Lithium divertor of KTM tokamak

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Abstract. At present time the project of Kazakh material science tokamak KTM is under implementation. In addition to solving problems in the study of materials for fusion technologies on tokamak is working out innovative design elements of the divertor. The design of the lithium divertor module based on lithium capillary-porous systems has been developed and successfully tested under real tokamak conditions. In this design, the solution to the problem of removal of heat flows of high density was implemented through the use of a liquid metal coolant based on the eutectic alloy Na-K. Requirements to improve the safety and compatibility of the design of the divertor with other in-vessel elements of the tokamak, cooled by water, and limiting the temperature of the lithium receiving surface at <600°C at heat flows of 10⁻²⁻²⁰ MW/m²² led to the creation of a new design solution for the experimental module of the divertor and the use of a new coolant – gas dispersed water flow (gas-water spray). The article describes and justifies the design solutions of the new version of the module, the parameters of the coolant and the cooling system scheme. Experimental results on determination of heat transfer coefficient for coolant based on gas-water spray are considered

1. Introduction

Tokamak KTM (Kazakh materials science tokamak) is a joint project of Kazakh and Russian scientists and has the status of the world's first technological tokamak for reactor materials science. It is a spherical tokamak with an aspect ratio equal to 2, a single-zero divertor plasma configuration, a maximum plasma current of 750 kA, a toroidal magnetic field of 1 T and a plasma retention time of up to 5 seconds. The basic physical parameters of the tokamak KTM are described in [1].

The main task of KTM is to conduct research on the interaction of materials with high-temperature plasma, test the materials of critical components of future fusion reactors (FR), sources of thermonuclear neutrons and hybrid fusion-fission reactors. The main qualitative difference of tokamak KTM from similar installations is the presence of transport-gateway and receiving-divertor units. This makes it possible to replace the samples in the shortest possible time, without depressurization of the vacuum chamber, which greatly increases the speed and volume of experimental data. Research and testing of divertor plates of various materials and designs is the main task of the installation. Currently,
the KTM experimental complex is preparing technological and diagnostic systems, as well as the experimental complex as a whole for the next stage of physical start-up.

2. Liquid metal divertor based on lithium capillary-porous system with liquid metal cooling

The use of liquid metals and, first of all, lithium is considered as a promising alternative to the protection of the elements of the first wall and the tokamak divertor. Lithium in-vessel elements are capable of self-regeneration and can provide, unlike solid materials (tungsten, etc.), long-term stationary operation of the tokamak.

Lithium module divertor plate of tokamak KTM was created on the basis of lithium capillary-porous system (CPS) with a stainless steel matrix. In a high loaded area of divertor plate was used porous tungsten. This material is the most promising for the creation of lithium components interacting with tokamak plasma.

A lithium divertor module (MLD) cooled by eutectic Na-K alloy based on lithium CPS was developed and tested at the KTM experimental facility. Liquid metal coolant to remove excess thermal energy coming from the plasma was chosen for the following main reasons: (1) low solidification temperature (-12.6°C) and, as a consequence, easy operation of the heat exchange system; (2) high thermophysical characteristics; (3) low pressure in the heat exchange system. One of the 24 sectors of the KTM vacuum vessel divertor table was replaced by a lithium divertor module. Module of lithium divertor cooled with eutectic Na-K, has been successfully tested, confirming its estimated thermal properties [7]. The main results of the studies are presented in [2].

Experiments on tokamaks T-11M, T-10, FTU and stellarator TJ-II showed that lithium CPS are able to withstand high quasi-stationary loads and due to capillary forces self-renew the surface in contact with the plasma. At the same time, the use of the eutectic Na-K alloy to maintain the required temperature regime is unsafe, because it is a chemically aggressive metal that can ignite in case of contact with air and reacts actively with water. In addition, Na-K eutectic, like other liquid metal heat carriers, has a serious limitation that prevents their use in thermonuclear systems with magnetic plasma retention. First of all, this is the magneto-hydrodynamic resistance to the flow of liquid metal in a transverse magnetic field [3]. This property of the liquid-metal coolant in combination with increased safety requirements and compatibility of the divertor design with other water-cooled in-vessel tokamak elements in modern fusion plants has led to the need to find other technological solutions for the lithium divertor module cooling system based on lithium CPS.

3. New coolant for lithium divertor KTM – gas-water dispersed flow

The removal of heat fluxes with a specific density of 10-20 MW/m², which are expected on the receiving surfaces of in-vessel elements (IVE) of tokamaks of the ITER and DEMO scale, is a critical problem. In addition, for IVE on the basis of liquid lithium, is also fundamentally important condition to limit the temperature of the receiving surface at a level no higher 700°C that with the active redeposition of vaporized lithium will allow to control to an acceptable level its flow into the plasma in a tokamak [4]. The analysis of the possibility of using traditional fusion reactors of heat transfer media (helium gas, water, liquid metals) showed that the convective mechanism of heat removal characteristic of single-phase heat carriers does not allow to divert such powerful heat flows at acceptable pressure and flow parameters (table 1).

