

Structured Porous Media for High Heat Flux Fusion Applications

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Abstract-- The use of structured porous media is a proposed technique to achieve higher heat transfer coefficients by increasing the specific surface area for heat transfer while aiming to maintain acceptable pressure drop and pumping power. The general design strategy is to minimize the coolant flow path through the porous medium while optimizing the porous medium characteristics to minimize the friction pressure drop for a given heat transfer performance.

A comprehensive thermo-fluid model called MERLOT [1] was used to assess the use of porous heat transfer media for fusion plasma facing component applications. A parametric study was performed to assess the relative importance on the heat transfer performance of key design parameters including the solid conductivity, the porosity magnitude and distribution, the microstructure characteristic dimension, and the local heat transfer coefficient. The analysis was carried out for different incident heat fluxes of up to 30 MW/m^2 with the goal of identifying particularly attractive sets of design parameters for plasma facing components.

I. INTRODUCTION

Porous metal heat exchangers have been studied in the past because of the large surface area they provide for heat transfer. For example, Thermacore has developed a porous metal heat exchanger applicable to fusion plasma-facing components [2,3]. A test article was fabricated and tested in the Sandia National Laboratory electron beam facility where it demonstrated relatively high overall heat transfer coefficients [3,4]. Such a configuration was also considered for the ARIES-ST divertor, as illustrated in Fig. 1 [5]. The heat augmentation effect provided by this concept must be evaluated with respect to the associated pressure drop penalty. For a given particle dimension, the pressure drop through a porous medium is highly dependent on the porosity, ϵ , while the heat transfer coefficient tends to depend more on the specific surface area, S_p . In a conventional particle bed, where d_p is the particle diameter, S_p is directly related to ϵ (1) such that it becomes difficult to optimize the bed characteristics.

$$S_p = 6(1-\epsilon)/d_p \quad (1)$$

Minimizing the flow path length, as achieved in the concept shown in Fig. 1, does help somewhat to reduce the pressure drop penalty.

An innovative design solution is based on a porous material using non-spherical fibers where the porosity and specific surface area can be optimized beyond their conventional particle bed dependence. Such a porous foam would have high porosity (which governs the pressure drop) but with specific surface area (influencing the heat transfer)

higher than a conventional packed bed can provide. For example, Ultramet has proposed a new class of open cell, low density, high-temperature performance refractory foams for a variety of aerospace and industrial applications [6]. These cellular materials can be optimized for various properties simultaneously, can be furnished in various sizes and configurations, and are easy to machine. Such materials would permit higher allowable heat flux for the helium-cooled concept while maintaining the safety advantages of using inert gas as coolant.

This work focuses on the assessment and optimization of porous heat transfer media using an improved phenomenological thermo-fluid model called MERLOT with the intent of guiding the direction of future modeling, material and experimental R&D.

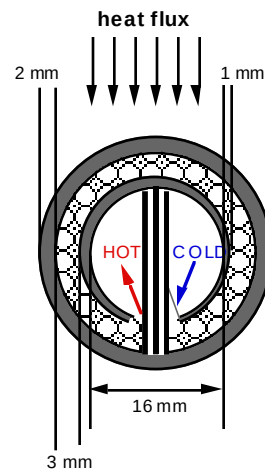


Fig. 1. Schematic of a plasma divertor tube with 3-mm porous heat exchanger and inlet and outlet helium headers separated with thermal insulation, proposed for ARIES-ST. The design heat flux normal to the tube is 5 MW/m^2 [5].

II. POROUS MEDIA ANALYSIS

A. Parametric Studies

Table I summarizes the parameters used for the parametric studies on the geometry shown in Fig. 1. The top half of the tube ($\theta=0$ to $\theta=\pi$) is subjected to heat flux, q'' . Constant, isotropic solid thermal conductivity and porosity are assumed for simplicity although neither is a requirement.

