Sustainable Energy Engineering & Applied Sciences
Vol.2.Issue.3.198-206.2025
https://seeasjournal.com/

Review Article

Advancements in Divertor Cooling Technologies: From Circular Channels to Advanced Thermal Transfer Structures

[1]Ali Hussain*, [2]Shahab Ud-Din Khan

[1]Pakistan Institute of Engineering and Applied Sciences, Nilore, Islamabad, 45650 Pakistan
[2]Pakistan Tokamak Plasma Research Institute (PTPRI), P. O. Box 3329, Islamabad, Pakistan

KEYWORDS

ABSTRACT

One of the key challenges in the commercialization of nuclear fusion is the thermal performance of divertor plasma facing components (PFCs). Effectively managing the intense heat fluxes produced in fusion reactors is essential to maintaining both the durability and efficiency of PFCs. Over recent decades, various cooling strategies, materials, and designs have been explored and tested, including water cooled systems, liquid metal cooling concepts, and helium cooled modular divertors. This review explores the evolution of these technologies, focusing on the progression from traditional circular cooling channels to advanced rectangular cooling channels with thermal transfer structures (TTS). Key innovations, such as enhanced cooling performance, optimized flow geometries, and the introduction of extended surfaces for improved heat transfer, are analyzed. Additionally, the introduction of novel plasma-facing unit (PFU) designs, such as hypervapotron based flat tile divertor, offers higher heat flux sustainability. This review highlights the current state of divertor cooling technology and outlines future directions for optimizing these systems to meet the demands of next-generation fusion reactors.

1. Introduction

The pursuit of commercially viable nuclear fusion energy has presented numerous engineering challenges, with the thermal management of plasma-facing components (PFCs) ranking among the most critical. In fusion reactors, the divertor—a key plasma-facing component—must handle extreme heat fluxes, often exceeding several megawatts per square meter, without compromising the reactor’s performance or structural integrity. Effective thermal management

Corresponding author email address: aliihusaainn@gmail.com

Received: 15 October 2024, Accepted: 14 March 2025

in divertors is essential for sustaining prolonged plasma operations, reducing the frequency of maintenance, and ensuring the overall economic feasibility of fusion energy.

Traditional approaches to divertor cooling, such as water-cooled tungsten monoblocks with circular cooling channels, have proven effective in experimental reactors like ITER. However, the increasing demands of future reactors, particularly the need to manage higher heat loads more efficiently, have driven the development of advanced cooling systems and novel designs. Innovations such as liquid metal-cooled concepts, helium-cooled modular divertors, and rectangular cooling channels with thermal transfer structures (TTS) represent significant strides in enhancing the cooling performance and durability of PFCs.

This review discusses the evolution of divertor cooling technologies, from early water-cooled designs to the more recent advancements in modular divertors and flat tile plasma-facing units (PFUs). It focuses on the shift from traditional circular cooling channels to advanced rectangular channels equipped with TTS, which offer improved heat transfer efficiency and higher heat flux (HF) handling capabilities. The introduction of hypervapotron-based flat tile divertors, with their optimized flow geometries and extended surfaces, demonstrates how contemporary designs are pushing the boundaries of thermal management in fusion reactors.

2. REVIEW

In recent decades, the thermal performance of divertor PFCs has been acknowledged as a critical challenge hindering the commercialization of nuclear fusion. To address this, various thermal transport mechanisms have been proposed, tested, and implemented in tokamaks worldwide. A notable effort followed the successful completion of the European fusion program’s feasibility and potential study of fusion power in the late 1990s. This led to the initiation of a three-year study called Power Plant Conceptual Studies (PPCS), which aimed to assess different power plant designs. The PPCS-A divertor initially utilized a water cooled divertor, with tungsten monoblock and CuCrZr coolant channel similar to the ITER divertor. A swirl tape was also inserted in the coolant channel. In order to accommodate thermal stresses oxygen free copper was utilized as inter layer connecting CuCrZr tube to W monoblock. A shallow cartesian grid shaped cutouts were also made on the target surface to prevent cracking as a result of thermal expansion. The study demonstrated that this design could endure HF as high as 15 MW/m² [1-5]. Subsequently, Reduced Activation Ferritic Martensitic (RAFM) steel was proposed as the material for coolant pipes to raise the coolant outlet temperature, thereby enhancing thermal efficiency [6-10].

