Applied Thermal Engineering 88 (2015) 473–479

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Heat transfer and thermal stress analysis in fluid-structure coupled field

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HIGHLIGHTS

- We use FVM and FEM to investigate FCI structural safety considering heat transfer and FSI effects.
- Higher convective heat transfer coefficient is beneficial for the FCI structural safety without much affect to bulk flow temperature.
- Smaller FCI thermal conductivity can better prevent heat leakage into helium, yet will increase FCI temperature gradient and thermal stress.
- Three-dimensional simulation on conjugate heat transfer in a fluid-structure coupled field was carried out.

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
1 August 2014
Accepted 20 September 2014
Available online 5 October 2014

Keywords:
Fluid channel insert
Fluid-structure interaction
Heat transfer
Thermal stress

ABSTRACT

In this work, three-dimensional simulation on conjugate heat transfer in a fluid-structure coupled field was carried out. The structure considered is from the dual-coolant lithium-lead (DCLL) blanket, which is the key technology of International Thermo-nuclear Experimental Reactor (ITER). The model was developed based on finite element-finite volume method and was employed to investigate mechanical behaviours of Flow Channel Insert (FCI) and heat transfer in the blanket under nuclear reaction. Temperature distribution, thermal deformation and thermal stresses were calculated in this work, and the effects of thermal conductivity, convection heat transfer coefficient and flow velocity were analyzed. Results show that temperature gradients and thermal stresses of FCI decrease when FCI has better heat conductivity. Higher convection heat transfer coefficient will result in lower temperature, thermal deformations and stresses in FCI. Analysis in this work could be a theoretical basis of blanket optimization.

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1. Introduction

Nuclear fusion would be a very promising energy source in the future. Many scholars in US, EU, Russia, China, etc have been working together in International Thermal-nuclear Experimental Reactor (ITER) project. In the dual-coolant lithium-lead (DCLL) blanket module concept, flow channel insert (FCI) acts as electrical and thermal insulator between the hot PbLi fluid and the load-bearing structural steel wall [1–3]. FCI is usually made of silicon carbide composites. S. Smolentsev et al., developed code for analysis of magneto-hydrodynamics (MHD) pressure drop in a liquid metal blanket [4,5]. Numerical simulations of MHD flow and heat transfer in poloidal metal channel of DCLL blanket with a SiC composites flow channel insert were carried out in UCLA [6,7]. In China, Z. Xu et al., studied the influence of MHD effects in blanket with the FCI. The experimental results implied that the FCI with pressure equalization slot (PES) or pressure equalization holes (PEH) greatly affected the velocity distribution of bulk flow in blanket [8,9]. W. Wang and Y. Wu analyzed MHD effects and thermal stresses of DFLL with numerical method [10,11]. Results indicated that magnetic field would make the velocity profile of liquid metal much more complicated, and led to different temperature distribution.

Despite much work about MHD and heat transfer analysis, less has been discussed about structural safety of FCI considering its material property under multi-physics fields. In this paper, numerical simulation on thermal fluid-structure coupled field was carried out. Thermal deformation and stress states in FCI were obtained by using the CFD and FEM code. The relationship between the maximum displacement and stress in FCI and physical characteristics of FCI were analyzed. The influences of FCI material characteristics and fluid flowing on heat transfer and temperature field were investigated.

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http://dx.doi.org/10.1016/j.applthermaleng.2014.09.071
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2. Mathematical model

This work studied temperature and thermal stress field of flow channel insert (FCI) in multi-physics coupled field using U.S. DEMO DCLL design as a prototype. The sketch of a typical blanket channel with FCI is shown in Fig. 1. FCI seats inside the blanket channel, forming a thin gap in the channel. Both the gap and space inside FCI are filled with flowing Pb–17Li driven by the same pressure head. In what follows, we refer to flow inside FCI as "bulk flow" and that in the space between the FCI and ferritic wall as "gap flow". Flow and heat transfer process in the blanket is shown in Fig. 2. The average entrance speed is 0.06 m/s, and inlet temperature is 733 K. Helium temperature outside ferritic wall is 673 K. Along the flow direction, heat from core area of blanket is transferred through FCI and ferritic wall to outside helium. FCI immersed in metal fluid is affected by high temperature fluid which would lead to thermal stress. In this model, x, y and z coordinate direction are set to be radial, toroidal and poloidal directions, respectively. The dimension and parameters of reference blanket are summarized in Table 1. To be noted, parameters in different designs are varied and still under optimization, in this case, parameters in a typical model are applied [6,7].

