Selection and strength check on fasteners of protective structure in cryogenic wind tunnel

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Abstract. Protective structure, acted as a substructure of internal insulation system in cryogenic wind tunnel, is in possession of such advantages of isolating insulation unit from cryogenic medium and reducing cold energy loss. However, the protective structure is continuously subjected to alternating pressure during the operation of cryogenic wind tunnel. Thus, the type selection and strength check on connecting fastener, acted as weak bearing component in protective structure, are investigated. Firstly, according to the composition of protective structure, three key connecting positions are determined and the corresponding connecting fasteners are selected. Then, according to the cryogenic wind tunnel working condition, the theoretical mechanical models of connecting fasteners are built under different working conditions. Finally, involving the force and moment balance, mechanics analysis and strength check are conducted on connecting fasteners. The obtained results show that the selected fasteners are conformed to the strength requirement of cryogenic wind tunnel in service, which paves the way for building the cryogenic wind tunnel in the future.

1. Introduction

Cryogenic wind tunnel is the best way to achieve large Reynolds number simulation by reducing the operating medium temperature [1]. In order to maintain the cryogenic environment of the cryogenic wind tunnel, it is necessary to adopt the insulation structure with high efficiency of insulation characteristic. Presently, there are four common used heat insulation methods in cryogenic wind tunnel, including external insulation method [2], cold box method [3], internal insulation method [4], and integration of internal and external insulation method [5], among which the internal insulation method is taken as the best way for large cryogenic wind tunnel because it can effectively shorten the operation time of the cooling process of the wind tunnel, reduce the number of components to be cooled and the noise of the wind tunnel.

The protective structure [6], acted as one of the subsystems of the internal insulation system in the cryogenic wind tunnel, is used for isolating the insulation unit and the cryogenic medium and reducing the cooling energy loss. However, the protective structure constantly bears the alternating pressure caused by the operation of the cryogenic wind tunnel. Thus, it is of great significance to carry out the investigation on type selection and strength check of protective structure, especially the connection fastener of the weak bearing part, for ensuring the bearing capacity of the protective structure.

On this account, this work focuses on the protection structure of cryogenic wind tunnel. Firstly, the type selection of the fasteners at the key connection position of the protective structure is carried out. Then, according to the different work conditions during the operation and maintenance of the wind tunnel, the theoretical mechanical model of the fasteners is established. Finally, the strength check on
the fasteners of protective structure is investigated. This work is of importance because it paves the way for the internal insulation system of cryogenic wind tunnel to be built.

2. Type selection of fasteners for protective structure
The protective structure is composed of protective plate, upper depression bar, lower depression bar and supporting parts. The protective plate is fixed between T-shaped upper and lower depression bars. The fasteners are used to connect upper and lower depression bars, to connect the lower depression bar and supporting parts and to connect the supporting parts and inner wall of wind tunnel. Thus, the key connections in protective structure are including (i) the connection between upper and lower depression bars, (ii) the connection between lower depression bar and supporting parts and (iii) the connection between supporting parts and inner wall of wind tunnel, as shown in Fig. 1. Specifically, 4 M10 screws are selected for the connection i, 1 M10 screw is selected for the connection ii, and 1 M16 studs is selected for the connection iii. Additionally, the selected screw and studs are made of 304L stainless steel with performance grade of A2-80. In order to verify the strength adaptability of such fasteners as screws and studs, and to ensure the safety of the protective structure, the strength check on these fasteners is conducted.

3. Strength check on fasteners in protective structure
According to [3, 7] of such large cryogenic wind tunnels as NTF and ETW, the operation and maintenance conditions include high pressure work condition of 70 kPa, low pressure work condition of 20 kPa and maintenance condition with gravity of 686 N for maintenance staff.

3.1. Strength check for connection i

3.1.1. High pressure work condition. In high pressure work condition, theoretical mechanical model of the screw in connection i is shown in Fig. 2, where $G_0$ is the gravity of protective plate of 72.64 N, $S_0$ is the stress area of the protective plate of 0.261 m², $L_0$ is the half width of protective plate of 0.128 m and $L_0'$ is the half width of upper depression bar of 0.04 m. Additionally, the $\alpha$ is of 7.5° and $P_0$ is $70\times10^3$ Pa.
According to the force and moment balance, yields:

\[
F = \frac{P_0 \times S_0 - G_0}{\cos \alpha} = 18381.17 N
\]

\[
F' = \frac{(P_0 \times S_0 - G_0) \times L_0}{L'} = 58231.55 N
\]

It is can be known that the yield stress, \(\sigma_s\), of 304L stainless steel with the performance grade of A2-80 is 600MPa from the GB/T 3098.6-2014. Involving the 4 time safety factor to meet the design requirements, the allowable stress, \([\sigma]\), can be obtained as follows.

\[
[\sigma] = \frac{\sigma_s}{4} = 150 \times 10^6 Pa
\]

Due to the 4 screws used for connection i, the diameter, \(D_1\), of each screw can be calculated.

\[
D_1 = \sqrt[\pi \times [\sigma]} = 9.20 mm < 10 mm
\]

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.

3.1.2. Low pressure work condition.

In low pressure work condition, theoretical mechanical model of the screw in connection i is shown in Fig. 3, where the relative parameters are consistent with that in high pressure work condition, except the \(P_0\) is of \(20 \times 10^3\) Pa.