A liquid metal cooled diverter was proposed for PPCS-D power plant model. It utilized led lithium as a coolant flowing through a square tube of composite material. This design was intended to remove the HF of up to 5 MW/m². A “T” shaped flow separator was inserted separating the square tube into three regions i.e., two large lower sections and one upper narrow region. The liquid metal flows from one of the lower sections i.e., inlet into the narrower region adjacent to target surface, thereby cooling it. The coolant then flows to the other lower section which acts as an outlet. It was found that the outlet temperatures were within acceptable limits under an absorbed HF of 5 MW/m^2 [11-13].

Helium was recognized as a more feasible cooling medium as compared to liquid metal mainly because of its chemical and neutron inertness along with better integration in fusion power plant as the same gas is utilized in various components as well. However, the lower thermal conductivity of helium required methods to increase heat transfer by increasing turbulence or contact area. These methods were further explored in PPCS B, C, and AB which utilized a helium cooled divertor. In the earlier design two eccentric tubes which acts as inlet and outlet are utilized. The interface between the outer tube and the channel structure consists of a porous medium. The coolant enters through the inlet tube and flows into a porous medium, enhancing turbulence before exiting via the outlet tube. This configuration was evaluated for its ability to dissipate HF of up to 6 MW/m^2, with an effective heat transfer coefficient (HTC) of 20 kW/m^2K. Building on this concept, a new design was introduced that replaces the porous medium with a narrow slit through which the coolant is forced to pass. This modification resulted in a HF removal capacity of up to 5 MW/m^2 and an effective HTC of 14 kW/m^2K, offering the additional benefit of simplified manufacturing. Further improvements were achieved by incorporating a significantly larger cooling slot, featuring dual internal channels to enhance thermal management. The coolant enters through the upper channel and is forced to pass through a narrow gap which tends to increase the velocity of coolant before coolant enters into the outlet channel. The shorter conduction path due to the larger slot, combined with the increased coolant velocity, enables this design to handle HF of up to 10 MW/m^2, with an effective HTC of 56 kW/m^2K [14-17].

The flat plate type divertors provide a continuous cooling surface for heat dissipation, utilizing strong mechanical supports to limit excessive bending, this results in the development of high thermal stresses. To overcome this problem modular diverters are proposed, which consist of a certain number of modules/elements connected in parallel making a unit. These units are then connected in series making a divertor target. Besides reducing thermal stresses, this design allows for easier post-installation testing, maintenance and replacement of modules. Based on this concept two helium cooled, modular divertor designs were studied in PPCS i.e., High Efficiency Thermal Shield (HETS) and HElium cooled Modular divertor with Jet cooling (HEMJ) . The HETS design consists of six elements connected in parallel making a module. Each element is made up of castellated tungsten armor to reduce thermal stresses and structure with a mushroom shaped semi-spherical channel connected to a helium jet [18-20]. This design allows for removal of an absorbed HF of up to 10 MW/m^2 with average HTC of 30 kW/m^2K [21, 22].

The HEMJ design on the other hand consists of hexagonal tungsten armor brazed to thimble. The thimble contains a cartridge having multiple helium jet holes forming a cooling finger unit. The helium jet impinges onto the cartridge and flows on the outside of cartridge thereby cooling the unit. Nine of these units are connected in parallel forming a module. A similar concept utilizes an extended surface of tungsten slot array to increase the heat transfer. The single jet instead of impinging on the cartridge, impinges on an extended surface located on the inner side of cartridge. This design is known as HElium cooled Modular divertor with Slot array (HEMS). Both HEMJ and HEMS can remove HF of up to 10 MW/m^2 with average HTC of 30 kW/m^2K and 21 kW/m^2K respectively [23-25].

Rimza et al. investigated the influence of various extended surfaces on the efficiency of cooling units, concluding that the height-to-jet diameter ratio of the extended surfaces played a crucial role in enhancing cooling performance. An optimal design was proposed having h/D of 0.75 and the pith i.e., distance between two consecutive concentric extrusions of 0.30 and 0.56 mm respectively. The position of extended surface on the circumference of cartridge and the jet diameter had a complex relation where optimization of one entity was possible only. Optimizing both result in the reduction of heat transfer [26-28].

