BOILING PERFORMANCE ENHANCEMENT THROUGH ENGINEERED SURFACE STRUCTURES AND JET FLOW FOR HIGH HEAT FLUX APPLICATIONS

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JULY 2025

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by

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Submitted in fulfillment of the requirements of the degree of Doctor of Philosophy
to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

Dedicated to My family and Teachers

Certificate

This is to certify that the thesis entitled **BOILING PERFORMANCE ENHANCEMENT THROUGH ENGINEERED SURFACE STRUCTURES AND JET FLOW FOR HIGH HEAT FLUX APPLICATIONS**, being submitted by **Mr. Rajesh Kumar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Mechanical Engineering is a bonafide record of the research work carried out by him under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard. We hereby declare that the content of the thesis, in full or in part, has not been submitted to any other Institute or University for the award of any degree or diploma.

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Date:

Acknowledgement

The journey of completing this thesis at IIT Delhi has been one of the most transformative and rewarding phases of my life. It has not only helped me grow as a researcher but also shaped me personally in countless ways. This work is the culmination of the guidance, support, and encouragement I received from several people, to whom I express my heartfelt gratitude.

First and foremost, I would like to express my deepest appreciation to my supervisor, Prof. B. Premachandran, for his invaluable guidance, constant encouragement, and unwavering support throughout the course of my Ph.D. His deep insights, timely feedback, and constructive discussions were instrumental in shaping the direction of my research. He has always inspired me to work hard, try to learn more to achieve the success in life. I am especially grateful for the patience and trust he placed in me, allowing me the freedom to explore ideas while always being available with wise counsel. I am extremely thankful to him for his technical and theoretical support.

I am sincerely thankful to the members of my research committee, Prof. M. R. Ravi, Prof. Subhra Datta, and Prof. Arghya Samanta for their valuable inputs and encouragement at every stage of my research work. Their suggestions helped refine the research and added significant depth to the outcomes presented in this thesis.

I sincerely thanks to my lab-mates and colleagues, Dr. Rohit Kumar, Dr. Sourabh Kumar, Dr. Thamil Kumaran, Ikhtedar Husain, Sudhir Kumar Gupta and Ajeet Kumar for the friendly atmosphere they fostered in the lab. I am incredibly grateful to my close friends, who stood by me outside the academic circle, offering emotional support and encouragement whenever I needed it most. Their presence helped me stay balanced and resilient.

Above all, I owe the deepest gratitude to my family members. They have been my lifelong pillars of strength, and their belief in me has always been my driving force. I am especially thankful to my wife, Supriya, whose patience and understanding have been a constant source of motivation. Her support during the most demanding times made this journey possible. I am also blessed to have our kids, Kayrav and Dhruvi, their joyful presence brought light and energy into my life, even on the most exhausting days.

Rajesh Kumar

Abstract

Boiling is a highly efficient process of thermal energy transfer widely found across various engineering and industrial applications such as nuclear power reactors, water distillation, cryogenic fuel storage, steam power plant, refrigeration and air conditioning and thermal management of electronic devices. It uses latent heat of vaporization to transfer significantly large quantity of heat at a very low temperature difference. Consequently, it offers remarkably high heat transfer coefficients (HTC), making it a preferred mechanism for higher heat dissipation applications. However, the maximum heat flux in boiling is limited by the critical heat flux (CHF). After reaching the CHF, a vapor layer tends to develop over the heated surface, thereby HTC decreases significantly. Enhancement in boiling performance directly contributes energy efficiency, environmental sustainability and water resource utilization. Moreover, the ever-growing demand for compact, lightweight, and high-performance electronic devices calls for advanced thermal management solutions capable of handling higher heat dissipation rates to ensure reliable and efficient operation. Therefore, simple and inexpensive methods are required to further enhance both HTC and CHF to simultaneously increase the efficiency and operational range of systems. Various active and passive methods have been explored to improve boiling heat transfer. The current research work mainly focusses on the development of scalable, cost-effective and easy to implement enhancement technique for the pool boiling.

