IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Study Of Laminar–Turbulent Transition In Pipe And Channel Flows

[1]Rajshekhar S Heera, [2]Dr. Sanjeevkumar D
[1]Senior Scale Lecturer, [2]Selection Grade Lecturer
[1,2]Department of Science
[1]Government Polytechnic Kalaburagi, [2]Government Polytechnic Aurad (B), Bidar India

Abstract: Since Osborne Reynolds' pioneering experiments in the nineteenth century, pipe flow has been regarded as a fundamental model for exploring the transition from laminar to turbulent motion in wall-bounded systems. Although the configuration of this flow appears straightforward, it has challenged and intrigued researchers for well over a century. In this review, we examine the transition problem from three complementary viewpoints: (a) the stability and vulnerability of laminar flow, (b) phase-transition concepts and spatiotemporal dynamics, and (c) dynamical systems approaches applied to the Navier–Stokes equations. These perspectives together have provided deep insights into the mechanisms underlying the emergence of turbulence in pipe flow. Finally, we highlight unresolved issues, extend the discussion to flows involving complex fluids, and draw parallels with other wall-bounded flow situations.

Index Terms -insert shear flow, transient growth, turbulent puff, turbulent slug, intermittency, transient chaos, directed percolation.

I. INTRODUCTION

What we truly cannot yet resolve is the behavior of real water flowing through a pipe. That is the central challenge that remains unsolved." This remark by **Richard Feynman (Feynman et al., 1963)** highlights how the seemingly ordinary motion of fluid through a pipe continues to pose one of the most fundamental and difficult problems in fluid mechanics. The difficulty arises because fluid flow in a pipe can shift from orderly laminar motion to chaotic turbulence—a process known as the **transition to turbulence**.

The concept of transition can be interpreted differently depending on perspective. An **engineer** might focus on the stability of the laminar state, asking how sensitive it is to external disturbances and identifying the threshold Reynolds number as a function of flow rate (Figure 1a). A **physicist** may treat the phenomenon as a type of phase transition, aiming to pinpoint the critical conditions under which turbulence first emerges (Figure 1b). A **mathematician**, in contrast, may inquire into the origin of alternative solutions to the laminar state, the mechanisms by which these lead to chaotic dynamics, and the boundaries that separate turbulent and laminar regimes (Figure 1c).

For flows that display clear linear instabilities—such as **Rayleigh–Bénard convection** or **Taylor–Couette flow**—these questions are naturally unified within a single theoretical framework. However, in pipe flow, the transition problem is far more intricate, requiring distinct approaches to address each viewpoint. As a result, there is no single universal answer to the transition problem. In what follows, we explore the different facets of this transition in pipe flow, outlining the perspective, motivation, and key insights gained from each line of inquiry.

II. EXPERIMENTS

Before examining the three perspectives on transition, it is useful to first revisit several key experimental observations and historically significant studies. Many of the ideas introduced here will be elaborated and expanded upon in the subsequent sections of this review.

2.1 NATURAL TRANSITION:

Although **Newtonian pipe flow** is theoretically characterized solely by the Reynolds number (Re), laboratory observations reveal that the onset of turbulence can occur across a broad range of Re values. In his classic experiments, **Reynolds (1883)** demonstrated that the transition threshold could vary from approximately $Re \approx 2{,}000$ up to $Re \approx 13{,}000$ depending on the level of inlet disturbances. Subsequent studies, such as those by **Pfenniger (1961)**, showed that under carefully controlled conditions, laminar flow could be sustained even at $Re = 100{,}000$.

