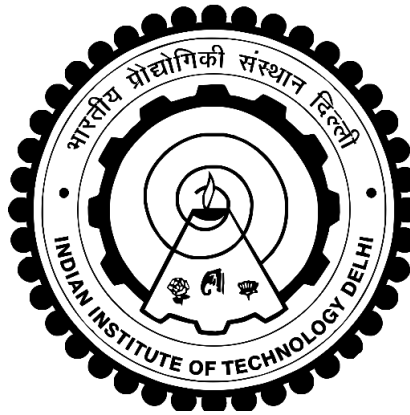


Numerical and Experimental Investigations of Turbulent Jet Impingement Flow and Heat transfer on Curved Surfaces

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July 2025

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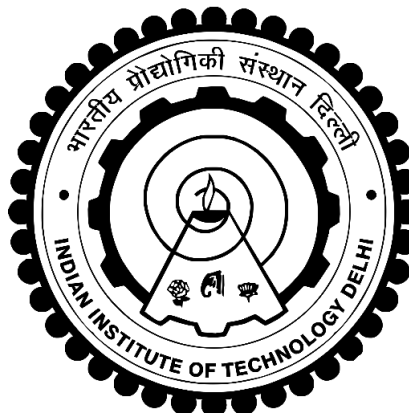
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Submitted

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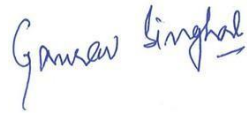


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CERTIFICATE

This is to certify that the thesis entitled, “**Numerical and Experimental Investigations of Turbulent Jet Impingement Flow and Heat transfer on Curved Surfaces**”, submitted by **Mr. Veerendra Kumar** to Indian Institute of Technology, Delhi (India), for the award of the degree of the **Doctor of Philosophy** is a record of bonafide research work carried out by him. He worked under my supervision for the submission of this thesis, which to the best of my knowledge has reached the requisite standard. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.



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(Veerendra Kumar)

ABSTRACT

The use of impinging fluid jets for rapid cooling or heating application is a well-established technique, particularly effective for localized cooling of heated surfaces in space-constrained scenarios. Traditionally, jet impingement has been widely employed in industries such as metal processing and casting, gas turbine blade cooling, rocket launcher systems, rotary cement kiln shell cooling, and welding spot cooling for large-diameter offshore pipelines. Its versatility stems from the flexibility to adjust various flow and geometric parameters, making it adaptable to diverse operational requirements.

Despite the wealth of research on jet impingement heat transfer, a critical gap remains in understanding its application to spherical convex and concave surfaces. In recent years, impingement cooling has found relevance in high-power laser systems, high-performance microprocessors, electrified automobiles, etc. These are new and emerging engineering applications where spherical surfaces may be encountered. For instance, directed energy weapon systems rely on high-intensity laser beams guided by convex and concave spherical lenses or mirrors, which require efficient cooling to minimize thermal distortions. In such scenarios, impingement cooling via cold air jets offers a promising and effective solution.

This study presents a combined experimental and numerical investigation of turbulent flow and heat transfer characteristics during circular air jet impingement on convex and concave spherical surfaces subjected to a constant heat flux. The specific research objectives are as follows:

- Experimental investigation of the heat transfer characteristics of a round air jet impinging on a hemispherical convex surface. Development of correlations from the experimental data to predict the stagnation point and average Nusselt numbers for the hemispherical convex surface.
- Numerical analysis of the jet impingement on a hemispherical convex surface using the v^2 - f turbulence model across a broad range of dimensionless parameters. Assess the effects of key dimensionless parameters on; potential core length of the jet, stagnation point Nusselt number, and local Nusselt number distribution over the convex surface.
- Derivation of correlations from extensive numerical data to estimate local Nusselt numbers at various positions on the convex surface.

- Numerical investigation of jet impingement on bowl-shaped concave spherical surfaces using the ν^2 - f turbulence model. Analyse the impact of dimensionless parameters on; potential core length, stagnation point Nusselt number and local Nusselt number distribution over the concave surface.
- Analysis of the influence of concave curvature on thermal behaviour by systematically comparing Nusselt number data between concave and flat surfaces under identical flow and geometric conditions. Development of correlations from the extensive numerical data to predict the stagnation point Nusselt numbers on the concave bowl-shaped surfaces.