An effective method of removing the heat is necessary in order to sustain fusion and ensure longevity of deviator. Various advancements in controlling flux through magnetic fields, improvements in divertor geometry and advanced materials having reduced neutron activation properties have been proposed. The majority of heat is however removed by active methods such as passing water or helium through tubes inside deviator. In helium cooled divertor instead of passing helium directly through the cooling pipe, it is observed that introduction of cooling gas by multiple jet impingent inside the main cooling pipe is more effective in removing the heat flux. The next logical improvement would be to add turbulence to the flow of gas. Turbulence is a random flow behavior which is associated with eddies as a means of energy transportation rather than molecules as in a laminar flow. This result is better mixing and hence improved heat transfer. Lim et al. examined the impact of turbulence enhancement by incorporating ribs in a multi-jet impingent helium-cooled divertor, exploring its influence on heat transfer and cooling efficiency. The analysis is performed using ANSYS CFX, with RANS and SST for turbulence prediction. The maximum temperature of the cooling pipe was just below the melting temperature of copper used as pipe material. Moreover, as a result of larger pressure drop from center towards outlet, the jets get deflected on one side leading to uneven fluid distribution and higher temperature near the cooling pipe wall. Also, the HTC decreased and thus temperature increased near the wall due to pressure variations. By introducing turbulence ribs, the maximum temperature of cooling pipe decreased by 50 C due to increase in heat transfer area and reduction of jet deflection. Moreover, the effect of rib height towards temperature reduction was much more as compared to the width [29-31].

Lim et al. investigated the issue of HF concentration within the circular cooling channels of divertor PFUs. Due to one-sided heating, heat flux tends to concentrate at the top of the circular channel, resulting in significantly higher HF at the coolant interface compared to the HF at the target face of the PFU. This phenomenon can lead to severe boiling and a reduction in the CHF margin, meaning that the HF at which CHF occurs in the cooling channel is reduced. The ratio of peak HF under one-sided heating conditions to the peak HF under uniform heating conditions is referred to as the "peaking factor," a critical parameter for evaluating thermal performance under non-uniform heating. Previous experimental studies demonstrated that when a HF of 23 MW/m^2 was applied to the target surface, the peak HF at the top of the cooling channel increased to 30 MW/m^2 due to HF concentration. In contrast, the HF at a point 90 degrees from the peak was significantly lower, measuring only 5 MW/m^2. Moreover, it was observed that thickness of Cu interlayer had negligible effect on peaking factor. Reducing the conduction path i.e., distance between target surface and the peak HF point on cooling channel, the peaking factor reduced as a result of reduction of concentrated HF. Based on these findings a flat cooling channel was proposed to reduce concentration of HF. However, the rectangular channel can lead to stress concentration at the corners of the channel, thus a filet is applied at the corners. The mono block is then accessed by MEAP (Monoblock Elastic Assessment Procedure) rule required for mono block design. MEAP is provided by ITER which requires the evaluation of deformation under periodic load, estimation of fatigue limit, temperature of CuCrZr must be below 300 C and the maximum HF must be less than CHF. The author analyzes the performance of the newly proposed cooling channel in three stages of 1: Manufacturing, 2: Standby and 3: Operation. In the manufacturing phase as a result of various heating and cooling cycles residual stresses are introduced in the material. These along with other manufacturing stress are accounted for by adding a 3mm fillet to the channel corners. In the standby state only, coolant is flowing through the channel while HF is gradually applied. The author reports that all the criterion of MEAP were satisfied except for the structural criterion during shutdown phase [32-37].

Similarly, Kyun Lim et al., optimized the shape the shape of mono block cooling channel using an elliptical channel and by keeping the cross-sectional area of new channel same as that of ITER monoblock. The author performs the optimization based on the concept that by flattening the circular cooling channel the HF concentration can be reduced. Thus, optimization resulted in reduction of maximum HF on the coolant channel by 78% as compared to circular cooling channel [38-40].

