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研究課題名（和文）Micro-tomographic measurements of elastic turbulence

研究課題名（英文）Micro-tomographic measurements of elastic turbulence

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交付決定額（研究期間全体）：（直接経費）　　3,500,000円

研究成果の概要（和文）：本研究では、最新の3D流れ測定技術を活用して、弾性乱流(ET)の流れ状態において流れるポリマー溶液を完全に測定し、ETを初めて完全に定量化します。ETは混合、熱輸送、高効率な油回収などの産業的な可能性を持っています。私たちは選択的レーザー誘起エッチング（SLE）によって構築された新しいマイクロ流体デバイスを使用して、広範な空間スケールでのETの進化を探求します。流れの運動学と流体の流れ学を組み合わせることで、ETの伝搬を流れ抵抗と弾性応力との間のフィードバックとして関連付けます。

研究成果の学術的意義や社会的意義
The results from this work have fundamental and industrial applications not only to elastic turbulence in general, but to viscoelastic porous media flow in particular, and to the use of microtomographic PIV for microfluidic research. This has yielded several publications in international journals.

研究成果の概要（英文）：Elastic turbulence (ET) is a nascent area of research in fluid mechanics, first classified only 20 years ago. ET is a chaotic flow state driven by nonlinear microstructure (i.e., polymer chains) stresses reacting with the flow, which has industrial potential for mixing, heat transport, enhanced oil recovery, and groundwater remediation as some examples. ET is inherently three-dimensional (3D), but until now has only been characterized in 2D. In this study we leverage state-of-the-art micro-scale 3D particle image velocimetry to fully measure the ET flow state. We combine this approach with novel microfluidic devices constructed from selective laser-induced etching (SLE) to probe the evolution of ET over broad spatial scales. Using flow kinematics coupled to the fluid rheology we relate the propagation of ET as the feedback between flow resistance and elastic stresses.

研究分野：Fluid-structure interaction

キーワード：Microfluidics　polymer solution　flow instability　Tomographic PIV　Viscoelasticity　porous media flow

１．研究開始当初の背景

Elastic turbulence (ET) is a nascent area of research in fluid mechanics, first classified only 20 years ago. ET is a chaotic flow state driven by nonlinear microstructure (i.e., polymer chains) stresses reacting with the flow, which has industrial potential for mixing, heat transport, enhanced oil recovery, and groundwater remediation as some examples. ET is inherently three-dimensional (3D), but until now has only been characterized in 2D. In this study we leverage state-of-the-art micro-scale 3D particle image velocimetry to fully measure the ET flow state. We combine this approach with novel microfluidic devices constructed from selective laser-induced etching (SLE) to probe the evolution of ET over broad spatial scales. Using flow kinematics coupled to the fluid rheology we relate the propagation of ET as the feedback between flow resistance and elastic stresses.

２．研究の目的

The purpose of the project was:

(1) Take the first volumetric flow measurements of elastic turbulence.
(2) Delineate the transition from laminar to elastic turbulence.
(3) Relate coherent structures in ET to the flow field and pressure fluctuations.
(4) Extend the use of microtomographic PIV for microfluidic research.

３．研究の方法

The research method involved:

(1) Preparation of refractive-index matched dilute polymer solutions with viscoelastic properties quantified in sheer and extensional rheometers.
(2) Manufacturing of glass microfluidic devices by selective laser-induced etching
(3) Impose flow through the device while imaging on a stereomicroscope for 3D PIV. Monitor the pressure drop along the device using a pressure transducer and data acquisition system.
(4) Analyze the time-resolved 3D flow fields for flow kinematics, the velocity gradient tensor, and established elastic instability criteria.

４．研究成果

The research has proven successful in providing the first 3D quantification of ET over broad spatial scales, the results of which have driven several publications in international peer-reviewed journals and international conferences. The insights gained are relevant not only to non-Newtonian fluid mechanics, but to more general biological and industrial applications as well.

Viscoelastic fluids exhibit dual viscous and elastic behaviours due to a microstructural contribution, such as polymer chains, which respond elastically under strain. Thus, viscous fluids can also sustain an elastic response. Viscoelastic solutions relax with a characteristic relaxation time λ, and if the local shear rate is sufficiently strong an elastic flow instability may occur. This is described by the Weissenberg number $Wi = \lambda U/L$ for a characteristic flow rate velocity U and length scale L.

