Experimental Studies of MHD Flow in a Rectangular Duct with FCIs

Zengyu Xu, Chuanjie Pan, Xiujie Zhang, Xuru Duan and Yong Liu

Southwestern Institute of Physics P.O. Box 432, Chengdu, Sichuan 610041, PRC

E-mail contact of main author: xuzy@swip.ac.cn

Abstract. The flow channel insert (FCI)，as a new concept to reduce liquid metal blanket MHD pressure drop, are adopted in ITER TBM and DEMO blanket system designs. The first experiments are carried out using the In-Ga-Sn liquid-metal loop in Southwestern Institute of Physics (SWIP), China in four FCI Cases: Case I, epoxy FCI with a pressure equilibrium slot (PES); Case II, epoxy FCI with a pressure equilibrium holes (PEHs);Case III, 304 stainless steel (SS) FCI with PES; Case IV: 304 SS FCI with PEHs. These experimental results indicate that FCI makes the complex velocity contribution in the cross section of the duct, and that the MHD pressure drop is lower in Case III than that in Case I. It is meaning that using non-conducting FCI, such as SiC/SiC FCI, is no necessary for reducing MHD pressure drop. As well as the complex velocity contribution may be a critical issue for the heat transfer design of a FCI flow system, but may help to understand MHD effects in other areas, such as the physics behind the H-mode plasma.

1. Introduction

Liquid metal blanket concepts are still an attractive ITER and DEMO blanket candidates as they have low operating pressure, simplicity and a convenient tritium breeding cycle [1- 4]. But how to reduce MHD pressure drop are still remained as key issues in these systems, especially in the system of the ducts with a silicon carbide composite (SiCf/SiC) flow channel insert (FCI), which is a new concept to reduce liquid metal blanket MHD pressure drop and is adopted in ITER TBM and DEMO blanket system designs.. Now, some numerical analysis results and primary experimental results of MHD flow in a duct with FCI can be found [5-8], but experimental data is limitation and out of modeling expectations. So, the more detail experimental investigation of FCI flow MHD effect program is implemented. As the SiCf/SiC suitable for experiment demand difficultly gotten and the SiCf/SiC conductivity varying during the period of the experiment to make a extra difficult of analyzing FCI MHD effect, so, epoxy and stainless steel FCIs are selected as FCI materials in the experimental investigation of MHD effects of FCI flow. In this paper, the conducting experiments and the experimental results are presented.

2. Experiment Description

The experimental investigation of FCI flow MHD effect program is implemented using the Ga-In- Sn liquid-metal loop in Southwestern Institute of Physics (SWIP), China included four FCI Cases: Case I, epoxy FCI with a pressure equilibrium slot (PES); Case II, epoxy FCI with a pressure equilibrium holes (PEHs); Case III, 304 stainless steel (SS) FCI with PES; Case IV: 304 SS FCI with PEHs. The Schematic of the test sections in the uniform magnetic field is shown in *FIG.1*. The major experimental parameters are in below: The uniform magnetic field space is 740 mm (length) x 170 mm (width) x 80 mm (height), in which the maximum transverse field intensity of B_0=2 T was applied. An electromagnetic (EM) meter measured the generally average velocity (V_0) and the error was better than 1.2%. The EM pump with a capacity of 5700kg/h drove the liquid metal ($Ga_{68}In_{12}Sn_{20}$) circulation. The sensor of pressure difference had a resolution of 18.75Pa and its error was better than 3%. In the test-section, the outer stainless steel rectangular duct is 1500 mm long, $(2a_2x2b_2)$=68 x 60 mm^2 in cross-sectional dimension and t_2=2 mm in wall thickness, while the inner FCI box made of epoxy or 304-type stainless steel is 1 m long and the cross-sectional dimensions of the test-article are $(2a_1x2b_1)$=54 x 46 mm and 56 x 48 mm, respectively; and the wall thickness are t_1=2 mm and 1 mm, respectively. FCI PES width is W_s=3 mm and FCI PEHs are 10 mm in diameter. The gap between FCI box and 304 SS duct is d = 5 mm. The pressure drop was measured over the L_0=500 mm long test section, which is well distanced from both the edges of the FCI box (250 mm apart) for the measured data in full developed flow region. The liquid-metal electro-magnetic velocity instrument (LEVI) from Argonne National Laboratory was mounted to measure the velocity distributions $V_x(z)$ on the center plane (y=0) of the cross section of the duct. The operating temperature is 85°C, the maximum Hartmann number, M, is 2400. M is defined as, M= (Electromagnetic Stress/Viscous Stress)$^{1/2}$≈ $a_0B_0(\sigma/\eta)^{1/2}$,where σ is electric conductivity, η is viscosity. The Maximum Interaction Parameter, N, is 10,000. N is defined as, N=(Electromagnetic Stress/Inertial Stress) = $M^2/Re \approx a_0B_0^2\sigma/(\rho V_0)$, where Re is Reynolds number, ρ is fluid density [9]. All data was acquired with a16-bit analog-to-digital board of 2.5 μV resolutions in a computer.

