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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Evgenii Kanin

PhD Program: Petroleum Engineering

Title of Thesis: Asymptotic models of coupled geomechanics/fluid mechanics phenomena of hydraulic fracture growth

Supervisor: Professor Andrei Osiptsov
Co-supervisor: Professor Dmitry Garagash, Dalhousie University, Canada

Name of the Reviewer: Professor Gennady Mishuris, Aberystwyth University, Wales

I confirm the absence of any conflict of interest	**Date: 01-08-2022**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

PhD thesis considers the problem of a hydraulic fracture propagating in a permeable reservoir.

The topic of the thesis is relevant to the PhD school program since a well treatment via Hydraulic Fracturing (HF) technique is widely used nowadays in the petroleum industry. This requires one to perform the accurate numerical modelling of the hydraulic fracture design before coming to field operations.

The Candidate has examined an impact of various hydrodynamical phenomena during fracture growth, namely:

(1) pressure-dependent leak-off,
(2) laminar-turbulent flow inside the fracture,
(3) fracturing fluid with yield stress and a strong non-linearity of the shear-stress.

He has analyzed how these effects impact on the major hydraulic fracture parameters during the propagation process. As far as I know, there has been a lacuna in the scientific literature where the detailed analyses of the phenomena (1)-(3) during the HF propagation is performed.

Evgenii has utilised two hydraulic fracture models for the investigations: semi-infinite fracture and penny-shaped fracture. The former model describes accurately the physical processes occurring near the fracture tip, and it is used in many numerical models for finite fractures as a propagation criterion; the latter model in the thesis is chosen as a suitable and commonly acceptable benchmark of a finite fracture.

In the case of the pressure-dependent fluid exchange between the fracture and the rock formation, the author has developed a near-tip region model and embedded it into a radial HF model. For the second fluid-mechanics phenomena, both the fracture tip and radial fracture models are utilized to study a transitional flow regime. Examination of a possible impact of the fluid yield stress was performed using a radial fracture model. For each HF model, Evgenii has carried out:

- a comparison between the developed solution and appropriate reference one, e.g., a pressure-dependent leak-off vs Carter's leak-off in the formation; a turbulent-laminar vs fully laminar flow and Herschel-Bulkley fluid vs power-law fluid. In all those comparisons, he has highlighted such cases when the considered fluid-mechanics phenomenon cannot be neglected and thus should be accounted for;
- an extensive exploration of the problem parametric spaces by utilizing both analytical and numerical methods. In addition to the widely used techniques, Evgenii has applied several novel numerical approaches explored recently.

The thesis is well-written and organized in a logical way. It consists of six chapters.

The first chapter presents an extensive literature review, while the second one outlines general problem formulation of the near-tip region and the penny-shaped HF models.

Next three chapters describe how pressure-dependent leak-off, laminar-to-turbulent flow regime transformation, and fracturing fluid yield stress influence on the HF propagation. Each of them problem under investigation includes a motivation to the analysis and its objectives; detailed problem's formulations; description of the modelling approach; respective results and their analyses.

Finally, the conclusions' section summarizes the main findings.

I believe that the results presented in PhD thesis are scientifically sounded and significant for application. Using them, a potential reader can estimate the importance of hydrodynamical effects (1) - (3) in the HF crack propagation and decide to account for them or not.

Moreover, the constructed numerical codes themselves can be of interest for researchers. For example, the developed fracture tip models can be implemented into a standard FEM models, e.g., EP3D or Planar3D, as an external tip element module. Finally, the penny-shaped model can be used as a benchmark solution for commercial simulators.

High level of the results delivered has been confirmed by their publication in the Q1/Q2 rated peer-review journals such as Journal of Fluid Mechanics, Journal of the Mechanics and Physics of Solids, Journal of Non-Newtonian Fluid Mechanics.

I have only two minor comments to the thesis:

- In field applications, HF surfaces are rather rough. Does the roughness impact the flow regime transition inside the fracture channel from laminar to turbulent?
- The author has applied two numerical approaches, identified as accurate and approximate, when he analyses an impact of the fracturing fluid yield stress on a radial crack propagation. However, the comparison between those numerical solutions is omitted. I believe such comparison (with clear estimation of the errors) would be a valuable addition for practitioners.

Finally, I would like to highlight the high quality of the work. I do believe that Evgenii Kanin deserves a PhD degree in Petroleum Engineering.

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*