COMPUTATIONAL INVESTIGATION OF FLOW AND HEAT TRANSFER CHARACTERISTICS OF TURBULENT SLOT JET IMPINGEMENT ON A HEATED PLATE USING LES AND RANS MODELLING

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CERTIFICATE

This is to certify that the thesis entitled **"Computational Investigation of Flow and Heat Transfer Characteristics of Turbulent Slot Jet Impingement on a Heated Plate using LES and RANS Modelling"** being submitted by **Mr. Anuj Kumar Shukla** is the report of bonafide research work carried out by him under my supervision. This thesis has been prepared in conformity with the rules and regulations on 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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ABSTRACT

Jet impingement heat transfer is an interesting flow configuration to study because of its industrial as well as fundamental significance. This configuration has received significant attention of researchers. Impinging jets are used wherever high-performance cooling, heating or drying of a surface is required. Impinging jets offer an effective and flexible approach to transfer energy or mass in many industrial applications by changing the flow and geometric parameters. Although jet impingement on a plate is geometrically simple, it involves a number of interesting complex physical flow configurations, namely, free-shear, stagnation and wall jet regions. These complex flow behaviours make this configuration an ideal choice to test performance of computational models. Several arrangements are possible to represent a physical situation, such as, jet impingement on a solid flat surface or a surface fitted with different kinds of turbulators, inclined plane surface, etc.

In the present thesis a detailed computational study of turbulent slot jet impingement heat transfer using RANS modelling, LES and hydrid modelling was undertaken. The simulations were performed using ANSYS Fluent 15.0 and OpenFOAM 4.1. OpenFOAM 4.1 is an open source CFD software based on the finite-volume method (FVM) using a co-located methodology and is written in C++ programming language. Two flow configurations were considered for jet impingement, i.e., jet impingement on a solid flat surface and a surface fitted with ribs at large and small jet to plate spacings (*H/B*). For a small jet to plate spacing a distinct secondary peak in local Nusselt number (*Nu*) profile has been reported in the literature. These two cases represent fundamental as well as practical situations. Effects of various parameters on flow and heat transfer characteristics have also been studied for flat and ribbed surfaces to obtain a good understanding and to investigate differences in features of the two flow configurations.

A computational study is carried out for slot jet impingements on flat and ribbed surfaces for different values jet to plate spacing and (*Re*). Various RANS based turbulence models were considered for computations. It was observed that none of the turbulence models considered predicts flow and heat transfer characteristics precisely, but a good qualitative trend may be obtained. The standard k-ω and SST k-ω models compute flow and heat transfer characteristics more accurately than those by other turbulence models considered for a small spacing and the standard k-ε shows a good performance for a high spacing. A significant effect of the placement of ribs on the impingement surface was observed. An increase in the rib clearance, position of the first rib in the streamwise direction, *Re*, slot width and jet to plate spacing had favorable effects on heat transfer. The detached rib configuration offered an augmentation in heat transfer compared to the attached rib arrangement.

Large eddy simulation was performed for a jet impingement on a heated surface for a small jet to plate spacing and Re = 20000 using four sub-grid stress (SGS) models. An open source code OpenFOAM 4.1 was used for computations. The computed results are compared with the reported experimental results especially in the vicinity of stagnation, impingement plate and wall jet regions. Further, mean and r.m.s. values of velocity, temperature, *Nu*, turbulence structures and iso-surfaces of various flow properties are presented and analyzed in detail in order to develop a good understanding of flow and heat transfer features. A secondary peak in *Nu* profile was observed using the four SGS models. The present results using the WALE and dynamic k-equation models matched well with the reported experimental results. It is shown that the present LES is capable of capturing small scale dynamics. The existence of large coherent structures, flow acceleration and augmentation in turbulence properties are correlated with the existence of a secondary peak in Nusselt number profile.

URANS and SAS simulations were performed using the SST *k*-*ω*, standard *k*-*ε* and SST SAS *k*-*ω* models for turbulent slot jet impingement heat transfer for a small nozzle to plate spacing. Flow and heat transfer characteristics were obtained and compared with the reported experimental and the present LES results. Mean streamwise velocity profiles using the SST *k*-*ω* and SST SAS *k*-*ω* models were identical at the same grid size. Mean streamwise velocity computations using the SST *k*-*ω* and SST SAS *k*-*ω* models showed a good agreement with the experimental results especially in the regions close to the stagnation point. However, the standard *k*-*ε* model performed better in the outer wall jet regions compared to the SST *k*-*ω* model. The profiles of streamwise turbulence were underpredicted at all the streamwise locations considered using the SST *k*-*ω* and SST SAS *k*-*ω* models. The assumption of isotropic turbulence in RANS based models is the main reason for underpredictions of turbulence profiles. Streamwise turbulence levels increased with streamwise distance while the mean streamwise velocity decreased with it. Profiles of *Nu* using the SST *k*-*ω* and SST-SAS *k*-*ω* turbulence models were nearly the same and showed a good agreement with the experimental results. However, the standard *k*-*ε* model did not accurately predict the profiles of *Nu*. No advantage with the SST SAS *k*-*ω* model compared to the SST *k*-*ω* model in computations of mean streamwise velocity, turbulence profile and heat transfer data was observed.

