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Opinion on the doctoral dissertation

"Numerical and experimental research on the influence of air on the cavitation dynamics"

by Mr. **Emad Hasani Malekshah**

PhD advisor: ***Prof. Włodzimierz Wróblewski****, Silesian University of Technology, Gliwice*

1. Motivation, actuality of the subject, research problem formulation

The present PhD work is motivated by the importance of cavitating flows in various branches of engineering, including hydropower, pumps, ship propellers etc. Such flows are inherently unsteady, involving turbulence and phase changes. Due to the presence of inert gases, typically air in water, additional physical effects appear. This is the focus of the present PhD dissertation. The inert gas may come either as dissolved in the carrier liquid or as injected to the flow system on purpose in order to improve the overall characteristics of the flow system or to mitigate some unwanted effects of cavitation. Both situations (dissolved or injected air) are analysed in the dissertation. Given the physical complexity of the cavitation phenomena and, usually, a non-trivial geometry of such flows, the expected degree of difficulty definitely justifies another PhD study devoted to this topic, difficult and challenging in many ways. It requires a sound understanding of turbulent multiphase flow modelling and computation, including for the phase change aspects. Despite tremendous progress since the advent of CFD that has allowed for some insights and quantitative prediction of cavitation phenomena, the experimental approach still remains the most reliable way of studying such flows, even though obtaining detailed information about the field quantities may be difficult.

The ambition of the Candidate has been to perform a comprehensive study, both experimental and computational, on the role of inert gas (here: air) in the dynamics of cavitating flows, leveraging on the expertise that has already been gathered in the research group of his PhD supervisor. The subject of the doctoral thesis is definitely of actuality and the research problem has been correctly stated. Formally, the thesis can be assigned to the research area of energy engineering; otherwise, it would also fit the field of mechanical engineering.

2. Methodology applied

Concerning the experimental part, an existing closed-loop water tunnel facility has been further used by the Candidate. For the purpose of the present work, it was supplied with the measurement of the dissolved air upstream of the test section. Moreover, to enable the study of the so-called ventilated cavitation, the hydrofoil was equipped with air injection holes on the suction side. Concerning the computational part of the present work, a commercial CFD package ANSYS Fluent has been used as a flow solver, both for two-phase (liquid water and its vapour) as well as three-phase systems (water, vapour and air). The flow solver is based on the finite volume method and the new elements of the mathematical models have been coded in the software using the UDF tool. To handle the carrier-phase turbulence, the numerical solution of the governing flow equations has been performed in the wellestablished statistical RANS approach to solve for the first and second-order flow statistics. The Eulerian mixture approach has been used (a single velocity field, no interphase slip) and the Lagrangian description of vapour and air bubble dynamics has served to provide closures for the source term in the phase continuity equations. Concerning the extensive parameterisation of the CFD model, values recommended in the literature have been applied; some more parameters have been fine-tuned using the in-house experimental benchmark data.

3. Brief description of the contents, assessment of original contributions

The present PhD thesis makes an impressive document of more than 240 pages. The document has the form of the so-called "article thesis" rather than a self-contained dissertation. The Candidate has chosen to prepare a 60-page summary part or "general guide" to his work, followed by nine original research papers ("the Papers", numbered I through IX). The summary contains an introduction chapter, a presentation of main results grouped in four chapters, a description of experimental facility, a conclusion chapter, and 1-page abstracts in English and in Polish. All the papers have been published in JCR-listed journals, including: *International Journal of Heat and Mass Transfer* (2 papers), *Physics of Fluids,* and *International Journal of Heat and Fluid Flow.* The Candidate has been the corresponding author in eight of the papers and the first author in seven of them; his Supervisor (Prof. Włodzimierz Wróblewski) has co-authored all the papers. According to the authorship statements provided, the Candidate's contribution in the papers varies from 25% to 70%.

I will now briefly describe the contents of the PhD document, referring to the Candidate's general guide of 60+ pages. I have also read the original research papers I-IX to learn more details and to check that their contents correspond to the description provided in the general guide.

The Candidate has chosen to structure the "general guide" into seven chapters. It starts with Introduction (Ch. 1) which is rather short (in particular, the state of the art overview of Sec. 1.8) and recalls some basic facts about cavitation phenomena, the ways to attack it, and the objectives of the PhD thesis. In Chapter 2, the Candidate's investigations on the dissolved air effects are reported; it discusses the ways to account for the presence of air in the mathematical models. The chapter is illustrated by experimental and computational results regarding the natural cavitation, taken from papers I-IV. Chapter 3 is based on papers V and VI. It is again rather short and reports on the necessary modifications of RANS turbulent viscosity models as applied to cavitating flows. Chapter 4 reports on an original model of merging vapour and gas bubbles (paper VII). It also discusses the effect of turbulent fluctuations of pressure on a single bubble growth. Finally, the effects on the injected air on cavitation dynamics are discussed in Chapter 5, based on an experimental-only paper VIII and on a comprehensive paper IX. The experimental facility is described in Chapter 6. Conclusion (Ch. 7) features a summary of original findings; regrettably, there is no attempt to provide an outlook (directions of further work).

