TECHNICAL REPORT

ISO/TR 6832

Space systems — Development technology of a thermal vacuum chamber

Systèmes spatiaux — Technologie de développement d'une chambre thermique sous vide

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Contents

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations.*

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Since the first artificial satellite was launched into space successfully in 1957, space activities have been developed over the decades. The large amount of experience collected during that period demonstrates that a significant number of failures or defects appearing during spacecraft in-orbit operation were induced by space environment factors. These factors include space vacuum, cold black background, solar radiation, and also albedo and eigenradiation of the Earth. Therefore, thermal balance tests and thermal vacuum tests for spacecraft are performed in a simulated environment generated by ground simulation facilities in order to evaluate spacecraft performance, to verify thermal analysis models, and to discover early failures and defects in the spacecraft design and manufacturing process.

Countries engaged in spacecraft development have established several thermal test facilities, known as thermal vacuum chambers. They also have standardized requirements for thermal vacuum tests and thermal balance tests. These efforts greatly improved spacecraft reliability and played an important role in space activities.

A thermal vacuum chamber is designed to simulate vacuum, cold black and heat flux environment that a spacecraft experiences during its mission in space. It is composed of vacuum vessel, shroud, nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system, etc. Based on the state-of-the-art simulation technology, the relevant test standards and experiences accumulated from facilities development, this document provides development technology of a thermal vacuum chamber.

Space systems — Development technology of a thermal vacuum chamber

1 Scope

This document describes the technology for simulating space environments such as vacuum, cold black, and heat flux, as well as the compositions and functions of a thermal vacuum chamber (TVC). This kind of facility defined in this document is suitable for thermal vacuum tests (TVT) and thermal balance tests (TBT) on spacecraft-system level as well as on large-spacecraft-component level.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
thermal vacuum chamber
TVC
space environment simulator
facility to simulate the space vacuum, cold black, and heat flux environment on the ground

Note 1 to entry: It is used for *thermal vacuum tests (TVT)* (3.4) and *thermal balance tests (TBT)* (3.5) of spacecraft.

3.2
shroud
subsystem of a *thermal vacuum chamber (TVC)* (3.1) to simulate the *cold black environment* (3.3) in space

Note 1 to entry: It is cooled by liquid nitrogen or gaseous nitrogen to simulate the cold black environment in space. It is also called heat sink.

3.3
cold black environment
space environment without considering the solar and Earth radiation and the Earth's atmospheric albedo

Note 1 to entry: The radiated energy from spacecraft under cold black environment will be completely absorbed.

3.4
thermal vacuum test
TVT
test which is conducted to demonstrate the capability of the test item and to operate according to requirements in vacuum at predefined temperature conditions

Note 1 to entry: A spacecraft is validated by a *thermal balance test (TBT)* (3.5) and a thermal vacuum test (TVT) in a similar environment provided by a *thermal vacuum chamber (TVC)* (3.1) prior to launch.

3.5
thermal balance test
TBT
test which is conducted to verify the adequacy of the thermal model and the adequacy of the thermal design

Note 1 to entry: A spacecraft is validated by a thermal balance test (TBT) and a *thermal vacuum test (TVT)* (3.4) in a similar environment provided by a *thermal vacuum chamber (TVC)* (3.1) prior to launch.

3.6
simulation chamber
main body of a *thermal vacuum chamber (TVC)* (3.1)

Note 1 to entry: It includes vacuum vessel and *shroud* (3.2) and provides test space for spacecrafts.

4 Symbols and abbreviated terms

B/S	browser/server
C/S	client/server
DCS	distributed control system
FCS	field bus control system
GN_2	gas nitrogen
HMI	human-machine interface
LAN	local area network
LN_2	liquid nitrogen
NPSH	net positive suction head
PLC	programmable logic controller
SCADA	supervisory control and data acquisition
SS	stainless steel
TVC	thermal vacuum chamber
TBT	thermal balance test
TCU	thermal conditioning unit
TVT	thermal vacuum test

5 Vacuum and thermal environment simulation

5.1 General

Spacecrafts in-orbit are exposed to high vacuum, cold black and heat flux radiation environment. Therefore, a spacecraft is validated by TBT and TVT in a similar environment provided by a TVC prior to launch. This allows to evaluate the thermal control system's performance, to verify the thermal analysis model, to discover early failures and defects in spacecraft design and manufacturing process, and to check the performance of spacecraft in extreme high and low temperatures. With decades of

technical development and the establishment of testing standards, the simulation methodology for the three environmental factors (vacuum, cold black and heat flux) tends to be mature.

