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Benefits of natural convection in solid breeder blankets with poloidal coolant channels under LOFA conditions

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This paper analyzes natural circulation flow in solid breeder blanket designs with poloidal coolant channels under a LOFA condition. Analyses couple the flow transient behaviors with transient heat transport models. While two-phase natural circulation exists in the system, a homogenous mixture model is used. The results of example calculations performed for an ITER solid breeder design concept indicate that in a 3-loop system with an elevation head (ΔZ) of 20 m, the removal of the afterheat (energy stored in the blanket elements and decay heat) depends on two-phase natural circulation flow with a quasi-equilibrium flow quality of 26% at the outlet of the blanket segment. However, if the available hydrostatic head is about 15 m or less, the amount of natural circulation flow is reduced due to significant increases of friction and acceleration losses in a two-phase system. To rely on natural circulation flow as an afterheat removal mechanism, the design of coolant system with its flow channels should be addressed analytically and experimentally to permit stable steady-state operation under conditions of the presence of vapor in the coolant channels.

1. Introduction

Natural circulation refers to flows driven without the help of an active mechanical device such as a pump. The flow is driven by density gradients around the flow loop which create a buoyancy effect. To enhance passive safety features, one of the design guidelines for a blanket coolant system layout might be to locate some components (e.g., heat exchanger) sufficiently above the blanket, and route the flow upward through the blanket segment, such as in the case of poloidally running coolant tubes. This paper focuses on such a coolant tube configuration and analyzes the associated benefits of natural convection in the case of loss of flow accident.

A typical tokamak blanket primary cooling system includes two main collectors, one hot and one cold, which are placed around the plasma ring inside the reactor building. The hot collector is directly connected to the inlet lines of heat exchangers. The heat exchanger discharge lines are connected with the surge lines of centrifugal pumps, which have discharge lines connected with the cold collectors. Coolant to the blanket segment is provided through supply and return lines, which are directly connected to the hot and cold collector. The coolant is distributed to each breeding tube, zone or layer through a manifold, which might be placed either in the back or on the top of the blanket segment. The blanket coolant system may consist of several heat transport loops, each loop containing one pump and one heat exchanger. Thus, depending on the coolant layout and accident scenario, the loss of flow accident may be categorized as either a partial (a loss of one pump in a multi-loop cooling system due to mechanical failure) or total loss of cooling to the blanket. An example of a schematic view of the outboard blanket coolant system is shown in fig. 1.

The loss of flow accident (LOFA) considered in the present analysis is assumed to result from the simultaneous failure of all pumps due either to catastrophic mechanical failure or to loss of power. In the analysis, the time-dependent conservation equations governing the flow and temperature distribution in a blanket natural circulation loop are solved simultaneously. A lumped-parameter method is used to calculate the transient behaviors of the average blanket element temperatures. In the event that two-phase natural circulation occurs, a homogenous model is used in the analysis.

2. Flow transient

To determine the flow transient, the pressure drop and flow relationships along with Kirchhoff's laws [1] are applied to the hydraulic systems, which include the coolant channels in the blanket zone and coolant channels in the remaining primary coolant system, say the loop. Under the assumption of negligible viscous dissipation, the pressure drop in coolant channel i of a blanket zone can be written as:

$$\Delta P_{b_i} = \left(\frac{L}{A}\right)_{bi} \frac{dW_{bi}}{dt} + \tilde{K}_{bi} \frac{W_{bi}^2}{2\bar{\rho}_{b_i}} + (\bar{\rho}\,\Delta Z)_{b_i},$$
$$i = 1,2,\cdots, N, \qquad (1)$$

where $\tilde{K}_{b_i}$ is the flow resistance and is estimated in terms of the Darcy–Weisback [1] friction factor f_{b_i} and the flow cross-sectional area A_{b_i}:

$$\tilde{K}_{b_i} = f_{b_i}\left(\frac{L}{D_h}\right)_{bi} / A_{bi}^2, \qquad (2)$$

where L is the channel length and D_h is the hydraulic diameter.

