MHD EFFECTS ON HEAT TRANSFER IN A MOLTEN SALT BLANKET

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Heat transfer in closed channel flows of molten salts (MS)s, such as FLiBe or FLiNaBe, has been considered under specific reactor conditions. MHD effects have been accessed for two blanket concepts: self-cooled MS blanket, and dual-coolant MS blanket. The effect of heat transfer degradation due to turbulence reduction by a magnetic field in the First Wall channels of the self-cooled blanket was analyzed with the K-ε model of turbulence. In the dual-coolant blanket, the MS flow is laminar. A 2-D MHD code was used to calculate the laminar velocity profile first. Then, the temperature field was calculated using a 3-D temperature code. Reasonable interface temperatures below the material limit of 550°C, and low heat escape from the breeder zone have been demonstrated. Model limitations and the ways of their improvement are also discussed.

I. INTRODUCTION

As a part of the US Advanced Power Extraction (APEX) program (1997-2003) and recently in the course of the US ITER TBM studies (2003-present), a number of blanket design options with molten salt (FLiBe or FLiNaBe) as the tritium breeder/coolant have been evaluated. In the re-circulating self-cooled blanket design [1], a re-circulation flow scheme was utilized that allows the coolant (high melting temperature FLiBe) mass flow rate in the First Wall (FW) channels to be considerably higher than the flow rate in the power conversion system. This effect was achieved by employing a bypass to the flow in the large central channel. The distinctive feature of the concept is that the flows in the FW channels are turbulent to provide a high heat transfer coefficient, and thus to ensure allowable FW temperatures. More recently [2], another design option was considered with the helium cooled ferritic structure and self-cooled breeder zone using either low melting temperature FLiBe or FLiNaBe as a breeding material. In this dual-coolant design, the molten salt flows slowly (U~5 cm/s) through a large central poloidal channel with a characteristic cross-sectional dimension of about 0.4 m. Such flow allows for a high MS exit temperature leading to a reasonably high blanket thermal efficiency (~40%). Unlike the flows in the self-coolant blanket, flows in the dual-coolant blanket are laminar. Typical dimensionless flow parameters for the outboard module are shown in Table 1: the Reynolds number, $Re=UD/\nu$, Hartmann number, $Ha=B_0D(\sigma/\nu\rho)^{0.5}$, (both built through the hydraulic diameter, D), and their ratio, Ha/Re. Here B_0 is the magnetic field (toroidal), σ is the electrical conductivity, ν is the kinematic viscosity, and ρ is the density. The parameter Ha/Re is the indication of the MHD flow regime. Usually, if $Ha/Re>(Ha/Re)_{cr}$ the flow is treated as laminar. The critical value of this parameter for a flow in a transverse magnetic field is about 1/200=0.005 [3].

TABLE I
Typical dimensionless parameters in the MS blanket flows at the outboard

Option	Ha	Re	Ha/Re
Self-cooled [1], FW flow	5	7000	7×10^{-4}
Dual-coolant [2]	200	2000	0.1

The main goal of the present study is to access the MHD effects on heat transfer in the range of the flow parameters relevant to a fusion reactor. The important MHD effect in the turbulent flows in the self-cooled blanket is turbulence reduction by a magnetic field through the Joule dissipation, which can result in heat transfer degradation. In the dual-coolant design, the MS flows are typically laminar. The effect of the magnetic field on heat transfer appears mostly due to modifications of the velocity profile caused by the Lorentz force.

