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THERMAL-HYDRAULIC AND STRUCTURAL DESIGN FOR THE LITHIUM-COOLED TITAN-I REVERSED-FIELD-PINCH REACTOR

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A thermal-hydraulic and structural design of the first wall and blanket for the 18 MW/m^2 neutron wall-loading TITAN reversed-field-pinch fusion reactor is presented. The primary coolant is liquid lithium and the structural material is the vanadium alloy, V–3Ti–1Si. Various design limits, which take the operational environment into consideration, for this vanadium alloy for the first wall and blanket are discussed. The first wall is made of small-diameter tubes. The blanket coolant channels are a combination of tubular, square, and rectangular channels. The first-wall and blanket coolant circuits are separate, allowing different coolant exit temperatures. The coolant channels are aligned with the larger poloidal magnetic field to reduce magnetohydrodynamic (MHD) pressure drops. At the design heat flux of 4.6 MW/m^2 on the first wall, MHD turbulent-flow heat transfer is used. Both the separation of the coolant circuits and the use of MHD turbulent-flow heat transfer substantially increase the heat flux limit on the first wall. These are favorable for high-power-density fusion reactors. The inlet temperature of lithium is 320 °C and the exit temperatures are 440 °C and 700 °C for the first wall and blanket, respectively. The pressure drop in the first wall circuit is 10 MPa and is less than 3 MPa for the blanket circuit. The pumping power is less than 5% of electric output. The maximum structure temperature is less than 750 °C and the material stresses are shown to be within the allowable limits. One-dimensional thermal and stress analyses are adequate for the thermal-hydraulic and structural design for TITAN-I. This is verified by two-dimensional, finite element analysis. The use of liquid lithium as the coolant and vanadium alloy as the structural material enables the removal of the reactor thermal energy at high temperature, which has resulted in a gross thermal efficiency of 44%.

1. Introduction

The TITAN study is a multi-institutional effort to investigate the potential of the Reversed-Field-Pinch (RFP) confinement concept as a high-power-density fusion reactor [1,2]. Two engineering designs of the fusion power core have emerged. TITAN-I is a self-cooled lithium design with vanadium alloy as the structural material [3]. This paper deals with TITAN-I. The other, TITAN-II, is an aqueous salt-solution, loop-in-pool design with ferritic steel as the structural material [4].

One of the important reasons for selecting liquid lithium as the coolant and vanadium alloy as the structural materials is to remove the thermal energy from the reactor at high temperature. This is possible because lithium has a high boiling point and vanadium alloys have high operating temperatures in the fusion environment [5]. Of all the liquid metals, liquid lithium has the best overall thermo-physical properties such as heat capacity, thermal conductivity, electrical conductivity, etc. In addition, lithium can serve as a breeder for tritium which is essential for a D–T fusion reactor. Lithium is also compatible with vanadium. Several earlier studies have proposed liquid lithium as the coolant for fusion applications [6–8].

TITAN-I fusion reactor operates at 18 MW/m^2 of neutron wall loading and 4.6 MW/m^2 of peak heat flux on the first wall at the design point. The design point corresponds to the radiation fraction of 0.95, which means that 95% of the alpha and ohmic dissipative power in the plasma is radiated directly on the first wall. For this high-power-density reactor, careful consideration must be given to the nature and spatial distribution of deposited thermal energy. A large amount of volumetric neutron thermal energy is deposited in the first few centimeters of the first-wall and blanket materials. Another component of thermal energy is in the form of a high surface heat flux incident only on the first wall. In RFPs, the poloidal magnetic field is dominant compared to the toroidal field. This characteristic feature of the RFP allows innovation and design solutions which are compatible with the nature and distribution of the thermal energy deposition.

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The first-wall and blanket coolant circuits have been separated, which gives the needed degree of flexibility to the design by allowing lower coolant-exit temperature and efficient, high-velocity turbulent-flow heat transfer in the first-wall coolant channels. A circular tube has optimum geometry for both efficient heat transfer and stress considerations and is suitable for the first-wall coolant channel where radiation heat flux is high and MHD pressure drop is considerable due to the high-velocity turbulent flow.

