

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

SARTAJ TANWEER



**DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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SQUARE CYLINDER**

by

SARTAJ TANWEER

Department of Applied Mechanics

Submitted

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Certificate

This is to certify that the thesis entitled “**Effects of Wake Confinement and Buoyancy on Flow Transitions and Heat Transfer for a Square Cylinder**” being submitted by **Mr. Sartaj Tanweer** is the report of bonafide research work carried by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology Delhi. We further certify that the thesis has attained a standard required for the award of **Doctor of Philosophy** degree of the institute. The research report and the results presented in the thesis have not been submitted, in part or full to any other institute or university for the award of any degree or diploma.

Dr. Anupam Dewan
Professor
Department of Applied Mechanics
Indian Institute of Technology Delhi
Huaz Khas, New Delhi-110016

Date:
Place: New Delhi

Dr. Sanjeev Sanghi
Professor
Department of Applied Mechanics
Indian Institute of Technology Delhi
Huaz Khas, New Delhi-110016

Date:
Place: New Delhi

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(Sartaj Tanweer)

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 .

सार

ब्लफ़-वस्तु से द्रव प्रवाह और उष्मा हस्तांतरण अकादमिक हित की एक मूलभूत समस्या है और इसकी विशाल व्यावहारिक अनुप्रयोग है, जैसे, इमारतों के पास का प्रवाह, अपतटीय संरचनाएं, इलेक्ट्रॉनिक्स उपकरण के ठंडा करने में, हीट एक्सचेंजर्स में, आदि। इन संरचनाओं और उपकरण का जीवन और प्रदर्शन, प्रवाह की गतिशीलता और उनकी सतहों के पास उष्मा हस्तांतरण विशेषताओं पर निर्भर करता है। व्यावहारिक अनुप्रयोगों में सामने आने वाले सबसे आम ब्लफ़-वस्तु बेलनाकार या वर्गाकार अनुप्रस्थ काट का होता है। विशेष रूप से, एक वर्गाकार अनुप्रस्थ वाले ब्लफ़-वस्तु में तीव्र कोनों की उपस्थिति के कारण, दिलचस्प प्रवाह की विशेषताएं होती हैं। इसमें Kármán भ्रमिलो के निर्माण के साथ आगे और पीछे के किनारे पर प्रवाह पृथक्करण, और Reynolds संख्या में वृद्धि के साथ त्रि-आयामी Mode A और Mode B भ्रमिल के गठन शामिल हैं। प्रवाह आस-पास की वस्तुओं, जैसे, एक स्थिर दीवार और बाहरी बल जैसे, उत्प्लावक बल से अत्यधिक प्रभावित होता है। जब एक वर्गाकार बेलन को किसी स्थिर दीवार के पास रखा जाता है, तो दीवार की उपस्थिति के कारण वेक-सीमित, और बेलन के पास बने अपरूपण-स्तर और दीवार पर बने परिसीमा-स्तर के परस्पर क्रिया के कारण प्रवाह प्रभावित होता है। परिणामी प्रवाह काफी जटिल है, और पैरामीटर की संख्या को कम करने के लिए ताकि प्रत्येक पैरामीटर का प्रभाव को स्पष्ट रूप से देखा जा सके, दीवार पर बने परिसीमा-स्तर को हटाना पड़ेगा। यह स्थिर दीवार को गतिशील दीवार से बदलकर पूरा किया जा सकता है। परिसीमा-स्तर की अनुपस्थिति में, प्रवाह अपेक्षाकृत सरल है, और इसका अध्ययन विस्तार से किया जा सकता है। इसलिए, वर्तमान थीसिस में गतिशील दीवार के समीप रखे एक वर्गाकार बेलन के पास प्रवाह का अध्ययन किया गया है।

