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ORIGINAL RESEARCH

Innovative Fusion Tokamak Powerplant and the Basic Engineering for Mhd Theory

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Abstract All around the world an endeavour to develop the fusion process as a major alternative energy has been going on for about a half century. Aries-St is the spherical tokamak (St) a innovative fusion reactor engineering. This toroidal reactor is a type of system that facilitates the occurrence of the nuclear fusion and fission events together (Tillack et al. in Fusion Energ Des 65:215–261, 2003; El-Guebaly in Fusion Energ Des 65:263–284, 2003). The Aries-St power core consist of the components directly surrounding the burning plasma and serves important functions. In fusion applications, liquid metals are traditionally considered to be the best working fluids. Sufficient tritium breed amount must be TBR >1.1 for Aries-St fusion tokamak power plant (Tillack et al. in Fusion Energ Des 65:215–261, 2003; El-Guebaly in Fusion Energ Des 65:263–284, 2003). The Aries-St power core has designed for correlation with an optimized St plasma that develop through the investigation of extensive range of plasma magnetohydrodynamic (Mhd) equations. In this study, the engineering design plasma parameters are described with respect to Mhd equilibrium and nuclear analysis, stability, radiation heat transfer conditions, current drive, and safety. In addition, turbulence model extended to an incompressible Mhd flows and monte carlo simulation are used for modeling of low-conductivity fluid. In this study the modeling of aries-st tokamak reactor produced by using aries design technology, has performed by using the monte carlo code and Endf/b-V-VI nuclear data. Monte carlo method is the general name for the solution of experimental and statistical problems with a random approach.

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Abbreviation

TF	Toroidal field
MCS	Montecarlo simulation
MCNP	Montecarlo n-particle
A	Major radius of toroid
a	Minor radius of toroid
$\beta = A/a$	Aspect ratio of plasma
TBR	t_6 t_7, Tritum breeding ratio
Mhd	Magneto hydrodynamic
$\int$ B.ds	Amper' laws
$R_{e:}Ha^2/N$	Reynolds number
H_a	Hartmann numbers
V(u,v,w)	Vectoral velocity
$J(j_x,j_y,j_z)$	Current density
$V_\dagger$	The perpendicular component of electron velocity
SOL	Scrape-off-layer
ST	Spherical torus
APEX	Advanced power extraction fusion reactor

Introduction

Aries-St is a fusion power reactor design study which has examined the ability of an advanced tokamak-based reactor to compete with future energy sources and play very important role in the future energy market. A tokamak is a device using a magnetic field to confine a plasma in the shape of a torus. This reactor has many attractive features, contain high beta and power density, low aspect ratio, low magnetic field high neutron walls and high self-driven current. The main concept of the Aries-St toroidal reactor systems has been used flowing liquids as the inner surface of the vacuum chamber that directly faces the plasma. Aries-St is 1,000 MW power plant with an aspect ratio of 1.6, a major radius of 3.2 m, a plasma elongation of 3.4 and triangularity of 0.64. Chamber technology refers to the pieces in reactor toroidal systems that directly plasma. A toroidal chamber where a plasma is magnetically trapped. It is used in nuclear fusion research. The systems made of advance complex design of magnetic fields that restrict the plasma of reactive charged particles in a hallow. The most extensively investigated toroidal confinement concept is the tokamak [1–3]. Magnetic constrict of plasmas is the most developed come up to controlled fusion. The most of the problem of fusion has been success of magnetic field system that actively confines the plasma. A successful systems has three states; the plasma have to be a time-independent equilibrium, the equilibrium must be macroscopically stable, the fugitive of plasma energy to the boundary wall must have minor. We could calculate the magnetic field inside a toroid which is a good example of power of Maxwell's law and government equations.