Detailed experimental studies were conducted to analyze the heat transfer characteristics of circular air jet impingement cooling of convex hemispherical surfaces. Empirical correlations were developed from the experimental data to predict both stagnation point (Nu_0) and average Nusselt numbers (Nu_{avg}) across a broad range of dimensionless parameters. The relevant dimensionless parameters are, nozzle-to-surface distance (L/d), diameter ratio of surface and nozzle or relative curvature (D/d), jet Reynolds number based on nozzle diameter (Re_d) and curvilinear distance along the surface (r/d). Also, corresponding numerical simulations employing the ν^2 - f turbulence model were also performed. The key findings are given below:

- *Stagnation point and average Nusselt numbers:* Both Nu_0 and Nu_{avg} are a strong function of Re_d across all ranges of parameters. Nu_0 remains relatively unaffected by dimensionless nozzle-to-surface distances for $L/d \leq 6$ but follows power-law decay for $6.67 \leq L/d \leq 16.67$.
- *Influence of Relative Curvature:* The D/d values significantly affects both Nu_0 and Nu_{avg} across all tested nozzle-to-surface distances ($2 \leq L/d \leq 16.67$) and jet Reynolds numbers ($29,000 \leq Re_d \leq 80,000$).
- *Local Nusselt number distribution:* In case of $L/d = 2$, a distinct secondary peak in the local Nusselt number profile is observed at $r/d \approx 2$.
- The ν^2 - f turbulence model is quite good at simulating the jet impingement phenomena. The simulation results give a local Nusselt number distribution around the target surface with a maximum 20% deviation from the experimental data.

An exhaustive computational analysis employing the ν^2 - f turbulence model was carried out to evaluate the thermo-fluidic characteristics of circular air jet impinging on convex hemispherical surfaces. The study systematically examined the influence of relevant non-dimensional

parameters on Nusselt number and flow dynamics. The key findings are briefly enumerated below:

- *Potential core length*: Based on the jet centerline velocity decay to 95%, the potential core length of the circular jet decreases with increasing Reynolds number (Re_d), ranging from $3.5d$ at $Re_d = 11,000$ to $2.6d$ at $Re_d = 50,000$. However, when defined as centerline velocity decay to 90%, the potential core length remains nearly constant at $5d$ across the entire range of parameters.
- *Stagnation point Nusselt number (Nu_0)*: It is maximum at $L/d = 8$ for all the relative curvature (D/d) and Re_d values. For, $L/d \leq 4$ and $Re_d \geq 23000$, a secondary maxima is observed in the local Nu distribution. The Nu/Nu_0 values at local minima and maxima decrease with decreasing values of D/d for the same L/d and Re_d . This ratio (Nu/Nu_0) also decreases with decreasing Re_d at the same relative curvature.
- *Spatial Nusselt number distribution*: For, $0 \leq r/d \leq 1.3$ (when $L/d \leq 4$ and $Re \geq 23,000$), Nu decreases linearly along the surface, strongly influenced by D/d . After the secondary peak, the local Nusselt number falls exponentially with respect to r/d as, $Nu \propto \exp\{-0.2(r/d)\}$. In this region, L/d has minimal effect, while D/d remains influential.

A comprehensive numerical investigation employing the v^2 - f turbulence model was conducted to examine the thermo-fluidic behaviour of the impingement cooling of concave bowl-shaped spherical surface using round air jets. For comparative analysis, computations were also performed for a flat surface under identical conditions. The study reveals distinct flow dynamics for concave surfaces compared to convex and flat configurations. The major inferences drawn from the results of the numerical computations are enumerated below:

- *Potential core length*: At low Re_d , the potential core length shortens significantly for concave surfaces compared to free jets or convex surfaces. The potential core length is also almost independent of Re_d for a fixed relative curvature (D/d), and increases with the increasing D/d value.
- *Heat transfer characteristics*: Concave curvature induces two opposing effects:
 - (i) Enhanced heat transfer due to improved fluid mixing and turbulence.
 - (ii) Reduced heat transfer caused by recirculation of heated fluid within the bowl-shaped volume.

- *Stagnation point Nusselt number:* Nu_0 are lower for concave surfaces than flat ones but approach flat-surface values as D/d increases. Nu_0 peaks at $L/d = 6$ across all tested parameter ranges and exhibits strong Reynolds number dependence. For $2 \leq L/d \leq 6$, Nu_0 shows a weak positive correlation with L/d , while for $8 \leq L/d \leq 10$, it shows a strong negative correlation. Increasing relative depth (H/D) consistently reduces Nu_0 .
- *Local Nusselt number distribution:* In the region $0 \leq r/d < 1$, local Nu values are lower for concave surfaces than flat ones. Unlike convex/flat surfaces, no secondary peak in Nu distribution is observed for concave surfaces. For $L/d \leq 4$, Nu distributions of concave and flat surfaces converge when $r/d > 2$. For $L/d \geq 6$, convergence begins at $r/d > 1$.

