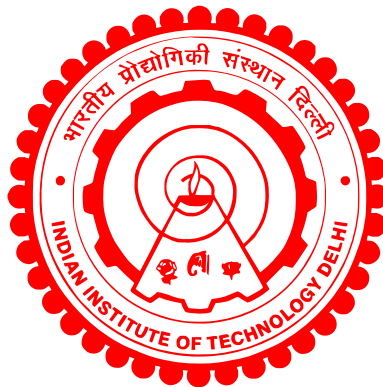


PHYSICS OF LIQUID JETS IN ELECTROHYDRODYNAMIC JET PRINTING

ABHISHEK KUMAR SINGH



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PHYSICS OF LIQUID JETS IN ELECTROHYDRODYNAMIC JET PRINTING

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ABHISHEK KUMAR SINGH

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Certificate

This is to certify that the thesis entitled “**Physics of liquid jets in electrohydrodynamic jet printing**”, being submitted by, **Mr. Abhishek K. Singh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of original research work carried out by him under our supervision in conformity with the rules and regulations of the institute. The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any Degree or Diploma.

Date: December 21, 2023

Dr. Supreet Singh Bahga

Associate Professor

Department of Mechanical Engineering,

Indian Institute of Technology Delhi,

New Delhi-110016, India

Dr. Rajiv K. Srivastava

Professor

Department of Textile and Fibre Engineering,

Indian Institute of Technology Delhi,

New Delhi-110016, India

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Abstract

Electrohydrodynamic (EHD) jet printing involves controlled deposition of a jet issuing from a stretched liquid meniscus attached to a metallic needle under the influence of a strong electric field between the needle and a grounded collector plate. The application of an electric field enables the production of the fine jet, whose diameter can be easily adjusted by varying the operating parameters and physical properties of the liquid. Using fine EHD jets, customized two-dimensional (2D)/three-dimensional (3D) patterns are made by layer-by-layer deposition of the jet onto a non-contact substrate attached to a motion-controlled translation stage. This single-step, mask-less, non-contact method offers high-resolution rapid prototyping of miniaturized 2D/3D patterns, which are generally fabricated through conventional lithographic techniques. Consequently, this method paves the way forward for additive printing in a broad spectrum of applications, including flexible electronics, biotechnology, and microfluidic networks. However, to achieve consistent and reliable printing results, a comprehensive understanding of the physics of liquid jets in the EHD jet printing configuration is essential. In the present study, we aim to discuss the physics of the liquid jets in the EHD jet printing configuration by analyzing the characteristics of the jet through experimental observations as well as mathematical modelling.

First, we experimentally investigate the effect of geometrical parameters on the stability domain, 2D space of the applied electric potential difference and the imposed flow, wherein a fine jet emanating from the tip of a stable conical meniscus, also known as Taylor cone-jet, is observed. In this study, we systematically vary the needle diameter, needle-to-collector distance, and physical properties of the liquids and observe the dynamic behavior of the cone-jet. We characterize the various jetting modes through ex-

perimental visualization of EHD jets at the needle outlet based on the geometrical shape of the deformed meniscus at varying flow rate and applied electric potential difference between the needle and the collector plate. We show that the various observed modes are similar to those observed in conventional electrospraying. Moreover, the stability domain significantly depends on the geometrical parameters and the physical properties of the liquid. In particular, our observations highlight that the stability domain substantially depends on the needle diameter for relatively viscous liquids; whereas, the stability domain does not exhibit any dependence on the needle diameter for relatively less viscous fluids. In contrast to the needle diameter, the needle-to-collector distance does not affect the jetting characteristics except the magnitude of the electric field at the needle tip.

Next, through experimental visualization of EHD jets and current measurements, we show that steady EHD jetting can occur broadly in three distinct regimes, namely, the cone-jet, moderately-stretched jet, and thick-jet regimes, depending on the flow rate, applied potential difference, and the needle-to-collector gap. To elucidate the underlying physics of these experimentally observed regimes, we perform order-of-magnitude analysis in the current transfer region, a region connecting the conical meniscus with the fine jet where conduction and surface convection currents are of comparable magnitude. Based on the relative size of the current transfer region and the jet diameter, we derive the criteria for observing the three steady EHD jetting regimes. For each of these regimes, we also describe the dependence of the jet diameter and the current carried by the jet on flow rate, potential difference, and aspect ratio in the form of scaling relations. The theoretical criteria for observing the distinct steady jetting regimes and the corresponding scaling relations for the jet diameter and current show good agreement with the experimental observations.

