

Thermal-Hydraulic Design of a Solid Particulate Fusion Reactor Blanket

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SUMMARY

This paper presents the scoping thermal-hydraulics design of the Advanced Reactor Innovation Evaluation Study (ARIES-I) fusion reactor blanket that is cooled by a mixture of SiC fine particles and CO₂ carrier gas. When compared to a conventional gas-cooled design, the primary advantage of this design is to greatly improve the volumetric heat capacity of the coolant, allowing lower flow velocity, pressure drops and reduced coolant pressure while maintaining the same heat transfer capability. Thermal-hydraulics parametric results and the SiC ceramic composite structured 5 atm pressure CO₂ gas reference design are presented in this paper.

1. INTRODUCTION

Fusion reactor research is at the transitional period of evolving from an experimental science to technology development in preparation for the demonstration of fusion power generation. Relatively complete conceptual designs have been performed to project the performance of fusion power reactor since 1973 [1]. The ARIES study [2] is a multi-institutional research effort, led by UCLA, to develop several design approaches for attractive tokamak reactors with varying degrees of extrapolation in physics and technology. This paper presents the scoping analysis of the blanket system of the ARIES-I design, one of three ARIES visions of tokamak reactors.

Since the initiation of conceptual fusion power reactor design, one of the design goals has been to optimize the environmental advantages of fusion. This led to the serious consideration of using ceramic material like SiC and SiC-composite as the structural material [3], based on the fact that the induced radioactivities of SiC-structured designs can be several orders of magnitude lower than metallic structured designs [4]. Due to its chemical inertness and its transparency to neutrons, the most commonly selected coolant for the ceramic structured designs is helium. Based on this selection of coolant, General Atomics (GA) completed the conceptual designs of several 50 atm pressure helium-cooled low activation fusion reactors [3,5]. This high coolant pressure was needed to maintain high volumetric heat capacity of the helium coolant. To further improve the gas-cooled ceramic-composite design, we proposed to the ARIES-I study [2] the use of a gas and particulate mixture as the reactor coolant. With this we are taking advantage of the much higher volumetric heat capacity of the gas and particulate mixture. The results of this scoping design are reported in this paper.

2. BLANKET MODULE DESIGN

For the ARIES-I fusion reactor design, the blanket module cross-section schematic is shown in Fig. 1. The blanket coolant flows in the poloidal direction around the toroidal chamber, flowing through the first wall from the bottom to the top of the blanket module, where it makes a 180° turn and then flows through the tritium breeder blanket zone from the top to the bottom of the module before it exits the reactor. The reactor design parameters are given in Table 1. To achieve a uniform circulating flow, we operate the particle and gas mixture in the dilute flow regime. The velocity range

of the coolant in the first wall and blanket is from 15 to 43 m/s, which is well above the choke flow velocity of 4.6 m/s [6] and below the particles erosion threshold velocity range of 40 to 80 m/s [7]. The average solid-to-gas mass ratio is 14 which is below the rule-of-thumb ratio of 15 [8], to ensure that flow instability and solid saltation (settling) will not occur.

3. THERMAL HYDRAULICS DESIGN

In concert with the selection of blanket material and module design, we evaluated the thermal-hydraulics performance of the gas and particulate mixture. The first wall maximum temperature has to be less than 1000°C for the SiC-composite material, and the coolant pressure drop has to be small. The latter was designed to a selected total first wall and blanket pumping power limit of less than 2 MW. The key heat transfer problem in a D-T cycle fusion reactor blanket is the cooling of the first wall. The first wall will experience surface loading from the plasma in addition to the maximum volumetric power generation in the material due to the absorption of neutron energy.

From energy balance of the ARIES-I design, the thermal power from the first wall and blanket, Q , can be equated to the product of coolant mass flow rate, M , the gas and particles mixture heat capacity, C_{pm} , and the temperature difference between the outlet and inlet coolant, ΔT . Therefore for a fixed Q and ΔT , the key thermal-hydraulics design parameter of the coolant velocity, V , will then become a function of coolant channel dimension, particle to gas mixture mass ratio which determines C_{pm} , and to a lesser extent the pressure of the gas. At the same time, we have to maintain high enough carrier gas density for the coolant to operate in the particles dilute flow regime. These are the trade-off studies we did to select the reference ARIES-I design.

