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FIRST-WALL FUSION-BLANKET HEAT TRANSFER **

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ABSTRACT

To accommodate the high heat flux and neutron and gamma heat generation in the first wall of a fusion reactor, an array of tubes or tube-bank forms a first wall shield of the blanket. A series solution to the two-dimensional (in r, θ coordinates), time-dependent heat conduction equation has been found in terms of Fourier-Bessel (modified Bessel) functions. Steady-state solutions are found as limiting solutions. The heat sources are pulsed on and off to simulate the plasma burn and cool down periods. In addition to the Biot numbers, the time-dependent solution is given in terms of the Fourier, Pomerantsev, and Kirpichev numbers and numerically evaluated for a wide range of plasma and first wall conditions. Comparison of the thermal responses of the first wall between aluminum, a high thermal conductivity material and stainless steel, a low thermal conductivity material, is made.

NOMENCLATURE

- A = ratio of inside to outside radii, R_i/R_o ,
 Bi = Biot number = hR_i/k ,
 c = specific heat, J/kgK,
 h = heat transfer coefficient, W/m² K,
 Ki = Kirpichev modulus = $qR_o/k(T_o - T_g)$,
 L = operator, $k \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} \right)$,
 L_r = operator, $(-\partial/\partial t + L/\rho c)$,
 Po = Pomerantsev modulus = $QR_o^2/k(T_o - T_g)$,
 q = surface heat flux, W/m²,
 Q = average volumetric heating, W/m³,
 r = radial coordinate, m,
 R_i = inside tube radius, m,
 R_o = outside tube radius, m,
 t = time, sec,
 T = temperature, K,
 κ = thermal diffusivity, m²/s, and
 ρ = density, kg/m³.

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Subscripts

- B = bulk coolant, and
 o = initial time.

1. INTRODUCTION

In the design of fusion reactor blankets, the first wall, i.e., the first material surface to interface the plasma, is a critical region since all of the emissions from a reacting plasma may intersect this wall. These include ions and neutral particles, primary neutrons, x-rays (Bremsstrahlung) and cyclotron radiation. In addition, scattered neutrons and gamma radiation generated in the blanket regions exterior to the first wall are also imposed on it. Finally, deuterium-tritium gas surrounding the plasma may react chemically with the first wall materials. One result of these many interactions is the generation of appreciable heat which can be up to 20% of the plasma output. In most analyses, these effects are lumped into a radiant flux incident on the first wall, i.e., an applied surface heat flux boundary condition. A number of ideas have been set forth to accommodate the high heat fluxes and neutron/gamma heat generation in first walls. A feature common to several of the designs is an array of tubes or tube-bank forming the first wall.

To gain some appreciation of the heat transfer problems of the first wall, it is convenient to first categorize the operating regimes of a fusion reactor under normal and off-normal conditions. Under normal operation, we consider reactor startup which is associated with initial plasma fueling. This is a transient condition. Assuming that the plasma burn is long enough so that the first wall coolant velocity, pressure, temperatures, etc., do not change with time, a steady-state mode of operation or condition may be postulated. Lastly, under normal operation, there is plasma shutdown, e.g., plasma pumpdown for removal of "ash" or impurities or the need to carry out maintenance during the "off" period.

Off-normal conditions can result as a consequence of plasma disruptions, e.g., the plasma becomes unstable and dumps its energy to the first wall in a very short period of time (milliseconds) resulting in melting and vaporization of the first wall. Loss-of-coolant, or coolant blockage in the first wall could likewise result in off-normal conditions.

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Experimental fusion reactor conditions will be characterized by short plasma burns, possibly tens of seconds if not slightly longer, as well as plasma shutdown which may be the same length of time. The response of the first wall, in this case, would be steady, periodic in nature.

This study is concerned with normal operating conditions. In addition to the initial transient response of the first wall, the general solution includes steady-state, and the steady, periodic thermal behavior of the first wall. Of ultimate concern is the thermal stress which the first wall will experience, and subsequent problems of thermal fatigue. A prerequisite to analyze thermal stress problems is a knowledge of the temperature behavior of the first wall which this analysis would provide.

