Assessment of a Nuclear Reactor-Thermal Energy Storage Coupled System

Saeed A. Alameri, Ahmed K. Alkaabi

Department of Nuclear Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, UAE,
saeed.alameri@kustar.ac.ae, ahmed.alkaabi@kustar.ac.ae

INTRODUCTION

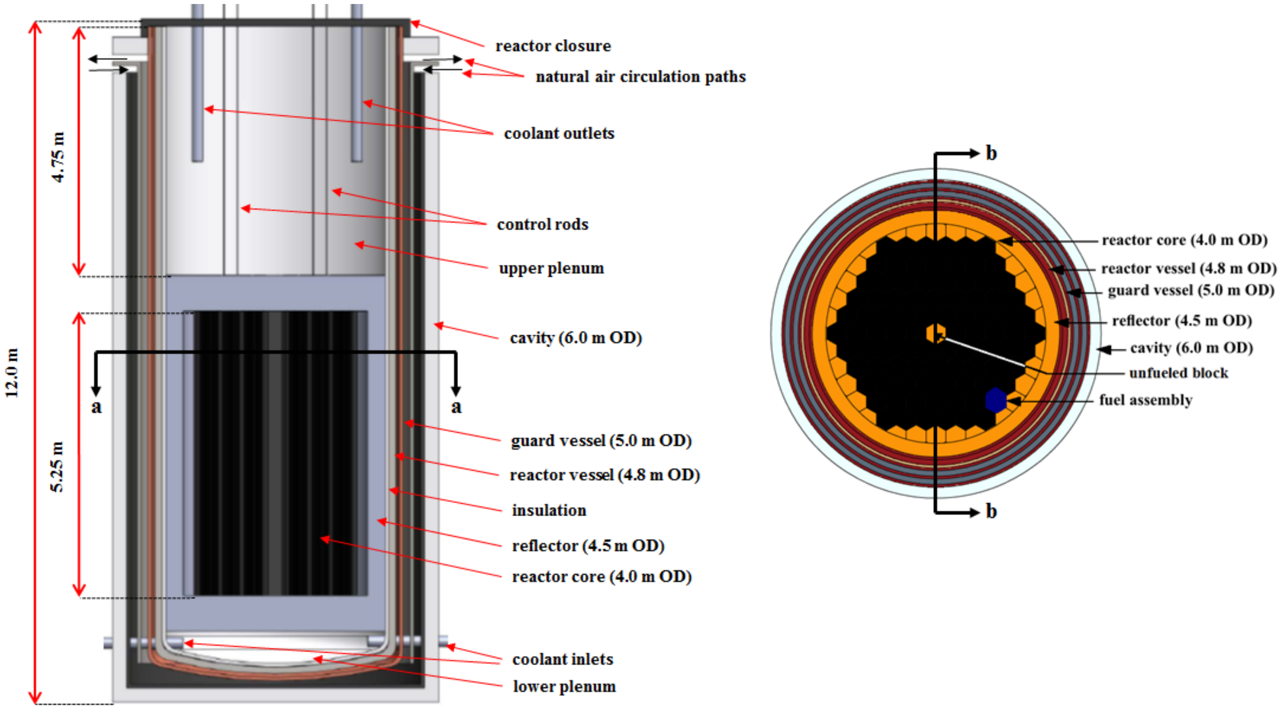
The Prismatic-core Advanced High Temperature Reactor (PAHTR) cooled by FLiBe (a mixture of lithium fluoride and beryllium fluoride), is designed to couple with a thermal energy storage (TES) block. In this system, the reactor provides constant power supplies to the TES which follows the power demand curve through a typical energy conversion cycle (such as Rankine cycle). Due to its high operating temperatures, the system can be utilized not only for electricity generation, but also for water desalination, hydrogen production, and other process heat applications.

The 300 MW_{th} power-rated PAHTR contains 10 metric tons of Tri-Structural-Isotropic (TRISO) UO_2 fuel with 19.75 wt% enrichment. The reactor has a five-year operating cycle without refueling. Fig. 1 presents axial and radial views of the PAHTR. This reactor is designed based on former high temperature reactors e.g. the pebble-bed modular reactor. The molten salt coolant has promising properties such as high operating temperatures and natural circulation capabilities. This leads to higher power densities desired for possible intermediate energy storage and higher efficiency power conversion systems.