When solid particles are mixed into the gas stream, the mixture coolant will have a much higher volumetric heat capacity than the pure gas. In comparison to conventional gas coolant, in order to remove the same amount of power, this increase of coolant volumetric heat capacity will allow lower flow velocity and pressure drops while maintaining the same heat transfer capability. In order to maintain a high volumetric heat capacity, we would like to operate the coolant at a high particle to gas mass ratio W_s/W_g . This mass ratio is limited to ≤ 15 in order to prevent saltation or settling of the particles. These guidelines indicate the use of high effective gas density. Since for the same effective gas density, we can operate a higher density gas like CO_2 at a much lower pressure than a lower density gas like He, we have selected CO_2 as our carrier gas.

The idea of using a mixture of solid particles and gas as the reactor coolant is not new. Similar concepts had been proposed by Babcock and Wilcox [9] and Armour Research Foundation [10] for fission reactor applications in the early 1960s. In order to find the suitable heat transfer and pressure drop equations that would fit the regime of operation of our proposed blanket design, we reviewed the literature and found that the heat transfer and pressure drop correlations suggested by Schluderberg [9] are the most suitable for our design. The heat transfer and pressure drop equations can be written as:

$$Nu = 0.02 (RePr)^{0.8} \left[1 + \left(\frac{W_s}{W_g} \right) \left(\frac{C_{ps}}{C_{pg}} \right) \right]^{0.45}, \quad (1)$$

and

$$\frac{\Delta P_m}{\Delta P_g} = 0.022 \left(\frac{D}{\mu} \right)^{0.25} \left(\frac{1}{\rho_g V} \right)^{0.02} \left(\frac{\rho_m}{\rho_g} \right)^{0.73}, \quad (2)$$

where

Nu = Nusselt number of the mixture
 Re = Reynolds number of the gas,
 Pr = Prandtl number of the gas,
 W_s = Mass flow rate of the solid particles, kg/sec
 W_g = Mass flow rate of carrier gas, kg/sec
 C_{ps} = Specific heat of solid, J/kg °C
 C_{pg} = Specific heat of carrier gas, J/kg °C

ΔP_m = Pressure drop of the gas
and particle mixture, Pa
 ΔP_g = Pressure drop of the gas, Pa
 D = Flow channel diameter, m
 μ = Gas viscosity, kg/m sec
 ρ_m = Density of the mixture, kg/m³
 ρ_g = Density of the gas, kg/m³
 V = Coolant velocity, m/sec.

These correlations were obtained by performing experiments with graphite or catalyst particles in He, N₂, air, or CF₄ gases. The particle size used was in the range of 1 to 5 microns, and the tube diameter was in the range of 0.8 to 2.2 cm in diameter. The ranges for solid to gas mass ratio, coolant velocity and coolant pressure are, 1 to 13, 6 to 61 m/s and 0.2 to 0.9 MPa, respectively. These ranges of experimental regime are very similar to the operating regime of our blanket design as shown in the following design parameters section. These heat transfer and pressure drop correlations were used in our thermal-hydraulics calculations of the ARIES-I blanket design. The heat transfer coefficient of the mixture coolant h_m is given by

$$Nu = \frac{h_m D}{k} \quad , \quad (3)$$

where k = thermal conductivity of the gas, W/m·K. The film drop temperature ΔT_f is then given by

$$\Delta T_f = \dot{q}'' / h_m \quad , \quad (4)$$

where \dot{q}'' = surface heat flux, W/m².

The maximum wall temperature T_{max} is then the sum of the coolant temperature, the film drop temperature ΔT_f and the solid drop temperature ΔT_s . When ΔP_m of the coolant loop is known, the pumping power can then be calculated as the product of ΔP_m and the volume flow rate of the coolant mixture.

4. RESULTS

The goals for the ARIES-I thermal-hydraulics design are to maintain the first wall maximum temperature to less than 1000°C and the total first wall and blanket pumping power to less than 2 MW. Figures 2 to 4 illustrate the parametric results of the design. All the calculations were performed with a fixed thermal power of 2608 MW and a fixed outlet to inlet coolant temperature difference of 450°C, other parameters that were held constant are listed in Table 1.