Fillo and Powell [1,2] have analyzed the "steady state" turbulent heat transfer problem in a circular tube with variable circumferential heat flux and volumetric heat generation in the tube wall. The current analysis allows for a wider range of conditions of interest for the fusion reactor, since it includes nonsteady heat transfer as well. The fluid energy equation is not coupled to the tube wall conduction equation, though.

2. GOVERNING EQUATIONS

For an applied surface heat flux with cosine circumferential variation at the outer tube wall, and an assumed uniform heat input on the backside of the tube due to contact with adjacent structures (see Figure 1), the temperature distribution in the tube wall can be determined. Both radial and circumferential temperature variations are permitted. While the internal heat generation in the tube wall due to neutron/gamma heating decays more or less exponentially with distance from the plasma, in this analysis it is assumed constant, i.e., averaged over the wall thickness. The energy equations for the tube wall and fluid are uncoupled so that the boundary condition at the inner tube wall is specified by a heat transfer coefficient.

The two-dimensional, time-dependent heat conduction equation for the tube wall is given by:

$$L_c(T) + \frac{\partial}{\partial t} \phi(t) = 0 \quad (1)$$

subject to the following boundary and initial conditions:

$$k \left(\frac{\partial T}{\partial r} \right)_{R_o} = q\phi(t) \cos \theta \quad 0 \leq \theta < \frac{\pi}{2} \quad (2a)$$

$$k \left(\frac{\partial T}{\partial r} \right)_{R_o} = \bar{q}\phi(t) \quad \frac{\pi}{2} \leq \theta < \pi \quad (2b)$$

$$-k \left(\frac{\partial T}{\partial r} \right)_{R_i} = h(T - T_c) \quad (3)$$

in addition to:

$$T = T_o \text{ at } t = 0 \quad (4)$$

Figure 1 Tubular first wall to remove heat from the plasma

The first boundary condition, Eq. (2a), is the applied heat flux at the outer tube wall and varies with the cosine of the angle. The second boundary condition, Eq. (2b), is the assumed uniform (in magnitude) heat input on the backside of the tube due to contact with adjacent "hot" structures. Equation (3) matches the heat flux at the boundary between the solid and fluid, allowing for the specification of a heat transfer coefficient. The initial condition, Eq. (4), assumes that initially, the structure is at a uniform temperature.

To allow for periodic thermal behavior of the first wall, we assume that the periodic heat fluxes and heat source are applied for $t > 0$, and that $\phi(t)$ is of rectangular wave form, i.e.,

$$\begin{aligned} \phi(t) &= 0, \quad t < 0 \\ \phi(t) &= 1, \quad n\tau < t < n\tau + \tau_1, \quad n = 0, 1, \dots \\ \phi(t) &= 0, \quad n\tau + \tau_1 < t < (n+1)\tau, \quad n = 0, 1, \dots \end{aligned} \quad (5)$$

In other words, the applied flux, $q\phi(t)$ (and $\bar{q}\phi(t)$) represents a flux q (and $\bar{q}$) which is "on" for time, τ , the plasma burn time, and "off" for time, $\tau - \tau_1$, with period, τ . In reality, the plasma "on-off" and burn cycle will look more like a ramp function, that is, current build-up and heating, followed by a flat-top and a ramp down to zero. The rectangular wave form should provide a satisfactory description of the thermal behavior.

3. SOLUTION FOR TIME-DEPENDENT HEAT FLUX AND HEAT SOURCE

Formulating the equations the way that we did permits us to develop the transient, steady-state, and steady, periodic solutions to Eqs. (1-4). For example, in Eqs. (1) and (2), setting $\phi(t) = 1$ for all t allows us to determine the transient solution, or simply, nonsteady temperature history relative to steady-state. The combined transient

and steady-state solutions to Eqs. (1-4) for $\phi(t)=1$ also forms the basis to determine the steady-periodic temperatures by simply applying Duhamel's theorem. This is carried out in the next Section.

The solution to Eqs. (1-4) for $\phi(t)=1$ is found by superposition of two solutions, one representing steady state, $u(r, \theta)$ and the other, the transient, $w(r, \theta, t)$.