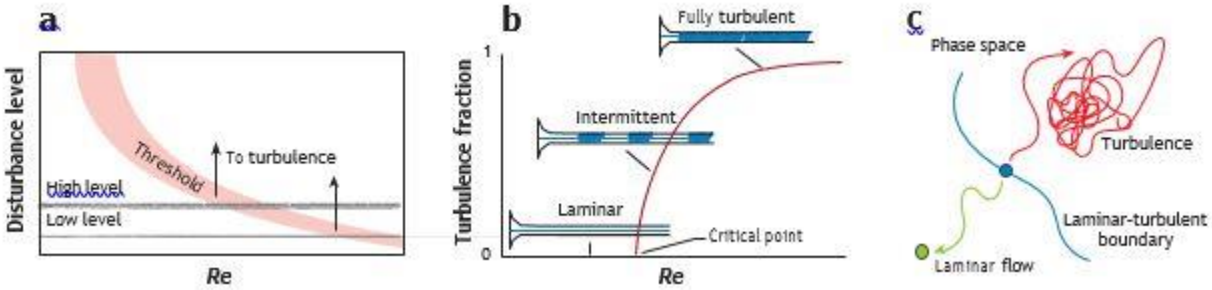


Figure 1 Shows Three perspectives on the transition problem for pipe flow. (*a*) Perspective of susceptibility of linearly stable laminar flow. Small disturbances to laminar flow may trigger a transition to turbulence beyond a certain Reynolds number *Re*, depending on both the level and the form of the disturbance. (*b*) Perspective of phase transitions. Once triggered, turbulence near onset is a spatiotemporally complex phenomenon whose critical behavior can be understood in the context of statistical phase transitions. (*c*) Perspective of the Navier–Stokes equations as a dynamical system. Each point in phase space represents a full velocity field. Trajectories, fixed points, and other sets in phase space provide a detailed understanding of the dynamics of turbulence.

We define the *natural transition point* as the effective threshold Reynolds number (Re) at which turbulence first appears in a given experimental apparatus. As outlined in Section 3, laminar **Hagen–Poiseuille (HP) flow** remains stable to infinitesimal disturbances even at very high, and possibly infinite, Reynolds numbers (Salwen et al. 1980; Meseguer & Trefethen 2003). Thus, turbulence arises only when finite-amplitude perturbations are introduced—an observation already noted by **Reynolds (1883)**. Since the susceptibility of HP flow to such perturbations increases with Re (see Figure 1a), minimizing noise and disturbances becomes essential for maintaining laminar flow at higher Re. This is particularly critical at the pipe entrance, where sophisticated inlet designs (e.g., Wygnanski & Champagne 1973) are required to sustain laminar flow well beyond Re = 10,000. Because experimental setups inevitably differ in their imperfections and background disturbance levels, the observed natural transition point varies accordingly.