The thermo-fluidic characteristics of dual-jet impingement on a convex spherical surface were studied through numerical computations with special emphasis on the jet-jet interaction. Parameters were varied as (same for both jets): L/d (2–10), Re_d (10000–50000), and D/d (5–15). Key observations are:

- *Fountain flow:* Opposing wall jets create a secondary stagnation zone, localized near the mid-plane. Width depends on D/d and Re_d ; outside this zone, flow resembles a single jet.
- *Effect of Re_d , D/d , and L/d on Fountain zone width:* Higher Re_d compresses the fountain zone (40% reduction at when Re_d increases from 10000 to 50000). Increasing the D/d expands the fountain zone (in terms of r/d) and scaling is linear. L/d has minimal influence on the fountain width.
- *Heat transfer characteristics:* Peak Nu in fountain zone is 50–100% higher than the periphery, most enhancements is at low Re_d and small L/d . Sharp Nu drop downstream indicates rapid boundary layer growth.

The findings of the present study will be useful in the optimum design of the jet impingement cooling of the convex and concave spherical target surfaces.

सारांश

हीटिंग या कूलिंग के लिए इम्पिंजिंग फ्लूइड जेट्स का उपयोग एक स्थापित तकनीक है, जो विशेष रूप से सीमित स्थानों में गर्म सतहों के स्थानीय शीतलीकरण के लिए अत्यंत प्रभावी मानी जाती है। परंपरागत रूप से, जेट इम्पिंजमेंट तकनीक का व्यापक उपयोग धातु प्रसंस्करण एवं कास्टिंग, गैस टरबाइन ब्लेड कूलिंग, रॉकेट लॉन्चर सिस्टम, रोटरी सीमेंट किर्लन शेल कूलिंग और बड़े-व्यास वाली ऑफशोर पाइपलाइनों के वेल्डिंग स्पॉट कूलिंग जैसी औद्योगिक प्रक्रियाओं में किया जाता रहा है। इसकी बहुउपयोगिता का मुख्य कारण विभिन्न प्रवाह और ज्यामितीय मापदंडों को अनुकूलित करने की सुविधा है, जिससे इसे विभिन्न परिचालन आवश्यकताओं के लिए अनुकूल बनाया जा सकता है।

यद्यपि जेट इम्पिंजमेंट हीट ट्रांसफर पर काफी अनुसंधान कार्य पहले से उपलब्ध है, फिर भी गोलाकार उत्तल (convex) एवं अवतल (concave) सतहों पर इसके व्यवहार को लेकर समझ में एक महत्वपूर्ण शोध अंतर बना हुआ है। हाल के वर्षों में, इम्पिंजमेंट कूलिंग का उपयोग हाई-पावर लेजर सिस्टम, उच्च प्रदर्शन माइक्रोप्रोसेसर, इलेक्ट्रिक वाहन आदि में प्रासंगिक हो गया है। ये उभरते हुए ऐसे इंजीनियरिंग क्षेत्र हैं, जहाँ गोलाकार सतहों का सामना किया जाता है। उदाहरण के लिए, डायरेक्टेड एनर्जी वेपन सिस्टम में उच्च तीव्रता वाले लेजर बीम को उत्तल या अवतल गोलाकार लेंस अथवा दर्पणों के माध्यम से संचालित किया जाता है, जिन्हें थर्मल विकृति से बचाने हेतु प्रभावी शीतलीकरण की आवश्यकता होती है। ऐसे परिदृश्यों में ठंडी हवा के जेट द्वारा इम्पिंजमेंट कूलिंग एक आशाजनक एवं प्रभावी समाधान के रूप में उभर कर आता है।

इस अध्ययन में गोलाकार उत्तल एवं अवतल सतहों पर स्थिर ऊष्मा प्रवाह की स्थिति में वृत्ताकार वायु जेट इम्पिंजमेंट के दौरान उत्पन्न अशांत प्रवाह एवं ऊष्मा हस्तांतरण विशेषताओं का संयुक्त रूप से प्रयोगात्मक और संख्यात्मक विश्लेषण प्रस्तुत किया गया है। इस शोध के विशेष उद्देश्य निम्नलिखित हैं:

