Institute of Experimental Physics
Slovak Academy of Sciences
Watsonova 47, 040 01 Košice, SLOVAKIA
Tel.: +421-55-7922201, Fax: +421-55-6336292, E-mail: sekr@saske.sk

Review report on PhD thesis by Emil Varga: Experimental and numerical investigation of quantum turbulence in He II

I read dissertation thesis by Emil Varga: Experimental and numerical investigation of quantum turbulence in He II, including attached preprints of published articles with a great interest. Elucidating and understanding of the dynamic of the classical (and quantum) turbulence is still an open and actual problem in current physics of the condensed matter. In fact, let say the understanding of the turbulent behaviour of the atmosphere and/or liquids (water) – the physical origin of its generation, its time evolution and decay allows us to increase the safety of the aerial transportation in the first case, and/or e.g. to design a more efficient propellers for ships in the second case. Obviously, the research in turbulence has significant impact on society and enormous applications in everyday life. However, there are physical systems allowing to investigate and to understand more fundamental underlying physics - physics of the quantum world, and in this particular case - the quantum turbulence. The quantum turbulence is a unique macroscopic phenomenon manifested only in two quantum fluids, i.e. the superfluid 4He and superfluid 3He (there is also possibility to generate vortices in BEC of ultra-cold gases, however, in reduced geometry).

Thesis by Emil Varga is focused on experimental investigation and theoretical (numerical) modeling of the quantum turbulence in superfluid 4He. Physical motivation was to understand the geometrical effects, in particular the influence of the walls acting on the quantum turbulence in superfluid He-II. This type of study is almost missing, and therefore, one can expect new effects to be discovered. In order to determine the influence of the finite geometry, author studied a decay of the quantum turbulence in presence of the counterflow or pure superflow (and coflow). He has found a non-trivial alteration of the energy spectrum during turbulence decay in counterflow, presented as a “bump” in this spectrum. However, this effect was almost completely suppressed in spectrum decay measured in superflow. This remarkable difference was interpreted in a following way: because the heat flux does not force normal component, this component can conform the superfluid on wider range of scales and, as a consequence, the coupled turbulent eddies are not torn apart by the mean counterflow. He also tried to investigate another geometric effect – detection of a boundary layer in vicinity of heater having similar property as boundary layer in classical thermal convection. However, it seems that experimental setup did not allow detect this layer due to small spatial resolution of the thermometer. In experiment performed using visualization technique, he studied decay in the wake of moving grid and he found a non-classical scaling in energy spectrum, suggesting a more complex coflow dynamics of He-II and observed that visualization particles trapped on the vortices act as additional channel of the energy transfer. Second part of thesis deals with numerical simulations. Here, I would like to stress the author’s contribution to the numerical modeling of the two particular phenomena in quantum turbulence: (i) dynamics of the interaction of solid particles with vortex tangles in thermal counterflow, which is directly related to the measurements using visualization experimental technique, and (ii) simulation of dynamics in the spherically symmetric counterflow allowing for quantum turbulence to reach a sustained regime.

To summarize: all scientific results presented in thesis are new, innovative and extend our knowledge on dynamics of classical and quantum fluids, in particular quantum turbulence in superfluid He-II and they are applicable in other fields of physics.

In order to achieve thesis goals, the applicant used three methods of investigations of the turbulence: (i) vortex line density i.e. a parameter describing "amount of turbulence" was measured using the second sound attenuation technique, the temperature profile of the flow in channel was monitored by the miniature thermometers, and application of the helium excimer molecules being visualized using laser-induced fluorescence technique allowed to study the dynamics of the normal flow in experiments. It is worth to note at this place, that Prague visualization laboratory is the first laboratory not only in the Czech Republic but in also Europe. I found that the applicant selected corresponding and adequate experimental techniques and methods to achieve the thesis goals, and he has completed them.

Presented thesis is written in English. From formal point of view, thesis is clearly and very well written with minimum misprints and grammar mistakes (e.g. S denotes the phase but also entropy). I appreciate rich graphical documentation including many graphs presenting the measured dependencies, based on which physical interpretations and conclusions were made.

