THE CONCEPT OF LITHIUM BASED PLASMA FACING ELEMENTS FOR STEADY STATE FUSION TOKAMAK-REACTOR AND ITS EXPERIMENTAL VALIDATION

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Abstract

The Russian strategy in the development of design of long-operating plasma facing element for steady-state fusion reactors is presented. The experimental validation of the main solutions of this strategy is considered and analysed on an example of liquid metal limiters for T-11M, FTU, KTM and T-15 tokamaks and laboratory investigations. The promising design of liquid lithium divertor target plate for DEMO reactor is presented and discussed.

INTRODUCTION

The most critical problem in the development of a stationary thermonuclear reactor is the design of its in-vessel plasma-facing elements (PFE). At present, it has become obvious that among the materials traditionally used for PFE there are no solid structural materials that would meet the requirements of long-term operation under the influence of a thermonuclear (14 MeV) neutron flow with a density of ~ 10^{14} cm^{-2} s^{-1} and a heat flux with a density of 10-20 MW m^{-2}.

An alternative solution to this problem is to use liquid metals (LM) as plasma-facing materials with a low charge number Z or a high Z but low vapor pressure. This will create a long-lived, undamaged and self-renewing surface of the PFE, which does not have a polluting effect on the plasma.

Only based on the analysis of the complex problems and requirements encountered in the development of PFE of the DEMO type reactor [1, 2], and the critical consideration of many limiting aspects in the use of LM in thermonuclear facilities with magnetic confinement [3-8], it is possible to formulate the main ideas of the alternative concept of PFE, based on the use of LM and taking into account modern experience and achievements in the field of design, materials science and technology.

The paper presents the experience of creating PFE of the number of tokamaks (T-11M, FTU, KTM), and discusses the main ideas of the concept of liquid metal based PFE of a stationary tokamak-reactors, which are being translated into promising design scheme divertor target of the DEMO type tokamak.

2 THE CONCEPT OF THE PFE WITH LITHIUM CAPILLARY SYSTEM

The most important point, on which the whole sense of the concept depends, is the choice of a scheme for the LM use. Based on the existing analytical reviews and the authors ' own experience [3-10], the most feasible scheme is using a slow drift of the liquid metal over a porous surface or in a body of solid matrix of a capillary-porous system (CPS). This scheme allows self-renewal of the PFE surface of any shape and orientation, stabilization of LM under the influence of electromagnetic forces due to capillary forces in the CPS. Slowly flowing LM (no more than a few millimeters per second) through the CPS under the influence of gravity will allow removing trapped tritium and accumulated impurities. In this case, the thermal energy coming from the plasma to the surface is discharged through the structure of the PFE to the flowing coolant. Use of well-proven porous metal felt, the properties of which are described in [11], is supposed as a material of CPS.

Lithium, tin and tin-lithium alloy are now actively considered as LM for use in fusion reactor [3-5]. The final choice of LM can be made only on the basis of the following selection criteria - the available experience of use in the tokamak conditions, the existence of the fulfilled technology of application, compatibility with PFE structural materials, physical and chemical properties [11-14]. It is believed that the upper temperature limit of applicability of LM is determined by the permissible flux of its vaporized or sputtered atoms into the plasma. For lithium and tin, it is ~500 °C and ~1000 °C respectively, but taking into account the mechanism of atomic re-deposition, it can reach ~700 °C and 1250 °C respectively [15]. The operation temperature limits determined from the LM compatibility with the PFE and CPS structural materials are shown in Table.1.

TABLE 1. TEMPERATURE LIMIT OF MATERIALS COMPATIBILITY WITH LM

Structural materials	Temperature limit,ºC	
	Li	Sn / Sn-Li alloy
Ferritic / ferritic-martensitic chromium steels	800	<400
Austenitic Cr-Ni steels	700	<400
V-Cr-Ti alloys	900	<700
Mo alloys	1200	1000
W alloys	1500	1200
Cu and alloys	incompatible >180	incompatible >230