In this work, two new microchannel configurations, i.e., asymmetric dual V-groove microchannels (VM) and orthogonally intersecting asymmetric dual V-groove microchannels (OIVM) have been introduced to study enhancement in pool boiling. The heat transfer enhancement due to the modified surfaces is established by comparing the heat transfer rates from a reference plain surface. Moreover, to investigate the effect of reentrant channel geometry on heat transfer, two novel structured surfaces, namely trapezoidal reentrant microchannel (TRM) and segmented trapezoidal reentrant microchannel (STRM) are developed and boiling characteristics are experimentally investigated. A scalable porous copper coating is also developed to enhance heat transfer in pool boiling. The effect of surface characteristic parameters on the heat transfer performance is investigated. The submerged wall jet flow over a top-facing horizontal surface has also been investigated on the plain and the coated surfaces to improve the pool boiling heat transfer. In these studies, experiments have

been performed using deionized water under saturation temperature at one atmosphere pressure. The bubble dynamics and interface morphology at various heat flux levels have been captured using high-speed camera and discussed in detail. Finally, to explore the combined effect of surface structure and surface additive on the pool boiling performance, investigation has been carried out on the VM and OIVM surface using Triton X-100 surfactant solution.

It was observed that microchannels on the heated surface improve the heat transfer in pool boiling. The OIVM surface provides an increase of 5.3 times in the maximum HTC and 2.4 times in the CHF compared to the reference plain surface. Similarly, the VM surface provides an improvement of 2.2 times in HTC and 1.7 times in CHF compared to the plain surface. The increased heat transfer rate with the OIVM and VM surfaces can be ascribed to large area for heat exchange, increased bubble initiation sites, bubble motion promoted macroconvection and efficient rewetting mechanism. The TRM surfaces exhibit an enhancement factor of 2.08 to 2.91 times in the CHF and 2.33 to 3.96 times in the HTC compared to the plain surface. The top-performing STRM surface shows the CHF of 4555.2 kW/m^2 which is 290% higher than the plain surface CHF. This surface demonstrates a maximum HTC of 842.5 kW/m^{2}K. The better heat transfer performance with the STRM surface compared to the TRM surface demonstrates that separated vapour release and liquid supply pathways, and better rewetting are the main reason for delayed CHF and higher HTC.

The coated surfaces provide better heat transfer performance than that of uncoated surface. The best-performing coated surface exhibits a HTC of 290.3 kW/m^{2}K and a CHF of 2700.3 kW/m^2, representing enhancements of 5.1 times in HTC and 2.3 times in CHF than the uncoated surface. The coated surface initiate boiling earlier and maintains lower surface superheats across the entire range of heat flux compared to the uncoated surfaces. The larger number of active nucleation sites on coated surfaces contributes to improving the heat transfer rate. The coated surface also exhibits capillary wicking properties. The enhancement ratio of CHF on coated surfaces demonstrates a linear relationship with the nondimensional wicking number (Wi). In the wall jet flow boiling study, it is observed that the wall jet flow effectively enhances the boiling performance in the low heat flux nucleate boiling regimes for both coated and plain surfaces. At higher heat fluxes, the heat transfer results for different jet velocities coincide and they overlap the pool boiling results. Hence, nucleate boiling predominantly governs the heat transfer in this regime, with minimal effect of wall jet flow. However, the wall jet flow significantly delays the CHF limit, which shows a linear relationship with jet velocity.

The VM and OIVM structured surfaces exhibit better heat transfer performance compared to the plain surface with the use of the surfactant solution as the working fluid. The OIVM surface provides enhancement of 334.2% in HTC and 110.9% in CHF. The VM surface demonstrates a 101.8% increase in the HTC and a 41.8% improvement in the CHF. The plain, VM, and OIVM surfaces demonstrated improvement in HTC when tested with the surfactant solution, as compared to their performance with pure deionized water, across all levels of heat flux. However, despite this enhancement in HTC, the use of the surfactant solution results in a reduction in enhancement of CHF relative to the corresponding values observed with deionized water. This decline in CHF is primarily due to vapor bubble crowding near the heated surface at higher heat flux conditions, which obstructs effective liquid rewetting and leads to early surface dryout. The pool boiling enhancement methods proposed in the present research work are simple, cost-effective, mechanically robust and easily scalable. Therefore, they can be employed for efficient heat transfer in a wide range of industrial applications.

