Fluid-thermal Analysis of the Green Revolution Energy Converter (GREC)

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Background

The Green Revolution Energy Converter (GREC) represents an innovative thermodynamic technology designed to convert low-grade thermal energy (e.g. from industrial waste heat, geothermal energy, solar energy, district heating systems, power stations, data centers, etc.) into electricity utilizing simplified rotary mechanisms with minimal moving components. The distinct attributes of this technology—namely decentralized energy conversion, fuel-versatile thermal utilization, mechanical simplicity, and a broad operational temperature range—render it highly relevant within the context of energy security and supply resilience. The GREC system functions as an external Carnot engine wherein a closed volume of gas—designated as the Work Generating Volume (WGV)—is contained within thin discs that rotate between hot and cold heat exchanger fins (Fig. 1). This rapid thermal transfer induces pressure oscillations, which are subsequently converted into electrical energy.

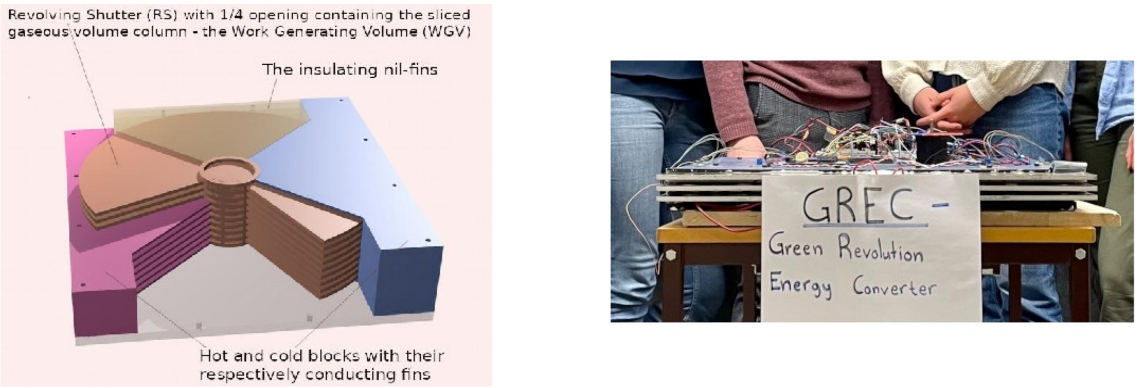

Figure 1: A schematic sketch (left) and (right) the physical rig of the GREC configuration. For more details and videos, see https://www.nilsinside.com.

Problem formulation

Developed by Nils Karlberg (nilsinside AB), the technology has been the subject of five comprehensive student research projects at Linköping University (LiU) since 2022 (see Appended Materials, "*Summary of the GREC Projec*"). This include CFD-studies (using e.g. COMSOL and Ansys) as well as the construction of and *LabModel v3* and its experimental validation (reproducing pressure oscillations at 3 Hz at 80 °C). Although this verified the technology proof-of-concept from a fluid-thermal perspective, there are still plenty of aspects in the GREC technology that are not well understood and need further investigations.

Scope

The objective of this project can be divided into several phases:

- **Phase 1**. Developing reliable simulation models, utilizing s GPU-compatible finite volume solvers (e.g Ansys Fluent or Star-CCM+), for a specified number of operating conditions of the existing GREC rig (LabModel v3). The analysis should provde an overview of different modeling strategies, evaluating their accuracy against computational cost.
- **Phase 2**. Broader evaluation of the GREC's performance—specifically focusing on power density and efficiency across a wider spectrum of input parameters (succh as, operating variables, working media, geometric modifications, etc.). This will involve identifying potential performance and modeling limitations, alongside determining requirements for further, advanced analyses through both simulations and experimental measurements. Ultimately, the insights gained will be utilized to understand scaling laws and to establish optimization guidelines for the next generation of the test rig.
- **Phase 3** (optional, if time allows). Develop one or several metamodels capable of predicting the GREC's performance under the various operating conditions, working media, and operational scenarios analyzed earlier in the project.