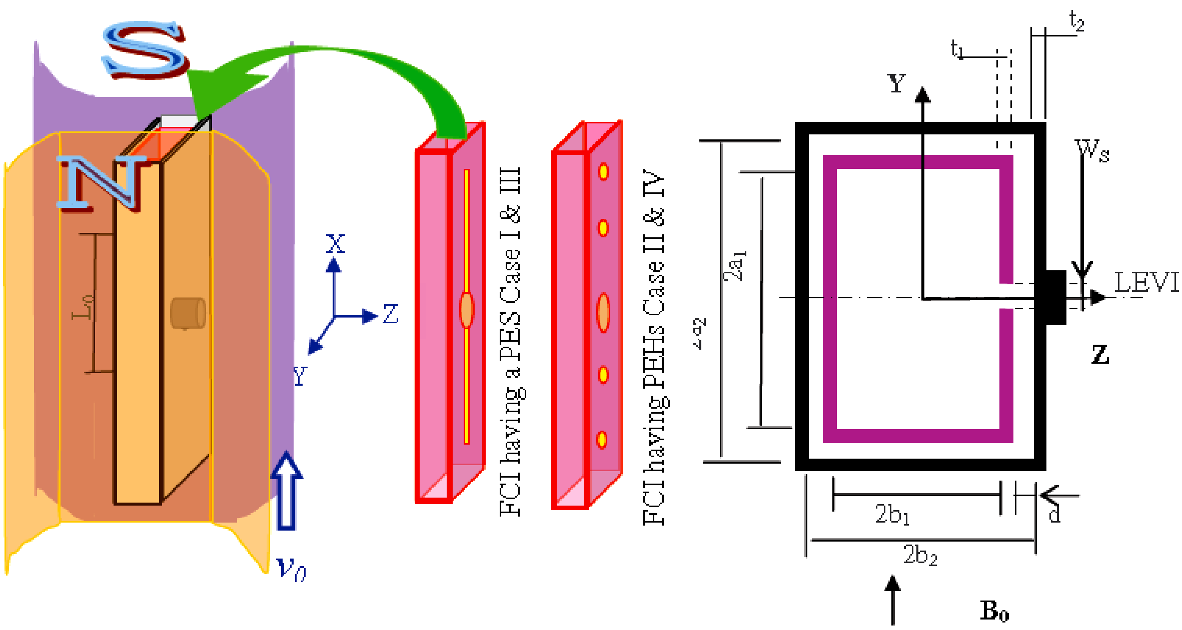

FIG.1. Schematic of the test sections in the uniform magnetic field

3. Experimental Results

The experiment measured data is included the electric potential difference profile at FCI box wall and out wall of the 304 SS duct, the velocity distribution on the center-plane (y=0) of the cross section of the duct with FCI and MHD pressure drop in the duct. The electric potential difference profile results indicate that the FCI (PES) flow in the data measured region can be treated as an approach full developed flow (in L_0=500 mm range (along x-axis), the electric potential difference, ΔU_w, is fluctuating in ~5%). Part of the results can be found in reference [7]. The velocity distribution on the center-plane (y=0) of the cross section of the duct and MHD pressure drop in the duct with FCI under several magnetic field, B_0 and average velocity in the duct, V_0, is shown in *FIG 2*, *FIG 3*. *FIG.2* shows the velocity distribution (left) and MHD pressure drop (right) in Case I and Case II. We find that the velocity distribution is complex; there are positive velocity peak and negative velocity peak in near FCI wall area or in the PES slot middle. The velocity in the center (at y=0) area also is in high value.

