

Review

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Review

Internal Transport Barriers in Fluids and Plasmas

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Abstract

Turbulent flow in neutral fluids and fusion plasmas is known to have many commonalities, one example being the application of energy and enstrophy cascades. In this review, we discuss a novel cyclic process which may also be common to both fluids and plasmas: This includes exact coherent states (or magnetic islands), Reynolds stress-driven (zonal) flows and internal interface layers (or internal transport barriers). We briefly review the current understanding of internal interface layers in fluids and discuss open questions and possible research directions to pursue. The main objective of our review is to create awareness of the shared mechanism to motivate further interdisciplinary research in this field, both by the fluid mechanics and plasma physics communities.

Keywords: internal transport barriers; internal interface layers; neutral fluids; plasmas; common cyclic process

1. Introduction

Thirty years ago, in 1995, two discoveries were published; one for (neutral) fluids, the other for (fusion) plasmas: In fluids, the existence of uniform momentum zones (UMZs) was presented [1] and in plasmas, internal transport barriers (ITBs) were observed [2,3]². These seemingly independent findings were not linked at the time, but evidence is mounting [4] that they may be manifestations of a common mechanism.

What has been compared in Ref. [4] is wall-bounded fluids in straight pipes and magnetically-bounded plasmas in tori. Although they appear very different, e.g. geometry (curvature) and boundary conditions (solid walls or magnetic fields), we have proposed a common cyclic process (CCP) consisting of these elements:

- Exact coherent states (ECS)/magnetic islands (MIs) $\implies$
- Reynolds stress (RS)-driven (zonal) flows $\implies$
- Internal interface layers (IILs)/internal transport barriers (ITBs) $\implies$

Here, the arrows indicate transitions to the next element.

This process is thought to be both self-regulating and self-sustaining; it is inspired by e.g. the self-sustaining process (SSP) [5] which consists of rolls, streaks and waves. The title of our review is a misnomer in the sense that IILs/ITBs are only one manifestation of the process.

The research that lies ahead is to understand the process in more detail, both by approaching it from a fluid and a plasma perspective. Initially, it does appear that neither curvature or electromagnetic effects are needed. However, both characteristics - and likely others - may work to enhance or suppress the mechanism.

We assume that the reader is familiar with fusion plasma physics concepts such as magnetic field properties [6], $E \times B$ flow shear decorrelation [7] and zonal flows (ZFs) [8].

Our review is organised as follows: A mini-review on IILs in fluids is contained in Section 2, followed by Section 3, in which knowledge gaps are identified and discussed. We make the case for possible research program areas in Section 4 and finally conclude in Section 5.

² The UMZ paper was published in April 1995, the ITB papers in December 1995.

2. A Mini-Review on Internal Interface Layers in Fluids

We present a condensed version of material in Ref. [4]; additional references can be found in the cited paper. The phenomena are introduced in chronological order, spanning the years 1955-2021.

The scope is IILs, excluding laminar/turbulent boundary layers (LBL/TBL) associated with solid walls [9].

The first identification of an IIL in fluids, in 1955, is the turbulent/non-turbulent interface (TNTI) which is the interface between a TBL and a non-turbulent free-streaming flow [10]. The interfacial layer has a complex structure and acts as a bidirectional transport barrier (TB) between turbulent (rotational) and non-turbulent (irrotational) regions. A high-shear region (velocity jump) exists at the TNTI which is also associated with intense vorticity.

Forty years later, in 1995, UMZs were discovered, consisting of regions of almost constant streamwise momentum separated by thin viscous-inertial shear layers [1]. The layer was interpreted as a collection of vortices as opposed to the interpretation of the TNTI as being a continuous vortex sheet. In 2014, a large UMZ has been found in the core of channel flows, extending to 40-45% of the channel [11]. This large UMZ has been named the "quiescent core", since it is only weakly turbulent.

Uniform thermal (or temperature) zones, UTZ, were first introduced in 2019; they consist of relatively constant temperature regions separated by thermal interface layers [12].

Both UMZs and UTZs have IILs which are related to velocity (momentum) and temperature (heat), respectively. They have been modelled both individually and combined as uniform zones separated by vortical and thermal fissures (VFs/TFs). When both types coexist, the IILs have been found to be at similar but not identical locations.

The final type of IIL in fluids is uniform concentration zones (UCZs), first defined in 2021 [13]. The mechanism of uniform zone separation for concentration is not understood, but it has similarities with ramp-cliff structures seen in turbulent mixing [14], which may also be related to sawtooth crashes in fusion plasmas [15].

Thus, we conclude that IILs in fluids which separate uniform zones of momentum, heat and concentration have strong similarities with ITBs in plasmas.

3. Gap Analysis

Here, we treat both existing research we have become aware of along with new research supporting elements of the conjectured CCP. We divide this into material originating from the fluid and plasma perspectives, where more material is devoted to fluids and less to plasmas.