![Figure 3](image)

According to the force and moment balance, yields:

\[
F' = \frac{P_0 \times S_0 + G_0}{\cos \alpha} = 5346.10 N
\]

\[
F = \frac{(P_0 \times S_0 + G_0) \times L_0}{L'} = 16936.45 N
\]

From high pressure work condition, It is can be known that the allowable stress, \([\sigma]\), of screw is 150MPa, thus the diameter, \(D_1\), of each screw can be calculated.

\[
D_1 = \sqrt[\pi \times [\sigma]} = 4.96 mm < 10 mm
\]

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.
3.1.3. Maintenance condition. In maintenance condition, the theoretical mechanical model of the screw in connection i is shown in Fig. 4, where \( G_1 \) is the gravity of maintenance staff of 686 N and other parameters are consistent with that in high pressure work condition.

![Figure 4. Theoretical mechanical model of the screw in connection i under maintenance condition.](image)

According to the force and moment balance, yields:

\[
F' = \frac{G_0 + G_1}{\cos \alpha} = 758.64 \text{N} \\
F = \frac{G_0 \times L_0 + G_1 \times L_1}{L'} = 4622.85 \text{N}
\]

Similarly, the diameter, \( D_1 \), of each screw can be calculated.

\[
D_1 = \sqrt{\frac{F - F'}{\pi \times [\sigma]}} = 2.86 \text{mm} < 10 \text{mm}
\]

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.

3.2. Strength check for connection ii

3.2.1. High pressure work condition. In high pressure work condition, the theoretical mechanical model of the screw in connection ii is shown in Fig. 5, where \( G_i \) is the sum gravity of protective plate, two upper protective plates and two lower protective plates of 317.29 N, \( S_0 \) is the stress area of the two protective plates of 0.52 m². Additionally, \( \alpha \) is of 7.5° and \( P_0 \) is \( 70 \times 10^3 \text{Pa} \).

![Figure 5. Theoretical mechanical model of the screw in connection ii under high pressure work condition.](image)

According to the force balance, yields:

\[
F = \frac{P_0 \times S_0 - G_0}{4 \cos \alpha} = 9111.80 \text{N}
\]

Due to the allowable stress, \([\sigma]\), of 150 MPa, the diameter, \( D_i \), of screw can be calculated.

\[
D_i = \sqrt{\frac{4F}{\pi \times [\sigma]}} = 8.80 \text{mm} < 10 \text{mm}
\]

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.
3.2.2. **Low pressure work condition.** In low pressure work condition, the theoretical mechanical model of the screw in connection ii is shown in Fig. 6, where the relative parameters are consistent with that in high pressure work condition, except the $P_0$ is of $20 \times 10^3$ Pa.

![Figure 6. Theoretical mechanical model of the screw in connection ii under low pressure work condition.](image)

According to the force balance, yields:

$$F = \frac{P_0 \times S_0 + G_0}{4 \cos \alpha} = 5130.63 N$$

Similarly, the diameter, $D_1$, of each screw can be calculated.

$$D_1 = \sqrt{\frac{4F}{\pi \times \sigma}} = 6.60 mm < 10 mm$$

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.

3.2.3. **Maintenance condition.** In maintenance condition, the theoretical mechanical model of the screw in connection ii is shown in Fig. 7, where $G_j$ is the gravity of maintenance staff of 686 N and other parameters are consistent with that in high pressure work condition.

![Figure 7. Theoretical mechanical model of the screw in connection ii under maintenance condition.](image)

According to the force balance, yields:

$$F = \frac{G_0 + G_j}{4 \cos \alpha} = 235.36 N$$

Similarly, the diameter, $D_1$, of each screw can be calculated.

$$D_1 = \sqrt{\frac{4F}{\pi \times \sigma}} = 1.47 mm < 10 mm$$

Therefore, M10 screw made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.
3.3. Strength check for connection iii

The connection iii is mainly checked for the high pressure work condition. In this case, the theoretical mechanical model of the studs in connection iii is consistent with that in Fig. 5, where $G_1$ is the sum gravity of protective plate, two upper protective plates, two lower protective plates and four supporting parts of 321.71 N, $S_0$ is the stress area of the two protective plates of 0.52 m². Additionally, $\alpha$ is of 7.5° and $P_0$ is 70×10³ Pa.

According to the force balance, yields:

$$F = \frac{P_0 \times S_0 - G_1}{4 \cos \alpha} = 9110.68 N$$

It is can be known that the yield stress, $\sigma_y$, of 304L stainless steel with the performance grade of A2-80 is 600MPa from the GB/T 3098.6-2014. Involving the 4 times safety factor to meet the design requirements, the allowable stress, $[\sigma]$, can be obtained as follows.

$$[\sigma] = \frac{\sigma_y}{4} = 150 \times 10^6 Pa$$

Due to the 1 studs used for connection iii, the diameter, $D_1$, of studs can be calculated.

$$D_1 = \frac{4F}{\pi \times [\sigma]} = 8.80 mm < 16 mm$$

Therefore, M16 studs made of 304L stainless steel with performance grade of A2-80 can meet the design requirements.

4. Conclusions

Aiming at the protective structure of the internal insulation system in the cryogenic wind tunnel, the connecting fastener of the weak bearing part of the protective structure is firstly selected. Then, according to the operation and maintenance conditions of the cryogenic wind tunnel, the theoretical mechanical model of the fastener is established, and the strength of the fastener is checked. The obtained conclusions are listed as follows.

1) The calculation results show that the fastener bears the maximum theoretical load under the condition of high pressure work condition. Specifically, the load of the screws in connection i is 39850 N, the load of the screws in connection ii is 9111.8 N and the load of the studs in connection iii is 9110.68 N. Thus, the high pressure work condition should be acted as a mainly factor for type selection the fasteners in protective structure.

2) The results of strength check show that the selected fasteners of the protective structure can meet the strength requirements of the cryogenic wind tunnel in service which lays a theoretical foundation for the design and construction of the protective structure of the cryogenic wind tunnel.

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