In this paper, the thermal-hydraulic and structural design of the first wall and blanket of TITAN-I is presented. The relevant properties of the vanadium alloy are briefly discussed in the next section. In Section 3, a description of the configurations of the first wall and blanket and the thermal-hydraulic design is provided. Two-dimensional finite element structural design is discussed in Section 4. Section 5 contains conclusions and a performance evaluation.

2. First-wall/blanket structural material

Vanadium alloys have a number of attractive features [5], particularly for the first-wall and blanket/shield design of the TITAN high-power-density fusion reactor. In addition to the low activation feature allowing near-surface radioactive waste disposal, the high melting temperature has a large impact on safety during accidents. The high ultimate tensile strength (~ 600 MPa at 600 °C), lower expansion coefficient, and high thermal conductivity of the vanadium alloys result in superior thermal stress resistance. Vanadium is compatible with lithium, thus making it possible to use lithium for cooling and tritium breeding.

Nuclear transmutation production of hydrogen and helium in the vanadium structure of the first wall and blanket is a design concern for several reasons. It has been experimentally observed that a hydrogen content above 5000 appm will cause a shift in the ductile-to-brittle transition temperature to above room temperature (as reported in ref. [5]). Helium, on the other hand, forms bubbles in the grain interior and on grain boundaries resulting in high-temperature helium embrittlement. The hydrogen problem may be avoided by operating the structure at high temperature (above 400 °C). Helium embrittlement can be mitigated by the appropriate choice of alloying elements and by limiting the maximum operational temperature. Among the various V-base alloys, the most promising candidates for fusion applications are V–15Cr–5Ti, VANSTAR-7 (V–9Cr–3Fe–1Zr), and V–3Ti–1Si. Based upon swelling and creep ductility, the V–3Ti–1Si alloy seems to be the most promising for our applications [9]. At the end of life, the maximum permissible primary stress is found to be 108 MPa at 650 °C and 44 MPA at 750 °C. The temperatures are taken to be average wall temperatures. The maximum allowable secondary stress is determined by not allowing the total equivalent stress to exceed the ultimate tensile stress at the operating temperature. For details of the method, see ref. [9].

3. Thermal-hydraulic design

Detail thermal-hydraulic design is provided in this section. The thermal and stress analyses are performed using one-dimensional approximations, except for the film temperature drop in the first-wall coolant tube because of the strong circumferential variation of the radiation heat flux incident on the first wall.

3.1. First-wall and blanket configurations

The first wall is made of small-diameter coolant tubes for several reasons (e.g., high heat transfer, high strength, and ease of manufacturing). The blanket consists of a combination of tubular, square, and rectangular channels. Fig. 1 shows the configuration of the first wall and blanket for TITAN-I. The coolant channels are set along the poloidal direction to reduce MHD pressure drops. The inner diameter of the first-wall tube is 8 mm and the wall thickness is 1.25 mm, which includes 0.25 mm for erosion allowance. The first-wall tubes, which are of constant diameter, slightly overlap at the in-board side to adjust for the shorter toroidal length. The diameter of the coolant tube is decided by a compromise between the heat transfer performance, which increases with the decrease in diameter, and total number of tubes, which increases with the decrease in diameter, thus increasing the probability of a tube failure during operation. The blanket is 75 cm thick and consists of two zones, a 30 cm thick integrated blanket coil (BC) [1] followed by a 45 cm thick hot shield. The IBC zone consists of 6 rows of tubular channels. The lithium in the tubular coolant channels of the IBC zone carriers the electric current for producing the toroidal magnetic field. The first 30 cm of the hot shield consists of square channels and the remaining 15 cm has thick-walled rectangular channels. The cross sections of the blanket and shield coolant channels change along the poloidal direction to adjust for the shorter toroidal length at the in-board side compared to that at the out-board side.

