様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　２年　６月１６日現在

機関番号：３８００５
研究種目：若手研究(B)
研究期間：2017～2019
課題番号：１７Ｋ１４５９４

研究課題名（和文）Test of the universality class for the transition to turbulence in pipe flow

研究課題名（英文）Test of the universality class for the transition to turbulence in pipe flow

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交付決定額（研究期間全体）：（直接経費）　2,700,000円

研究成果の概要（和文）：パイプ流が層流から乱流へ遷移される時に、層流の中に渦巻いている流れ、「パッフ」と「スラグ」、が局在的に生じる。乱流は今まで遷移領域と遙かに違うように思われていたにもかかわらず、異なるパッフとスラグはどうやって層流から乱流へ仲介することが殆ど取り調べられていない。当研究でこの遷移構造は詳細まで高い流速の乱流と一致していることが明らかにされた。摩擦係数、速度分布の普遍性などでこのことを証明した。この結果によって、乱流遷移と乱流の必要な繋がりを見つけ出した。

研究成果の学術的意義や社会的意義
The results obtained by our research efforts allow researchers to use the multitude of tools from high Reynolds number turbulence to study the transition. This is of practical use as well, since engineers now have the information necessary to predict energy costs for transitioning pipelines.

研究成果の概要（英文）：When pipe flow transitions from the laminar to the turbulent state, packets of eddying flow called "puffs" and "slugs" invade the laminar flow. Although turbulence has long been understood to be different from this transitional regime, how these different puffs and slugs can act as mediators of the transition has not been investigated. In our research we showed in detail that puffs and slugs have the same quantitative structure as fully developed turbulence by looking at diagnostics such as friction and the universality of velocity fluctuation statistics. This result furnishes the necessary link between turbulence and its transition.

研究分野：乱流

キーワード：乱流遷移

１．研究開始当初の背景

At low flow speeds, pipe flow is laminar: smooth, regular and without fluctuations. At high flow speeds the flow becomes turbulent: rough, irregular and with fluctuations. The transition from laminar to turbulent flow in pipes proceeds through several distinct stages occurring over specific ranges of the non-dimensional Reynolds number Re = UD/ν, where U is the mean flow speed, D is the pipe diameter, and ν is the kinematic viscosity. Laminar flow persists for any initial condition for Re ≲ 1600. In the range 1600 ≲ Re ≲ 2250 and with suitably large perturbations, localized patches of fluctuating flow invade the laminar flow which are called "puffs". Puffs always remain of fixed size, although they can spontaneously die, and (at least in constant pressure gradient flows) split into two statistically identical puffs. For Re ≳ 2250, non-continuous perturbations will produce slugs, which unlike puffs do not decay or split but expand aggressively. At Re ≳ 2700, continuous perturbations will produce continuous fluctuations: turbulence. This complicated transition scenario is illustrated as a schematic in Fig. 1, where the horizontal axis is Re and the vertical axis is a qualitative representation of the strength of the perturbation to the laminar flow.

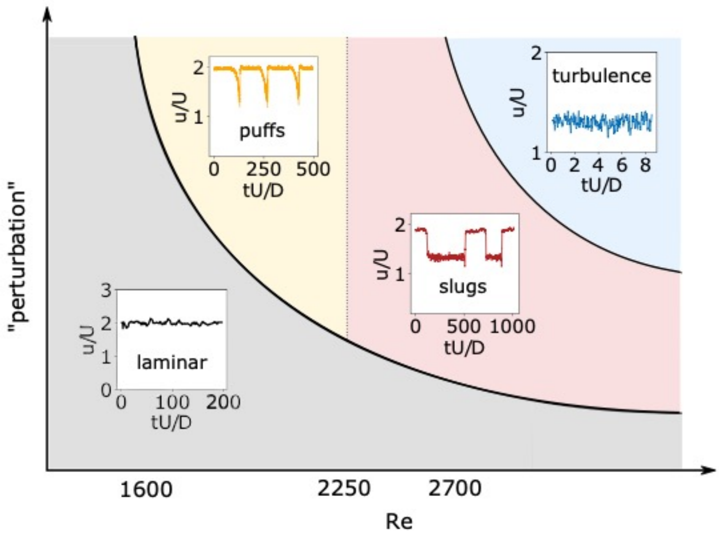

Figure 1: Schematic of pipe transition. In the time-series insets, the normalized velocity at the centerline is u/U = 2 when the flow is laminar. Deviations below this value with fluctuations indicate puffs, slugs or turbulence. As Re increases, the laminar flow becomes increasingly susceptible to perturbations, first allowing puffs (1600 ≲ Re ≲ 2250), then slugs (Re ≳ 2250), with sufficiently strong continuous perturbations giving rise to fully developed turbulence (Re ≳ 2700). Taken from Ref. [1].