Let

$$T(r, \theta, t) = u(r, \theta) + w(r, \theta, t) \quad (6)$$

where

$$L(u) + Q = 0 \quad (7)$$

subject to:

$$k \frac{\partial u}{\partial r} \bigg|_{R_0} = q \cos \theta \quad 0 \leq \theta < \frac{\pi}{2} \quad (8a)$$

$$k \frac{\partial u}{\partial r} \bigg|_{R_0} = -\bar{q} \quad \frac{\pi}{2} < \theta < \pi \quad (8b)$$

$$k \frac{\partial u}{\partial r} \bigg|_{R_1} = h(u - T_B) \quad (9)$$

In addition,

$$L_c(w) = 0 \quad (10)$$

subject to:

$$k \frac{\partial w}{\partial r} \bigg|_{R_0} = 0 \quad (\text{all } \theta) \quad (11)$$

$$k \frac{\partial w}{\partial r} \bigg|_{R_1} = hw \quad (12)$$

and the initial condition, $t=0$:

$$w = T_0 - u(r, \theta) \quad (13)$$

The solutions to Eqs. (7 through 13) are found by superposition of solutions and the method of separation of variables. The steady-state solution is readily found to be:

$$u(r, \theta) = \frac{QR_0^2}{4k} A^2 (1 - \zeta^2) + \left(\frac{QR_0^2}{2k} + \frac{qR_0}{\pi k} \right) + \frac{\bar{q}R_0}{2k} \ln \zeta + \left[\frac{QR_0^2}{2k} (1 - \zeta^2) + \frac{qR_0}{\pi k} + \frac{\bar{q}R_0}{2k} \right] \frac{1}{Bi} + \sum_{n=1}^{\infty} D_n R_1^n \left[\left(\frac{n-Bi}{n+Bi} \right) \zeta^{-n} + \zeta^n \right] \cos n\theta + T_B \quad (14)$$

where:

$$D_n R_1 = \left(\frac{qR_0}{2k} - \frac{2\bar{q}R_0}{\pi k} \right) A / \left[1 + A^2 \left(\frac{Bi-1}{Bi+1} \right) \right] \quad (15a)$$

$$D_n R_1^n = \frac{2qR_0}{\pi k} \frac{(-1)^{n/2+1}}{n(n^2-1)} A^n / \left[1 + A^2 \left(\frac{Bi-n}{Bi+n} \right) \right],$$

$$n \text{ even, } n \geq 2 \quad (15b)$$

$$D_n R_1^n = \frac{2\bar{q}R_0}{\pi k} \frac{(-1)^{n+1/2}}{n^2} A^n / \left[1 + A^2 \left(\frac{Bi-n}{Bi+n} \right) \right], \quad n \text{ odd, } n \geq 3 \quad (15c)$$

The time-dependent or transient solution may be written as:

$$w(r, \theta, t) = \sum_{s=1}^{\infty} \sum_{n=0}^{\infty} a_{n,s} \cos n\theta U_n(\alpha_s r) e^{-\alpha_s^2 t} \quad (16)$$

where: U_n are cylinder functions (or Bessel functions of order n), and the α 's are eigenvalues.

The cylinder functions are given by:

$$U_n(\alpha r) = \left[\alpha Y_{n-1}(\alpha R_0) - \frac{n}{R_0} Y_n(\alpha R_0) \right] J_n(\alpha r) - \left[\alpha J_{n-1}(\alpha R_0) - \frac{n}{R_0} J_n(\alpha R_0) \right] Y_n(\alpha r) \quad (17)$$

while the equations to determine the eigenvalues are given by:

$$\begin{aligned} & \left[\alpha J_{n-1}(\alpha R_1) - \frac{(n+Bi)}{R_1} J_n(\alpha R_1) \right] \left[\alpha Y_{n-1}(\alpha R_0) - \frac{n}{R_0} Y_n(\alpha R_0) \right] \\ & - \left[\alpha Y_{n-1}(\alpha R_1) - \frac{(n+Bi)}{R_1} Y_n(\alpha R_1) \right] \left[\alpha J_{n-1}(\alpha R_0) - \frac{n}{R_0} J_n(\alpha R_0) \right] \\ & = 0, n \geq 0 \quad (18) \end{aligned}$$

The subscripts on the α 's are dropped.