Figure 2 shows that as the first wall channel width increases, the first wall coolant velocity will decrease as indicated by the increase of first wall temperature and the corresponding decrease of pressure drop and pumping power. Figure 3 shows that an increase of particle volume fraction in the gas, which results in a decrease of carrier gas volume flow rate and lower first wall coolant velocity, yields a corresponding increase of first wall temperature and decrease of pumping power. Figure 4 shows that increase of the coolant pressure will reduce W_s/W_g , yet the corresponding increase in coolant density dominates the increase of the heat transfer coefficient from the increase of the gaseous Reynolds number, as shown in Eq. (1). The increase of coolant pressure also leads to a slight decrease of coolant velocity which leads to a slight decrease of pumping power. In order to obtain a low stress ceramic design, we would like to maintain the coolant pressure as low as possible. It can also be noted in Fig. 4 that the coolant pressure should not be reduced too much lower than 0.5 MPa, since this can lead to an increase of first wall temperature to over 1000°C.

Based on the parametric results presented in Figs. 2 to 4, the reference thermal-hydraulics design for ARIES-I was selected and is presented in Table 2. It should be noted that we have assumed the model of a uniform circumferential heat depositon around a circular tube in our calculations, therefore with the configuration of our blanket module design which has surface heating to one side of the module, the potential decrease of effective heat transfer coefficient due to non-symmetric surface loading on the first wall has not been accounted for [11]. However, this effect is expected to be small, and as indicated in Fig. 2, it can potentially be compensated for by reducing the first wall channel dimension which will then lead to an increased heat transfer coefficient at the expense of an increase in pumping power.

TABLE 1
ARIES-I DESIGN PARAMETERS

Structure material, SiC	ceramic-composite
Gas, CO ₂	@ 0.5 MPa
Particles, SiC	@ 5 to 10 microns
Particles volume fraction, ϵ	1.5% in CO ₂
Average particles to gas mass ratio	14
Total reactor thermal power	2608 MW
Neutron wall loading	3.7 MW/m ²
First wall surface heat flux	0.55 MW/m ²
Maximum first wall volumetric power generation	23.9 MW/m ³
Blanket module width	0.35 m
Blanket module height	8.0 m
First wall channel diameter	0.029 m
First wall thickness	0.005 m
Li ₂ O blanket channel width	0.0025 m
Li ₂ O plate thickness	0.01 m

TABLE 2
REFERENCE FIRST WALL
AND BLANKET DESIGN

Coolant pressure	0.5 MPa
T_{in}	250°C
T_{out}	700°C
First wall T_{max}	946°C
First wall maximum velocity	43 m/s
First wall inlet velocity	37 m/s
First wall pressure drop	0.01 MPa
Blanket Li ₂ O T_{max}	954°C
Blanket coolant velocity	14.7 m/s
First wall and blanket total pressure drop	0.017 MPa
First wall and blanket pumping power	1.7 MW

5. CONCLUSIONS

Based on the ARIES-I first wall and blanket design, we have performed the thermal-hydraulics calculations for using a mixture of SiC particles at 1.5 volume percent, and CO₂ at 5 atm as the coolant. A design that can satisfy all the thermal-hydraulics requirements is presented. This design makes the use of ceramic-composite structural material more attractive because of lower coolant pressure. This scoping design shows the feasibility of the gas-carried particulate cooling concept for fusion reactors. More detailed analytically and experimental studies specific to the ARIES-I design will be needed. Some of these are in the areas of dilute flow design including flow distribution, control of particle erosion and detailed module flow channel design.

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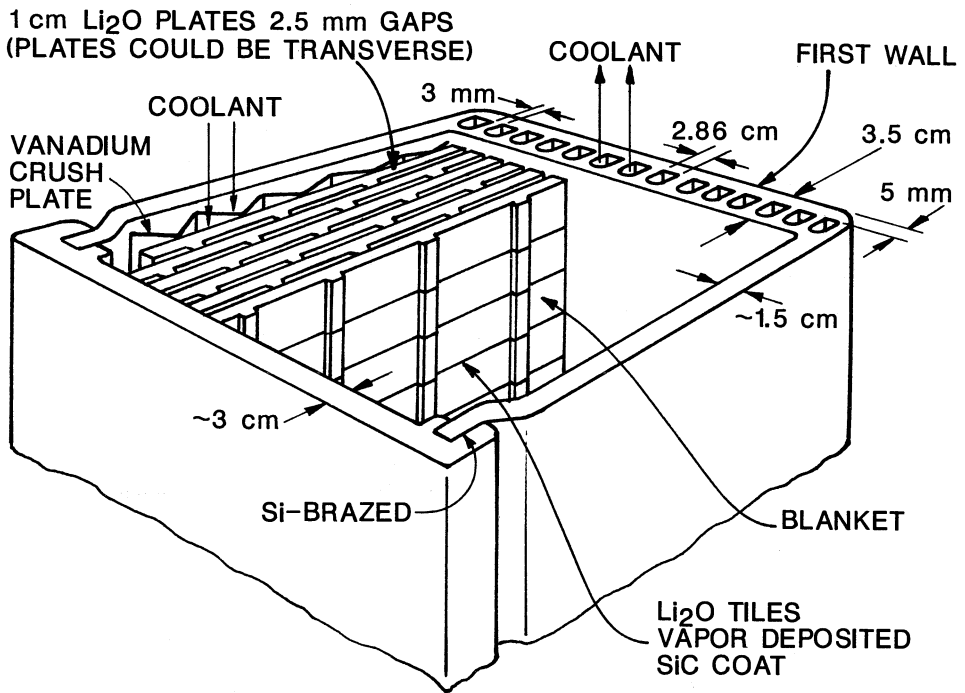


