Modelling of a regenerative heat exchanger using CFD to determine the performance of a VHTR cycle

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Abstract:

Gas-cooled nuclear power cycles are characterized by relatively simple system configurations. In addition to the reactor, turbine, compressor and cooler, a regenerative heat exchanger plays a particularly important role, as its effectiveness and associated pressure losses significantly influence the overall thermodynamic performance of the system. In high-temperature applications such as the Very High Temperature Reactor (VHTR), the recuperator becomes a key component determining both cycle efficiency and net power output. The present study focuses on the design, modelling and performance assessment of a recuperator operating within a VHTR Brayton cycle. The research methodology is based on a coupled multiscale approach. Initially, a zero-dimensional (0D) thermodynamic model of the VHTR cycle was developed to determine the principal operating parameters and validate system-level calculations through comparison with results obtained using the commercial software Ebsilon. Based on the boundary conditions derived from the 0D analysis, the geometry of the regenerative heat exchanger was designed and modelled, followed by detailed CFD simulations performed in Autodesk CFD 2026. The numerical analysis enabled the determination of temperature fields, local heat transfer characteristics, pressure drops and the thermal effectiveness of the recuperator under realistic operating conditions. The calculated pressure losses and updated effectiveness values were subsequently reintroduced into the 0D cycle model. Two scenarios were analysed: one including pressure losses within the recuperator and the other incorporating CFD-derived effectiveness values. This iterative coupling allowed for a refined evaluation of the influence of component-level phenomena on overall cycle efficiency and power output. The study demonstrates how detailed CFD-based modelling of a key heat transfer component affects system-level thermodynamic performance, contributing to the optimization of advanced high-temperature gas-cooled nuclear systems for efficient and low-carbon power generation.

Keywords:

Nuclear energy, high–temperature gas–cooled reactor, CFD, cycle modelling.

1. Introduction

The global energy sector is currently undergoing a significant transformation driven by the need to reduce greenhouse gas emissions and ensure stable and reliable energy supply [1,2]. Traditional energy systems have been largely based on fossil fuels such as coal, oil, and natural gas. However, increasing environmental regulations and international climate policies are imposing strict limitations on the use of carbon-intensive energy sources [1]. At the same time, many countries aim to reduce their dependence on imported energy resources, which can be subject to geopolitical conflicts and lead to unstable energy prices.

In response to these challenges, renewable energy sources such as wind and solar power have been rapidly developed [3]. These technologies provide clean energy and contribute to the reduction of CO_2 emissions [3]. However, renewable sources are inherently intermittent and strongly dependent on weather conditions [4]. For example, wind power generation decreases when wind speeds are low, while solar power output is reduced during cloudy conditions or at night. As a result, relying exclusively on renewable energy sources may lead to challenges in maintaining a stable and reliable power supply [1,3,5]. Therefore, the development of stable, low-carbon energy technologies remains an important objective of modern energy systems [1,2,6].

Nuclear energy is widely considered one of the most promising solutions capable of providing large-scale, low-carbon electricity generation [7,8]. Unlike renewable energy sources, nuclear power plants can operate continuously and are not dependent on weather conditions [7]. In recent years, significant research efforts have been focused on the development of Generation IV nuclear reactors, which aim to improve safety, sustainability, and efficiency of nuclear power systems [8,9]. These reactors are designed with advanced safety features, including passive and inherent safety mechanisms, as well as improved fuel utilization and the potential for fuel recycling

[8,9]. In addition, advanced reactors may support new applications such as hydrogen production and industrial heat supply [7,10].

Among the proposed Generation IV concepts, the Very High Temperature Reactor (VHTR) has attracted considerable attention [11-13]. Table 1 gathers the operating parameters of gas cycles in VHTR-related studies. The VHTR operates at significantly higher outlet temperatures compared to conventional nuclear reactors, typically in the range of 900–1050 K [11,14]. Such high operating temperatures enable the use of advanced thermodynamic cycles with improved efficiency [12,13]. One of the most promising solutions is the helium Brayton cycle, where helium is used as the working fluid due to its chemical inertness and favourable thermophysical properties at high temperatures [12,15].

