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Development of a liquid-metal fusion reactor divertor with a capillary-pore system

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Abstract

The absence of a satisfactorily developed fusion reactor (FR) divertor approach (having no lost layers of sputtered plate materials and/or replaceable blocks) has become the reason for the development of the new concept of liquid-metal divertor (LMD) with a capillary-pore (CP) lithium protection system. Creative and novel design and material solutions, combined with unique natural thermophysical properties of Li working in a gas target evaporation–radiation mode, ensures the prolonged and steady performance of a FR divertor (D).

1. Introduction

The highest loaded element of a tokamak FR (or any other FR possessing a separatrix) is its divertor. While the neutron load in the divertor zone is lower than on the first blanket wall, its specific thermal loads are many times higher; their values incorporate flows of high-energy particles carried out of the plasma zone. The peak operational mode of target plates is non-destructive absorption of energy flows during plasma disruption. In this case, a significant part of energy accumulated in the plasma current is discharged within several milliseconds. The conditions of future commercial FRs operation are illustrated, to a certain extent, by working parameters of the ITER reactor being developed at present and by calculated characteristics of "DEMO" reactor operating conditions (Table 1).

Designs using realistic materials capable of tolerating such high stationary and especially pulsed heat flows without mechanical damage and sputtering under the influence of particle flows during an extended period of time [3–5] do not exist. There have been a number of suggested solutions to this problem [6]:

- organization of liquid-metal films quickly flowing along a cooled substrate,
- creation of a "screen" by a liquid-metal flow,
- creation of drops for a liquid-metal screen,
- creation of a screen of dropping solid balls, and
- placement of rotating cylinders in the divertor.

These ideas seem simple and convincing since they are based on well-known principles of divertor target plate cooling. However, it turns out to be difficult to implement them due to the necessity to combine, in one device, a number of new technical approaches that have not been demonstrated separately. It also requires the use of diverse constructional materials, various heat-carriers and coolers and a combination of static and dynamic conditions involving instabilities in the working zone.

Since no acceptable solutions for such proposals have been found for the FR operating conditions, the problem remains unresolved. A model of divertor plate protection, suggested by Dr. P.-H. Rebut, is now being considered for ITER. He suggested that an inert gas, such as Ne or Ar, be bled into divertor. The inert gas would absorb energy from the high-energy particles exiting the plasma volume, thus

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Table 1
Divertor's work conditions in ITER and DEMO projects [1,2]

Parameter	ITER	DEMO
Fusion power (MW)	1500	3350
Normal operation		
Average neutron load (MW/m^2)	0.5	2.9
Surface heat flux total both channels (MW)	≤ 300	670
Local thermal load normal to surface (MW/m^2)		
normal value	5	300
local peak for sub-pulses of 10 s	15	300
Peak transient surface heat flux (< 10 s) (MW/m^2)	< 30	< 100
Average surface heat flux (MW/m^2)	1	
Number of pulses (at full load) (10^4)	≤ 1	≤ 25
Pulse time (s)	1000	3400
Incident peak flux DT/ions ($10^{20}/m^2 s$)	4000	6000
Incident energy DT/ions (eV)	50-200	800
Disruptions		
Number at full current, full energy	500	150-300
Total number	3000	3000
Time (ms)	0.1-3.0	0.1-0.3
Disruption load (MJ/m^2)	≤ 100	100

reducing the density of the energy flow towards the plate material. The principle of periodic divertor element replacement, which has a cassette structure, is employed. The divertor targets which are cooled by water in the supporting substrate would be made of Be, W, or graphite. The thermal conductivity of the Be or W layer 10-15 mm thick, or of a graphite layer 30 mm thick restricts the established heat flux to the target divertor plates to be less than 5 MW/m^2. It is planned that the divertor of this type would survive up to 1000 burn cycles before replacement, that is ~ 300 h of operation and ~ 200 plasma disruptions. To implement this type of a divertor, it is necessary to build an acceptable divertor water cooling system and to develop a reliable technology for bonding the plasma-facing materials with the water-cooled substrate materials, such as copper alloys and stainless steel. This is quite problematic.

2. Basic principles of the developed concept

The new concept is based on the use of evaporation cooling for eliminating high thermal loads. Evaporation-condensation devices with LM as the heat carrier are known to be the most effective means of power/energy removal in high temperature facilities [7].

