

## REVIEW

of the official reviewer for dissertation work of  
**Makhmut Yerlan on the theme «Development of hybrid high-performance algorithms for  
numerical simulation of oil displacement problems»**  
presented for the degree of Doctor of Philosophy (PhD) in the specialty «8D06105 – System  
Engineering»

| №  | Criteria                                                                                                                               | Eligibility (one of the options must be checked)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Justification of the position of the official reviewer                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
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| 1. | The topic of the thesis (as of the date of its approval) corresponds to the directions of development of science and/or state programs | <p>1.1 Compliance with priority areas of science development or government programs:</p> <p>1) The thesis was completed within the framework of a project or target program financed from the state budget (indicate the name and number of the project or program)</p> <p>2) The thesis was completed within the framework of another state program (indicate the name of the program)</p> <p>3) <u>The dissertation corresponds to the priority direction of the development of science, approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan</u> (indicate the direction)</p> | The reviewed research falls under the nationally prioritised direction “Advanced Production, Digital and Space Technologies,” approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan. The work additionally contributes to the deliverables of the grant-funded project “High-Performance Computer Modelling of Multiphase Fluid Flow in Porous Media under Uncertainty” (registration No. AP09260564), in which the author was directly involved. The orientation of the dissertation toward the design of heterogeneous CPU–GPU computing software for industrially relevant simulation tasks is consistent with the national agenda on digital transformation of the energy sector. |
| 2. | Importance for science                                                                                                                 | The work <u>makes/does not make a significant contribution</u> to science, and its importance is <u>well disclosed/not disclosed</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | From a systems-engineering perspective, the dissertation advances the practice of designing, validating, and benchmarking coupled-physics simulation software across the full heterogeneous-hardware hierarchy. The contribution is significant precisely because it does not treat parallelism as an isolated optimisation step but as an integrated design discipline spanning seven execution                                                                                                                                                                                                                                                                                                                                              |

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|    |                               |                                                                                                                            | configurations. The importance is convincingly disclosed through reproducible measurements, hardware-ceiling analysis, and the systematic identification of binding constraints at each tier of the parallel hierarchy.                                                                                                                                                                                                                                                                                                                            |
| 3. | The principle of independence | Self-reliance level:<br>1) <u>High</u> ;<br>2) Medium;<br>3) Low;<br>4) No independence                                    | The author has personally designed and engineered the entire seven-variant implementation portfolio, including the sequential reference simulator, the three CPU-parallel configurations, the two single-GPU CUDA variants, and the two multi-GPU hybrid configurations. The independent execution of the profiling campaign — covering Intel VTune, mpiP, NVIDIA Nsight Compute, and NVIDIA Nsight Systems — and the formulation of the hardware-ceiling interpretation framework further attest to a high degree of autonomous engineering work. |
| 4. | The principle of inner unity  | 4.1 Justification of the relevance of the thesis:<br>1) <u>Justified</u> ;<br>2) Partially justified;<br>3) Not justified. | The relevance is well established by the combination of an industrially significant target problem — polymer flooding in oil reservoirs — and a clearly stated computational bottleneck arising from the strong nonlinearity and tight coupling of the governing equations. The author makes a convincing case that progress in this domain now depends as much on heterogeneous-hardware engineering as on the underlying numerical schemes.                                                                                                      |
|    |                               | 4.2 The content of the thesis reflects the topic of the thesis:<br>1) <u>Reflects</u> ;                                    | Each chapter contributes directly to the declared topic. The dissertation moves from the physical                                                                                                                                                                                                                                                                                                                                                                                                                                                  |