सबसे पहले, भ्रमिल बहा के शुरुआत/दमन और उष्मा हस्तांतरण पर वेक-सीमित और उत्प्लावकता के प्रभावों का अध्ययन, एक गतिशील दीवार के पास रखे वर्गाकार बेलन के निकट दो-आयामी प्रवाह के लिए, किया गया है। एक स्थिर दीवार के मामले के विपरीत, भ्रमिल वर्तमान मामले में अंतर अनुपात ($G/D = 0.1$) के काफी कम मानों के लिए भी देखा गया है। भ्रमिल बहा के दमन के लिए Re का महत्वपूर्ण मान पहले घटता है और फिर G/D के मान में वृद्धि के साथ बढ़ता है। भ्रमिल बहा पर उत्प्लावकता का प्रभाव दिए गए कॉन्फ़िगरेशन के लिए $0.1 \leq G/D \leq 1$ और $-1 \leq Ri \leq 1$ के लिए जांच की गई है, जहां सिलेंडर को गर्म या ठंडा करके उत्प्लावकता प्रभाव पैदा किया जाता है। स्थिर दीवार के मामले के विपरीत, उत्प्लावकता की दोहरी भूमिका देखी गई है। कम अंतराल अनुपात पर यह एक स्थिर तंत्र के रूप में कार्य करता है, जबकि यह बड़े अंतराल अनुपात में प्रवाह को अस्थिर करता है। $G/D \approx 0.5$ के लिए दिलचस्प परिणाम प्राप्त होते हैं, जहां भ्रमिल बहा की शुरुआत सकारात्मक उत्प्लावकता (गर्म सिलेंडर) और ऋणात्मक उत्प्लावकता (ठंडा सिलेंडर) दोनों के लिए देखी जाती है। यह देखा गया है कि उत्प्लावकता की प्रतिक्रिया एक वर्गाकार बेलन और उसके परिबद्ध वृत्ताकार बेलन के लिए समान होती है। G/D , Re , और Ri के विभिन्न मानों के लिए तापमान रूपरेखा और नुसेल्ट संख्या (Nu) दिखाया गया है। वर्गाकार बेलन की पिछली सतह को छोड़कर सभी सतहों पर, सकारात्मक उत्प्लावकता ($Ri > 0$) के लिए Nu बढ़ जाती है और ऋणात्मक उत्प्लावकता ($Ri < 0$) के लिए घट जाती है। समय-औसत कर्षण गुणांक Re के साथ बढ़ता है और समय-औसत उत्थापन गुणांक, $G/D = 0.1$ को छोड़कर, Re के साथ घटता है।

इसके बाद गतिशील दीवार के पास रखे वर्गाकार बेलन के निकट त्रिविमीय प्रवाह का अध्ययन डायरेक्ट न्यूमेरिकल सिमुलेशन (DNS) द्वारा किया गया है, जहां त्रि-आयामी वेक संक्रमण पर अंतर-अनुपात के प्रभावों की जांच की गई है। G/D का मान 0.1 से 4.0 तक अध्ययन किया गया है। तीन भिन्न $Re = 160, 180$ और 200 लिया गया है, जो मुक्त धारा में रखे वर्गाकार बेलन के निकट विभिन्न प्रवाह संक्रमण के लिए Re के महत्वपूर्ण मान से थोड़े कम हैं। गतिशील दीवार के उपस्थिति में भ्रमिल अव्यवस्थाओं का दमन देखा जाता है। G/D में कमी के साथ, एक प्रवाह व्यवस्था से दूसरे प्रवाह व्यवस्था में संक्रमण मुक्त धारा की तुलना में Re के कम मान पर होता है। $Re = 160$ पर, G/D में कमी के साथ, अंतराल क्षेत्र में प्रवाह के त्वरण के कारण, त्रि-आयामी प्रवाह की शुरुआत Mode A भ्रमिल के गठन के साथ होती है। $G/D = 0.4$ पर, $2.5D$ तरंगदैर्घ्य वाले धारा के अनुसार भ्रमिल, जिसे Mode S कहते हैं, प्रवाह में दिखाई देते हैं। ये भ्रमिल अवधि-दोहरीकरण की घटना दिखाते हैं। $G/D \leq 0.3$ के लिए, प्रवाह में त्रि-आयामीता बेलन और दीवार के निकट बने अपरूपण-स्तरो के बीच परस्पर क्रिया के कारण होती है। G/D के निम्न मान पर, एक प्रारंभिक संक्रमण द्वि-आयामी स्थिर-अवस्था से त्रि-आयामी स्थिर-अवस्था में होता है। बेलन की सतहों पर, G/D और Re के साथ स्पैनवाइज दिशा में नुसेल्ट संख्या में परिवर्तन का अध्ययन किया गया है। सिलेंडर की सतहों पर G/D के साथ ग्लोबल नुसेल्ट संख्या में बदलाव को तीन भागों में विभाजित किया जा सकता है। $G/D \geq 0.5$ के लिए, G/D में कमी के साथ Nu बढ़ता है, और $G/D \approx 0.5$ पर अधिकतम होता है। $0.5 \leq G/D \leq 0.3$ के लिए, यह G/D के साथ घटता है और $G/D \approx 0.3$ पर न्यूनतम होता है। $G/D \leq 0.3$ के लिए, यह G/D में कमी के साथ फिर से बढ़ता है। Re में वृद्धि के साथ, G/D के उच्च और निम्न मानों पर कर्षण गुणांक क्रमशः बढ़ता और घटता है।