Table 1. *Operating parameters of gas cycles in VHTR-related studies.*

Type of study	Cycle / system	Working fluid	Pressure, MPa	Temperature [K]	Reference
Review	Gen IV systems	He	3-7	up to 1000	[8]
Reference	VHTR concept	He	3-7	900-1050	[11]
Theoretical	Brayton (marine)	He	3-7	800-1000	[13]
Theoretical	Adv. VHTR cycle	He	2-5	700-950	[14]
Theoretical	sCO_2	CO_2	7-25	500-700	[16]
Design study	HTGR-GT	He	~7	850-950	[17]
Experimental	HTTF (DCC/PCC)	He / N_2	0.17-0.8	125-590	[18]
Experimental	HTTF (inlet plenum)	He	0.2-0.4	up to ~600	[19]
Design study	HTR/bottoming	$He/C_2H_5OH-H_2O-NH_3$	5.87	850	[20]
Theoretical/design	VHTR	He	6.595	950	This study

The operating conditions of gas-based cycles reported in the literature are summarized in Table 1. A clear distinction can be observed between experimental and theoretical studies. Experimental facilities operate at reduced pressures and temperatures due to technical constraints, whereas theoretical and design studies consider conditions closer to actual VHTR operation, with helium pressures of several MPa and temperatures reaching up to 1000-1050 K. In addition, alternative working fluids, such as supercritical CO_2, are considered in advanced Brayton cycle configurations. In addition, experimental setups [18,19] and studies on the design of individual system components—particularly the final stages of the turbine and heat exchangers—provide us with extensive knowledge of possible operating parameters [20].

In Brayton-based cycles coupled with VHTR systems, regenerative heat exchangers (recuperators) play a crucial role in improving the overall cycle efficiency [16,17]. The recuperator transfers heat from the hot, low-pressure helium leaving the turbine to the compressed high-pressure helium before entering the reactor [18] or any other source of heat [21]. In this way, part of the thermal energy that would otherwise be lost is recovered and reused within the cycle. As a result, the application of a recuperator significantly improves the thermodynamic efficiency of the system [17,22]. However, the performance of the recuperator is strongly influenced not only by its heat transfer effectiveness but also by pressure losses occurring within the heat exchanger [23]. Excessive pressure drops may negatively affect the overall cycle performance, which creates an important design challenge [23].

Computational Fluid Dynamics (CFD) has become a widely used tool for detailed analysis of flow and heat transfer processes in complex thermal systems [24]. CFD simulations allow investigation of local temperature distributions, velocity fields, and pressure losses within heat exchangers, providing insights that cannot be obtained using simplified thermodynamic models [24,25]. Such detailed analysis is particularly important for high-temperature systems where heat transfer and flow characteristics have a significant influence on the overall performance of the energy conversion cycle [25].

The design and optimization of heat exchangers used in nuclear power systems involve complex thermal-hydraulic problems and require careful consideration of heat transfer effectiveness, pressure losses, and structural constraints [26]. These aspects are especially important in advanced nuclear systems such as Very High Temperature Reactors (VHTR), where compact and highly efficient heat exchangers are required [24,26].

Despite numerous studies on VHTR-based thermodynamic cycles and heat exchanger technologies, the detailed influence of recuperator performance and associated pressure losses on the efficiency of VHTR cycles remains insufficiently investigated [24,26]. In particular, comprehensive CFD analyses that link heat exchanger performance with the overall thermodynamic behaviour of the cycle is still limited [20,24,26].

Therefore, the aim of this study is to develop a CFD model of a regenerative heat exchanger operating within a VHTR-based Brayton cycle and to investigate its influence on the performance of the entire thermodynamic system. Special attention is given to the relationship between heat transfer effectiveness, pressure losses, and the resulting efficiency of the cycle.

2. Description of the VHTR Cycle and Heat Exchanger

2.1. VHTR power cycle configuration

The analysed energy conversion system is based on a Very High Temperature Reactor (VHTR) coupled with a closed Brayton power cycle using helium as the working fluid. VHTR reactors belong to the family of Generation IV nuclear systems, which are designed to achieve higher thermal efficiencies and improved safety compared to conventional nuclear power plants. Due to the high outlet temperature of the reactor, typically ranging from 700 K to 950 K, VHTR systems are particularly well suited for coupling with gas turbine power cycles.

Helium is commonly used as the working fluid in such systems because of its favourable thermophysical and chemical properties. It is chemically inert, remains in the gaseous phase over the entire operating range of the cycle and exhibits relatively high thermal conductivity. These characteristics enable stable operation at high temperatures and pressures while minimizing corrosion and material degradation.