For achieving the future goals of fusion power plants, the divertor is required to remove large HF for longer time duration. Moreover, the heat exchange capability of circular cooling channel in monoblock is much lower than rectangular channel in one sided heating. To enhance the heat transfer performance of Plasma Facing Units (PFUs), Lei Li et al. introduced an innovative concept of a flat cooling channel integrated with a specialized thermal transfer structure (TTS). This novel design features a flat tile divertor with a tungsten target, a copper (Cu) interlayer, an upper heat sink, a lower heat sink, inlet/outlet pipes, supporting legs, and the TTS. CuCrZr was selected for the upper heat sink due to its superior thermal conductivity, while SS-316L was chosen for the lower heat sink for its mechanical strength. By subjecting the top surface to a HF of 10 MW/m² and performing response surface optimization to minimize the maximum temperature, an optimal TTS configuration was identified. The study found that increasing the width, thickness, and length of the TTS resulted in a decrease in maximum temperature, up to a certain point, after which the maximum temperature began to rise again. However, with the increase in TTS height the temperature continued to decrease gradually. For the optimized design the thickness of TTS had a much higher contribution in reducing maximum temperature followed by length, width and height. By applying a HF of 20 MW/m² to the surface, it was observed that the maximum temperature exhibited exponential decay as the coolant velocity increased, while it decreased linearly with the reduction in the thickness of the tungsten target. This design resulted in increasing the heat transfer efficiency by 13% from rectangular channel with circular channel and 30 % from ITER like mono-block [41-43].

Zhen Chen et al., optimized the hypervapotron tungsten/Cu flat plate PFU based on the dimensions of TTS. The flat plate PFU consists of a tungsten armor attached to a CuCrZr heat sink via Cu inter layer. In the traditional hypervapotron concept the CuCrZr surface is extended in the cooling channel in the form of longitudinal ribs and transverse ribs to form a cross-rib structure. Based on previous studies increasing the channel cross-sectional area reduces the surface temperature. However, it weakens the structure and presents overall difficulty in manufacturing. Thus, the mockup with width of 36 mm was selected. For the optimization of longitudinal ribs, the effect of transverse ribs was ignored, and they were not modeled. Increasing the height of longitudinal rib had much more impact on the reduction of surface temperature thus a rib height of 4 mm was adopted. However, for the transverse ribs, it was observed that change in surface temperature was not prominent with the increase in rib height. But increasing the rib height meant increasing the depth of gap between two consecutive transverse ribs. A larger depth results in a full vortex formation inside the gap which coupled with low velocity resulted in slightly higher surface temperature. This suggests that larger height of transverse ribs is not favorable. Moreover, the optimized PFU had lower pressure drop as compared to the conventional concept [44-46].

Advanced designs like the flat tile divertor with thermal transfer structures (TTS) and the hypervapotron concept for tungsten/Cu plasma-facing units (PFUs) have shown promising results, significantly enhancing heat transfer efficiency and extending the lifetime of components [47-50]. Future research will likely focus on fine-tuning these designs to withstand even higher thermal loads, improve manufacturability, and ensure the structural integrity of divertor components under operational conditions. These advancements are critical for meeting the stringent thermal and mechanical demands of fusion power plants, ultimately paving the way for the successful deployment of commercial nuclear fusion.

3. Acknowledgement

Pakistan Institute of Engineering & Applied Sciences (PIEAS)

4. References

[1] A. Li Puma, L. Giancarli, Y. Poitevin, J. F. Salavy, P. Sardain, and J. Szczepanski, "Optimization of a water-cooled divertor for the European power plant conceptual study," *Fusion Engineering and Design,* vol. 61-62, pp. 177-183, 2002/11/01/ 2002, doi: https://doi.org/10.1016/S0920-3796(02)00116-3.

[2] S. U.-D. Khan *et al.*, "Cost-Effective Microwave Assisted ECR Heating Using Combination of Quasi-Locked Low-Power Magnetrons on GLAST-III," *IEEE Transactions on Plasma Science,* 2024.

[3] S. Shakir *et al.*, "Optimization of ECR assisted pre-ionization in GLAST-III via Multiphysics simulation," *Kerntechnik,* vol. 89, no. 4, pp. 438-447, 2024.

[4] K. Javid, S. Khan, S. U.-D. Khan, and A. Afzal, "Slip and chemical reaction effects on the peristaltic rheology of a viscoplastic liquid in different wave frames: application of a high-permeability medium," *The European Physical Journal Plus,* vol. 139, no. 3, pp. 1-28, 2024.

