EFFECTS OF WAKE CONFINEMENT AND BUOYANCY ON FLOW TRANSITIONS AND HEAT TRANSFER FOR A SQUARE CYLINDER

Abstract

Fluid flow and heat transfer from a bluff body is a fundamental problem of academic interest and has vast practical applications, such as, flow past buildings, offshore structures, cooling of electronics equipment, heat exchangers, etc. The lives and performances of these structures and devices depend on the flow dynamics and heat transfer characteristics near their surfaces. The most common bluff bodies encountered in practical applications have a square or circular cross-section. In particular, a bluff body with a square cross-section possesses interesting flow characteristics due to the presence of sharp corners. It involves flow separation at the trailing and leading edges with the formation of von-Kármán vortices, three-dimensional transitions with the formations of Mode A and Mode B vortices with an increase in Reynolds number. The flow is highly influenced by nearby objects, such as, a wall and external forces, such as, buoyancy. When a square cylinder is placed near a stationary wall, the flow is affected by the confinement of the wake due to the presence of the wall, and interactions of the shear-layers formed near the cylinder with the boundary-layer formed on the stationary wall. The resultant flow is quite complex, and in order to reduce the number of parameters so that the influence of each parameter can be observed clearly the conventional boundary-layer on the wall has to be removed. It can be accomplished by replacing the stationary wall with a moving wall. With the absence of the wall boundary-layer, the flow is relatively simple, and it can be studied thoroughly. Therefore, in the present thesis the flow past a square cylinder approaching a moving wall is considered.

First, a study on the effects of wake confinement and buoyancy on the onset/suppression of vortex shedding and heat transfer is carried out for a two-dimensional flow past a square cylinder placed near a moving wall. In contrast to the case of a stationary wall, the vortex shedding in the present case is observed even for quite low values of the gap ratio ($G/D = 0.1$). The critical value of Re for the suppression of the vortex shedding first decreases and then increases with an increase in the value of G/D. The influence of buoyancy on the vortex shedding for the given configuration is examined for $0.1 \leq G/D \leq 1$ and for $-1 \leq Ri \leq 1$, where the buoyancy effects are introduced by heating or cooling the cylinder. Unlike the case of a stationary wall, dual roles of buoyancy have been observed. It acts as a stabilizing mechanism

at low gap ratios while it destabilizes the flow at large gap ratios. Interesting results are obtained for $G/D \approx 0.5$, where the onset of vortex shedding is observed both for positive buoyancy (heated cylinder) as well as negative buoyancy (cooled cylinder). It is observed that the response of buoyancy is similar for a square cylinder and its circumscribed circular cylinder. Temperature contours and Nusselt number for different values of G/D, Re, and Ri are presented. The Nusselt number increases for a positive buoyancy ($Ri > 0$) and decreases for a negative buoyancy ($Ri < 0$) at all the surfaces of the square cylinder except at the rear surface. The time-averaged drag coefficient increases with Ri and the time-averaged lift coefficient decreases with Ri except for $G/D = 0.1$.

Three-dimensional flow past a square cylinder placed near a moving wall is then studied, where the effects of the gap-ratio on three-dimensional wake transitions are examined using Direct Numerical Simulations (DNS). The value of G/D is varied from 0.1 to 4.0. Three different values of $Re = 160$, 180 and 200 are considered, which are slightly less than the critical Re for different flow transitions corresponding to a free-stream flow past a square cylinder. A suppression of the vortex dislocations is observed in the presence of the moving wall. With a decrease in G/D, the transition from one flow regime to another takes place at lower values of Re compared to a free-stream flow. At $Re = 160$, with a decrease in G/D, an onset of three-dimensionality in the flow with the formation of Mode A vortices takes place due to an acceleration of the flow in the gap. At $G/D = 0.4$, the streamwise vortices of the wavelength $2.5D$, called Mode S, appear in the flow. These vortices show period doubling phenomenon. For $G/D \leq 0.3$, three-dimensionality in the flow occurs due to the interaction of the shear-layers formed near the cylinder and moving wall. At low values of G/D, an initial transition occurs from a two-dimensional steady-state to a three-dimensional steady-state. Variations in Nusselt number with G/D and Re in the spanwise direction and along the surfaces of the cylinder have been studied. Variation in the global Nusselt number on the cylinder surfaces with G/D can be divided in three parts. For $G/D \geq 0.5$, Nu increases with a decrease in G/D and is maximum at $G/D \approx 0.5$. For $0.5 \leq G/D \leq 0.3$, it decreases with G/D and is minimum at $G/D \approx 0.3$. For $G/D \leq 0.3$, it again increases with a decrease in G/D. With an increase in Re, the drag coefficient increases and decreases at high and low values of G/D, respectively.

Further, simulations are also carried out to study the three-dimensional wake transitions for a rectangular cylinder near a moving wall at the gap ratio $G/D = 0.4$, 0.5 and 1.0 for $0.5 \leq AR$ (aspect ratio, width/height of cylinder) ≤ 2.0 at a constant value of $Re = 160$ using DNS and the linear stability analysis. Mode A vortices for all G/D values, Mode B

for G/D = 0.4 and Mode C for G/D = 0.4 and 0.5 are observed for different values of AR. A change in the flow rate near the cylinder and shear-layer interactions are identified as the causes of the wake transitions. Interaction of shear-layers is a dominant factor for low values of G/D and high values of AR. For low values of the gap-ratio, the transition is supercritical and the flow is non-hysteretic and with an increase in the gap-ratio the tendency of the flow to become hysteretic increases. Similarly, for low values of the aspect ratio the tendency of the flow to be non-hysteretic is large and it decreases with an increase in the aspect ratio. For G/D = 0.5, the three-dimensionality first decreases for $AR \leq 1.25$ and then increases with AR. The flows are periodic at low values of AR and become quasi-periodic at high values of AR. The wavenumber of the unstable mode has been obtained using Floquet analysis and is quite close to the DNS results.

In the last part of the study, flow past a square cylinder near a moving wall is investigated for $0.1 \leq G/D \leq 1.0$ at a constant Reynolds number of 22000 using large eddy simulations. Unlike the case of a stationary wall, no ground vortex is formed in the present case. It is observed that for $G/D \leq 0.3$, a regular Kármán vortex shedding from the cylinder gets suppressed which causes a large change in the flow dynamics. For $G/D = 1.0$, turbulence is strong in the near wake region and for low G/D values (≤ 0.3) it gets weaker and shifts downstream. With a decrease in G/D, an early reattachment of the lower shear-layer with the bottom surface of the cylinder occurs while the upper shear-layer is deflected, and K-H instability occurs away from the top surface. The so-called ‘extreme events’ which contain high-frequency fluctuations are observed for $G/D = 1.0$ and these disappear for low G/D values. Large coherent structures are observed for high values of G/D (≥ 0.5) while for low values of G/D uniformly distributed small structures are formed. Evolution of enstrophy has been examined for $G/D = 0.1$ and the role of the strain-rate tensor in the enstrophy production has been investigated. The lift coefficients are negative for all G/D values while the drag coefficients decrease with a decrement in G/D and are nearly constant for $G/D \leq 0.3$. Unlike the case of a laminar flow, Nusselt number on the cylinder surface monotonically decreases with a decrease in G/D.