MHD CHARACTERISTICS OF TEST BLANKET MODULE ELEMENTS

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Abstract: MHD characteristics of TBM elements in magnetic field up to 1T were studied experimentally in NaK loop at temperature around 60°C: round pipe in transverse non-uniform magnetic field and a mock-up of TBM inlet manifold including inlet pipe, inlet collector and two rows of parallel poloidal (vertical) ducts with electrical heater between them to simulate ceramic element. MHD pressure drop and flow rate distribution were compared with engineering correlations.

1. Experiment description

MHD characteristics of Test Blanket Module (TBM) elements in high magnetic field (up to 1T) were studied experimentally as part of R&D program in support of Indian TBM concept to be tested in International Thermonuclear Experimental Reactor (ITER) [1, 2]. The TBM uses ceramic breeder and eutectic lead-lithium (LL) alloy as tritium breeders and helium and LL as coolants. Helium removes heat from the TBM first wall and structure elements, while LL flowing in a number of poloidal rectangular ducts removes heat generated in ceramic elements placed between these ducts.

MHD tests were performed in NaK loop at temperature around 60°C in magnetic field up to 1T on two mock-ups: round pipe in transverse non-uniform magnetic field and a mock-up of TBM inlet manifold.

A round pipe 1700 mm long with the outer radius $r_0 = 15.1$ mm, inner radius $r_i = L = 9.75$ mm, wall thickness 5.35 mm (SS) was placed in non-uniform magnetic field with characteristic lengths $x_0/r_i = 18$ and 32, where x_0 is non-uniform magnetic field region half length. To get $x_0/r_i = 32$ at one end of the magnet specially profiled pole pieces were used. For TBM tests in ITER this characteristic dimension x_0/r_i will be around 60.

TBM inlet manifold included inlet pipe, inlet collector and two rows of parallel poloidal (vertical) ducts with electrical heater between them to simulate ceramic element (Fig. 1). Its outer dimension along the magnetic field lines was 105 mm with 3 mm wall thickness. Region of uniform magnetic field had 470 mm height including 48 mm of inlet collector (with 3 mm bottom plate). The first poloidal duct (close to the inlet pipe) had two sub ducts of rectangular cross section 12×48 mm, the second one – three sub ducts 12×31 mm, inlet pipe inner diameter is 28 mm (wall thickness 3 mm).

Test parameters based on the corresponding characteristic length and B=1 T were: for round pipe – Ha≤385, $N=Ha^2/Re\leq 46$; for inlet manifold – Ha≤860, N≤ 325 as compared to those of TBM: Ha=2100, N≤115. Automatic data measuring system was used with pressure (pressure difference) sensors and wall potential sensors.

There was no electrical insulation on the duct and round pipe walls to simulate the possible first stage of TBM tests in ITER without electrical barriers.

2. Results and discussion

Experiments for the round pipe in a fringing magnetic field were conducted in 2011 and reported at the Russian Conference on Magnetohydrodynamics, Perm, 2012. Previous experimental results [3] for round and rectangular ducts were for $x_0/L \leq 15$. Later on, the results for round pipe with $x_0/L \approx 27$ were also published [4].

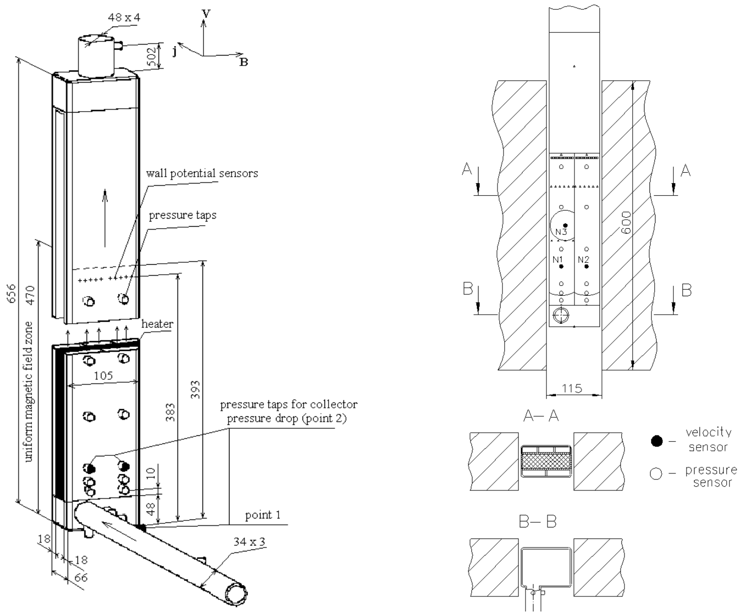

Figure 1: TBM manifold mock-up (a) and its placement in a magnetic field (b).