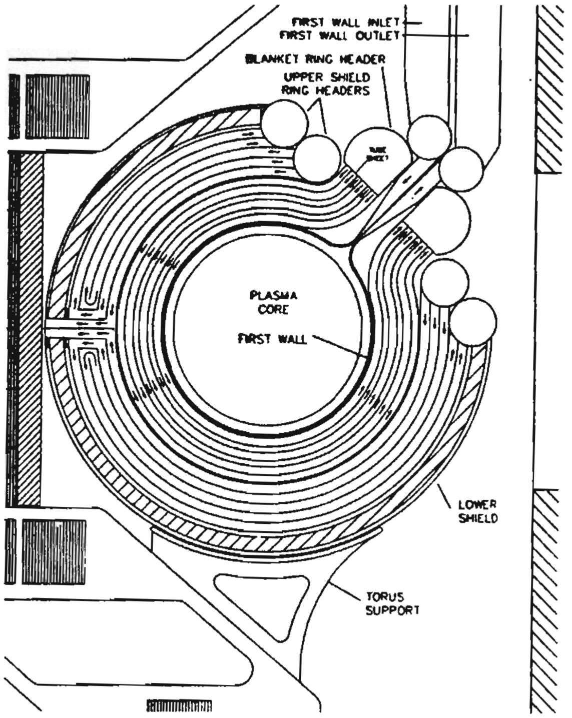

Fig. 1. Configuration of the first wall and blanket for TITAN-I. The figure shows a schematic of the cut across the torus in the vertical plane.

3.2. Design procedure

The thermal-hydraulic design is based on concepts reported by Hasan and Ghoniem [10]. The design calculations are performed by a thermal-hydraulic design code for the design of the first wall and blanket of a RFP reactor [11]. The objective of the design calculations is to obtain a design window for a given coolant inlet temperature and coolant channel geometry. A design window shows maximum allowable coolant-exit temperatures as a function of heat flux on the first wall. The limiting coolant-exit temperature is obtained by satisfying the design limits on maximum allowable structure temperature, pumping power for coolant circulation, and material stress. For a given heat flux on the first wall, the maximum allowable structure temperature determines the highest coolant-exit temperature possible. The limits on pumping power and pressure stress each sets one minimum possible coolant-exit temperature. Pumping power and pressure limits are reached by gradually decreasing the coolant-exit temperature, which increases the coolant velocity. Hence, the pressure drop, pumping power, and pressure stress also increase. As the heat flux on the first wall increases, permissible maximum and minimum coolant-exit temperatures approach one another and close the design window. Thermal-hydraulic design with any higher heat flux on the first wall is not possible without exceeding one or more of the three design limits. Separation of the coolant circuits allows lower exit temperature for the first wall and thus extends the design window.

The maximum structure temperature is obtained by adding the temperature drops across the tube wall (ΔT_w) and across the coolant boundary layer (ΔT_f) to the coolant-exit temperature. ΔT_w is calculated using one-dimensional heat conduction in the channel wall. ΔT_f is determined for laminar flow from a two-dimensional analytical solution with arbitrary circumferential heat flux on the first-wall tube [10]. For turbulent flow, ΔT_f is obtained from an empirical correlation for Nusselt number given by Kovner et al. [12]. The turbulent-flow velocity is determined from the relations, $\mathrm{Re}_t = 60\ H_{\parallel}$ to $\mathrm{Re}_t = 500\ H_{\perp}$ suggested in ref. [13]. Here Re_t is the transition Reynolds number, and $H_{\parallel}$ and $H_{\perp}$ are the parallel and transverse Hartmann numbers, respectively. The MHD pressure drops are calculated by using the available theoretical/empirical equations reported in refs. [6,10]. The pressure and thermal stresses are obtained from one-dimensional equations for a thick-walled cylinder [14,15]. For the determination of the design window, the blanket is treated as a lumped parameter. This is a reasonable approximation for the design-window calculation because the heat load on the blanket coolant channels is entirely due to nuclear heating and hence is much smaller than that on the first-wall coolant channels. After a design point is selected from the design window, detailed blanket design is carried out by treating each row of coolant channels individually.

3.3. Design results

A summary of TITAN-I parameters which are relevant to the thermal-hydraulic design are furnished in table 1. Fig. 2 shows the design window. The window is determined by the upper curve, which sets the upper limit of coolant exit temperature, and the middle curve, which sets its lower limit. Coolant exit temperature above the upper curve will cause the structure Temperature to exceed the limit of 750 ° C. And coolant temperature below the middle curve will cause the pumping power to exceed the the limit of 5%. It can be seen from this figure that design is possible up to about 5 MW/m^2 heat flux on the first wall. The heat flux on the first wall at the design point is 4.6 MW/m^2 for TITAN-I, which