If the design of the target substrate is done properly, such a way of eliminating thermal loads can provide excellent performance, which achieves hundreds of MW/m^2 [7]. To supply the evaporation surface with liquid metal, a porous construction of the target plate with a capillary-pore "pumping" system for the liquid metal is used. The characteristics of the capillary-pore system (changing porosity, permeation anisotropy, working surface geometry, etc.) are maintained in broad ranges by using appropriate manufacturing technologies.

The design provides sufficient working pressure in the supply system without applying external pressure by using only capillary force pressure. This system is self-sustaining and self-regulating because the pressure distribution of the liquid-metal coolant in the capillary-pore structure reacts to local changes of the thermal load distribution on its surface. This phenomenon is similar to that observed in "heat pipes" [8,9].

The use of such a technological approach satisfies all of the critical requirements that designers might have when selecting materials and ITER divertor design and construction approaches.

If the divertor change-out frequency is to satisfy economic requirements (say, not more than once per year or more) for a commercial reactor or experimental availability for an ITER, the long-term operation of the target plates provides the following attractive features of the liquid-metal divertor:

(1) Divertor target plate surface erosion is almost absent due to constant supply of liquid lithium.
(2) Temperature gradients in the liquid-metal filled capillary-pore system will produce negligible thermal stress. Therefore, cracking and fracturing of the target plates, which is typical of solid-type divertors, is not expected.
(3) Capillary-pore system bonding problems with the supporting structure of the divertor do not exist.
(4) There is no issue with the radiation resistance of the capillary-pore system material.
(5) Tritium accumulation in the divertor target systems can be managed by limiting its concentration at a low level in the circulating liquid metal.
(6) Having been liquefied (from the gaseous phase) in the condenser zone, liquid metal will then enter the tritium recovery system and, unlike in the solid divertor, tritium will not accumulate in the divertor and adjacent reactor areas.
(7) Both low speed of the liquid lithium flows and "self-healing" electrical insulator surfaces [10] placed on the inner surfaces of the liquid-metal tubes allows significant reduction of MHD-effects.

The use of liquid lithium is the only and the best variant of working fluid for LMD. Due to the unique complex of nuclear, physical and chemical properties it possesses, it is unique for application in LM systems of FR.

The use of lithium makes the divertor concept developed in this work most effective, having a number of

essentially new characteristics and fabricability due to the following reasons:
(1) The Z value of lithium is low, which practically eliminates its influence on plasma radiation upon appearance of lithium atoms in the plasma burning zone.
(2) The high latent heat lithium steam formation values, effective reradiation and ionization in steam cloud discharge a significant part of energy brought by high-energy particle flow from plasma into divertor's volume in which case a gas dynamic target is activated thus decreasing divertor's specific power loads without introducing a flow of heavy gas.
(3) The liquid lithium use in the divertor is compatible with the self-cooling lithium–lithium blanket reactor design. It makes possible the use of the same servicing systems, the same technology for tritium extraction and the same use of low activation V-alloy materials compatible with lithium in a wide range of temperatures (up to 700°C) for both the blanket and the divertor.
(4) Lithium possesses a unique complex of thermophysical properties (Table 2) and is extremely effective for the implementation of the proposed concept of evaporation-irradiation divertor target plates load discharge.

Lithium actively interacts with hydrogen and its isotopes, forming solutions and hydrides as a result of such interaction. Helium and other inert gases do not interact with lithium. This property, and the appropriate selection of the cooler-condenser's temperature modes, makes it possible to separate hydrogen isotopes from helium in the pumping system (by dissolving hydrogen isotopes in lithium and then removing them into extraction system). This can altogether eliminate the need for cryogenic panels or, at a minimum, reduce their area.

Table 2
Physical and thermophysical properties of the lithium [9,11]