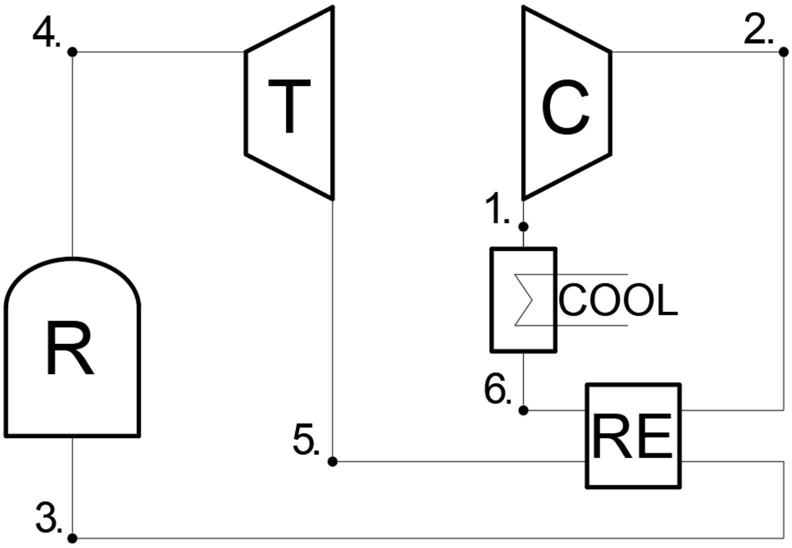


Figure. 1. *Simplified schematic diagram of the analysed VHTR Brayton cycle.*

A simplified schematic diagram of the analysed VHTR Brayton cycle is presented in Figure 1. The system consists of five main components: the nuclear reactor (R), turbine (T), compressor (C), regenerative heat exchanger (recuperator, RE) and cooling heat exchanger (COOL).

Helium is compressed (process 1–2), preheated in the recuperator (2–3), and further heated in the reactor (3–4). The high-temperature helium expands in the turbine (4–5), producing mechanical work. The turbine and compressor operate on a single shaft. The exhaust helium transfers heat to the compressed stream in the recuperator (5–6) and is then cooled before returning to the compressor inlet, completing the cycle.

Table 2. *Thermodynamic parameters assumed for the analysed VHTR Brayton cycle.*

Parameter	Symbol	Value	Unit
Pressure at reactor inlet	p_3	6.570	MPa
Temperature after reactor	T_4	1223.150	K
Temperature before compressor	T_1	329.150	K
Compressor pressure ratio	π_C	1.998	-
Turbine pressure ratio	π_T	1.919	-
Recuperator effectiveness	δ_{RE}	0.960	-
Compressor efficiency	η_C	0.910	-
Turbine efficiency	η_T	0.930	-

The main thermodynamic parameters assumed in the present analysis are summarized in Table 2. The adopted values correspond to typical operating conditions reported in the literature for helium Brayton cycles in VHTR systems. Turbine efficiencies of about 0.92–0.93 and compressor efficiencies of 0.89–0.91 are commonly assumed in design studies of HTGR gas turbine systems [17]. The recuperator effectiveness is typically in the range of 0.95–0.96 for compact heat exchangers, such as printed circuit heat exchangers [22,24,25]. Reactor outlet temperatures of up to 950°C and operating pressures around 6–7 MPa are characteristic for VHTR systems [14].

The assumed efficiencies of the turbine and compressor were selected based on values reported in previous studies of high-temperature helium turbomachinery. In addition, pressure losses in the main system components were taken into account, including pressure drops in the reactor, cooling heat exchanger and recuperator.

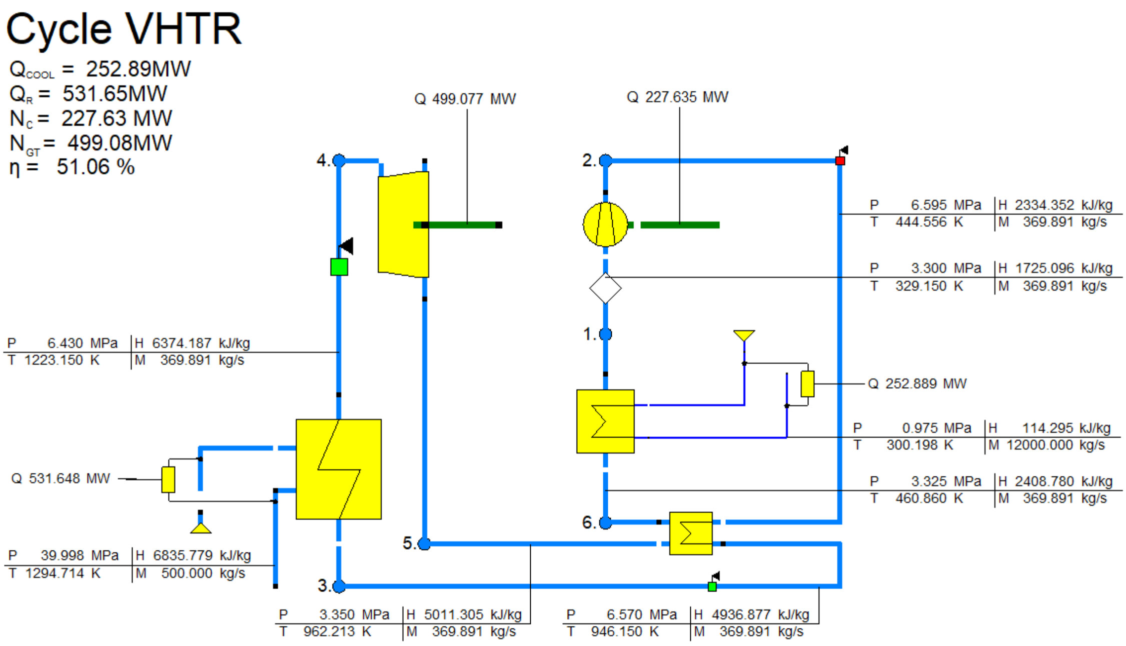


Figure. 2. *Thermodynamic model of the VHTR Brayton cycle implemented in the Ebsilon Professional software.*