[5] M. Abdullah *et al.*, "Optimization of Wall-Conditioning Techniques on the MT-II Tokamak," *Fusion Science and Technology,* vol. 80, no. 6, pp. 731-740, 2024.

[6] L. Giancarli, J. Bonal, A. L. Puma, B. Michel, P. Sardain, and J. Salavy, "Conceptual design of a high temperature water-cooled divertor for a fusion power reactor," *Fusion engineering and design,* vol. 75, pp. 383-386, 2005.

[7] S. Ud-Din Khan *et al.*, "Determination of limiter design and material composition of MT-II spherical tokamak," *Kerntechnik,* vol. 88, no. 1, pp. 54-62, 2023.

[8] A. Alam *et al.*, "Optimization of divertor design for Pakistan spherical tokamak," *Kerntechnik,* vol. 88, no. 4, pp. 437-445, 2023.

[9] Z. M. Elqahtani, N. Alwadai, S. U.-D. Khan, and S. U.-D. Khan, "Physical behavior of nanoparticles-enhanced PCM including transient conduction," *International Journal of Modern Physics B,* vol. 37, no. 10, p. 2350091, 2023.

[10] S. U.-D. Khan, R. Khan, and S. Hussain, "Suitability of thermal plasma for solid waste treatment and non-thermal plasma for nano-scale high-tech plasmonic materials: a concise review," *Applied Nanoscience,* vol. 12, no. 11, pp. 3111-3126, 2022.

[11] A. L. Puma, L. Giancarli, H. Golfier, Y. Poitevin, and J. Szczepanski, "Potential performances of a divertor concept based on liquid metal cooled SiCf/SiC structures," *Fusion engineering and design,* vol. 66, pp. 401-405, 2003.

[12] T. M. Khan, S. U.-D. Khan, M. Raffi, and R. Khan, "Theoretical–computational study of atmospheric DBD plasma and its utility for nanoscale biocompatible plasmonic coating," *Molecules,* vol. 26, no. 16, p. 5106, 2021.

[13] S. U.-D. Khan, S. O. Alaswad, Y. Song, S. Hussain, and R. Khan, "Impurity transport and halo current effects on tungsten divertor system," *Journal of Radiation Research and Applied Sciences,* vol. 13, no. 1, pp. 309-317, 2020.

[14] P. Norajitra *et al.*, "Divertor conceptual designs for a fusion power plant," *Fusion Engineering and Design,* vol. 83, no. 7, pp. 893-902, 2008/12/01/ 2008, doi: https://doi.org/10.1016/j.fusengdes.2008.05.022.

[15] S. U.-D. Khan, S. U.-D. Khan, R. Khan, Y. Song, S. Hussain, and S. Haider, "Development and verification of numerical study to calculate focal points of temperature in helium cooled ceramic blanket (HCCB) system in CFETR," *Modern Physics Letters B,* vol. 33, no. 16, p. 1950173, 2019.

[16] T. M. Khan, S. U.-d. Khan, S. U.-d. Khan, A. Ahmad, and S. A. Abbasi, "A new strategy of using dielectric barrier discharge plasma in tubular geometry for surface coating and extension to biomedical application," *Review of Scientific Instruments,* vol. 91, no. 7, 2020.

[17] T. M. Khan *et al.*, "Silver nanoparticle films by flowing gas atmospheric pulsed laser deposition and application to surface-enhanced Raman spectroscopy," *International Journal of Energy Research,* vol. 44, no. 14, pp. 11443-11452, 2020.

[18] A. Pizzuto, P. J. Karditsas, C. Nardi, and S. Papastergiou, "HETS performances in He cooled power plant divertor," *Fusion engineering and design,* vol. 75, pp. 481-484, 2005.

[19] S. U.-D. Khan, J. Wang, Y. Song, S. U.-D. Khan, U. A. Rana, and R. Khan, "Steady state and transient analysis of novel design helium cooled ceramic blanket (HCCB) system of China fusion engineering test reactor (CFETR)," *Journal of Fusion Energy,* vol. 37, pp. 308-316, 2018.

