HEAT TRANSFER OF INSULATION STRUCTURE FOR LARGE CRYOGENIC WIND TUNNEL

by

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In order to maintain the cryogenic environment of cryogenic wind tunnel in service, heat transfer of insulation structure is investigated in this work. Firstly, the design and material selection of insulation structure is conducted. Afterwards, theoretical calculation on heat transfer of insulation structure is carried out based on 1-D heat conduction model. Subsequently, the finite element model of insulation structure is established, on this basis, involving the actual work condition of cryogenic wind tunnel, heat transfer of the insulation structure is numerically calculated. Finally, the testing platform able to simulate the work environment of cryogenic wind tunnel is built and the temperature measurement experiments at the cryogenic condition and at the cryogenic pressure condition are carried out, respectively. The obtained results show that the designed insulation structure is in possession of great insulation characteristics to ensure the cryogenic environment of cryogenic wind tunnel. Additionally, the established testing platform can provide a testing method to investigate the heat transfer character of other materials or structures in cryogenic environment.

Key words: *cryogenic wind tunnel, insulation structure, heat transfer, theoretical calculation, numerical simulation, experimental investigation*

Introduction

Recently, such aerial vehicles as air bus, large transport airplane, long-range combat aircraft*, etc.* has been developed rapidly. To pursue the great economy and safety, wind tunnel experiments must be carried out under such similarity criterions as Mach number, Reynolds number, Prandtl number, *etc.* [1]. However, due to the limitation of size of wind tunnel testing section and the increasing geometric parameters of aircraft structure, Reynolds number is relative low and does not meet the demands of Reynolds similarity criterion using conventional wind tunnel, resulting in large deviation in the aerodynamic design and in the performance prediction of aircraft, which may lead to the alternation of design project, the abundant loss of economy, even delay of development period.

To realize the capability to simulate the high Reynolds number, a practical method is to utilize the cryogenic wind tunnel [2-4]. Presently, about 20 cryogenic wind tunnels have been established. Especially, such large cryogenic wind tunnels with the caliber more than 2 m as National Transonic Facility (NTF) [5-7], Kryo-Kanal Kolen (KKK) [8] and European

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Transonic Wind Tunnel (ETW) [9, 10], have provided the reliable testing platform for large airbuses and transport planes, promoting the development of aerospace industry in America and Europe. However, the cryogenic wind tunnel in China is with the caliber about 0.3 m [11, 12], which does not meet the demands of wind testing for large aerospace vehicles. It is therefore, urged to investigate the key technologies of large cryogenic wind tunnel. Liao *et al*. [13] pointed out that the insulation structure with excellent heat insulation characteristic acted as a key technology to develop the large cryogenic wind tunnel, which could reduce the consumption of liquid nitrogen and ensure the reliable operation of cryogenic wind tunnel. According to the insulation structure used in NTF, KKK, and ETW, Song *et al*. [14] analyzed the advantages and disadvantages of the common used insulation methods such as external insulation, internal insulation, cold box insulation and integration of internal and external insulation. The obtained results showed that the internal insulation is the optimal insulation method for large cryogenic wind tunnel. Additionally, they pointed out that the insulation structure should be designed as the formation of several sub-insulation elements to facilitate the protection and production of insulation structure. Actually, the insulation structure plays an important role to maintain the cryogenic environment in the cryogenic wind tunnel, as a result, the insulation structure must be adaptable to cryogenic environment. Thus it is of great significance to investigate the heat transfer characteristic of insulation structure for the construction of cryogenic wind tunnel.

On this account, the heat transfer of insulation structure is investigated in this work. Firstly, the design and material selection for insulation structure are carried out. On this basis, involving the cryogenic environment in which the insulation structure is located during wind tunnel operation, the physical model and numerical simulation model of heat transfer for insulation structure are established, respectively and the heat transfer characteristic of insulation structure are investigated under the work conditions of cryogenic wind tunnel, which is finally validated by the temperature measurement experiment that is conducted using the established test platform. This work is of great importance because it paves the way for the construction of large cryogenic wind tunnel.