II. MODEL, CODE, AND RESULTS FOR THE SELF-COOLED MS BLANKET

The turbulence model used in the analysis is the “K-ε” model, which was modified to incorporate MHD effects [4]. The difference between the present model and the standard “K-ε” model is an additional sink term on the RHS of the equation for the turbulent kinetic energy (K) and a destruction term on the RHS of the equation for the dissipation rate (ε):

$$\frac{\partial K}{\partial t}+\langle v_j\rangle\frac{\partial K}{\partial x_j}=\underbrace{\nu_t\left(\frac{\partial v_i}{\partial x_j}\right)^2}_{Production}+\underbrace{\frac{\partial}{\partial x_j}[(\nu+\frac{\nu_t}{\sigma_K})\frac{\partial K}{\partial x_j}]}_{Diffusion}-\underbrace{\varepsilon-\varepsilon_{em}^K}_{Dissipation};$$

$$\frac{\partial\varepsilon}{\partial t}+\langle v_j\rangle\frac{\partial\varepsilon}{\partial x_j}=C_1\frac{\varepsilon}{K}\nu_t\left(\frac{\partial\langle v_i\rangle}{\partial x_j}\right)^2+\frac{\partial}{\partial x_j}[(\nu+\frac{\nu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_j}]-C_2\frac{\varepsilon}{K}\varepsilon-\varepsilon^{\varepsilon}_{em}.$$

The correlations in the equations had been adjusted for three magnetic field orientations: wall-normal, spanwise, and streamwise [4]. The numerical code solves the flow equations written in the boundary layer approximation along with the equations for K and ε using a non-uniform mesh, which clusters the mesh points near the walls. The calculated values of K and ε are then used to calculate the eddy viscosity (ν_t) to close the model: $\nu_t = C_\nu K^2/\varepsilon$.

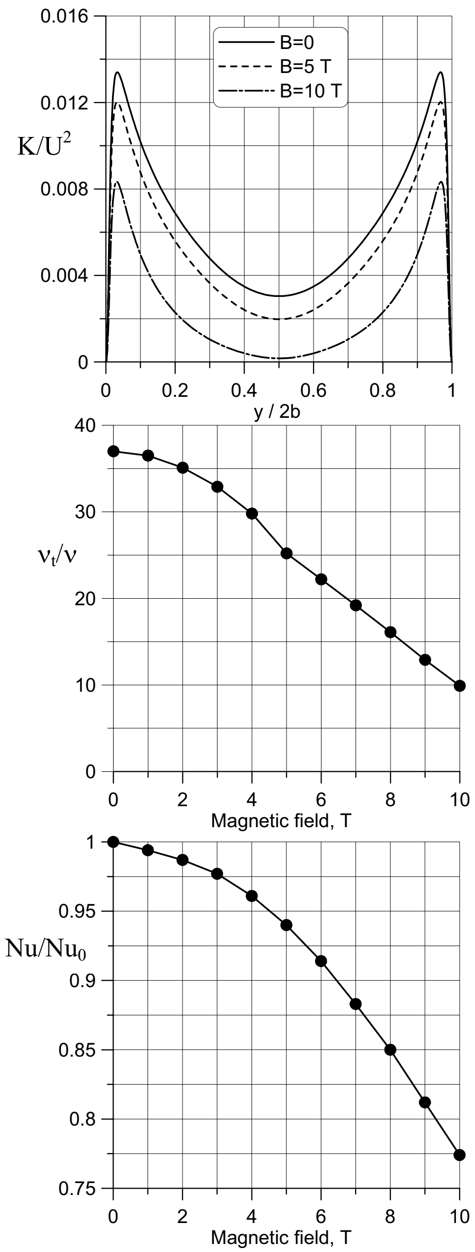

Fig.1. Effect of the wall-normal magnetic field on the reference FLiBe turbulent flow: U=5 m/s, b=1 cm (channel half-width). The plots are for: kinetic energy, eddy viscosity, and fully-developed Nusselt number.

The calculations were conducted for high melting temperature FLiBe ($(LiF)_2\bullet(BeF_2)$, T_m=742 K). The channel characteristic cross-sectional dimension is 2 cm. The velocity is 5; 10; and 15 m/s. The channel length is 8 m. The surface heat flux at the FW is 1 MW/m^2. The magnetic field is 0 to 10 T. The calculated results for the case of the wall-normal magnetic field are shown in Fig.1.

