*The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World*
Chattanooga, Tennessee, April 17–21, 2005, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2005)

# HYBRID MONTE CARLO – DETERMINISTIC ANALYSIS OF THE FISSION FRAGMENT MAGNETIC COLLIMATOR REACTOR SYSTEMS

**Pavel V. Tsvetkov and Ron R. Hart**
Department of Nuclear Engineering
Texas A&M University
129 Zachry Engineering Center, College Station, TX 77843-3133
tsvetkov@tamu.edu

## ABSTRACT

Direct conversion of fission energy to electricity can be achieved by collecting fission fragments before energy is turned into heat. Safety, simplicity, and high conversion efficiency are the unique advantages of direct energy conversion (DEC). The recently completed US DOE NERI DEC Project identified the fission fragment magnetic collimator reactor (FFMCR) as one of the promising DEC concepts. According to the computational studies, the FFMCR systems offer performance characteristics which cannot be achieved by conventional nuclear power methods. The calculated energy conversion efficiencies for the presented final technologically feasible designs are up to 60%. The analysis indicates that efficiencies up to 90% are potentially achievable. The US DOE NERI DEC Proof of Principle project began in October of 2002 with the goal to experimentally demonstrate performance principles of the promising DEC systems including FFMCRs. The hybrid Monte Carlo-deterministic methodology has been developed and applied for the coupled neutronics-electromagnetics-thermohydraulics design analysis of the FFMCR system. The created computer code system allows automated coupled 3D modeling with optimization of the major performance characteristics. The nuclear reactor calculations, electromagnetic component calculations and thermohydraulics calculations are joined together to provide the FFMCR system design characteristics. The DECA (Direct Energy Conversion Analyzer) driver code enables coupled modeling capability.

*Key Words*: Fission Fragments, Direct Energy Conversion, Collimator, Collector, FFMCR

## 1 INTRODUCTION

Behavior of the advanced nuclear energy systems, like Generation IV reactors and systems for space applications, is difficult to predict due to inherent safety features resulting in tight coupling between energy production, transport and conversion, and system behavior during normal operation and off-normal situations. To create advanced nuclear energy systems it is desirable to have a modeling-based design development, which relies on simulating features of the entire life cycle of the system before actual physical prototyping - from concept development to detailed design, prototyping, and safety analysis. This approach should provide explicit consistency between neutronics and other performance aspects over the considered time of operation. The suggested integrated/hybrid Monte-Carlo-deterministic modeling approach offers the desirable analysis capabilities for the FFMCR design studies.

Use of robust Monte Carlo codes assures explicit 3D whole-core/reactor modeling of the key reactor physics areas such as the double and multi-level heterogeneity, neutron streaming in the low-density regions, and neutron spectrum transitions at the interfaces. Similarly, use of the advanced electromagnetics and thermal-hydraulics modules allows 3D whole-core/reactor/DEC system modeling accounting for relevant performance features. Coupling approach is extremely important for modeling of the dynamic behavior and assessment of inherent safety. Space and burnup dependent reactivity coefficients and feedback analysis have paramount importance for inherent safety confirmation.

The developed computer code system allows automated coupled integrated/hybrid Monte Carlo-deterministic approaches for the coupled 3D modeling with optimization of the major performance characteristics. It is also implemented to provide capabilities for concurrent engineering. The nuclear reactor calculations, electromagnetic component calculations and thermohydraulics calculations are joined together to provide the FFMCR system design characteristics. The DECA (Direct Energy Conversion Analyzer) driver code enables coupled modeling capability.

## 2 COMPUTATIONAL MODELING OF THE FFMCR SYSTEM

The FFMCR concept is an innovative approach that combines advantageous design solutions developed for fission reactors and fusion systems. In the FFMCR system, the nuclear reactor components and the electromagnetic components are joined together to form a unique system with performance characteristics determined by both component groups and their interfaces. [1]

