Relaminarisation of fully turbulent pipe flow

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Numerical simulations: Baofang Song (Tjanjin), Burak Budanur (IST), Ashley Willis (Sheffield) and Marc Avila (Bremen)
Reynolds pipe experiments

O. Reynolds Phil. Trans. R. Soc. 1883

- Re = UD / ν = velocity × diameter / kin. viscosisty ~ inertial/viscous forces
- Reynolds number is the **only** parameter of the problem
- small Re ➞ laminar flow
- large Re ➞ turbulence

However: transition usually occurred at Re=2000, but for an improved set up at Re=13 000

Laminar flow is linearly stable
Friction in pipes

\[ \Delta p = f \rho U^2 \frac{L}{2D} \]

**Friction factor**

**Reynolds number**

Nikuradse 1933

Laminar flow: \( f \sim \frac{1}{\text{Re}} \quad f \sim U \)

Turbulent flow: \( f \sim \frac{1}{\text{Re}^{0.25}} \quad f \sim U^{1.75} \)
turbulent friction / laminar friction

\[ \text{Re} \]

\[ \text{Re} \]

friction factor

laminar

turbulent

\[ \text{Re} \]

\[ \text{Re} \]

turbulent friction / laminar friction

\[ \text{Re} \]

\[ \text{Re} \]
The onset of turbulence

Can we define a critical point for transition?

Prandtl (1921): “…and so, once more, we do not obtain a critical Reynolds number. There seems to be a very nasty devil in the turbulence so that all mathematical efforts are doomed to failure.”

O. Reynolds Phil. Trans. R. Soc. Lond. A 174 1883

if in a tube of sufficient length the water were at first admitted in a high state of disturbance, then as the water proceeded along the tube the disturbance would settle down into a steady condition, which condition would be one of eddies or steady motion, according to whether the velocity was above or below what may be called the real critical value.
Experimental difficulties

Dependence on perturbation:

Re=2100
Dynamics of individual puffs

Decay of turbulent puffs

- Turbulent puffs decay suddenly after long times
- Memoryless process

\[ P(t, \text{Re}) = \exp(-t / \tau(\text{Re})) \]

Transition (in Couette flow) belongs to the "directed percolation" universality class (Lemoult et al. Nature Physics 2017)
Why is turbulence localised?
Puff interactions

Hof, deLozar, Avila, Tu, Schneider Science 2010
A different frame of reference

Puffs are ‘parasites’ that feed on the upstream laminar flow.

See also van Doorne and Westerweel
Phil.Trans.Roy.Soc. 2009

Barkley PRE 2011
Barkley JFM 2017
Laminar Turbulent fronts

Barkley, Song, Mukund, Lemoult, Avila & Hof
Nature 2015

Prediction: Profile change can make fully turbulent flow refractory
Relaminarization in direct numerical simulations

DNS pipe flow by Marc Avila: Flow relaminarizes if profile is flattened

(see also Hof et al. Science 2010)
Making the flow more turbulent

DNS by Baofang Song and Burak Budanur
Re=3500
Re=3500
Re=3500
Passive device: mechanism
Re = 4000, camera comoving with bulk velocity of the flow
Injection through a radial gap: mechanism
Re = 5000, injection off-on
Shifting wall: control mechanism

- Linear actuator
- $s \ldots$ shift length
- $u_{\text{wall}} \ldots$ wall velocity
- Perspex pipe (movable)
- Thin-walled stainless steel pipe (stationary)
- LDV

$\Delta p$
Re = 5000, video in slow-motion (25% of original speed)

Wall at rest
Common feature of all control mechanisms

- streamwise velocity profile more flat/blunt due to
  - increased turbulence intensity and/or
  - incr. velocity at the wall/decr. vel. in the center
  - steeper gradient at the wall, increased friction
The self sustaining process

Lift up mechanism
transient growth

See e.g. Brandt E.J.Mech. B/Fluids 2014,
Reddy&Henningson JFM 1993,
Trefethen et al. Science 1994....
Transient/optimal growth
Drag reduction

Kühnen, Song, Scarselli, Budanur, Riedl, Willis, Avila & Hof Nature Physics 2018