EXPERIMENTAL RESULTS OF PRESSURE DROP MEASUREMENT IN ITER CS MODEL COIL TESTS

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ABSTRACT

Pressure drop characteristics of the cable-in-conduit conductor adopted in the ITER Central Solenoid Model Coil (CSMC) were first measured through the CSMC experiment in the ITER relevant cooling condition. The conductor has two parallel flow channels such as a bundle channel and a central channel. Previous studies have proposed pressure drop correlations between the friction factor and Reynolds number for the central channel. In this report, the measured pressure drop data were compared with these correlations. Results indicate that the measured pressure drop characteristic shows a large deviation from prediction. Friction factor for the central channel is less sensitive to Reynolds number in comparison with modified Blasius type correlation. The correlations proposed by Colebrook and Zanino show a relatively good prediction.

INTRODUCTION

To develop the superconducting magnet to be applicable for the International Thermonuclear Experimental Reactor (ITER), a Central Solenoid Model Coil (CSMC) and CS Insert were fabricated and tested under the international collaboration of the R&D program in the ITER Engineering Design Activities [1-4]. The conductor adopted in the CSMC and the CS insert has almost the same parameters as a practical conductor in ITER magnets. The conductor adopts a cable-in-conduit type with two parallel flow channels such as a central channel and a bundle channel. To analyze the helium flow behavior inside the conductor, studies of the pressure drop performance for such a conductor have been performed using the ITER 1/5 sub-size conductor (QUELL) at 4 K region and the full size conductor at room temperature conditions with nitrogen gas and/or water, respectively [5-8]. The pressure drop performance with a practical conductor and ITER relevant helium conditions had not been measured before it was first measured through the ITER

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CSMC experiment that was carried out from March to August in 2000 in the CSMC test facility at the Japan Atomic Energy Research Institute [9, 10]. Previous studies provided a good correlation between the friction factor and the Reynolds number for the pressure drop performance for the bundle channel of the conductor [8, 9]. However, the performance for the central channel was still under discussion, although some correlation equations were developed for the central channel. Therefore, this paper describes the pressure drop performance data acquired through the CSMC experiment and the friction factor characteristics for the central channel and evaluates the proposed correlations by comparing them with the measured data in the CSMC experiments. Note that analysis for pressure drop characteristic on the CS Insert is presented in a companion paper [12].

CSMC AND CONDUCTOR

The CSMC is composed of 18 layers and adopts a two-in-hand winding to reduce the cooling channel length, resulting in a total of 36 conductors. FIGURE 1 shows the CSMC and its conductor. The main feature of the conductor is to have two parallel cooling flow channels. One is a bundle channel with about 1100- Nb_3Sn strands of 0.8-mm diameter and the other is the central channel of 9- or 10-mm inner diameter. Two kinds of conductor were used in CSMC. One is a high magnetic field conductor (CS1) used in 1,2,3 and 4th layer. The other is a lower magnetic field conductor (CS2) used in 5th to 18th layer. Major hydraulic parameters for each conductor are summarized in TABLE 1.

MEASUREMENT METHOD AND RESULTS

FIGURE 2 shows a schematic cooling circuit of the CSMC and the CS insert. During cool-down and warm-up operations, helium gas with the temperature range from room temperature to about 10 K and pressure of about 0.6 MPa was supplied from a 5 kW refrigerator. Temperature difference between inlet and outlet of conductor was controlled within 50 K. During coil operation, a supercritical-helium circulation pump provided about 0.6 MPa and 4.5 K helium to the coil and the structure [13].

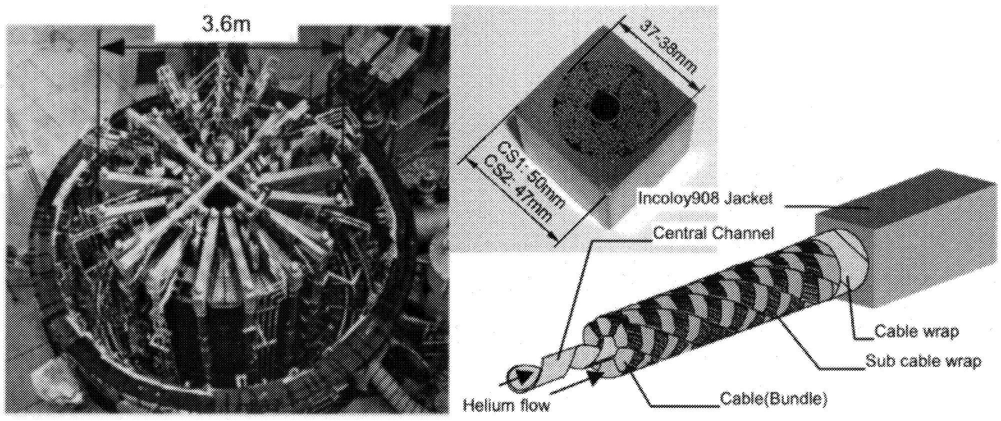


FIGURE 1. CSMC in test facility (left) and CICC used in ITER CSMC (right).