The current enclosed by the dashed line is just the number of loop times the current in each loop. We can show from Amper's law for toroid systems $\int \mathrm{B.ds} = \mu_0 \mathrm{iN}$ or $\mathrm{B}.2\pi\mathrm{R} = \mu_0\mathrm{iN} \rightarrow \mathrm{B}_{\mathrm{toroidal}} = \mu_0\mathrm{iN}/2\pi\mathrm{R}$ where, R is the distance from the center of tube to the center of the torus. The interference of currents with the magnetic field caused Lorents forces that have to be considered in the momentum balance [8, 10, 11, 20]

$$\frac{1}{2}\left[\frac{\partial v}{\partial t} + (v\nabla)v\right] = -\nabla p + \frac{1}{Ha^2}\nabla^2 v + \mathrm{j}\times\mathrm{B}.$$

Innovative Spherical Tokamak Reactors

There are several trials of St reactors with use of a solid cooper center rod for Tf (toroidal fields) coils, and tight aspect tokamak with super-conducting tf coils. The parameters of Stpp (st power plant), Aries-st and Vector (very compact tokamak reactor) and slimcs are given Table 1. Tf coils of stpp and Aries-st use a solid copper center rod, so that b_t is small and requirements of β_n~8 and $H_{98y2\sim1.6\ \mathrm{or}\ 1.8}$ are demanding. Vector is a tokamak reactor with super-conducting Tf coils Bi_2Sr_2 Ca_1 Cu_2 O_x(Bi2212)/Ag/AgMgSb (20 K) and low aspect ratio a~2 by removing the center solenoid (Cs) coil system from standard tokamak (A~3). The Fig. 1 shows a cross-section of Aries-st fusion power core replacement unit. This spherical tokamak reactor has he-cooled ferritic steel structure with flowing PbLi breeder and tungsten plasma-mutually composition [15, 17, 18].

The more realistic demo reactor SlimCS is proposed. The parameters are $\mathrm{A} = 2.6, \mathrm{B_{max}} = 16.4\mathrm{T}(\mathrm{Nb_3Al})$, $\beta_\mathrm{N} = 4.3$ and $\mathrm{H}_{98\mathrm{y}2} = 1.3$. Potential theoretical advantages of spherical tokamak (ST) have been outlined by Peng and Stricker, in which aspect ratio A/a of the standard tokamak is substantially reduced toward unity. Predicted advantages include a natural high elongation (k > 2), high toroidal beta and tokamak-like confinement. These predictions have been confirmed experimentally, in particular by START (small tight aspect ratio tokamak) at Culham (A/a = 13.1), $I_p \approx 0{,}25$ MA, $B_t \approx 0{,}15$T. The toroidal beta reached 40 % β = 3.5~5.9. The record plasma beta recently achieved on the START experiment has advanced the concepts of spherical tokamak (ST) as a potential power plant and volumetric neutron source. At the beginning of 1999, the Aries group has completed the design of Aries-St, a commercial fusion power plant based on this concept [5, 14, 15].

Table 1 Parameters of Aries-St, sttp, Vector2, Slimcs [15]

Parameters	Aries-st	Sttp	Vector2	Slimcs
A/a (m)	3.20/ 2.00	3.42/ 2.44	3.75/ 1.90	5.50/ 2.10
A	1.6	1.4	2.0	2.6
ǩ/ɗ	3.42/ 0.64	3.20/ 0.55	3.75/ 0.10	2.00/ 0.40
I_p (ma)	30.8	31.0	18.3	16.7
Bt/B_{max} (T)	2.14/7.6	1.77/–	4.70/ 19.6	6.00/ 16.4
$\beta t(\%)/\beta_n$	54/8.0	59/8.2	7.74/ 3.75	5.70/4.3
T_e (kev)	–	22	–	17.0
p_{fusion} (gw)	2.86	3.10	1.80	3.0
$H_{98y2}/h_{iter93h}$	–/1.83	1.6/–	1.8/–	1.3/–
cd_{power} (MW)	31	50	40	59
Nml (MW/m^2)	4.10	3.50	3.50	3.20
Tf coil ohmic loss (MW)	288	–	0	0

Design of Aries-St Fusion Blanket Structure

There have been a number of major fusion reactor design studies especially during the last 30 years. In Aries-St fusion, the coolant of LiPb is considered to be used as not only energy carrier but also tritium breeder [4.8,13,16]. In recently, montecarlo method are used to obtain analytical solution of the governing differential equations. This analysis determined the definition of the Aries-St design point. The Aries-St investigated as a national U.S. effort to survey the potential of the spherical tokamak concept as a fusion power plant and as a vehicle for fusion development. The 1000 MW Aries-St power plant has an aspect ratio of 1.6, a major radius of 3.2 m, a plasma elongation (at 95 % flux surface) of 3.4 and triangularity of 0.64. This configuration