सारांश

जेट इम्पिंजमेन्ट हीट ट्रांसफर अपने औद्योगिक और मौलिक महत्व के कारण अध्ययन के लिए एक दिलचस्प प्रवाह विन्यास है। इस विन्यास ने शोधकर्ताओं का महत्वपूर्ण ध्यान आकर्षित किया है। जहाँ भी ठंडा करने, गर्म करने या सतह को सुखाने के लिये उच्च-प्रदर्शन की आवश्यकता होती है, वहां जेट इम्पिंजमेन्ट का उपयोग किया जाता है। कई औद्योगिक अनुप्रयोगों में, जहाँ पर ऊर्जा या द्रव्यमान को स्थानांतरित करने की ज़रुरत होती है वहां पर जेट इम्पिंजमेन्ट एक प्रभावी और सुविधाजनक दृष्टिकोण प्रदान करते हैं। हालांकि जेट इम्पिंजमेन्ट एक प्लेट पर ज्यामितीय रूप से सरल है, परंतु इसमें कई दिलचस्प तथा जटिल भौतिक प्रवाह विन्यास शामिल है जैसे कि मुक्त-कतरनी, ठहराव और दीवार जेट वाले क्षेत्र। ये जटिल प्रवाह व्यवहार इस विन्यास को कम्प्यूटेशनल मॉडल के प्रदर्शन का परीक्षण करने के लिए एक आदर्श विकल्प बनाते है। एक भौतिक स्थिति को दर्शाने लिए कई व्यवस्थाएं संभव हैं, जैसे कि एक ठोस सपाट सतह पर जेट का प्रवाह या विभिन्न प्रकार के टर्ब्यूलेटर लगे हुए सतह, झुकाव वाले सतह, आदि।

वर्तमान थीसिस (निबंध) में रान्स (RANS) मॉडलिंग, एलईएस (LES) और संकर प्रतिरूपण का उपयोग करते हुए अशांत स्लॉट जेट इम्पिंजमेन्ट जिसमे ऊष्मा का हस्तांतरण हो रहा है, का विस्तृत कम्प्यूटेशनल अध्ययन किया गया है । अभिकलन के लिए ANSYS Fluent15.0 और OpenFOAM 4.1 का उपयोग किया गया है । OpenFOAM 4.1 एक खुला स्रोत सी ऍफ़ डी (CFD) सॉफ्टवेयर है जो सह-स्थित कार्यप्रणाली का उपयोग करते हुए परिमित मात्रा विधि (FVM) पर आधारित है और C++ प्रोग्रामिंग भाषा में लिखा गया है। जेट प्रवाह के लिए दो प्रवाह विन्यासों पर विचार किया गया है अर्थात्, एक ठोस सपाट सतह पर जेट का अतिक्रमण और दूसरा विभिन्न प्रकार के टर्ब्यूलेटर लगे हुए सतह पर जेट का अतिक्रमण तथा दोनों ही विन्यास जेट और इम्पिंजमेन्ट सतह के बीच कम और ज़्यादा दूरी के लिए भी विचार किया गया है । एक कम दूरी (जेट से इम्पिंजमेन्ट सतह के बीच की दूरी) के लिए Nusselt संख्या (*Nu*) प्रोफ़ाइल में एक अलग से माध्यमिक शिखर को पहले से प्रदर्शित साहित्य में देखा और सूचित किया गया है। ये दोनों मामले मौलिक और व्यावहारिक स्थितियों का प्रतिनिधित्व करते है। एक अच्छी समझ प्राप्त करने और दो प्रवाह विन्यासों की विशेषताओं में अंतर की जांच करने के लिए ठोस सपाट और टर्ब्यूलेटर लगे हुए सतहों के लिए प्रवाह और ऊष्मा हस्तांतरण की विशेषताओं पर विभिन्न मापदंडों और उनके प्रभावों का भी अध्ययन किया गया है।