TABLE 1. Major hydraulic parameters of the CSMC conductor used in calculations

Conductor Name*	1A(CS1)	5A, 7A(CS2)	11A, 15A, 17A(CS2)
Length (m)	83.8	5A: 116.7 7A: 128.2	11A: 153.7 15A: 176.8 17A: 188.3
Strand diameter (mm)	0.81	0.81	0.81
Number of strand	1152	1080	1080
Hydraulic diameter of bundle (mm)	0.423	0.459	0.459
Helium flow cross section of bundle (mm^2)	367	362	362
I.D./O.D. of central channel (mm)	10/12	9/12	10/12
Gap in spiral (mm)	3	1.5	3
Void Fraction (%)	35.4	37.4	37.4
Strand twist pitch angle (cos δ)	0.931	0.967	0.967
Cabling place	U.S.A	U.S.A	11,15:Japan 17:U.S.A

* For example, 5A means 'A' conductor of 5th layer. There are two conductors (A and B) wound in two-in-hand for one layer.

Mass flow rate in each conductor was controlled to be around 10 g/s in the coil operation and the total helium flow rate summed to around 400 g/s. Pressure drop measurement was performed on the conductors 1A, 5A, 7A, 11A, 15A and 17A. In the cooling path of the above conductors, temperature sensors, pressure sensors at inlet and outlet of the conductor, a differential pressure sensor and an orifice type flow meter are installed to measure detailed pressure drop characteristics.

Since the inlet and the outlet pressure taps are located at the coil bottom and the top with the vertical distance of 5~6 m, a gravity pressure head due to the pressure tap location should be considered to determine net differential pressure caused by the helium flow. Since helium density at 4 K region is around 140 kg/m^3, the gravity pressure head is not negligible over this vertical distance. Therefore, pressure drop through the conductor was evaluated by subtracting the gravity pressure head of around 6 kPa at 4.5 K, 0.6 MPa.

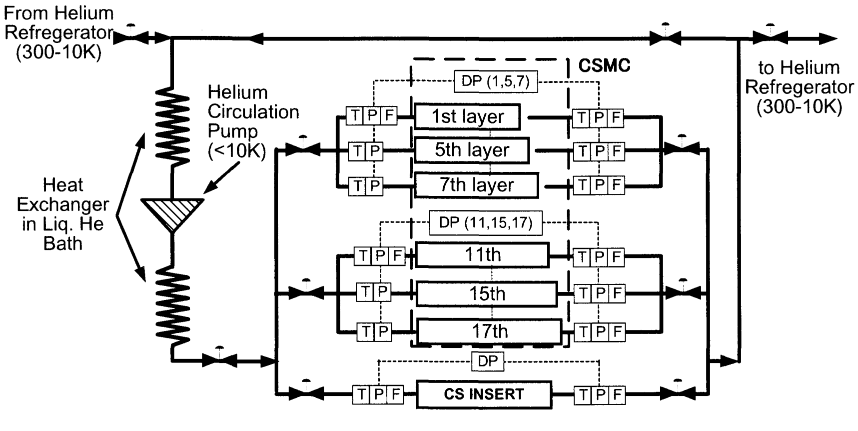


FIGURE 2. Schematic cooling flow diagram of CSMC and CS insert. P, T, DP and F indicate the pressure sensor, thermometer, differential pressure sensor and flow meter, respectively. From 300 to 10 K, helium gas is supplied from a refrigerator, and supercritical helium is supplied by a circulation pump below 10 K.

The pressure drop per unit length, namely pressure gradient, for each conductor at 4.5K, 0.6MPa is shown in FIG 3. Significant differences of the pressure gradient are observed among conductors. Especially conductors 5A and 7A indicate a large pressure drop, compared with the other conductors. The reason for the large pressure drop was investigated and it is proposed that the difference in the central channel configuration might generate the large difference. Indeed, the CSMC conductor adopts two kinds of central channel as shown in FIG 4. One is a spring-type central channel with 9/12-mm inner/outer diameter. The spring is made of INCOLOY 908 and is applied to 5A and 7A conductors, respectively. The other is a spiral-type central channel with 10/12-mm inner/outer diameter made of thin stainless steel tape.