- अर्धगोलाकार उत्तल सतह पर इम्पिंज होने वाले वायु जेट के ऊष्मा हस्तांतरण व्यवहार का प्रयोगात्मक अध्ययन। प्रयोगात्मक आंकड़ों के आधार पर अर्धगोलाकार सतह के लिए स्थिर बिंदु (stagnation point) और औसत नुसल्ट संख्या (Nusselt number) का पूर्वानुमान करने हेतु सहसंबंध विकसित करना।
- v_2 -f टर्बुलेंस मॉडल का उपयोग करते हुए अर्धगोलाकार उत्तल सतह पर जेट इम्पिंजमेंट का संख्यात्मक विश्लेषण, जिसमें व्यापक डाइमेंशनलेस (आयामहीन) मापदंडों का अध्ययन किया गया। प्रमुख आयामहीन मापदंडों का जेट के पोटेंशियल कोर की लंबाई, स्थिर बिंदु नुसल्ट संख्या तथा सतह पर स्थानीय नुसल्ट वितरण पर प्रभाव का आकलन करना।
- विस्तृत संख्यात्मक आंकड़ों से अर्धगोलाकार सतह पर विभिन्न स्थानों के लिए स्थानीय नुसल्ट संख्याओं के पूर्वानुमान हेतु सहसंबंध विकसित करना।
- v_2 -f टर्बुलेंस मॉडल का उपयोग करते हुए कटोरेनुमा अवतल गोलाकार सतहों पर जेट इम्पिंजमेंट का संख्यात्मक अध्ययन। प्रमुख आयामहीन मापदंडों का पोटेंशियल कोर लंबाई, स्थिर बिंदु नुसल्ट संख्या तथा सतह पर स्थानीय नुसल्ट वितरण पर प्रभाव का विश्लेषण।
- समान प्रवाह एवं ज्यामितीय परिस्थितियों में अवतल तथा समतल सतहों के बीच नुसल्ट संख्याओं की तुलना कर अवतल वक्रता के तापीय व्यवहार पर प्रभाव का विश्लेषण। विस्तृत संख्यात्मक आंकड़ों के आधार पर कटोरेनुमा अवतल सतहों के लिए स्थिर बिंदु नुसल्ट संख्या के पूर्वानुमान हेतु सहसंबंध विकसित करना।

अर्धगोलाकार उत्तल सतहों पर वृत्ताकार वायु जेट इम्पिंजमेंट कूलिंग के ऊष्मा हस्तांतरण व्यवहार के विश्लेषण हेतु विस्तृत प्रयोगात्मक अध्ययन किया गया। प्रयोगात्मक आंकड़ों के आधार पर आयामहीन

मापदंडों की विस्तृत सीमा के लिए स्थिर बिंदु (Nu_0) एवं औसत नुसल्ट संख्या (Nu_{avg}) के पूर्वानुमान हेतु अनुभवजन्य सहसंबंध विकसित किए गए। प्रासंगिक आयामहीन मापदंडों में नोजल-सतह दूरी (L/d), सतह और नोजल का व्यास अनुपात या सापेक्ष वक्रता (D/d), नोजल व्यास पर आधारित जेट रेनॉल्ड्स संख्या (Re_d) और सतह के साथ घुमावदार दूरी (r/d) सम्मिलित हैं। इसके साथ ही v_2 -f टर्बुलेंस मॉडल द्वारा संबंधित संख्यात्मक विश्लेषण भी किया गया। प्रमुख निष्कर्ष निम्नलिखित हैं:

- **स्थिर बिंदु एवं औसत नुसल्ट संख्या:** Nu_0 और Nu_{avg} दोनों ही Re_d के लिए अत्यधिक संवेदनशील हैं। $L/d \leq 6$ के लिए Nu_0 पर नोजल-सतह दूरी का विशेष प्रभाव नहीं दिखता, लेकिन $6.67 \leq L/d \leq 16.67$ के लिए यह पावर लॉ के अनुसार घटता है।
- **सापेक्ष वक्रता का प्रभाव:** D/d का मान Nu_0 और Nu_{avg} दोनों को सभी परीक्षण की गई नोजल-सतह दूरी ($2 \leq L/d \leq 16.67$) और जेट रेनॉल्ड्स संख्या ($29,000 \leq Re_d \leq 80,000$) पर महत्वपूर्ण रूप से प्रभावित करता है।
- **स्थानीय नुसल्ट वितरण:** $L/d = 2$ की स्थिति में $r/d \approx 2$ पर स्थानीय नुसल्ट संख्या प्रोफाइल में द्वितीयक पीक स्पष्ट रूप से दिखाई देती है।
- v_2 -f टर्बुलेंस मॉडल जेट इम्पिंजमेंट व्यवहार को सटीकता से अनुकरण करने में सक्षम है। सतह के चारों ओर स्थानीय नुसल्ट वितरण में अधिकतम 20% विचलन देखा गया।