The thermodynamic analysis of the cycle was performed using the Ebsilon Professional software, which is widely used for modelling complex thermal power systems. The implemented model of the VHTR Brayton cycle is shown in Figure 2. The model includes all main components of the system and allows the calculation of thermodynamic parameters such as pressure, temperature, specific enthalpy and mass flow rate at characteristic points of the cycle [27].

The results obtained from the Ebsilon simulation were treated as a reference case and used to define the boundary conditions for the subsequent CFD analysis of the regenerative heat exchanger (see Figure 3). The basic case was later compared with the updated cycle parameters obtained from the iterative CFD-based approach.

The thermal efficiency of the basic cycle is defined as:

$$\eta = \frac{N_{GT} - N_C}{Q_R}, \tag{1}$$

where η is the thermal efficiency of the cycle [-], N_{GT} is the turbine work [W], N_C is the compressor work [W], and Q_R is the thermal power supplied by the reactor [W].

2.2. Regenerative heat exchanger

The regenerative heat exchanger (recuperator) is used to transfer heat from the turbine outlet stream to the compressed helium upstream of the reactor, improving the overall cycle efficiency.

Due to the high operating temperatures and pressures of VHTR systems, compact heat exchangers such as Printed Circuit Heat Exchangers (PCHE) are considered. PCHEs offer high heat transfer performance and compactness, making them suitable for high-temperature applications [24,25].

In the present study, a PCHE with straight parallel microchannels is analysed. This simplified configuration enables detailed investigation of heat transfer and pressure drop characteristics while retaining the key features of the real device.

Since a full-scale PCHE consists of a large number of microchannels, direct numerical simulation of the entire geometry would be computationally expensive. Therefore, a representative section of the exchanger is considered (see Figure 4).

Adiabatic boundary conditions are applied on the external walls of the computational domain, while the flow and thermal conditions at the inlets are defined based on the system-level analysis of the VHTR Brayton cycle. Furthermore, the thermal performance of the recuperator was evaluated using its effectiveness, defined as:

$$\delta_{RE} = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}}, \tag{2}$$

where δ_{RE} is the temperature-based effectiveness of the recuperator [-], $T_{cold,out}$ and $T_{cold,in}$ are the outlet and inlet temperatures of the cold side [K], respectively, and $T_{hot,in}$ is the inlet temperature of the hot side [K]

2.3. Methodology

The performance of the analysed VHTR power cycle was evaluated using a coupled thermodynamic–CFD approach. In the first stage, a system-level model of the closed Brayton cycle was developed in the Ebsilon Professional software, allowing the determination of thermodynamic parameters at characteristic points of the cycle.

The obtained parameters were used as boundary conditions for the CFD simulations of the regenerative heat exchanger. A representative periodic section of the PCHE was modelled in order to analyse heat transfer and pressure losses within the exchanger channels. The mass, momentum and energy equation was employed to describe process in heat exchanger [28]. The mass conservation equation is expressed as follows:

$$\mathrm{div}(\rho\vec{v}) = 0, \tag{3}$$

where $\vec{v}$ means velocity vector $[m/s]$, ρ is density $[\mathrm{kg}\cdot\mathrm{m}^{-3}]$. The momentum equation is expressed as:

$$\mathrm{div}(\rho\vec{v}\otimes\vec{v}) = -\mathrm{grad}(p) + \mathrm{div}\boldsymbol{\tau}, \tag{4}$$

where p represents the pressure $[Pa]$ and $\boldsymbol{\tau}$ defines the viscous stress tensor $[Pa]$. The energy equation takes the form:

$$\mathrm{div}\left(\rho\vec{v}c_pT\right) = \mathrm{div}(k\mathrm{grad}T) + \mathrm{div}((\boldsymbol{\tau} - p\boldsymbol{I})\vec{v}), \tag{5}$$

where T is the temperature $[K]$, c_p expresses the specific heat capacity $[J\cdot kg^{-1}\cdot K^{-1}]$, k describes the thermal conductivity $[W\cdot m^{-1}\cdot K^{-1}]$, and $\boldsymbol{I}$ means unit tensor.

The results of the CFD analysis were subsequently implemented into the thermodynamic model to update the recuperator performance. The procedure was carried out iteratively until convergence was achieved. A convergence criterion based on a relative difference below 0.1% was adopted.

The overall workflow of the applied methodology is presented in Figure 3.