The measured magnetic field and pressure distribution are shown in Fig. 2 (magnet was moved in vertical direction while round mock-up was fixed to get more measuring points).

Pressure was measured with strain gage transducers (maximum pressure 0.6 MPa, main error 0.5% from measured pressure). Comparison of experimental data for non-dimensional pressure drop with theoretical ones (solid lines) is presented in Fig. 3 as a function of interaction parameter N= Ha^2/Re for three zones of magnetic field distribution (Fig. 2): 1 – region of non-uniform magnetic field with $x_0/r_i = 32$; 2 – region of close to uniform magnetic field; 3 - region of non-uniform magnetic field with $x_0/r_i = 18$. Well known correlations (see [3] for example) were used:

$$\Delta\bar{p} = \frac{\Delta p}{\sigma V_0 B_0^2 r_i} = \frac{k_p}{r_i}\int_{x_1}^{x_2} \bar{B}^2(x)dx \quad , \qquad (1)$$

where $k_p = \dfrac{1}{1+c}$, $c = \dfrac{\sigma_w\left(r_o^2 - r_i^2\right)}{\sigma\left(r_o^2 + r_i^2\right)}$, σ, σ_w – liquid metal and duct wall electrical conductivities, V_0 – mean flow rate velocity, B_0 = 0.91 T – mean value in uniform field region, $\bar{B} = B/B_0$ – dimensionless magnetic field.

Having in mind the error of experimental data shown in Fig. 3, it may be concluded that under experimental conditions they are close and slightly higher than theoretical ones. 3-D effects in non-uniform field zones (1 and 3) are not large, so correlation (1) may be used for engineering estimation of MHD pressure drop in non-uniform magnetic field with $x_0/r_i \geq 18$. The same conclusion for $x_0/r_i \approx 27$ is made also in [4].

For the mock-up of TBM inlet manifold pressure distribution along the flow path obtained with pressure sensors is shown in Fig. 4 for flow rate 8 m^3/h, B=1 T, Ha=860 (for inlet pipe). More or less linear pressure distribution along the sub ducts may be seen. Inlet pipe is completely in magnetic field fringing zone just from the collector.

Non-dimensional MHD pressure drop in inlet manifold obtained with differential pressure sensors (between points 1 and 2 in Fig. 1) versus inlet pipe interaction parameter is shown in Fig. 5 for all sub ducts. Pressure drop is normalized with $\rho \cdot V_0^2 / 2$, where V_0 is inlet pipe mean flow velocity. Experimental error is not more than 6% as a rule.

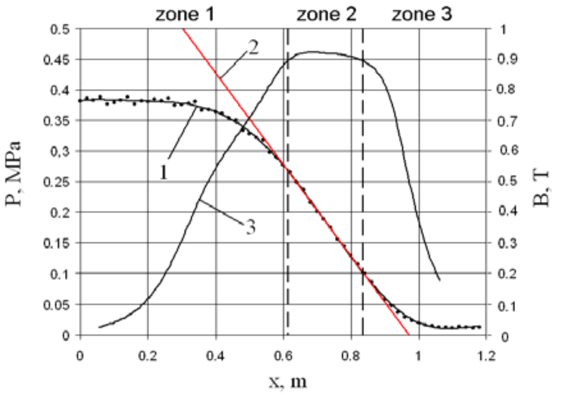

Figure 2: Magnetic field and pressure distribution over the pipe. 1 – pressure distribution along the duct (experimental points and approximation curve); 2 – linear dependence of pressure in close to uniform magnetic field zone (zone 2); 3 – magnetic field distribution

