

# **INVESTIGATION OF VELOCITY FIELDS, MIXING AND FLOW REGIMES IN COILED TUBES AND COILED FLOW INVERTER GEOMETRIES**

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# **INVESTIGATION OF VELOCITY FIELDS, MIXING AND FLOW REGIMES IN COILED TUBES AND COILED FLOW INVERTER GEOMETRIES**

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*in fulfillment of the requirements of the degree of Doctor of Philosophy*

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## **CERTIFICATE**

This is to certify that the thesis entitled '**Investigation of velocity fields, mixing and flow regimes in coiled tubes and coiled flow inverter geometries**' being submitted by **Ms. Loveleen Sharma** to the Indian Institute of Technology Delhi for award of **Doctor of Philosophy** is a record of bona fide research work carried out by her under our guidance and supervision in conformity with the rules and regulations of Indian Institute of Technology Delhi. The research report and results presented in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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## ABSTRACT

Flow through coiled tubes is associated with twin vortices in the flow cross section (perpendicular to the local direction of mean flow), owing to centrifugal forces imposed by coil curvature. This kind of flow pattern, known as Dean circulations, is believed to result in good radial mixing. Studies have established that a narrower Residence Time Distribution (RTD) can be achieved for fluid flow through a coiled path, as compared to a straight tube of equal length and volume, even in laminar flow regime. For the processing of complex molecules or heat-sensitive materials, much of which are usually rather viscous and tend to have a lower Reynolds number of flow, the advantages of such efficient radial mixing (while being in the laminar flow regime) are considerable.

Several literature contributions showed the benefits of coiled geometries (coiled tubes and coiled flow inverters) in reducing axial dispersion, and thereby increasing heat and mass transfer without any commensurate pressure drop penalty. However, these claims have been based on overall measurements of the transport coefficients and behaviour of coiled geometries as process units. Moreover, no direct measurements of velocity profile under Dean's flow have ever been reported; also, there is no clear picture as yet to show how the cross-sectional circulation evolves with the addition of a second phase. The limited understanding of the complex nature of two-phase flow resists its widespread applications in industries. Thus, the motivation of this work has been to explore the performance of coiled geometries (coiled tubes and coiled flow inverters) over a wide flow range (covering laminar as well as turbulent flow regime) using single and multiphase flows (liquid only, gas-liquid and liquid-liquid).

In the first part of the study, Residence Time Distribution (RTD) and pressure drop experiments were conducted on straight tubes and various coiled configurations (using different geometrical parameters such as flow inversion ( $n$ ) and curvature ratios ( $\lambda$ )) of identical volume, to examine the relative importance of these design parameters on flow. The outcome of this study showed three distinct zones for the coiled flow over a large enough range of flow velocities, clearly from laminar to turbulent flow regime. Besides these, this work has established the trends for the extent of axial dispersion in terms of a "Master Plot"; and

identified a scaling relationship to consider the effect of varying fluid properties and coil dimensions on the extent of axial dispersion.

In the second part of the study, two-phase experiments were performed to capture the hydrodynamics of the complex nature of flow subjected to multiphase interaction on employing a single radioactive particle for Time of Flight (TOF) measurements. To complement the results from TOF analysis, pressure drop and holdup measurements were also conducted. This data has been interpreted in a novel manner to discern the flow regimes that exist in two phase flow through coiled geometries.

The most significant and challenging part of this work has been in the implementation of novel flow imaging technique Radioactive Particle Tracking (RPT), arguably for the first time on a coiled (non-regular) geometry. RPT is used to characterize the flow behaviour in a coiled tube for investigating the hydrodynamics (single and two-phase flow) in terms of the instantaneous, mean and fluctuating components of flow and thus provides insights of flow therein. In case of multiphase flows, the data from tracer particle occurrence density was interpreted to obtain volume fraction (VOF) distribution, which characterizes the flow patterns for air-water and oil-water flow through coiled geometry. Aside from the actual implementation of RPT technique and possibly the first complete experimental visualization of Dean circulation, this work also discussed various implementation challenges for RPT in coiled geometries, and the solution to such challenges (both theoretically, as well as through suitable experimental implementation).