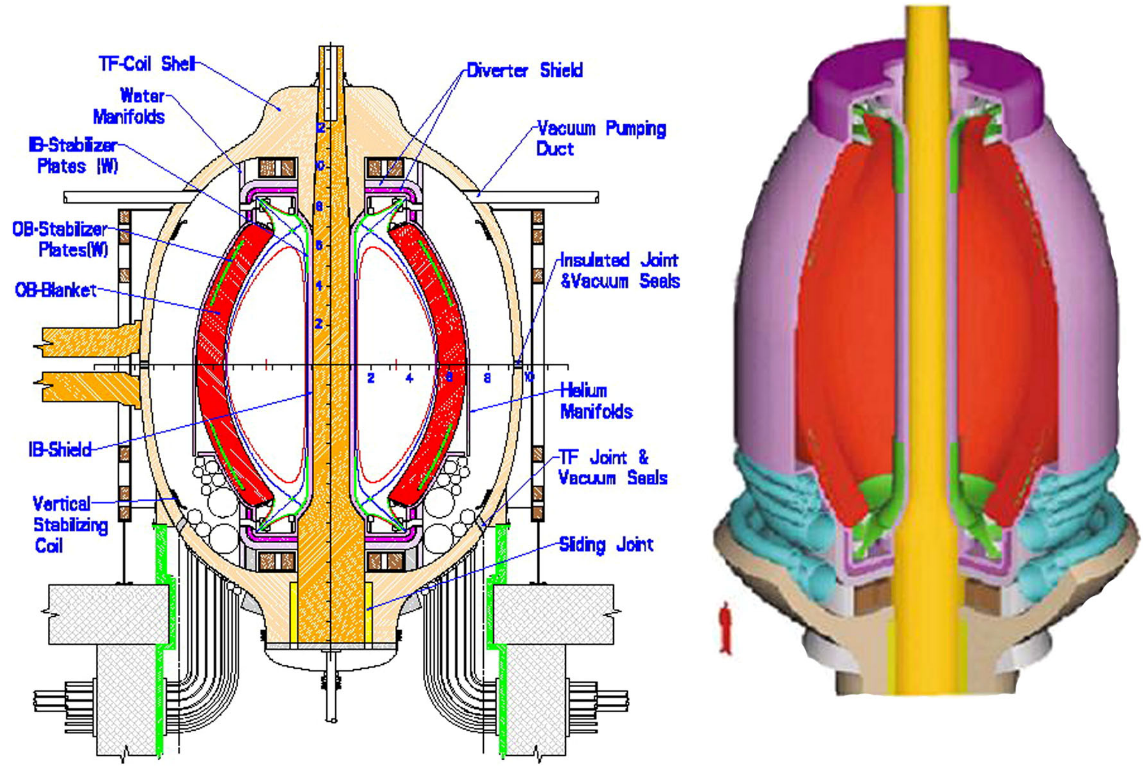

Fig. 1 Cross-section of Aries-St fusion power core replacement unit [1–3, 9]

attains of 54 % (which is 90 % of the maximum theoretical Transfer of coolants is very important in toroidal hybrid reactor system, because it effect the neutronic performance of the reactors remarkably. The candidates are given the liquid metals, lithium, $Li1_7Pb_{83}$ and Li-Sn and the molten salts (Li2BeF4) and LiNaBeF4. The important properties for these candidate tritium breeders are given in Table 2. The influence of the magnetic field on liquid wall flow characteristics and heat transfer is crucial for both. In the inner blanket of the Aries-ST structure consist of the zones and zone thickness, which is HTS(high temperature shield) and FW(first wall) regions. They has a ferritic steel structure cooled by helium gas [4.8,13,16]. There is no breeding zone for tritium breeding in the inner blanket must be supplied from the outer blanket where 4 different zones exist(FW, MSZ, HM, LTS). Self sufficient tritium breeding ratio (TBR>1,1) has been taken into account to determine the upper limit of the fraction of heavy metal salt in the mixture. Tritium breeding ratio, TBR, is defined as the ratio of the rate of tritium production in the system to the rate of tritium burned in plasma. In order to provide adequate tritium breeding, the flowing liquid must be a lithium containing medium. The tritium production reactions are as follows; [4, 10, 13, 14, 22].

