4.2.4 MHD pressure drop geometry sensitivity correction factors

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Liquid metal blanket concepts are still attractive ITER and DEMO blanket candidates as they have low operating pressure, simplicity and a convenient tritium breeding cycle. But how to reduce MHD pressure drop still remains a key issue, especially in the new concept system of the rectangular ducts with flow channel insert (FCI). The numerical and experimental studies of MHD flow in a rectangular with FCI indicated that MHD pressure drop from experimental measured is higher than that from theory or modeling.

The more experiments of MHD effect in the FCI flow were performed using the Ga-In-Sn loop in Southwestern Institute of Physics, China. A rectangular duct with two small weld slots, short the ‘S-duct’, which was fabricated with two simple U-type 304 stainless steel channels welded at the middle line of the lengthwise sides to reduce the manufacture cost while conducting an experimental investigation MHD effect of FCI flow, but a dramatic influence on the flow structure, pressure gradient and electric potential distribution had been measured.

For convenience, the major parameters of the test units are shown here again; The case I, the duct with FCI having one pressure equilibrium slot (PES) are: 304 stainless steel duct, \(2a_2 = 68\, \text{mm}, 2b_2 = 60\, \text{mm}, t_2 = 2\, \text{mm}\); epoxy FCI, \(2a_1 = 54\, \text{mm}, 2b_1 = 46\, \text{mm}, t_1 = 2\, \text{mm}\); the gap between 304 SS duct and FCI, \(d = 5\, \text{mm}\) slot width \(W = 3\, \text{mm}\), MHD pressure drop measurement distance, \(L_0\), equate to 500 mm. The total length of the duct with FCI is 1500 mm. For the Case II, the epoxy FCI having pressure equilibrium holes (PEHs), there are seven PEHs with 10 mm in diameter.

The Case III, the S-duct in weld zone produced small slots (\(d < 5\, \text{mm}\) in dept, \(2w < 10\, \text{mm}\) in width), and have a section \(2a \times 2b = 68 \times 60\, \text{mm}\), wall thickness \(t_e = 2\, \text{mm}\). The detail experimental procedure can be found in references.

According to classic magneto-hydrodynamics theory the MHD pressure drop in normal thin wall conducting duct (short in ‘N-duct’) is:

\[
\Delta p = \kappa_e \sigma \frac{\varepsilon}{B_0^2 L_0}\]  

(1)

Here \(\Delta p\) is the MHD pressure drop; \(\kappa_e\) is the characteristic of the duct (called as the dimensionless MHD pressure drop/gradient), \(\varepsilon\) is the average velocity of the duct flow, \(B_0\) is transverse magnetic field, \(L_0\) is the distance of measured MHD pressure drop. The dimensionless MHD pressure drop from theory is:

\[
\kappa_e = \frac{\varphi}{1 + \frac{a}{3b + \varphi}}
\]

(2)

Here \(\varphi = \sigma \nu \nu / \sigma_i\), \(a\) is the wall conductance ratio, \(\sigma_i\), and \(\sigma_e\) is the liquid metal conductivity and the duct conductivity, respectively. The experimentally measured dimensionless MHD pressure drop is:

\[
\kappa_e = \frac{\Delta p}{\sigma_i \varepsilon B_0^2 L_0}
\]

(3)

Here \(\Delta p\) is measured from pressure sensor, \(\varepsilon\), \(B_0\) and \(L_0\) also is measured data, \(\sigma_i\) has been known.

From classical hydrodynamics, it is known that the velocity relates to the circumference of cross section of the flow (it is concealed in the area of the duct), and reference from the previous 3-D MHD pressure drop effect caused by a manifold flow. If \(\kappa_e\), \(d\ll a\ and \ b\), then the geometry sensitivity factor, \(\kappa_i\), the slots making the dramatic velocity profile and higher MHD pressure drop in S-duct., can be tentatively supposed as:

\[
\kappa_i = \frac{w_d}{a b}
\]

(4)

Here \(w\) is the width of the slot, \(a\ and \ b\) is the cross section of the duct in length and width, respectively.

The slots also making extra blocking force; and the blocking force factor, \(\kappa_{\text{se}}\), will also be included. If the \(Re\) is taken 1200, then considering magnetic field interaction with flow, we attempt to take the \(\kappa_{\text{se}}\) as:

\[
\kappa_{\text{se}} = \frac{24 \cdot 1200}{Re}
\]

(5)

Therefore, if using \(\kappa\) expressed the dimensionless MHD pressure drop of S-duct, then the \(\kappa\) is as the follow:

\[
\kappa = \kappa_e + \kappa_i + \kappa_{\text{se}}
\]

(6)

And MHD pressure drop is:

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\[ \Delta P_{\text{bulk}} = \kappa \sigma_v v_0 R_i^2 L_0 \]  

(7)

If the \( w_i \) and \( d_i \) is taken as 4 mm and 5 mm, respectively, and together \( a, b, t, \), as well as other experimental conditions into Eqs. (4) – (7), then the value of \( \kappa \) is obtained.