It should be noted that from the point of view of the activation and the effect of radiation damage on the properties of the materials the chromium stainless steels, vanadium alloys and tungsten alloys are acceptable, copper alloys are only in a very limited amount. The analysis should take into account the possible real design of PFE and the existence of available technologies for their manufacture. For example, it is difficult to suppose the PFE, entirely consisting of tungsten or its alloys. Tungsten can be successfully used in the form of a fiber based material for the CPS. From these positions, the temperature threshold for the use of lithium and tin is determined by the lowest threshold for the material contacting with the LM. In this case, the contact of copper and its alloys with the LM is unacceptable. Thus, the threshold for lithium is 800 ºC, and for tin – 400 ºC. As a result, when using lithium, the surface temperature can be supposed equal to 700 °C, and for tin only to 400 °C. Among other things the wetting angle of Li and Sn fore selected structural materials are ~ 0 º and 20-30º respectively. Problem with wetting in Sn take place and development of wetting technology is needed. From all these reasons, lithium has distinct advantages over tin and lithium - tin alloy.

From safety reasons the total amount of lithium in a reactor chamber should not exceed 20 kg. It is determined from the maximum possible hydrogen pressure of 0.2 MPa in the chamber arising from a chemical reaction of the total amount of lithium with spilled water [16]. The estimated amount of lithium in the DEMO divertor with lithium CPS will be ~13 l (~6.5 kg) for a supposed receiving plate area of ~66 m^2, CPS thickness of 0.5 mm and a CPS porosity of 40%, which meets the safety requirements.

Since lithium is an active absorber of hydrogen species at operating temperatures, there is a problem of capture and accumulation of radioactive tritium in the tokamak-reactor chamber. From a DEMO scale reactor limits the permissible amount of captured tritium should not exceed 1 kg [16]. At a lithium flow rate in the CPS equal to 2 10^{-3} m s^{-1} the exposure time of 6.5 kg of lithium in the chamber will be ~350 s (the height of the receiving panel of the divertor is assumed to be 0.7 m). A conservative estimation of the amount of dissolved hydrogen species in lithium at a surface temperature of 600 °C and a pressure of ~100 Pa in the divertor region gives a value of ~26 g, which corresponds to an average concentration of C_H = 2.8 at %. Thus, the realized rate of lithium renewal in the divertor does not allow the formation of lithium hydride / tritide, and the total amount of captured tritium in the chamber is significantly lower than the maximum permissible value.

Taking into account the effect of neutron irradiation (radiation damage up to 5 dpa/fpy) on the properties of structural materials of the divertor, the permissible temperature range of their use in the design of the PFE is [2]: for Eurofer type steel - 350-550 ° C; for V-Cr-Ti alloy - 400-700 ° C; for Cu – 200-350 ° C; for W alloys – more than 650 °C. It means for the PFE design development that applied materials should be placed in the PFE structure areas with permissible temperatures. For these reasons, LM compatibility limit with materials (Table. 1), material thermal properties and demands of the ITER structural design criteria (SDC-IC) it is possible to estimate the maximum permissible heat flux on the PFE surface from considering materials (Tab.2).

TABLE 2. HEAT LOAD LIMIT FOR PFE MATERIALS*

Material	Power flux, MW m^{-2}
Ferritic / ferritic-martensitic chromium steels	3
V-Cr-Ti alloys	9
67%W fiber+ 33% Eurofer steel	17
W	38

*1 mm wall+0.5 mm of the CPS with lithium, T_{Surf} = 650 °C, gas-water spray coolant.

From the analysis it follows that only tungsten corresponds to operating condition at 10-20 MW m^2. However, as shown in Table. 2, the composition of 67% W fiber + 33% Eurofer type steel and V-Cr-Ti alloys can serve as a promising structural material of DEMO divertor. In addition, presented composite material can be quite technologically when connecting the wall of the receiving surface with other PFE elements made of Eurofer type steel. It will be necessary to produce and investigate such material to confirm this assumption.

An important aspect of the concept is the coolant and the design of the heat removal system. Typically, the heat transferring media as water, liquid metal (lithium), gas (argon) are considered as the coolants of PFE for fusion reactor [1]. Recently, it has been proposed to use a fine water spray in the gas stream [17]. Comparing there typical operating parameters and heat transfer coefficients (Table. 3) it can be seen that the efficiency of the heat removal, the pressure level and flow rate of gas-water spray coolant has great advantages. Only liquid lithium and gas-water spray can be considered to ensure acceptable surface temperatures at the required heat fluxes up to 20 MW m^{-2}. Other coolant should have too high pressures and flow rate, which leads to large wall thicknesses and exceeding the limits for the LM temperature. For liquid lithium, a critical problem is the high flow resistance in the cooling system due to MHD forces. Thus, a gas-water spray can be considered as the optimal coolant for PFE with LM. Water consumption for DEMO divertor cooling the with such a coolant will be ~ 60 l s^{-1}, and gas – 1.7 m^3 s^{-1}. In terms of the consequences of water spill into the reactor vacuum chamber with lithium-containing PFE such coolant is less dangerous than pressurized hot liquid water.