The project suggested work packages:

- **WP1: Experimental measurements**. Conduct a series of measurements on the existing LabModel v3 under normal operating conditions, i.e. when the rig reaches a steady state behavior for the pressure oscillations. Evaluate the impact of, for example, pressure, temperature, rotational speed, and heat input. Geometric parameters will not be analyzed.
- **WP2: CFD analysis – Verification & Validation**. Develop reliable CFD models of the existing LabModel v3 for multiple design points under normal operating conditions. The methods will be validated using measurement data from WP1. The CFD models and simulations will be developed in Ansys Fluent or StarCCM+, enabling the possibility to use the GPU-solvers. The initial focus will be on RANS-based methods, which are less computationally intensive, thereby facilitating larger parameter studies in WP3. If this model validation does not meet expectations, more sophisticated CFD modeling strategies should be evaluated.
- **WP3: CFD analysis – Parameter studies**. Conduct an extensive parameter study, building upon the measurement series from WP1 using the validated CFD methodology developed in WP2. The number of design points in this study will be determined by the computational cost in relation to available computing resources. Data from the measurement series and sensitivity analyses will also be used to define the boundaries of the design space. The analysis will, for example, cover (but not excluded to):
  - Operating parameters (pressure, temperature, rotational speed, and heat influx)
  - Working media (air, helium, CO, refrigerant)
  - Geometric modifications (WGV radius, layer thickness)
  - Normal operating conditions as well as various contingency scenarios (startup transient, varying temperature, start/stop cycles, degraded cooling)

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Pre-requisites

The following qualifications are meriting for the project:

- Experience with Ansys CFD tools such as Ansys Fluent or StarCCM+
- Experience in heat transfer modeling
- Experience with visualization and data analysis in Paraview
- Experience with high-performance computing (HPC)

Contact

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Summary of the GREC Project

The **Green Revolution Energy Converter (GREC)** is a novel heat engine that converts a heat gradient into mechanical work. Early days of the project pV=nRT simulations in excel and comparisons with reciprocating external heat engines indicated promising potential for the project so the GREC is now extensively studied.

GREC Reports from Linköping University

Based on the information that claud.ai found, here are the documented GREC projects at Linköping University:

1. Spring 2022 - Part 1: Theoretical Proof of Concept For The Green Revolution Energy Converter

Authors: Gustav Edholm, John Malmdal, Lukas Haglund, Markus Eriksson, and Oscar Magnusson.
This team achieved a significant milestone by developing a custom analytical framework to theoretically validate the GREC technology. Their report established a mathematical model based on Carnot engine principles, performed material analysis, developed calculation models in MATLAB, thermal simulations in ANSYS, and CAD geometry in CREO.
To get an overview of how the heat transfer coefficient (HTC) behaved in the model, the change of airflow was computed along the radius, a mathematical tool for performance calculations was developed to theoretically verify the technology of the GREC. By applying a few simplifications and assumptions, the tool provided reasonable results compared to scientific theory. How different scales affect the performance of the GREC was examined and results showed that a larger GREC model would be more effective and able to produce more power at several given source temperatures. The rotation speed proves to impact the heat transfer capability in the engine, primarily by affecting the magnitude of the heat transfer coefficient but also the achieved temperature difference in the WGV. A higher temperature difference between the heat sources also leads to a significantly higher obtained power output and efficiency, making it a promising concept to study further.

The research team's conclusions explicitly acknowledged that "real experiments with similar operating modes must be conducted and compared" to validate their mathematical framework.

From Theory to Computational Investigations:

The Spring 2022 analytical predictions established testable hypotheses regarding GREC thermal performance. To validate these computational findings and quantify parametric dependencies between geometric configurations and system performance, Linköping University launched two parallel experimental investigations in Autumn 2022.