इसके अलावा, एक गतिशील दीवार के पास एक आयताकार सिलेंडर के लिए त्रि-आयामी वेक संक्रमण का अध्ययन अंतराल-अनुपात $G/D = 0.4, 0.5$ और 1.0 पर और $0.5 \leq$ पहलू अनुपात (AR) ≤ 2.0 (पहलू अनुपात, सिलेंडर की चौड़ाई/ऊंचाई) पर $Re = 160$ के लिए DNS और रैखिक स्थिरता विश्लेषण द्वारा किया गया है। Mode A भ्रमिल सभी G/D मानों के लिए, Mode B भ्रमिल $G/D = 0.4$ के लिए, और Mode C भ्रमिल $G/D = 0.4$ और 0.5 के लिए, AR के विभिन्न मानों के लिए पाये गए हैं। सिलेंडर के पास प्रवाह दर में परिवर्तन और अपरूपण-स्तरो के बीच परस्पर क्रिया को वेक संक्रमण के कारणों के रूप में पहचाना गया है। G/D के निम्न मानों और AR के उच्च मानों के लिए अपरूपण-परतों के बीच परस्पर क्रिया एक प्रमुख कारक है। G/D के निम्न मानों के लिए, संक्रमण अति-क्रिटिकल है और प्रवाह गैर-हिस्टेरेटिक है, और अंतराल-अनुपात में वृद्धि के साथ प्रवाह की हिस्टेरेटिक बनने की प्रवृत्ति बढ़ जाता है। इसी प्रकार, AR के निम्न मानों के लिए प्रवाह की प्रवृत्ति गैर-हिस्टेरेटिक है, और यह प्रवृत्ति AR में वृद्धि के साथ घटता है। $G/D = 0.5$ के लिए, त्रि-आयामीता पहले $AR \leq 1.25$ के लिए घट जाती है और फिर AR के साथ बढ़ जाती है। प्रवाह AR के कम मानों पर आवधिक और AR के उच्च मानों पर अर्ध-आवधिक बन जाते हैं। फ्लोक्वेट विश्लेषण का उपयोग करके अस्थिर मोड का वेवनंबर प्राप्त किया गया है और यह परिणाम DNS के काफी करीब है।

अध्ययन के अंतिम भाग में, एक गतिशील दीवार के पास एक वर्गाकार बेलन के पीछे प्रवाह की जांच $0.1 \leq G/D \leq 1$ और $Re = 160$ के लिए large eddy सिमुलेशन द्वारा की गई है। एक स्थिर दीवार के मामले के विपरीत, वर्तमान मामले में कोई जमीनी भ्रमिल नहीं बनता है। यह देखा गया है

कि $G/D \leq 0.3$ के लिए, सिलेंडर से निकलने वाला एक नियमित Kármán भ्रमिल का दमन हो जाता, जो प्रवाह की गतिशीलता में बड़े बदलाव का कारण बनता है। $G/D = 1.0$ के लिए, निकट वेक क्षेत्र में विक्षोभ मजबूत होता है और कम G/D मान (≤ 0.3) के लिए यह कमजोर हो जाता है और अनुप्रवाह की ओर शिफ्ट हो जाता है। G/D में कमी के साथ, निचली अपरूपण-स्तर का सिलेंडर की निचली सतह के साथ शीघ्र पुनर्संयोजन हो जाता है, जबकी ऊपरी अपरूपण-स्तर विक्षेपित हो जाती है, और K-H अस्थिरता ऊपरी सतह से दूर होती है। तथाकथित “चरम घटनाएं” जिनमें उच्च आवृत्ति उतार-चढ़ाव शामिल हैं, $G/D = 1.0$ के लिए देखा गया है, तथा G/D के निम्न मान के लिए गायब हो जाता है। $G/D (\geq 0.5)$ के उच्च मान के लिए बड़ी सुसंगत संरचनाएं देखी जाती हैं, जबकि G/D के निम्न मान के लिए समान रूप से वितरित छोटी संरचनाएं बनती हैं। $G/D = 0.1$ के लिए एन्स्ट्रोफी विकास की जांच की गई है, और एन्स्ट्रोफी उत्पादन में तनाव-दर टेंसर की भूमिका की जांच की गई है। उत्पादन गुणांक G/D के सभी मानों के लिए ऋणात्मक हैं, जबकि कर्षण गुणांक G/D में कमी के साथ घटते हैं और $G/D < 0.3$ के लिए लगभग स्थिर होते हैं। पटलीय प्रवाह के मामले के विपरीत, सिलेंडर की सतह पर नुसेल्ट संख्या G/D में कमी के साथ एक ताल से घट जाती है।

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