TABLE 3. MAIN PARAMETERS AND HEAT TRANSFER COEFFICIENT OF COOLANTS

Coolant	Pressure, MPa	Flow rate, m s^{-1}	Temperature, °C	Heat transfer coefficient, kW m^{-2} K
Liquid lithium	0.1	1	200	44
Liquid water	5	8	200	52 (swirl flow), 25 (normal flow)
Gas (helium)	15	135	200	20
Water-gas spray	0.2	40 G_{gas}/G_{water}>0.06 (ratio of mass flow)	20	70-100

3. THE EXPERIENCE OF CREATING A PFE WITH ACTIVE COOLING

Realization of the considered concept was tested on a series of models of stationary operating PFE with LM for tokamaks T-11M, FTU, KTM [17-22]. The created models have the design capability to provide operation in the temperature range of 200-550 °C at stationary power flux up to 10 MW m^{-2}.

A series of liquid lithium limiters (LLL) of T-11M and FTU tokamaks were created on the basis of CPS from tungsten felt with lithium and used as coolant water at a temperature of 210-230 °C under pressure up to 4 MPa with a flow rate of 0.05-0.5 l s^{-1}. The area of the lithium surface of the limiters was 40 cm^2 and 100 cm^2, respectively. The initial heating of the litters to a temperature above the lithium melting point and the heat removal when exposed to plasma was carried out by pumping the liquid water coolant. The operational experience of limiters demonstrated the functionality of their design, but the high thermal inertia of the heat removal system resulted in the complexity and stability of temperature control. Due to the fact that the duration of the plasma discharge of these tokamaks was 0.2-0.3 s (T-11M) and 1.5 s (FTU), it was difficult to demonstrate the efficiency of the cooling system during the plasma discharge. Nevertheless, activity on creation and testing of such limiters allowed to develop design decisions, technologies of their production and application in tokamak conditions. No damages of CPS surface and uncontrollable injection of LM into the plasma have been observed.

The prototype of the lithium divertor module (MLD) of KTM tokamak based on lithium CPS (lithium surface area of 1000 cm^2) was made to apply a liquid metal coolant (eutectic alloy 22% Na + 78% K) with high thermal properties and boiling point. A pressure in the cooling channel was 0.2-0.5 MPa and flow rate was equal to 0.1-1.5 l s^{-1}. LMD testing has been postponed until the beginning of the tokamak experimental campaign with a full-power plasma. To date, the following MLD tests have been carried out [22]. Hydraulic tests of the external temperature stabilization system in the temperature range of 20-200 °C were performed in the conditions of the laboratory bench. As a result, the efficiency of the system and its key elements proper operation were confirmed, the experience in system operation control was obtained. The un-cooled model of in-vessel element of LMD has been tested in the conditions of the tokamak KTM in the temperature range of the lithium surface of 200-550 ^{o}C with an electric heater. It demonstrated the module design capability and compatibility with the tokamak plasma.

The world's first steady-state operating limiter based on CPS with tin (TLL) was developed and created for tokamak FTU [17]. The surface of LM area was 85 cm^2. It was also the first case of new gas-water spray coolant application (see Tab.3 for coolant parameters). This made it possible to considerably reduce the pressure in the coolant channel and amount of coolant, provide low inertial heat removal capability. The energy removal process in TLL design based on the evaporation of small droplets of the liquid fraction of the coolant, which is more efficient in comparison with the process due to the thermal conductivity to a single-phase liquid coolant. Testing of the limiter is currently ongoing. The limiter is designed to operate in the temperature range of the LM surface of 240-900 °C at power flux up to 10 MW m^{-2}.

A detailed study of the operation of the cooling system with a gas-water spray coolant was carried out in a laboratory facility with PFE model made of copper (Fig.1a). The scheme of the external part of the system is shown in Fig. 1b. A fine gas–water mixture was fed into the internal cavity of the model (1) by means of the atomizer (2), and it was possible to adjust the parameters of the coolant (pressure, flow rate, the ratio of the gas and liquid fractions. The thermal load on the model surface was set by a scanning electron beam. The heat flux density was regulated in the range of 0-12 MW m^{-2}.

