

**OPENFOAM BASED UNSTEADY SIMULATION OF
HEAT TRANSFER FROM RECTANGULAR CYLINDER
USING PANS AND LES APPROACHES**

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CERTIFICATE

This is to certify that the thesis entitled “**OpenFOAM Based Unsteady Simulation of Heat Transfer from Rectangular Cylinder using PANS and LES Approaches**” being submitted by **Mr. Pritanshu Ranjan** is the report of bonafide research work carried by him under my supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology Delhi. I further certify that the thesis has attained a standard required for the award of **Doctor of Philosophy** degree of the Institute. The research reported 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 other degree or diploma.

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(Pritanshu Ranjan)

ABSTRACT

Fluid flow and heat transfer from bluff bodies has always remained a topic of intense research. Bluff bodies with rectangular shapes often find practical applications in various applications, such as, heat exchangers, electronic cooling, civil and mechanical structures, etc. Heat transfer in such cases is generally due to turbulence. Predicting such kind of flows is difficult on account of various complex characteristics, such as, stagnation, vortex shedding, separation and interaction of separated shear-layers associated with it. In this context, the present study deals with heat transfer from rectangular cylinders under various physical conditions. A variable resolution modeling approach, namely, the Partially-Averaged Navier-Stokes (PANS) approach, and Large Eddy Simulation (LES) are used to model turbulence.

First, a study on the effects of unstructured grid and different wall treatment approaches on flow and thermal behavior from a square cylinder was carried out. The PANS methodology based on the SST $k-\omega$ model was used to solve the governing turbulence equations. An unstructured grid arrangement with tetrahedral elements was used and the results were compared with those obtained using the structured mesh with hexahedral elements. Two types of wall treatment were used, first a wall function model and second a wall resolve approach. It was observed that, there was no effect of the unstructured mesh or grid shape on the flow and heat transfer characteristics from a square cylinder. The wall function model used, was able to predict the flow behavior, but largely under-predicted the heat transfer. With the wall resolve approach both fluid flow and thermal behavior were accurately predicted compared with the experimental data. Hence, the wall resolve technique was used for subsequent studies.

Turbulent flow over rectangular cylinders was then studied using the PANS approach with the wall resolving technique. Rectangular cylinders were characterized based on the ratio of the

length of the streamwise face to the height of the cross-stream face (side ratio, R). Two critical side ratios were obtained from the present study, $R = 0.62$ and 3.0 . At $R = 0.62$, the maximum values of the drag coefficient (C_d), base pressure coefficient and global Nusselt number were attained. At $R = 3.0$ a sharp discontinuous increase of 140% was also observed for Strouhal number and global Nusselt number, due to reattachment of separated flow on the side faces.

Further, simulations were also carried out to study the forced convection from a heated square cylinder placed near a plane wall boundary in a channel. The parameters that were studied are Reynolds number (Re) and the distance between the cylinder and the plane wall (gap ratio). For $Re = 22000$ the critical value of the gap ratio was found to be 0.3 at which the vortex shedding was completely suppressed. The face-averaged value of the Nusselt number for the back face dropped below the front face value for the gap ratio less than 0.5 . The effect of Re was also studied for the gap ratio of 0.4 , and it was observed that up to $Re = 1000$, increase in total Nusselt number from the cylinder was linear, but as the wake became unsteady and turbulent, the Nusselt number increased exponentially with Re .

In the last part, a study of the effect of the free-stream turbulence (FST) was undertaken using LES methodology. Turbulent intensity (I_u) was varied from 0 to 12% of the mean free-stream velocity and the turbulent integral length scale (L_u) was kept constant at $0.75D$. It was observed that the mean pressure coefficient increased with increasing turbulent intensity and the fluctuating pressure decreased. As expected, the heat transfer from the cylinder increased with increasing turbulent intensity at the inlet, but the major changes were only observed at the side faces. At the rear face, due to a reduction in the strength of the vortex street, the heat transfer was not as enhanced as on side faces.

सारांश

ब्लफ बाँड़ी से द्रव प्रवाह और उष्मा स्थानांतरण हमेशा से गहन शोध का विषय बना हुआ है। आयताकार आकृति वाले ब्लफ़ निकायों को अक्सर विभिन्न औद्योगिक अनुप्रयोगों में प्रासंगिकता मिलती है, जैसे हीट एक्सचेंजर्स, इलेक्ट्रॉनिक शीतलन, सिविल और यांत्रिक संरचना आदि। ऐसे मामलों में उष्मा स्थानांतरण आम तौर पर प्रवाह में विक्षोभ के कारण होता है। विभिन्न जटिल विशेषताओं, जैसे कि, गतिहीनता, भ्रमिल अलगन, प्रवाह पृथक्करण, इन पृथक अपरूपण परतों का पारस्परिक संपर्क आदि, के कारण इस तरह के प्रवाह की पूर्वानुमान करना मुश्किल है। इस संदर्भ में, वर्तमान अध्ययन विभिन्न भौतिक स्थितियों के अंतर्गत आयताकार बेलन से उष्मा स्थानांतरण के विषय में है। एक चर संकल्प मॉडलिंग दृष्टिकोण, अर्थात्, पार्शियली एवरेज्ड नॉर्विएर स्टोक्स)PANS दृष्टिकोण और (लार्ज एडी सिम्युलेशन) LES का उपयोग (विक्षोभ को हल करने के लिए किया गया है।