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|   |          | 2) Partially reflects;<br>3) Does not reflect                                                                                                                                                                                                                                                      | formulation and constitutive relations, through the sequential numerical scheme, to the parallel software variants, and finally to a unified empirical evaluation — with no superfluous material and no missing logical link between the topic and the chapters.                                                                                                                         |
|   |          | 4.3. The purpose and objectives correspond to the topic of the thesis:<br>1) <u>correspond</u> ;<br>2) partially correspond;<br>3) do not correspond                                                                                                                                               | The stated purpose — designing and systematically comparing hybrid high-performance algorithms for the oil-displacement problem — is directly mirrored by the seven enumerated research tasks. Each task maps to a chapter, and each chapter delivers a measurable outcome traceable to the overall objective.                                                                           |
|   |          | 4.4 All sections and provisions of the thesis are logically interconnected:<br>1) <u>completely interconnected</u> ;<br>2) the interconnection is partial;<br>3) there is no interconnection                                                                                                       | The chapters compose a coherent engineering progression: mathematical model → sequential reference → CPU parallelism → single-GPU acceleration → multi-GPU hybridisation → unified empirical evaluation. Each successive layer reuses the validated artefacts of the previous one, which strengthens the internal cohesion of the manuscript.                                            |
|   |          | 4.5 The new solutions (principles, methods) proposed by the author are reasoned and evaluated in comparison with the known solutions:<br>1) <u>there is a critical analysis</u> ;<br>2) partial analysis;<br>3) the analysis does not represent one's own opinions, but quotes from other authors; | Chapter 2 surveys prior GPU-accelerated reservoir-simulation studies and explicitly identifies three literature gaps: predominant reliance on a single GPU, selective rather than full-pipeline use of shared-memory tiling, and the absence of an integrated three-level hybrid for coupled polymer-flooding physics. The author's contributions are positioned against these gaps with |

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|    |                              | 4) the analysis is absent.                                                                                                                                         | reasoned argumentation rather than mere citation.                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| 5. | Scientific novelty principle | 5.1 Are the scientific results and provisions new?<br>1) completely new;<br>2) <u>partially new (25–75% are new)</u> ;<br>3) not new (less than 25% are new)       | The constitutive model and the IMPES discretisation rest on established theory, whereas the engineering integration of the three coupled physics kernels into a single shared-memory CUDA pipeline, together with the disciplined fusion of MPI, OpenMP, and CUDA into a coherent triple-hybrid solver, represent genuinely new implementation-level contributions. The cumulative novelty is partial but unambiguous and is sufficient for a doctoral specialty in System Engineering. |
|    |                              | 5.2 Are the dissertation findings new?<br>1) completely new;<br>2) <u>partially new (25–75% are new)</u> ;<br>3) not new (less than 25% are new)                   | The empirical findings — a peak speedup of 34.7× for the triple-hybrid variant and 20.2× for the fully coupled single-GPU pipeline against the optimised sequential baseline — are obtained on a uniform problem set and are accompanied by a principled hardware interpretation. The mapping from observed performance to the FP64 throughput limit and the L2 residency regime is, to the reviewer's knowledge, original within the polymer-flooding literature.                      |
|    |                              | 5.3 Technical, technological, economic or management decisions are new and reasonable:<br>1) <u>completely new</u> ;<br>2) <u>partially new (25–75% are new)</u> ; | The principal technical decisions — the warp-level shuffle reductions, the SM-resident tiling of the three coupled physics kernels, and the host-side overlap of MPI collectives with GPU execution in the triple-hybrid configuration — are well motivated by hardware properties of                                                                                                                                                                                                   |

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|    |                                     | 3) not new (less than 25% are new)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | the Turing microarchitecture and are reasonable in their implementation.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| 6. | The validity of the main findings   | All main conclusions <u>are</u> /are not <u>based</u> on scientifically significant evidence or well-grounded (for qualitative research and areas of training in the arts and humanities)                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Every performance claim is anchored in three independent forms of evidence: (i) timing measurements against a shared sequential baseline; (ii) profiling data from four industry-standard tools; and (iii) bitwise validation against the analytical Buckley–Leverett solution. The convergence of these three forms of evidence places the main conclusions on solid empirical ground.                                                                                                                                                                                                                                                                                                                                                                                                |
| 7. | The main provisions for the defense | <p>It is necessary to answer the following questions for each provision separately:</p> <p>7.1 Is the provision proven?</p> <p>1) <u>proven</u>;</p> <p>2) rather proven;</p> <p>3) rather not proven;</p> <p>4) not proven;</p> <p>5) in its current wording, it is impossible to verify whether the statement has been proven.</p> <p>7.2 Is it trivial?</p> <p>1) yes;</p> <p>2) <u>no</u>;</p> <p>3) in its current wording, it is impossible to verify whether the statement is trivial.</p> <p>7.3 Is it new?</p> <p>1) <u>yes</u>;</p> <p>2) no;</p> <p>3) in its current wording, it is impossible to verify the novelty of the statement.</p> | <p><b>Main provision 1: Fully coupled GPU implementation with shared-memory tiling.</b></p> <p>The provision is proven through the CUDA source code, the bank-conflict-free indexing, and the measured 20.2× speedup that approaches near-peak FP64 throughput. The supporting article “A CUDA Performance Study of Global- and Shared-Memory Kernels for the Buckley–Leverett Polymer-Flooding Problem” (Applied Sciences, 2026) corroborates this provision in the peer-reviewed literature.</p> <p><b>Main provision 2: Scalable triple-hybrid MPI+OpenMP+CUDA algorithm.</b></p> <p>The provision is proven by the engineered three-tier orchestration that demonstrably integrates MPI domain decomposition, OpenMP host coordination, and CUDA shared-memory kernels without</p> |