Ever since Osborne Reynolds first observed puffs and slugs (both of which he called "flashes") [2], research has focused on discovering their large-scale behavior. The lifetime statistics, propagation speeds, and many other features are well documented, but there is no clear link between flashes and the high Re turbulence they precede. Based on their disparate behavior, puffs appear to be different from slugs, and both appear to be different from turbulence.

２．研究の目的

A main goal of the project was to demonstrate that the transition to turbulence in pipe flow belongs to (or does not belong to) the Directed Percolation universality class. This is a group of systems which outwardly appear very different: forest fires, diseases spreading through populations, and liquid percolating through a porous medium. And yet when near a critical point of some control parameter, the systems behave statistically the same. The control parameter for a percolating liquid is the probability that the liquid will be able to move to the next pore space, while for pipe flow it is Re. We quickly realized that before working on this goal, some important questions needed answering. In particular, the word "turbulence" is often used loosely to mean chaotic flow with fluctuations. However, in pipe flow and in many other systems, the meaning is much more exact. Turbulence, especially at high Re, possesses quantitative features such as the mean value of the velocity at different pipe radii, or the mean value of the friction (pressure drop) as a function of Re, or, even more fundamental, the statistics of velocity fluctuations at small scales. The loose use of the word "turbulence" encompasses high Re turbulence, puffs and slugs, since all of these are chaotic and have fluctuations, but it is not at all obvious that they are the same. In fact, based on the description above they appear very different. So before we can begin to talk about a transition to turbulence, we need to be clear about what we actually mean by turbulence. Before our work that addressed this question, there was apparently only one other study that tried to compare puffs, slugs and turbulence, the seminal work of Wygnanski et al. [3]. However, as we shall see, their important work required some re-examination.

３．研究の方法

We performed extensive experiments and simulations of pipe flow over a large range of Re. Fig. 2 shows a schematic of our experimental setup, which is a recirculating pipe system driven by gravity (for stability) with water as the working fluid. We measured the flow rate, the pressure drop over different sections of the pipe, and the flow velocity using a Laser Doppler Velocimeter (LDV). More information about the experiments can be found in [4]. The simulations were performed using the open-source, hybrid spectral code Openpipeflow [4]. We benchmarked the code using well-known results from previous experiments and simulations for the mean velocity profile and rms profile at Re = 5300, and ran simulations that complemented the experimental findings.

４．研究成果

A. Friction

A problem seemingly unrelated problem to determine whether puffs and slugs are turbulent is to determine the fluid friction f in the transition. Here $f = 2D\Delta P/\rho L U^2$, where ΔP is the pressure drop over a length of pipe L and ρ is the density. Reynolds demonstrated that f is a unique but vastly different function of Re for both laminar and fully turbulent flows [2], but neither he nor anyone else has been able to determine any "laws of resistance" for transitional flows (flows with puffs and slugs surrounded by laminar flow). Standard engineering plots of f vs. Re, Moody diagrams, leave the transitional region blank or hashed out.

Using extensive experiments and simulations, we recently showed that by taking (conditional) averages over the puffs and slugs and surrounding laminar flow separately (which required technical innovation such as sufficiently reducing L), the jumble of data in the transition resolves into the two original laws of resistance that Reynolds had already found for laminar and turbulent flows [2] (see Fig. 2). The friction inside puffs and slugs is the same as fully turbulent flow. Thus not only did we uncover the source of confusion for laws of resistance in the transition, but we also gained a key insight into the transition itself: despite all outward differences, puffs and slugs share some of the same quantitative features as turbulence.