The $a_{n,s}$ are given by:

$$a_{0,s} = \frac{2(T_0 - T_B)Bi}{(\alpha R_0)^2 U_0^2(\alpha R_0) - (\alpha^2 R_1^2 + Bi^2) U_0^2(\alpha R_1)} \times \left\{ \left[1 - \frac{QR_0^2}{k(T_0 - T_B)(\alpha R_0)^2} U_0(\alpha R_1) \right] - \frac{1}{Bi} \left[\frac{qR_0}{k(T_0 - T_B)} + \frac{\bar{q}R_0}{2k(T_0 - T_B)} \right] U_0(\alpha R_0) \right\} \quad (19a)$$

$$a_{n,s} = \frac{(T_0 - T_B)}{[(\alpha R_0)^2 - n^2] U_n^2(\alpha R_0) - (\alpha R_1^2 + Bi^2 - n^2) U_n^2(\alpha R_1)} \times \frac{2n}{\pi A^n R_0 (T_0 - T_B)} \left[1 + A^2 \left(\frac{Bi-n}{Bi+n} \right) \right], n \geq 1 \quad (19b)$$

All of the significant parameters governing the solution are apparent. In addition to the Fourier number, $Fo = \tau/R_0^2$ and Biot modulus, $Bi = hR_0/k$, the solution is dependent on the Pomerantsev modulus [3], $Po = QR_0/k(T_0 - T_B)$, and Kirpichev modulus, $Ki = qR_0/k(T_0 - T_B)$ (or $\bar{q}$ in place of q).

Projections for future machines indicate that heat fluxes can be quite high so that on a comparative basis K_1 will be greater than P_0 . For the cases investigated, K_1 is approximately a factor of 5 greater than P_0 . This is not to imply that volumetric heating of the first wall should be neglected relative to surface heat flux when calculating the first wall temperatures.

4. STEADY PERIODIC TEMPERATURE

The solution to Eq. (1) subject to Eqs. (2-5) follows from Eq. (16) and application of Duhamel's theorem, i.e.,

$$T - T_B = -\alpha_s^2 \sum_{s=1}^{\infty} \sum_{n=0}^{\infty} \cos n\theta U_n(\alpha_s r) \int_0^t a_{n,s}(\lambda) e^{-\alpha_s^2(\tau-\lambda)} d\lambda \quad (20)$$

where Q is replaced by $Q(\lambda)$, etc., in the expressions for $a_{n,s}$.

The steady, periodic variation in temperature may be found in a number of ways. The method of Weber [4] is quite general, and has the advantage that the resulting series converges rapidly for the values of time which are of interest.

The results given in ref. 4 are immediately available for any problem in which the solution for the constant external condition is given as a series of exponentials of the form $(-Y_{n,s}t)$, and the solution for the external conditions (as well as the heat source) are represented by Eq. (5), is to be obtained by Duhamel's theorem. Rather than repeat the derivation, we simply state the results for the integrals for the "on" and "off" periods.

4.1 Solution for the "on" period.

For the "on" period, we let:

$\tau = \tau_1 + \tau'$, where $0 < \tau' < \tau_1$, and τ is large. Setting:

$Y_{n,s} = \alpha_s^2$ and $\phi_1(\lambda) = Q(\lambda)$, $q(\lambda)$, and $\bar{q}(\lambda)$,

we have to evaluate integrals of the type:

$$a_{n,s} = \int_0^{\tau} Q_1(\lambda) e^{-Y_{n,s}\lambda} d\lambda \quad (21)$$

which becomes, for large values of τ ,

$$\frac{1}{Y} \left[1 - \frac{e^{-Y(\tau_1-\tau')}}{1-e^{-Y\tau}} \right] \quad (22)$$

where $i=1, 2, 3$ ($\phi_1=Q$, $\phi_2=q$, and $\phi_3=\bar{q}$).

Consequently, for large values of time, the solution to Eq. (20) is:

$$T - T_B = \sum_{s=1}^{\infty} \sum_{n=0}^{\infty} \left[\frac{2Bi(T_0 - T_B)U_0(\alpha_s R_1)U_0(\alpha_s r)}{(\alpha_s R_0)^2 U_0^2(\alpha_s R_0) - (\alpha_s^2 R_1^2 + Bi^2)U_0(\alpha_s R_1)} \right]$$

$$\times \left[1 - \frac{e^{-\alpha_s^2(\tau_1-\tau')}}{1-e^{-\alpha_s^2\tau}} \right] - a_{n,s} \cos n\theta U_n(\alpha_s r) \quad (23)$$