The reactor core consists of 90 prismatic fuel assemblies with a 5.25 m height as shown in Fig. 1. Each of these assemblies contains 358 fuel rods, 216 coolant channels and 20 control rods in graphite blocks with flat-to-flat dimension of 36 cm (see Fig. 1b). The fuel rods made out of a graphite material packed with 35% TRISO fuel particles. More details of the PAHTR design can be found in [1].

TRANSIENT SYSTEM MODEL DESCRIPTION

A transient model is constructed in Matlab/Simulink using mathematical representations reflecting the physical phenomena of different parts of the overall coupled system. This transient model consists of a reactor kinetics model that calculates reactor power using the six-delayed group point kinetics, a thermal-hydraulics model which calculates the average and maximum temperatures of the core coolant and fuel, a reactor decay heating model that tracks decay heating using the 23 delayed power groups, and finally a thermal storage heat transfer model that estimates liquid portions of the phase change material (PCM) and estimates the primary and secondary loops, and storage material temperatures.



a) Axial view b-b

b) Radial view a-a

Fig. 1. Axial and radial views of the PAHTR.

RESULTS

In a general case of a typical nuclear reactor connected to an electricity grid, the reactor thermal power is mostly following the power demand curve while nuclear reactors have limits and constrains for load-following conditions. This load-following operation implies great fluctuations in the reactor operating power which typically should be avoided in nuclear power plants operation. Results from a Matlab/Simulink transient model shows that the load following features of the PAHTR can be improved by coupling it to the TES system such that the reactor constantly operates at a certain power level with varying power demand curve.

In early stage of the design process, the reactor is coupled to a LiCl-based TES block with an initial design of 300 units each containing 1135 PCM tubes with LiCl region thickness of 4.7 cm as shown Fig. 2 (Design A). This coupling enhanced the reactor operation with the thermal power still has large variations during a 24-hour operation in the load-following mode (see Fig. 3). Due to these large variations in the reactor power, the TES Design A is not suitable for load-following operations. Later, the TES design is optimized to enhance the transients of the coupled system. It is redesigned to have 1000 units each consisting of 11000 tubes with a PCM thickness of 0.5 cm (Design B). Fig. 3 shows how the reactor thermal power remains at almost a constant level during one day of operation.

Then, the behavior of the coupled system with TES Design B, is examined in several accident scenario cases. For loss of forced circulation accidents, even 1% of the primary flow is adequate to keep the peak fuel temperature below 1200 °C. Even with loosing 100% of the primary flow, the reactor only requires a passive reactor vessel auxiliary cooling system with 0.07% heat removal rate as a fraction of the reactor rated power to sustain the peak fuel temperature from reaching TRISO fuel safety limit (around 1600 °C) [2]. During loss of ultimate heat sink event, the system proved a passive safety operation of the reactor in which the excess decay heating from the reactor fuel is absorbed totally by the TES block. For reactivity insertion accidents, the PAHTR can absorb almost \$1 of reactivity insertion without shutdown, and with reactor shutdown response assumption of 0.1 second, almost \$2 of reactivity insertion can safely be attained.

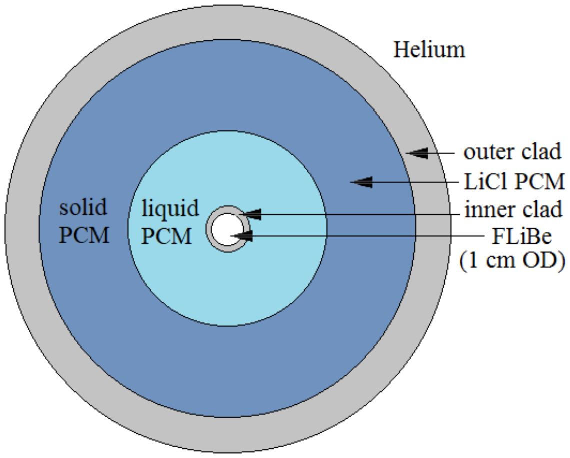


Fig. 2. A PCM tube in a TES block.