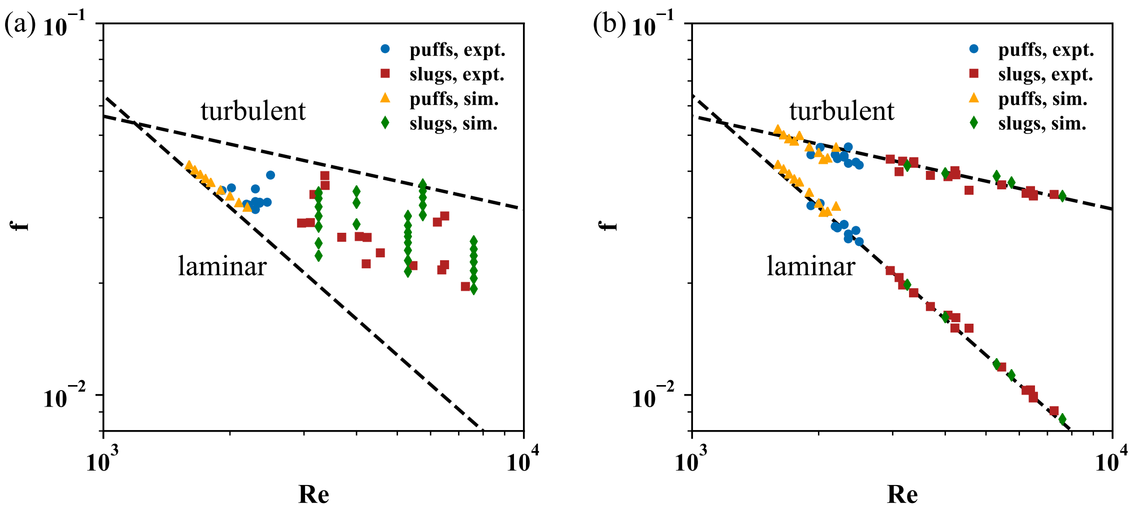

Figure 2: (a) Friction data highlighting the "complexity" of the transition region, where the aver- age is taken over all time and space for a particular Re. (b) After looking at the puffs, slugs, and laminar portions of the intermittent transitional flow separately, the friction factors collapse on the well-known laminar and turbulent laws. Taken from Ref. [3].

B. Velocity fluctuations

More recent work continued this theme for the velocity fluctuations inside puffs and slugs [1]. Over 70 years ago, A.N. Kolmogorov predicted that at small scales, all truly turbulent flows should look the same [6]. More specifically, he predicted that at very small scales the energy spectra E(k), where k is the wavenumber, will collapse onto a universal curve when normalized by the viscous dissipation scale η and the viscosity ν. However, as the title of his seminal paper suggests, "The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers", this universality is only expected for very large Re. The basic reason for this expectation is that the "scale separation", or separation between the non-universal large scales and the potentially universal small scales, increases with Re. (See inset to Fig. 3b.) Most experiments and simulations, in accord with this expectation, have pushed to ever higher Re. In our work we did just the opposite. We took the limit of decreasing Re to the final point where fluctuations can be observed at all: transitional flows. To our knowledge, no one has tested for Kolmogorov's universality in any transitional flow, nor would anyone expect it. Nevertheless, the structure of the fluctuations in transitional puffs and slugs, as represented by E(k), is of the same stuff as turbulence.

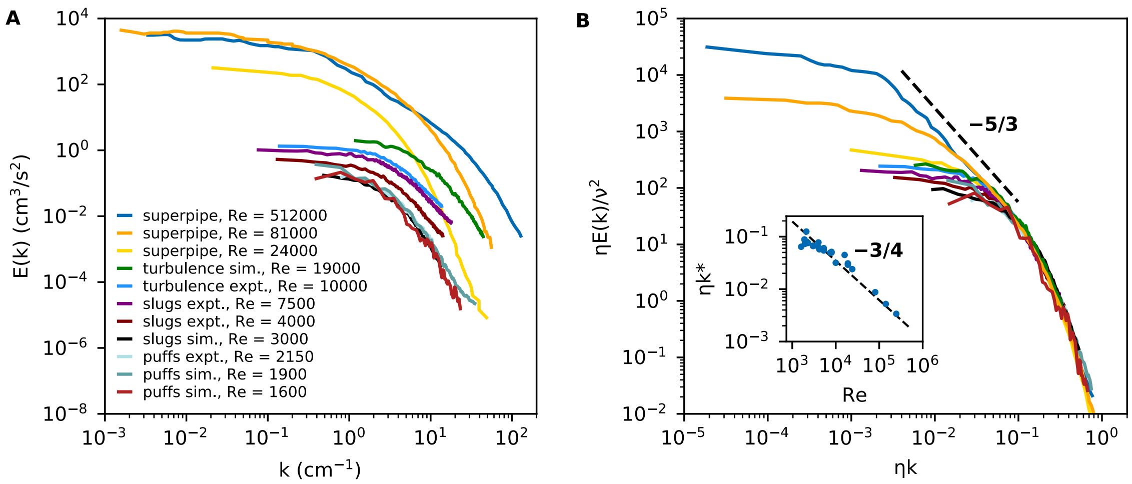

Figure 3: Testing small-scale universality. (A) Plots of spectra, E(k) vs. k, for several epresentative puff flows, slug flows, and turbulent flows from our experiments and DNS; we also show a few high-Re turbulent flows from the high Re superpipe experiment. (B) Plots of rescaled spectra, ηE(k)/ν2 vs. ηk, corresponding to the flows in panel A. Irrespective of the type of flow, the rescaled spectra at high ηk collapse onto a common universal curve. At Re ≳ 80, 000, the rescaled spectra conform not only to small-scale universality but also to the 5/3 law. Inset (panel B): the scaling of data points (ηk∗, Re) is also in accord with the Kolmogorovian framework. Taken from Ref. [1].