सार

उबालना ऊष्मीय ऊर्जा हस्तांतरण की एक अत्यधिक कुशल प्रक्रिया है जो परमाणु ऊर्जा रिएक्टर, जल आसवन, क्रायोजेनिक ईंधन भंडारण, भाप बिजली संयंत्र, प्रशीतन और वातानुकूलन और इलेक्ट्रॉनिक उपकरणों के ऊष्मीय प्रबंधन जैसे विभिन्न इंजीनियरिंग और औद्योगिक अनुप्रयोगों में व्यापक रूप से पाई जाती है। यह बहुत कम तापमान अंतर पर काफी बड़ी मात्रा में ऊष्मा स्थानांतरित करने के लिए वाष्पीकरण की गुप्त ऊष्मा का उपयोग करता है। नतीजतन, यह उल्लेखनीय रूप से उच्च ऊष्मा हस्तांतरण गुणांक (एचटीसी) प्रदान करता है, जो इसे उच्च ऊष्मा अपव्यय अनुप्रयोगों के लिए एक पसंदीदा तंत्र बनाता है। हालाँकि, उबलने में अधिकतम ऊष्मा प्रवाह महत्वपूर्ण ऊष्मा प्रवाह (एचटीसी) द्वारा सीमित होता है। एचटीसी तक पहुँचने के बाद, गर्म सतह पर वाष्प की एक परत विकसित होने लगती है, जिससे एचटीसी काफी कम हो जाता है। उबलने के प्रदर्शन में वृद्धि सीधे ऊर्जा दक्षता, पर्यावरणीय स्थिरता और जल संसाधन उपयोग में योगदान देती है। इसके अलावा, कॉम्पैक्ट, हल्के और उच्च प्रदर्शन वाले इलेक्ट्रॉनिक उपकरणों की लगातार बढ़ती मांग विश्वसनीय और कुशल संचालन सुनिश्चित करने के लिए उच्च ऊष्मा अपव्यय दरों को संभालने में सक्षम उन्नत थर्मल प्रबंधन समाधानों की मांग करती है। इसलिए, सिस्टम की दक्षता और परिचालन सीमा को एक साथ बढ़ाने के लिए एचटीसी और एचटीसी दोनों को और बढ़ाने के लिए सरल और सस्ते तरीकों की आवश्यकता है। उबलते हुए ऊष्मा हस्तांतरण को बेहतर बनाने के लिए विभिन्न सक्रिय और निष्क्रिय तरीकों की खोज की गई है। वर्तमान शोध कार्य मुख्य रूप से पूल उबलने के लिए स्केलेबल, लागत प्रभावी और आसानी से लागू होने वाली संवर्द्धन तकनीक के विकास पर केंद्रित है

इस कार्य में, दो नए माइक्रोचैनल विन्यास, यानी असममित दोहरी वी-नाली माइक्रोचैनल (वीएम) और ऑर्थोगोनली इंटरसेक्टिंग असममित दोहरी वी-नाली माइक्रोचैनल (ओआईवीएम) को पूल उबलने में वृद्धि का अध्ययन करने के लिए पेश किया गया है। संशोधित सतहों के कारण गर्मी हस्तांतरण वृद्धि एक संदर्भ सादे सतह से गर्मी हस्तांतरण दरों की तुलना करके स्थापित की जाती है। इसके अलावा, गर्मी हस्तांतरण पर पुनः प्रवेश चैनल ज्यामिति के प्रभाव की जांच करने के लिए, दो उपन्यास संरचित सतहों, अर्थात् ट्रेपेज़ॉइडल पुनः प्रवेश माइक्रोचैनल (टीआरएम) और खंडित ट्रेपेज़ॉइडल पुनः प्रवेश माइक्रोचैनल (एसटीआरएम) विकसित किए गए हैं और उबलते विशेषताओं की प्रयोगात्मक रूप से जांच की गई है। पूल उबलने में गर्मी हस्तांतरण को बढ़ाने के लिए एक स्केलेबल छिद्रपूर्ण तांबे की कोटिंग भी विकसित की गई है। गर्मी हस्तांतरण प्रदर्शन पर सतह विशेषता मापदंडों के प्रभाव की जांच की जाती है। पूल उबलने की गर्मी हस्तांतरण में सुधार करने के लिए सादे और लेपित सतहों पर एक शीर्ष-सामने वाली क्षैतिज सतह पर डूबी हुई दीवार जेट प्रवाह की भी जांच की गई है। इन अध्ययनों में, एक वायुमंडलीय दबाव पर संतृप्ति तापमान के तहत विआयनीकृत पानी का उपयोग करके प्रयोग किए गए हैं। विभिन्न ताप प्रवाह स्तरों पर बुलबुला गतिशीलता और इंटरफ़ेस आकृति विज्ञान को उच्च गति वाले कैमरे का उपयोग करके कैप्चर किया गया है और विस्तार से चर्चा की गई है। अंत में, पूल उबलने के प्रदर्शन पर सतह