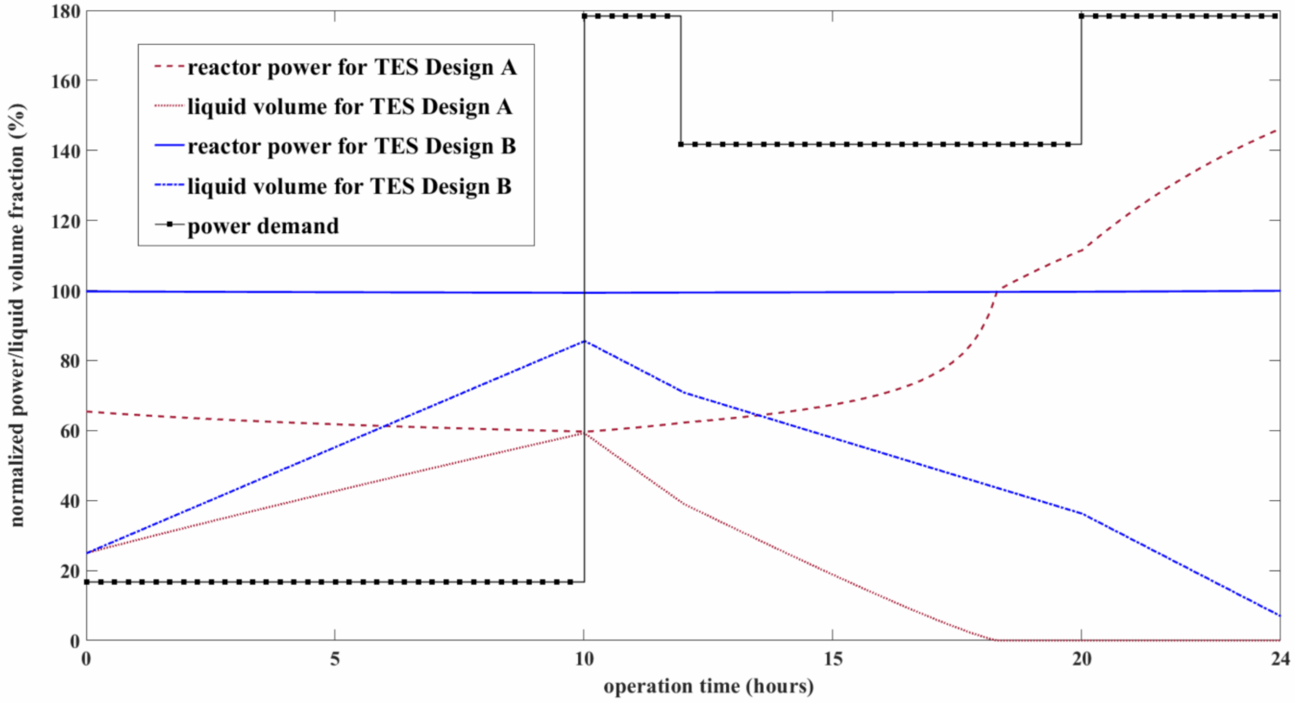


Fig. 3. Normalized reactor power and LiCl liquid fraction in 24-hour operations.

CONCLUSIONS AND FUTURE WORK

The nuclear reactor-TES coupled system studied in this research shows that reactor's marginal capacity factor can be improved during load-follow conditions. Coupling a nuclear reactor with a TES block that has thinner PCM regions demonstrates better and safe load-following operations. The safety assessments done using the transient model in the present work proves that restart capabilities and safety margins for the PAHTR are enhanced by the proposed coupled system.

As this research examined the neutronic parameters of the PAHTR, further studies are needed to enhance the reactor core neutronic parameters that include fuel concept and power distribution optimization, fuel management, flattening the reactivity swing during burn-up, and reactivity feedback coefficients of the optimized design. In addition, the preliminary control system mechanisms of the PAHTR studied in this research needs more investigations for possibly incorporate burnable absorbers such as Boron Carbide or Gadolinia that leads to an enhanced capacity factor and reduced hot channel peaking factors.

The thermal hydraulic (TH) investigation of the PAHTR done by [3], introduced a new correlation for the mixed convection flow with a constant heat flux while further assessment of the reactor's specific power distribution profile needs to be studied. These correlations should be incorporated in the transient model to give a more accurate analysis. For future development, fuel integrity at high burn-up rates to be studied along with a safety analysis of the nuclear reactor and for the overall coupled system, more importantly, with the feedback effects of the TES block to the reactor's transients. This will lead to study the behavior of the reactor during normal and abnormal conditions, and the melting progression of the PCM taking in consideration its natural convection. Finally, results from this research showed the significance of investigating the code coupling of neutronic and thermal hydraulic calculations of the PAHTR to achieve more accurate and realistic results.

REFERENCES

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