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|    |                                                                               | <p>7.4 Application level:</p> <p>1) narrow;</p> <p>2) <u>medium</u>;</p> <p>3) wide;</p> <p>4) in its current wording, it is impossible to determine the scope of application of the statement.</p> <p>7.5 Is it proven in the article?</p> <p>1) <u>yes</u>;</p> <p>2) no;</p> <p>3) in its current wording, it is impossible to verify whether the statement has been proven in the article.</p>                                                                                                                         | <p>algorithmic compromise. The <math>34.7\times</math> peak speedup and the consistent victory across five of the six grid sizes substantiate the claim. The application level is justifiably medium, given that the demonstration targets a one-dimensional model but provides a template directly transferable to higher-dimensional reservoir codes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| 8. | The principle of reliability. Reliability of sources and information provided | <p>8.1 Choice of methodology — is justified or the methodology is described in sufficient detail</p> <p>1) <u>yes</u>;</p> <p>2) no</p> <p>8.2 The results of the thesis were obtained using modern methods of scientific research and methods of processing and interpreting data using computer technologies:</p> <p>1) <u>yes</u>;</p> <p>2) no</p> <p>8.3 Theoretical conclusions, models, identified relationships and patterns have been proven and confirmed by experimental research (for areas of training in</p> | <p>The methodological framework is described at a level of detail that would allow an independent group to reconstruct the implementation portfolio. The author clearly states modelling assumptions, discretisation choices, time-stepping scheme, convergence tolerances, and hardware configuration.</p> <p>The instrumentation reflects current best practice in HPC software engineering: parallel programming models (OpenMP, MPI, CUDA), performance instrumentation across the CPU–GPU boundary (Intel VTune, mpiP, NVIDIA Nsight Compute, NVIDIA Nsight Systems), and reproducibility through a controlled experimental design.</p> <p>The theoretical performance expectations — in particular, the predicted dominance of the L2-cache residency at intermediate grid sizes and the FP64-throughput limit</p> |

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|    |                           | <p>pedagogical sciences, the results have been proven on the basis of a pedagogical experiment):</p> <p>1) <u>yes</u>;</p> <p>2) no</p>                           | <p>at large grid sizes — are confirmed by the measurement data. The patterns identified in the analysis align with the recorded experiments.</p>                                                                                                                                                                                                                                 |
|    |                           | <p>8.4 Important statements are <u>confirmed</u> / partially confirmed / not confirmed by references to current and reliable scientific literature</p>            | <p>Substantive claims are anchored in peer-reviewed sources spanning four research areas — polymer flooding, numerical methods for porous-media flow, parallel algorithm design, and GPU computing — with appropriate weighting of recent and seminal references.</p>                                                                                                            |
|    |                           | <p>8.5 Used literature sources are <u>sufficient</u>/not sufficient for a literature review</p>                                                                   | <p>The bibliography is sufficient and well chosen for a dissertation of this scope. Coverage of the four pertinent research areas is balanced, with no apparent omissions of works that would alter the positioning of the contributions.</p>                                                                                                                                    |
| 9. | Practical value principle | <p>9.1 The thesis has theoretical value:</p> <p>1) <u>yes</u>;</p> <p>2) no</p>                                                                                   | <p>The theoretical value lies in the formulation of an integrated design methodology for heterogeneous CPU–GPU simulation software, in which the parallelisation strategy is selected by reference to hardware ceilings rather than by trial. This methodology generalises beyond polymer flooding to other coupled-PDE problems with shared spatial neighbourhood patterns.</p> |
|    |                           | <p>9.2 The thesis is of practical importance and there is a high probability of applying the results obtained in practice:</p> <p>1) <u>yes</u>;</p> <p>2) no</p> | <p>Because the results are obtained on workstation-class hardware (an Intel Core i9 CPU and two NVIDIA GeForce RTX 2080 Ti consumer GPUs), they are directly transferable to the computing environments of university research groups and small engineering teams. The</p>                                                                                                       |