3. Governing equations and solution method

PbLi metal fluid in bulk flow and gap flow is considered as incompressible fluid and is governed by N–S Equation (1), continuity Equation (2), and energy Equation (3).

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{v} \tag{1}$$

$$\nabla\cdot\vec{v} = 0 \tag{2}$$

$$\rho C_v\left(\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla T\right) = k\nabla^2 T \tag{3}$$

where, $\vec{v}$, p, T are velocity vector of fluid, kinetic pressure and temperature, respectively. ν, k, C_v, ρ refer to the fluid viscosity, thermal conductivity, specific heat capacity and fluid density.

FCI and ferritic wall meet heat conduction Equation (4).

$$k\nabla^2 T = 0 \tag{4}$$

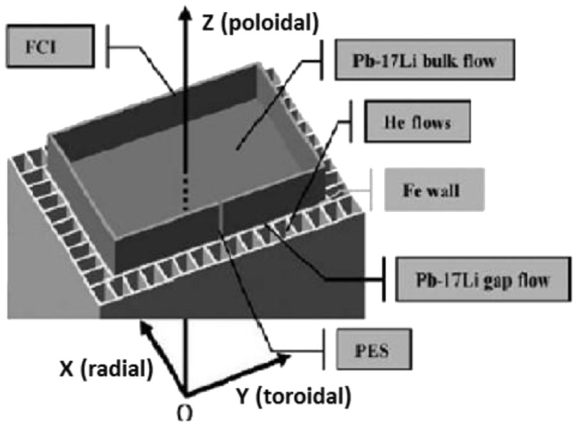

Fig. 1. Geometry of DCLL blanket [6].

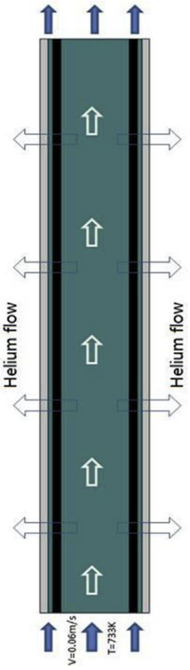

Fig. 2. Sketch of flow and heat transfer in DCLL.

The inlet end of fluid is set with a constant velocity and temperature. Pressure boundary condition is applied for outlet end. Outside the structure, convective heat transfer between steel wall and helium is assumed, the third boundary condition is satisfied here.

$$q'' = h\left(T_{\mathrm{fe}} - T_{\mathrm{he}}\right) \tag{5}$$

where, h means the convective heat transfer coefficient. T_{fe} and T_{he} express the temperature of steel wall and helium as a coolant.

Following conjugated heat transfer conditions (6) and (7) should be satisfied on the fluid-structure interaction surfaces, i.e., interface between bulk flow and FCI, FCI and gap flow, gap flow and ferritic wall.

$$T_{\mathrm{s}} = T_{\mathrm{f}} \tag{6}$$

$$q_{\mathrm{s}} = q_{\mathrm{f}} \tag{7}$$

Here, T, q indicate temperature and heat flow. And the subscripts s, f signify solid and fluid, respectively.

Geometric equation for small deformation in FCI is

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) + \alpha\Delta T\delta_{ij} \quad (i,j = x,y,z) \tag{8}$$

Table 1
Typical blanket channel parameter and boundary conditions.

Poloidal length	2 m
FCI channel inner sizes	0.3 m * 0.2 m (toroidal * radial)
FCI thickness	0.005 m
Gap width	0.002 m
Ferritic wall thickness	0.005 m
Pb–17Li mean flow velocity	0.06 m/s
Helium temperature	400 °C
Inlet Pb–17Li temperature	460 °C
Heat transfer coefficient in helium	4000 W/m^2 K

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