Lastly, through experiments and numerical simulations, we describe the physics of the moderately-stretched EHD jet applicable to the EHD jet printing process. Through comparison with experimental measurements, we show that our simulations correctly predict the jet shape for varying flow rates and applied potential difference. We present the physical mechanism of inertia-dominated slender EHD jets based on the dominant

driving and resisting forces and relevant dimensionless numbers. We show that the slender EHD jet stretches and accelerates primarily due to the balance of driving tangential electric shear and resisting inertia forces in the developed jet region, whereas in the vicinity of the needle, driving charge repulsion and resisting surface tension forces govern the cone shape. The findings of the work presented in this thesis can help in operational understanding and better control of the EHD jet printing process.

सार

(ईएचडी) जेट प्रिंटिंग में धातु की नलिका और संग्राहक के बीच एक मजबूत विद्युतीय क्षेत्र लगाकर धातु की नलिका से निकलने वाले तरल से बनने वाले सूक्ष्म जेट को नियंत्रित तरीके से एक संग्राहक पर जमा किया जाता है। विद्युतीय क्षेत्र के अनुप्रयोग से ही सूक्ष्म जेट का उत्पादन संभव हो पाता है, साथ ही साथ तरल के सूक्ष्म जेट के व्यास को भी तरल के भौतिक गुणों और परिचालन मानक मापदंडों को पृथक-पृथक तरीके से परिवर्तित करके नियंत्रित किया जा सकता है। इसी सूक्ष्म ईएचडी जेट का उपयोग करके, गति-नियंत्रित यन्त्र पर स्थापित समतल सतह के ऊपर (ईएचडी) जेट को परत-दर-परत जमा करके दो-आयामी (2डी)/तीन-आयामी (3डी) अनुकूलित सूक्ष्म संरचनाएं बनायीं जाती हैं। यह एकल-चरण, मुखौटा-रहित, बिना संपर्क वाली प्रक्रिया, उच्च-रिज़ॉल्यूशन के सूक्ष्म और अतिसूक्ष्म 2डी/3डी संरचनाओं को तीव्र गति से निर्मित करने में सहायक होती है, जो कि आम तौर पर पारंपरिक लिथोग्राफिक तकनीकों के माध्यम से निर्मित की जाती हैं। नतीजतन, यह विधि लचीले इलेक्ट्रॉनिक्स, जैव प्रौद्योगिकी और माइक्रोफ्लुइडिक नेटवर्क सहित विभिन्न क्षेत्रों में एडिटिव प्रिंटिंग के माध्यम से अनेकों संरचनाओं के निर्माण के मार्ग को अग्रसर करती है। हालाँकि, एक बेहतर, सुसंगठित और विश्वसनीय प्रिंटिंग परिणाम को प्राप्त करने के लिए, ईएचडी जेट प्रिंटिंग प्रक्रिया में तरल जेट की भौतिकी की व्यापक समझ आवश्यक है। इसलिए वर्तमान अध्ययन में हमारा लक्ष्य प्रायोगिक अवलोकनों के साथ-साथ गणितीय मॉडलिंग के माध्यम से जेट की भौतिकी का व्यापक विश्लेषण करना है।

सबसे पहले, हमने प्रयोगात्मक रूप से जेट की स्थिरता कार्यक्षेत्र पर ज्यामितीय मापदंडों के प्रभाव का अध्ययन किया। जेट की स्थिरता कार्यक्षेत्र में एक स्थिर शंकुकार मेनिसकस की नोक से एक अतिसूक्ष्म जेट बनता है, जिसे टेलर कोन-जेट के नाम से भी परिभाषित किया जाता है। जेट की स्थिरता कार्यक्षेत्र को नलिका और संग्राहक सतह के बीच लगने वाले विद्युतीय क्षेत्र के परिमाण और धातु की नलिका में तरल प्रवाह की दर के माध्यम से दर्शाया जाता है। इस अध्ययन में, हम नलिका के व्यास, नलिका से संग्राहक सतह की दूरी और तरल पदार्थों के भौतिक गुणों को व्यवस्थित रूप से परिवर्तित करके शंकु-जेट के गतिशील व्यवहार का निरीक्षण करते हैं। हम अलग-अलग प्रवाह दर और नलिका और संग्राहक सतह के बीच में लगने वाले विद्युतीय क्षेत्र पर कोन और जेट के दृश्यों के माध्यम से तरल सतह के ज्यामितीय आकार के आधार पर जेट के व्यवहार को विभिन्न जेटिंग मोड में गुणात्मक रूप से विभाजित करते हैं। अपने वैज्ञानिक प्रयोगों से हम दिखाते हैं कि विभिन्न देखे गए जेटिंग मोड, पारंपरिक इलेक्ट्रोस्प्रैइंग में देखे गए जेटिंग मोड के समान हैं। इसके अलावा, जेट की स्थिरता कार्यक्षेत्र ज्यामितीय मापदंडों और तरल के भौतिक गुणों पर निर्भर करता है। विशेष रूप से, हमारे अवलोकन इस बात पर प्रकाश डालते हैं कि जेट स्थिरता का क्षेत्र अपेक्षाकृत चिपचिपे तरल पदार्थों के लिए नलिका के व्यास पर काफी हद तक निर्भर करता है; जबकि, जेट की स्थिरता कार्यक्षेत्र अपेक्षाकृत कम चिपचिपे तरल पदार्थों के लिए नलिका के व्यास पर कोई निर्भरता प्रदर्शित नहीं करता है। साथ ही साथ हमने यह भी पाया कि नलिका के व्यास के भांति, नलिका से संग्राहक की दूरी का जेटिंग मोड पर कोई प्रभाव नहीं पड़ता।