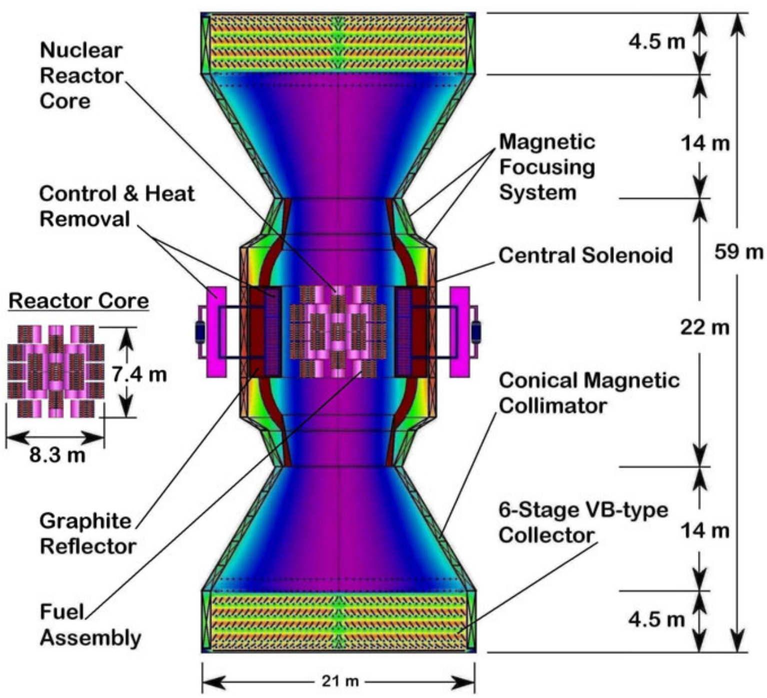


**Figure 1. FFMCR system.**

Direct conversion of fission energy to electricity can be achieved by collecting fission fragments before energy is turned into heat. The final FFMCR layout is shown in Fig. 1. The system consists of a nuclear reactor core surrounded by a solenoid, collimators and collectors.

The core is composed of a lattice of fuel-coated graphite fibers. After fission fragments exit the fuel element, they are captured on magnetic field lines and are directed out of the core and through magnetic collimators to produce electricity. [2] The method envisioned for direct energy conversion to electricity is the deceleration of fission fragments in a stationary electrostatic field. A multi-stage Venetian Blind charged particle collector is considered to be one of the most efficient direct collectors for such a system. The integrated design has to provide efficient energy extraction with minimal collision losses. If power production is desirable, the escaping FFs and free electrons must be separated to avoid neutralization. A complex design procedure, which takes into account the component groups and their interfaces, is required.

A consistent analysis and evaluation of the technological feasibility of the FFMCR concept has been performed using state-of-the-art computer codes that allow realistic modeling of the important physical processes governing performance of the system. The design process is automated using the DECA driver code.

The DECA computational scheme of the analysis is shown in Fig. 2. This scheme is followed as an overall design procedure for the FFMCR system. A special effort was made to verify that the computational modeling is consistent and realistic. The results describe performance of the entire FFMCR system and allow conclusions regarding the concept's feasibility and possible directions for further analysis and development.