FIG.3 shows the velocity distribution (left) and MHD pressure drop (right) in Case III and Case IV. Comparing with the results in Case I and Case II, the velocity distribution in Case II and Case IV is very difference in peaks and peek position; inhere, there are not negative velocity peak and the outline of the velocity distribution in Case III is similar that in Case I, but their peak positions are shift to core area.; the outline of the velocity distribution in Case IV is entirety different from that in Case II. MHD pressure drop is reduced in all of the four cases. Comparing of the experimental data in *FIG.2* and *FIG.3*, we can found that MHD pressure drop in duct with 304 FCI PES (Case III) is lower than that in the duct with epoxy FCI PES (Case I). It is reproduced in *FIG.4*.

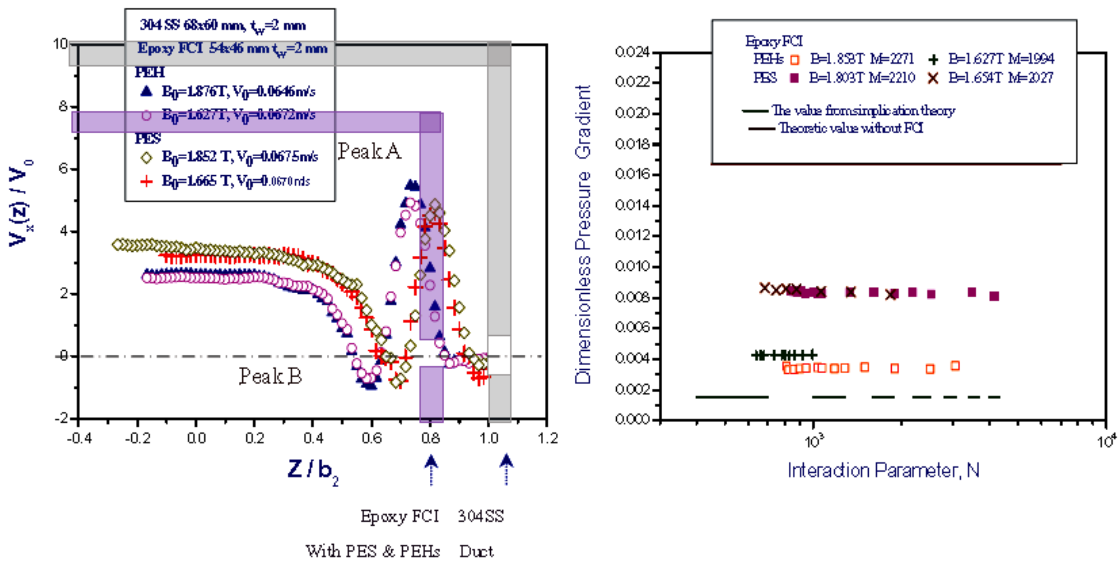

FIG.2. The velocity distribution (left) on the center-plane (y=0) of the cross section of the duct and MHD pressure drop (right) in the duct with epoxy FCI (Case I and Case II) under several magnetic field, B_0 and average velocity, V_0,