ठोस सपाट सतह और विभिन्न प्रकार के टर्ब्यूलेटर लगे हुए सतह पर जेट का अतिक्रमण और दोनों ही विन्यास अलग अलग रेनॉल्ड्स नंबर (*Re*) और जेट और सतह के बीच की दूरी के लिये कम्प्यूटेशनल गणना

की गई है । विभिन्न रान्स (RANS) आधारित टर्बुलेंस मॉडलों को गणना के लिए विचार किया गया है । यह देखा गया कि सभी टर्बुलेंस मॉडलों में से कोई भी सटीक रूप से प्रवाह और ऊष्मा हस्तांतरण विशेषताओं पर सटीक विचार नहीं करता है, लेकिन एक अच्छा गुणात्मक प्रवृत्ति प्राप्त की जा सकती है। जेट और इम्पिंजमेन्ट सतह के बीच कम दूरी के लिए Standard k-ω और SST k-ω टर्बुलेंस मॉडल, अन्य टर्बुलेंस मॉडल की तुलना में प्रवाह और ऊष्मा हस्तांतरण की विशेषताओं को अधिक सटीक रूप से गणना करते हैं । तथा जेट और इम्पिंजमेन्ट सतह के बीच ज़्यादा दूरी के लिये Standard k-ε अच्छा प्रदर्शन दिखाता है। टर्ब्यूलेटर (रिब) लगे हुए सतह का प्रवाह विन्यास पर एक महत्वपूर्ण प्रभाव देखा गया है । रिब (टर्ब्यूलेटर लगे हुए सतह) और इम्पिंजमेन्ट सतह के बीच की दूरी में वृद्धि, इम्पिंजमेन्ट सतह पर प्रवाह के दिशा में पहली रिब की स्थिति, रेनॉल्ड्स नंबर, स्लॉट की चौड़ाई और जेट से इम्पिंजमेन्ट सतह के बीच की दूरी का ऊष्मा हस्तांतरण पर अनुकूल प्रभाव पड़ा। इम्पिंजमेन्ट सतह जिससे रिब नहीं जुड़ा है, ने संलग्न रिब व्यवस्था की तुलना में ऊष्मा हस्तांतरण में वृद्धि की पेशकश की।

एक ठोस और गर्म सतह जो की जेट से कम दूरी पर स्थित है, के लिये लार्ज एडी सिमुलेशन (LES) से संबंधित चार सब ग्रिड स्केल मॉडल अभिकलन के लिये प्रयोग गया है और रेनॉल्ड्स नंबर २०,००० है। OpenFOAM 4.1 (एक खुला स्रोत CFD सॉफ्टवेयर) का उपयोग अभिकलन के लिए किया गया है। अभिकलन किए गए परिणामों की तुलना विशेष रूप से ठहराव, इम्पिंजेमेंट प्लेट और वॉल जेट क्षेत्रों के आसपास पहले से प्रदर्शित प्रयोगात्मक परिणामों के साथ की गई है। इसके अलावा, माध्य और वर्गमूल औसत का वर्ग (r.m.s) प्रवाह वेग, तापमान, Nu, अशांत संरचनाओं और एक ही मूल्य की सतहों को प्रवाह और ऊष्मा हस्तांतरण की अच्छी समझ विकसित करने के लिए इन सब गुणों को विस्तार से प्रस्तुत और विश्लेषण किया गया है। Nu प्रोफाइल में एक माध्यमिक शिखर चारो एस जी एस मॉडल का उपयोग करके देखा गया। वर्तमान परिणाम, WALE और डायनामिक k-समीकरण मॉडल का उपयोग करके, पहले प्रदर्शित किए गए प्रयोगात्मक परिणामों के साथ अच्छी तरह से मेल खाते हैं। वर्तमान एल ई एस अभिकलन छोटे पैमाने की अशांत संरचना को दिखाने में सक्षम है। तथा बड़े सुसंगत अशांत संरचनाओं का अस्तित्व, प्रवाह त्वरण और अशांति गुणों में वृद्धि को *Nu* प्रोफ़ाइल में एक माध्यमिक शिखर के अस्तित्व के साथ सहसंबद्ध देखा गया. है।

URANS और SAS अभिकलन SST k-ω, Standard k-ε और SST SAS k-ω मॉडलों का उपयोग एक अशांत जेट इम्पिंजमेन्ट हीट ट्रांसफर को एक कम जेट से इम्पिंजमेन्ट सतह के बीच की दूरी के अध्ययन लिए किया गया है। प्रवाह और ऊष्मा हस्तांतरण की विशेषताओं को पहले से प्रदर्शित किए गए प्रयोगात्मक और वर्तमान एलईएस परिणामों के साथ प्राप्त किया गया है। इम्पिंजेमेंट सतह पर प्रवाह की दिशा में माध्य वेग की