FIG. 1. ARIES-1 blanket module cross-section schematic.

h_{ex} — First wall heat transfer coefficient at coolant exit
 T_{ex-max} — First wall maximum temperature at coolant exit
 ΔP — First wall coolant pressure drop
 Power — Total first wall and blanket pumping power

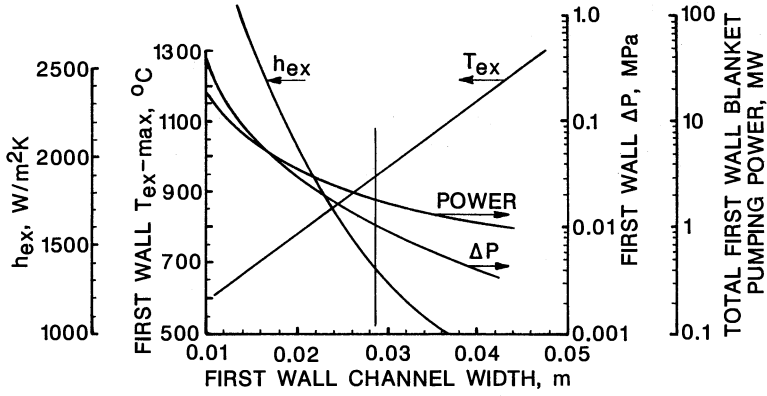


FIG. 2. Design parameters as functions of first wall channel width.

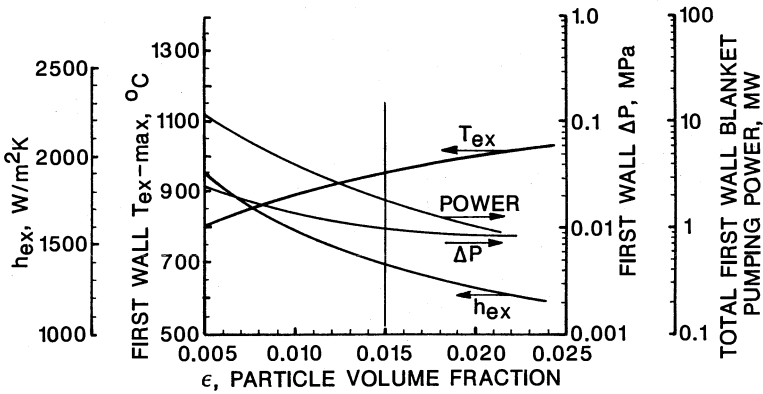


FIG. 3. Design parameters as functions of particle volume fraction in the coolant.

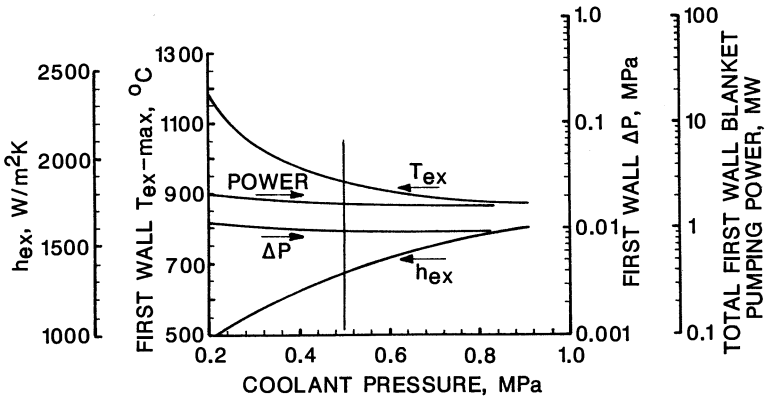


FIG. 4. Design parameters as functions of coolant pressure.