An example of a poloidally oriented coolant flow channel arrangement inside a blanket segment is shown in fig. 2. The design can be characterized as a number of flow channels having common inlet and outlet manifolds operating hydraulically in parallel. In this connection, we have

$$\Delta P_{b1} = \Delta P_{b2} = \Delta P_{b3} = \cdots \Delta P_{bN} = \Delta P_b$$

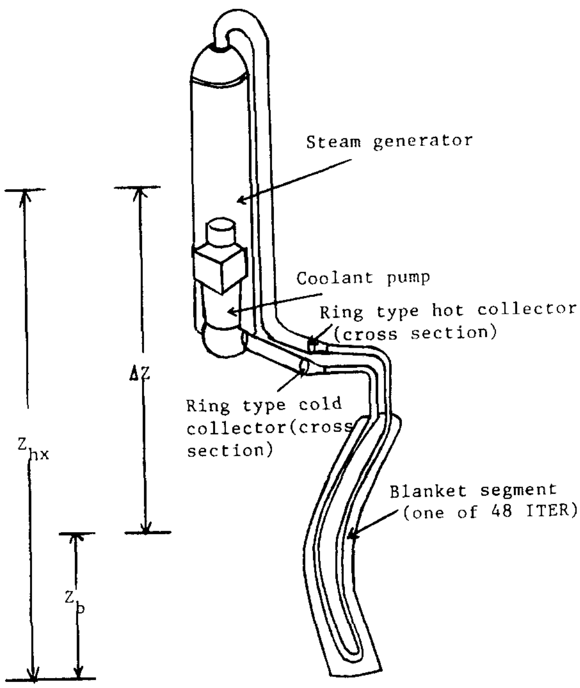

Fig. 1. Illustration of a poloidally oriented outboard blanket primary cooling system (one of the loop).

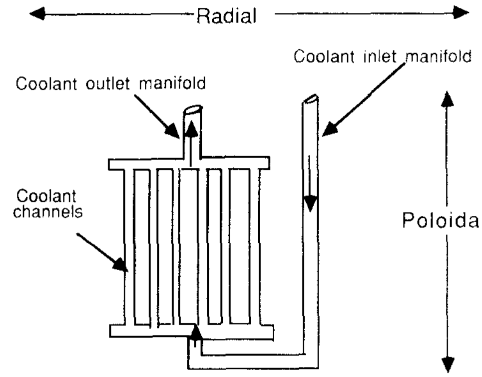

Fig. 2. An example of a poloidally oriented channel arrangement inside a blanket segment.

and

$$\frac{dW_b}{dt} = \frac{dW_{b1}}{dt} + \frac{dW_{b2}}{dt} + \frac{dW_{b3}}{dt} + \cdots + \frac{dW_bN}{dt}. \qquad (3)$$

Rewriting eq. (1) in terms of W_b and assuming average values of channel coolant flow rates and flow resistances, the following expression is obtained:

$$\Delta P_b = \frac{\left(\frac{L}{A}\right)_b}{N} \frac{dW_b}{dt} + \frac{\tilde{K}_b}{N^2} \frac{W_b^2}{2\bar{\rho}_b} + (\bar{\rho}\,\Delta Z)_b. \qquad (4)$$

The coolant pressure drop in the remainder of the loop is written as:

$$\Delta P_l = \left(\frac{L}{A}\right)_l \frac{dW_l}{dt} + \tilde{K}_l \frac{W_l^2}{2\bar{\rho}_l} + (\bar{\rho}\,\Delta Z)_l - \bar{\rho}_l\left(\frac{\omega}{\omega_0}\right)^2 H_p, \qquad (5)$$

where $\tilde{K}_l$ is the appropriate friction coefficient divided by the square of the flow area for the loop, which accounts for the flow paths, entrance and exit frictions. Kirchhoff's law states that the sum of the pressure drops around any loop of the channels must be equal to zero, which gives:

$$\Delta P_b + \Delta P_l = 0. \qquad (6)$$

The continuity criterion requires that:

$$W_l = \frac{N_{bs}}{N_p} \times W_b, \qquad (7)$$

where N_{bs} is the total numbers of blanket segments and N_p the number of parallel pumps used in the blanket coolant system. Combining these expressions with eqs. (1) and (2) we obtain the following relationship:

$$\left(\frac{L}{A}\right)_{\mathrm{pr}} \frac{\mathrm{d}W_{\mathrm{b}}}{\mathrm{d}t} + \tilde{K}_{\mathrm{pr}} \frac{W_{\mathrm{b}}^2}{2\bar{\rho}} + (\bar{\rho}\,\Delta Z)_{\mathrm{pr}} - \bar{\rho}\left(\frac{\omega}{\omega_0}\right)^2 H_{\mathrm{p}} = 0, \tag{8}$$