For the FCI flow, the \( \kappa \) from simplification modeling is expressed as:

\[ \kappa = \frac{[1 + (1 - K)s] \sigma_v t \lambda_i \lambda_i}{\sigma_v \lambda_i (a_i + b_i) + \sigma_v t \lambda_i b_i} \]  

(8)

\[ K = \frac{t_i a_i \left[ \sigma_v t \lambda_i (a_i + b_i) + \sigma_v t \lambda_i b_i \right] (1 + h - d/b_2)(1 + s)}{\sigma_v \lambda_i (a_i + b_i) t_i t_i d + \sigma_v \lambda_i b_i t_i t_i d + \left[ \sigma_v t \lambda_i d t \lambda_i a_i (a_i + b_i) + \sigma_v t \lambda_i b_i t \lambda_i a_i (a_i + b_i + d_i) \right] (1 + h - d/b_2) s} \]  

(9a)

From mass conservation law, the ratio of velocity in the core and average velocity in the duct, \( K_c \), is:

\[ K_c = 1 + (1 - K) s \]  

(9b)

According to the view of the core flow (in FCI box), the pressure equalization holes (PEH) and one pressure equalization slot (PES) can be treated as geometry sensitivity like-S duct case and addition considered FCI out site boundary area flow effect. For FCI with PES (Case I), the \( \kappa_{c, \text{PES}} \) is taken as:

\[ \kappa_{c, \text{PES}} = \frac{d \cdot w_i}{4 \cdot a_i b_i} \cdot K_c \]  

(10)

Where \( w_i \) is the width of the PES.

For FCI with PEHs (Case II), we changed the PEHs to equivalent slot width:

\[ w_{\text{PEH}} = \frac{\pi R_{\text{PEH}}}{L_{\text{PEH}}} \]  

(11a)

here \( L_{\text{PEH}} \) is the distance between two PEHs, then the \( \kappa_{c, \text{PEH}} \) is:

\[ \kappa_{c, \text{PEH}} = \frac{d \cdot \pi R_{\text{PEH}}}{4 \cdot a_i b_i L_{\text{PEH}}} \cdot K_c \]  

(11b)

Because there are the boundary flows in the gap distance between FCI and duct, the slot or holes will not cause an extra blocking force likely in S-duct case (Case III). But similar to the normal rectangular duct flow, maybe the 2-D MHD pressure drop effect shall be considered. According to the role of reference and considering the FCI-duct character here, the \( \kappa_{c, 0} \) is taken as:

\[ \kappa_{c, 0} = \frac{b_i b_i}{a_i a_i}, \left( M^{-1/2} - 0.023 \right) \frac{K_c}{K_c} \]  

(12)

Therefore, the dimensionless MHD pressure drop in FCI with PEHs is:

\[ \kappa_{c, \text{PEH}} = \kappa_c + \kappa_{c, \text{PEH}} + \kappa_{c, 0} \]  

(13)

and that in FCI having PES is:

\[ \kappa_{c, \text{PES}} = \kappa_c + \kappa_{c, \text{PES}} + \kappa_{c, 0} \]  

(14)

Or, MHD pressure drop is:

\[ \Delta P_{\text{FCI-PEH}} = \kappa_{c, \text{PEH}} \sigma_v v_0 R_i^2 L_0 \]  

(15)

\[ \Delta P_{\text{FCI-PES}} = \kappa_{c, \text{PES}} \sigma_v v_0 R_i^2 L_0 \]  

(16)

Using conditions of FCI with PEHs and PES in Eqs. (12) and (13), the \( \kappa_{c, \text{PEH}} \) and \( \kappa_{c, \text{PES}} \) have a good agreement with experimental data \( \kappa_c \).

The higher velocity profile in the center-plane of the cross section of the duct results in the higher MHD pressure drop. The MHD pressure drop geometry sensitivity correction factors can be used to explain why quantitatively the experimental data are higher than theory expectation. One conclusion is that MHD duct flow geometry sensitivity can be used to reduce MHD pressure drop and to control velocity profile in the duct. But more detailed study both experimentally and theoretically, is necessary.