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2. Autumn 2022 - Part 2: Internal and external heat transfer investigation of the GREC

Building on the theoretical foundation established in Spring 2022, nine technologists were organised into two complementary researchers teams: the Internal Heat Transfer group (Johan Hagströmmer, Mattias Reijm, Oscar Torsteinsrud, Vendela Stenholm) focused on convective phenomena within the WGV, while the External Heat Transfer group (Emma Gustafsson, Maja Abrahamsson Bolstad, Matilda Eriksson, Wilma Fager, Emma Andersson) investigated thermal coupling between the GREC system and external energy reservoirs.

Autumn 2022 IHT: Investigation of the internal heat transfer in GREC

From Theory to Experimental Validation: The Spring 2022 analytical predictions established testable hypotheses regarding GREC thermal performance. To validate these computational findings and quantify parametric dependencies between geometric configurations and system performance, Linköping University launched parallel experimental investigations in Autumn 2022.

The following Autumn 2022 Internal Heat Transfer research group recognised this perfectly, identifying that a simple and quick CFD model of the WGV domain enhances the understanding since a larger number of simulations can be done during the time of the project. Thus, a more trial and error approach can be implemented. represent an essential bridge between analytical modeling and experimental validation.

Research Team and Methodology: The Internal Heat Transfer group (Johan Hagströmmer, Mattias Reijm, Oscar Torsteinsrud, Vendela Stenholm) report "Investigation of the internal heat transfer in GREC" advanced the research frontier by implementing three-dimensional CFD simulations in COMSOL Multiphysics. Modeling the Work Generating Volume (WGV) with solid boundary walls representing the conducting fins, using moving mesh to simulate revolving motion.

Research Objectives: The team systematically investigated critical design parameters: - WGV airflow characteristics as functions of rotor speed (500-3000 rpm), radius (0.145-0.58 m), and thickness (0.005-0.011 m) - Revolving Shutter (RS) geometry optimization (quarter-disc vs. dual-eighth configuration) - Turbulence enhancement via flow disturbance elements - Conjugate heat transfer dynamics and subsequent pressure oscillations

Key Scientific Findings: Computational results demonstrated that high work output correlates with elevated heat transfer coefficients, achievable through increased rotation speed, extended rotor radius, turbulence optimization, and the dual-eighth Revolving Shutter configuration. Performance scaling revealed that larger GREC configurations exhibited stronger pressure and temperature oscillations, implying higher theoretical work output when adequate thermal energy is available.

Model Validation: Comparative analysis with Laboratory Model v2.0 experimental data showed computational predictions within the same order of magnitude as measured values, establishing model credibility while acknowledging that physical prototypes incorporate friction and dead volume effects not fully captured in this CFD framework.

Research Impact: This pioneering CFD investigation provided the first high-fidelity computational validation of GREC thermodynamic principles, establishing parametric relationships essential for prototype scaling and performance optimization. The methodology developed enables systematic investigation of geometric variants prior to physical fabrication.

Autumn 2022 EHT: Thermal Investigation of the Green Revolution Energy Converter

Operating in parallel with the Internal Heat Transfer group (IHT), the External Heat Transfer team (EHT) Emma Gustafsson, Maja Abrahamsson Bolstad, Matilda Eriksson, Wilma Fager and Emma Andersson investigated thermal coupling between GREC and external energy reservoirs—a critical interface for practical deployment.

Research Objectives: The research team systematically evaluated heat transfer mechanisms for delivering thermal energy to the Work Generating Volume through conducting fins and heat blocks. Two distinct thermal management architectures were investigated: None Pipe Heat Transfer (NPHT) employing pure conduction, and Pipe Heat Transfer (PHT) utilising embedded fluid circulation networks.

Methodological Framework: Computational analysis in ANSYS Workbench coupled with MATLAB calculations examined parametric dependencies across multiple geometric scales (radius: 0.145-0.58 m; thickness: 0.6-1.8 cm) and thermal boundary conditions (100°C-500°C source temperatures). An iterative convergence methodology between ANSYS steady-state simulations and the Internal Heat Transfer group's COMSOL transient model established thermally-consistent boundary conditions.