प्रोफाइल SST *k-ω* और SST SAS *k-ω* मॉडलों का उपयोग एक सामान ग्रिड पर किया गया तो परिणाम में अन्तर नहीं पाया गया। SST *k-ω* और SST SAS *k-ω* मॉडलों का उपयोग करते हुए धारा प्रवाह के वेग की गणना में प्रयोगात्मक परिणामों के साथ एक अच्छा समझौता पाया गया, विशेष रूप से प्रवाह के ठहराव वाले निकट स्थान पर। हालांकि, Standard *k-ε* मॉडल ने बाहरी दीवार जेट क्षेत्रों में SST *k-ω* मॉडल की तुलना में बेहतर प्रदर्शन किया। SST *k-ω* और SST SAS *k-ω* मॉडलों का उपयोग करते हुए विचारणीय सभी स्थानों पर (इम्पिंजमेन्ट सतह पर प्रवाह के दिशा वाले) इम्पिंजमेन्ट सतह के निकट प्रवाह के दिशा वाले टर्बुलेंस प्रोफाइल में कमी देखने को मिलता है। रान्स (RANS) आधारित मॉडल में समदैशिक टर्बुलेंस की धारणा टर्बुलेंस प्रोफाइल में कमी पाए जाने का मुख्य कारण है। प्रवाह के दिशा वाले टर्बुलेंस प्रोफाइल का स्तर प्रवाह के दिशा वाले दूरी के साथ बढ़ गया जबकि माध्य प्रवाह वेग इसके साथ कम हो गया। SST *k-ω* और SST-SAS *k-ω* टर्बुलेंस मॉडलों का उपयोग करने पर Nu के लेखाचित्र लगभग समान थे और प्रयोगात्मक परिणामों के साथ एक अच्छा समझौता पाया गया। हालांकि, Standard *k-ε* मॉडल ने *Nu* के लेखाचित्र का सही आकलन नहीं किया। SST SAS *k-ω* मॉडल के साथ SST *k-ω* मॉडल की तुलना में माध्य प्रवाह वेग, अशांति लेखाचित्र और ऊष्मा हस्तांतरण के नतीजों की गणना में कोई लाभ नहीं पाया गया।

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NOMENCLATURE

B	slot jet width, m
C	rib clearance, m
c/e	non-dimensional rib to plate clearance
D	nozzle exit diameter for round jets, m
e	rib height, m
H	distance between nozzle exit to impingement plate, m
H/B	normalized nozzle to plate spacing
h	surface heat transfer coefficient, $h = \frac{k_a \frac{\partial T}{\partial y}\Big\vert_{y=0}}{(T_w - T_0)}$, W/m^2-K
Nu	Nusselt number at the wall, $Nu = \frac{hB}{k_a}$
P	mean pressure
Pr	Prandtl number, $Pr = \frac{\mu C_p}{k_a}$
Pr_t	turbulent Prandtl number
p/e	non-dimensional rib pitch
Re	Reynolds number , $Re = \frac{\rho V_0 B}{\mu}$
S	Strain rate tensor
T	sub-grid stress tensor
T	static temperature, K
t^*	non dimensional time unit
u_i	velocity vector, m/s
V_0	wall-normal velocity at the jet inlet, m/s

$x/B(R_1)$	position of first rib
x,y,z	coordinate directions

Greek Symbols

α	thermal diffusivity m^2/s
k	turbulence kinetic energy, m^2/s^2
ε	turbulent dissipation rate, m^2/s^3
ω	specific dissipation rate, 1/s
ρ	density of the working fluid, kg/m^3
μ	dynamic Viscosity, kg/m-s
μ_t	turbulent viscosity, kg/m-s
ν	kinematic viscosity, m^2/sec (μ/ρ)
k_a	thermal Conductivity of air, W/m-K
$\mathbf{\Omega}$	vorticity magnitude
ε_{SGS}	sub-grid scale dissipation
ν_{SGS}	sub-grid scale kinematic viscosity
Δ	grid size

Subscript

avg	average
a	air
f	fluid
i,j	index of coordinate direction
0	quantities at the inlet

st	stagnation point
t	turbulent
eff	effective
r.m.s.	root mean square

Superscript

'	fluctuating quantity
‾	time averaged quantity
+	normalized quantity in wall coordinates

Abbreviation

SST	Shear Stress Transport
LES	large Eddy Simulation
SAS	Scale Adaptive Simulation
RANS	Reynolds Averaged Navier Stokes
PANS	Partially Averaged Navier Stokes
SGS	Sub-Grid Stress
DES	Detached Eddy Simulation