Table 1
Major parameters of TITAN-I

Major radius, R	3.9 m
First wall radius, a	0.66 m
Neutron wall load	18 MW/m^2
Poloidal field at first wall	5.44 T
Toroidal field at first wall	−0.36 T
Total thermal power, P_{th}	2918 MW$_t$
Power to first wall circuit	736 MW$_t$
Power to divertor circuit	29 MW$_t$
Power to blanket circuit	2153 MW$_t$
Lithium inlet temperature	320° C

corresponds to a plasma radiation fraction of 0.95. The design window shows that 5% pumping power limit is more restricting than the imposed pressure stress limit of 80 MPa. At the design point, the coolant velocity in the first wall tube is 21 m/s and about 0.,5 m/s in the blanket channels. The corresponding exit temperatures are 440 ° C and 700 ° C, respectively. The pressure drops in the first wall and blanket channels are shown in fig. 3. The delivery pressure of the first wall/divertor pump is 12 MPa as the maximum divertor pressure drop is 12 MPa. The pressure drop in the first and sixth rows of the IBC coolant channels are 3 MPa and 0.5 MPa, respectively. Pressure drops in the hot-shield channels are negligible since they are situated beyond the IBC zone which carries the current for toroidal magnetic field. Orifices are used to reduce the delivery pressure of the pump to those required at the inlet of the coolant channels. The pressure and thermal stresses in the first-wall tubes are below the design limits.

As a verification and final tune-up of the one-dimensional structural design presented in this section, two-dimensional, axisymmetric finite element structural design is presented in the next section.

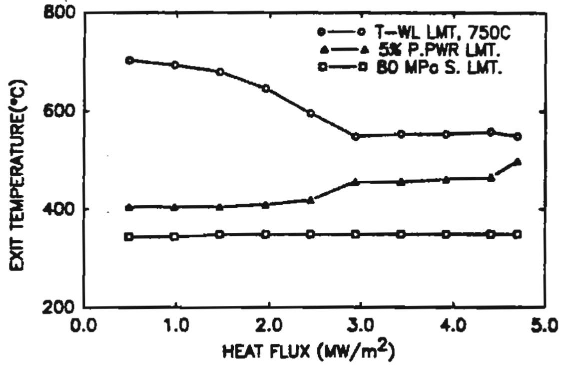

Fig. 2. Design window for the thermal-hydraulic design. The window lies between the upper curve for wall temperature limit (750 ° C) and the middle curve for pumping power limit (5%).

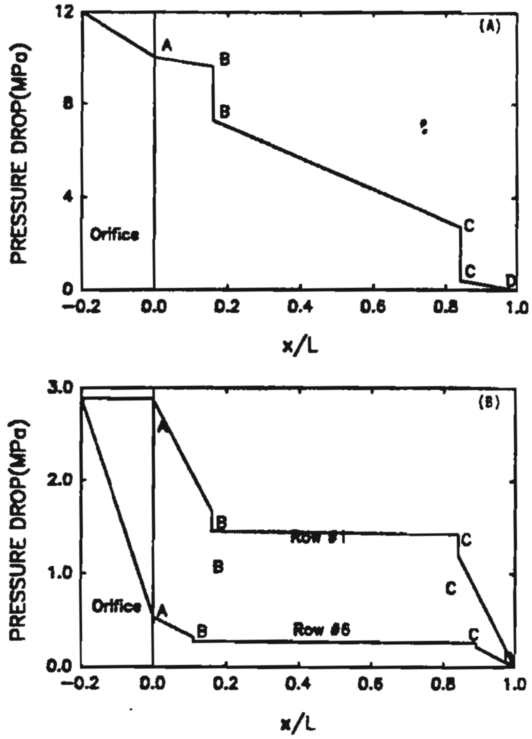

Fig. 3. Pressure drop in coolant circuits: (A) first wall; (B) blanket. (AB and Cd are the inlet and outlet ducts. There are 90 ° bends at B and C. BC is the length of the channel.)

4. Structural design

In this section, results of two-dimensional thermal and stress analyses performed using the finite element code ANSYS [16] are presented for the final design. A detailed comparison [1] of these plane stress, plane strain, and axisymmetric stress analyses indicates that axisymmetric models are the most accurate for computing thermal stresses in toroidal tubes such as those in TITAN-I. Hence, the following results are based on an axisymmetric finite element model of the first-wall tubes.