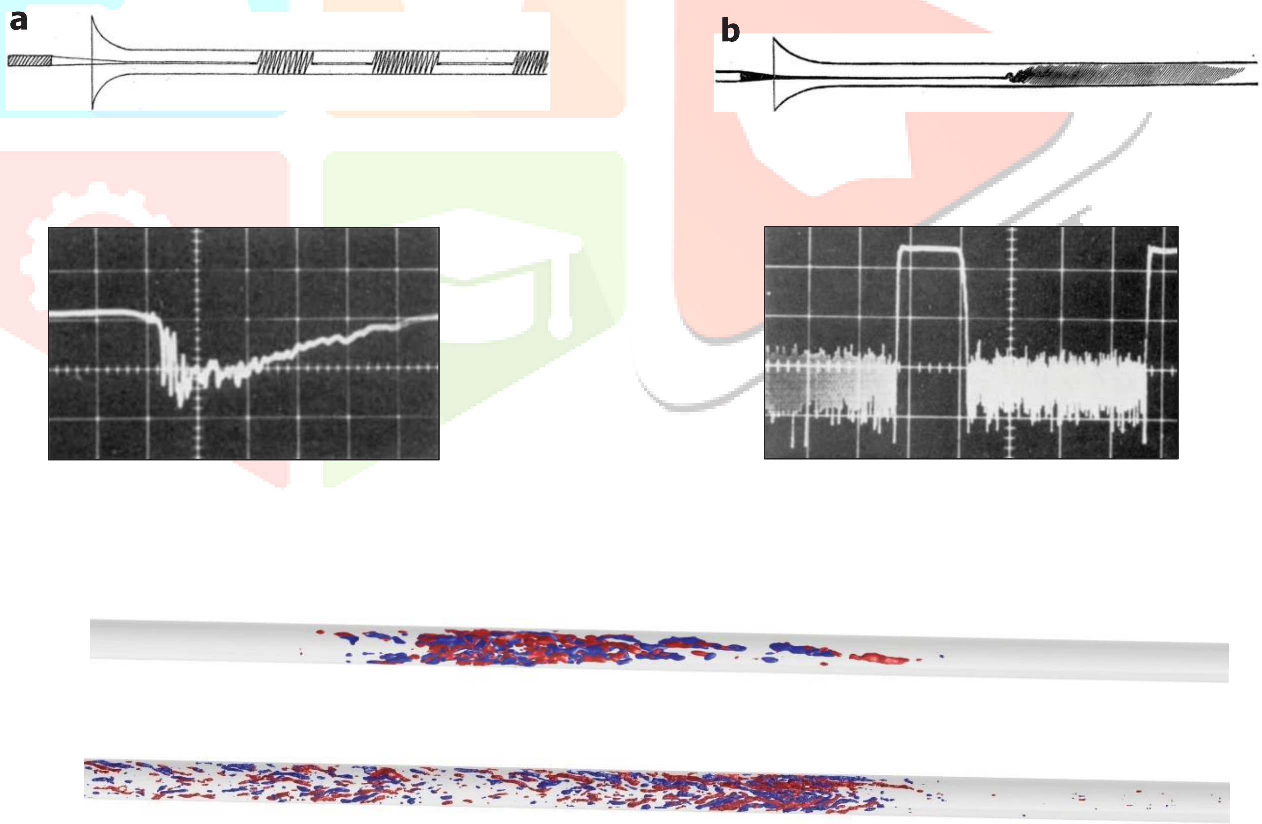
Even when laminar entrance conditions are achieved, the velocity profile at high Re may diverge significantly from the parabolic HP profile. In some cases, pipe lengths are insufficient for the fully developed parabolic profile to form, while at high Re even subtle influences such as the **Coriolis force** can produce notable distortions (Draad & Nieuwstadt 1998). As a result, the precise value of the natural transition point is shaped by multiple factors, and, in principle, flows in two otherwise identical setups may transition at very different Re—for example, due to variations in latitude, ambient temperature, or fluid properties.

2.2. REYNOLDS CRITICAL POINT

Since the natural transition point is highly dependent on the specifics of the experimental setup, **Reynolds (1883)** introduced a method to identify a reproducible critical threshold for the onset of turbulence (see sidebar *Reynolds Critical Point*). His approach involved deliberately perturbing the flow in a controlled manner and then examining, sufficiently far downstream, whether the flow remained laminar or developed turbulence. This procedure allowed the determination of a well-defined critical Reynolds number, beyond which turbulence could be sustained indefinitely in pipes of adequate length. Remarkably, this nineteenth-century insight aligns closely with the modern understanding of critical phenomena in systems characterized by the coexistence of an **absorbing state** (stable laminar flow) and an **active state** (turbulence). The Reynolds critical point is further discussed in Section 5.

2.3. LOCALIZED AND EXPANDING TURBULENCE: PUFFS AND SLUGS

At the lowest Reynolds numbers (Re) where turbulence can be sustained, it does not fill the pipe uniformly but instead appears as **localized structures**. In his pioneering experiments, **Reynolds (1883)** referred to these as *flashes*, though they are now more commonly known as *puffs* (see Figure 2a, c, e). Early experimental observations of puffs were reported by **Rotta (1956)** and **Lindgren (1957)**, with more detailed studies later conducted by **Wygnanski & Champagne (1973)**. Subsequent work has shown that turbulent puffs can exist at Re as low as ≈1,500 (**Hof et al. 2005**). These puffs are convected downstream at nearly the bulk flow velocity and exhibit a distinct, reproducible structure with well-defined spatial characteristics.



The **upstream front** of a puff is characterized by a sharp reduction in the centerline velocity, while downstream the velocity gradually recovers to its laminar profile (Figure 2c). As the Reynolds number increases, turbulence becomes less localized: puffs evolve into expanding turbulent regions known as **slugs** (**Wygnanski & Champagne 1973; Darbyshire & Mullin 1995**) (see Figure 2b, d, f). In contrast to puffs, the size of a slug is not fixed; rather, it depends on both the nature of the initial perturbation and the time elapsed since its formation.