$$^{6}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + Q(4,784\ MeV)$$

$$^{7}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + {}^{1}n + Q(-2,467\ MeV).$$

Mhd Theory Modeling for Aries-St Tokamak Systems

The Mhd model is the extension of fluid dynamics to electrically conducting fluids such as plasmas, with the inclusion of the effects of electromagnetic forces. The mhd equations consist of macroscopic transport equations and magnetic induction equation. Plasmas can be explain as magnetohydrodynamic two fluids of ion and electron with densities ϱ_i, $\varrho_{e,}$ charge density $\varrho_{,current}$ density j, flow velocities υ_i, υ_e, and pressures P_i,P_e In this study, turbulence model extended to an incompressible Mhd flows and monte carlo simulation(mcs) and homotopy analysis are used for modeling of low-conductivity fluids. Turbulent models based on Navier–stokes-Maxwell equations are applied to be calculated simultaneously with other flow quantities

Table 2 Properties of working liquid parameters [10–12]

Properties	Li	$Li_{17}Pb_{83}$	Li_2BeF_4	$Li_{20}Sn80$	flinabe
Melting point(°c)	180	235	459	330	300
Density (g/cm^3)	0.48	8.98	2.00	6.20	2.00
Li density (g/cm^3)	0.48	0.062	0.28	0.09	0.12
Tritium solubility	High	Very low	Very low	–	–

thick and thin liquid wall concepts. As two sorts of liquids are the candidates for the working fluid, the molten salt (flibe) and liquids metals (Li, Sn-Li),two separate treatments are needed.

The MHD model treats the plasma as a single, quasi-neutral, magnetized fluid and it solves the following set of MHD equations in non-conservative form. The movement of the electrically conducting fluid through the plasma-confining strong magnetic field induces an electric field and drives electric currents inside the liquid metal. The current density is determined by Ohm's law as [15].

$$j = \nabla\emptyset + v \times B.$$

The interaction of currents with the magnetic field give rise to electromagnetic Lorents forces that have to be considered in the momentum balance. The Fig. 2 shows that the hartmann number and interaction paremeter are large in fusion blankets where magnetic field are very strong. The liquid has velocity Um in the X direction, the direction of the pipe axis. The magnetic field of Bz in strength is imposed in the Z direction perpendicular to the pipe axis. The wall has electrical conductivity while the liquid is σ. In these equations the vectors v, Bz, and j stand for velocity, magnetic flux density and current density, scaled by the reference values ϑ, Bz, and σvBz, respectively.

The pressure scaled by σvLB^2 is denoted as p and the electric potential normalized with □ LBz is written as $\emptyset$. A typical length scale of the problem is L, the half distance better and between Hartmann walls and ρ, σ and □ stand for density, electric conductivity and kinematic viscosity of the fluid. The flow is governed by the interaction parameter and the hartman number,

$$N = \frac{\sigma LB^2}{\rho v}, \mathrm{Ha} = \mathrm{LB}\sqrt{[1]}\frac{\sigma}{\rho v}.$$