इसके बाद, ईएचडी जेट में विद्युत प्रवाह और जेट के दृश्यों के गुणात्मक तुलना के माध्यम से हम दिखाते हैं कि स्थिर ईएचडी जेटिंग को तीन अलग-अलग क्षेत्रों में विभाजित किया जा सकता है, जो कि, कोनजेट, मोडरेटेली-स्ट्रेचड जेट, और थिन-जेट क्षेत्र, जो की तरल की प्रवाह दर, नलिका और संग्राहक सतह के बीच लगाए गए विद्युत वोल्टेज, नलिका और संग्राहक सतह के बीच की दूरी पर निर्भर करते हैं। प्रयोगात्मक रूप से देखे गए इन क्षेत्रों की अंतर्निहित भौतिकी को स्पष्ट करने के लिए, हम विद्युत प्रवाह स्थानांतरण क्षेत्र में आर्डर-ऑफ़-मैग्नीट्यूड विश्लेषण करते हैं। विद्युत प्रवाह स्थानांतरण क्षेत्र शंकुकार तरल सतह और सूक्ष्म जेट से जोड़ने वाला क्षेत्र जहाँ चालन और सतह संवहन धाराओं का परिमाण लगभग सामान्य होता है। विद्युत प्रवाह स्थानांतरण क्षेत्र की लम्बाई और जेट के व्यास के आधार पर, हम तीन स्थिर ईएचडी जेटिंग क्षेत्रों के अवलोकन के लिए मानदंड प्राप्त करते हैं। इनमें से प्रत्येक

क्षेत्र के लिए, हम स्केलिंग संबंधों के रूप में जेट की व्यास और जेट द्वारा प्रवाहित धारा की तरल प्रवाह दर, लगाया गया विद्युत वोल्टेज और नलिका और संग्राहक सतह के बीच की दूरी का नलिका के व्यास से अनुपात की निर्भरता का भी वर्णन करते हैं। हमने यह पाया की प्रयोगात्मक विधि से प्राप्त अलग-अलग स्थिर जेटिंग क्षेत्रों में जेट के व्यास और विद्युत प्रवाह के स्केलिंग संबंध सैद्धांतिक मानदंड से प्राप्त टिप्पणियों से अवलोकित संबंधों के साथ शुद्ध रूप से मेल खाता है

अंत में, प्रयोगों और संख्यात्मक सिमुलेशन के माध्यम से, हम ईएचडी जेट प्रिंटिंग प्रक्रिया में पाए जाने वाले मोडरेटेली स्ट्रेचर्ड ईएचडी जेट की भौतिकी का वर्णन करते हैं। प्रयोगात्मक मापों के साथ तुलना के माध्यम से, हम दिखाते हैं कि हमारे सिमुलेशन अलग-अलग प्रवाह दर और विद्युत वोल्टेज लिए जेट के आकार की सही भविष्यवाणी करते हैं। हम प्रमुख प्रेरित और प्रतिरोधी बलों और प्रासंगिक आयाम रहित संख्याओं के आधार पर जड़ता-प्रधान पतले ईएचडी जेट के भौतिकी को प्रस्तुत करते हैं। हम दिखाते हैं कि टेंगेंशियल-इलेक्ट्रिक-शियर और जड़ता बलों के परस्पर प्रतिरोध के संतुलन के कारण ही सूक्ष्म ईएचडी जेट मुख्य रूप से बनता है। जबकि, नलिका के आसपास, प्रेरित चार्ज रिलैक्सेशन और प्रतिरोधी इंटरफेसियल-टेंशन बल ही तरल के शंकु आकार को नियंत्रित करते हैं। इस शोध प्रवन्ध में प्रस्तुत कार्य के निष्कर्ष ईएचडी जेट प्रिंटिंग प्रक्रिया की परिचालन समझ और बेहतर नियंत्रण में मदद कर सकते हैं।

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List of Acronyms

EHD Electrohydrodynamic	iv
2D two-dimensional	iv
3D three-dimensional	iv
DIW Direct ink writing	1
LHS left-hand side	52
RHS right-hand side	52