संरचना और सतह योजक के संयुक्त प्रभाव का पता लगाने के लिए, ट्राइटन एक्स-100 सर्फेक्टेंट समाधान का उपयोग करके वीएम और ओआईवीएम सतह पर जांच की गई है

यह देखा गया कि गर्म सतह पर सूक्ष्म चैनल पूल उबलने में ऊष्मा स्थानांतरण में सुधार करते हैं। ओआईवीएम सतह संदर्भ समतल सतह की तुलना में अधिकतम एचटीसी में 5.3 गुना और एचटीसी में 2.4 गुना वृद्धि प्रदान करती है। इसी तरह, वीएम सतह समतल सतह की तुलना में एचटीसी में 2.2 गुना और एचटीसी में 1.7 गुना सुधार प्रदान करती है। ओआईवीएम और वीएम सतहों के साथ बढ़ी हुई ऊष्मा स्थानांतरण दर को ऊष्मा विनिमय के लिए बड़े क्षेत्र, बुलबुला आरंभ स्थलों में वृद्धि, बुलबुला गति द्वारा बढ़ावा दिया गया मैक्रोकन्वेक्शन और कुशल रीवेटिंग तंत्र के लिए जिम्मेदार ठहराया जा सकता है। टीआरएम सतह समतल सतह की तुलना में एचटीसी में 2.08 से 2.91 गुना और एचटीसी में 2.33 से 3.96 गुना वृद्धि कारक प्रदर्शित करती है। शीर्ष प्रदर्शन करने वाली एसटीआरएम सतह 4555.2 kW/m^2 का एचटीसी दिखाती है जो समतल सतह एचटीसी से 290% अधिक है। यह सतह 842.5 kW/m^{2}K का अधिकतम एचटीसी प्रदर्शित करती है। टीआरएम सतह की तुलना में एसटीआरएम सतह के साथ बेहतर ताप स्थानांतरण प्रदर्शन यह दर्शाता है कि पृथक वाष्प उत्सर्जन और द्रव आपूर्ति मार्ग, तथा बेहतर पुनः आर्द्रीकरण विलंबित सीएचएफ और उच्च एचटीसी का मुख्य कारण हैं

लेपित सतहें बिना लेपित सतह की तुलना में बेहतर ऊष्मा स्थानांतरण प्रदर्शन प्रदान करती हैं। सबसे अच्छा प्रदर्शन करने वाली लेपित सतह 290.3 kW/m^{2}K का एचटीसी और 2700.3 kW/m^2 का एचटीसी प्रदर्शित करती है, जो बिना लेपित सतह की तुलना में एचटीसी में 5.1 गुना और एचटीसी में 2.3 गुना वृद्धि दर्शाती है। लेपित सतह पहले उबलना शुरू करती है और बिना लेपित सतहों की तुलना में ऊष्मा प्रवाह की पूरी श्रृंखला में कम सतही अतिताप बनाए रखती है। लेपित सतहों पर सक्रिय न्यूक्लियेशन साइटों की बड़ी संख्या ऊष्मा स्थानांतरण दर को बेहतर बनाने में योगदान देती है। लेपित सतह केशिका विकिंग गुण भी प्रदर्शित करती है। लेपित सतहों पर एचटीसी का वृद्धि अनुपात गैर-आयामी विकिंग संख्या (Wi) के साथ एक रैखिक संबंध प्रदर्शित करता है। वॉल जेट प्रवाह क्वथन अध्ययन में, यह देखा गया है कि वॉल जेट प्रवाह लेपित और सादे सतहों दोनों के लिए कम ऊष्मा प्रवाह न्यूक्लिएट क्वथन शासन में क्वथन प्रदर्शन को प्रभावी ढंग से बढ़ाता है। उच्च तापीय प्रवाह पर, विभिन्न जेट वेगों के लिए ऊष्मा स्थानांतरण परिणाम मेल खाते हैं और वे पूल क्वथन परिणामों को ओवरलैप करते हैं। इसलिए, नाभिकीय क्वथन मुख्य रूप से इस शासन में ऊष्मा स्थानांतरण को नियंत्रित करता है, जिसमें दीवार जेट प्रवाह का न्यूनतम प्रभाव होता है। हालाँकि, दीवार जेट प्रवाह एचटीसी सीमा में काफी देरी करता है, जो जेट वेग के साथ एक रैखिक संबंध दर्शाता है