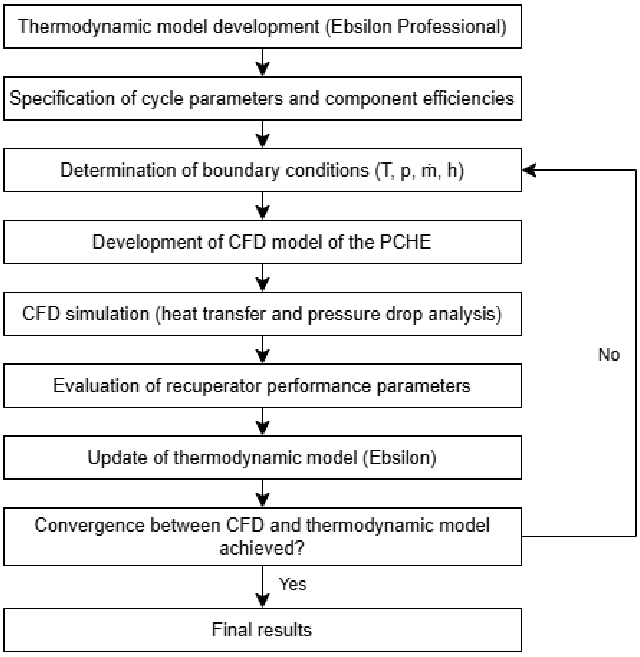
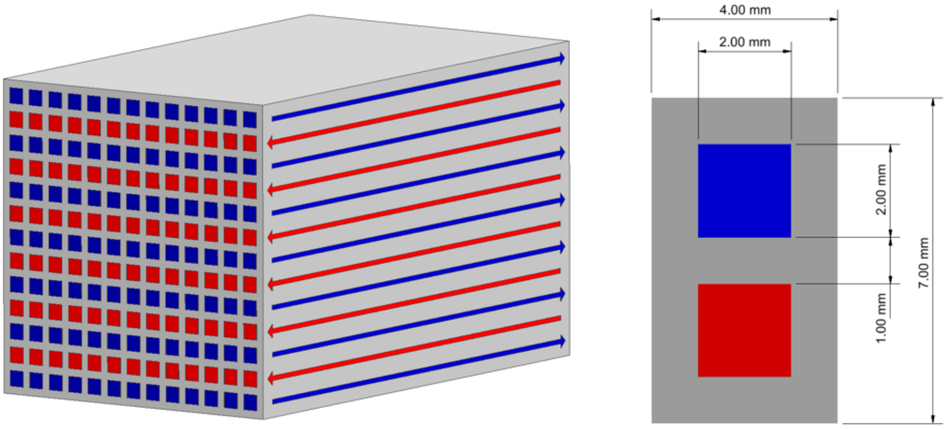


Figure. 3. *Flowchart of the coupled thermodynamic–CFD methodology applied in the analysis of the VHTR Brayton cycle and the PCHE recuperator.*

2.4. Geometry of the analysed heat exchanger

The analysed heat exchanger is based on a Printed Circuit Heat Exchanger (PCHE) with straight parallel microchannels. The geometry of the analysed configuration is presented in Figure 4.



a) *b)*

Figure. 4. *Geometry of the analysed PCHE: a) arrangement of parallel microchannels and flow directions; b) cross-section of the computational domain with characteristic dimensions.*

Due to the complex internal structure and large size of a full-scale PCHE, direct numerical simulation of the entire exchanger would be computationally expensive. Therefore, a representative section of the exchanger was selected for detailed analysis. The blue and red colours denote the cold and hot helium streams, respectively.

The computational domain consists of parallel channels representing a fragment of the real exchanger geometry. Each channel has approximate dimensions of 2 mm × 2 mm × 7.6 m.

The model was constructed to preserve the key flow characteristics of the full-scale device. In particular, the Reynolds number was maintained to ensure dynamic similarity between the simplified CFD model and the actual heat exchanger.

The analysed configuration is assumed to be representative of the overall behaviour of the regenerative heat exchanger.

2.5. Numerical model and assumptions

A three-dimensional, steady-state CFD model was developed to analyse heat transfer and fluid flow in the regenerative heat exchanger. The computational domain consists of a simplified representation of a pair of adjacent channels corresponding to the hot and cold streams.

Helium was modelled as a single-phase working fluid with temperature-dependent thermophysical properties. The fluid properties, including density, viscosity and specific heat capacity, were obtained from the NIST database.

Heat transfer between the hot and cold channels was accounted for through the solid wall separating the channels, while the external walls of the computational domain were assumed to be adiabatic.

The flow was assumed to be laminar, with a Reynolds number of approximately 2000. Fully developed flow conditions were considered.

The inlet boundary conditions, including temperature, pressure and mass flow rate, were derived from the system-level thermodynamic analysis of the VHTR Brayton cycle (Section 2.1). A mass flow inlet and pressure outlet boundary condition were applied.