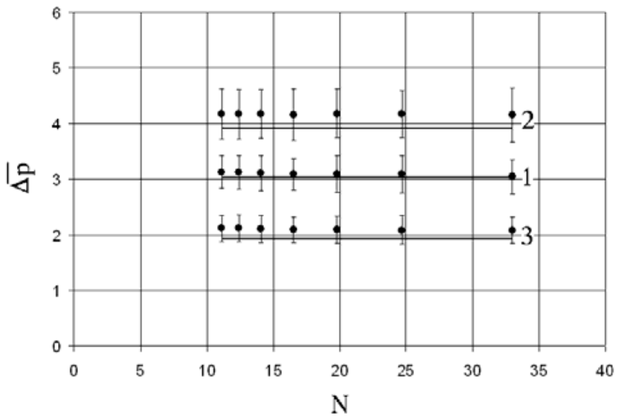

Figure 3: Non-dimensional pressure drop in zones 1-3 as a function of the interaction parameter (Ha_{max} = 385).

Pressure drop in part of the inlet pipe from point 1 to collector outer wall accounts for around 37.5% of pressure drop in manifold. Two curves corresponding to approximate theoretical predictions [5, 6] are shown for comparison:

- for transition from circular pipe to collector plus from collector to ducts

$$\Delta p_{3-D}^{MHD} = \sqrt{N} \cdot \frac{\rho \cdot V_0^2}{2} + \sigma \cdot V_{col.} \cdot L_{col.} \cdot B^2 \cdot Ha^{-1}, \tag{2}$$

- for flow in complex geometries

$$\Delta p_{3-D}^{MHD} = k \cdot N \cdot \frac{\rho \cdot V_0^2}{2}, \tag{3}$$

where L_{col} – collector half width in magnetic field direction (52.5 mm), V_{col} – collector mean flow velocity $V_{col} = \frac{Q}{2 \cdot L_{col} \cdot H_{col}}$, Q – flow rate, H_{col} – collector height (45 mm), k – parameter of geometry complexity (for TBM design optimization we used k=1.5). Experimental data correspond to the following empirical correlation:

$$\Delta p_{3-D}^{MHD} = 0.881 \cdot N \cdot \frac{\rho \cdot V_0^2}{2}.$$

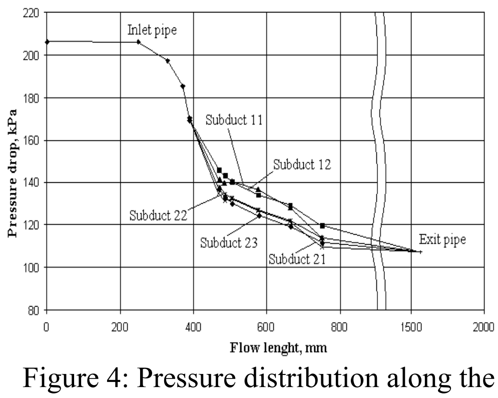

Figure 4: Pressure distribution along the flow path.

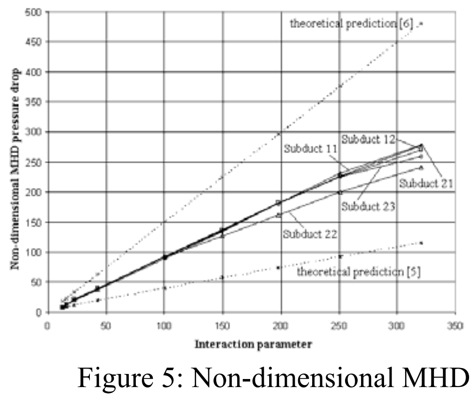

Figure 5: Non-dimensional MHD pressure drop in inlet manifold versus interaction parameter for different sub ducts.

Distribution of potential difference between side walls over ducts width (magnetic field direction) is shown in Fig. 6. Averaged over duct height liquid metal velocity obtained from circuit theory with known potential distribution and calculated electrical resistances of liquid metal and outer walls is also presented in Fig. 6. Integration of velocity distribution over sub ducts cross section gives flow rate in sub ducts (Table 1), sum of these flow rates differs from total flow rate measured with electromagnetic flow meter (EFM) less than 3%.