[20] S. Ud-Din Khan, M. Peng, S. Yuntao, S. Ud-Din Khan, and S. Haider, "Simulation and Verification Studies of Reactivity Initiated Accident by Comparative approach of NK/TH coupling codes and RELAP5 code," *Atw. Internationale Zeitschrift fuer Kernenergie,* vol. 62, no. 2, pp. 125-130, 2017.

[21] P. J. Karditsas, "Optimization of the HETS he-cooled divertor concept: Thermal fluid and structural analysis," *Fusion science and technology,* vol. 47, no. 3, pp. 729-733, 2005.

[22] K. Wang, Y. Song, H. Wu, X. Wei, S. U.-D. Khan, and Y. Cheng, "Inverse kinematics research using obstacle avoidance geometry method for EAST Articulated Maintenance Arm (EAMA)," *Fusion Engineering and Design,* vol. 119, pp. 1-11, 2017.

[23] T. Ihli, R. Kruessmann, I. Ovchinnikov, P. Norajitra, V. Kuznetsov, and R. Giniyatulin, "An advanced He-cooled divertor concept: Design, cooling technology, and thermohydraulic analyses with CFD," *Fusion Engineering and Design,* vol. 75, pp. 371-375, 2005.

[24] P. Norajitra *et al.*, "Development of He-cooled divertors for fusion power plants," *Fusion Engineering and Design,* vol. 82, no. 15, pp. 2740-2744, 2007.

[25] S. U. D. Khan, S. Yuntao, X. Liu, and S. U. D. Khan, "Development of theoretical model for 3D plasma energy behavior and characteristics," *International Journal of Energy Research,* vol. 40, no. 3, pp. 400-407, 2016.

[26] S. Rimza, K. Satpathy, S. Khirwadkar, and K. Velusamy, "Optimal design of divertor heat sink with different geometric configurations of sectorial extended surfaces," *Fusion Engineering and Design,* vol. 100, pp. 581-595, 2015.

[27] S. Shi *et al.*, "Design and implementation of storage cask system for EAST articulated inspection arm (AIA) robot," *Journal of Fusion Energy,* vol. 34, pp. 711-716, 2015.

[28] S. U. D. Khan, Y. Song, and S. U. D. Khan, "Theoretical investigation of plasma dynamical behavior and halo current analysis," *International Journal of Energy Research,* vol. 40, no. 4, pp. 497-506, 2016.

[29] J.-S. Lim, N. Lee, B.-E. Ghidersa, and H. H. Cho, "Enhancement of cooling performance of a helium-cooled divertor through the addition of rib structures on the jet-impingement area," *Fusion Engineering and Design,* vol. 136, pp. 655-660, 2018.

[30] S. U. D. Khan, Z. Almutairi, M. Alanazi, and S. U. D. Khan, "Safety analysis of pool-type double containment of system-integrated modular advanced reactor: a case study for Saudi Arabia," *International Journal of Energy Research,* vol. 45, no. 8, pp. 12047-12058, 2021.

[31] L. H. Salwiczek, N. J. Emery, B. Schlinger, and N. S. Clayton, "The development of caching and object permanence in western scrub-jays (*Aphelocoma californica*): Which emerges first?," *J. Comp. Psychol.,* Article vol. 123, no. 3, pp. 295-303, Aug 2009, doi: 10.1037/a0016303.

[32] J. H. Lim and M. Park, "A numerical-experimental analysis of qualification assessment for mono-block plasma-facing component with flat heat sink," *Engineering Research Express,* vol. 3, no. 4, p. 046001, 2021.

[33] S. U.-D. Khan and S. U.-D. Khan, "Karachi Nuclear Power Plant (KANUPP): As case study for techno-economic assessment of nuclear power coupled with water desalination," *Energy,* vol. 127, pp. 372-380, 2017.

[34] S. U.-D. Khan, Y. Song, and S. U.-D. Khan, "Thermal hydraulic analysis of China fusion engineering test reactor during thermal quenching by comparative approach of Relap5 and THEATRe codes," *Modern Physics Letters B,* vol. 30, no. 30, p. 1650357, 2016.

[35] A. Shahzad, R. Ali, M. Kamran, S. U.-D. Khan, S. U.-D. Khan, and A. Farooq, "Axisymmetric flow with heat transfer over exponentially stretching sheet: a computational approach," *Physica A: Statistical Mechanics and its Applications,* vol. 554, p. 124242, 2020.