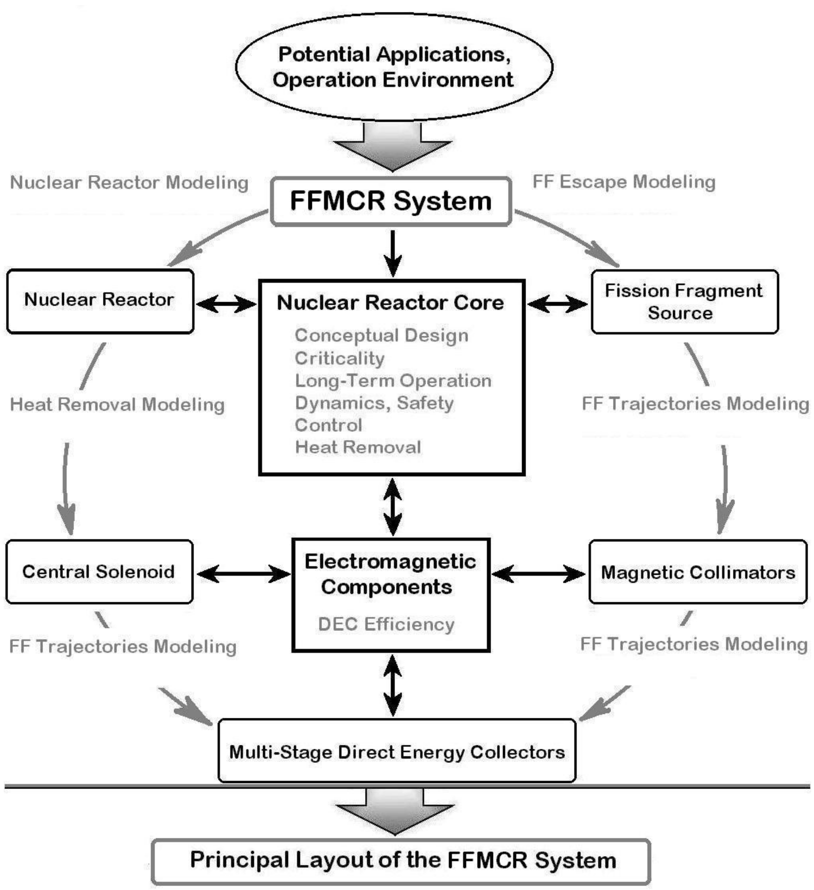


**Figure 2. Computational modeling of the FFMCR system.**

The constructed DECA code system utilizes capabilities of the following subject-specific external computer code systems:

- SRIM (3D Monte Carlo computer code system for calculations of the energy loss of ions in solids, liquids and gases, prediction of energetic ion ranges in matter, ion transmission and reflection from matter); [3]
- TriComp (3D finite element computer code system for electrostatics, magnetostatics, electromagnetostatics, thermal transport, permanent magnets, charged particle optics and electromagnetic radiation calculations); [4]
- MCNP (3D general-purpose Monte Carlo computer code system for neutron, photon, electron, or coupled neutron/photon/electron transport calculations, including the capability to obtain eigenvalues for neutron multiplying systems); [5]
- SCALE (general-purpose code system for reactivity, criticality and fuel depletion calculations); [6]
- General-purpose software packages and computer code systems for applied mathematics.

The nuclear reactor calculations are coupled with the electromagnetic component calculations using input-output information within the DECA computational scheme. Several auxiliary computer codes provide the required specialized data processing.

Performance analysis of the individual components and the entire FFMCR system includes calculations of the overall efficiency for comparison with other DEC systems. The overall efficiency of the FFMCR system can be defined as:

$$\bar{\eta}_{FFMCR} = \frac{1}{R_f}\left[ R_{f,FF}^{VBDEC} + R_f^{HRS} \right], \tag{1}$$

where $R_f$ is the rate of the total fission energy release within the nuclear reactor core, $R_{f,FF}^{VBDEC}$ is the rate of the fission fragment kinetic energy conversion via the VB-type direct energy collectors (VBDEC), and $R_f^{HRS}$ is the rate of the energy conversion via the heat removal system (HRS). This definition assumes partial recovery of all of the energy forms released by fission that are not directly recoverable in the collectors. As it is represented by the last term in brackets in Eq. (1), the HRS design may include a bottoming thermodynamic cycle to utilize heat removed from the nuclear reactor core. The term $\bar{\eta}_{FFMCR}$, defined by Eq. (1), can be written in an expanded form using the following specific performance characteristics of the FFMCR system components:

- Nuclear reactor core and central solenoid:

  $f_{FF}$ is the fraction of the nuclear fission energy released in the form of kinetic energy of fission fragments;

  $\varepsilon_{FF}^{FE}$ is the fraction of the fission fragment kinetic energy that escapes from a fuel element (FE);

$\varepsilon_{FF}^{NRC}$ is the fraction of the fission fragment kinetic energy that is successfully transmitted through the nuclear reactor core (NRC).

- Conical magnetic collimators (CMC):

  $\overline{\eta}_{CMC}$ is the CMC efficiency defined by the ratio of the fission fragment parallel kinetic energy with respect to the field lines at the collimator exit to the fission fragment kinetic energy at the collimator entrance.