TABLE I
PARAMETERS USED FOR PARAMETRIC STUDIES

Fluid	He
Fluid properties	Varied as $f(T)$
He inlet pressure, P_{in}	4 MPa
He inlet temperature, T_{in}	823 K
He outlet temperature, T_{out}	various
Solid thermal conductivity, k_s	50-200 W/m-K
Porous medium characteristic dimension, d_{char}	0.1 mm (unless noted)
Bulk porosity, ϵ	various
Porosity variation in bulk	constant
Inner radius, r_{in}	9 mm (unless noted)
Outer radius, r_{out}	12 mm (unless noted)
Heat flux, q''	5 and 30 MW/m ²

As a measure of the heat transfer performance, an effective heat transfer coefficient, h_{eff} , is calculated at each location along the heated wall by dividing the applied heat flux by the difference between the wall temperature and the average coolant temperature at this θ location. The effective heat transfer coefficient is much higher at the entrance and decreases to a constant value as the flow becomes thermally developed indicating the attractiveness of designing for high heat flux accommodation close to the entrance region. However, when evaluating different configurations, h_{eff} at the coolant outlet is chosen as a reasonable comparative measure of heat transfer performance.

1) Porosity and Velocity

The parametric studies started by investigating the effect on heat transfer performance of changing the bulk porosity. Fig. 2 shows the variation of h_{eff} with porosity as calculated by MERLOT for a heat flux of 5 MW/m² and for different solid thermal conductivities. The effective heat transfer coefficient decreases with increasing porosity approaching the regular channel value at 100% porosity. The solid thermal conductivity has an important effect on h_{eff} in particular at lower porosities. High solid thermal conductivity is desirable since it does not adversely affect the pressure drop while increasing h_{eff} .

Fig. 3 shows the variation of h_{eff} with velocity for different porosity values for $q''=5$ MW/m². The effective heat transfer coefficient increases with velocity but decreasingly so at higher velocities where the fluid contribution to the overall heat transfer is high enough that conduction through the solid becomes the limiting factor. Fig. 4 shows the corresponding maximum wall temperature at the interface with the fluid outlet.

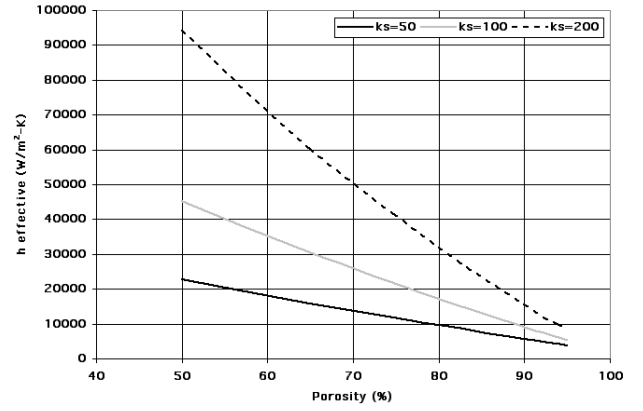


Fig. 2. Effective heat transfer coefficient (W/m²-K) at outlet as a function of porosity for different solid thermal conductivities ($q''=5$ MW/m², $d_{char}=0.1$ mm, He $T_{in}=823$ K, He $T_{out}=1223$ K).

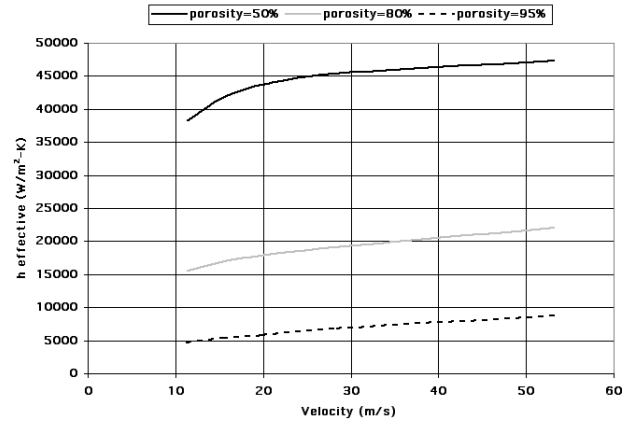


Fig. 3. Effective heat transfer coefficient (W/m²-K) at outlet as a function of velocity for different porosities ($q''=5$ MW/m², $d_{char}=0.1$ mm, $k_s=100$ W/m-K, He $T_{in}=823$ K).