Design of insulation structure

In large cryogenic wind tunnel, the insulation structure plays an important role to maintain the cryogenic environment and to determine the insulation property of the wind tunnel. In order to prevent the fracture of insulation structure under cryogenic environment and to facilitate the production, transportation, assemblage and maintenance of insulation structure, the insulation structure is designed as the formation of a series of insulation elements. In addition, Zhang *et al.* [15] pointed out that the combination of flexible foamed plastic and rigid foamed plastic could effectively reduce the thermal stress of insulation element. Thus, the insulation structure is designed as multi-layer debonding composite structure, as shown in fig. 1. The insulation structure is composed of several insulation elements with the thickness of 150 mm, including the inner layer of 70 mm, the intermediate insulation layer of 10 mm, the intermediate compensation layer of 10 mm and

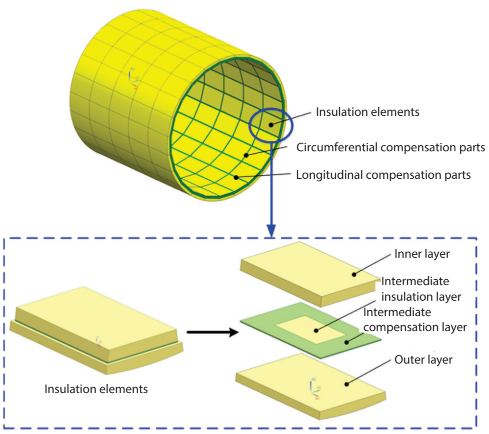

Figure 1. Composition of insulation structure

the outer layer of 70 mm. It is noting that the intermediate compensation layer is embedded in the intermediate insulation layer. The inner layer, intermediate insulation layer and outer layer, made of rigid polyurethane foams, are used to prevent the cold energy in the wind to leak outside and the heat outside to penetrate into the wind, while the intermediate compensation layer, made of flexible polyurethane foams, is used to compensate for the deformation avoid damaging the insulation elements. Additionally, the compensation parts made of flexible polyurethane foams are adopted among the insulation elements to reduce the local stress concentration.

Heat transfer calculation of insulation element

Theoretical model

According to the working condition of insulation element, the heat transfer model of insulation element is established, shown in fig. 2, based on the following hypotheses:
- Stable state.
- 1-D heat transfer is among the layers.
- Physical parameters are all constant.
- Heat resistance between the insulation element and wind wall is ignored because the insulation element and wind wall are in close contact.
- Heat radiation is ignored because the heat radiaton at cryogenic environment is very small.

In fig. 2, A is the area of insulation element, V_{N_2} – the flow rate of cryogenic nitrogen, T_0 – the temperature, H – the thickness of insulation element, λ_1 – the heat conductivity of insulation element, T_1 – the inner surface temperature of insulation element, T_2 – the contact surface temperature between insulation element and wind tunnel wall, δ – the thickness of wind tunnel wall, λ_2 – the heat conductivity of wind tunnel wall, T_3 – the external surface temperature of wind tunnel wall, and T_a – the environment temperature. Additionally, h_{c1} and h_{c2} are the heat convection coefficients between the insulation element and cryogenic nitrogen, and between the wind tunnel wall and environment, respectively.

Heat flux calculation of insulation element

According to the heat transfer model in fig. 2, the heat quantity, Q, can be obtained:

$$Q = \frac{T_0 - T_a}{R} \tag{1}$$

where R is the total heat resistance:

$$R = R_{c1} + R_1 + R_2 + R_{c2} \tag{2}$$

with

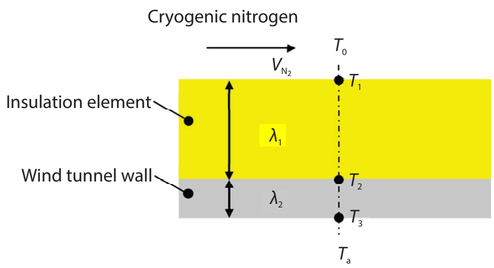

Figure 2. Heat transfer model of insulation element

$$R_{c1} = \frac{1}{h_{c1}A} \tag{3}$$

$$R_1 = \frac{H}{\lambda_1 A} \tag{4}$$

$$R_2 = \frac{\delta}{\lambda_2 A} \tag{5}$$

$$R_{c2} = \frac{1}{h_{c2}A} \tag{6}$$

Replacing eq. (2) with eqs. (3)-(6) yields:

$$R=\frac{1}{A}\left(\frac{1}{h_{c1}}+\frac{H}{\lambda_1}+\frac{\delta}{\lambda_2}+\frac{1}{h_{c2}}\right) \tag{7}$$