Key Scientific Findings: Results demonstrated that the PHT configuration achieved substantially higher effective heat transfer rates (approximately up to three times, depending on geometry) and more uniform temperature distribution across conducting fins. For NPHT systems, geometric scaling dominated performance more significantly than source temperature—a finding with direct implications for application-specific design optimization.

Application Feasibility: Analysis indicated GREC compatibility with district heating systems (80°C operating temperature) via PHT architecture, while NPHT configurations showed viability for high-temperature applications including fuel cell waste heat recovery (500°C), contingent upon appropriate geometric scaling.

Research Impact: This investigation established foundational thermal management design principles for GREC prototype research, demonstrating that application-specific optimisation of heat transfer architecture, geometric parameters, and source temperatures constitutes the critical determinant of technological readiness advancement. The comprehensive parametric investigation furnishes rigorous design constraints essential for Laboratory Model v3 engineering specifications.

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3. Spring 2023 - Part 3: Laboratory Model v3 Development

LabModel v3: Integrated Prototype Fabrication: Nine researchers organised into three specialised teams executed the comprehensive design, fabrication, and instrumentation of LabModel v3, achieving a critical milestone in GREC technological maturation by delivering the first fully operational prototype capable of systematic experimental validation.

- Construction team: **Design and development of a working prototype for the Green Revolution Energy Converter** Andrei Toader, Ida Hellström and Simon Sandström, providing comprehensive engineering specifications including complete CAD documentation for LabModel v3 mechanical architecture.

- Thermodynamics team: **The thermodynamics of the GREC version 3** Johan Åsmo, Jakob Ross and Vidar Jeirud, conducting theoretical and experimental investigations of thermodynamic cycle performance, energy conversion efficiency, and operational characteristics under varying thermal boundary conditions.

- Mechatronics team: **Development of a mechatronic solution for a new type of heat engine** Oskar Brodin, Lisa Vilhemsson and Max Hollsten. specifying electronic component selection criteria, sensor integration protocols, and real-time control system architecture enabling autonomous operation and data acquisition for the GREC laboratory prototype "LabModel v3".

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4. Spring 2024 - Part 4: Further development of the Green Revolution Energy Converter

Experimental validation: Erik Widström, Simon Eriksson, and Richard Zetterman executed systematic experimental characterisation of the LabModel v3, achieving critical technological validation milestones that advanced GREC from laboratory demonstration to empirically-validated proof-of-concept.

- **Research Objectives**: The investigation addressed three primary technical challenges: establishing pressure integrity through systematic leak identification and remediation, implementing quantitative power output measurement methodologies, and enhancing operational accessibility through control system refinement and comprehensive documentation.

- **Methodological Innovations**: The research team implemented Raspberry Pi-based control architecture enabling web interface motor control, systematically identified and sealed pressure leakage pathways using high-temperature acetoxy silicone sealant capable of withstanding 250°C, and developed dual power measurement approaches utilising acoustic transducer conversion (tweeter as linear generator) and hydrostatic column displacement methods.

- **Experimental Validation Results**: Comprehensive testing demonstrated pressure homogeneity throughout the system volume at operating conditions up to 3 Hz revolving frequency with a temperature difference of 80 °C between hot and cold fins. Repeatable pressure oscillations were achieved, with measurements confirming consistency across multiple test sequences. Power output characterisation revealed proof-of-concept functionality, with results enabling extrapolation to larger geometries, elevated thermal gradients, and increased revolving velocities.

- **Parametric Performance Characterisation**: Systematic investigation established non-linear relationships between operational parameters: pressure differential increased exponentially with thermal gradient rather than linearly as initially hypothesized, while maintaining substantial pressure oscillations despite doubled and tripled rotation frequencies. Power output demonstrated linear correlation with internal pressure differential, validating fundamental thermodynamic predictions. Research Significance: This experimental campaign successfully transitioned GREC technology from computational/analytical validation to empirical demonstration, establishing repeatability protocols, quantifying performance metrics, and generating the first experimental dataset enabling validation of prior theoretical predictions. The innovative application of acoustic transducers for mechanical-to-electrical energy conversion, while yielding modest absolute power levels, validated scaling principles essential for prototype development. The comprehensive documentation framework substantially reduces activation energy for subsequent research initiatives.