To determine the relation between the measured pressure drop and the friction factor, the correlation defined by the ITER Design Criteria is used as follows [14].

In ITER, pressure drop characteristic for a CICC with central channel is estimated by a parallel flow model in the central channel and the bundle, and the calculation method is based on the conventional equation defined by Fanning as indicated in the following equation.

$$dP = 4f\frac{\rho \cdot v^2}{2}\frac{L}{d_h} \tag{1}$$

Here, dP: pressure drop, f: friction factor, v: flow speed ($=\dot{m}/\rho/A$), $\dot{m}$: mass flow rate, ρ : density, L: conductor length, d_h: hydraulic diameter.

In ITER Design Criteria, friction factor for the Bundle channel (f_{bundle}) is expressed by the

$$f_{bundle} = \frac{1}{4 \cdot void^{0.72}}\left(\frac{19.5}{\mathrm{Re}^{0.88}} + 0.051\right) \tag{2}$$

Here, $void$: void fraction of bundle, Re : Reynolds number.

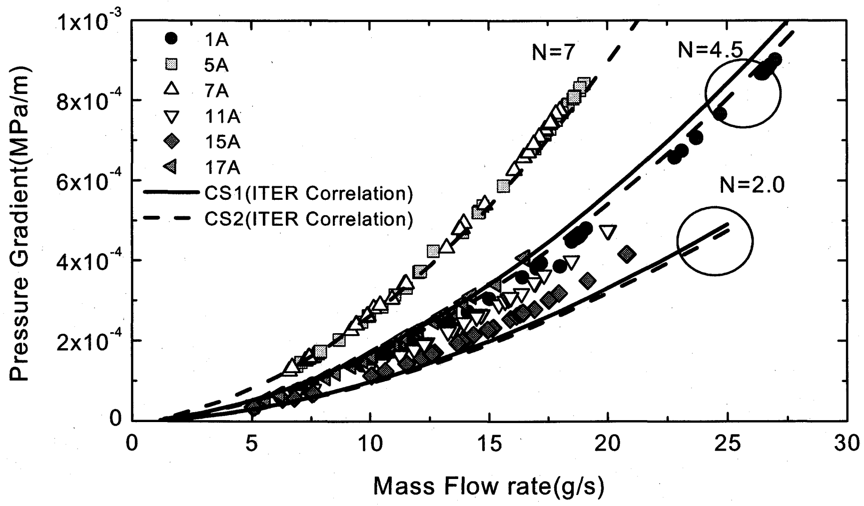
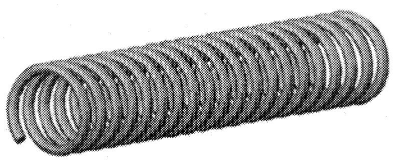
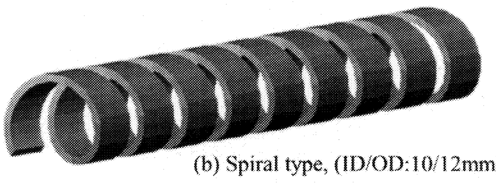


FIGURE 3. Measurement results of the pressure gradient at 4.5 K, 0.6 MPa. Gravity pressure head is subtracted from the pressure difference between helium inlet and outlet of the conductor. Solid and dash lines are calculated from equation (1), (2) and (3) using Table 1



(a)Spring Type, (ID/OD:9/12mm)



(b) Spiral type, (ID/OD:10/12mm)

FIGURE 4. Central channel configuration used in CSMC conductor. (a) Spring type used in conductors from 5 layer to 8th layer and used in cabling company in U.S.A. (b) Spiral type used in conductors in other layers and used in Japanese and European cabling companies

On the other hand, for the friction factor of the central channel ($f^{ITER}_{central\,channel}$), the following correlation is proposed in the ITER design criteria.

$$f^{ITER}_{central\ channel} = 0.046 \times N \times \frac{1}{\mathrm{Re}^{0.2}} \tag{3}$$

Here, f: friction factor, N: correction factor (ITER recommendation: N=2.0)

Using equation (1) to (3), pressure drop as a function of mass flow rate is evaluated. Pressure drop at 4.5 K and 0.6 MPa were also evaluated by using hydraulic parameters in TABLE 1, as shown in FIG 3.

Evaluation results indicate a higher N-factor than that of the ITER prediction, and large deviation of the N-value is observed for several conductors. The N-factor of the conductors with spiral–type central channel distributes in the range from N=2.0 to 4.5. In case of the 5A and 7A conductors, $N\approx7$ is well fitted.