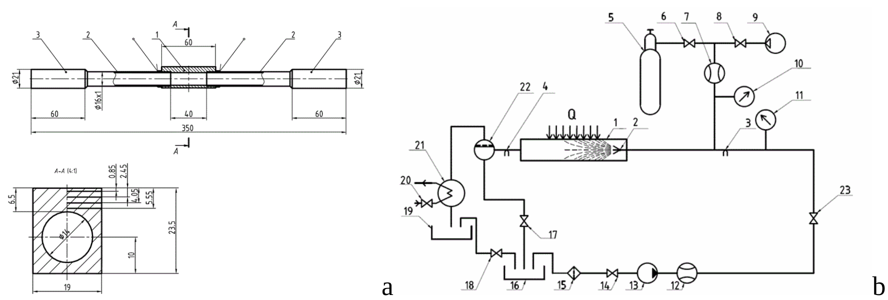

Fig. 1. Scheme of the PFE model (a) and experimental facility (b) for the study of the heat removal process by gas-water spray

In this study was found that the cooling efficiency increases with increasing of the liquid phase dispersion, which grew with an increase in the mass flow rate of gas against water flow rate (Fig.2-3). The process of fine droplet evaporation provides intensive heat exchange on a cooling surface interacting with flowing spray. With an increase in the water flow rate at optimal dispersion of the liquid (droplet diameter of <50 microns), it was possible to obtain heat transfer coefficients at the level of 70-100 kW m^{-2} K^{-1}. This value considerably exceeds values for traditional coolants (see Table. 3).

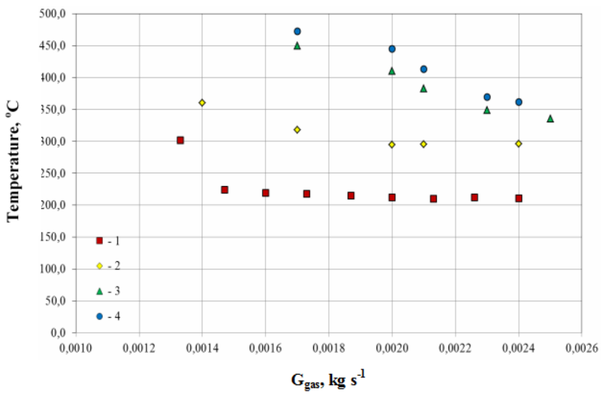

Fig. 2. Cooled surface temperature dependence on gas flow rate G_{gas}

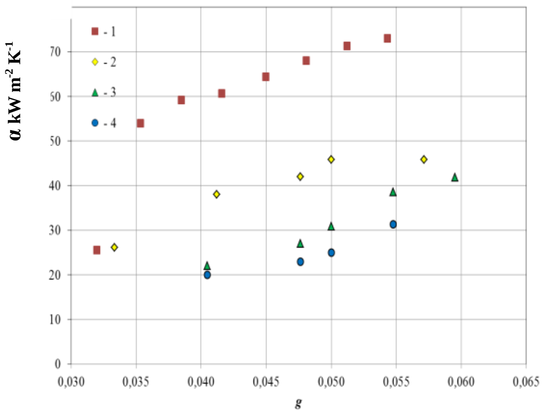

Fig. 3. Dependence of heat transfer coefficient on specific gas flow rate g = Ggas/Gwater: 1- 4.2 MW м$^{-2}$; 2 - 5.8 MW м$^{-2}$; 3 - 7.12 MW м$^{-2}$; 4 – 8.3 2 MW м$^{-2}$

The acquired experience in development, creation and testing in tokamak conditions of steady-state operating PFE with LM served as the basis for the development of the design of liquid lithium limiter for T-15 tokamak, which embodied the basic ideas of the concept of PFE for stationary tokamak-reactors (Fig.4). The limiter is designed for stationary operation at a thermal load of 10 MW m^{-2}. Moreover, such a limiter can work in tandem with a similar one, acting alternately as an emitter or collector of lithium, thereby ensuring the closed circuit of the circulation of lithium atoms in the tokamak chamber, which prevents the accumulation of lithium on the walls of the tokamak in the process of long-term operation. The gas-water spray is used as a heat transfer medium of the heat removal system. The limiter is provided with lithium (for limiter filling and lithium circulation) by electromagnetic pump from an external system. The limiter is equipped with a system of movement relative to the tokamak plasma.