- Multi-stage VB-type direct energy collectors:

  $\overline{\eta}_{VBDEC}$ is the energy conversion efficiency of the multi-stage VB-type direct energy collectors (VBDEC);

thus, Eq. (1) can now be written as:

$$\overline{\eta}_{DFFEC-MC} = f_{FF} \cdot \varepsilon_{FF}^{FE} \cdot \varepsilon_{FE}^{NRC} \cdot \overline{\eta}_{CMC} \cdot \overline{\eta}_{VBDEC} + \left(1 - f_{FF} \cdot \varepsilon_{FF}^{FE} \cdot \varepsilon_{FE}^{NRC}\right) \cdot \overline{\eta}_{HRS}^{th} . \quad (2)$$

where $\overline{\eta}_{HRS}^{th}$ is the efficiency of the applied HRS bottoming cycle. Detailed derivation of Eq. (2) is given in Appendix. Although Eq. (2) provides a relatively simple expression for the overall efficiency of a FFMCR system, calculations of the various terms are computationally intense and involve application of the developed hybrid Monte Carlo-deterministic methodology for the coupled neutronics-electromagnetics-thermohydraulics design analysis.

## 3 CONCLUSIONS

The resulting FFMCR system is fundamentally different from existing nuclear reactors and proposed innovative systems. The difference is based on the out-of-core DEC approach that is fully implemented in the suggested system.

The design characteristics of the individual FFMCR components have been defined, developed and analyzed using the DECA code system and taking into account their performance in the FFMCR system as a whole. As it is illustrated in Fig. 2, this analysis approach permits to derive the integrated system layout given in Fig. 1 with consistently determined characteristics. Capabilities of TriComp have allowed the exact 3D modeling of magnetostatic and electrostatic fields and FF trajectories in the azimuthally symmetric geometry of the axial component layout.

A distinctive feature of the design is that the electromagnetic components form a continuous vacuum space that entirely encloses the nuclear reactor components. Furthermore, since all active elements of the control rod system and the heat removal system channels are located in the graphite reflector, the nuclear reactor core has no moving internal components, coolant channels or auxiliary mechanical systems, and hence, it is a completely passive structure. This eliminates all potential in-core accidents due to mechanical failures or operational malfunctions. Thus, the suggested radiatively cooled configuration offers full realization of the passive safety principle by incorporating it as an inherent design feature.

The calculated overall efficiencies for the presented conceptual FFMCR system designs without a bottoming cycle (pure direct fission fragment energy conversion) and with the $D_2O$-

based bottoming cycle are 52% and 62%, respectively. [2] The performed analysis indicates that overall efficiencies up to 90% are achievable in technologically feasible FFMCR systems employing large magnetic collimators, up to 40 VB-type collection stages in the collectors, and highly efficient thermodynamic cycles in the heat removal systems. [1, 2] Figure 3 illustrates calculations of the component efficiencies as well as the overall energy conversion efficiency of the FFMCR system.