It is well observed that in the pressure drop measurement results at 4.5K, the central channel configuration should play a key role on the pressure drop characteristic of the ITER CSMC conductor. Therefore, using ITER correlations, pressure drop of the conductor with spiral type central channel in the region of mass flow rate less than 20 g/s with 0.6 MPa, 4.5 K involves around 50% accuracy, according to the ratio between 15A(higher case) and 17A (lower case) as shown in FIG 3.

DISCUSSION

For the spiral type central channel, some correlations to predict the friction factor performance for the central channel have been proposed, which were derived from the basic experiment results including ITER sub size conductor experiments. We tried to evaluate the data from the CSMC experiments by using the proposed correlations and the results were compared in the wide range of Reynolds number from 1 x10^4 to 6 x 10^5.

Evaluation methods were as follows;

1) The mass flow rate in the bundle channel of the conductor was estimated by equations (1) and (2), where the input data are the measured pressure drop through the specified conductor, and averaged values of the inlet and the outlet helium conditions such as helium density and viscosity that are determined by the measured pressures and temperatures. In this evaluation, according to definition of hydraulic diameter discussed in Ref. 12, we used a hydraulic diameter for the bundle as 0.540 mm for 5A, 7A, 11A, 15A and 17A, and 0.498 mm for 1A instead of that sheet in TABLE 1,
2) The mass flow rate of the central channel was calculated to subtract the estimated mass flow rate of the bundle channel from the measured total mass flow rate at the conductor.
3) The friction factor of the central channel was calculated to substitute the input data determined by the mass flow rate of the central channel into the equation (1) again.

The above calculation sequence was applied to several coil operation modes such as the cool-down, the steady state operation at 4 K region, and the warm-up operation where the Reynolds number in the conductor were changed. The relations between the friction factor and the Reynolds number were collected for conductors of 1A, 5A, 7A, 11A, 15A and 17A. Their results are summarized in FIG 5. In the figure, the friction factors were evaluated to be in the turbulent flow region even in the case of the cool-down and the warm-up operation. Note that the Reynolds numbers of less than 10^5 are obtained in the cool-down and the warm-up and that the values being higher than 10^5 are derived from the steady state operation at 4 K region, respectively. The friction factors of the 5A and 7A conductors have a similar behavior and a large difference compared to the others.

The proposed correlations for spiral type central channel are indicated by the following equations;

K. Hamada: QUELL, based on ITER design criteria [5,13]

$$f = 0.046 \cdot 2.5 \cdot \frac{1}{\mathrm{Re}^{0.2}} \tag{4}$$

R. Zanino [7]:

$$R(h^+) = \sqrt{\frac{2}{f}} + 2.5 \cdot \ln\left(\frac{2h}{D_h}\right) + 3.75 \tag{5}$$

$$R(h^+) = 11.88(h^+)^{0.039} \cdot \left(\frac{g}{h}\right)^{-0.299}$$

$$h^+ = \frac{h}{D_h} \cdot \mathrm{Re} \cdot \sqrt{\frac{f}{2}}$$

g: gap length of spiral, h: thickness of central channel wall

S. Nicollet: Colebrook equation [6]

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{ke}{3.7d} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right), \quad \lambda = 4f \tag{6}$$

ke/d is a relative roughness

P. Bruzzone: modified Blasius equation [8]

$$\lambda = 0.866 \cdot \frac{1}{\mathrm{Re}^{0.252}} \tag{7}$$

Calculation results by the above correlations are over-plotted in FIG 5. It can be seen that it is difficult to obtain a good correlation between the friction factor and Reynolds number systematically. The behavior of the friction factor dependency on Reynolds number is rather flat in comparison with the modified Blasius formula such as equations (4) and (7). In the above proposed correlations, the equations (5) and (6) indicate relatively good expression for the tendency of the friction factor as a rough surface tube. The relative roughness (k_e/d) in equation (6) was assumed varying ad-hoc in the range from 0.01 to 0.025 in order to fit the data from 1A, 11A, 15A and 17A and 0.07 for 5A and 7A conductors, respectively. Such a large pressure drop caused by the spring type will derive an additional heat load in proportion to the pressure drop in the cryogenic circulation pump [13]. Therefore, the spring type is not recommended for use in the ITER conductor.