The model was constructed under the following assumptions: steady-state operation, negligible gravitational effects, negligible thermal radiation, and no heat losses to the surroundings. No leakage or interaction between neighbouring channels beyond the modelled domain was considered.

2.6. Mesh independence study

A mesh independence study was performed using three computational grids with increasing density, consisting of approximately 0.63, 1.02 and 2.01 million elements.

The results were compared in terms of outlet temperature and pressure drop for both the hot and cold streams. A significant difference was observed between the coarse and medium grids, while the variation between the medium and fine grids was relatively small, indicating that the solution approaches mesh independence.

Therefore, the fine mesh was selected for further simulations to ensure accurate prediction of thermal and hydraulic performance. The detailed results are summarized in Table 3.

Table 3. *Results of the mesh independence study.*

Mesh	Elements [-]	$T_{hot,out}$ [K]	Δp_{hot} [kPa]	$T_{cold,out}$ [K]	Δp_{cold} [kPa]
Coarse	633,456	444.98	12.68	918.97	12.56
Medium	1,021,762	477.23	29.01	929.79	15.29
Fine	2,009,164	472.07	29.67	934.52	15.47

3. Results and discussion

3.1. Temperature and pressure distribution

The axial distributions of temperature and pressure for the hot and cold helium streams are presented in Figure 5.

The temperature of the cold stream increases along the channel length, while the hot stream exhibits a corresponding decrease. The temperature profiles are approximately linear, indicating a relatively uniform heat transfer rate along the heat exchanger.

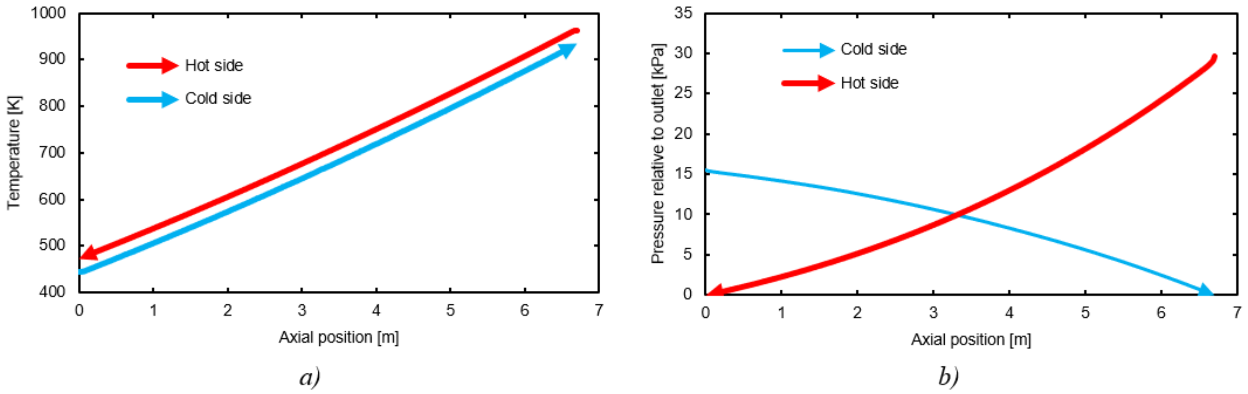


Figure. 5. *Axial distribution: a) temperature; b) pressure of helium streams in the heat exchanger.*

The minimum temperature difference between the streams (pinch point) can be expressed as:

$$\Delta T_{min} = \min\left(T_{hot,in} - T_{cold,out}, T_{hot,out} - T_{cold,in}\right), \tag{6}$$

where ΔT_{min} is the minimum temperature difference [K], $T_{hot,in}$ and $T_{hot,out}$ are the inlet and outlet temperatures of the hot helium [K], and $T_{cold,in}$ and $T_{cold,out}$ are the inlet and outlet temperatures of the cold helium [K].

Based on the obtained results, the temperature difference at the hot inlet–cold outlet side is equal to 27.5 K, while at the opposite end of the heat exchanger it reaches 27.09 K. Therefore, the minimum temperature difference (pinch point) is equal to 27.09 K.

The pinch point is located at the end of the heat exchanger, indicating a near-optimal thermal coupling between the hot and cold streams. The small difference between the two evaluated temperature differences is negligible and does not significantly affect the overall heat exchanger performance. This confirms that the heat exchanger operates close to its thermodynamic limit, and further reduction of the minimum temperature difference would require a substantial increase in the heat transfer surface area, resulting in a larger and more complex exchanger design.

The pressure decreases continuously along the flow direction for both streams due to frictional losses within the channels. The pressure drop exhibits a non-linear behaviour, with a more pronounced decrease towards the outlet region.

The calculated pressure drops are equal to 29.67 kPa for the hot stream and 15.47 kPa for the cold stream. These values are significantly lower than those assumed in the basic thermodynamic model, where the pressure drops were equal to 50 kPa and 25 kPa for the hot and cold streams, respectively.