Microtomographic particle image velocimetry is an image-based flow quantification measurement whereby synchronous imaging from different line of sight of a common volume of interest can be related to reconstruct the flow of a particle-laden fluid over time. To begin we considered a glass contraction-expansion section. This is a canonical geometry for viscoelastic instability, but the current work is the first to capture this flow in 3D at any length scale, let alone with the associated difficulties of working at micro-scale.

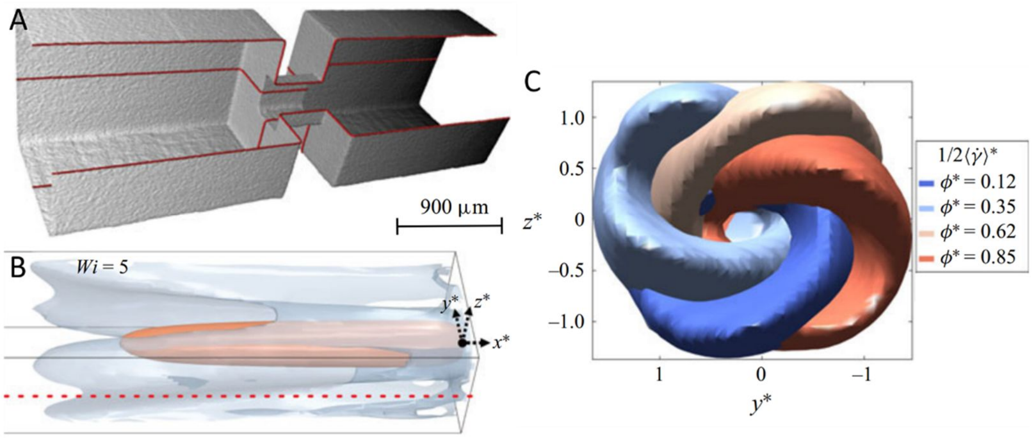

Figure 1: Computed x-ray tomographic surface of the glass microfluidic channel. (B) isosurfaces of flow velocity demarcating the primary flow instability: separation of a polymer flow from the walls upstream of the contraction. (C) isosurfaces of the rate-of-strain tensor at Wi = 87 to infer the feedback of strain hardening on the circulation of the central jet. Reproduced from [1].

For a dilute (107 ppm) polyacrylamide solution flowing through the contraction, a primary viscoelastic flow instability occurs above a critical Wi_c whereby flow separates from the walls upstream of the contraction, driving a corner eddy about the salient corners of the contraction (figure 1 [1]). At higher Wi the flow becomes time-dependent yet periodic, and near Wi = 80 develops a chaotic response. From a spectral analysis we can infer that elastic turbulence (ET) has developed in this geometry (a steep decay of -3.5 in the fluctuating velocity power spectrum), however a hurdle in applying this description is that ET is typified by the dominance of the nonlinear interaction of a few large-scale spatial modes. To wit, at the scale of the contraction. In order to probe ET evolving in 3D we thus need to consider several vessel scales.

We manufactured a novel ordered porous medium also from glass with the SLE method as a uniform grid of 70x5x5 spheres. In this system, imaging flow about a given elevation will thus elucidate the history flow as it propagates through the array. We use a similar PAA formulation as [1]. We compare the fluctuating pressure and velocity power spectra to confirm the ET flow state at Wi > 2 with power law decays of -3 and -3.5, respectively. Close to Wi = 2, an elastic instability manifests as streamline excursion between neighboring pores in crossflow. We further quantified this state via an established elastic instability criterion (Pakdel-McKinley criterion [3-4]). With this metric we see that the unstable state can propagate upstream due to locally increased flow resistance (decreased velocity U), and furthermore that the unstable state precludes the possibility of flow instability in crossflow peers.

