DESIGN WINDOWS FOR A He COOLED FUSION REACTOR*

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ABSTRACT

A design window concept is developed for a He-cooled fusion reactor blanket and divertor design. This concept allows study of a parameter regime under which a possible design exists with different design requirements, such as allowable pumping fraction. The concept identifies not only the required parameter regime, but also investigates the robustness of the design, i.e., the validity of the design with change of design parameters and requirements. Some recent directions of helium cooled design for ITER and for divertor can also be explained by this design window concept.

INTRODUCTION

Helium is an attractive coolant for both fusion and fission reactors. However, due to its low volumetric heat capacity ($\rho\ C_p$), and its low thermal conductivity, it requires high pumping power and has difficulty to handle high heat fluxes. Thus, the available design window to satisfy both heat transfer and pumping power is limited. To alleviate these problems, more recent design studies have gone to higher pressure, from 5 MPa [1], to 10 MPa [2], and up to 20 MPa [3]. Also, the flow length of the coolant has been reduced [4]. Both of these approaches are in the right directions from heat transfer and pumping power point of views. However, the design becomes more complicated with either higher pressure or large number of coolant tubes. Thus, the design window considerations are important to select the optimum regime of the design.

From thermal hydraulics aspect of a helium cooled reactor design, there are four governing equations which will determine the design window bounded by heat transfer, pressure drop, flow stability, and tritium breeding requirements. In this paper we derive these equations, simplify them, and calculate the available design window which will indicate the degree of robustness of the design under particular conditions.

The design window considerations can be modified by the change of the system design. If, for instance, a surface roughness is required to improve heat transfer, we just need to use the proper equations for heat transfer and pumping power for the proper coolant tube configurations to replace the two equations used here. The design window can then be generated by the new equations, and the size of the design window of the new design can be compared to the ones with smooth tubes. Thus, the advantages of changing the design can easily be compared to the original design.

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EQUATION DERIVATION

The governing equations of the thermal hydraulic design of a helium cooled reactor are:

1. The pumping power fraction (VΔP/Q) has to be smaller than a design value (taken to be 0.05 here).

2. The heat transfer coefficient has to be larger than a design value (taken to be 5000 W/m^2-K here).

3. The structural fraction (assuming a SiC structure) has to be smaller than a design value (taken to be 20% here).

4. The Reynold's number has to be larger than a certain value (taken to be 5000 here).

With proper derivations, those four governing equations can be shown to have the following forms:

$$\frac{V\ \Delta P}{Q} = \left(\frac{32\ f}{\pi^2}\right)\left(\frac{1}{\rho^2\ C_p^3}\right)\left(\frac{L^3\ q''^2\ x^2}{D^3\ \Delta T^3}\right) \times 10^{-6} \qquad (1)$$

≤ 0.05

$$h = 0.024\left(\frac{k}{\mu^{0.8}\ C_p^{0.8}}\right)\left(\frac{L^{0.8}\ q''^{0.8}\ x^{0.8}}{D\ \Delta T^{0.8}}\right) \qquad (2)$$

≥ 5000 MW/m^2 - °C

$$(SiC)/(SiC + Li_2O) \leq 0.2 \qquad (3)$$

$$Re = \frac{4}{\pi}\left(\frac{1}{\mu\ C_p}\right)\left(\frac{L\ q''\ x}{\Delta T}\right) \qquad \geq 5000 \qquad (4)$$

in which

f = friction factor
ρ = density
C_p = specific heat
k = thermal conductivity
q″ = surface heat load, MW/m^2
L = coolant tube length, m
x = heat load correction factor (for $D_o > D_{in}$, nuclear heating in the tube and heat load from the back of the tube etc.)
D = coolant tube ID
ΔT = coolant temperature rise
μ = coolant viscosity

The material properties are taken at 500°C and 10 MPa pressure. The equations can be further simplified to the following forms:

$$\frac{1}{D^3}\left(\frac{L}{\Delta T}\right)^3 (q'' x)^2 \le 15.6 \quad (5)$$

$$\frac{1}{D}\left(\frac{L}{\Delta T}\right)^{0.8} (q'' x)^{0.8} \ge 3.27 \quad (6)$$

$$\frac{SiC}{SiC + Li_2O} \le 0.2 \quad (7)$$

$$\left(\frac{L}{\Delta T}\right)(q'' x) \ge 0.001 \quad (8)$$

Thus, the important parameters are $L / \Delta T$ and D. These are the two parameters we will use to demonstrate the design window range of a helium cooled reactor under different helium conditions. If the blanket configuration is fixed, the only important parameter we can change is the density of helium, i.e., helium pressure.