This indicates that the simplified assumptions used in the system-level model were conservative. The CFD results suggest that the actual pressure losses in the analyzed heat exchanger are lower, which may positively influence the overall cycle performance by reducing compressor work. However, it should be noted that the final efficiency of the VHTR cycle is determined by the combined effect of pressure losses and recuperator effectiveness, both of which are strongly coupled.

3.2. Heat transfer performance

Temperature distributions in selected cross-sections of the heat exchanger are presented in Figure 6.

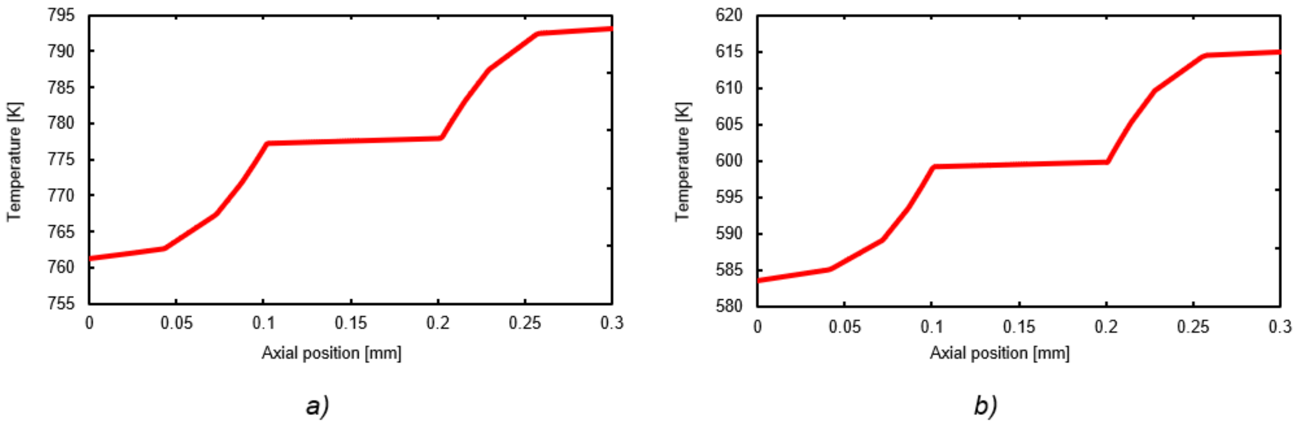


Figure. 6. *Temperature distribution in selected cross-sections of the heat exchanger: a) at x = 2.14 m; b) at x = 4.56 m.*

The results correspond to two axial positions, illustrating the thermal interaction between the hot and cold channels.

An increase in temperature is observed along the flow direction of the cold stream, indicating continuous heat absorption from the hot stream. The profiles show non-uniform behaviour, reflecting local variations in heat transfer intensity within the exchanger.

The calculated effectiveness based on the CFD results is equal to $\delta_{RE} = 0.947$, which is in good agreement with the assumed value of $\delta_{RE} = 0.96$.

3.4. Effect of operating conditions

The basic case thermodynamic cycle achieved an efficiency of 51.06%, assuming idealised heat exchanger performance and simplified pressure losses. The updated configuration of the cycle, including the parameters obtained from CFD analysis, is presented in Figure 7.