Replacing eq. (1) with eq. (7) yields:

$$Q=\frac{T_0-T_\mathrm{a}}{\dfrac{1}{A}\left(\dfrac{1}{h_{c1}}+\dfrac{H}{\lambda_1}+\dfrac{\delta}{\lambda_2}+\dfrac{1}{h_{c2}}\right)} \tag{8}$$

Thus, the heat flux, q, of insulation element can be obtained:

$$q=\frac{Q}{A}=\frac{T_0-T_\mathrm{a}}{\dfrac{1}{h_{c1}}+\dfrac{H}{\lambda_1}+\dfrac{\delta}{\lambda_2}+\dfrac{1}{h_{c2}}} \tag{9}$$

Additionally, because the h_{c1} changes with the V_{N_2}, the Reynolds number of cryogenic nitrogen should be involved in the calculation of q:

$$\mathrm{Re}=\frac{V_{\mathrm{N}_2}d}{\nu_{\mathrm{N}_2}} \tag{10}$$

where ν_{N_2} is kinematic viscosity coefficient of cryogenic nitrogen and d is the flow length.

Moreover, in order to characterize h_{c1}, the Nusselt number is introduced as shown:

$$\mathrm{Nu}=\frac{h_{c1}L}{\lambda_{\mathrm{N}_2}} \tag{11}$$

where L is characteristic length and λ_{N_2} is heat conductivity of cryogenic nitrogen.

The relationship between Nusselt and Reynolds numbers can be expressed by the following semi empirical formula:

$$\mathrm{Nu}=\left(0.037\,\mathrm{Re}^{4/5}-871\right)\mathrm{Pr}^{1/3} \tag{12}$$

where Pr is Prandtl number.

Combining eqs. (11) and (12) yields:

$$h_{c1}=\frac{\mathrm{Nu}\lambda_{\mathrm{N}_2}}{L}=\frac{\lambda_{\mathrm{N}_2}\left(0.037\,\mathrm{Re}^{4/5}-871\right)\mathrm{Pr}^{1/3}}{L} \tag{13}$$

Due to the minimum temperature of 78 K and the range of flow rate of cryogenic nitrogen from 2.76-476 m/s, the heat flux are calculated under the condition of two extreme velocities and the corresponding parameters are listed in tab. 1.

Table 1. The value of parameters

T_0	T_a	H	λ_1	δ	λ_2	h_{c_2}	ν_{N_2}	Pr
78 K	305.6 K	0.18 m	0.037 W/mK	0.03 m	16 W/mK	10 W/m^{2}K	$1.218 \cdot 10^{-6}$ m^2/s	0.85

Working Condition 1: T_0 = 78 K, V_{N_2} = 2.76 m/s.

According to eq. (10) yields:

$$\mathrm{Re}=\frac{V_{\mathrm{N}_2}d}{\nu_{\mathrm{N}_2}}=\frac{2.76\cdot 1}{1.218\cdot 10^{-6}}=2.27\cdot 10^6 \tag{14}$$

Combining the eqs. (13) and (14), h_{c_1} can be obtained of 30.4 W/m^{2}K, thus, according to eq. (9) yields $q_1 = 43.13$ W/m^2.

Working Condition 2: $T_0 = 78$ K, $V_{N_2} = 476$ m/s

Similar to the calculation process of working Condition 1, the heat flux in working Condition 2 can be obtained as $q_2 = -43.39$ W/m^2.