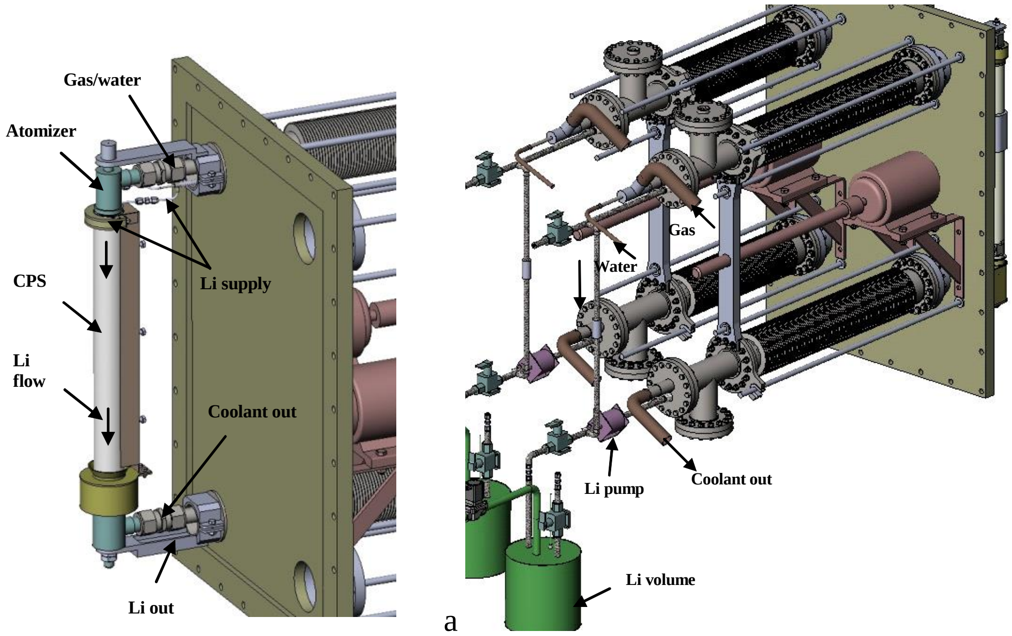

Fig. 4. Scheme of liquid lithium limiter for T-15 tokamak: a- in-vessel element; b- out-vessel Li supply and cooling systems

4. DEVELOPMENT OF A PROTOTYPE OF DEMO DIVERTOR TARGET

Taking the above concept of a steady-state operating PFE with LM as a basis, we can offer an alternative version of the design of the divertor target for tokamak DEMO. The divertor target based on lithium CPS is developed on the assumption that the thermal load in the contact zone (height ~0.3 m) with the plasma flow can reach 10 MW m^{-2}, and in the outside zone of 0.5-1 MW m^{-2} [16]. The CPS surface temperature should not exceed 650 °C. The surface temperature distribution in the plasma interacting zone should be uniform. Mechanical stresses in the target structure should meet the requirements of the ITER structural design criteria (SDC-IC).

Often used scheme of cooling system based on tubular channels (Fig.5a) is not able to ensure the uniformity of the CPS surface temperature distribution [23]. In this regard, it is proposed to use the target design with a flat thin-walled cooling channel (Fig.5b) [19, 24]. The thickness of the lithium CPS on the outer surface of the target first wall is 0.5 mm. The first wall with 2 mm thick is made of the material with high thermal conductivity and mechanical strength. The wall is cooled by a gas-water spray generated in an atomizer.

The proposed divertor target has a modular design (Fig. 5b). The central module is located in the separatrix strike zone and is designed for a stationary power flux of 10 MW m^{-2} with transient peak up to 20 MW m^{-2}. Two auxiliary modules are located in the power flux zone about 1 MW m^{-2}. The module operation scheme is presented in Fig. 6.