where for the entire blanket primary coolant system:

$$\left(\frac{L}{A}\right)_{\mathrm{pr}} = \frac{1}{N}\left(\frac{L}{A}\right)_{\mathrm{b}} + \frac{N_{\mathrm{bs}}}{N_{\mathrm{p}}}\left(\frac{L}{A}\right)_1 \tag{9}$$

and

$$\tilde{K}_{\mathrm{pr}} = \frac{\tilde{K}_{\mathrm{b}}}{N^2} + \left(\frac{N_{\mathrm{bs}}}{N_{\mathrm{p}}}\right)^2 \tilde{K}_1. \tag{10}$$

2.1. Flow transient behavior with zero pump inertia

Following the loss of power to all the coolant pumps, the coolant flow is driven by both pump head and fluid inertia. In general, this is referred to as the flow coastdown. During the flow coastdown period, the amount of flow depends highly on the characteristics of the pumps and can be significant if the coolant pumps are designed with sufficiently large flywheels. Discussions of flow coastdown due to pump inertia for fusion blanket residual power removal can be found in refs. 2–4 as examples. In the present analysis, it is assumed that the flow is driven only by the hydrostatic head. This will give an upper estimate of the blanket element temperature. To evaluate the hydrostatic pressure head we must determine the elevation change and the coolant density for each segment of the primary loop. Suppose we model the blanket primary system as indicated in fig. 1. The path of the coolant would then consist of th blanket, the coolant supply, the heat exchanger, the coolant return, and coolant distribution and collection manifolds. Here, it is assumed that the density in the fluid varies approximately linearly (based on the assumptions of uniform heat input and removal in the blanket and heat exchanger, respectively) as it passes through the blanket and heat exchanger. The final expression of the hydrostatic pressure head can be written as:

$$(\bar{\rho}\,\Delta z)_{\mathrm{pr}} = -(\rho_i - \rho_0)(Z_{\mathrm{hx}} - Z_{\mathrm{b}}) = -(\rho_i - \rho_0)\,\Delta Z, \tag{11}$$

where Z_{hx} and Z_{b} are the heat exchanger and core midplane elevations. The density change across the blanket can be written as:

$$\rho_i - \rho_0 = \bar{\rho}\beta\,\Delta T_{\mathrm{b}}, \tag{12}$$

where β represents the volumetric coefficient of thermal expansion and is defined as:

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}\bigg|_p. \tag{13}$$

For a constant pressure, β increases as coolant temperature increases. Substituting eqs. (11) and (12) into eq. (5), we have:

$$\left(\frac{L}{A}\right)_{\mathrm{pr}} \frac{\mathrm{d}W_{\mathrm{b}}}{\mathrm{d}t} + \tilde{K}_{\mathrm{pr}} \frac{W_{\mathrm{b}}^2}{2\bar{\rho}} + (\bar{\rho}\beta\,\Delta T_{\mathrm{b}}\,\Delta Z)_{\mathrm{pr}} = 0. \tag{14}$$

To estimate the flow transient, models to predict the coolant temperature histories are needed since the amount of flow depends on the available bouyancy force.

3. Transient heat transport model

A simple way to estimate the thermal behavior for a relatively slow transient such as a LOFA is to use a lumped parameter technique. In this lumped parameter procedure, each component quantity is lumped at the middle of the physical geometry and axial conduction is neglected. The thermal resistances and the capacitances of the blanket module components are evaluated at their average condition in time and space. This method provides a rapid means for obtaining approximate estimates, yet is accurate enough to understand the interaction of the various phenomena involved.

One of the lumped parameter techniques is based on two energy balances, one for the energy contained in all the blanket elements (such as breeder, clad, multiplier) and a second one for the energy stored in the coolant within the coolant channel. This is the so-called singly lumped model. The singly lumped parameter model yields the average thermal behavior of the blanket element under a LOFA condition. If the thermal behavior of the breeder itself is important to determine the likelihood of failure as a result of a LOFA, when the plasma stays on for a significant time for example, a better estimate of the local breeder thermal behavior should be considered. A simplified analytical method to determine the thermal behavior of critical and non-critical regions separately is to use a doubly lumped parameter model. For the present analysis, different thermal energy balances are written for the breeder region and for the combined clad and multiplier regions. The energy balance for the breeder zone may be written as:

$$M_b C_b \frac{\mathrm{d}T_b}{\mathrm{d}t} = P_b(t) - \frac{1}{R_{eq.b}}\left[\tilde{T}_b(t) - \tilde{T}_m(t)\right]. \quad (15)$$

