Flow balancing orifice for ITER toroidal field coil

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Abstract. Flow balancing orifices (FBOs) are used in in International thermonuclear experimental reactor (ITER) Toroidal Field coil to uniform flow rate of cooling gas in the side double pancakes which have a different conductor length: 99 m and 305 m, respectively. FBOs consist of straight parts, elbows produced from a 316L stainless steel tube 21.34 x 2.11 mm and orifices made from a 316L stainless steel rod. Each of right and left FBOs contains 6 orifices, straight FBOs contain 4 and 6 orifices. Before manufacturing of qualification samples D.V. Efremov Institute of Electrophysical Apparatus (JSC NIIEFA) proposed to ITER a new approach to provide the seamless connection between a tube and a plate therefore the most critical weld between the orifice with 1 mm thickness and the tube removed from the FBOs final design. The proposed orifice diameter is three times less than the minimum requirement of the ISO 5167, therefore it was tasked to define accuracy of calculation flow characteristics at room temperature and compare with the experimental data. In 2015 the qualification samples of flow balancing orifices were produced and tested. The results of experimental data showed that the deviation of calculated data is less than 7%. Based on this result and other tests ITER approved the design of FBOs, which made it possible to start the serial production. In 2016 JSC NIIEFA delivered 50 FBOs to ITER, i.e. 24 left side, 24 right side and 2 straight FBOs. In order to define the quality of FBOs the test facility in JSC NIIEFA was prepared. The helium tightness test at $10^{-9}$ m$^3$/Pa/s the pressure up to 3 MPa, flow rate measuring at the various pressure drops, the non-destructive tests of orifices and weld seams (ISO 5817, class B) were conducted. Other tests such as check dimensions and thermo cycling 300 - 80 - 300 K also were carried out for each FBO.

1. Introduction

The ITER superconducting magnet system includes 18 toroidal field coils (TF coil), each one consists of 7 double pancakes: two side and five central double pancakes with the Nb$_3$Sn superconductor installed in radial plates to form superconducting winding. Each TF coil has two 404 m in length conductors of side double pancakes and five 760 m in length conductors of regular double pancakes. The side double pancake has an asymmetrical cross section and two parallel cooling paths – 99 m and 305 m, respectively. Each of fourteen pancakes is cooled down with supercritical helium in parallel, flow rate balance depends on a cooling path length. In order to obtain uniform flow distribution on each pancake, the shortest pancake conductor is required a flow adjusting system. There are two types of flow adjusting systems: active and passive.

The Flow balancing orifice (FBO) is a passive flow system intended to reduce the flow rate in the shorter conductor of the side double pancake. Each of eighteen TF coils includes two FBOs, which operate in the temperature range from the room temperature to $T=4.5$ K; internal pressure of the FBO is up to $P=3$ MPa; atmospheric pressure or under vacuum $10^{-2}$ Pa; and magnetic field outside the FBO is $B\leq3$T. Figure 1 shows the location of the FBO set in the terminal box of the TF coil winding pack.
The orifice was selected as a narrowing device for creation the required pressure drop and related flow rate. The principle of measurement method is based on installation of an orifice plate into a tube with a fluid running full. The presence of the orifice plate causes a static pressure difference between plate upstream and downstream sides. The mass flow rate $q_m$ can be determined by the following formula according to ISO 5167-2 [1]:

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{\sqrt{2 \Delta p \cdot \rho_1}}{\rho}$$

*Where:* 
- $C$ - coefficient of discharge; 
- $d$ - orifice diameter; 
- $\varepsilon$ - expansibility factor; 
- $\rho$ - fluid density; 
- $\Delta p$ - pressure drop; 
- $\beta$ - diameter ratio $(D/d)$.

Expansibility factor is a correction factor for the change in density between two pressure measurement areas in a constricted flow and can be determined by following formula according to [1]:

$$\varepsilon = 1 - (0.351 + 0.256 \beta^4 + 0.93 \beta^8) \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}\right]$$

*Where:* 
- $p_1$ - inlet pressure; 
- $p_2$ - outlet pressure; 
- $k$ - ratio of specific heats; 
- $\beta$ - diameter ratio $(D/d)$.