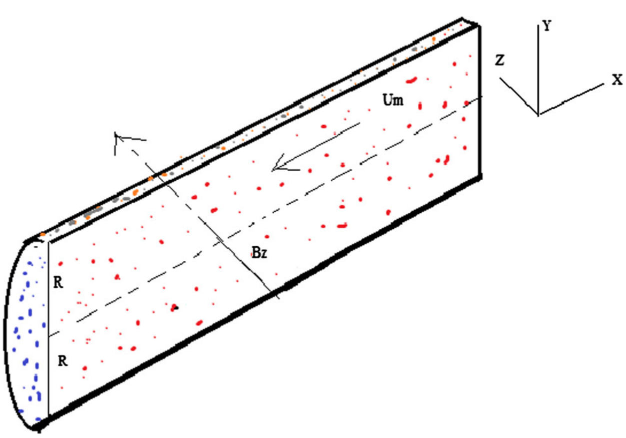

Fig. 2 The liquid flow a boundary coordinate system in B_z magnetic field

The interplay features gives the ratio of electromagnetic forces to inertia forces, while the square of the Hartmann number stands for the ratio of lorentz forces to viscous forces [8, 20]. The hydrodynamic Reynolds number is given in terms of these groups as $\mathrm{Re} = \mathrm{Ha}^2/\mathrm{N}$.. For many MHD flows at high Hartmann numbers currents j in Ohm's law are small in comparison with $\nabla\emptyset$ or $\mathrm{v} \times \mathrm{B}$. In fully developed flows the magnitude of j is usually of the order of c, where $c = t_G\sigma_G/L\sigma$ stands for the wall conductance ratio. With thickness t_G and conductivity σ_G we find typical values of $c = 0.014 \ll 1$ for the present experiment. For such conditions it is possible to solve (1) for velocity and we find for a magnetic field $B = Z^{\sim}$ the components $u = -(\partial\emptyset)/\partial y \quad v = -(\partial\emptyset)/\partial x$ [8, 10, 15, 20]. The mean velocity between two potential sensor at positions y_1 and y_2 is then obtained as $u^{\sim} = -\frac{\emptyset 2-\emptyset 1}{y2-y1}$, moreover, since for $\mathrm{Ha} \gg 1$ the electric potential is constant along magnetic field lines. There are many modeling approaches used to study fusion system plasma interactions. The three most common are magneto hydrodynamic (mhd), test-particle/monte carlo and hybrid simulations [8, 10, 15, 20]. Each approach can be used to study ion motions but only the test particle/monte-carlo method can be applied to electron motion. Neoclassical diffusion of electrons in tokamak is given by $B = B_0(1- {}_t\cos\emptyset)$,where $E_t = a/A$. Consequently, when the perpendicular component $V_\dagger$ of an electron velocity is much larger the parallel component $V_{H,}$ that is $V_\dagger/V_{H,} = (a/A)^{-1/2}$ the electron is trapped outside of the torus. At Table 3 structural properties of aries-st is given at high temperature where the magnetic field is weak.

It has predicted theoretically that radial diffusion induces a current in the toroidal direction and the current can be large in the banana region. This is an important process which can provide the means to sustain the plasma current in tokamak in steady state. The current density due to the drift velocity V_{untrap}. The plasma performance is governed by the simple relation, where A is the aspect ratio, I_{bs} is the bootstrap current fraction, K_b ~ 0.6 is a profile dependent

Table 3 General paremeters of Aries-St at high temperature [1–3]

Structural modification	Area (m^2)	Nuclear heating (MW)	Surface heating (MW)	Total power (MW)
Outboard first wall	421	100	195	295
Inboard first wall	67	18	52	70
Inboard shells	54	71	73	144
Inboard shield	–	199	0	199
Diverter	128	201 (hts)	250	451
Outboard ferritic steel	–	~340	–	330
Outboard pbli	–	~1,600	–	1,614
Total	–	~2,533	570	3,103

constant, $\check{k}$ is the plasma elongation and $\beta_N = \beta.\,(I_{P/Ab})^{-1}$ is the normalized β [5, 8, 15, 21]. Superconductors are used in confining the plasma in a magnetic field using toroidal systems. Superconducting materials are prone to technological applications and are materials in progress to date [17, 18, 21].

$$I_{bs=}\,A^{-1/2}K_{bs}.(1+\check{k}^2)/2.(\,\beta_{N.}2^{-1/2})^2.\ \beta^{-1}$$

Numerical Calculation

In this study, cross-sectional view of aries-st designed by using mcnp-4b -computer code A monte carlo method can be loosely described as a statistical method used in simulation of data. Monte Carlo, is a numerical method that is used for solving mathematical problems by the simulation of random variables. The statistical simulations are conducted by the monte carlo method using the randomly generated numbers [6, 7, 10, 14].