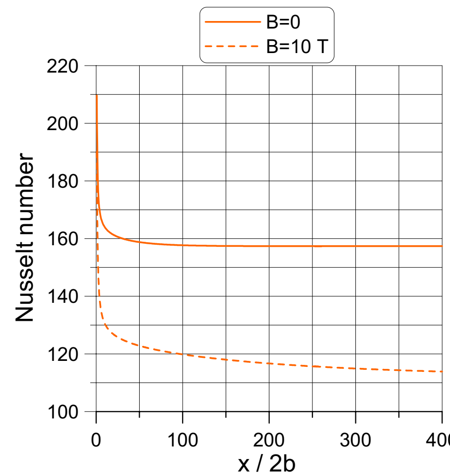

Fig.2. Nusselt number distribution along the channel with and without a magnetic field. The flow parameters are shown in Fig.1

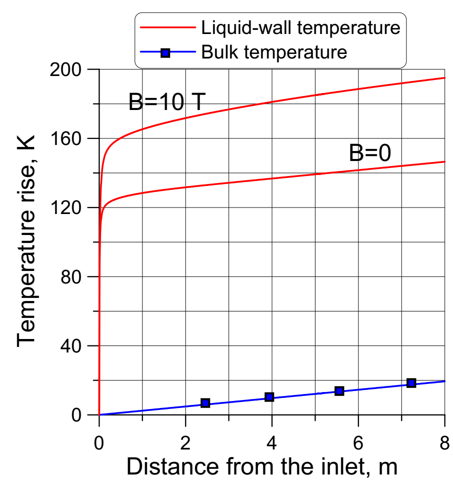

Fig.3. FLiBe temperature rise at the heated wall with and without a magnetic field. The flow parameters are shown in Fig.1.

One can see that the magnetic field growth results in pronounced reduction of both the turbulent kinetic energy and eddy viscosity. It also reduces the fully-developed Nusselt number by about 25% when the magnetic field changes from 0 to 10 T. The Nusselt number distribution along the channel is shown in Fig.2. Additionally to heat transfer degradation, one can see that in the presence of a magnetic field the transition length becomes longer.

Figure 3 demonstrates the temperature rise in the liquid at the heated wall.

It should be noted that the wall-normal magnetic field has the strongest effect on turbulence. Less effect is demonstrated in the spanwise magnetic field, and the least effect in a streamwise magnetic field. The streamwise magnetic field case corresponds to a toroidal blanket and is not related to the present design. However, for the sake of completeness we put here data for all three orientations of the magnetic field. The tendencies in turbulence reduction by a magnetic field are demonstrated in Table II. One can see that for the velocities of 15 m/s, the MHD effect on heat transfer is insignificant for all three orientations of the magnetic field. It is also insignificant if the liquid flows toroidally.

TABLE II
Temperature rise (K) at the heated wall in the reference MS flow for three orientations of the magnetic field

Case	Wall-normal	Spanwise	Streamwise
5 m/s, 0 T	127.1	127.1	127.1
5 m/s, 5 T	135.9	131.1	127.1
5 m/s, 10 T	175.5	143.7	127.3
10 m/s, 0 T	67.4	67.4	67.4
10 m/s, 5 T	69.3	68.2	67.4
10 m/s, 10 T	75.5	70.9	67.5
15 m/s, 0 T	46.6	46.6	46.6
15 m/s, 5 T	47.4	46.9	46.6
15 m/s, 10 T	49.8	48.1	46.6

III. MODEL, CODE, AND RESULTS FOR THE DUAL-COOLANT MS BLANKET

Detailed description of the design is given in [2]. The radial build of the blanket module with basic dimensions is shown in Fig.4. Reduced Activation Ferritic Steel (RAFS) with the allowable maximum temperature of 550°C is used as a structural material. Two breeders were considered: low melting point FliBe ((LiF)•(BeF2), T_m=653 K), and FLiNaBe (T_m=580 K).