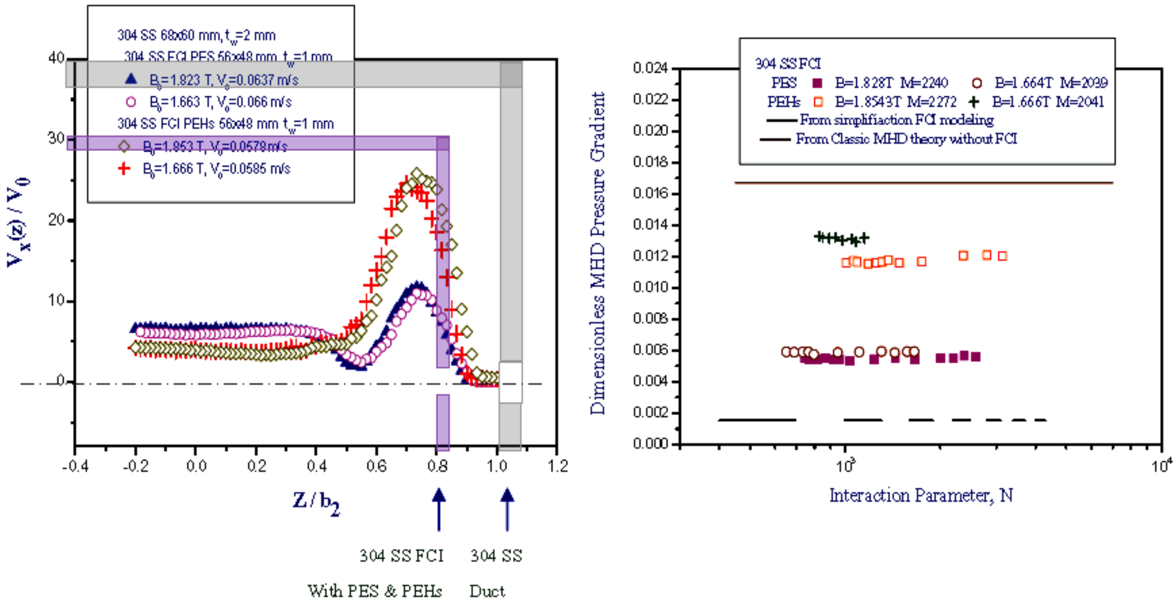

FIG.3. The velocity distribution (left) on the center-plane (y=0) of the cross section of the duct and MHD pressure drop (right) in the duct with 304 SS FCI (Case III and Case IV) under several magnetic field, B_0 and average velocity, V_0,

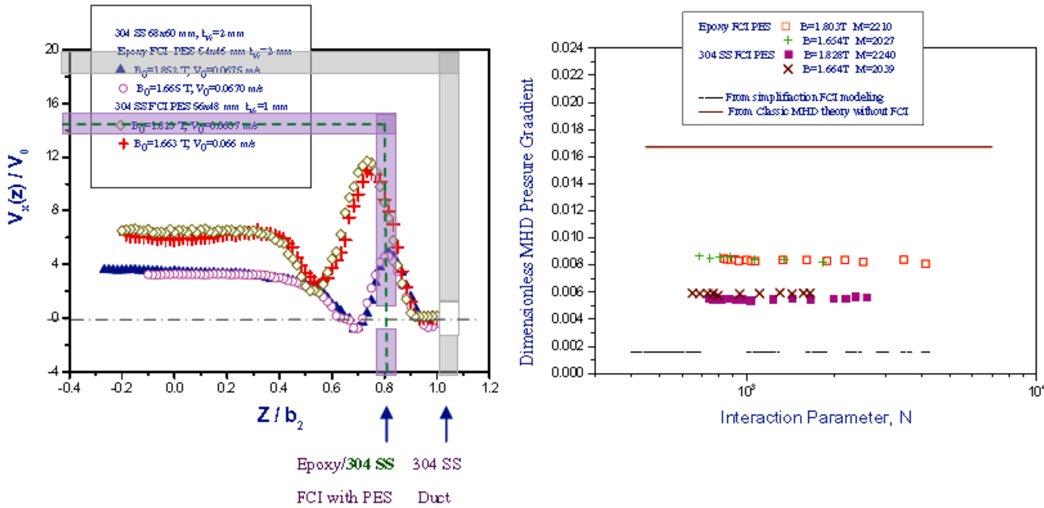

FIG.4. Comparing the velocity distribution (left) on the center-plane (y=0) of the cross section of the duct and MHD pressure drop (right) in Case I with that in Case III