The advantages of this device are as follows: the simple design, compactness and convenience for the subsequent application of electrical insulation. The initial design was offered by IO and based on welds between the tube and the orifice. The preliminary qualification showed that such type of construction was not reliable enough and complicated to repeat in serial manufacturing. For these reasons, JSC NIIEFA proposed to IO ITER to provide the seamless connection between the tube and the plate where the tube with the orifice produced from a 316L stainless steel rod as one unit, therefore the most critical weld between the orifice with 1 mm thickness and the tube was removed from the final design of FBOs. The current approach without seams allows to simplify the manufacture procedure and to fulfil the quality requirements. The dimensional tolerances of each orifice presented in figure 2 meet the dimensional requirements of the orifice according to [1] and it goes up to 0.005 mm. All dimensions of the orifice in mm are presented in figure 2 and were controlled by measuring machine HERA NT 15.9.7.
2. Manufacturing

The proposed diameter of the orifice is 4.5 mm, which is three times less than the minimum requirement of the [1]. It has been required to determine the accuracy rated characteristics of the flow at room temperature and compare it with experimental data.

The FBO consists of straight parts, elbows produced from a 316L stainless steel tube 21.34 x 2.11 mm and orifices from a 316L stainless steel rod. Each of right and left FBOs contains 6 orifices, straight FBOs contain 4 and 6 orifices respectively.

The required quality of manufactured FBOs has been verified by the following tests according to Technical Specification [2]:
- Non-Destructive Tests (X-Ray, Visual control, Penetrant test) of the weld seams and the orifices;
- Dimensional Check of FBO assembly parts and the manufactured FBO;
- Helium Leak Test of the FBO (Q \( \leq 10^{-9} \text{ m}^3 \cdot \text{Pa/s} \));
- Thermocycling of the FBO (300-78-300 K);
- Flow Test of the FBO.

Since the total number of the weld seams while manufacturing the FBOs is greater than 600, it was determined to use orbital automatic welding to reduce the probability of defects during serial production. In JSC NIEFA certification of welding technology and welder was performed according to ISO 15614-1:2004/Amd 1:2008 [3]. Based on the results of certification WPQR was prepared [4]. In addition, the repair technology was developed for the possible defects in the weld seams which could appear during manufacturing.

Due to the limited gap area in the TF coils where the FBOs are installed, it is necessary to retain certain overall dimensions with tolerance of \( \pm 2 \text{ mm} \) and geometric orientation. To fulfill this condition, the equipment tool was designed, manufactured and enables to fix and join the parts of the FBOs in the correct position (Figure 3). Figure 4 shows one of the right FBOs with 6 orifices, which has passed all required tests.
Each of the FBOs was subjected to 10 thermocycles and to the helium leak test under pressure 3 MPa inside the FBO. To reduce the test time of each FBO, the thermoshock and leak test of two FBOs at once were carried out. The assembly of two FBOs before leak test and the thermoshock is shown in Figure 5.

During the test for the helium flow through the FBO, Endress + Houser flow meter was used. Flow meter consist of registrator of signal RMC 621 and sensors: temperature, pressure, drop pressure. Two pressure sensors are connected to the inlet and outlet flow direction of FBO. The principle of determination helium flow rate based on creating required helium pressures by helium compressor in inlet and outlet of FBO which are regulated by valves. Then helium flow exits from FBO and measured by Endress + Houser flow meter.

Figure 3. Fixing tool for FBO.  Figure 4. Right FBO with 6 orifices.  Figure 5. The assembly of two FBOs.
3. Acceptance tests and results
The following conclusions have been drawn from the test results:

- The performed NDT tests have confirmed that the quality of the weld seams fulfills the requirements ISO 5817, Class B [5];
- Each FBO and parts of the FBO assembly meet the requirements of Check dimension procedure [6];
- The leak test and thermal shock do not affect the integrity of the product;
- The flow test results have confirmed the accuracy of calculations [1], with the difference around 7% (Figure 6).

![Figure 6. Comparison of experimental and calculation data flow test results of FBOs.](image)

4. Conclusions
According to the obtained results of qualification phase, the FBO design was approved for serial manufacturing. JSC NIIEFA has manufactured and delivered 50 FBOs (24 left+24 right and 2 straight FBOs with six and four orifices) to ITER Organization.

5. References
[1] ISO 5167-2 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full: Orifice plates
[2] Technical Specification “Flow balancing orifice for TF coil”
[3] ISO 15614-1 Specification and qualification of welding procedures for metallic materials - Welding procedure test: Arc and gas welding of steels and arc welding of nickel and nickel alloys
[4] Welding procedure qualification record WPQR SC-10
[5] ISO 5817 Welding – Fusion welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections
[6] Check dimension procedure of Flow Balancing Orifices