It can be shown that Eq. (23) can be written as:

$$T - T_B = T_{SS} - \sum_{s=1}^{\infty} \sum_{n=0}^{\infty} \left[\frac{2Bi(T_0 - T_B)U_0(\alpha_s R_1)U_0(\alpha_s r)}{(\alpha_s R_0)^2 U_0^2(\alpha_s R_0) - (\alpha_s^2 R_1^2 + Bi^2)U_0(\alpha_s R_1)} \right] e^{-\alpha_s^2(\tau_1-\tau')} - a_{n,s} \cos n\theta U_n(\alpha_s r) \quad (24)$$

The first term, $T_{SS}(=u(r, \theta))$, is the steady-state solution, while the last term represents the steady, periodic variation of temperature with respect to the "true" steady state. Actually, the solution turns out to be a perturbation about the steady state.

4.2 Solution for the "off" period

In an analogous way for the plasma "off" period, we set:

$$\tau = \tau_1 + \tau'' \quad (25)$$

where τ is again large. For this case:

$$a_{n,s} = \int_0^{\tau} \phi_1(\lambda) e^{-Y_{n,s}\lambda} d\lambda = \frac{1}{Y} \frac{e^{-Y(\tau_1-\tau'')}}{1-e^{-Y\tau}} \quad (26)$$

so that the temperature, for large values of time becomes:

$$T - T_B = \sum_{s=1}^{\infty} \sum_{n=0}^{\infty} (a-b)(c) \quad (27)$$

$$a = \frac{2Bi(T_0 - T_B)U_0(\alpha_s R_1)U_0(\alpha r)}{(\alpha_s R_0)^2 U_0^2(\alpha_s R_0) - (\alpha_s^2 R_1^2 + Bi^2)U_0(\alpha_s R_1)}$$

$$b = a_{n,s} \cos n\theta U_n(\alpha_s r) \quad , \quad \text{and}$$

$$c = \frac{e^{-\alpha_s^2(\tau_1-\tau'')}}{1-e^{-\alpha_s^2\tau}}$$

Figure 2 Radial temperature distribution across tube wall

Figure 3 Radial temperature distribution across tube wall

5. DISCUSSION AND RESULTS

Steady-state temperature profiles (temperature difference above the mean fluid temperature) shown in Figures 2 and 3 are comparisons between aluminum and stainless steel tubes for three circumferential locations. These materials are characterized by their thermal conductivities, the former being high while the latter is a low conductivity material. Maximum heat flux occurs for $\theta=0$. Input for all calculations are found in Table 1. Surface heat flux and volumetric heating rates are taken from ref. 5. For comparison, modern boiler tubes in power plant furnaces absorb 55 W/cm² on clean boiler surfaces. This is to be compared with 85 W/cm² for the first wall fusion

Table 1 Heat transfer properties and parameters

	Aluminum	Stainless Steel
k (W/m K)	170.00	18.00
ρ (g/cc)	2.71	7.97
c (J/g K)	.921	.500
q (W/cm ²)	85.00	85.00
$\dot{q}$ (W/cm ²)	10.00	10.00

Table 2 First wall temperature difference, $Bi=10$, $Q=30$ W/cc

r/R_i	$\theta=0$		$\theta=\pi/2$		$\theta=\pi$	
	SS	Al	SS	Al	SS	Al
1	26.03	2.80	9.50	1.02	5.62	.60
1	23.78	2.56	8.42	.90	4.92	.53
1	28.93	3.11	10.01	1.08	6.10	.66
1.714 ^a	172.53	18.54	50.78	5.46	32.04	3.44
1.692 ^b	154.80	16.60	44.57	4.79	28.01	3.01
1.625 ^c	174.17	18.72	49.24	5.29	31.85	3.42

NOTE: $a=R_i=.325$ cm; $b=R_i=.35$ cm; and $c=R_i=.4$ cm.