We focus on the ingredients of the CCP, but also make statements on the causality of the ingredients when possible, see Table 1.

Table 1. An overview of transitions in the CCP for fluids and plasmas.

Fluids	Plasmas
ECS $\implies$ ZFs	MIs $\implies$ ZFs
ZFs $\implies$ IILs	ZFs $\implies$ ITBs
IILs $\implies$ ECS	ITBs $\implies$ MIs

Using a flux-gradient terminology, where the radial flux is equal to the diffusion coefficient multiplied by the radial gradient, fluids and plasmas behave comparably without and with IILs/ITBs:

- Without IILs/ITBs: A large diffusion coefficient and a moderate radial gradient leading to a high radial flux
- With IILs/ITBs: A small diffusion coefficient and a steep radial gradient leading to a low radial flux

3.1. Fluids

3.1.1. Exact Coherent States

The first element (or ingredient) of the CCP is ECS, which are invariant solutions to the Navier-Stokes equations (NSE) [16]. They can be observed as either travelling waves (TWs) or relative periodic orbits (RPOs). These solutions to the NSE have mainly been identified for transitional flow, e.g. flow at the laminar/turbulent transition. They are difficult to identify for higher Reynolds numbers (Re) due to computational and theoretical limitations. However, they are currently a relatively mature part of fluids research.

3.1.2. Zonal Flows

ZFs in fluids, the second element, have been introduced for geophysical flows through studies of geostrophic turbulence, which is fluid dynamics "near a state of geostrophic and hydrostatic balance" [17]. Here, a necessary component is system rotation - stratospheric geostrophic flow is mentioned as an example of flow shear decorrelation in Ref. [7].

An example of laboratory experiments with rotating fluids where a coupling to plasmas is explicitly made is Ref. [18]. ZFs are generated by mixing and homogenization of potential vorticity [17], where mixing is forced by pumping water in and out of holes in the bottom of a rotating tank.

ZFs have also been generated by Rayleigh-Bénard convection; here, vertical buoyancy due to a temperature difference can generate horizontal ZF leading to burstlike vertical heat transport [19]. Again, parallels to transport in plasmas are drawn; for example, ZFs in both fluids and plasmas are sheared normally to their directions of motion and reduce transport in this normal direction: Azimuthal/poloidal ZFs will reduce radial transport. Further, both fluid and plasma motion is roughly two-dimensional (2D) where ZFs have been found.

One case of ZFs in straight pipes has been reported for transitional flow [20,21]. Direct numerical simulations (DNSs) demonstrate that ZF is generated by RS which in turn suppresses small-scale turbulence leading to stochastic predator-prey dynamics [8]. The ZF is in the azimuthal direction, i.e. perpendicular to the streamwise flow and thereby 2D in nature. It is observed without external rotation and thermal forcing, which implies that these features are not necessary for ZF generation in fluids. However, it is proposed that ZF can be assisted by rotating the pipe, which would lead the transition to turbulence to take place at lower Re .

Another case where ZFs may exist for flow without rotation and thermal forcing is flow through curved pipes, where secondary vortices are generated perpendicular to the streamwise flow [22,23]. These secondary vortices may be generating ZFs, which would explain the delayed transition to turbulence for curved pipes compared to straight pipes [24]. This is then similar to the "Dimits shift" for plasmas where ZFs delay the onset of turbulence [25].

3.1.3. Internal Interface Layers

As we discussed in Section 2, there is a solid body of evidence for the existence of IILs.

3.1.4. Transitions

An example of the first transition, $ECS \implies ZFs$, is the generation of ZFs by travelling thermal waves [26]. The sequence of TWs leading to RS which in turn leads to ZFs thus appears plausible.

The next transition, $ZFs \implies IILs$ has also been observed in thermal systems as mentioned in our discussion of ZFs [19].

The final transition, $IILs \implies ECS$, is the backreaction of IILs on ECS. This transition is the one associated with most uncertainty: We have not been able to identify this process in the literature and it represents a gap (or weakness) in the CCP.

3.2. Plasmas

3.2.1. Elements

All elements of the CCP, i.e. MIs, ZFs and ITBs have been firmly established over several decades, so their existence is not in dispute.

3.2.2. Transitions

The first transition, $\text{MIs} \Rightarrow \text{ZFs}$ has been identified and studied for a longer period, see e.g. [27,28]; zonal fields, the magnetic counterpart to ZFs, also interact with the MIs [29].

The second transition, $\text{ZFs} \Rightarrow \text{ITBs}$, is discussed in Ref. [8] and it is shown that ZFs are an essential element in the formation of ITBs. Note that in addition to RS, ZFs can also be generated by drift waves.