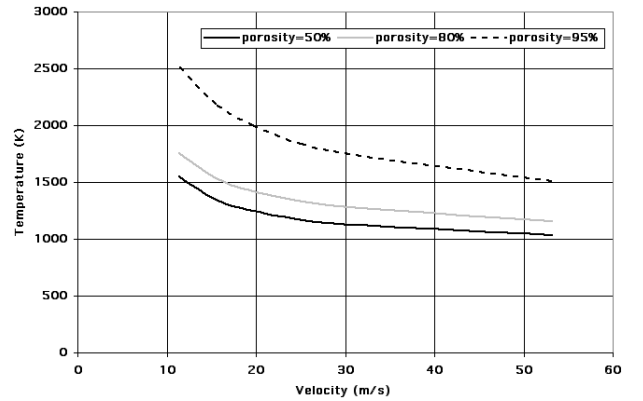


Fig. 4. Maximum wall temperature (K) at the fluid outlet interface as a function of velocity for different porosities ($q''=5$ MW/m², $d_{char}=0.1$ mm, $k_s=100$ W/m-K, He $T_{in}=823$ K).

Fig. 5 shows the variation of the He pressure drop, ΔP , with velocity. ΔP increases exponentially with velocity and is much higher for cases with lower porosities.

The design optimization must balance the heat transfer performance for the given porous configuration with the pressure drop penalty. An interesting performance to penalty measure is the ratio of h_{eff} to pressure drop, which is shown as

a function of velocity in Fig. 6. This ratio is much higher at lower velocities and decreases rapidly with velocity, indicating the benefit of optimization at the lowest possible velocity. Interestingly, it also indicates the benefit of optimization at the highest possible porosity as the ratio decreases sharply with decreasing porosity.

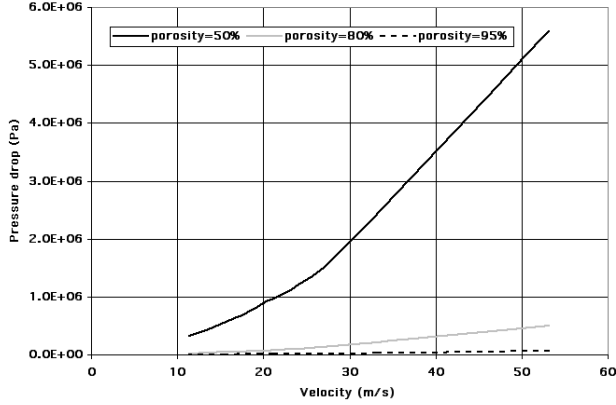


Fig. 5. Pressure drop (Pa) as a function of velocity for different porosities ($q''=5\text{MW/m}^2$, $d_{\text{char}}=0.1\text{ mm}$, He $T_{\text{in}}=823\text{K}$).

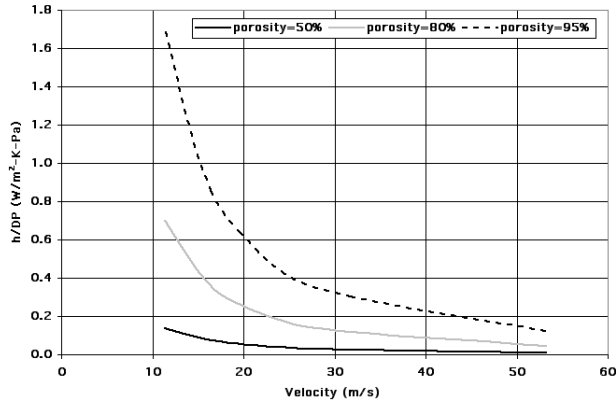


Fig. 6. Ratio of effective heat transfer coefficient at outlet to pressure drop as a function of velocity for different porosities ($q''=5\text{MW/m}^2$, $d_{\text{char}}=0.1\text{ mm}$, $k_s=100\text{ W/m-K}$, He $T_{\text{in}}=823\text{K}$).