C. Wygnanski and slugs

Using both fluid friction and velocity spectra as diagnostics, we showed that puffs and slugs are equivalent to each other and to turbulence. This result is partially in accord and partially in disagreement with the well-known work of Wygnanski and co-workers [3], who claimed that puffs are different from fully turbulent flow, while "the structure of the flow in the interior of a slug is identical to that in a fully developed turbulent pipe flow". Leaving puffs aside, we focused on slugs. Unfortunately, a re-analysis of Wygnanski et al.'s evidence for their strong conclusion [3], the mean velocity profiles, root-mean-square velocity profiles and total stress profiles, actually appears to show that slugs are not the same as fully turbulent flow. If this is true, and if our previous two results for friction and velocity spectra are true, then this leaves us with a strange situation in which slugs possess only some of the properties of turbulence. To rectify this situation we redid the classic experiments of Wygnanski et al. [3], as well as performed numerical simulations, and reanalyzed the same diagnostic tools they did. We found that a key issue not addressed by Wygnanski et al. [3] was the Re-dependence of these diagnostics at low Re. Once this was taken into account correctly, by comparing slugs and fully turbulent flow at the same Re, we could properly show for the first time that slugs and fully turbulent flow are identical [7] (see Fig. 4). We also showed how the flow at the interface between slugs and the surrounding laminar flow evolves from being laminar on the outside to fully turbulent on the inside of the slug. This result highlights the rich Re-dependence of transitional pipe flows.

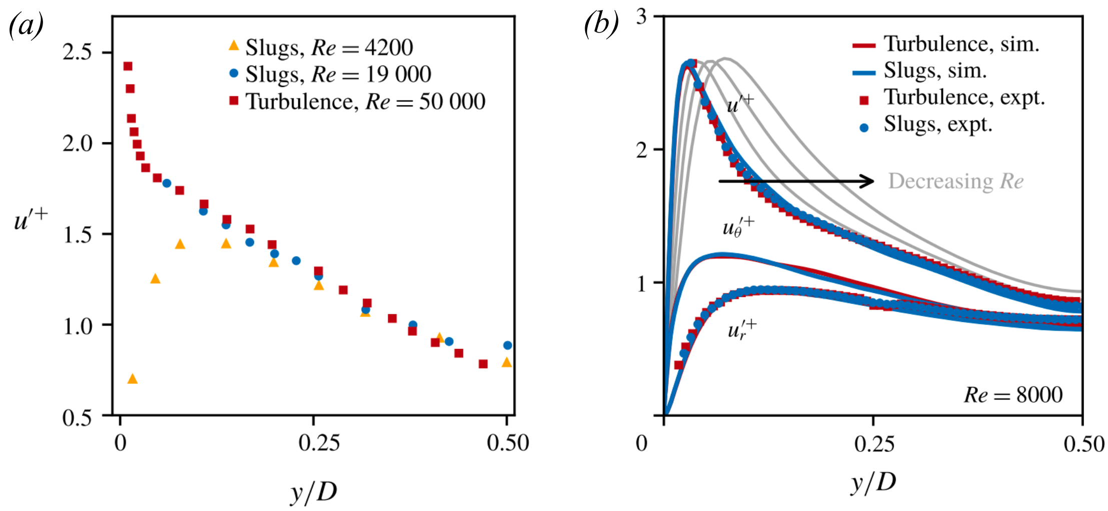

Figure 4: Comparing slug flow and fully turbulent flow using r.m.s. profiles. (a) The evidence provided by Wygnanski et al. [3]. Here only the streamwise component is included. There are significant disparities between especially the low Re profile and the turbulent benchmark. (b) Plot of r.m.s. profiles from our experiments (expt.) and DNS (sim.) for Re = 8000 for all three velocity components. We include the curves from DNS at lower Re (fully turbulent flow) in grey to highlight the Re-dependence of the r.m.s. profiles. Taken from Ref. [7].

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５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Rory T. Cerbus, Chien-chia Liu, Gustavo Gioia, and Pinaki Chakraborty	４．巻 120
２．論文標題 Laws of Resistance in Transitional Pipe Flows	５．発行年 2018年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 54502
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.120.054502	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12件（うち招待講演　9件／うち国際学会　1件）

１．発表者名 Rory T. Cerbus
２．発表標題 The turbulent flow in a slug
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３．学会等名 Fluid Mechanics Research Group at the University of Melbourne, Australia（招待講演）
４．発表年 2019年

１．発表者名 Rory T. Cerbus
２．発表標題 Friction and fluctuations in transitional pipe flow
３．学会等名 Physics Department at the Australian National University, Australia（招待講演）
４．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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