The third transition, $\text{ITBs} \Rightarrow \text{MIs}$ can be studied by e.g. external magnetic field configuration scans where MIs are manipulated to modify the ITBs [30]. This is strictly speaking an inverse transition, $\text{MIs} \Rightarrow \text{ITBs}$; however, the forward transition has also been demonstrated by scanning internal heat deposition instead of the external magnetic field configuration [31].

4. Roadmap Topics

For the reader searching for books which combine fluids and plasmas more comprehensively, we recommend Refs. [32,33]. On the connection between fluids and astrophysical plasmas, Ref. [34] is a very useful resource.

Interdisciplinary efforts in fluid-plasma research remain highly relevant, as e.g. demonstrated by the joint special topic on fluid and plasma turbulence in Phys. Fluids and Phys. Plasmas [35]. To cite from this Editorial, possible common ground includes "the role in many fluid systems of nonlinearly self-organized structures and the role in many plasma systems of collective modes of the linearized dynamical equations". Our work fits very nicely into this overlapping region of fluids and plasmas.

Below we collect various open points which can be addressed to improve our understanding of phenomena common to fluids and plasmas.

4.1. Missing Fluid Transition

We have not been able to identify research on the fluid transition $\text{IILs} \Rightarrow \text{ECS}$ in the literature. This may be due to lack of knowledge, because the research has not been done or because the transition does not exist.

We propose research in this direction to find an answer to the question of the existence of this transition.

4.2. Is the Common Cyclic Process Applicable to Fluids?

This question remains relevant; it could also be the case that the CCP is not applicable to both fluids and plasmas. This would imply that complete universality does not exist, i.e. that the process does not consist of exactly the same ingredients for fluids and plasmas.

An interesting point to consider is e.g. whether ZFs are needed for the fluid process? Figures 21 and 22 in Ref. [36] show that TWs lead to momentum transport barriers as seen by the streamwise velocity gradients. Is this a direct transition from an ECS to an IIL? From the plasma point of view, note the similarity to Figure 1 in Ref. [3], where a comparable structure of the ion toroidal rotation frequency is found.

4.3. Decoupling of Transport Channels in Fluids?

Decoupling of transport channels has been observed in plasmas. It has often been associated with (quasi-)coherent modes, which are thought to lead to increased radial particle transport in contrast to reduced radial energy transport. However, we have not found similar observations in the fluids literature.

Can ECS in fluids play a similar role, e.g. to allow momentum transport while still enabling an energy transport barrier?

We have seen the coexistence of multiple transport barriers in fluids as well as plasmas; the question is whether ECS or a different coherent mode could degrade the UMZ without impacting the UTZ?

4.4. Toroidal Geometries with Fluids

An interesting development has been taking place in the field of toroidal geometries with fluids over the last fifteen years, both simulations [37,38] and experiments [39,40]. This facilitates a direct comparison between fluids and plasmas in toroidal geometries.

The research has been focused on the transition of laminar to turbulent flow and how that depends both on Re and the curvature, i.e. the ratio of the torus minor and major radii or the inverse aspect ratio to use the plasma terminology.

TWs have been observed at the transition along with cross-stream flow structures, such as azimuthal flow close to the wall. Thus, two elements of the CCP have been observed, but clear evidence of UMZ does not exist yet. It would be interesting to pursue this, perhaps by re-analysing existing measurements and simulations as a first step.

4.5. Linear Plasma Devices?

We have initiated a literature review on the CCP in linear plasma devices; in terms of ingredients, there is evidence of ZFs [41] and edge transport barriers (ETBs) [42] but not ITBs.

We have not found evidence for MIs in linear devices and no clear transitions. This may also be because we are not aware of the relevant research papers.

4.6. New Experimental Devices

In addition to theoretical work and model-building, it is obvious to consider the design and construction of new flexible experiments to study fluids and plasmas. This is supported by statements in e.g. Refs. [7,8] which are collected in Ref. [4].

Ideally, a device would have a flexible geometry (straight/toroidal) and include shaping options for the cross-section. It should have the capability of containing both a fluid and a plasma in the same geometry.

5. Conclusions

Fluids and plasmas have large areas of common ground; one manifestation is internal interface layers in fluids and internal transport barriers in plasmas. In this review we attempt to build a case for a common cyclic process which includes coherent structures and zonal flow in addition to interface layers or transport barriers.

We focus on material for fluids, since this is a plasma physics journal where readers have a stronger background in plasmas. Our mini-review on internal interface layers in fluids shows that they are very similar to internal transport barriers in fluids.

For the common cyclic process, we detail both the individual elements and their transitions to identify known results and possible knowledge gaps.

Finally, a research program - or roadmap - contains areas which merit further investigation. This is not something which can be carried out by individual persons or even solitary research groups. Therefore this review is a call to action for the combined fluid and plasma communities to get involved: The potential gains for both fields make a common path the obvious way forward.

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