The first term on the right-hand side of eq. (15), $P(t)$, represents the nuclear heating power, and the second term represents the rate at which energy is transported across the breeder surface into the clad and/or multiplier regions. The energy balance for the combined clad and multiplier regions may be written as:

$$M_m C_m \frac{\mathrm{d}\tilde{T}_m}{\mathrm{d}t} = P_m(t) + \frac{1}{r_{eq.b}}\left[\tilde{T}_b(t) - \tilde{T}_m(t)\right] - \frac{1}{R_{eq.m}}\left[\tilde{T}_m(t) - \tilde{T}_c(t)\right]. \quad (16)$$

The energy balance for the coolant within the coolant channel may be written as:

$$M_c C_c \frac{\mathrm{d}\tilde{T}_c}{\mathrm{d}t} = \frac{1}{R_{eq.m}}\left[\tilde{T}_m(t) - \tilde{T}_c(t)\right] - W(t)C_c\left[\tilde{T}_c(t) - \tilde{T}_i(t)\right]. \quad (17)$$

The first term on the right-hand side of eq. (17) represents the rate at which energy is transported from the clad and/or multiplier regions into the coolant, and the second term represents the net rate of convective heat transport out of the coolant channel. More detailed descriptions of the model and the derivations of quantities can be found in Refs. [1,4,5].

In the event that boiling occurs, the coolant temperature will stay the same and the coolant enthalpy and flow quality become important parameters. Here, we consider the case of constant system pressure (under this assumption, a system of expansion tank is needed for accommodating the thermal expansion of coolant) and neglect the axial pressure drop compared to the constant system pressure; the energy equation of a homogenous mixture two-phase flow can be stated as [6]:

$$\bar{\rho}\delta_c \frac{\partial \tilde{h}}{\partial t} + 2W(\tilde{h} - h_{in}) = \frac{1}{R_{eq.b}}\left[\tilde{T}_m - T_{sat}\right], \quad (18)$$

and the average flow quality is calculated as:

$$\langle x \rangle = \frac{\tilde{h} - h_f}{h_{fg}}, \quad (19)$$

whereas the homogeneous mixture density is given as:

$$\bar{\rho} = 1/\left\{\frac{1}{\rho_f} + \langle x \rangle \frac{1}{\rho_{fg}}\right\}. \quad (20)$$

The average flow quality at the outlet of the blanket segment is calculated as:

$$\langle x \rangle_{out} = \frac{h_{out} - h_f}{h_{fg}}, \quad \text{where} \quad h_{out} = 2\tilde{h} - h_{in}. \quad (21)$$

In addition, the frictional pressure drop in a flowing two-phase system is much larger than a single-phase system. In general, the frictional pressure drop in a two-phase system is calculated by multiplying the equivalent saturated single-phase pressure loss by an empirical multiplier. Here, the correlation suggested by Jones [7] is used to adjust the frictional loss coefficient $\tilde{K}_{pr}$, given in eq. (14). Again, the spatial acceleration pressure loss is neglected in the momentum equation.

4. Results

The flow transient equation is linked to the transient heat transport model to determine the blanket and coolant temperature histories for different transient conditions. Example calculations were performed for ITER blanket design concepts, assuming 1-loop and 3-loop cooling circuits. During normal operation, the

Table 1
Thermal-hydraulics loop parameters used for transient calculations

Design parameter	3-loop	1-loop
Equivalent loop diameter (m)	0.6	1.0016
Steady-state equivalent loop velocity (m/s)	7.7	8.12
Equivalent ring inlet/outlet collector flow path (m)	$\frac{1}{3}\pi r$ ($r = 12$ m)	πr
Flow path from outlet ring collector to HX/pump (m)	7.5	7.5
Flow path from HX/pump to inlet ring collector (m)	7.5	7.5
Total loop flow path (for $\Delta Z = 15$ m) (m)	70.0	120.
Steady-state loop pressure drop (MPa)	0.039	0.039