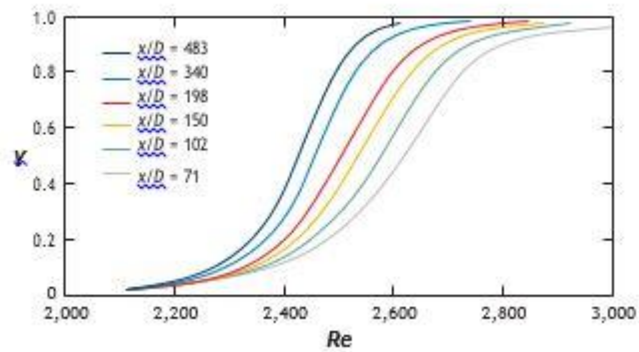
A deeper understanding of **puffs and slugs** is essential, as they represent fundamental building blocks in the study of pipe flow transition. Historically, these structures have played a central role in shaping our knowledge of turbulence onset. Moreover, the dynamics of puffs, in particular, are directly linked to determining the **Reynolds critical point**, as will be discussed in Section 5.

2.4. PERTURBATION SCHEMES

Using controlled perturbations to achieve reproducible behavior in experiments naturally raises two key questions: **what is the most effective way to disturb the flow, and does the nature of the disturbance influence the resulting flow states?**

2.4.1. CONTINUOUS PERTURBATIONS

In early experiments, continuous disturbances were often introduced using fixed static devices, such as an orifice at the pipe entrance. These perturbations produced more reproducible results compared to natural transition; however, they still fell short of converging to the true critical velocity originally anticipated by **Reynolds** (see Mukund & Hof 2012 for a discussion on proposed critical points). Figure 3 illustrates the experimental findings of **Rotta (1956)**, obtained using an orifice-generated disturbance. In these studies, the **intermittency factor (γ)**—which represents the fraction of the flow that is turbulent—was found to vary with the measurement location along the pipe. As the downstream distance increased, the proportion of turbulent flow also grew correspondingly.



At a fixed Reynolds number, the proportion of turbulence increases with downstream distance, leading to a leftward shift of the curves. This behavior demonstrates that, even several hundred pipe diameters downstream of the inlet, the flow has not yet reached a fully steady state. Such **long development lengths** present a major challenge in identifying the true critical point. They arise from the inherently long timescales governing the dynamics in this transitional regime, as will be discussed in Section 5.

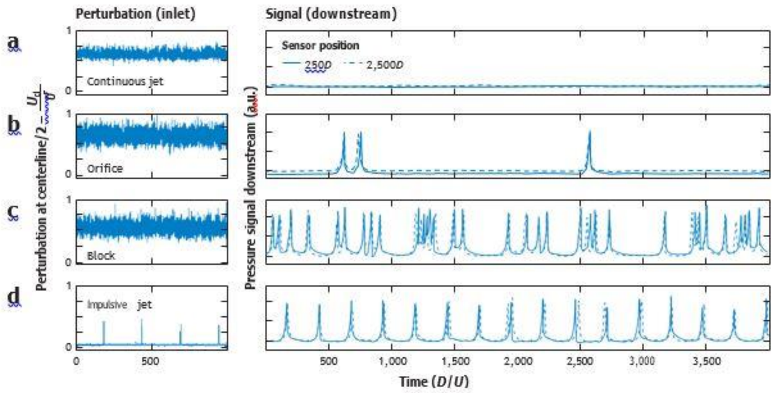
2.4.2. IMPULSIVE PERTURBATIONS

More recent experiments have employed **impulsive perturbations** (**Wygnanski et al. 1975; Darbyshire & Mullin 1995**), which are particularly well suited for studying transition. These disturbances are typically generated by injecting a short jet of fluid through one or more small holes in the pipe wall. A single pulse can trigger a localized turbulent structure, and such experiments demonstrated the robustness of **turbulent puffs** as near-equilibrium entities (**Wygnanski et al. 1975**), at least over typical laboratory observation times.