संख्यात्मक विश्लेषण के निष्कर्ष (उत्तल सतह के लिए):

- **पोटेंशियल कोर लंबाई:** जेट के केंद्र रेखा वेग के 95% तक घटने के आधार पर पोटेंशियल कोर लंबाई Re_d बढ़ने के साथ घटती है ($Re_d = 11,000$ पर 3.5d से लेकर $Re_d = 50,000$ पर 2.6d तक)। परंतु 90% वेग ह्रास के आधार पर कोर लंबाई पूरे दायरे में लगभग 5d स्थिर रहती है।
- **स्थिर बिंदु नुसल्ट संख्या (Nu_0):** सभी D/d और Re_d के लिए अधिकतम Nu_0 , $L/d = 8$ पर प्राप्त होता है। $L/d \leq 4$ और $Re_d \geq 23000$ के लिए स्थानीय Nu वितरण में द्वितीयक पीक भी दिखती है। स्थानीय न्यूनतम और अधिकतम पर Nu/Nu_0 का मान D/d में कमी के साथ घटता है। इसी प्रकार Re_d में कमी के साथ भी यह घटता है।
- **स्थानिक नुसल्ट वितरण:** $L/d \leq 4$ और $Re \geq 23,000$ की स्थिति में $0 \leq r/d \leq 1.3$ तक Nu रैखिक रूप से घटता है, जिस पर D/d का प्रभाव अत्यधिक है। द्वितीयक पीक के बाद Nu , r/d के सापेक्ष घातांकीय रूप से घटता है, $Nu \propto \exp\{-0.2(r/d)\}$ । इस क्षेत्र में L/d का प्रभाव नगण्य परंतु D/d का प्रभाव बना रहता है।

संख्यात्मक विश्लेषण (अवतल सतह के लिए):

- v_2 -f टर्बुलेंस मॉडल का उपयोग कर कटोरेनुमा अवतल सतह पर वायु जेट इम्पिंजमेंट कूलिंग के थर्मो-फ्लूइडिक व्यवहार का विश्लेषण किया गया। तुलनात्मक दृष्टि से समतल सतह के लिए भी समान परिस्थितियों में गणनाएँ की गईं। अवतल सतहों के लिए प्रवाह व्यवहार उत्तल एवं समतल सतहों से भिन्न पाया गया। मुख्य निष्कर्ष निम्नलिखित हैं:
- **पोटेंशियल कोर लंबाई:** निम्न Re_d पर अवतल सतहों के लिए पोटेंशियल कोर लंबाई फ्री जेट अथवा उत्तल सतहों की तुलना में काफी कम पाई गई। स्थिर D/d पर यह Re_d से लगभग स्वतंत्र रही और D/d के बढ़ने पर यह बढ़ती है।
- **ऊष्मा स्थानांतरण व्यवहार:** अवतल वक्रता दो विपरीत प्रभाव उत्पन्न करती है:
 - (i) बेहतर मिक्सिंग और टर्बुलेंस के कारण ऊष्मा स्थानांतरण में वृद्धि।
 - (ii) कटोरेनुमा क्षेत्र में गर्म द्रव के रीसर्कुलेशन के कारण ऊष्मा स्थानांतरण में कमी।

- **स्थिर बिंदु नुसल्ट संख्या (Nu_0):** अवतल सतहों पर Nu_0 समतल सतह की तुलना में कम लेकिन D/d बढ़ने पर समतल सतह के समीप पहुँचती है। सभी परिस्थितियों में Nu_0 , $L/d = 6$ पर अधिकतम पाया गया और यह Re_d पर अत्यधिक निर्भर है। $2 \leq L/d \leq 6$ के लिए Nu_0 का L/d के साथ हल्का सकारात्मक संबंध और $8 \leq L/d \leq 10$ के लिए नकारात्मक संबंध पाया गया। H/D बढ़ने पर Nu_0 घटता है।
- **स्थानीय नुसल्ट वितरण:** $0 \leq r/d < 1$ के लिए अवतल सतहों पर स्थानीय Nu मान समतल सतह से कम हैं। उत्तल/समतल सतहों की तरह द्वितीयक पीक नहीं पाई गई। $L/d \leq 4$ के लिए $r/d > 2$ पर अवतल और समतल सतहों के वितरण समान हो जाते हैं। $L/d \geq 6$ पर यह समानता $r/d > 1$ से प्रारंभ होती है।