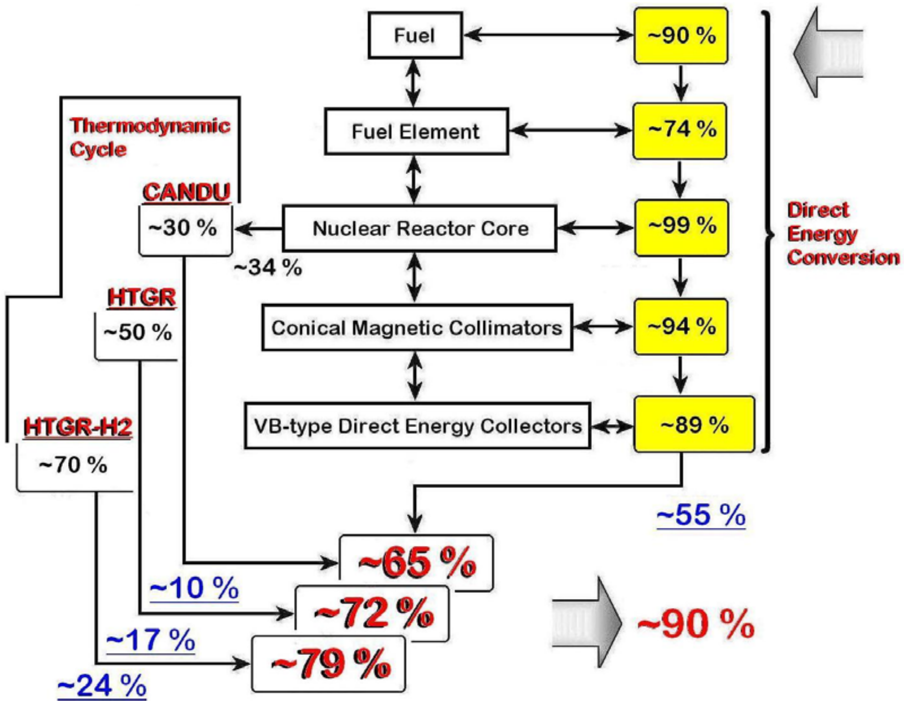


**Figure 3. Energy conversion efficiency of the FFMCR system.**

Further studies of the developed FFMCR concept are required in order to address the existing design challenges. Experimental investigations are vitally important for the FFMCR technology. The current US DOE NERI DEC Proof-of-Principle project is focused on experimental verification of the FFMCR performance principles. [7] In this project, computational modeling capabilities of the DECA code system are used for studies of the FFMCR prototype performance characteristics and optimization of the layout. Successful completion of this project should confirm the concept, provide better understanding of its performance characteristics, facilitate optimization and serve as the basis for validation benchmark studies of the DECA computer code system.

Significant performance and design improvements are anticipated from future investigations. Optimization studies for the FFMCR system, which use the layouts obtained in this work as a starting point, should provide designs that may allow winning in competition with existing reactors and suggested innovative concepts. Further analysis of combinations with efficient thermodynamic cycles may lead to the almost complete utilization of the released fission energy. Application of the hybrid Monte Carlo-deterministic methodology assures realistic performance analysis.

## 4 ACKNOWLEDGMENTS

This research work was supported by the US Department of Energy as part of the Nuclear Energy Research Initiative (NERI) Projects on Direct Energy Conversion (project MS-99-0199) and on Experimental Verification of Magnetic Insulation of DEC Fission Reactors (project 2002-068) under leadership of the Sandia National Laboratories.

## 5 REFERENCES

1. P. V. Tsvetkov, Direct Fission Fragment Energy Conversion Utilizing Magnetic Collimation (Ph.D. Dissertation, December 2002), Texas A&M University, College Station, USA (2002).
2. P. V. Tsvetkov, R. R. Hart, T. A. Parish, "Highly Efficient Power System Based on Direct Fission Fragment Energy Conversion Utilizing Magnetic Collimation", *Proceedings of the 11th International Conference on Nuclear Engineering* (ICONE 11), April 20-23, 2003, Tokyo, Japan (ICONE11-36275), American Society of Mechanical Engineers (2003).
3. J. F. Ziegler, J. P. Biersack, U. Littmark, *The Stopping Power and Range of Ions in Solids*, Pergamon Press, London, United Kingdom (1985).
4. S. Humphries, Jr., *Field Solutions on Computers*, CRC Press, Boca Raton, Florida (1997).
5. J. F. Briesmeister, editor, "MCNP: A General Monte Carlo N-Particle Transport Code, Version 4C", LA-13709-M/UC700/CCC700, Los Alamos National Laboratory, Los Alamos, New Mexico (2000).
6. "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation", ORNL/NUREG/CSD-2/R5, RSIC/CCC-545, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1997).
7. P. V. Tsvetkov, R. R. Hart, D. B. King, "Fission Fragment Magnetic Collimator Reactor: Current Status of the Experimental Program", *Transactions of the American Nuclear Society*, **91**, pp. 927 – 928 (2004).

## APPENDIX

As it is stated by Eq. (1), the overall efficiency of a FFMCR system, $\bar{\eta}_{FFMCR}$, is defined as the ratio of the recovered energy to the total energy released in fission. It is desirable to obtain $\bar{\eta}_{FFMCR}$ in the form that is suitable for the developed computational scheme. To accomplish that, $\bar{\eta}_{FFMCR}$ can be expanded as:

$$\bar{\eta}_{FFMCR} = \frac{R_{f,FF}^{VBDEC} + R_f^{HRS}}{R_f} = \left(\frac{R_{f,FF}}{R_f}\right)\cdot\left(\frac{R_{f,FF}^{FE}}{R_{f,FF}}\right)\cdot\left(\frac{R_{f,FF}^{NRC}}{R_{f,FF}^{FE}}\right)\cdot\left(\frac{R_{f,FF}^{CMC}}{R_{f,FF}^{NRC}}\right)\cdot\left(\frac{R_{f,FF}^{VBDEC}}{R_{f,FF}^{CMC}}\right) + \frac{R_f^{HRS}}{R_f}. \qquad (3)$$