The calculations were performed for the outboard blanket segment with the maximum neutron wall loading 3 MW/m^2, and the maximum surface heat flux 0.42 MW/m^2. The poloidal flow length is 8 m. The calculations take into account poloidal variations in the thermal loads. First, the laminar velocity profile is calculated using a 2-D code [5]. The flow is supposed to be fully developed and driven by a pressure gradient. The "banana shape" effect at the ends of the blanket segment is presently not taken into account. Also, the effect of the spatial field variations is not considered. The velocity profile is shown in Fig.5. The velocity profile demonstrates "M shape" due to electrically conducting channel walls. However the side-wall jets are not very pronounced due to moderate *Ha*.

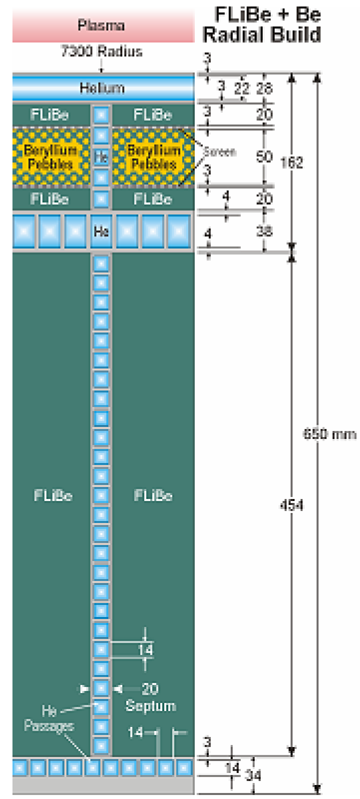

Fig.4. Radial build of the dual-coolant MS blanket.

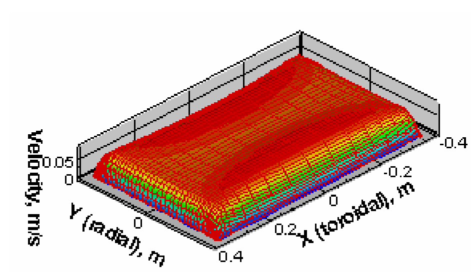

Fig.5. 2-D velocity profile in the reference FLiBe MHD flow in the dual-coolant MS blanket: Re=7000, Ha=200.

The calculated velocity profile was then used as an input to a 3-D heat transfer code. The heat transfer code solves the energy equation, which includes the diffusion and convection terms as well as the source term that stands for the volumetric heat generated by neutrons:

$$\rho C_p\left(\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}\right)=$$
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q'''.$$

A special procedure was used to ensure energy conservation in the calculations, since the whole integration domain consists of several sub-domains of different physical properties. With this procedure the energy equation was solved in a continuous manner over the whole domain using conservative finite-volume formulation. Also, non-uniform meshes were used to concentrate mesh points near the interfaces.

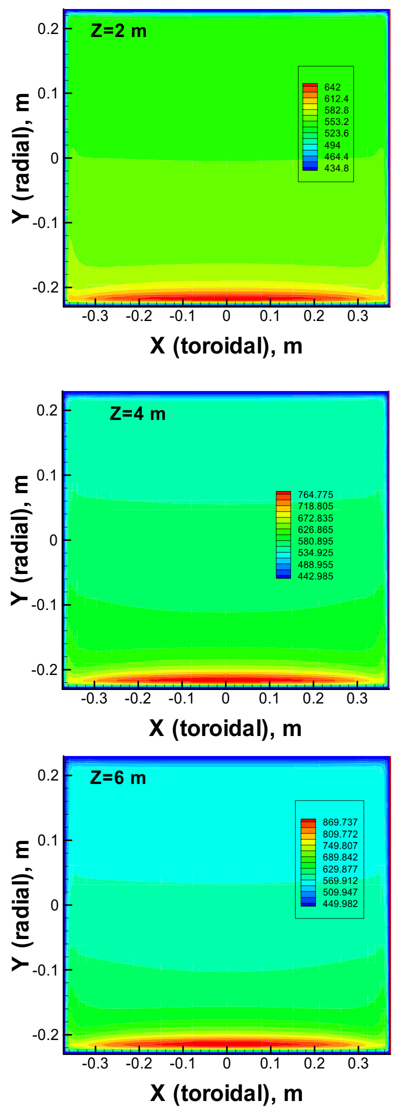

Fig.6. Temperature distribution in the domain consisted of the FliBe fklow and He-cooled walls at three poloidal locations: z=2 m (near the top); 4 m (middle); and 6 m (near the bottom).