Property	Temperature range (°C)	Equation, value
Melting point (°C)		180.54
Boiling point (°C)		1342.7
Density (kg/m^3)	300–1125	$\rho = 0.5368 - 1.0208 \times 10^{-4} T$
	200	0.51
	600	0.47
	1200	0.41
Specific heat capacity (J/gK)	180–900	$c_p = 4.76 - 8.23 \times 10^{-4} T$
	600	4.16
	1200	4.23
Electrical conductivity (1/Ωm)	180–1300	$k = 0.9249 \times 10^9/(T+273) + 2.3167 \times 10^6 - 0.7131 \times 10^3(T+273)$
	200	3.810×10^{-6}
	600	2.703×10^{-6}
	1200	1.864×10^{-6}
Thermal conductivity (W/mK)	180–1300	$\lambda = 24.8 + 45 \times 10^{-3}(T+273) - 11.6 \times 10^{-6}(T+273)^2$
	200	44.4
	600	55.9
	1200	66.2
Interfacial tension coefficient (mN/m)	180–1300	$\sigma = 438.98 - 18.4 \times 10^{-3}(T+273) - 132.2 \times 10^{-6}(T+273)^2 + 37.44 \times 10^{-9}(T+273)$
	200	401.4
	600	342.6
	1200	240.2
Vapor pressure (Pa)	180–1300	$\log P = 12.4037 - 8283.1/T - 0.7081 \log T$
	200	1.4×10^{-6}
	600	14.8
	1200	42640
Vapor density (kg/m^3)	600	0.128×10^{-4}
	800	0.413×10^{-3}
	1000	0.444×10^{-2}
	1200	0.250×10^{-1}
Evaporation heat (J/kg)	180–1300	$L_e = 2.4525 \times 10^7 - 2967.14(T+273) - 0.1762(T+273)^2$
	600	21.76×10^6
	800	21.39×10^6
	1000	20.93×10^6
	1200	20.37×10^6

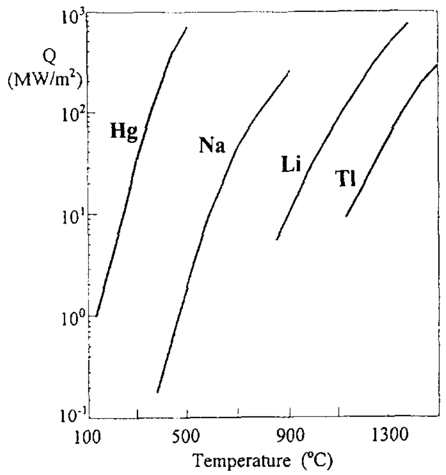

Fig. 1. Maximum thermal load released at open surface evaporation.

According to small-scale experiments, the capillary-pore system with liquid-lithium metal has the capability of absorbing the energy under plasma disruptions without failure. If specific energy of the order of 100 MJ/m^2 during several milliseconds is released on the surface of such a divertor, the evaporating lithium can effectively cool the capillary-pore system substrate (material W) and thus protect it. Experiments performed on a capillary-pore system without lithium showed the following: even under such conditions, the processes of erosion and redeposition taking place under plasma influence do not lead to the deterioration of capillary-pore system performance. The porosity in surface layers remains open and allows the divertor to continue working in stationary conditions.

3. Capillary-pore liquid lithium system

Table 2 presents physical and thermophysical lithium properties defining its use in a FR LMD. The combination of these characteristics is the best for low melting metals.

Fig. 1 shows maximum values of specific thermal flow discharged by evaporation from a free surface for some heat carriers. For lithium, such a maximum thermal flow can be 700 MW/m^2 for temperatures below boiling point. This encompasses the possible stationary thermal loads in

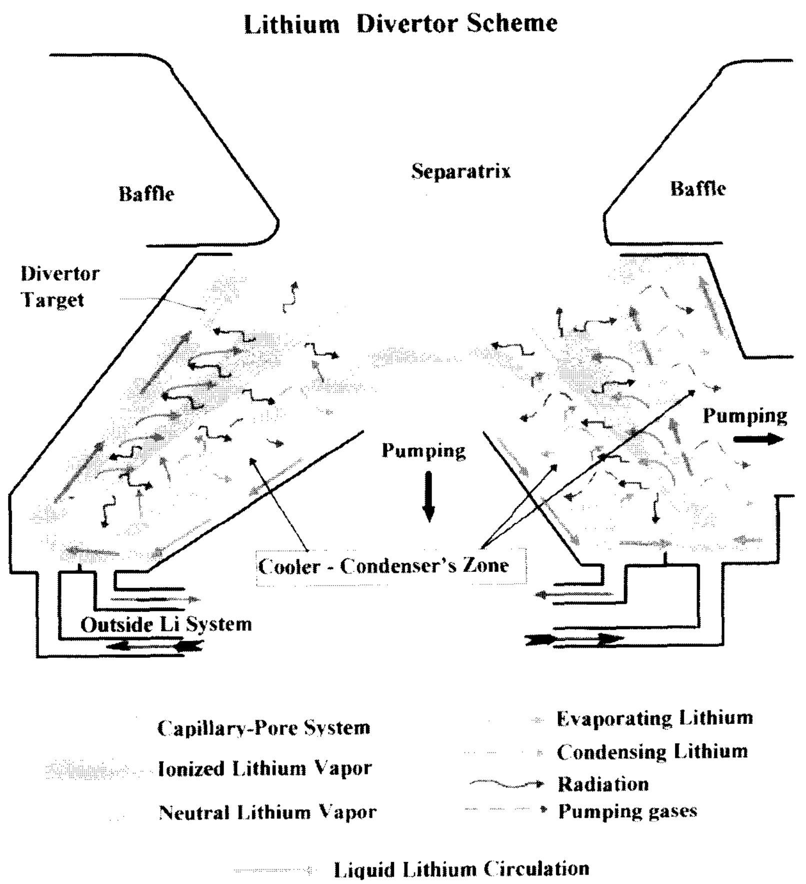

Fig. 2. The scheme of LMD energy transformation and lithium circulation.