Table 3 First wall temperature difference, $Bi=6$, $Q=30$ W/cc

r/R_i	$\theta=0$		$\theta=\pi/2$		$\theta=\pi$	
	SS	Al	SS	Al	SS	Al
1	42.40	4.56	16.27	1.75	9.49	1.02
1	38.73	4.16	14.45	1.55	8.31	.89
1	47.14	5.07	17.19	1.85	10.25	1.10
1.714	187.39	20.14	58.20	6.25	36.11	3.88
1.692	168.39	18.10	51.18	5.50	31.53	3.39
1.625	190.80	20.51	57.09	6.14	36.12	3.88

Table 4 First wall temperature difference, $Q=35$ W/cc

r/R_i	$\theta=0$		$\theta=\pi/2$		$\theta=\pi$	
	SS	Al	SS	Al	SS	Al
1 ^a	24.05	2.58	8.69	.93	5.19	.56
1 ^b	29.81	3.20	10.99	1.18	6.52	.70
1 ^c	39.19	4.21	14.91	1.60	8.76	.94
1.692 ^a	155.68	16.73	45.45	4.88	28.87	3.10
1.692 ^b	160.91	17.29	47.98	5.16	30.25	3.25
1.692 ^c	169.46	18.21	52.25	5.61	32.60	3.50

NOTE: $a=Bi=10$; $b=Bi=8$; and $c=Bi=6$.

design. While the volumetric heating rates are for stainless steel, the heating rates for Al are assumed to be the same. If anything, they would be slightly lower than stainless steel. As a consequence of its higher thermal conductivity, this is not significant since Al exhibits a very low temperature gradient across the thin tube wall. The dominant contribution to the temperature variation is from the surface heat flux, q . The Biot number is fixed for comparison between the two cases. In real designs, the Biot numbers would be different for stainless steel and Al.

Tables 2, 3, and 4 show the temperature at the inside wall and outside tube surface for three circumferential locations. The first two tables are for fixed Biot modulus while the inside and outside tube radii are allowed to vary. The temperatures in Table 4 are for slightly higher volumetric heating rate, 35 W/cc, compared with 30 W/cc for fixed inside and outside tube radii. The Biot modulus is varied. Basically, the results show that the temperature gradient (or temperature difference across the tube wall) increases with tube wall thickness. For the range of Biot numbers considered, the temperature difference, for fixed inside and outside tube radii, remains virtually constant. What changes, though, are the maximum temperatures as well as the temperature drop between the inner tube wall and bulk cooling, increasing with decreasing Biot modulus. Increasing the volumetric heating had very little effect on the temperature.

The maximum temperature difference, ΔT_m , across the tube wall can be correlated with $\chi(R_o - R_i)/k$, i.e.,

$$\Delta T_m = 0.12 \chi(R_o - R_i)/k$$

where χ is the wall loading. In this case, the wall load is defined to be the gross fusion power divided by the first wall area. This reconfirms results found elsewhere [2,6] for different first wall materials as well as boundary conditions.

Table 5 lists a few of the significant eigenvalues for the time-dependent problems as a function of Biot modulus and tube size. For the cases studied here, the eigenvalues are large so that the approach to steady-state temperatures is quite rapid even for short plasma burn times. The Biot modulus is significant for the determination of the eigenvalues. The implication is that one would like to operate the coolant ducts at as high a heat transfer coefficient as possible to achieve steady-state behavior in as short a time as possible within the plasma burn time. Numerical evaluation of Eq. (24) indicates that steady state is achieved within a few seconds in the plasma burn.

Table 5 Eigenvalues as a function of Biot modulus and tube size

$R_o/R_i = 1.714$		
Bi	n=0	n=1
10	4.8636, 16.5876, 28.2527,...	0, 16.7367, 28.3406,...
3	4.7124, 16.2439, 27.8572,...	0, 16.3975, 27.9465,...
$R_o/R_i = 1.692$		
10	5.3990, 18.3819, 31.3303,...	0, 18.5401, 31.4233,...
3	5.2276, 17.9959, 30.8916,...	0, 17.6436, 30.4520,...

For the cases studied, the infinite series in Eqs. (24 and 27) can be represented by a single term (only one eigenvalue is required), or to a good approximation within a few percent of the more exact solution.

$$T - T_B = T_{SS} (1 - e^{-\alpha_s^2 t}) \quad , \text{"on"} \quad (28)$$

and

$$T - T_B = T_{SS} e^{-\alpha_s^2 t} \quad , \text{"off"} \quad (29)$$

This is significant since it permits one to study the steady, periodic behavior of the first wall with a relatively simple set of equations for design purposes. Of course, the eigenvalues still need to be obtained. An examination of Eq. (28) indicates that reducing the plasma burn time reduces the rate of approach to steady state.