Compared with q_1 and q_2, it is can be found that the difference between q_1 and q_2 is 0.26 W/m^2, which is quite little. Therefore, the influence of flow rate of cryogenic nitrogen on heat transfer of insulation element can be ignored.

Calculation for T_3

According to the aforementioned theoretical derivation, yields:

$$q = \frac{Q}{A} = \frac{T_0 - T_3}{\dfrac{1}{h_{c1}} + \dfrac{H}{\lambda_1} + \dfrac{\delta}{\lambda_2}} \tag{15}$$

Thus, the T_3 can be obtained:

$$T_3 = T_0 - q\left(\frac{1}{h_{c1}} + \frac{H}{\lambda_1} + \frac{\delta}{\lambda_2}\right) \tag{16}$$

Calculating the eq. (16) yields $T_3 = 288.68$ K and the temperature difference between the wind tunnel wall and cryogenic nitrogen is 210.68 K, which indicates that the insulation element is in possession of sound insulation characteristic and able to maintain the cryogenic environment inside the wind tunnel.

Numerical simulation

As indicated, the insulation structure is composed of several insulation elements. In order to reduce the local stress concentration, the compensation parts are set between the insulation elements, which leads to the heat transfer of insulation structure is complex. In this case, it is difficult to solve the analytical solution. Thus, numerical simulation is carried out to investigate the heat transfer of insulation structure in this section.

Numerical calculation model

The numerical calculation model is established as shown in fig. 3, in which the FEM is composed of wind tunnel wall and insulation structure. The wind tunnel wall is made of 304 stainless steel with the diameter of 5 m, insulation structure is composed of insulation element, circumferential compensation parts and longitudinal compensation parts. The corresponding materials are listed in tab. 2. For the sake of calculation, the 1/4 model is used for calculation because the model is centrosymmetric. Eight node force thermal coupled hexahedral element is used for meshing with the total grids number of 101883.

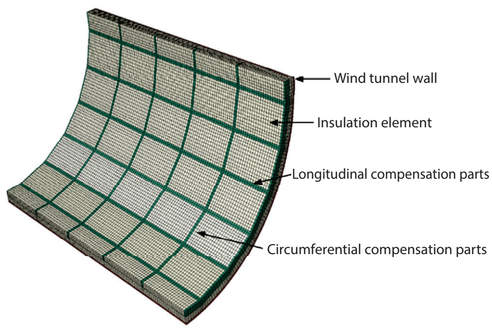

Figure 3. Numerical calculation model

Additionally, as is known from section *Heat transfer calculation of insulation element*, the cryogenic nitrogen flow rate has few influences on the heat flux of insulation element. Therefore, the nitrogen flow rate is ignored in the numerical simulation.

Table 2. Physical parameters of materials

Materials	Heat conductivity [$Wm^{-1}K^{-1}$]	Density [kgm^{-3}]	Specific heat [$Jkg^{-1}K^{-1}$]
Stainless steel	16	8000	500
Rigid polyurethane foams	0.018 (110 K) 0.024 (313 K)	100	1200
Flexible polyurethane foams	0.05	8	1060

Loading

The temperature load and pressure load are involved in the calculation, which are listed as follows.

Temperature load, *T*: the temperature of cryogenic nitrogen is 78 K, environment temperature is 305.6 K and the initial temperature is set as 305.6 K.

Pressure load, *P*: the working pressure is 0.45 MPa.

Boundary

The convective heat transfer coefficient between the insulation structure and cryogenic nitrogen is 5 W/m^2K.

The convective heat transfer coefficient between the wind tunnel wall and surrounding environment is 10 W/m^2K.

Default insulation is set on all sides.

One side of the model constrains *X*-direction displacement and the other side is free. Additionally, the *X-Z* plane constrains the *Y*-direction displacement and the *X-Y* plane constrains the *Z*-direction displacement.

Calculation

According to the actual working condition, the heat transfer of insulation structure under the condition of temperature working condition, *T,* and of temperature pressure working condition ($T + P$) is intensively investigated.

Temperature work condition, *T*:

The influence of *T* on the heat transfer characteristics of insulation structure under normal pressure.

Temperature pressure work condition ($T + P$):

The influence of *T* and *P* on the heat transfer characteristics of insulation structure.