2) Porous Medium Characteristic Dimension and Channel Width

The porous medium characteristic dimension and channel width were then adjusted to understand their effect on the heat transfer performance and corresponding pressure drop. Fig. 7 shows the variation of h_{eff} with the characteristic particle dimension for a heat flux of 5 MW/m^2 . The surface area to volume ratio decreases with increasing porous medium characteristic dimension, so the drop in the effective heat transfer coefficient for increasing porous medium characteristic dimension is expected. Decoupling the pebble bed relationship between surface area and characteristic particle dimension found in (1) by tailoring the microstructure (as in a porous foam), should improve the heat transfer to pressure ratio considerably over that of conventional spherical particles.

Fig. 8 shows that the pressure drop also decreases with increasing particle characteristic dimension. Fig. 9 is a plot of $h_{\text{eff}}/\Delta P$ as a function of particle dimension and shows that a

larger characteristic dimension gives better results for the cases considered. This is probably more applicable to porous media approximating the shape of spherical particles or cylindrical fibers which better fit the model of permeability assumed for the analysis.

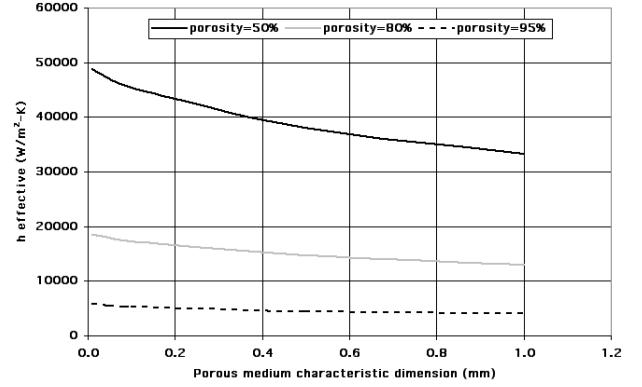


Fig. 7. Effective heat transfer coefficient at outlet as a function of porous medium characteristic dimension for different porosities ($q''=5\text{MW/m}^2$, $k_s=100\text{ W/m-K}$, He $T_{\text{in}}=823\text{K}$, He $T_{\text{out}}=1223\text{K}$).

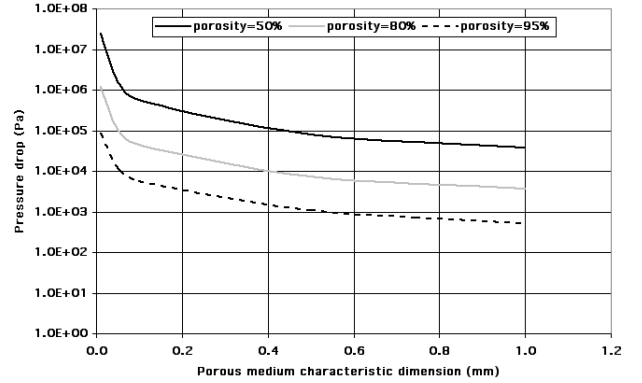


Fig. 8. Pressure drop as a function of porous medium characteristic dimension for different porosities ($q''=5\text{MW/m}^2$, He $T_{\text{in}}=823\text{K}$, He $T_{\text{out}}=1223\text{K}$).

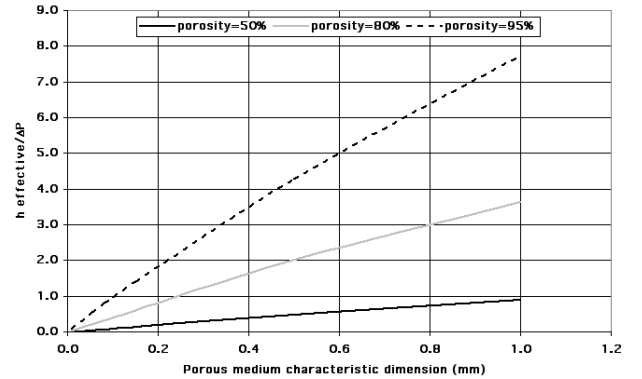


Fig. 9. Ratio of effective heat transfer coefficient at outlet to pressure drop as a function of porous medium characteristic dimension ($q''=5\text{MW/m}^2$, $k_s=100\text{ W/m-K}$, He $T_{\text{in}}=823\text{K}$, He $T_{\text{out}}=1223\text{K}$).