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5. Winter 2024/25 – Part 5: The Green Revolution Energy Converter at ICAM

Following the successful proof-of-concept validation of Laboratory Model v3 at Linköping University in 2024, the Green Revolution Energy Converter project entered an international continuation phase at **ICAM (Toulouse)** under the supervision of **Michael Peyrony-Rapatout** and **Pierre Le Provost**. The ICAM study extended the Swedish findings by developing coupled **thermal–thermodynamic numerical models** aimed at quantifying the converter's useful energy output and efficiency under controlled conditions. Two complementary tools were implemented: an **ANSYS transient model** representing the Work Generating Volume (WGV) and its hot and cold fin blocks, and a **MATLAB dynamic model** reproducing the idealized pV-cycle of a piston–crank mechanism driven by the periodic heating of the WGV. The coupling of these models enabled parametric evaluation of key variables—frequency, heat-transfer coefficient (HTC), and thermal gradient (ΔT)—identified in earlier Linköping work as the dominant performance determinants.

Simulations were conducted for operating frequencies between **0.5 Hz and 3 Hz**, with hot- and cold-side temperatures of **150 °C and 10 °C**, respectively. The ANSYS model resolved the transient thermal field within the rotating WGV and quantified spatial HTC gradients as functions of radius and Reynolds number, revealing that higher rotational frequency enhances convective exchange but shifts the optimal operating point toward higher HTC values. The MATLAB cycle model, fed with HTC data extracted from ANSYS, predicted a volumetric power density of approximately **340 W m ^{3}** and a theoretical efficiency near **6 %** for the reference case, with mechanical energy consumption for rotation estimated two orders of magnitude lower. These results confirmed the potential of the GREC concept to achieve performance comparable to compact low-temperature Rankine or Ericsson-type systems, provided that HTC optimisation can be realised experimentally. Future work defined by the ICAM team includes incorporating **grooved-fin geometries**, **pipe-based heat-transfer architectures**, and the **design of a low-temperature (200 °C) laboratory prototype**, thereby establishing a direct experimental bridge between the Swedish and French research phases.

CFD Work on GREC

TotalSim UK (December 2016) OpenFOAM with Revolving-Shutter

Commercial Masters of OpenFOAM: We met with Rob Lewis at their office close to Silverstone. Graham Martin did an OpenFOAM simulation showing an open layer of the GREC with a rotating Revolving-Shutter so one could follow an internal swirl forming in the WGV. Very informative and pedagogic simulation. Rob underlined the importance of the HTC value in the WGV, and the possibility to perhaps keep a laminar flow in the dead volume along the Revolving-Shutter surfaces facing the boundary fins. If that would be the case we could gain on installing laminar flow breakers to avoid laminar flow in the WGV. TotalSim were not able to do closed volumes at the time so the mesh with the revolving WGV was open.

ALMI Joakim Wren (October 2017) COMSOL Multiphysics Study

Pioneering Computational Analysis: In 2017, Dr. Joakim Wren conducted preliminary computational fluid dynamics investigations of GREC thermal performance utilising COMSOL Multiphysics. This early-stage numerical analysis provided foundational insights into fin temperature distributions and thermal transport characteristics prior to the comprehensive student research campaigns at Linköping University.