An advantage of impulsive perturbations is the ability to control the **timing** of the pulses, which introduces an additional experimental degree of freedom. The **pulse length** plays a decisive role in determining the scaling of the turbulence transition threshold (**Hof et al. 2003**), while the **pulse frequency** enables the study of interactions between localized turbulent structures (**Samanta et al. 2011**). Notably, impulsive perturbations can generate turbulence much more effectively at low Reynolds numbers than continuous disturbances. For example, as illustrated in Figure 4, a continuous jet disturbance—even one producing strong local fluctuations and profile distortions—fails to trigger puffs, leaving the downstream flow laminar. Similarly, an orifice at the pipe inlet generates puffs only sporadically and unpredictably. In contrast, impulsive perturbations reliably trigger puffs in a controlled fashion and with significantly lower disturbance amplitudes at the same Re.

This difference arises because puffs extract energy from the incoming laminar flow; a sufficiently developed **parabolic profile** is essential to sustain them (**van Doorne & Westerweel 2009**). Continuous disturbances disrupt this profile, and if their amplitude is large, the resulting velocity distribution becomes too flat to maintain puffs—paradoxically leading the flow to **relaminarize** (**Kühnen et al. 2012**). Furthermore, when two puffs are spaced too closely (less than ~20D), the downstream puff enters the energetically depleted wake of the upstream puff and decays (**Hof et al. 2010; Samanta et al. 2011**).

For these reasons, impulsive perturbations have become a central experimental tool, allowing single puffs to be triggered in a controlled and reproducible manner, even at low Re. Once formed, however, puffs lose any memory of their initial disturbance (Figure 4). While flow structures near the perturbation site may reflect the details of the applied pulse, sufficiently far downstream the puff dynamics are universal and independent of how they were initiated.



At distances greater than approximately **250D** downstream from the perturbation site, turbulent puffs become statistically indistinguishable on average. This universality also extends to injection perturbations that initially generate **hairpin vortex streets** (**van Doorne 2004; Peixinho & Mullin 2007; Philip & Cohen 2010; Wu et al. 2015**). Although hairpin vortex structures are typically triggered in the near-wall region, their downstream evolution depends on the Reynolds number: they may either **decay and relaminarize** or develop into sustained turbulence, forming **puffs or slugs** (**van Doorne 2004**).

3. INSTABILITY

From the preceding discussion, it is evident that **perturbations to laminar flow—whether natural or externally imposed—play a central role in experimental studies of pipe flow**. This observation leads directly to the first and historically oldest perspective on the transition problem: that of **hydrodynamic stability** (Figure 1a). Within this framework, the key questions concern **which perturbations are most effective in triggering turbulence** and how the **amplitude threshold for transition varies with Reynolds number (Re)** for a given perturbation type (Figure 1a).

3.1. Linear Approaches to the Problem of Transition

The stability of laminar HP flow $\mathbf{U}_{HP}$ to a perturbation $\mathbf{u}$ can be investigated by decomposing the full velocity field as $\mathbf{v} = \mathbf{U}_{HP} + \mathbf{u}$, and inserting this into the incompressible Navier–Stokes equations, in dimensionless form