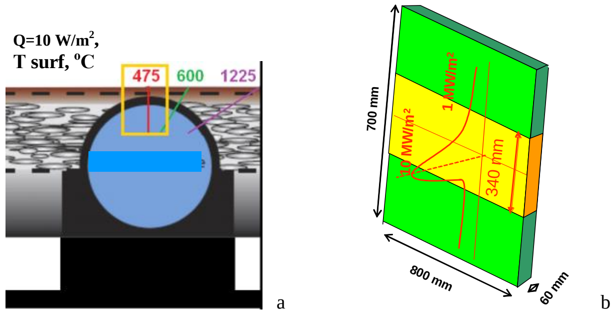

Fig. 5. Schematic solutions of the divertor target design: a-tubular channel [18]; b-flat channel

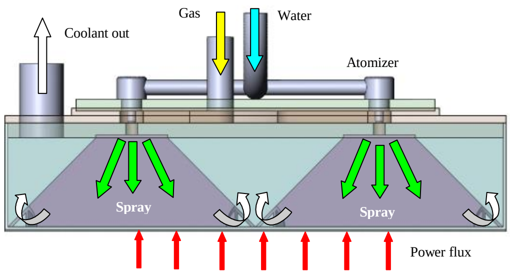

Fig.6. Scheme of the target operation

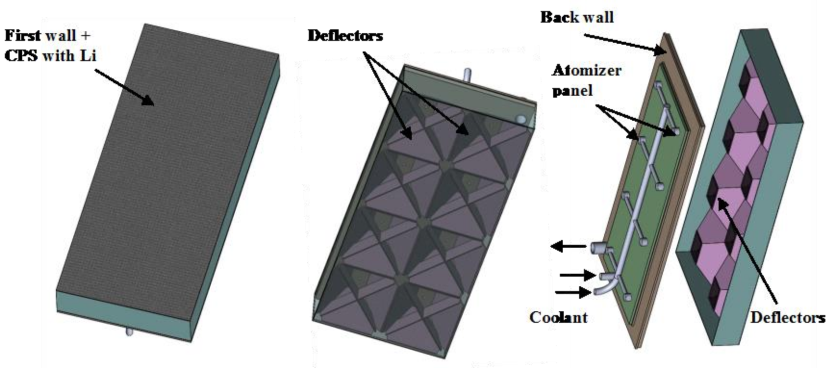

Fig. 7. Structure scheme of central module

The central module has a structure with 8 identical cells (Fig.7). Each cell is equipped with an atomizer for the cooling spray generating. Two auxiliary modules have 4 cells each. The lithium CPS of the first wall is fixed on the outer side of the cooling channel wall. This wall is connected by welding with structural elements and forms an internal sealed cavity of the cooling channel and divided into two parts – the feed cavity and the cavity of the coolant outlet. Gas-water spray through the atomizer is supplied at a pressure of 0.2 MPa to the first cavity and is directed by deflectors to the inner surface of the first wall. The heated coolant exits through the holes in the deflector into the discharge cavity and is removed from the module. The deflector plates form a structure in the form of a truncated four-sided pyramid. The upper and lower bases of the pyramid are attached respectively to the back and first walls of the channel, which provide rigidity of the module structure. The atomizers of the module cells are provided with gas and water supply to the appropriate collectors.

Specific volume consumption for cooling of the divertor target is: for water G_w~ 1 l s^{-1} m^{-2}; for gas G_{gas}~ 25 l s^{-1} m^{-2}. Thus, for cooling the DEMO divertor target (~0.56 m^2) volume flow of coolant components at a pressure of 0.2 MPa will be the following: water ΣG_w ~0.5 l s^{-1}; gas ΣG_{gas} ~ 14 l s^{-1}.

The choice of the structural material for divertor target first wall is based on the assessment of the permissible heat flux Q_{max}, which is the minimal value among fluxes determined from the limits on the mechanical stresses (Q_{mech}) taking into account SDC-IC and the surface temperature limit (Q_{temp}). According to the results of the calculation analysis (Table. 4) and taking into account the possible target production technology, the composite material (67% W of the fiber+ 33% steel Eurofer) is considered as a promising material.

TABLE 4. MAXIMAL AVAILABLE HEAT FLUX FOR FIRST WALL MATERIAL

Material	Q_{mech}, MW m^{-2}	Q_{temp}, MW m^{-2}	Q_{max}, MW m^{-2}
Eurofer	1,7	6	1,7
63%W- 33%Eurofer	10	14	10
W	20	17	17
V	4	7	4

The results of the calculation of the thermal state and stress in the structure at a power flux of 10 MW m^{-2} are shown in Fig. 8. The first wall of target has a uniform temperature distribution in a range of 430 ± 30 ºC. The maximum total stresses in the structure do not exceed 250 MPa, which is significantly lower than the yield strength Sy = 486 MPa of proposed first wall material. This indicates that the proposed design meets the requirements of SDC-IC.