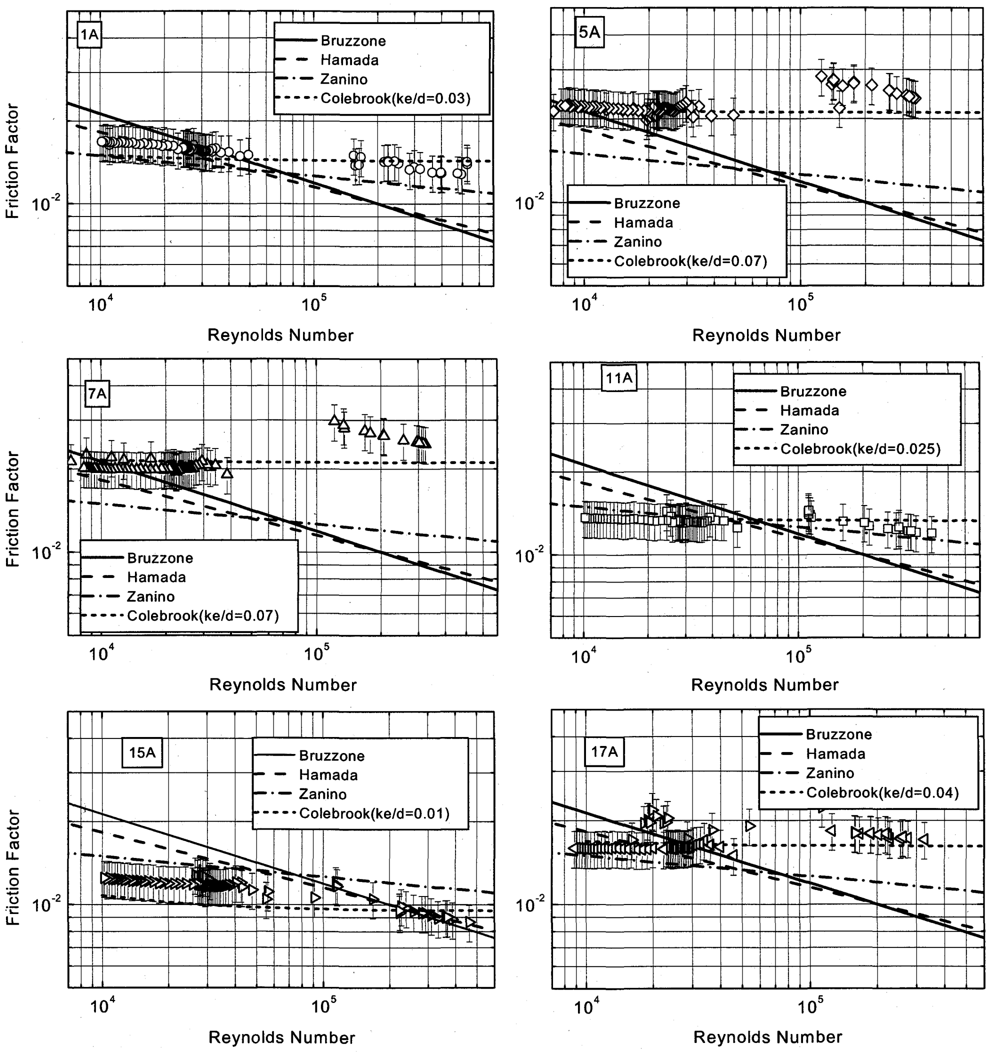


FIGURE 5. Comparison of the evaluated friction factor of the central channel with various correlations. Solid line: equation (7), dotted line: equation (4), dash line: equation (5), light solid line: equation (6). From discussion of reference 12, 0.540 mm is used for 5A, 7A, 11A, 15A and 17A, and 0.498 mm is used for 1A in this calculation, instead of hydraulic diameter listed in Table 1.

CONCLUSION

The pressure drop characteristics of the ITER full size conductor were first measured under the ITER relevant condition. The pressure drop characteristics are evaluated as follows;

(1) Pressure drop of the CSMC conductors at 4.5 K and 0.6 MPa indicate higher values than the prediction by the ITER design criteria. N-factor defined in equation (3) is estimated to be in the range from 2.0 to 7.0.

(2) In the CSMC, the spring type central channel indicates 2-3 times higher friction factor than that of the spiral type central channel. The spring type central channel is not preferable from the viewpoint of a large pressure drop.

(3) The correlations between the friction factor and the Reynolds number are evaluated. There are large differences among conductors. In this stage, it is difficult to clearly express the friction factor by one of the proposed correlations. The dependence of the friction factor on the Reynolds number in the central channel is flatter than that of the Blasius type equation. The correlations of Colebrook type and Zanino are relatively close to the tendency of experimental data.

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