Computational Methodology: Dr. Wren employed a 2D axisymmetric model representing a planar circular disc with 5 mm aluminum conducting fin thickness. The computational domain simulated one quarter of the full rotational cycle, with power output results scaled accordingly. Parametric sweep studies investigated three thermal boundary condition scenarios (20-80°C, 20-180°C, and 20-280°C), utilising mean Work Generating Volume temperatures

(50°C, 100°C, and 150°C respectively) as fin cooling temperatures. Simulations systematically varied heat transfer coefficients (HTC = 40 and 100 W/m²K), rotational frequencies (1, 2, 4, and 8 rpm), and WGV thickness dimensions (5, 8, and 12 mm) to characterize performance across operational parameter space.

Preliminary Findings: Temperature distribution analyses along the fin radius (from 30 mm radial position) revealed systematic thermal gradients dependent upon rotational frequency and geometric configuration. These early computational results established baseline expectations for thermal behavior, subsequently validated and refined through the comprehensive analytical and experimental investigations conducted by Linköping University research teams between 2022-2024.

Internal Heat Transfer CFD Study (December 2022)

Up till now, the most significant WGV CFD work was the “Investigation of the internal heat transfer in GREC – TMPE09 - Project Report” (12/2022) by J. Hagströmmer, M. Reijm, O. Torsteinsrud, and V. Stenholm from Linköping University.

Ongoing CFD Development (Intermediate GREC, July 2025)

A CFD model in OpenFOAM was created based on the Linköping University group project “Investigation of the internal heat transfer in GREC – TMPE09 - Project Report” (12/2022), J. Hagströmmer, M. Reijm, O. Torsteinsrud and V. Stenholm, intended as a foundation for future technology research including analyses, dimensioning, and optimisation for future applications. The Intermediate GREC -CFD project replicates the IHT COMSOL-based thermofluid analysis. The original IHT study models periodic heat-driven pressure changes inside a closed air-filled system to explore a novel mechanical energy conversion concept using hot and cold fins. The Intermediate GREC - CFD project goal is to replicate the Linköping analysis using OpenFOAM’s `chtMultiRegionFoam` solver.

OpenFOAM Case Summary:
- Domain: Revolving-Shutter (RS) 1/4-disc sector of GREC geometry
- Fluid: Air (perfect gas), in a sealed cavity (Work Generating Volume, WGV)
- Solids: Three ”rotating” aluminum walls, three Bakelite-insulated walls
- Rotation simulation: Time-dependent temperature cycling on patch walls
- Boundary conditions: Hot (373.15 K), Cold (283.15 K), Neutral
- Time stepping: 1500 RPM (25 Hz) with 20 samples per revolution
- Solver: chtMultiRegionFoam (OpenFOAM v2412)
- Mesh: SnappyHexMesh from Blender-generated STL patches - MRF momentum source activated via fvOptions
- Initial velocity field from `#codeStream` internal field
- Wall temperatures via dynamic codedFixedValue patch BCs

Complete case folder, Blender file, Chat-GPT log available.

Outstanding Work and Future Development Directions

Identified Gaps/Future Work:
- Further CFD studies
- LabModel v3 experiments
- Partial phase shift research
- Advanced power extraction methods testing
- Optimisation for high-, mid- and low- temperature gradient cases
- Comprehensive performance validation at scale

The project is struggling at Technology Readiness Level (TRL) 3-4, moving from theoretical proof of concept to validated lab-scale prototypes, with CFD work just beginning to support the next phase of research.

Acknowledgements and Outlook

The **Green Revolution Energy Converter sustainable project** gratefully acknowledge the numerous researchers, engineers, students and friends who have contributed to the GREC research since its inception—spanning analytical modeling, computational simulations, and LabModel realisations. From the early theoretical developments in the UK and in Sweden to the advanced numerical and experimental work undertaken at Linköping University and ICAM, each phase has built upon the dedication and creativity of successive teams. *No one mentioned, no one forgotten.*

The Linköping University **LabModel v3**, now installed and operational in **Brassac** France, stands as a functional research platform prepared to validate forthcoming **theoretical, computational, and experimental** investigations. It serves as both a symbol of international collaboration and a practical foundation for future innovation in thermomechanical energy conversion in times when life on Earth is suffering from rising temperatures.