The fractions in Eq. (3) are the specific performance characteristics of the FFMCR components:

- $f_{FF} = R_{f,FF} / R_f$ is the fission energy fraction released in the form of kinetic energy of FFs;
- $\varepsilon_{FF}^{FE} = R_{f,FF}^{FE} / R_{f,FF}$ is the FF kinetic energy fraction that escapes from a fuel element (FE);
- $\varepsilon_{FE}^{NRC} = R_{f,FF}^{NRC} / R_{f,FF}^{FE}$ is the fraction of the escaping FF kinetic energy that is successfully transmitted through the nuclear reactor core (NRC);
- $\overline{\eta}_{CMC} = R_{f,FF}^{CMC} / R_{f,FF}^{NRC}$ is the conical magnetic collimators (CMC) efficiency defined by the ratio of the FF parallel kinetic energy with respect to the field lines at the collimator exit to the FF kinetic energy at the collimator entrance;
- $\overline{\eta}_{VBDEC} = R_{f,FF}^{VBDEC} / R_{f,FF}^{CMC}$ is the energy conversion efficiency of the multi-stage VB-type direct energy collectors (VBDEC);

and hence:

$$\overline{\eta}_{FFMCR} = f_{FF} \cdot \varepsilon_{FF}^{FE} \cdot \varepsilon_{FE}^{NRC} \cdot \overline{\eta}_{CMC} \cdot \overline{\eta}_{VBDEC} + \frac{R_f^{HRS}}{R_f} . \quad (4)$$

The remaining fraction in Eq. (4) can be expanded following the fission energy release balance between FFs, neutrons and other radiations. The released FFs can dissipate their kinetic energy within a FE or can escape with some fraction of their initial energy. The processes are characterized by the dissipation rate $R_{f,FF}^{(DIS,FE)}$ and the escape rate $R_{f,FF}^{FE}$, respectively. Although the design should allow the FFs to be successfully transmitted with minimized losses, some of the escaping FFs may interact with the NRC internal components and structures. These interactions result in the FF energy dissipation within the NRC. The FF energy dissipation process within the NRC is characterized by the corresponding dissipation rate $R_{f,FF}^{(DIS,NRC)}$. The fission energy release with neutrons and other radiations is described by the rate $R_{f,n+RAD}$.Consequently, the fission energy release balance is given by:

$$R_f = R_{f,n+RAD} + R_{f,FF}^{(DIS,FE)} + R_{f,FF}^{(DIS,NRC)} + R_{f,FF}^{NRC} . \quad (5)$$

According to the FFMCR concept, only $R_{f,n+RAD}$, $R_{f,FF}^{(DIS,FE)}$, and $R_{f,FF}^{(DIS,NRC)}$ contribute to the heat release within the NRC. Therefore, the total heat release rate, $R_f^{(H)}$, due to dissipation and retention of the fission energy within the NRC is the sum of $R_{f,n+RAD}$, $R_{f,FF}^{(DIS,FE)}$ and $R_{f,FF}^{(DIS,NRC)}$. Consequently, the remaining fraction in Eq. (4) can be transformed as:

$$\frac{R_f^{HRS}}{R_f} = \left(\frac{R_f^{(H)}}{R_f}\right) \cdot \left(\frac{R_f^{HRS}}{R_f^{(H)}}\right) = \left(\frac{R_{f,n+RAD}}{R_f} + \frac{R_{f,FF}^{(DIS,FE)}}{R_f} + \frac{R_{f,FF}^{(DIS,NRC)}}{R_f}\right) \cdot \frac{R_f^{HRS}}{R_f^{(H)}}, \quad (6)$$

and using $f_{FF}$, $\varepsilon_{FF}^{FE}$, and $\varepsilon_{FE}^{NRC}$:

$$\frac{R_f^{HRS}}{R_f} = \left(1 - f_{FF} \cdot \varepsilon_{FF}^{FE} \cdot \varepsilon_{FE}^{NRC}\right) \cdot \overline{\eta}_{HRS}^{th}, \quad (7)$$

where $\overline{\eta}_{HRS}^{th}$ is the efficiency of the applied HRS bottoming cycle. Thus, the overall efficiency of a FFMCR system is given by Eq. (2) that allows evaluation using the developed computational scheme.