Propagation of a Turbulent Fronts in Quantum Fluids

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Abstract This paper is part of our series of studies on the dynamics of inhomogeneous vortex tangles. We consider here the motion of turbulent fronts. There are a number of experiments in which the authors observed the development of superfluid turbulence in quantum fluids in the form of propagating fronts. There are also experiments in which the authors observed the appearance of the moving structures (“plugs”), regions with the high vortex line density in the counterflowing superfluid helium. These phenomena have both scientific and applied interest. For example, the possibility of spontaneous formation of “plugs” can radically affect heat transfer in channels with superfluid helium, which is used as a refrigerant for cooling superconducting devices. There are a number of hypotheses for how the fronts and “plugs” appear and what their dynamics are, in particular, how to evaluate the velocity of propagations. In the present work we elaborate the approach of the combustion-like propagation of the superfluid turbulent domain. A key assumption is that propagation of the front occurs in diffusion manner of diffusion with the source of the vortices behind the front, just like the combustion process. Additionally, there is a drift motion of the vortex tangles due to polarization of the vortex loops. Interplay of these effects determines the speed of the turbulent front propagation. We performed a comparison with the experimental data.

Keywords Superfluid turbulence · Quantum vortices · Nonuniform vortex tangle

1 Introduction and Background

One of the significant phenomena of the dynamics of the inhomogeneous vortex tangles in quantum systems is the motion of turbulent fronts. The history of this phenomenon is very long, almost as long as that of superfluid turbulence itself. Thus,
Peshkov and Tkachenko (1961) [1] and Bhagat et al. (1964) [2] studied the kinetics of formation of the superfluid turbulence (ST) in long (up to 8 m) capillaries under the influence of small heat fluxes. Van Sciver (1979) [3] studied a similar problem but for much larger heat fluxes of the order of 1 W cm\(^{-2}\). Moving fronts and plugs were investigated extensively by the Leiden group [4, 5]. Besides the counterflowing cases they also investigated flows with arbitrary normal \(v_n\) and superfluid \(v_s\) velocities. In particular the authors observed the repetitive “plug” structures. The different (left and right) boundaries of these plugs moved in unperturbed helium with different velocities. This led to motion of the “plugs” as a whole. More recent examples are the observation of the turbulent fronts in rotating \(^3\)He performed by the Helsinki group [6]. It is very important to note that propagation of the front was observed at very low temperature, when the interaction with the normal component is absent, and the motion of lines in a direction perpendicular to the relative velocity \(v_{ns}\) the cannot be explained in terms of the mutual friction. The propagating turbulent fronts were also observed in numerical simulations. As an example we would like to point out results of numerical simulations on the developing turbulent state in the rotating \(^3\)He [6]) where a picture of how the domains of the dense vortex tangle are propagating in space are presented.

Attempts to describe the above processes theoretically were made by van Beelen et al. [4]. They proposed the use of a modifying Vinen equation adding the diffusion term into its r.h.s. Geurst [5] gives some arguments (without any calculations) supporting the existence of the diffusion term. The authors were not able to restore the value of the diffusion coefficient from experimental data. These results are reviewed and discussed in the review article [10]. Fiszdon et al. (see in [10]) predicted the stepwise solution for vortex line density (VLD) \(L(x, t)\), which was not a propagating profile but rather a standing wave. It was not confirmed experimentally, maybe due to boundary effects. In paper by the author (see in [10]) the running stepwise solution for the vortex line density \(L(x, t)\) was obtained. The physical meaning of the solution obtained is of interest. The soliton, step-wise structure appeared due to intensive dissipation processes behind the front, where the vortex line density is large. This dissipation leads to a temperature drop which in turn induces and supports a counterflow. The interplay of these two effects leads to a propagating step-like solution. One more approach to describe the motion of the front (in the rotating helium) and obtain its speed was the assumption that lines on the front are perpendicular to the relative velocity \(v_{ns}\) and their common velocity (coinciding with the speed of the front) are calculated on the base of the vortex line dynamics [6].

In the present work we elaborate the idea that the superfluid turbulent domain propagates in a combustion-like manner. Namely, the diffusion-like spread of the vortex tangle is accompanied by intensive production of the vortices behind the front, just like in the combustion processes. Besides, there is drift motion of the vortex tangles due to polarization of the vortex loops. Interplay of these two effects determines the speed of the turbulent front propagation. We performed a comparison with the experimental data presented by Peshkov and Tkachenko (1961) [1].