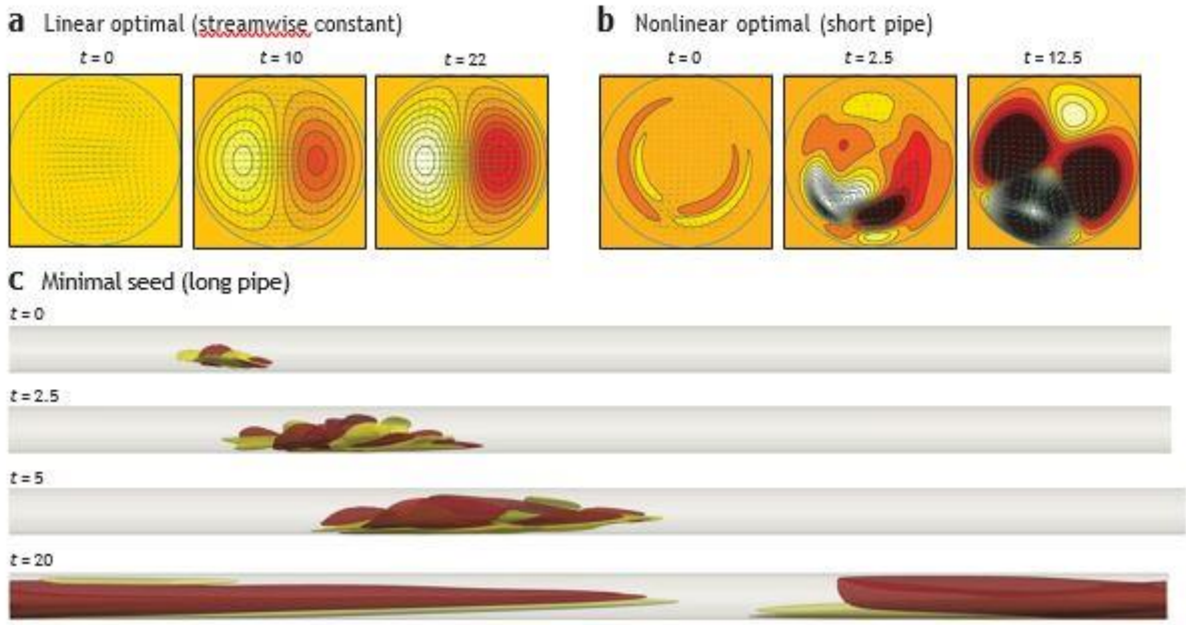


Figure 5

(*a*) Optimal linear nonmodal disturbance of pipe flow at Reynolds number *Re* = 1,750 consisting of a pair of streamwise vortices (*faint arrows*), which over time generates one streak of high streamwise velocity and one of low streamwise velocity. (*b*) Corresponding nonlinear optimal disturbance (t = 0) and its evolution for a pipe of length $L = (\pi/2)D$. In both panels, the color map runs from white and yellow, corresponding to low-velocity streaks, to red and black, corresponding to high-velocity streaks. Panels *a* and *b* adapted from Pringle & Kerswell (2010) with permission; copyright 2010 American Physical Society. (*c*) Snapshots of the temporal evolution of an initial condition close to the minimal seed at *Re* = 2,400 in a 25*D*-long pipe. Panel *c* adapted from Kerswell (2012) with permission.

Where pp denotes the perturbation pressure (Drazin & Reid 2004). Although Reynolds (1883) had emphasized that *"the condition might be one of instability for disturbances of a certain magnitude and stable for smaller disturbances"*, early theoretical approaches to the transition problem—pioneered by figures such as Lord Rayleigh, Lord Kelvin, Lorentz, Orr, Sommerfeld, and Heisenberg—focused primarily on **infinitesimal disturbances to laminar flow** (Eckert 2010, 2015). This approach effectively neglects the last term in Equation 1a. Assuming axial periodicity, the linear stability problem reduces to a **one-dimensional radial eigenvalue problem**, whose numerical solutions have consistently shown that all eigenvalues possess negative real parts. Consequently, Hagen–Poiseuille (HP) flow remains linearly stable at least up to Re=107\text{Re} = 10^7 (Meseguer & Trefethen 2003).

Beyond this point, however, suppressing disturbances becomes increasingly challenging—even in double-precision numerical calculations (Meseguer & Trefethen 2003). The underlying cause is the **nonnormality of the linearized Navier–Stokes equations** (Schmid & Henningson 2001; Schmid 2007). Because modal disturbances are not mutually orthogonal, their linear combinations can lead to **large transient growth of nonmodal (shape-changing) disturbances**. This effect, first identified by Boberg & Brosa (1988) and later popularized by Trefethen et al. (1993), provides a pathway for substantial amplification despite linear stability.

In laminar pipe flow, the **optimal nonmodal disturbances**—those maximizing transient energy growth—are **streamwise vortices**. Specifically, a pair of infinitesimal-amplitude (ϵ\epsilon) streamwise vortices lifts **low-speed fluid from the near-wall region toward the pipe center** and displaces **high-speed fluid from the center toward the wall** (Brandt 2014), as illustrated in Figure 5a. This mechanism creates strong local streamwise velocity differences that play a pivotal role in transition dynamics.

REFERENCES

[1] Agrawal N, Choueiri GH, Hof B. 2012. Transition to turbulence in particle laden flows. *Phys. Rev. Lett.*122(11):114502.