Results

According to the previous loading conditions and boundary conditions, the calculation results under the two work conditions are obtained.

Temperature work condition

The calculation results of insulation structure under temperature work condition are obtained as shown in figs. 4 and 5.

From fig. 4, it is can be found that the temperature field of the insulation structure is overall uniform. The inner surface temperature of insulation structure is 83.71 K, while the outer surface temperature of the wind tunnel wall is 302 K, which indicates that the designed insulation structure is able to maintain the cryogenic temperature environment inside the wind tunnel and possesses excellent insulation characteristics. Figure 5, indicates that the heat flux

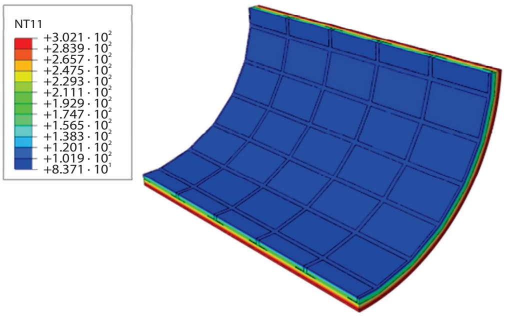

Figure 4. Temperature field of insulation structure under temperature work condition

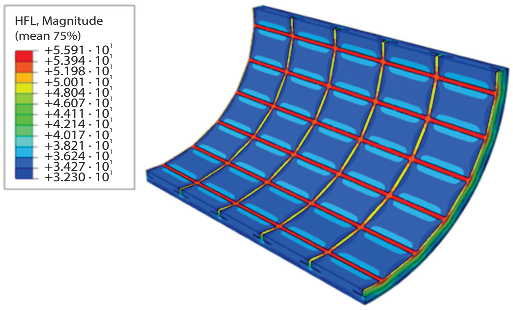

Figure 5. Heat flux of insulation structure under temperature work condition

of the insulation structure gradually decreases along the thickness direction of the insulation structure with the value less than 50 W/m^2, while the heat flux at the longitudinal compensation parts is 55.91 W/m^2. This is mainly because the compensation parts are made of flexible foamed plastic, which is prone to form the thermal bridges, resulting in cold energy loss.

For the sake of further understand the heat transfer characteristics of the insulation structure at cryogenic temperature work condition, an insulation element in the insulation structure is extracted to analyze in detail.

Figures 6 and 7 show the temperature field and heat flux of insulation element, respectively. From fig. 6, it is can be seen that the temperature field of the insulation element is overall uniform. The inner surface temperature of insulation element is 83.71 K, while the outer surface temperature of the wind tunnel wall is 302 K, *i. e.*, the temperature difference between insulation element and wind tunnel wall is about 218 K, which further indicates the insulation element is in possession of excellent insulation characteristics. In fig. 7, the maximum heat flux of insulation element is located at the four corners, where the flexible foamed plastics are filled to lead to the thermal bridges, consistent with results obtained in fig. 5.

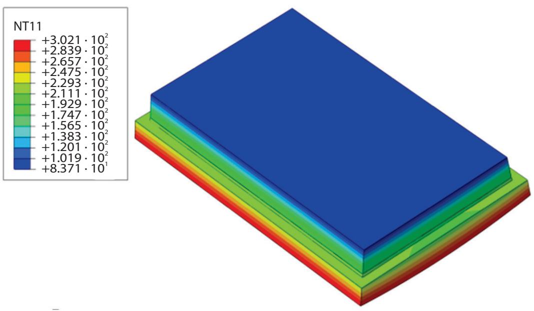

Figure 6. Temperature field of insulation element under temperature work condition