From a thermal standpoint results from this study indicate the advantages which would accrue using a high thermal conductivity material such as Al in the design of the first wall. The tube wall thickness has been kept rather thin, the point being that for stainless steel rather large temperature drops can occur for thin wall (~ 2 mm) structures as well as high surface temperatures. Increasing the tube thickness implies larger increases to thermal response and will impose intolerable thermal stress problem. The study indicates that significantly thicker wall structures could be made out of Al. This is significant in view of the fact that the first wall will undergo some degradation, that is material loss due to sputtering and erosion. Added significance is achieved by considering the desirability of low activation blanket structures. Very pure Al can be used for first walls to shorten the waiting period for contact maintenance, if not on the wall itself, then on nearby reactor components with a modest amount of shielding.

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ABSTRACT

To accommodate the high heat flux and neutron and gamma heat generation in the first wall of a fusion reactor, an array of tubes or tube-bank forms a first wall shield of the blanket. A series solution to the two-dimensional (in r, θ coordinates), time-dependent heat conduction equation has been found in terms of Fourier-Bessel (modified Bessel) functions. Steady-state solutions are found as limiting solutions. The heat sources are pulsed on and off to simulate the plasma burn and cool down periods. In addition to the Biot numbers, the time-dependent solution is given in terms of the Fourier, Pomerantsev, and Kirpichev numbers and numerically evaluated for a wide range of plasma and first wall conditions. Comparison of the thermal responses of the first wall between aluminum, a high thermal conductivity material and stainless steel, a low thermal conductivity material, is made.

NOMENCLATURE

A = ratio of inside to outside radii, R_i/R_o ,
Bi = Biot number = hR_i/k ,
c = specific heat, J/ksk,
h = heat transfer coefficient, $W/m^2 K$,
Ki = Kirpichev modulus = $qR_o^2/k(T_o - T_B)$,
L = operator, $k \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} \right)$,
 L_t = operator, $(-\partial/\partial t + L/\rho c)$,
Po = Pomerantsev modulus = $QR_o^2/k(T_o - T_B)$,
q = surface heat flux, W/m^2 ,
Q = average volumetric heating, W/m^3 ,
r = radial coordinate, m,
 R_i = inside tube radius, m,
 R_o = outside tube radius, m,
t = time, sec,
T = temperature, K,
 α = thermal diffusivity, m^2/s , and
 ρ = density, kg/m^3 .

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Subscripts

B = bulk coolant, and
o = initial time.

1. INTRODUCTION

In the design of fusion reactor blankets, the first wall, i.e., the first material surface to interface the plasma, is a critical region since all of the emissions from a reacting plasma may intersect this wall. These include ions and neutral particles, primary neutrons, x-rays (Bremsstrahlung) and cyclotron radiation. In addition, scattered neutrons and gamma radiation generated in the blanket regions exterior to the first wall are also imposed on it. Finally, deuterium-tritium gas surrounding the plasma may react chemically with the first wall materials. One result of these many interactions is the generation of appreciable heat which can be up to 20% of the plasma output. In most analyses, these effects are lumped into a radiant flux incident on the first wall, i.e., an applied surface heat flux boundary condition. A number of ideas have been set forth to accommodate the high heat fluxes and neutron/gamma heat generation in first walls. A feature common to several of the designs is an array of tubes or tube-bank forming the first wall.

To gain some appreciation of the heat transfer problems of the first wall, it is convenient to first categorize the operating regimes of a fusion reactor under normal and off-normal conditions. Under normal operation, we consider reactor startup which is associated with initial plasma fueling. This is a transient condition. Assuming that the plasma burn is long enough so that the first wall coolant velocity, pressure, temperatures, etc., do not change with time, a steady-state mode of operation or condition may be postulated. Lastly, under normal operation, there is plasma shutdown, e.g., plasma pumpdown for removal of "ash" or impurities or the need to carry out maintenance during the "off" period.

Off-normal conditions can result as a consequence of plasma disruptions, e.g., the plasma becomes unstable and dumps its energy to the first wall in a very short period of time (milliseconds) resulting in melting and vaporization of the first wall. Loss-of-coolant, or coolant blockage in the first wall could likewise result in off-normal conditions.