the divertor (Table 1). The LMD capillary-pore system work efficiency is defined by its design, the lithium ability to "wet" the solid transfer media, and capillary-pore pressure value.

The fact that lithium density is minimal for metals increases the capillary-pore system efficiency. The candidate materials for the capillary-pore system – V alloys as a reference and W for its outer layers – are wetted by lithium and are compatible with it up to very high temperatures [11]. The use of these materials satisfies the low activation criterion necessary for the development of commercial FR.

4. Design and experimental models of LMD

Fig. 2 shows the principles of liquid-metal divertor operation, as well as energy transfer in it, and the lithium flow paths.

Fig. 3 shows a fabricable design model which provides the demonstration of the liquid-metal lithium divertor concept. Each sector of the divertor has two independent cooling systems.

The first system is formed by the capillary-pore structure, which covers the target plates of the divertor. Lithium evaporates from it and the generated vapour, having interacted with the plasma flow to the divertor chamber, passes into the condenser zone. At its surface, condensation and lithium cooling takes place. From there, capillary force returns the lithium to the evaporating panels.

The condenser surface area should be not less than 20 times larger than the lithium evaporation surface area to provide effective lithium vapour condensation and its direction of flow to the plasma zone. Capillary force provides circulation in this system. It has its own supply system which permits pressure variation in the system as well as compensation for lithium losses and provides constant removal of deuterium, tritium and other impurities, including those of corrosive–erosive natures.

The second system is made of cooling channels in the lithium condensing system and removes heat from the divertor. Liquid lithium cooling is used in the condenser. Thermal/hydraulic analysis of the divertor cooling systems has confirmed high efficiency performance for this particular design.

In order to experimentally confirm the concept of the LMD with the capillary-pore system, experimental models of target devices were manufactured and tested by loading with electronic beam irradiation of various configurations. These tests showed [12] that a simple prototype of LMD can absorb specific thermal loads of up to ~ 50 MW/m^2.

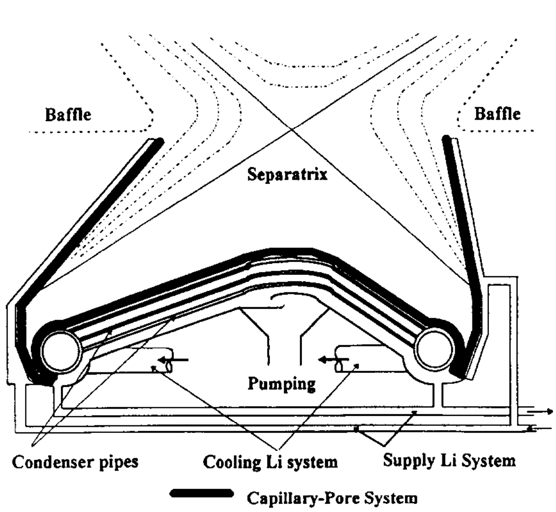

Fig. 3. LM lithium divertor with capillary-pore system design scheme.

5. Conclusions

The proposed concept of the liquid-metal divertor based on the evaporation-radiation principle of protecting the target elements and substrate provides for long-term operation of not less than one year with a short maintenance period.This performance is achieved by:

(1) New design of the target plates with a capillary-pore system which operates under plasma disruptions and steady-state conditions.
(2) Resolution of technological problems of assembly, welding and filling complex capillary-pore structures with lithium.
(3) Design with no plasma-facing "sacrificial" plates.
(4) Use of low-activation materials in the design: vanadium alloys and natural lithium which have the best properties for thermonuclear reactors.
(5) Use of electrical insulation coatings in liquid-metal ducts which reduces MHD effects.
(6) Keeping tritium concentration in the liquid-metal divertor systems at an acceptable level by controlling the lithium clean-up rate.

The use of liquid lithium in the divertor will allow separation of gases with their subsequent removal without additional energy resources and design complexity.

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