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Editor

Advances in Turbulence XII

Proceedings of the 12th EUROMECH
European Turbulence Conference,
September 7–10, 2009, Marburg, Germany

With 594 Figures

Springer

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ISSN 0930-8989 e-ISSN 1867-4941
ISBN 978-3-642-03084-0 e-ISBN 978-3-642-03085-7
DOI 10.1007/978-3-642-03085-7
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009931716

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Cover design: SPi Publisher Services

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Universality of Kolmogorov law in spectrally condensed turbulence in thin layers

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The four-fifth Kolmogorov law relates the third-order structure function and the energy dissipation rate ϵ in three-dimensional turbulence (see, e.g. [1]. This law for 2D turbulence reads: $S_{L3} = (3/2)\epsilon r$, where $S_{L3} = \langle \delta v_L^3 \rangle$ is the third moment of the longitudinal velocity increments at the scale r . Angular brackets denote averaging over the box size and time. This relationship allows the energy dissipation rate, or the energy flux within the inertial range to be determined by analyzing the third-order velocity moments in laboratory experiments or in observational data. The Kolmogorov law has been confirmed in direct numerical simulations of 2D turbulence [2], however previous experimental attempts to derive ϵ from the third-order longitudinal structure functions were not successful [3], probably due the insufficient statistics in the calculations of $\langle \delta v_L^3 \rangle$. In this paper we present the results of the $S_3(r)$ measurements in quasi-2D turbulence in laboratory experiments. We are particularly interested in estimating the energy flux in the energy inertial interval and in comparison of its value with independently obtained energy dissipation rate.

Another practically interesting question is how the presence of the self-generated coherent flows in 2D turbulence affects the Kolmogorov law in the regime of spectral condensation. We investigate this in the thin stratified layers of fluid where turbulence is driven electromagnetically as described in [4, 5]. When the flow is bounded the inverse energy cascade leads to the accumulation of the spectral energy at the scale close to the boundary size and generation of mean flow. By controlling the bottom dissipation rate (via the thickness of the fluid layers) and the size of the boundary, large vortices of different strengths, or condensates, can be obtained as discussed in [5].

Figure 1 shows time-averaged (over about 100s) velocity fields measured with the boundary size of $L=0.11$ m for 3 different damping rates. The large-scale vortex becomes more symmetric as its turnover time becomes shorter and approaches the inverse damping rate $1/\alpha$.

Fig. 1. Time-averaged velocity field of the condensate at $L \approx 0.10$ m with different linear damping rate: (a) $\alpha = 0.25 \text{ s}^{-1}$, (b) $\alpha = 0.15 \text{ s}^{-1}$ and (c) $\alpha = 0.05 \text{ s}^{-1}$.

Fig. 2. (a) Time evolution of the kinetic energy during turbulence decay for the 3 cases of Fig. 1. (b) 3rd-order structure function computed for the case of Fig. 1(c) by subtracting mean flow velocity.

The presence of the mean flow greatly affects the velocity moments, as discussed in [5]. However by subtracting mean (time-averaged) velocity field from instantaneous fields before computing the 3rd-order structure function $S_3 = (S_{3L} + S_{3T})/2$ one recovers physically meaningful values of $\epsilon = S_3/r$. This is verified by comparing ϵ with the energy dissipation rate derived from the time evolution of the turbulence energy in the initial stage and during the decay: $dE/dt - \alpha E = \epsilon$. During the decay $\epsilon \approx \alpha E$, while at the early stage of the turbulence development $dE/dt \approx \epsilon$. This result has been confirmed at different strengths of the condensate flow, even in the regimes when the presence of the condensate leads to the onset of non-Gaussian statistics in condensed turbulence (larger flatness).

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