RESULTS

Fig. 1 through 4 show the results of heat transfer and pumping power limitations for four different helium pressures. It can be seen that the design window increases as the helium pressure increases. At 2 or 5 MPa, the available design window is very small. Even at higher pressure, the window is rather small, unless we can accept a low heat transfer coefficient.

Increasing the allowable pumping power is usually not an effective way to increase the size of the design window. It can be seen that the pumping power fraction is very sensitive to all the parameters, either to the square or to the cubic power dependence. This explains the difficulties facing the ITER blanket design, since L is large (~20 m), and ΔT is rather small (~200°C). The only way to reach a reasonable design window is to increase the helium pressure (i.e., to increase density of helium).

The heat transfer is much less sensitive to such parameters, as can be seen on Eq. (2). It depends on all the parameters either linearly, or by 0.8 power dependence. Therefore, reducing the required heat transfer coefficient is a cost effective way to increase the size of the design window. Therefore, different heat transfer coefficients were used on the figures to demonstrate the effect on heat transfer requirements and consequently on the size of the design window.

It should also be noted that the ratio of $L / \Delta T$ has both upper and lower bound. Both of those limits have to be observed on the selection of design parameters and on the heat transfer.

For the case of helium pressure of 5 MPa, the maximum achievable heat transfer coefficient is approximately 3000 W/m^2-K. If the coolant tube diameter is kept at around 0.01 m, the L/ΔT has to be between 0.015 to 0.035 m/C. If the helium temperature rise is kept at 200°C, the coolant path length has to be between 3 m and 7 m. The heat transfer coefficient will be below 2000 MW/m^2-K if the coolant tube length is less than 3 m, and the pumping power will exceed the design limit if the tube length exceeds 7 m. This put an important design limitation on the selection of the blanket configuration. A similar limitation exists with a larger coolant tube diameter.

If coolant flow path is 20 m, and the coolant ΔT is 200°C, the only way to obtain a reasonable design point is to push the helium pressure toward 20 MPa, as shown in Fig. 4. The pumping power limit corresponds to a large value of L/ΔT. Also, high heat transfer coefficient can be achieved.

CONCLUSIONS

A design window consideration for thermal hydraulic design of a fusion reactor blanket has been established. It demonstrated that the design space is very limited for helium coolant with a pressure lower than 5 MPa. When helium pressure increases, the design window becomes larger, indicating a more robust design. For the ITER design, with a very long coolant path, the helium pressure has to be around 20 MPa in order to have a reasonable design window. This calculation is consistent with the trend of helium cooled design, i.e., pushing toward higher helium pressure. However, higher helium pressure will cause more complexity of the engineering system to contain the helium.

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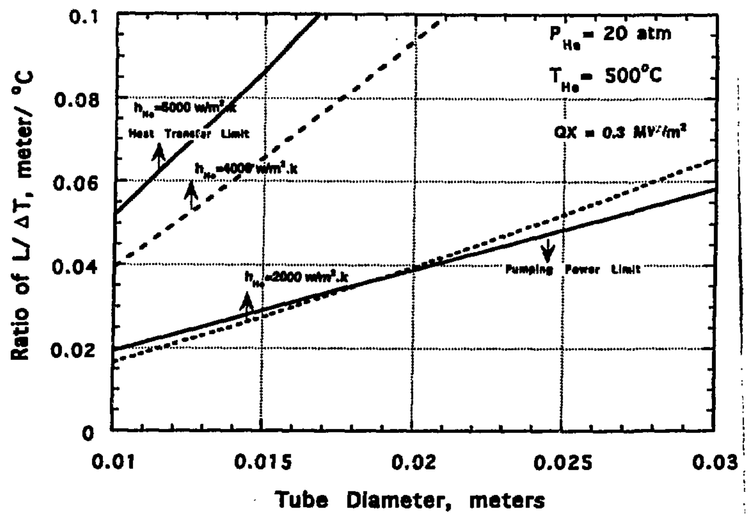