[2] Brandt, L. (2014). The lift-up effect: The linear mechanism behind transition and turbulence in shear flows. *European Journal of Mechanics - B/Fluids*, 47, 80–96.

[3] Drazin, P. G., & Reid, W. H. (2004). *Hydrodynamic stability* (2nd ed.). Cambridge University Press.

[4] Eckert, M. (2010). *The Sommerfeld school and the turbulence problem in the early 20th century*. EPJ H, 35, 29–51.

[5] Eckert, M. (2012). *The turbulent history of fluid dynamics: Science and the quest for a theory of turbulence*. Springer.

[6] Meseguer, A., & Trefethen, L. N. (2003). Linearized pipe flow to Reynolds number 10710^7107. *Journal of Computational Physics*, 186(1), 178–197.

[7] Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London*, 174, 935–982.

[8] Schmid, P. J. (2007). Nonmodal stability theory. *Annual Review of Fluid Mechanics*, 39, 129–162.

[9] Schmid, P. J., & Henningson, D. S. (2001). *Stability and transition in shear flows*. Springer.

[10] Trefethen, L. N., Trefethen, A. E., Reddy, S. C., & Driscoll, T. A. (1993). Hydrodynamic stability without eigenvalues. *Science*, 261(5121), 578–584.

[11] Darbyshire, A. G., & Mullin, T. (1995). Transition to turbulence in constant-mass-flux pipe flow. *Journal of Fluid Mechanics*, 289, 83–114.

[12] Hof, B., Juel, A., & Mullin, T. (2003). Scaling of the turbulence transition threshold in a pipe. *Physical Review Letters*, 91(24), 244502.

[13] Hof, B., de Lozar, A., Kuik, D. J., & Westerweel, J. (2010). Repelling coherent states organize pipe turbulence. *Physical Review Letters*, 101(21), 214501.

[14] Kühnen, J., Song, B., Scarselli, D., Budanur, N. B., Riedl, M., Willis, A. P., … Hof, B. (2012). Destabilizing turbulence in pipe flow. *Nature Physics*, 14(4), 386–390.

[15] Mukund, V., & Hof, B. (2012). The critical point of the transition to turbulence in pipe flow. *Journal of Fluid Mechanics*, 839, 76–94.

[16] Peixinho, J., & Mullin, T. (2007). Finite-amplitude thresholds for transition in pipe flow. *Journal of Fluid Mechanics*, 582, 169–178.

[17] Pfenniger, W. (1961). Transition in the inlet length of tubes at high Reynolds numbers. In *Boundary Layer and Flow Control* (Vol. 2, pp. 970–980). Pergamon.

[18] Philip, J., & Cohen, J. (2010). Vortex structures in transitional pipe flow. *Journal of Fluid Mechanics*, 638, 1–19.

[19] Rotta, J. (1956). Experimenteller Beitrag zur Entstehung der Turbulenz. *Ingenieur-Archiv*, 24(3), 258–281.

[20] Samanta, D., de Lozar, A., & Hof, B. (2011). Experimental investigation of laminar turbulent intermittency in pipe flow. *Journal of Fluid Mechanics*, 681, 193–204.

[21] van Doorne, C. W. H. (2004). *Experimental study of transition to turbulence in pipe flow*. Ph.D. thesis, Delft University of Technology.

[22] van Doorne, C. W. H., & Westerweel, J. (2009). The flow structure of a puff. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 367(1888), 489–507.

[23] Wu, X., Moin, P., Wallace, J. M., Skarda, J., Lozano-Durán, A., & Hickey, J. P. (2015). Transitional–turbulent spots and turbulent–turbulent spots in boundary layers. *Proceedings of the National Academy of Sciences*, 112(26), 7920–7924.

[24] Wygnanski, I. J., & Champagne, F. H. (1973). On transition in a pipe. Part 1: The origin of puffs and slugs and the flow in a turbulent slug. *Journal of Fluid Mechanics*, 59(2), 281–335.

[25] Wygnanski, I. J., Sokolov, M., & Friedman, D. (1975). On transition in a pipe. Part 2: The equilibrium puff. *Journal of Fluid Mechanics*, 69(2), 283–304.