सबसे पहले, असंरचित ग्रिड और विभिन्न वॉल ट्रीटमेंट के प्रभाव का एक वर्ग बेलन से प्रवाह और उष्णीय व्यवहार पर अध्ययन किया गया। विक्षोभिय प्रवाह के समीकरणों को हल करने के लिए SST k- ω मॉडल पर आधारित PANS पद्धति का इस्तेमाल किया गया। टेट्राहेड्रल तत्वों के साथ एक असंरचित ग्रिड व्यवस्था का इस्तेमाल किया गया और इन परिणामों की तुलना हेक्साहेड्रल तत्वों के साथ संरचित ग्रिड के परिणाम से की गई। दो प्रकार के वॉल ट्रीटमेंट का भी उपयोग किया गया, पहले एक वॉल फंक्शन मॉडल और दूसरी वॉल रेसॉल्व दृष्टिकोण। यह देखा गया कि, वर्ग बेलन से प्रवाह और उष्मा स्थानांतरण विशेषताओं पर असंरचित ग्रिड या ग्रिड आकृति का कोई प्रभाव नहीं पड़ा। वॉल फंक्शन मॉडल का उपयोग, प्रवाह व्यवहार का पुर्वानुमान करने में सक्षम था, लेकिन उष्मा स्थानांतरण के पुर्वानुमान में पूरी तरह असक्षम था। प्रयोगात्मक आंकड़ों के मुकाबले वॉल रेसॉल्व दृष्टिकोण, द्रव प्रवाह और उष्णीय व्यवहार दोनों का सटीक रूप से पुर्वानुमान करने में सक्षम था। इसलिए, वॉल रेसॉल्व तकनीक का उपयोग बाद के अध्ययनों के लिए भी किया गया है।

इसके उपरांत आयताकार बेलन पर विक्षोभ प्रवाह का अध्ययन वॉल रेसॉल्व तकनीक के साथ PANS दृष्टिकोण का उपयोग करके किया गया। आयताकार सिलेंडर, प्रवाह की ओर की पृष्ठ की लम्बाई और प्रवाह के लम्बवत पृष्ठ की ऊंचाई के अनुपात (साइड अनुपात, R) पर आधारित है। वर्तमान अध्ययन से $R=0.62$ और 3.0 दो महत्वपूर्ण भुजा अनुपात प्राप्त किए गए। $R=0.62$ पर, कर्षण गुणांक (C_D), आधार दबाव गुणांक और वैश्विक नसेल्ट नंबर के अधिकतम मूल्य प्राप्त किए गए थे। $R=3.0$ पर 140% की एक तेज असंतत वृद्धि स्ट्रॉहल नंबर और नसेल्ट नंबर के लिए देखी गई, जिसका कारण प्रवाह की ओर की पृष्ठ पर पृथक अपरूपण परत के पुनः संयोजन पाया गया।

इसके आगे, एक चैनल में समतल दीवार सीमा के पास स्थित एक गर्म वर्ग सिलेंडर से जबरन संवहन का अध्ययन करने के लिए सिमुलेशन भी किया गया। अध्ययन किए गए मापदण्ड रेनॉल्ड्स नंबर (Re) और सिलेंडर और समतल दीवार (गैप अनुपात) के बीच की दूरी है। $Re = 22000$ के लिए गैप अनुपात का महत्वपूर्ण मान 0.3 पाया गया जिस पर भ्रमिल अलगन पूरी तरह विलुप्त हो गया। गैप अनुपात 0.5 से कम के लिए, वर्ग बेलन के विमुख पृष्ठ का सतह-औसत नसेल्ट नंबर का मूल्य सम्मुख पृष्ठ के सतह-औसत नसेल्ट नंबर के मूल्य से नीचे गिर गया। Re के प्रभाव का अध्ययन 0.4 के गैप अनुपात के लिए भी किया गया, और यह देखा गया कि $Re=1000$ तक, बेलन से कुल नसेल्ट नंबर में वृद्धि रैखिक होती है, लेकिन जब प्रक्षिप्त हवा अस्थिर और विक्षोभित हो जाती है तब नसेल्ट नंबर में वृद्धि घातांकी रूप से होती है Re के साथ।

आखिरी भाग में, फ्री-स्ट्रीम विक्षोभ (FST) के प्रभाव का अध्ययन LES पद्धति का उपयोग करके किया गया है। विक्षोभिय तीव्रता (I_u), औसत मुक्त-धारा वेग का 0 से 12% के बीच बदला गया और विक्षोभिय समाकलित लंबाई पैमाने (L_u) $0.75D$ पर स्थिर रखा गया। यह देखा गया कि औसत दबाव गुणांक बढ़ती विक्षोभिय तीव्रता के साथ बढ़ता है और प्रत्यावर्ती दबाव में कमी आई है। उम्मीद के मुताबिक, सिलेंडर से उष्मा स्थानांतरण बढ़ती विक्षोभिय तीव्रता के साथ बढ़ता है, लेकिन बड़े बदलाव केवल प्रवाह की ओर की पृष्ठ पर ही देखे गए। विमुख पृष्ठ पर भ्रमिल मार्ग की ताकत में कमी के कारण उष्मा स्थानांतरण उतना नहीं बढ़ा जितना की प्रवाह की ओर की पृष्ठ पर बढ़ा।

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