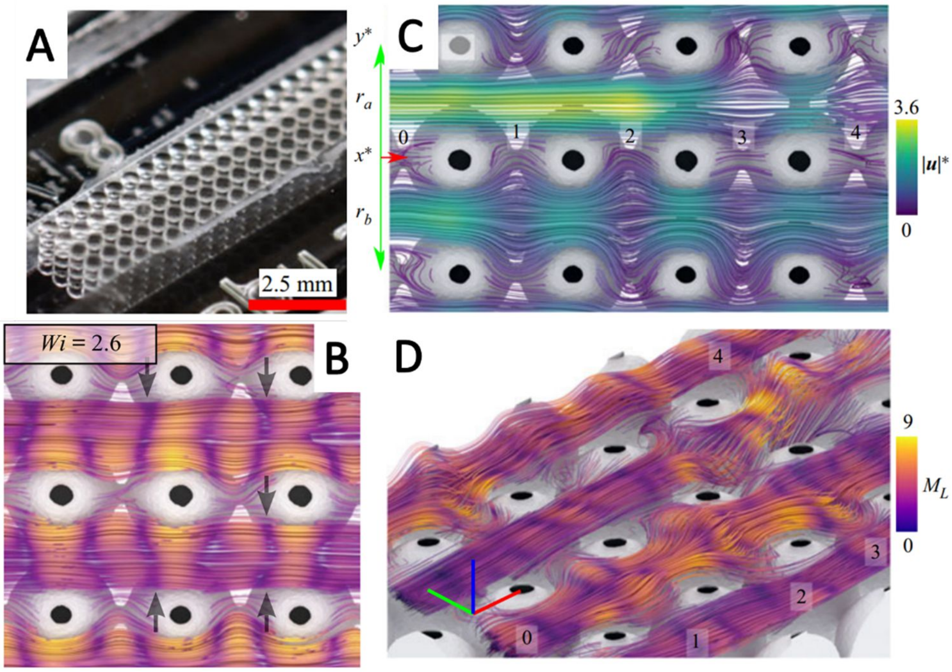

Figure 2: (A) The glass array of spheres. (B) Onset of elastic instability typified by extruding streamlines (coloured by M_L [3-4])[. (C, D) Streamlines at Wi = 8.2 coloured by dimensionless velocity magnitude u and M_L. Reproduced from [2].*

These findings mark a significant step towards the understanding of elastic turbulence. As the first volumetric assessment of ET over broad spatial scales, whether experimental or numerical, this research gives better understanding to the nature of ET in general, and furthermore has implications for porous media flow and for the use of microtomographic particle image velocimetry as a method for microfluidic research [5].

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[1] D. W. Carlson, A. Q. Shen, S. J. Haward. Microtomographic particle image velocimetry measurements of viscoelastic instabilities in a three-dimensional microcontraction. Journal of Fluid Mechanics, 923, R6, (2021).

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５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　3件）

１．著者名 Carlson Daniel W.、Shen Amy Q.、Haward Simon J.	４．巻 923
２．論文標題 Microtomographic particle image velocimetry measurements of viscoelastic instabilities in a three-dimensional microcontraction	５．発行年 2021年
３．雑誌名 Journal of Fluid Mechanics	６．最初と最後の頁 R6
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/jfm.2021.620	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Carlson Daniel W.、Toda-Peters Kazumi、Shen Amy Q.、Haward Simon J.	４．巻 950
２．論文標題 Volumetric evolution of elastic turbulence in porous media	５．発行年 2022年
３．雑誌名 Journal of Fluid Mechanics	６．最初と最後の頁 A36
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/jfm.2022.836	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Haward Simon J.、Pimenta Franciso,、Varchanis Stylianos,、Carlson Daniel W.、Toda-Peters Kazumi,、Alves Manuel A.、Shen Amy Q.	４．巻 In press
２．論文標題 Extensional rheometry of mobile fluids. Part I: OUBER, an optimized uniaxial and biaxial extensional rheometer	５．発行年 2023年
３．雑誌名 Journal of rheology	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　2件）

１．発表者名 Carlson Daniel W.、Shen Amy Q.、Haward Simon J.
２．発表標題 Microtomographic particle image velocimetry measurements of viscoelastic instabilities in a three-dimensional microcontraction
３．学会等名 European Fluid Mechanics Conference（国際学会）
４．発表年 2022年

１．発表者名 Carlson Daniel W.、Toda-Peters Kazumi、Shen Amy Q.、Haward Simon J.
２．発表標題 Volumetric evolution of elastic turbulence in porous media
３．学会等名 Society of Rheology（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関