The pressure stresses are quite small, with a peak of 39 MPa. The thermal analysis, which was also performed with ANSYS, indicates a peak temperature of 741 ° C occurring at the surface nearest the plasma. The temperature at the rear of the tube remains near the coolant bulk temperature. The thermal gradient caused by the incident heat flux causes relatively large thermal

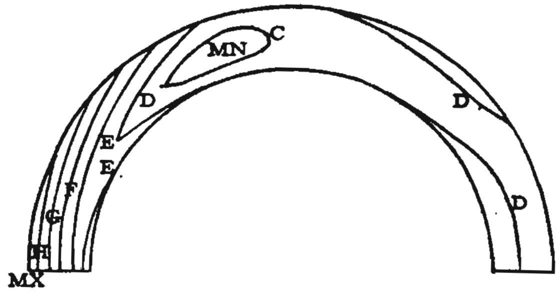

Fig. 4. Contours of total equivalent stress (pressure plus thermal) (MPa) in the FW coolant channel. (MX = 279, MN = 11.8, C = 40, D = 80, E = 120, F = 160, G = 200, and H = 240).

stresses, as seen in fig. 4 which shows the equivalent thermal stress contours for the first wall. The peak thermal stress is 279 MPa. Given the allowable primary stress of 108 MPa at an average first-wall temperature of 650 ° C, which indicates an allowable pressure plus thermal stress of 324 MPa, the analysis indicates that the present first-wall design conforms to the ASME Boiler and Pressure Code and the design is viable.

Tubular blanket channels are chosen to avoid stress concentrations introduced by the existence of corners in a square cross section and to avoid welds near the first wall. The blanket tubes are subjected to volumetric heating and internal coolant pressure. Because the coolant pressure in the blanket is fairly low (1 to 3 MPa) compared to the strength of the vanadium, the tube thickness is much less than its radius, so a simple one-dimensional analysis is sufficient. The tubes are designed to have a fixed coolant-exit temperature of 700 ° C for high thermal conversion efficiency and a fixed structure fraction for high energy multiplication. The structure fraction is controlled by adjusting the radius-to-thickness ratio of the tubes and by adjusting the spacing between adjoining tubes. The one-dimensional analysis of the tubes indicates that a thickness of 2.5 mm and a radius of 2.5 cm satisfies these design requirements and the ASME Code.

The structure volume fractions are 30% and 90% in the first and last zones of the shield, respectively. The size of the square channel is 6 cm side length and 0.5 cm wall thickness. The outer size of the rectangular channels is 11.25 cm by 3.75 cm. The wall thickness is 1.625 cm. The dimensions of these coolant channels are determined mainly on the basis of the limit on wall temperature and required structure volume fractions. Thermal and pressure stresses are very small because the temperature gradient across the wall is small and the pressure drop in these channels is negligible.

5. Conclusions and performance evaluation

The thermal-hydraulic and structural design of the fusion power core of the 18 MW/m^2 neutron wall-loading TITAN-RFP reactor using liquid lithium as the primary coolant and V–3Ti–1Si as structural material results in an attractive and economic design. The high coolant-exit temperatures give a gross thermal efficiency of 44%, which is substantially higher than that obtainable with water as the primary coolant [17]. The MHD pressure drops and pumping power are moderate. The maximum structure temperature and material stresses are below the design limits. The one-dimensional calculations for temperature and material stresses are adequate for scoping design purposes, as substantiated by the two-dimensional finite element calculations.

The distinguishing features of the present design are summarized as follows:

(1) Liquid lithium is the primary coolant and V–3Ti–1Si is the structural material.
(2) Small round tubes are used as first-wall coolant channels.
(3) In order to efficiently remove the heat flux incident on the first wall, MHD turbulent-flow heat transfer is used.
(4) Alignment of the coolant channels with the stronger poloidal magnetic field reduces the MHD pressure drops.
(5) Separation of the first wall and blanket coolant circuits, each with its own coolant circulation pump and coolant exit temperature, broadens the design window and achieves maximum thermal cycle efficiency.

For high-temperature applications, the vanadium structure and lithium coolant combination has several advantages, especially for compact RFP reactors where the magnetic field topology is favorable.

Acknowledgement

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