustained vortex shedding. The imbalance between positively and negatively signed baroclinic term Γ_z introduces asymmetry in the wake, contributing to negative (downward) lift generation and an earlier onset of vortex shedding. The competing influences of the baroclinic terms Γ_x and Γ_z govern the degree of wake three-dimensionality, exhibiting distinct mechanisms across buoyancy configurations. Under aiding buoyancy, Γ_z suppresses vortex shedding and consequently weakens three-dimensionality. Conversely, in the cross-buoyancy case, the stronger Γ_x enhances the Ω_x, promoting increased three-dimensionality despite the presence of suppressive effects from Γ_z.

Finally, the evolution of wake instability modes is examined for a heated cylinder in cross-flow configuration under large-scale heating ($\varepsilon = 1.0$) across a Reynolds number range of $Re = 50$ to 300. A critical Reynolds number of $Re_{cr} = 113$ is identified for the onset of three-dimensional flow. Four distinct instability modes (such as Mode-D, Mode-E, Mode-D*, and Mode-D*) are observed, each corresponding to a specific Reynolds number range. These mode transitions are characterized by both gradual and abrupt variations in the Strouhal number–Reynolds number (St-Re) relationship. Vortex dislocations are found to significantly influence the wake structure and associated hydrodynamic forces. Additionally, the study establishes that a periodic spanwise domain length of $H_z = 6L$ is sufficient to resolve all relevant wake features with both qualitative and quantitative accuracy.