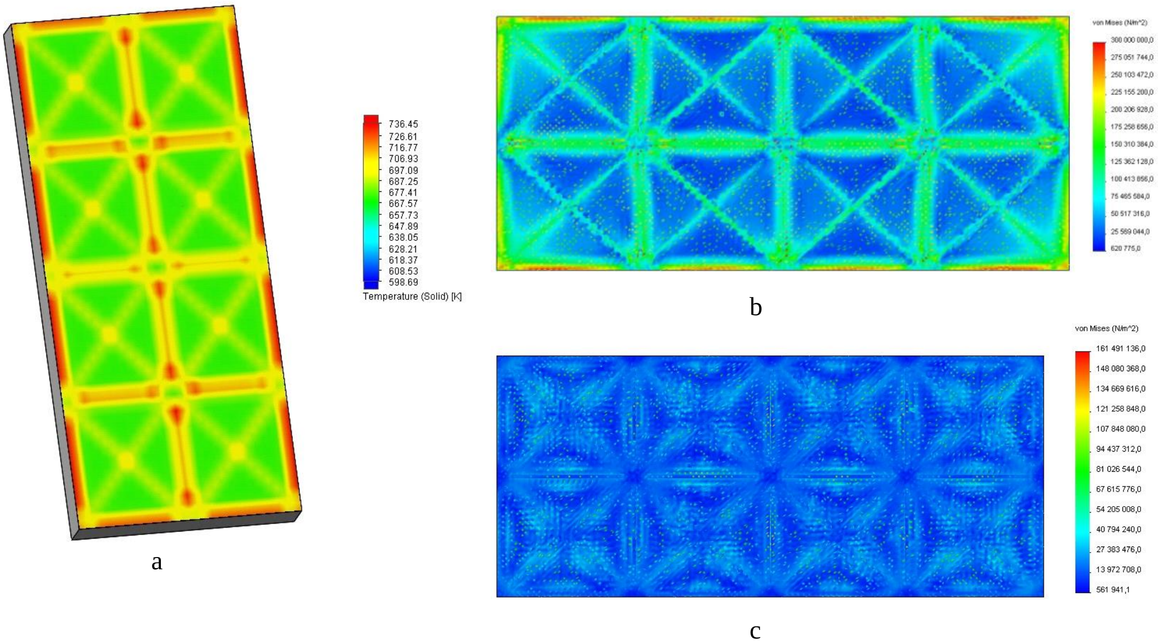

Fig.8. Results of DEMO divertor target analyses for power flux of 10 MW m^{-2}: a – temperature distribution; b- thermal stress; c- mechanical stress

The total amount of lithium in the target is ~ 0.1 l (~50 g). The creation of lithium flow through the CPS structure of the first wall to remove impurities and feed CPS is provided by the lithium feed collector at the upper end of the upper auxiliary module, and the removal – by the collector at the lower end of the lower module (Fig. 5b). The flow rate under the gravity force at a magnetic field of ~4 T will be about 2 mm s^{-1}. A complete change of lithium in CPS is expected through time of 350 s and the tritium concentration in lithium will not exceed C_H = 2.8 at %. The lithium consumption will be 0.3 cm^3 s^{-1}. The removed lithium will enter to the external system for a tritium extraction and feed into the target again.

5. CONCLUSION

The developed concept and the hands-on experience in steady-state operating LM PFE creation and tests allows the solving a number of critical issues in the development of appropriate PFE design that meet the requirements for long-term operation at DEMO type tokamak conditions.

Tungsten fiber based CPS with lithium provides PFE surface protection and renewal under expected power flux. Thin-walled cooling system ensures maintenance of LM surface temperature at an appropriate level preventing plasma pollution. The new composite structural material (67%W fibers + 33% Eurofer steel) for the PFE first wall is presented to meet requirement in radiation stability, thermal and stress capabilities. New type of coolant based on water-gas spray is considered and proposed as more convenient coolant for lithium-containing PFE that meet temperature limit and safety demands. All these points allow to elaborate promising design of the DEMO divertor target plate.

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