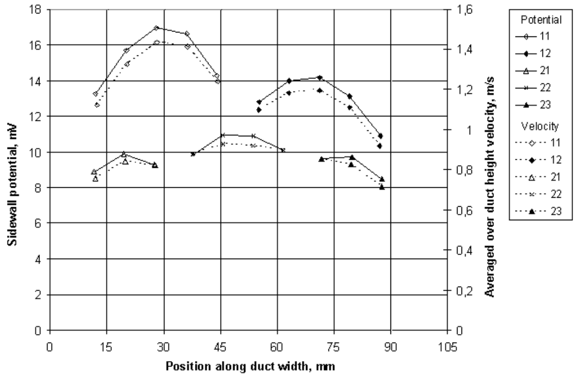

Figure 6: Potential and average over duct height velocity distribution in two sub ducts (sub ducts numeration from left to right – 11, 12) and three sub ducts (21, 22, 23)

As may be seen from Table 1 flow rate in sub duct 11 is larger than in sub duct 12 and that in sub duct 22 is larger than in sub ducts 21 and 23 for all total flow rates. There are two reasons for this phenomenon: different effective thickness of inner Hartman walls (all outer walls and sub ducts partitions were 3 mm) and influence of inlet pipe. Sub ducts 11 and 12 are symmetrical with respect to inner Hartmann wall, and flow rate increase in sub duct 11 may be explained exclusively by inlet pipe asymmetry with regard to channel 1 center line (inlet pipe is just opposite sub duct 11). This flow rates asymmetry is decreasing with interaction parameter increasing from 17.3% at N≈12 up to 15.2 % at N≈310.

Practically equal flow rates in sub ducts 21 and 23 reveal small influence of inlet pipe asymmetry on these ducts. At the same time sub ducts 21 and 23 are symmetrical with respect to Hartmann wall effective thickness and differ in that to sub duct 22. For sub duct 21 thickness of left Hartman wall is 3 mm, while effective thickness of right Hartman wall may be estimated as 1.5 mm, while for sub duct 22 effective thickness of both Hartman walls is 1.5 mm. Let's compare MHD pressure drop in sub ducts 21 and 22 using the following correlation [3]:

$$\Delta p^{MHD} = k_p \cdot \sigma \cdot V \cdot B^2 \cdot L,$$

where $k_p = \left[1 + \frac{\sigma \cdot a}{\sigma_{hw} \cdot t_{hw}} + \frac{1}{3 \cdot \beta} \cdot \frac{\sigma \cdot a}{\sigma_{sw} \cdot t_{sw}} \right]^{-1}$, σ_{hw}, σ_{sw} – electrical conductivity of Hartman and side walls; t_{hw}, t_{sw} – thickness of Hartman and side walls; a –sub ducts half width; β – ratio of sub duct half thickness to half width; L – sub duct length.

The ratio of MHD pressure drop in sub ducts 21 and 22 is the ratio of k_p: $\Delta p_{21}/\Delta p_{22}$ = k_{p21}/ k_{p22} = =1.3, and one may expect mean flow velocity (volume flow rate) in sub duct 22 higher by the same value in comparison to sub duct 21.

According to experiment (Table 1) Q_{22}/Q_{21}=1.1-1.12, i.e. slightly less, and this is explained by multichannel effect between sub ducts 22 and 21.

Table 1 .Flow rate in mock-up and sub ducts, m^3/h

Total flow rate (EMF)	CHANNEL-1		CHANNEL-2			Total flow rate in sub ducts and deviation from EMF
	Sub duct 11	Sub duct 12	Sub duct 21	Sub duct 22	Sub duct 23	
8.0	2.70	2.27	1.03	1.15	1.02	8.16 (2%)
6.29	2.12	1.79	0.80	0.89	0.79	6.39 (1.6%)
4.3	1.45	1.23	0.54	0.61	0.54	4.37 (1.6%)
2.3	0.77	0.66	0.29	0.33	0.29	2.33 (1.3%)
0.31	0.092	0.079	0.042	0.046	0.043	0.30 (3%)

3. Conclusion

MHD pressure drop for the round electro-conducting pipe in a fringing magnetic field with normalized decay length larger, at least x_0/r_i=18 may be estimated with the use of engineering correlations for fully developed flow and local magnetic field values.

For the mock-up of TBM inlet manifold with electro-conducting walls engineering correlations for pressure drop were derived. It was shown that influence of manifold on flow rate distribution between poloidal subducts is decreasing with parameter N increasing and for TBM conditions will be less than 5-7%. Different thickness of Hartmann walls in subducts will cause some nonuniformity in flow rate distribution between parallel sub ducts.

4. References

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