| Coolant         | Pressure (MPa) | Flow rate (m/s) | Temperature (°C) | Heat transfer coefficient (kW/m² K) |
|-----------------|----------------|-----------------|------------------|-------------------------------------|
| Liquid lithium  | 0.01           | 1               | 200              | 44                                  |
| Water           | 5              | 10              | 200              | 25-50                               |
| Helium          | 15             | 135             | 200              | 20                                  |
| Gas-water flow  | 0.2            | 20              | 20               | 70-90                               |
As a new approach to solving the problem of effective heat removal from energy-loaded elements, it is proposed to use a finely dispersed gas-water flow (water spray in the gas flow) [5]. The main advantage of this coolant is the high efficiency of heat removal due to the heat of the water-steam phase transition in the fine dispersed liquid phase. Latent heat of evaporation of water is 2.4 MJ/kg the gas phase provides a supply of liquid droplets to the cooled surface and the steam. In addition, such a coolant is not inherent in the occurrence of crisis phenomena in heat transfer. Comparing the operating parameters and heat transfer coefficients given in table 1, it can be concluded that the gas-water spray has great advantages in heat transfer coefficient.

A detailed study [6] of the operation of the cooling system with a coolant based on a gas-water spray was studied in a laboratory setting on model samples of IVE made from copper. In the study, it was possible to adjust the parameters of the coolant-pressure, flow, ratio of gas and liquid phases. The thermal load on the sample surface was determined by a scanning electron beam. The heat flux density was regulated in the range of 0-12 MW/m². It was found that the cooling efficiency increased with increasing dispersion of the liquid phase (figure 1), which grew with the growth of the specific flow rate of gas supplied to the nozzle at a constant flow rate of water. With increasing the flow rate of liquid phase at the optimum dispersion of the liquid in the spray jet (drop diameter ~50 microns) was able to achieve values of heat transfer coefficient at the level of 70-90 kW/m² K. This value significantly exceeds the values for conventional coolants (see table 1). Thus, it was shown that the heat removal system based on a two-phase gas – water coolant implemented for the first time for IVE has a number of significant advantages-low coolant pressure, high heat transfer coefficient, high controllability of the system operation and low inertia, absence of heat transfer crisis phenomena at high temperatures of the cooled wall.

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\begin{align*}
\alpha, \text{kW/m}^2/\text{K} : 1 &- G_{\text{water}} = 0.033 \text{ kg/sec}; \\
2 &- G_{\text{water}} = 0.042 \text{ kg/sec}; \\
3 &- G_{\text{water}} = 0.050 \text{ kg/sec}
\end{align*}
\]

The proposed coolant in practice was first used in the design of a cooled liquid metal tokamak limiter FTU, based on the use of a CPS filled by tin [7].

Given the advantages of the considered coolant is proposed to use in the construction of stationary lithium IVE (divertor, limiter) tokamak T-11M, T-15, liquid metal divertor target tokamak DEMO [8] and as a new option divertor target of the tokamak KTM.

4. Constructive solution of lithium divertor tokamak KTM based on use of gas-water coolant

To realize the possibility of using a coolant based on gas-water spray, a new design of the tokamak lithium divertor module KTM has been developed. MLD of tokamak KTM is a box structure with a capillary-porous structure installed on its upper part and is attached by means of a bracket to the flange of the equatorial branch of the tokamak KTM.
Coolant removal is carried out through the drain hole and the discharge pipe. To compensate for the loss of lithium during operation of the device, a tank is provided in which the CPS has a hydraulic contact with the lithium reserve. If necessary, it is possible to replenish lithium through a special filling line. The MLD is attached to the cassette using pins mounted on the bottom of the module. External MLD systems are regulated sources of distilled water and gas (air, argon, helium). The discharged water vapour-gas mixture enters the condenser and is cooled in the water-water heat exchanger. At the next stages of the work it is planned to design and manufacture a MLD based on GPS with a thermal stabilization system with a vapor-gas mixture of low pressure and conduct its bench tests to assess the effectiveness of the cooling system.

5. Conclusions
Analysis of the state of development of the optimal design of the tokamak lithium divertor module KTM showed that the previously developed version with cooling eutectic Na-K alloy has significant drawbacks. Since there is a potential possibility of a situation with a coolant leak in the vacuum chamber (1) or outside it (2), in the first case it will be necessary to use a deliberately complex and unworked procedure for removing liquid metal from the vacuum chamber of the tokamak, or in the second case, the coolant may ignite when it interacts with air. In addition, the high pumping resistance in the cooling system due to the emerging forces of the magnetohydrodynamic nature will significantly complicate its operation even at relatively low (~1 m/s) pumping speeds of the liquid metal.

The use of a finely dispersed gas-water flow as a coolant for cooling the lithium divertor module, which, as shown by experimental studies, has high thermophysical characteristics, will reduce the pressure in the cooling paths and have a low volumetric water content in the cooling paths of the lithium module. These properties of the coolant will simplify the design of the divertor module and make working with it safe. For the proposed coolant, there is no problem of MHD resistance during its flow in the magnetic field of the tokamak. The constructive scheme of the lithium divertor module of new modification is developed. In the next stages of the work is expected to design and make a model of lithium divertor on the basis of CPS with the stabilisation of the steam-gas mixture low pressure and hold it bench tests to evaluate the effectiveness of the cooling system.

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