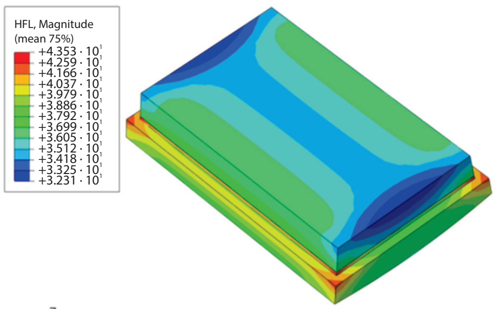

Figure 7. Heat flux of insulation element under temperature work condition

Temperature pressure work condition

The temperature field and heat flux of insulation structure under temperature pressure work condition are calculated as shown in figs. 8 and 9, respectively. Correspondingly, the temperature field and heat flux of insulation element are shown in figs. 10 and 11. Compared with the calculation results obtained under temperature pressure work condition and that obtained

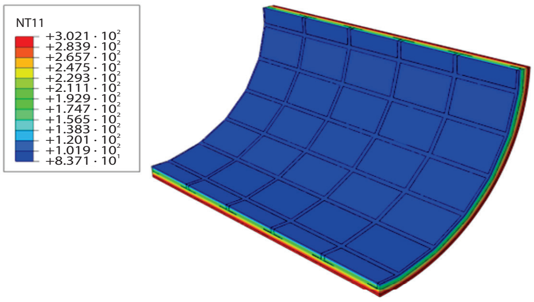

Figure 8. Temperature field of insulation structure under temperature pressure work condition

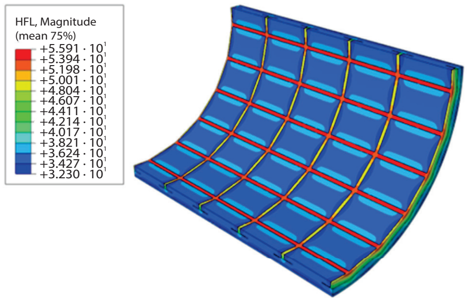

Figure 9. Heat flux of insulation structure under temperature pressure work condition

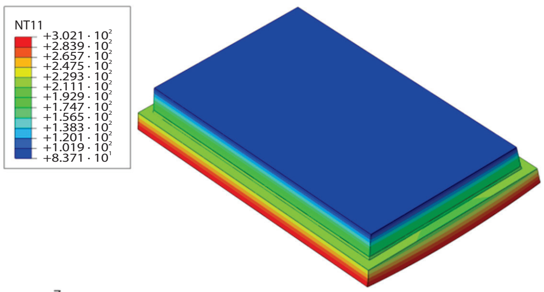

Figure 10. Temperature field of insulation element under temperature pressure work condition

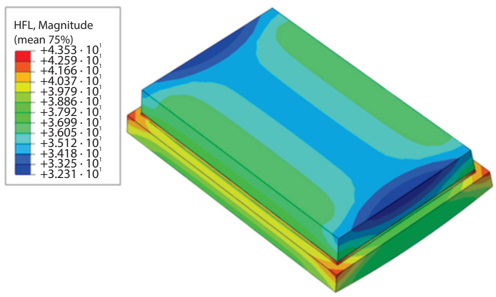

Figure 11. Heat flux of insulation element under temperature pressure work condition

under temperature work condition, it is can be found that the temperature field and heat flux obtained at the aforementioned two work conditions are consistent, which indicates that the pressure load has no influences on the heat transfer of insulation structure.

Experimental investigation

In order to further investigate the insulation characteristics of the insulation structure, experimental investigation is carried out in this section.

Experimental details

Involving the cryogenic environment of insulation structure in service, the test platform is self-established as shown in fig. 12, which is composed of seven subsystems and corresponding function of these subsystems are described as follows:

– Cryogenic nitrogen supply system is mainly used to store liquid nitrogen and to provide cryogenic nitrogen for test.
– Normal nitrogen supply system is mainly used to provide the normal nitrogen to control the pressure.
– Heating system is mainly used to heat the gas in the cryogenic chamber by forced convection.
– Vacuum system is mainly used to accelerate the cleaning of the cryogenic chamber and shorten the cleaning time
– Cryogenic chamber, as shown in fig. 13, is mainly used to form the cryogenic environment similar to that in the cryogenic wind tunnel to carry out test.

– Insulation system, as shown in fig. 14, is composed of insulation structure, which is acted as test object to be pasted on the inner wall of the cryogenic chamber, as shown in fig. 13.
– Control system is used to realize the operation control with safety during the test.