Finally, the effect on the heat transfer performance of changing the channel width while maintaining the same mass flow and pressure drop was investigated. In order to maintain the same mass flow for different sized channels, the velocity

must be increased as the channel width is decreased. In order to maintain the same pressure drop for different channel widths, the porosity was adjusted (for a fixed porous medium characteristic dimension of 0.15 mm) to offset the increased pressure drop incurred from the increased velocity. There is a definite advantage to a small channel dimension with a high porosity medium and high fluid velocity.

B. Example Optimization for a Specific Divertor Case

The results from the above parametric studies were used in the determination of an attractive set of parameters for the ARIES-ST divertor with an assumed tungsten armor thickness of 3-mm. The operating temperature range for tungsten is assumed to be from ~973-1073K to 1673 K (~ 700-800°C to ~1400°C), consistent with [7]. For a design heat flux of 5 MW/m² and assumed thermal conductivity of 100 W/m-K, the temperature drop through the W armor is about 150 K which when added to the maximum channel wall temperature would yield the maximum W temperature. From the results shown in Fig. 4, the required velocities to maintain the maximum W temperature <1400°C are about 11, 15 and 53 m/s for porosity values of 50%, 80% and 95%, respectively. From Fig. 6, the ΔP 's corresponding to velocities of 11, 15 and 53 m/s and porosity values of 50%, 80% and 95% are 0.32, 0.07 and 0.07 MPa, respectively.

For the 30 MW/m² case, the temperature drop for a 3-mm W wall is about 900 K, leaving little room for a reasonable film drop to meet the requirement of a maximum W temperature of 1673 K. Thus, such a porous medium cannot satisfy the requirement unless very low porosity and very high pressure drop are allowed. However, if the W thickness is reduced to 1 mm, the maximum W temperature can be maintained <1673 K with velocities of about 60 m/s and 120 m/s for porosities of 50% and 80% respectively. The corresponding pressure drops are 7 MPa and 2 MPa, respectively.

III. CONCLUSIONS

MERLOT was used to perform detailed parametric studies to assess and optimize porous media for high heat flux applications. Specific and well-characterized experimental results on such configurations are scarce and these parametric studies are useful in determining key variables and in guiding future R&D.

The major observations from the results of the studies presented in this paper are summarized below:

- The local effective heat transfer coefficient, h_{eff} , is much higher at the entrance region indicating the attractiveness of designing for high heat flux accommodation close to the entrance region.
- High solid thermal conductivity has an important, beneficial effect on h_{eff} especially at lower porosity.
- The ratio of h_{eff} to pressure drop is much higher at lower velocities and decreases rapidly with velocity, indicating the benefit of optimization at the lowest possible velocity for a given porosity. Interestingly, for a given velocity, it also indicates the benefit of optimization at the highest possible

porosity as the ratio decreases sharply with decreasing porosity. The ratio of h_{eff} to pressure drop also increases with increasing porous medium characteristic dimension.

- Decoupling the pebble bed relationship between surface area and characteristic particle dimension by tailoring the microstructure (as in a porous foam), would significantly improve the h_{eff} to pressure ratio over that of a conventional particle bed.

- Except in the case of change in solid thermal conductivity, the relative pressure drop penalty seems to be dominant over the corresponding enhancement in h_{eff} when adjusting all other parameters considered. Therefore, a strategy to minimize the pressure drop should be used.

- There is an advantage to a small channel dimension with a high porosity medium and high fluid velocity. More simply, a higher velocity is preferable to a lower porosity when maximizing the heat transfer performance for a given pressure drop.

- A He-cooled porous medium design seems to be an attractive divertor candidate. It is able to comfortably accommodate heat fluxes of ~5 MW/m² and possibly up to 20-30 MW/m² at the cost of higher pressure drops (~2 MPa in the latter case) and higher system pressure, and/or lower coolant inlet temperature and lower-quality heat extraction.

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