4. Discussion

How to understand the complex velocity distribution in the FCI duct (in *FIG.2*)? Limitation of the current MHD theory developing and the computer technology levels, it is seemly impossible to explain the velocity distribution in exact theory and modeling simulation. But if using the induced current paths in the cross section of the duct (see *FIG. 5*), it is possible to understand the complex velocity distribution on physics. From *FIG. 5* (left), we can find that there are four parallel current paths, two paths through the PES are flowing in FCI box to made the loops, and other two paths is made the loop in gap area. The sum of the induced current is smallest at the middle of PES, so, in this position, the velocity is highest (peak A); and near PES slot, the sum of the induced current have a maximum value and at this position, the velocity is smallest (peak B). The negative peek B, it may be caused by turbulent flow due to PES. *FIG. 5* (right) shows the induced current paths in the cross section of the duct with epoxy FCI PEHs, between the holes, the induced current paths in the FCI box is in complex three dimension loops (see reference [7]), though the sum of the induced current is smallest at the middle of PEHs, but the flow can not flow along x-axis by PEH limited, so, the maximum velocity value is decided by in the FCI box complex three dimension induced current loops and it is near the inner wall of FCI box as well as the velocity distribution will be changed from slug distribution to the complex p distribution (in *FIG.2*) between holes (PEHs) .

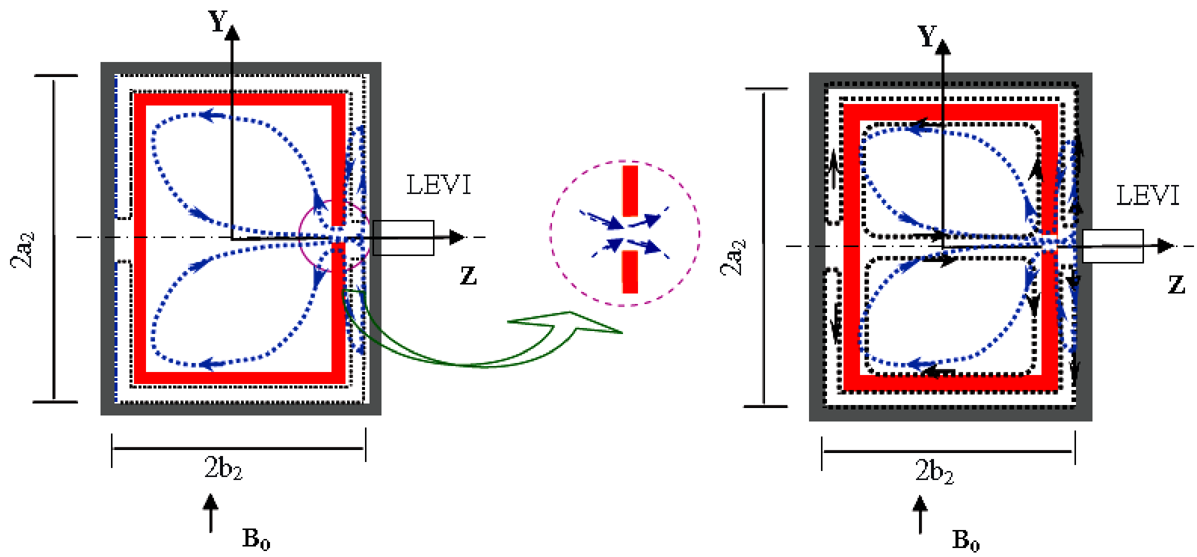

FIG.5 Schematic of the induced current paths in Case I (left) and in Case II (right)

How to understand the velocity distribution in Case III and Case IV? It is more difficult than understanding that in Case I and Case II. In Case III and Case IV, the induced current can cross 304 SS FCI from one side gap to the other side gap, in the FCI box, there are also independent induced current loops and in meantime, the PES and PEHs lead the secondary flow. In Case III, the secondary flow due to the PES is the dominant effect for global duct flow, and in Case IV, the dominant effect is the independent induced current loops. Though the secondary flow is very strength at the PEHs, but for global duct flow, the secondary flow effect in Case IV is much weaker than that in Case III. These results in the velocity distribution in *FIG.4* (left). It is a qualitative analysis on physics. Now, it is impossible to explain it using the current theory and numerical modeling, because the secondary flow in hydraulic flow is no so clear and it in MHD flow is more complex.