The performance parameters of the test platform are including the temperature range of 100 K to 300 K, the temperature uniformity of ±1 K, the temperature stability of ±1 K, and the pressure range of 0.01-0.45 MPa.

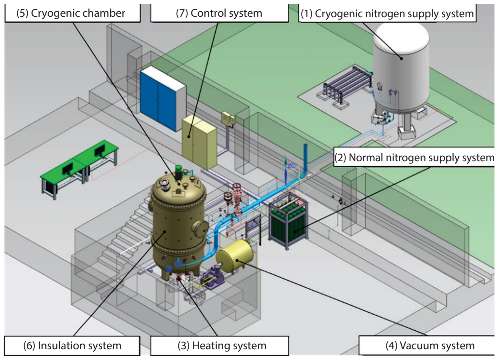

Figure 12. Test platform


Figure 13. Cryogenic chamber


Figure 14. Insulation system

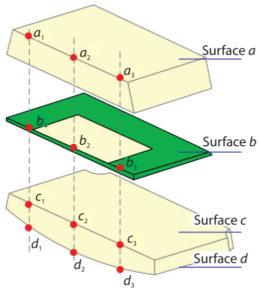

Figure 15. Measurement points

To verify the applicability of the designed insulation structure in cryogenic wind tunnel, the cryogenic tests under normal pressure and under 0.45 MPa pressure are carried out using the test platform, respectively and the corresponding test steps are described as follows.

– The steps of cryogenic test under normal pressure:

Step 1: Cool down the temperature of cryogenic chamber to 110 K and keep the temperature steady.

Step 2: Keep temperature steady in cryogenic chamber at 110 K for 2 hours.

Step 3: Heat the cryogenic chamber to normal temperature and end the test.

As for the steps of cryogenic test under 0.45 MPa pressure, pressurize the cryogenic chamber to 0.45 MPa firstly and repeat the aforementioned three steps.

It is noting that during the test, the temperature of insulation structure is measured using the temperature sensor.

During the test, thermocouple, made of *T*-type copper constantan, is acted as a temperature sensor to measure the temperature of insulation structure, which can measure the temperature range from 50-370 K with the accuracy of 0.5 K. For the sake of characterizing the real-time changeable temperature of insulation structure comprehensively, three thermocouples are arranged on the inner surface (*i. e.* surface *a* with measurement points of a_1~a_3), middle layer (*i. e.* surface *b* and surface *c* with measurement points b_1~b_3 and c_1~c_3, respectively) and outer surface (*i. e.* surface *d* a with measurement points d_1~d_3) of the insulation element along the thickness direction of the central axis and the corresponding location and number of measurement points are shown in fig. 15.

Result analysis

According to the aforementioned steps, the temperature variation of each measurement point under the normal pressure and the 0.45 MPa pressure is measured using the thermocouple, respectively. And the mean temperature variation of three measurement points on each surface is obtained as shown in figs. 16 and 17.

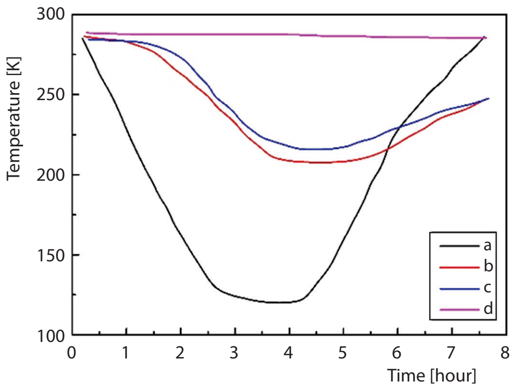

Figure 16. The mean temperature variation of measurement points under normal pressure