वीएम और ओआईवीएम संरचित सतहें कार्यशील तरल के रूप में सर्फेक्टेंट घोल के उपयोग के साथ सादे सतह की तुलना में बेहतर ताप हस्तांतरण प्रदर्शन प्रदर्शित करती हैं। ओआईवीएम सतह एचटीसी में 334.2% और एचटीसी में 110.9% की वृद्धि प्रदान करती है। वीएम सतह एचटीसी में 101.8% वृद्धि और एचटीसी में 41.8% सुधार प्रदर्शित करती है। सादे, वीएम, और ओआईवीएम सतहों ने ताप प्रवाह के सभी स्तरों पर शुद्ध विआयनीकृत जल के साथ उनके प्रदर्शन की तुलना में सर्फेक्टेंट घोल के साथ परीक्षण करने पर एचटीसी में सुधार प्रदर्शित किया। हालांकि, एचटीसी में इस वृद्धि के बावजूद, सर्फेक्टेंट घोल के उपयोग से विआयनीकृत जल के साथ देखे गए संगत मानों की तुलना में एचटीसी की वृद्धि में कमी आती है वर्तमान शोध कार्य में प्रस्तावित पूल क्वथन वृद्धि विधियाँ सरल, लागत-प्रभावी,

यांत्रिक रूप से मजबूत और आसानी से मापनीय हैं। इसलिए, उन्हें औद्योगिक अनुप्रयोगों की एक विस्तृत श्रृंखला में कुशल ताप हस्तांतरण के लिए नियोजित किया जा सकता है

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Nomenclature

a	channel opening (m)
A	surface area (m^2)
A_w	wetted area (m^2)
b	channel base width (m)
c_p	specific heat at constant pressure (J/kgK)
D, d	depth of channel (m)
d_b	bubble departure diameter (m)
$\mathrm{D_h}$	hydraulic diameter (m)
f_b	bubble departure frequency (/s)
g	Acceleration due to gravity ($\mathrm{m/s^2}$)
h	heat transfer coefficient ($\mathrm{W/m^2K}$)
h_{fg}	latent heat of vaporization (J/kg)
I	electrical current (A)
k	thermal conductivity (W/mK)
N	number of channels
P, p	pitch of channels (m)
Pr	Prandtl number $\left(\frac{\mu c_p}{k}\right)$
q''	heat flux ($\mathrm{W/m^2}$)
Re	Reynold number $\left(\frac{\rho V L_c}{\mu}\right)$
S	distance between nozzle and heated surface (m)
t	time (s)
t_g	growth time (s)
t_w	waiting time (s)
T	temperature (K)
U	uncertainty
V	voltage (V)
Vw_j	wall jet velocity (m/s)
V_0''	initial wicked flux (m/s)
W	width of channel (m)
Wi	nondimensional wicking number
X	distance (m)

Greek symbols

ΔT	wall superheat (K)
ΔX	spacing between two adjacent thermocouples (m)
φ	inclination angle (°)
μ	dynamic viscosity (Ns/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ	contact angle (°)

Subscripts

Cu	copper
f	liquid
g	vapour
in	input
sat	saturation
sub	subcooling
sup	superheat
w	wall
wj	wall jet

Abbreviations

CHF	Critical heat flux
CMC	Critical micelle concentration
EDS	Energy dispersive X-ray spectroscopy
FESEM	Field emission scanning electron microscope
HTC	Heat transfer coefficient
MHU	Main heating unit
OIVM	Orthogonally intersecting asymmetric dual V-groove microchannels surface
RM	Rectangular microchannels surface
SEM	Scanning electron microscope
STRM	Segmented trapezoidal reentrant microchannels surface
TRM	Trapezoidal reentrant microchannels surface
VM	Asymmetric dual V-groove microchannels surface
WEDM	Wire electric discharge machining
XRD	X-ray diffraction