water coolant flow rate in each ITER blanket segment is set to remove 22 MW thermal power (a thermal blanket energy multiplication factor of 1.25 is used) with a temperature rise of about 40 °C [8]. A typical blanket pressure drop and steady-state velocity are 0.3 MPa (coolant normal operating pressure is 1.5 MPa) and 3.0 m/s respectively [8]. The blanket coolant flow path is twice the poloidal length and a total flow area of 0.04 m^2 with a typical hydraulic diameter of 0.8 cm is used. The loop thermal-hydraulics parameters listed in table 1 were chosen, based on minimizing the loop pressure drop and on keeping the same steady-state total pumping power for the different cooling concepts (notice that a larger coolant tube is needed for the single loop system to provide the same amount of loop pressure drop as for the 3-loop system). In general, a 3-loop or multi-loop cooling system would be preferred since it would provide a partial active cooling for afterheat removal in case that one pump fails due to its mechanical malfunction. Instantaneous shut down of the plasma, i.e. complete cessation of operating power, is assumed to occur at the onset of a LOFA. The resulting flow histories following a LOFA for different elevations are shown in fig. 3. For a 3-loop design, the flow drops to less than 10% of the steady-state value at about 7 s following a LOFA. In this design, the average coolant temperature reaches its boiling point at about 22 and 30 s following a LOFA for ΔZ of 10 and 15 m, respectively. The flow reduction is then further aggravated by an increase of flow resistance and hence a decrease in the flow. However, if the average coolant is able to stay below the boiling point, the flow increases slightly due to the increase of the buoyancy forces. The

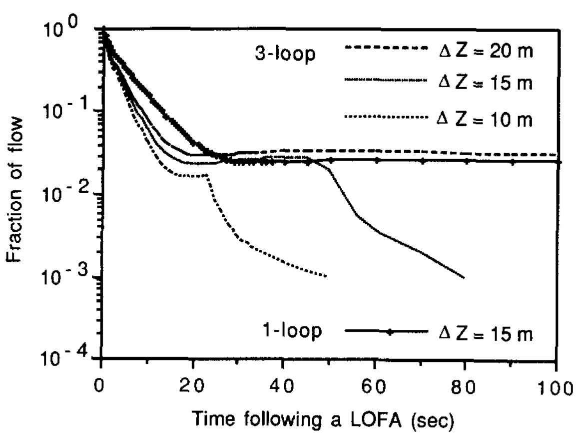

Fig. 3. Transient flow behaviors following a LOFA for different hydrostatic heads (ITER layered pebble bed design concept).

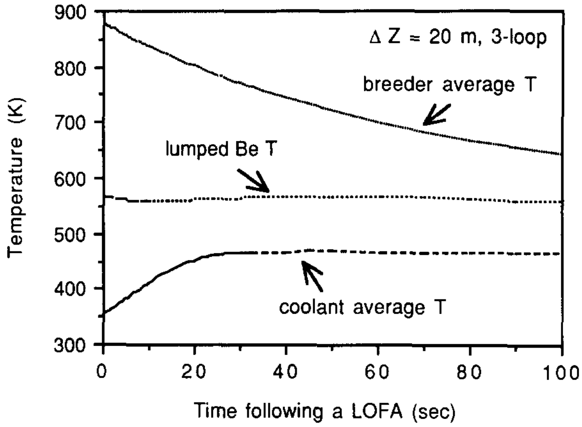

Fig. 4. Temperature histories of solid breeder, lumped Be region and of coolant following a LOFA for hydrostatic head of 20 m, 3-loop system.

flow reaches its quasi-equilibrium value at about 30 s following a LOFA for a ΔZ of 20 m. The effect of longer flow path in a 1-loop system results in a slower flow reduction rate. This allows for adequate natural circulation flow for afterheat removal for an elevation head ΔZ of 15 m. In contrary, a similar elevation head for the 3-loop system would result in a sharper flow rate reduction at about 50 s following a LOFA (see fig. 3).

The results of the average breeder, lumped beryllium region and coolant temperature histories for the case of $\Delta Z = 20$ m are shown in fig. 4. These results indicate that the breeder temperatures fall immediately if the plasma is turned off at the time when a LOFA occurs. The lumped beryllium temperature decreases slightly and appears to be nearly constant for the first 100 s following a LOFA. This is due to the thermal time constant ($R_{eq,b} M_b C_b$) of the breeding zone being similar to that of the lumped beryllium region for the design considered. The heat transported from the breeding zone to the lumped Be region is directly transferred to the coolant. For these cases, the decay power is assumed to be constant equal to 2% of the operating power.