A simulation is defined to be a method that utilizes sequences of random numbers as data. Mathematical analysis of mc method (a simple integral) consider the simple integral, It is possible to calculate the multiple integrals on phase transitions by monte carlo method. The simplest and the most basic system for reliability analyses is the serial system. At the serial system, the reliability of the serial system is equal to the product of the reliability values of the elements; as seen on Fig. 3 and [6, 7, 10, 14]. When the integral of an f(x) function, it becomes by randomly tossing darts at a graph of the function and tallying the ratio of hits inside and outside the function [8, 10, 11].

$$I = \int_R f(x)dx = \Delta x^d \sum_{i_1=1}^{N} \sum_{i_2=1}^{N} \ldots \sum_{i_3=1}^{N} f\left(x_{i_1}^1 \ldots x_{i_d}^d\right)$$

The primary source of nuclear data used by Mcnp4b-code is evaluations from the evaluated nuclear data file (Endf) system. Endf/B–V and Endf/B–VI are the evaluated nuclear data files. In the calculations, the plasma liquid has been modeled as the neutron source which the inside surface of the first wall has been subject to homogenously. The inner region is consisting of plasma and vacuum. Following this, first liquid wall, blanket, ferritic steel, shield, stainless steel and ferritic steel zone take place. In the present study, the Aries-St fusion reactor used in this study has been designed in 3 d torus shape by using the mc

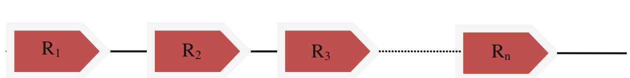

Fig. 3 Monte carlo serial system model for simulation

computer software that uses the monte carlo technique, using the Aries-St reactor model which has been realized in the scope of fusion studies. Following modeling, plasma has designed as neutron source that the inner surface of first liquid wall exposed to neutrons homogeneously and the calculations have conducted with the fusion neutron spectrum shown in Fig. 4 [8, 10, 11]. In Fig. 5 shows that radiation heat flux profile of core radiation, SOL impunity and SOL hydrogen in the external driven systems. Radiation heat slowly decreases to inner of torus and after owing to lithium density a slightly increase in this area and then radiation heat is increasing. In Fig. 6, the thermal fluid heat flux limit is very easily made out in the light of the temperature window of operation. Utilising biased to make rough on the plasma-facing first wall(FW),the functioning window is attained [1, 2]. The choices of ST design parameters and blanket materials can reduce general Tbr to average level of 1.1 or less. A generic breeding-related issue encountered in all power plant design is whether the integral blanket system will over-breed or under-breed after plant operation. In the Aries-St must be tritium breeding (overall Tbr>1) [3, 8, 11, 16]. The inboard leg of TF coils(Bi-2212),the centerpost, is the most critical system in ST [8, 9]. Mechanical design of the centerpost is also a challenge even though the on-axis field is low(~2T in Aries-St). The forces on the TF coils are comparable to superconducting tokamaks because of the high field on the centerpost (~7, 6T in Aries-St) caused by 1/R dependence