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|     |                                   |                                                                                                                                                 | implementation patterns scale upward to data-centre accelerators without algorithmic redesign, which broadens the practical reach of the work.                                                                                                                                                                                                                                                                                                                                                                                          |
|     |                                   | 9.3 Are the practice suggestions new?<br>1) completely new;<br>2) <u>partially new (25–75% are new)</u> ;<br>3) not new (less than 25% are new) | The practical guidance — in particular, the rule of thumb for selecting between MPI+CUDA and the triple-hybrid configuration as a function of problem size — is partially new and constitutes a useful engineering heuristic for practitioners building similar simulators.                                                                                                                                                                                                                                                             |
| 10. | The quality of writing and design | Academic writing quality:<br>1) <u>high</u> ;<br>2) average;<br>3) below average;<br>4) low.                                                    | The manuscript is clearly written and well organised. The technical figures and benchmark plots communicate the results effectively, and the language is appropriate for a doctoral monograph. A small number of typographical inconsistencies and figure-caption irregularities were observed but they do not impede comprehension.                                                                                                                                                                                                    |
| 11. | Notes on a thesis                 |                                                                                                                                                 | The dissertation is a mature engineering work that meets the standard of an independent PhD contribution. As constructive recommendations for follow-on research, the reviewer suggests three directions: (i) consolidating the implementation portfolio into an open-source software artefact with documented build instructions to amplify reproducibility and downstream adoption; (ii) evaluating the portability of the triple-hybrid pattern across non-NVIDIA accelerators (for example, AMD and Intel GPUs through HIP or SYCL) |

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|     |                                                                                                                                                                                                                                                                                           |                                                  | <p>in order to test the architectural generality of the design; and (iii) integrating the simulator with surrogate or reduced-order machine-learning models so that the high-performance solver can be deployed inside iterative reservoir-optimisation loops. These observations are intended as encouragement for future work and do not detract from the positive assessment of the dissertation.</p>                                                                                                                                                                                                                                                                                                                                                                                            |
| 12. | <p>Scientific level of the doctoral student's articles on the topic of research (in case of defense of the dissertation in the form of a series of articles, the official reviewers comment on the scientific level of each article of the doctoral student on the topic of research)</p> |                                                  | <p>The author's ten publications are well distributed across venues at different visibility tiers and collectively cover every principal contribution of the dissertation. The article in Applied Sciences (Q1) on global- and shared-memory CUDA kernels for the Buckley–Leverett polymer-flooding problem corresponds directly to the first main provision for defense; the article in Energies (Q1) extends the application context with machine-learning surrogates; the contribution in IET Quantum Communication (Q1) demonstrates the author's reach into adjacent computational paradigms; and the conference papers in the ECMOR series document the staged development of the hybrid algorithms. Their scientific level is sufficient for the specialty 8D06105 – System Engineering.</p> |
| 13. | <p>Decision of the official reviewer (pursuant to paragraph 28 of the present Model Regulations)</p>                                                                                                                                                                                      |                                                  | <p>In view of the methodological rigour, the substantiated scientific novelty, the systematic empirical evaluation, and the publications corresponding to the dissertation</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |

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|   |          |                                                  | topic, I recommend that the academic degree of Doctor of Philosophy (PhD) in the specialty «8D06105 – System Engineering» be conferred upon Makhmut Yerlan. |

**Official Reviewer:**

PhD., Professor,  
Kazakh-British Technical  
University



(signature)

**Zharasbek Baishemirov**