दोहरी जेट इम्पिंजमेंट (उत्तल सतह के लिए):

- उत्तल सतह पर दो जेट के इम्पिंजमेंट का संख्यात्मक विश्लेषण विशेष रूप से जेट-जेट अंतःक्रिया पर केंद्रित था। दोनों जेट के लिए मापदंड समान रखे गए: L/d (2–10), Re_d (10000–50000), D/d (5–15)। प्रमुख निष्कर्ष:
- **फाउंटेन फ्लो:** आपस में टकराते वॉल-जेट्स सतह के मध्य में द्वितीयक स्थिर क्षेत्र बनाते हैं, जिसकी चौड़ाई D/d और Re_d पर निर्भर है; इस क्षेत्र से बाहर प्रवाह एक जेट जैसा व्यवहार करता है।
- **Re_d , D/d और L/d का फाउंटेन क्षेत्र पर प्रभाव:** उच्च Re_d फाउंटेन क्षेत्र को संकुचित करता है ($Re_d = 10000$ से 50000 पर 40% कमी)। D/d बढ़ने से फाउंटेन क्षेत्र चौड़ा होता है और वृद्धि रेखीय होती है। L/d का प्रभाव न्यूनतम है।
- **ऊष्मा स्थानांतरण व्यवहार:** फाउंटेन क्षेत्र में Nu , किनारे के मुकाबले 50-100% अधिक पाया गया, विशेषकर कम Re_d और छोटे L/d पर। डाउनस्ट्रीम में Nu में तीव्र गिरावट, बाउंडरी लेयर के तीव्र विकास को दर्शाती है।

इस अध्ययन के निष्कर्ष उत्तल एवं अवतल गोलाकार सतहों के जेट इम्पिंजमेंट कूलिंग के अनुकूल डिजाइन हेतु उपयोगी सिद्ध होंगे।

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Nomenclature

A	surface area of the SS foil
b	slot width
$C_1, C_2, C_\eta, C_\mu, C_L, C_{\varepsilon 1}, C_{\varepsilon 2}$	turbulence model parameters
D	surface diameter
d	nozzle jet diameter
f	elliptical relaxation frequency
H	heat transfer coefficient at target surface
I	current supplied to the SS foil
K	thermal conductivity of jet fluid
k	turbulent kinetic energy
L	distance between nozzle and surface
l	turbulence length scale
$\dot{m}$	mass flow rate of air jet
Nu	local Nusselt number
Nu_0	stagnation Nusselt number
Nu_{avg}	stagnation Nusselt number
P	production of turbulent kinetic energy
p	pressure
Pr	Prandtl number
r	curvilinear distance along the curved surface
Re	Reynolds number
Re_d	jet Reynolds number
S	mean strain rate
T_j	temperature of jet
T_s	temperature of surface
T_∞	ambient temperature
T	turbulence time scale
U	jet centerline velocity

V	voltage applied across SS foil
U_c	initial jet centerline velocity
u_i	velocity in i^{th} direction
x_i	coordinate in i^{th} direction
Y^+	non dimensional wall coordinate

Greek Symbols

σ	Stefan-Boltzmann constant
ε	emissivity of the SS foil
$\mathcal{E}$	dissipation rate of turbulence kinetic energy
ρ	density
ν	kinematic viscosity
ν_t	eddy viscosity

Acronyms

ASM	algebraic stress model
CFD	computational fluid dynamics
DES	detached eddy simulation
DEW	directed energy weapon
DNS	direct numerical simulation
DSM	dynamic Smagorinsky model
EVM	eddy viscosity model
HPLDA	high power laser diode array
LES	large eddy simulation
RANS	Reynolds averaged Navier Stokes equations
RSM	Reynolds stress model
SGS	sub-grid scale
SST	shear-stress transport
WALE	wall-adapting local eddy viscosity sub-grid scale model
ZNLES	zonal numerical large eddy simulation