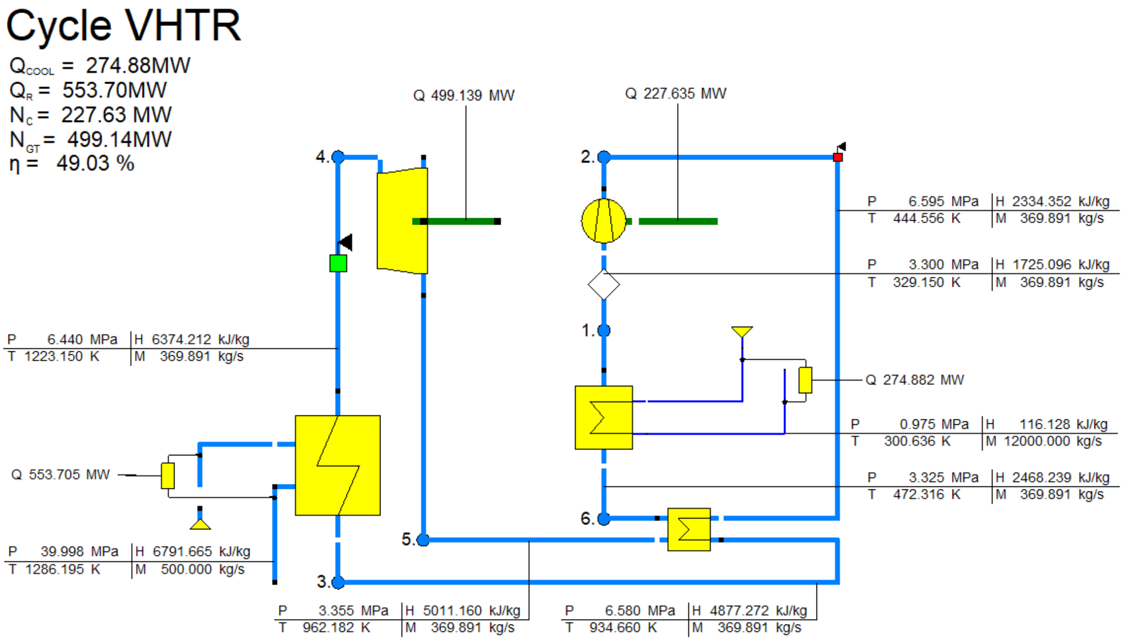


Figure. 7. *Thermodynamic model of the VHTR Brayton cycle with updated heat exchanger performance parameters.*

After incorporating the CFD-based results, including the calculated recuperator effectiveness ($\delta_{RE} = 0.947$) and the pressure drops predicted by CFD, the updated cycle efficiency decreased to 49.03%.

The obtained cycle efficiency of 49.03% is consistent with values reported in the literature for VHTR Brayton systems, where efficiencies close to 49% have been demonstrated for advanced configurations [14]. Such values significantly exceed those of conventional nuclear systems, which are typically limited to approximately 35% [8].

The calculated recuperator effectiveness is also in good agreement with typical values reported for compact heat exchangers, where effectiveness levels of approximately 0.95–0.96 are required to achieve high cycle efficiency [25]. Although higher effectiveness values are theoretically achievable, they are associated with a significant increase in heat transfer surface area and, consequently, a larger and more complex exchanger design.

It should be emphasized that the performance of the recuperator is governed by a trade-off between heat transfer and pressure losses. Increasing thermal performance leads to higher effectiveness, but also results in increased pressure drop within the exchanger [22,24]. The present results confirm that both effectiveness and pressure drop have a significant impact on the overall cycle efficiency, as also reported in previous studies [26].

4. Conclusions

The present study investigated the influence of a regenerative heat exchanger on the performance of a VHTR Brayton cycle using a coupled thermodynamic–CFD approach. The main contribution of this work is the demonstration that the overall cycle efficiency is strongly affected by both the recuperator effectiveness and the associated pressure losses, highlighting the critical role of this component in system-level performance.

A modular PCHE with straight channels was analysed, and its performance was evaluated in terms of heat transfer and pressure losses. The applied multiscale methodology, combining a 3D CFD model with a system-level thermodynamic model, enabled consistent interaction between local flow phenomena and global cycle performance.

The calculated effectiveness of the recuperator was equal to 0.947, which is in good agreement with the assumed value of 0.96. The corresponding pressure drops were found to be 29.67 kPa and 15.47 kPa for the hot and cold streams, respectively. The incorporation of these parameters into the thermodynamic cycle resulted in a decrease in the overall cycle efficiency from 51.06% to 49.03%.

These results demonstrate that even relatively small deviations in heat exchanger performance can significantly affect system-level behaviour. In particular, pressure losses in the recuperator increase the required compressor work, leading to a reduction in net cycle efficiency. This confirms that neglecting pressure losses may lead to an overestimation of cycle performance.

The study also shows that the recuperator can be considered a key component governing the performance of the VHTR Brayton cycle. An optimal design requires a balance between heat transfer effectiveness and pressure losses, as improving thermal performance is inherently associated with increased hydraulic resistance.

The findings highlight the importance of accurate modelling of heat exchangers in advanced nuclear energy systems and demonstrate the necessity of multiscale approaches for reliable performance prediction. The proposed methodology can be extended to other advanced power cycles, including high-temperature and supercritical systems.

Finally, further research is recommended to investigate more complex geometries of PCHE and to validate the results using alternative CFD tools. Such studies would improve the robustness of the predictions and support the development of high-efficiency nuclear power systems.

5. Acknowledgments

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Nomenclature

c_p	specific heat capacity, $J/(kg \cdot K)$
$\boldsymbol{I}$	unit tensor, -
k	thermal conductivity, $W/(m \cdot K)$
N	power, W
p	pressure, Pa
Q	heat transfer rate, W
T	temperature, K
v	velocity, m/s
ΔT	temperature difference, K

Greek symbols

δ	effectiveness, -
η	efficiency, -
π	pressure ratio, -
ρ	density, kg/m^3
$\boldsymbol{\tau}$	viscous stress tensor, Pa

Subscripts

C	compressor
COOL	cooler
cold	cold helium
GT	gas turbine
hot	hot helium
in	inlet
out	outlet
R	reactor
RE	recuperator
T	turbine

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