The temperature field calculated with the code in the domain consisted of the large central channel with FLiBe and He-cooled channel walls is shown in Fig.6 for three poloidal locations. The temperature grows poloidally as the FLiBe moves down. The temperature is distributed almost uniformly in the toroidal direction, but experiences significant variations in the radial direction. This can be explained by the fact that volumetric heating drops exponentially in the radial direction and does not vary in the toroidal direction. The maximum temperature in each cross section can be observed close to the channel side facing the first wall. The maximum temperature of about 900°C in the liquid is reached in the bottom cross-section. However the maximum wall temperature is always below 550°C due to effective cooling by helium. It has also been observed that the amount of heat escaping from the breeder zone to cooling helium channels is not significant: only about 7% of the total volumetric heat generated in the FLiBe channel. As a result, the ratio of power accumulated in the molten salt to the total power in the blanket module (MS power/total power) is high, about 80%. The regime parameters and the most important calculated results are summarized in Table III.

TABLE III
Results of the thermal-hydraulics analysis including MHD effects for the dual-coolant MS blanket (outboard module)

Parameter	FLiBe	FLiNaBe
He inlet T, °C	380	320
He outlet T, °C	460	440
He Pressure, MPa	10	10
He mass flow rate kg/s	21.5	14.3
He pressure drop, MPa	0.16	0.07
MS inlet T, °C	420	360
MS outlet T, °C	650	690
MS mass flow rate, kg/s	54.3	37.8
MS pressure drop, MPa	0.025	0.017
He power/total power, %	23	23
MS power/total power, %	77	77
Maximum structure T, °C	<550	<550

IV. CONCLUDING REMARKS

The most critical issues related to MHD effects on heat transfer have been addressed for two blanket concepts using molten salts. For the self-cooled blanket, the effect of heat transfer degradation has been assessed in a wide range of blanket relevant parameters and different orientations of a magnetic field with respect to the flow. For the dual-coolant blanket, full thermal-hydraulics assessment was performed that included MHD effects through taking into account modifications of the velocity profile by a magnetic field. The mathematical models and basic assumptions used in the analysis have been explained.

Here, we would also like to mention some limitations of the models used and discuss further ways of extending them. First, the K-ε model of turbulence has been adjusted using experimental data for flows in non-conducting channels and strictly speaking should be applied to turbulent flows in conducting channels with care. There are discrepant conclusions on the effect of electrically conducting walls on turbulence [3]. Our opinion is that turbulence damping in the presence of conducting walls will be more intensive due to stronger Joule dissipation, especially in the case of a wall-normal magnetic field. However reliable experimental data for turbulent flows in conducting channels have not been available. The applicability of the model to flows in conducting channels should be verified and necessary readjustments performed once new experimental data appeared. Another way of adjusting the model is term-by-tem modeling using DNS data. Unfortunately DNS data for electrically conducting channels have not been available either, but could be available in the near future [6].

In the present calculations for the dual-coolant blanket, the effect of natural convection was not included. Including this effect will require coupling between the full set of 3-D MHD flow equations and the energy equation. The numerical results obtained recently for liquid metal flows under the fusion reactor conditions [7] show that natural convection is not negligible. One can also expect a pronounced natural convection effect in the reference MS flows. This may cause, for example, more mixing in the MS and as a result more uniform temperatures. The natural convection phenomena under the dual-coolant blanket conditions will be a subject for future considerations.

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