Fig. 1 Design limitations for helium pressure of 2 MPa

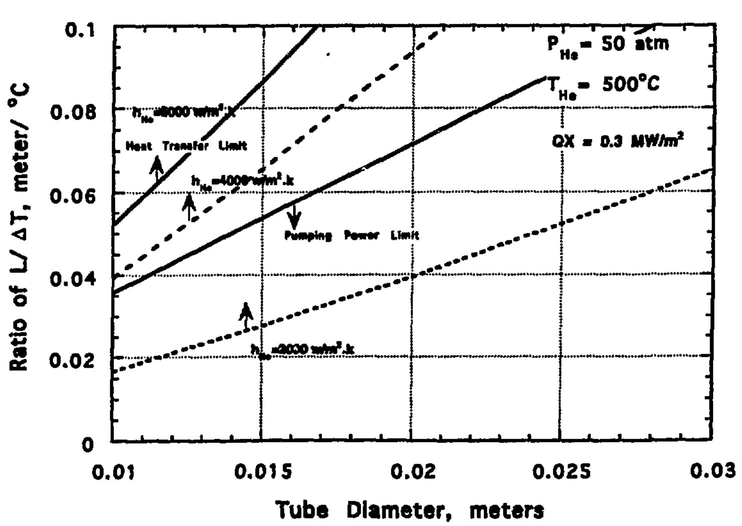

Fig. 2 Design limitations for helium pressure of 5 MPa.

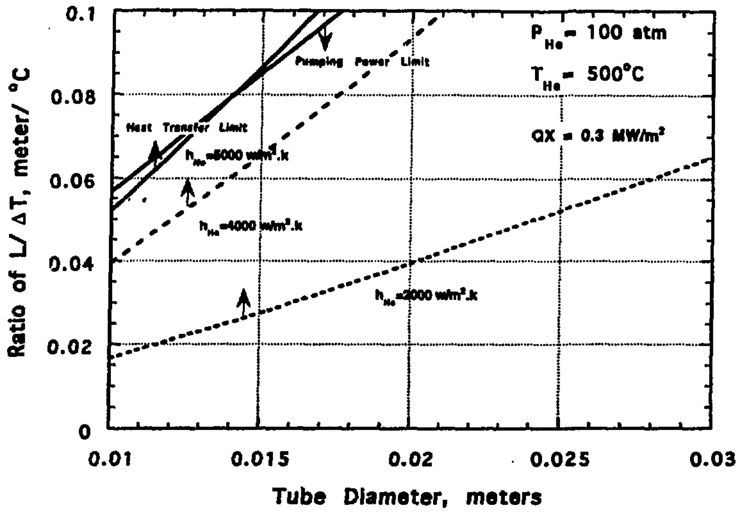

Fig. 3 Design limitations for helium pressure of 10 MPa.

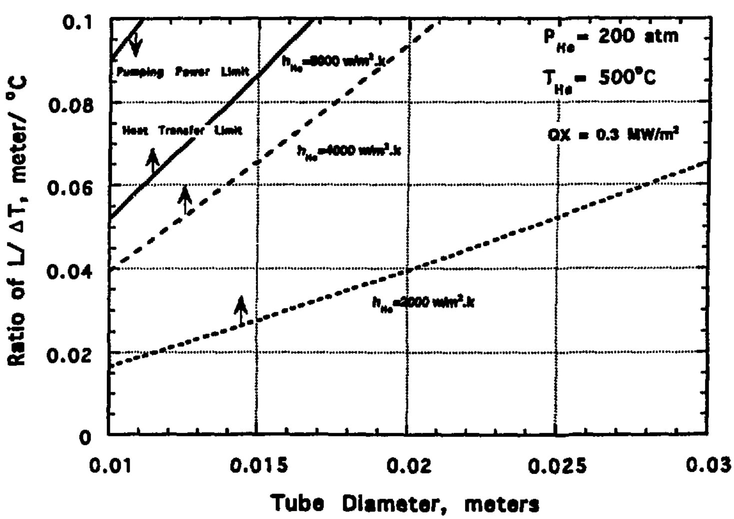

Fig. 4 Design limitations for helium pressure of 20 MPa.