Finally, the vision to achieve further process intensification using coiled geometries has resulted in novel designs of rectangular spiral pattern-compact coiled flow inverter (RSP-CCFI) and crosshatch pattern-compact coiled flow inverter (CHP-CCFI). The CHP-CCFI design, as presented in this work, gives more intensified mixing per unit occupied floor area in comparison to existing coiled tubes and coiled flow inverter (CFI).

## सार

कुंडली ट्यूब्स के माध्यम से प्रवाह के पार अनुभाग में जुड़वां व्हाटिस के साथ जुड़ा हुआ है (कुंडली वक्रता द्वारा लगाए गए केन्द्रापसारक बलों के कारण मध्य प्रवाह के स्थानीय दिशा में सीधा)। इस तरह के प्रवाह पैटर्न, डीन परिसंचरण के रूप में जाना जाता है, माना जाता है कि अच्छा रेडियल मिश्रण होता है। अध्ययनों ने स्थापित किया है कि लामिना प्रवाह में भी, समान लंबाई और मात्रा की सीधी ट्यूब की तुलना में, एक संकुचित निवास समय वितरण (आरटीडी) तरंग प्रवाह के लिए एक स्याही रास्ते से प्राप्त किया जा सकता है। जटिल अणुओं या गर्मी-संवेदनशील सामग्री के प्रसंस्करण के लिए, जिनमें से अधिकांश आमतौर पर चिपचिपा होते हैं और निचले रेनॉल्ड्स के प्रवाह की संख्या रखते हैं, ऐसे कुशल रेडियल मिश्रण (लामिना प्रवाह प्रवाह में होने के दौरान) के फायदे काफी हैं।

कई साहित्य योगदानों में अक्षीय फैलाव को कम करने में कुंडित ज्यामितीय (कॉयलेड ट्यूब और कॉइल फ्लो इनवर्टर) के लाभों को दिखाया गया, और इस तरह कोई भी उचित दबाव ड्रॉप दंड के बिना गर्मी और बड़े पैमाने पर स्थानांतरण बढ़ गया। हालांकि, इन दावों को परिवहन गुणांक के समग्र माप और कुंडल ज्यामिति के व्यवहार के आधार पर प्रक्रिया इकाइयों के आधार पर किया गया है। इसके अलावा, डीन के प्रवाह के तहत वेग प्रोफाइल की कोई प्रत्यक्ष माप कभी भी नहीं दर्ज किया गया है; इसके अलावा, कोई स्पष्ट तस्वीर नहीं है कि अभी तक यह दिखाया गया है कि दूसरे चरण के साथ क्रॉस-सेक्शनल परिसंचरण कैसे विकसित होता है। दो चरण के प्रवाह की जटिल प्रकृति की सीमित समझ उद्योगों में अपने बड़े अनुप्रयोगों का विरोध करती है। इस प्रकार, एकल और मल्टीफेस प्रवाह (केवल तरल, गैस-प्रकार के प्रवाह का उपयोग करके), इस काम की प्रेरणा, एक व्यापक प्रवाह सीमा (कोमलता के साथ-साथ अशांत प्रवाह व्यवस्था को कवर करने पर) कोयल जियोमेट्रीज़ (कॉयलेड ट्यूबों और कॉयल फ्लो इनवर्टर) के प्रदर्शन का पता लगाने के लिए किया गया है। (तरल और तरल तरल)।

अध्ययन के पहले भाग में, रेसटाइस् टाइम डिस्ट्रीब्यूशन (आरटीडी) और दबाव ड्रॉप प्रयोग सीधे ट्यूबों और विभिन्न कॉयल कॉन्फिगरेशन (अलग-अलग ज्यामितीय पैरामीटरों जैसे प्रवाह उलटा (एन) और वक्रता अनुपात ()) पर समान मात्रा के लिए आयोजित किए गए थे प्रवाह पर इन डिजाइन पैरामीटर के सापेक्ष महत्व की जांच करें। इस अध्ययन के परिणाम प्रवाह वेगों की एक बहुत बड़ी सीमा पर स्याही प्रवाह के लिए तीन अलग-अलग जोन दिखाते हैं, स्पष्ट रूप से लामिना से अशांत प्रवाह व्यवस्था में। इनके अलावा, इस काम ने "मास्टर प्लॉट" के संदर्भ में अक्षीय