[36] S. U.-D. Khan, S. Yuntao, and S. U.-D. Khan, "Theoretical calculation and simulation studies for sideways force on vacuum vessel during VDEs in east," in *2016 IEEE International Conference on Plasma Science (ICOPS)*, 2016: IEEE, pp. 1-1.

[37] S. Ud-Din Khan, Y. Song, and S. Ud-Din Khan, "Theoretical Calculation and Simulation Studies of Axisymmetric Plasma and Halo Current Analysis in EAST," *Transactions of the American Nuclear Society,* vol. 114, no. 1, 2016.

[38] D. K. Lim, Y. Park, H. Kim, and E. S. Kim, "CFD-based shape optimization on cross-section of monoblock fusion divertor cooling channel for minimizing local heat flux," *Fusion Engineering and Design,* vol. 136, pp. 1100-1105, 2018.

[39] S. U.-D. Khan, S. U.-D. Khan, Y. Song, and C. Dalong, "Theoretical relation between halo current-plasma energy displacement/deformation in EAST," *Journal of Theoretical and Applied Physics,* vol. 12, pp. 23-31, 2018.

[40] J. Ahmed, A. Shahzad, A. Farooq, M. Kamran, S. U.-D. Khan, and S. U.-D. Khan, "Radiative heat transfer in Homann stagnation-point flow of hybrid nanofluid," *Applied Nanoscience,* vol. 10, pp. 5305-5314, 2020.

[41] L. Lei *et al.*, "Conceptual design and heat transfer performance of a flat-tile water-cooled divertor target," *Plasma Science and Technology,* vol. 23, no. 9, p. 095601, 2021.

[42] J. Ahmed, A. Shahzad, A. Farooq, M. Kamran, S. Ud-Din Khan, and S. Ud-Din Khan, "Thermal analysis in swirling flow of titanium dioxide–aluminum oxide water hybrid nanofluid over a rotating cylinder," *Journal of Thermal Analysis and Calorimetry,* vol. 144, pp. 2175-2185, 2021.

[43] S. U. D. Khan, M. Peng, and S. U. D. Khan, "Neutronics and thermal hydraulic coupling analysis of integrated pressurized water reactor," *International journal of energy research,* vol. 37, no. 13, pp. 1709-1717, 2013.

[44] Z. Chen *et al.*, "Study of W/Cu flat-type mock-ups with novel hypervapotron cooling structure for CFETR divertor," *Fusion Engineering and Design,* vol. 172, p. 112919, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.fusengdes.2021.112919.

[45] S. U.-D. Khan, M. Peng, L. Li, and S. U.-D. Khan, "Modification and validation of THEATRe code for the plate type fuel nuclear reactor," *Annals of Nuclear Energy,* vol. 53, pp. 519-528, 2013.

[46] S. U.-D. Khan, S. U.-D. Khan, and Y. Zhifei, "Modification of neutron kinetic code for plate type fuel nuclear reactor," *Science and Technology of Nuclear Installations,* vol. 2013, no. 1, p. 487604, 2013.

[47] S. U. Khan, M. Peng, S. U. Khan, K. Ahmad, and S. N. Danish, "Simulation of Normal/Abnormal Operational Conditions of Integral Pressurized Water Reactor by Using RELAP5/MOD3. 4," *International Journal of Modelling and Simulation,* vol. 32, no. 4, pp. 229-236, 2012.

[48] S. Khan, M. Peng, and S. Khan, "Thermal hydraulic analysis of small nuclear reactor core by using comparative approach of THEATRe and Relap5 code," *Int. J. of Nuclear Energy Science and Technology,* vol. 6, pp. 271-283, 01/01 2011, doi: 10.1504/IJNEST.2011.045097.

[49] S. U. D. Khan, S. N. Danish, S. Haider, and S. U. D. Khan, "Theoretical calculation simulation studies of ABV nuclear reactor coupled with desalination system," *International Journal of Energy Research,* vol. 39, no. 11, pp. 1554-1563, 2015.

[50] S. U.-D. Khan, S. U.-D. Khan, and M. Peng, "Flow blockage accident or loss of flow accident by using comparative approach of NK/TH coupling codes and RELAP5 code," *Annals of Nuclear Energy,* vol. 64, pp. 311-319, 2014.