Concerning the papers I-IX, they nicely document the progress of the Candidate in the course of his PhD. However, looked at from *a posteriori* perspective, some material is repeated there and the contents of these publication series could have been condensed or even, ideally, communicated in a smaller number of papers.

As for the original contributions of the Candidate, they are twofold: (I) He has participated in the measurement campaigns on the test rig, has conducted the experiments, and applied the image processing techniques on the high-speed camera data and pressure time series, as well as the Fourier transform techniques for relevant flow quantities to extract dominant frequencies of the cavitation structures' shedding from the hydrofoil and the spectra (in terms of the power spectral density). A number of well documented observations on the role of inert gas in the cavitation dynamics have been formulated. These original findings from the benchmark experiment have next served to tune and to assess the mathematical model. Indeed, on the computational side, (II) the contributions of the Candidate include some modifications of the cavitating flow model model (adjustment of the turbulent viscosity formula in the region of the vapour-liquid interface as well as a modified gas-vapour cavitation model whose idea is based on merging of air and vapour bubbles in a volume), followed by extensive studies of the air impact. They have been validated on two benchmark cases, reported in the literature and from the in-house experimental facility: a convergent-divergent nozzle and a hydrofoil.

Points for discussion, critical remarks and questions

The extensive 60-page summary could have been given more attention by the Candidate: it is a bit difficult to read as a standalone document. Some important notions are not adequately explained here (such as the re-entrant jet), and some relevant quantities or symbols in the equations are not introduced. There also are some controversial statements or factual errors (indicated in the list below). From this referee point of view, two aspects of the mathematical modelling applied in the work would deserve more attention. First, the mixture model is obviously simpler to apply and less costly in terms of computer resources. However, can the Candidate comment on the use of two-fluid modelling for the purpose: its advantages, drawbacks, and achievable results (**Question 1**)? I mean: models where the velocities of the respective phases may differ. Perhaps, the origin of the reported need for density correction to prevent excessive turbulent viscosity comes from the mixture assumption and it might be alleviated in two-fluid models. Please comment. Also, what is the rationale behind a rather complex interpolation-type formula, Eq. 3.10, which is the essence of the filter-based density correction model (page 38)? The same remark pertains to the filter-based model: if I am not wrong, it belongs to the RANS-only category (and not hybrid LES-RANS), so why is it mesh-dependent (through the Δ/l_{RANS} factor)? Moreover, the symbols ρ_{m} and γ are not introduced. Concerning the LES approach in general, such simulations have become increasingly popular nowadays. Therefore, a comment on the LES of cavitating flows would be timely **(Question 2)**.

Concerning the mathematical modelling presented in Sec 2.2, no pressure-density relationship is introduced. Please explain it (**Question 3**). A somewhat related remark pertains to the role of pressure fluctuations. Does the bubble radius evolution illustrated in Fig. 4.2 account for the pressure of inert (non-condensing) gas **(Question 4)**? If so (the gas pressure is apparently present in Eq. 4.1), then why the bubble collapses?

As a whole, the document is written in a generally good English language: there are only some minor imperfections regarding grammar and style, as well as few misprints, but they do not affect the understanding of the whole text.

Minor remarks:

a) first paragraph of Sec. 1.8.2 and of Sec. 6.1: the statement about the role of experiments ("The primary goal of experimental investigations is to validate numerical results") sounds like a shift in paradigm. Experiments are invaluable *per se*, and not only to validate computational models. Therefore, it is reassuring to read (page 23) that "experiments play a crucial role in every stage of research" (the good old paradigm is back).

b) The list of symbols would be easier to be referred if the Roman symbols were separated from the Greek ones. Then, quite some important symbols are missing from the list. Also, please check the units of the normal vector.

c) In Sec. 1.6, the statement about "interfacial instabilities" is not clear. The explosion or collapse of a bubble are inherent to the R-P equation where the bubble interface remains perfectly spherical (no shape instability).

d) the LHS of the diffusion equation (1.4) rather contains the material (and not local) derivative;

e) page 31: what are "streamlines vectors"?

f) precisely, p_t in Eq. 28 of paper VII is not the pressure fluctuation;

g) the Abstract in Polish (page 71) contains a number of mistakes (is it due to a machine translation?)

5. Final conclusion

The Candidate has proven his good knowledge and advanced skills in the subject area of fluid dynamics, and in particular multiphase water-vapour-air flows with phase change. He demonstrated his capabilities to critically scrutinize the bibliography of the subject, to plan and conduct both an experimental study and a numerical investigation, including the mathematical model development. The PhD thesis contains original analyses and new research findings beyond the state of the art. They have been documented: (i) in the extended summary or "general guide" to the doctoral dissertation and (ii) in nine journal papers that make the basis of it.

As the bottom line, **my final conclusion about Mr. Emad Hasani Malekshah being a doctoral candidate is positive** and I recommend that **he orally defends the PhD thesis** with no reserve at all. Moreover, one needs to note: (i) the degree of difficulty of the subject as well as comprehensive experimental and computational studies undertaken by the Candidate, (ii) the quality findings reported in the PhD work, listed in this review and published in renowned research journals, shedding new light on the influence of inert gas on cavity dynamics. For these reasons, **I propose that the PhD dissertation of Mr. Emad Hasani Malekshah be awarded distinction** (*summa cum laude*).

Podpisał Jacek Pozorski