

Multiphysics Simulations of DC Non-Transferred Arc Thermal Plasma Torch for Optimal Performance

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Submitted

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Certificate

This is to certify that the thesis entitled “**Multiphysics Simulations of DC Non-Transferred Arc Thermal Plasma Torch for Optimal Performance**” being submitted by Mr. Akash Yadav to the Indian Institute of Technology Delhi for the award of the degree of DOCTOR OF PHILOSOPHY is a record of the original bonafide research carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of the thesis. The results presented in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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Abstract

Plasma torches operating on the principle of arc discharge are fundamental components in various industrial thermal plasma processes, including but not limited to applications such as plasma spraying, metal cutting and welding, thermal plasma chemical vapor deposition (CVD), metal melting, remelting, waste treatment, and gas production. Despite their apparent simplicity, the operation of these torches involves intricate interactions among thermal, chemical, electrical, and fluid dynamics phenomena. Numerical modeling serves as a valuable tool for comprehensively understanding the underlying physical processes.

This doctoral thesis investigates the complex interplay of thermal, chemical, electrical, and fluid dynamics phenomena inherent in thermal plasma torches. The research centers on the development and application of a laminar steady-state 2D axisymmetric model employing a magneto-hydrodynamic approach for a direct current (DC) thermal plasma torch. The comprehensive model encompasses the entire torch system, including plasma gas injection, the inner torch region, and the jet exiting into the ambient environment.

Numerical simulations are conducted with two distinct power inputs derived from published experimental data, demonstrating excellent agreement between predicted and experimentally observed temperature profiles at the torch exit. An in-depth analysis of plasma jet velocity highlights the significant influence of electromagnetic forces, particularly the Lorentz force, on jet acceleration, especially near the cathode tip. The temperature and velocity profiles align closely with characteristics indicative of a long laminar plasma jet. An optimal operating heat transfer coefficient (h) is suggested to ensure low anode erosion rates and acceptable thermal

efficiency, with argon identified as the plasma gas with the highest temperature and longest jet length.

Building upon this foundational model, this thesis also presents a numerical study that studies the thermal behavior and performance variations of the torch under diverse cathode tip conditions representing erosion. Temperature contours and axial line plots reveal impacts on torch temperature as the cathode tip erodes, with pointed tips experiencing higher peak temperatures due to increased ohmic heating near the cathode tip. Eroded tips exhibit lower maximum temperatures as overall temperature decreases with reduced current density.

Further investigations include axial velocity distributions, pressure gradient profiles, and the effects of Lorentz forces for distinct cathode tips. The study also examines the alterations in arc-root attachment positions and temperature on the anode wall, influencing anode material deterioration and overall torch performance. Notably, the research identifies the optimal stage of cathode erosion for maximizing power and efficiency while balancing anode life, thus contributing essential insights for enhancing torch performance and longevity in industrial applications.

सार

आर्क डिस्चार्ज के सिद्धांत पर कार्य करने वाले प्लाज्मा टॉर्च विभिन्न औद्योगिक थर्मल प्लाज्मा प्रक्रियाओं के मौलिक घटक हैं, जिनमें प्लाज्मा स्प्रेइंग, धातु काटने और वेल्डिंग, थर्मल प्लाज्मा केमिकल वेपर डिपोजिशन (CVD), धातु पिघलाने, पुनर्पिघलाने, कचरा उपचार, और गैस उत्पादन जैसी अनुप्रयोग शामिल हैं। उनकी सादगी के बावजूद, इन टॉर्च के संचालन में थर्मल, रासायनिक, विद्युत और द्रव गतिशीलता घटनाओं के बीच जटिल इंटरैक्शन शामिल होते हैं। अंतर्निहित भौतिक प्रक्रियाओं को पूरी तरह से समझने के लिए संख्यात्मक मॉडलिंग एक मूल्यवान उपकरण है।