Final part of thesis consists of preprints of the selected scientific articles of the author. There are six preprints of articles: Phys Rev. B 2x, JLTP 2x and two articles submitted for publications. It is worth to note, that results of the thesis had been presented by the applicant as an invited talk on recent conference QFS 2018 held in Tokyo, Japan. This also demonstrates the eligibility of the applicant for independent work.

Although many of in thesis presented results have already been published in articles and therefore, they already passed a review process, I have a few questions to the applicant related to the results presented in thesis:

- My first question is related to basic physics of superfluid He-II – when you cool the helium-4 into the superfluid state, do you have a vortex free state, or there are some vortices generated during this phase transition process? Could you discuss this problem more general?

- On page 10 – You wrote: "Note that a roll-off exponent higher than 5/3 signifies energy dissipation at all scales, contrary to the dissipation-free inertial range of classical turbulence. It is believed that this dissipation is caused by mutual friction attenuating eddies in the two components which are torn apart by the mean counterflow". What physics is behind exponent higher than 5/3 ? The sentence above is very general. Is this fact a special case only for He-II or there are other systems behaving in similar way?

- Page 14 – The stability of the bath in a steady state was about 0.1 mK. This is a good stability keeping in mind that experiments were performed above 1 K. What was the thermometers sensitivity? Was there a particular reason to use 8th order Chebyshev polynomial to fit the T-R dependence?

- Page 16 (last paragraph) – You used simple and traditional technique where one mechanical resonator works like a speaker and the second one like a microphone. The first resonator generates and emits a first sound and incoming sound wave is detected by the second resonator as an electric current created as consequence of the changes in the capacitance

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(oscillation of the membrane). Is there a particular reason to use the terms "a second sound transducer and a receiver", when the second sound in reality is generated by a heater?

- There is slight difference in VLD measured using sensor L1 and L2 at temperature 1.65 K (see Fig. 3.14 on page 44). Others measurements of VLD are almost the same. What is the reason for this small discrepancy, can you comment it? Even more, I would expect green points to be at the position of red empty squares.

- On page 48 is written: "the approach to the steady state from growth side is monotonous; the growth does not depend on the pulse width, while the decay is clearly history dependent. For these reasons, the vortex line density growth appears to be a more suitable transient process for studying the intrinsic dynamics of the vortex tangle". However, there is a big difference between the growth regime and decay regime from point of view of the energy transfer. In first case you feed the system with energy and this energy is distributed in this system via intrinsic mechanisms including dissipations in order to achieve steady state. In the second case, having the steady state set i.e. the state of the energy equilibrium, when the energy source is switched off, the system dissipates energy via relaxation processes in order to set the state of the energy minimum. Therefore, I would like to ask you what kind intrinsic dynamics you have meant to study, if according to my point of view, two regimes (growth and decay) are not physically reversible. Can you comment this issue?

- I presume that simulation presented in thesis on spherically symmetric counter flow (Fig. 4.9 page 83) considers an open (infinite) geometry of the cell. However, any experiment is preformed in a close geometry, and therefore the presence of the walls has an impact on results. How the effect of the close (or finite) geometry i.e. a back-reflection of the flow from the walls would affect your theoretical conclusions - presence of a critical temperature below which turbulence may a reach sustained regime?

In conclusion, I would like to declare that the dissertation thesis by Emil Varga: Experimental and numerical investigation of quantum turbulence in He II has a high scientific level, scientific results presented in the thesis are new and they extended our knowledge on quantum turbulence. Results have been published in internationally accepted scientific journals and there are sufficient numbers of scientific citations on them. I checked scientific outputs of the applicant in scientific database WoS, and I was agreeable surprised: the applicant is a co-author of 12 scientific articles and has more than 100 citations. For a student just finishing his PhD study - it seems to be an excellent starting point for his scientific carrier demonstrating his ability of the independent scientific work.

Finally, I declare that thesis by Emil Varga: "Experimental and numerical investigation of quantum turbulence in He II" fulfills all requirements for dissertation thesis required by the law, I recommend this thesis to be defended and after successful habilitation I support the nomination of Emil Varga for the scientific degree "philosophiae doctor" - PhD.

Košice, August 23nd, 2018 RNDr. Peter Skyba, DrSc.