The flow quality histories at the blanket outlet are shown in fig. 5. For the case in which the heat exchanger midplane elevation is 10 m above the blanket midplane elevation for a 3-loop system, a two-phase natural circulation flow occurs at about 8 s following a LOFA. The amount of vapor at the blanket outlet increases sharply once the average coolant temperature reaches its boiling point. The same type of coolant behavior occurs at a later time for a ΔZ of 15 m. In the case of a ΔZ or 20 m for the 3-loop system, the flow quality at the blanket outlet increases to 26% at about

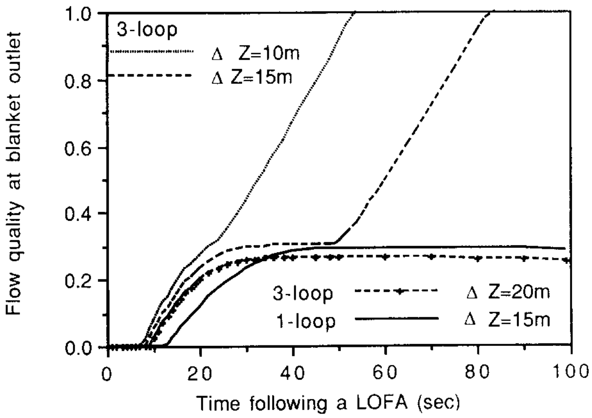

Fig. 5. Flow quality histories at blanket outlet following a LOFA for different designs.

30 s following a LOFA and stays nearly constant for the following 70 s. For a 1-loop cooling system, a slower transient results in an adequate amount of two-phase natural circulation flow to remove the heat transferred to the coolant and the quasi flow quality at the blanket outlet is about 29% for a ΔZ of 15 m. These cases were run under the assumption that the secondary system is intact and removes heat at the same rate as it is produced.

5. Conclusions

The analyses have shown that after a complete loss of flow in an ITER-blanket with poloidal coolant layout, two-phase natural circulation is the afterheat removal mechanism and dryout will not occur for an elevation head (ΔZ) of 20 m for a 3-loop heat transport system. Whether the formation of vapor will hamper the natural circulation flow or not will depend on the geometric configuration and may require experimental investigations using scaling loops. For a 1-loop cooling circuit, the effect of longer flow path results in a slower flow reduction rate. This allows an adequate amount of natural circulation flow being established in time for afterheat removal for an elevation head of 15 m. In the event that the average coolant temperature reaches the boiling point, which results in local dryout towards the end of the coolant outlet (if ΔZ is about 15 m or less in a 3-loop system), the hydraulic resistance (and acceleration loss) of the channel increases rapidly with the presence of void in the channel. As a result, an unstable thermal-hydraulic coupling comes into play, in which reduced flow rate causes boiling and a further increase in flow resistance. If a pump inertia is not large enough to provide an adequate amount of residual flow for afterheat removal and the natural circulation flow is to be relied on as afterheat removal mechanism in a blanket with poloidal coolant channels, the flow channels and thermalhydraulic coupling must be designed to permit stable steady-state operation under two-phase conditions in the coolant channels. As in the case of a toroidal coolant channel layout, it seems prudent to include in the design a system of back-up pumps and back-up generators as an additional safety measure.

Acknowledgement

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Nomenclature

A	equivalent coolant flow area,
C	specific heat per unit mass,
D	equivalent hydraulic diameter,
L	equivalent coolant flow length,
H_p	pump head,
h	enthalpy,
M	mass,
N	number of parallel coolant channels inside a blanket segment,
P	nuclear heating rate,
R_{eq}	equivalent thermal resistance,
$\tilde{T}$	average temperature,
ΔT	coolant temperature rise,
t	time,
W	average coolant flow rate,
x	flow quality,
δ_c	coolant channel half width,
ρ	average density,
ω	pump speed.

Subscript

b	breeder,
c	coolant,
eq	equilibrium,
f	saturated liquid,
fg	the difference between saturated vapor and liquid properties,
1	primary coolant loop
i	inlet of a blanket segment,
in	inlet,
m	clad and/or multiplier,

o initial condition, outlet of a blanket segment,
out outlet,
pr primary coolant system,
sat saturation.

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