फैलाव की सीमा के लिए रुझान स्थापित किए हैं; और अक्षीय फैलाव की सीमा पर द्रव गुणों और कुंडली के आयामों के प्रभाव के बारे में विचार करने के लिए एक स्केलिंग रिश्ते की पहचान की।

अध्ययन के दूसरे भाग में, टाइम-फ्लाईट (टीओएफ) माप के लिए एक एकल रेडियोधर्मी कण को रोजगार पर बहुपक्षीय संपर्क के अधीन प्रवाह के जटिल प्रकृति के हाइड्रोडायनामिक्स पर कब्जा करने के लिए दो-चरण प्रयोग किए गए थे। टीओएफ विश्लेषण के परिणामों को पूरा करने के लिए दबाव ड्रॉप और होल्डअप माप भी आयोजित किए गए थे। इस डेटा को एक नए तरीके से व्याख्या किया गया है ताकि प्रवाही नियमों को पता लगाया जा सके जो दो चरण के प्रवाह में कुंड भौतिकी के माध्यम से मौजूद होते हैं।

इस काम का सबसे महत्वपूर्ण और चुनौतीपूर्ण हिस्सा, उपन्यास प्रवाह इमेजिंग तकनीक रेडियोधर्मी कण ट्रैकिंग (आरपीटी) के कार्यान्वयन में रहा है, जो पहले से एक कुंड (गैर-नियमित) ज्यामिति पर पहली बार है आरपीटी का उपयोग प्रवाह के तात्कालिक, माध्य और अस्थिर घटकों के संदर्भ में हाइड्रोडायमिक्स (एकल और दो चरण के प्रवाह) की जांच के लिए एक coiled ट्यूब में प्रवाह व्यवहार को चिह्नित करने के लिए किया जाता है और इस प्रकार उसमें प्रवाह की अंतर्दृष्टि प्रदान करता है बहुपक्षीय प्रवाह के मामले में, रेखा अंश (वीओएफ) वितरण प्राप्त करने के लिए ट्रेसर कण घटना घनत्व से डेटा की व्याख्या की गई थी, जो कुंडली ज्यामिति के माध्यम से वायु-पानी और तेल-जल प्रवाह के प्रवाह के लक्षणों को दर्शाती है। आरपीटी तकनीक के वास्तविक कार्यान्वयन और संभवतः डीन परिसंचरण के पहले पूर्ण प्रयोगात्मक दृश्य के अलावा, इस काम में सीपीयेट भौगोलिक में आरपीटी के लिए विभिन्न कार्यान्वयन चुनौतियों और इस तरह की चुनौतियों का समाधान (सैद्धांतिक रूप से, साथ ही उपयुक्त प्रायोगिक कार्यान्वयन के माध्यम से) पर भी चर्चा हुई। ।

अंत में, कोयल जियोमेट्री का उपयोग करने के लिए आगे की प्रक्रिया गहनता प्राप्त करने के लिए दृष्टिकोण में आयताकार सर्पिल पैटर्न-कॉम्पैक्ट कॉयल फ्लो इन्वर्टर (आरएसपी-सीसीएफआई) और क्रॉसहेच पैटर्न-कॉम्पैक्ट कॉयल फ्लो इन्वर्टर (सीएचपी-सीसीएफआई) के उपन्यास डिजाइन शामिल हैं। सीपीपी-सीसीएफआई डिजाइन, जैसा कि इस काम में प्रस्तुत किया गया है, विद्यमान कोल्ड ट्यूबों और कॉयल फ्लो इन्वर्टर (सीएफआई) की तुलना में प्रति यूनिट पर कब्जा कर लिया गया फ्लोर एरिया का अधिक तीव्र मिश्रण प्रदान करता है।

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