Why is MHD pressure drop in the duct with 304 FCI PES case lower than that in the duct with epoxy FCI PES case (see *FIG.4*). This result is out of the expectations from the liquid metal MHD classical theory. It can not be understood and explained by classical MHD theory. But the MHD geometry sensitivity effect (or call the secondary flow MHD effect, short in “S-MHD”)

[10] can help us to understand it. From *FIG.4*, we can found that more liquid metal work mass flow to FCI box through slot (PES) due to S-MHD effect in 304 SS FCI PES case (Case III) than that in epoxy FCI PES (Case I), and the MHD pressure drop is dependent on flow rate in gap area. Therefore, the MHD pressure drop in the duct with 304 FCI PES case (Case III) is lower than that in the duct with epoxy FCI PES case (Case I). It is mean that to reduce MHD pressure drop, using non-conductivity or small conductivity FCI is no necessary (the conductivity FCI is best chose) and to heat transfer design, the complex velocity distribution is a great challenge. However, if the mechanism of the velocity suddenly higher due to S-MHD effect is clear, it may help us to understand MHD effects in other areas, such as the physics behind the H-mode plasma.

5. Conclusions

Base on above experimental results and discussion, the tentative conclusions and a deduction can be obtained in the following: a) Epoxy or 304 SS FCI makes the complex velocity distribution in the cross section of the duct. b) MHD pressure drop in the duct with 304 FCI PES case is lower than that in the duct with epoxy FCI PES case. c) For reducing MHD pressure drop, conductivity FCI PES is better than non-conductivity FCI PES. d) For the blanket heat transfer design, FCI flow is a great challenge. e) The secondary flow is a domination mechanism in FCI flow MHD effect.

Acknowledgement

The LEVI was supplied by Argonne National Laboratory under the collaboration of the 1995 People’s Republic of China/United States program of cooperation in magnetic fusion. China National Nature Science Foundation grants 10775042 supports part of the work.

Reference

[1] D.L. Smith “Blanket comparison and selection study” Fusion Technology 8 10 (1985)
[2] R. Pampin and P.J. Karditsas “Fusion power plant performance analysis using the HERCULES code” Fusion Engineering and Design 81.1231 (2006)
[3] B.A.Pint, J.L.Moser and P.F. Tortorelli “ Liquid compatibility issues for test blank modules” Fusion Engineering and Design 81, 901 (2006)
[4] Y. Wu, S, Zheng, X. Zhu and W. Wang et al “Conceptual design of the fusion-driven sub critical system FDS-I” Fusion Engineering and Design 81, 1305 (2006).
[5] S. Smolentsev, M. Abdou, N.B. Morley a, M. Sawanb et al “Numerical analysis of MHD flow and heat transfer in a poloidal channel of the DCLL blanket with a SiCf/SiC flow channel insert” Fusion Engineering and Design 81, 549 (2006)
[6] XU Zeng-yu, PAN Chuan-jie, ZHANG Xiu-jie A simplified theoretical study on MHD flow with FCI in liquid metal blanket system Nuclear Fusion and Plasma Physics (in Chinese)V28, No 3, (2008）205-208

[7] XU Zengyu, PAN Chuanjie, ZHANG Xiujie, ZHAO Li et al, Primary experimental results of an MHD flow in the duct with flow channel insert, Nuclear Fusion and Plasma Physics (in Chinese).V29 6-9 (2009)

[8] Sergey Smolentsev , Zengyu Xu, Chuanjie Pan , Mohamed Abdou Numerical and experimental studies of MHD flow in a rectangular duct with a non-conducting flow channel insert, Magneto-hydrodynamics V46 99-111 (2010)

[9] J. C. R. Hunt , R. J. Holroryd Application of Lab. “And theoretical MHD duct flow studies in fusion reactor technology” Dept. of engineering, Univ. of Cambridge 1977.

[10] XU Zengyu, PAN Chuanjie , ZHANG Xiujie, ZHAO Li et al Geometry Sensitivity of Magnetohydrodynamic Duct Flow and Some Abnormal Phenomena, Plasma science and technology V11 August, 2009, 499-503