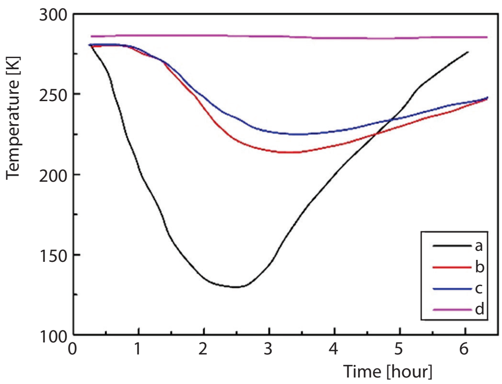

Figure 17. The mean temperature variation of measurement points under 0.45 MPa pressure

From fig. 16, it can be found that the temperature curve completely shows the whole process of cooling, steady-state and heating. In cryogenic environment, there is a temperature gradient along the thickness of the insulation element, *i. e.*, the temperature of the insulation element increases gradually from the inner surface *a* to the outer surface *d*, with temperature value of $T_a = 120$ K, $T_b = 220$ K, $T_c = 240$ K, $T_d = 280$ K, respectively, among which the temperature at outer surface *d* is almost unchanged during the cryogenic test process, close to the room temperature, indicating that the insulation structure can maintain the cryogenic environment in the chamber with excellent insulation characteristic.

From fig.17, it also can be found that the temperature curve shows the whole process of cooling, steady-state and heating and the temperature variation is consistent with that in fig. 16, which indicates the pressure load has no influences on the heat transfer of insulation structure, consistent with the results obtained by numerical calculation.

Compared with the experimental result, simulation result and theoretical calculation result, we can find out that in the theoretical calculation, the external surface temperature of wind tunnel wall, $T_3 = 288.68$ K, while the environment temperature, $T_a = 305.6$ K, the temperature difference between T_3 and $T_a = 16.92$ K. In numerical simulation, the external surface temperature of the wind tunnel wall is 302 K, while the environment temperature is 305.6 K, the temperature difference is 3.6 K. In experiment, the temperature at external surface is 280 K, which is close to the room temperature and almost unchanged during the cryogenic test process. the temperature difference between external surface temperature and environment temperature in theoretical calculation is larger than that in the numerical simulation and experiment due to the simplified theoretical model. Totally, the temperature differences between external surface temperature and environment temperature obtained in experimental, numerical simulation and theoretical calculation are all relatively small, which indicates reliability of theoretical calculation and simulation results.

Conclusions

In order to maintain the cryogenic environment of cryogenic wind tunnel in service, the insulation structure is designed. On this basis, heat transfer characteristic of insulation structure is investigated in combination of theoretical analysis, numerical calculation and test. The obtained conclusions are listed as follows.

- Based on the 1-D heat transfer model, the heat flux of the insulation element and the external surface temperature of wind tunnel wall are calculated theoretically. The results show that the heat flux of the insulation element is less than 50 W/m^2, the external surface temperature of wind tunnel wall is 288.68 K and the temperature difference between the wind tunnel wall and cryogenic nitrogen is 210.68K, which indicates that the insulation element is in possession of excellent insulation characteristic.
- The insulation characteristic of insulation structure is validated through numerical calculation and test. Moreover, the pressure load has no influences on the heat transfer of insulation structure.

Additionally, the test platform established in this work provides an effective test method to assess the thermodynamic characteristics of materials or structures in cryogenic environment.

Acknowledgment

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Nomenclature

A – area of insulation element, [m^2]
H – thickness of insulation element, [m]
h_{c1} – heat convection coefficient between the insulation element and cryogenic nitrogen, [Wm^{-2}K^{-1}]
h_{c2} – eat convection coefficient between the wind tunnel wall and environment [Wm^{-2}K^{-1}]
Re – Reynolds number, ($=Ud/n$)
T_a – environment temperature, [K]
T_0 – temperature, [K]
T_1 – inner surface temperature of insulation element, [K]
T_2 – contact surface temperature between insulation element and wind tunnel wall, [K]
T_3 – external surface temperature of wind tunnel wall, [K]
V_{N_2} – flow rate of cryogenic nitrogen, [ms^{-1}]

Greek symbols

δ – thickness of wind tunnel wall, [m]
λ_1 – heat conductivity of insulation element, [Wm^{-1}K^{-1}]
λ_2 – heat conductivity of wind tunnel wall, [Wm^{-1}K^{-1}]

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