यह डॉक्टरल थीसिस थर्मल प्लाज्मा टॉर्च में अंतर्निहित थर्मल, रासायनिक, विद्युत और द्रव गतिशीलता घटनाओं की जटिल इंटरप्ले की जांच करती है। शोध का केंद्र एक प्रत्यक्ष वर्तमान (DC) थर्मल प्लाज्मा टॉर्च के लिए एक चुंबकीय-हाइड्रोडायनामिक दृष्टिकोण का उपयोग करते हुए एक लामिनार स्थिर-स्थिति 2D अक्षीय सममित मॉडल के विकास और अनुप्रयोग पर है। व्यापक मॉडल में प्लाज्मा गैस इंजेक्शन, आंतरिक टॉर्च क्षेत्र, और परिवेशी वातावरण में निकलने वाली जेट शामिल है। प्रकाशित प्रायोगिक डेटा से प्राप्त दो अलग-अलग पावर इनपुट के साथ संख्यात्मक सिमुलेशन किए गए हैं, जो टॉर्च निकास पर भविष्यवाणी की गई और प्रायोगिक रूप से देखी गई तापमान प्रोफाइल के बीच उत्कृष्ट समझौता दिखाते हैं।

प्लाज्मा जेट वेग का गहन विश्लेषण इलेक्ट्रोमैग्नेटिक बलों, विशेष रूप से कैथोड टिप के पास जेट त्वरण पर लोरेन्ज बल के महत्वपूर्ण प्रभाव को उजागर करता है। तापमान और वेग प्रोफाइल लंबी लामिनार प्लाज्मा जेट की विशेषताओं के साथ निकटता से मेल खाते हैं। कम एनोड क्षरण दरों और स्वीकार्य थर्मल दक्षता सुनिश्चित करने के लिए एक इष्टतम ऑपरेटिंग हीट ट्रांसफर गुणांक (h) का सुझाव दिया गया है, जिसमें आर्गन को सबसे उच्च तापमान और सबसे लंबी जेट लंबाई के साथ प्लाज्मा गैस के रूप में पहचाना गया है।

इस बुनियादी मॉडल पर निर्माण करते हुए, यह थीसिस एक संख्यात्मक अध्ययन भी प्रस्तुत करती है जो क्षरण का प्रतिनिधित्व करने वाले विभिन्न कैथोड टिप स्थितियों के तहत टॉर्च के थर्मल व्यवहार और प्रदर्शन भिन्नताओं का अध्ययन करती है। तापमान कॉन्ट्रोल और अक्षीय रेखा प्लॉट्स कैथोड टिप के क्षरण के रूप में टॉर्च तापमान पर प्रभावों को प्रकट करते हैं, जिसमें कैथोड टिप के पास बढ़ी हुई ओमिक हीटिंग के कारण नुकली टिप्स उच्चतम तापमान का अनुभव करती हैं। क्षरित टिप्स कमतम तापमान प्रदर्शित करते हैं क्योंकि कम करंट घनत्व के साथ समग्र तापमान कम हो जाता है।

आगे की जांच में अलग-अलग कैथोड टिप्स के लिए अक्षीय वेग वितरण, दबाव ग्रेडियंट प्रोफाइल और लोरेन्ट्ज बलों के प्रभाव शामिल हैं। अध्ययन आर्क-रूट संलग्नक स्थानों और एनोड दीवार पर तापमान में परिवर्तन की भी जांच करता है, जो एनोड सामग्री के पतन और समग्र टॉर्च प्रदर्शन को प्रभावित करता है। विशेष रूप से, शोध अधिकतम शक्ति और दक्षता को संतुलित करते हुए एनोड जीवन को संतुलित करने के लिए कैथोड क्षरण के इष्टतम चरण की पहचान करता है, इस प्रकार औद्योगिक अनुप्रयोगों में टॉर्च प्रदर्शन और दीर्घायु को बढ़ाने के लिए आवश्यक अंतर्दृष्टि प्रदान करता है।

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