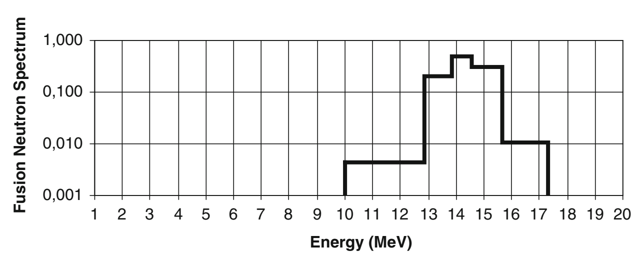

Fig. 4 Neutron spectrum used in the calculations for Aries-St tokmak systems

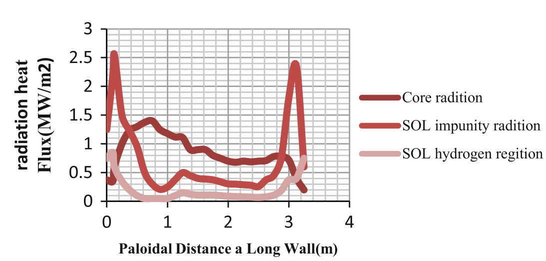

Fig. 5 Radiation heat spectrum at different location of the tokamak zones

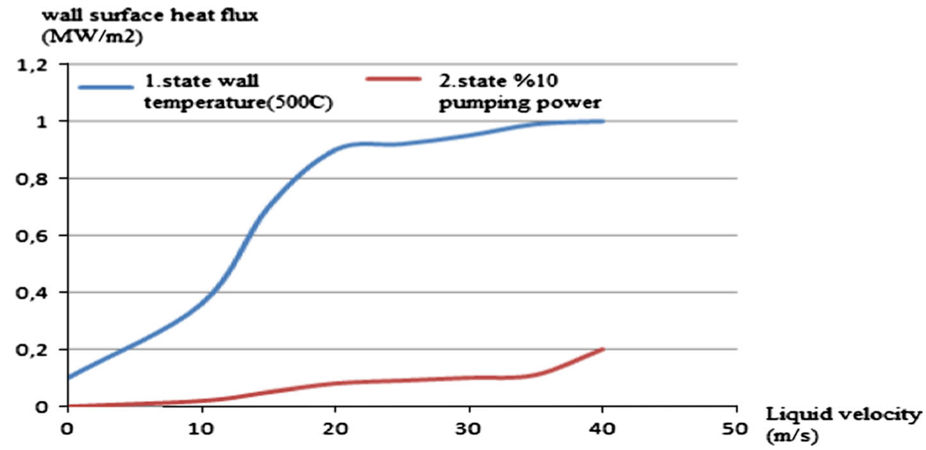

Fig. 6 The thermal flow heat flux boundary condition in the FW

of the toroidal field and large plasma current. Superconducting center post are much bigger than normal conducting ones because of large space needed for shielding. In the integrated blanket coil concept, liquid lithium serves as a breeding material, a conductor, and a coolant with the joule losses directly in the coolant and partially recovered by the power conversion system. For the centerpost conductor, copper is the best because of its very high conductivity.

In particular copper alloys (CuCrZr) or (GlidCop) as such provide sufficient strength to handle mechanical loads [9, 17–19]. Fusion neutrons spectrum from D-T plasma have several characteristics that result in attractive performance for such application. The high neutron energy enhances the neutron multiplication through (n, 2n) (n, 3n), and the fast fission reactions, which increases the disposal rate of the rate of long-lived fission products [22, 23].

Conclusion and Comments

Controlled nuclear fusion can be a very important energy choice for humankind in the future owing to both being environmentally friendly and having unlimited fuel reserves. It needs a long time period to be commercialized. General the Aries-St study has shown that the St concepts lead to attractive fusion power plants. In the advanced ARIES-ST reactor project, safety and environmental concerns considered up front, as designs evolve, so that the goal of safety and environmental attractiveness is realized [4, 10, 13, 14]. Current concepts for fusion energy systems will have clear environmental and safety advantages. In fusion and hybrid reactors, it is necessary to provide the Tbr >1, 1 terms in order to maintain the continuity of the operation of the reactors.

Then the only practical liquids for first wall and blanket are lithium, lead–lithium, Flibe, and Sn–Li. Flowing liquid metals may require the use of electrical insulators to overcome the MHD drag, while for Flibe free surface flows, MHD (Magneto hydrodynamics) effects caused by the interaction with the mean flow are less significant. Monte carlo method of turbulent free-surface flow of various pr fluids has been carried out with a constant heat flux from the free-surface and an adiabatic condition imposed on the wall [12, 13, 22]. The collision number per neutrons and fertile fuel added to the blanket, total fusion and fissile material increases while tritium production rate decreases. Because of the fertile fuel nucleuses increasing in the blanket, the probability of the interaction of the neutrons that are radiated at the plasma with the lithium isotopes and the Tbr ratio related to this, decreases. However, all this argument is valid due the condition that the lithium ratio at the blanket is stable. Design and calculations of Aries-ST have carried out as 3-D torus by using Mcnp-4b computer code [6, 7, 14]. Turbulent statistics have been obtained and the flow structure has been investigated via computational flow visualization technique. In this study, free surface of the open channel flow as shown in Fig. 2 is received the uniform heat flux from the plasma and the bottom wall of the channel is assumed to be adiabatic. The aries-st plasma equilibrium yields a pressure-driven current of about 99 % requiring <1 % on axis current drive [8, 9]. Compatibility between materials at high temperature raises several concerns both inside the blanket and in the heat transport loop. The primary concern results from the use of PbLi, for which very limited data are available [8, 9, 12].

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