5.2 Vacuum environment simulation technology

The pressure in space varies with the orbital altitude of the spacecraft. The higher the orbital altitude is, the lower the pressure would be. The pressure at the Earth's sea level is about $1,013 \times 10^5$ Pa, and the pressure in the flight orbit of Earth spacecrafts is between 10^{-2} Pa and 10^{-12} Pa. According to the heat exchange theory, under the condition that the pressure is lower than 10^{-2} Pa, heat exchange between spacecrafts and space environment is mainly radiation, and conduction and convective heat transfer is negligible. According to the purpose and standards of TVT and TBT of spacecraft, the vacuum environment simulation is satisfied when the test specimen is under test condition with not higher than $1,33 \times 10^{-2}$ Pa. According to the development of vacuum acquisition technology, Roots pump-dry pump unit, molecular pump and cryopump are generally combined for obtaining an ultimate pressure about 10^{-5} Pa under non-load condition, so as to ensure that the pressure is not higher than $1,33 \times 10^{-2}$ Pa with load and meet the test for spacecrafts.

5.3 Cold black environment simulation technology

Without considering the solar radiation and earth (or other planet) albedo and eigenradiation, deep space is similar to an infinite dissipation black body. Under such conditions a passive body experiences a balance temperature between $-270,15$ °C (3 K) and $-269,15$ °C (4 K), and the black body energy density is about 5×10^{-6} W/m². This concept, known as cold black environment, implies that the heat emitted by a spacecraft will be absorbed completely. The device on the ground which simulates this environment is called shroud. However, to generate the exact space environment on the ground is economically unviable and proved to be unnecessary. Based on the error analysis, generating an environment of below 100 K, shroud absorptivity of about 0,95, and shroud emissivity of no less than 0,9 can reduce the temperature error on the spacecraft to less than 1 % under vacuum environment. Therefore, the state-of-the-art simulation requirement for cold black environment requires a balance of performance, cost and schedule that can be achieved in the design and production of thermal systems. Typically shroud consists of SS or aluminium. Its surfaces facing towards the test volume are coated with black paint to obtain high absorptivity (α) and high emissivity (ε). The volume inside of the shroud is part of a cooling circuit with fluids that are capable of cooling down the shroud to a temperature of approximately $-173,15$ °C (100 K). Nitrogen with a boiling point at 77 K is widely used for that purpose since it is relatively cheap compared to hydrogen, oxygen or helium.

5.4 Space heat flux simulation technology

5.4.1 General

The external heat flux experienced by spacecrafts in Earth orbit comes from solar radiation, albedo and eigenradiation of the earth. The space heat flux is simulated in two different ways, the incident heat flux simulation and the absorbed heat flux simulation.

5.4.2 Incident heat flux simulation technology

The incident heat flux method is used to simulate the effect of solar radiation only. For the incident heat flux method, the heat flux is generated by a solar simulator.

A predefined volume of the thermal vacuum chamber is exposed to solar type energetic illumination which complies in each respect with the basic parameters of the sun: irradiance, spectrum, divergence, illumination stability, and spatial uniformity. This is typically achieved by collect light from xenon lamps through an arrangement of lenses and mirrors. The light beam is focused and superimposed to the predefined volume. Typically, a solar simulator provides the range of irradiance from 0,5 to 1,3 solar constant and collimation angle of no more than ±2°. A solar simulator provides an accurate simulation of the actual solar spectrum. A solar simulator is restricted in application due to high-cost, complicated

system and fixed illumination surface. In addition, when using a solar simulator, the satellite can be installed on the motion simulator which guides the spacecraft with respect to artificial solar beam.

5.4.3 Absorbed heat flux simulation technology

For the absorbed heat flux simulation technology, the heat flux is generated by heat sources within the test volume. State-of-the-art, there are three ways to generate absorbed heat flux. The first way is using infrared heat flux simulator, such as infrared lamps, infrared cage, or thermal controlled panel, to generate infrared radiation to simulate the absorbed heat flux. The second way is using resistive film heater attached to the specimen surface with the absorbed heat flux controlled by electrical power. The third way is using a temperature-adjustable shroud to simulate the absorbed heat flux. It requires a set of GN_2 thermal conditioning unit (TCU).

The first two ways are widely used due to the characteristics of low-cost, flexible combination and simple system configuration. However, the equipment used for these two ways will partially block the radiation of the shroud to the specimen during the test, which brings difficulties to the realization of low-temperature conditions for the specimen. In addition, due to poor versatility, infrared heat flux simulators and resistive film heaters must be designed and manufactured according to the structural dimensions and heat flux requirements of spacecrafts. When the third way is adopted, there is no need to develop extra heat flux simulator for thermal test, which saves preparation time and cost. However, it has low simulation accuracy and slow heat reflection.

6 Design of TVC

6.1 Configuration of TVC

A thermal vacuum chamber is designed to simulate vacuum, cold black and heat flux environment that a spacecraft experiences during its mission in space. It is composed of vacuum vessel, shroud, nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system, etc. The heat flux simulation system can consist of any combination of the different heat flux simulation technology: solar simulator, infrared flux simulator and temperature-adjustable shroud. The system composition of TVC is shown in Figure 1.
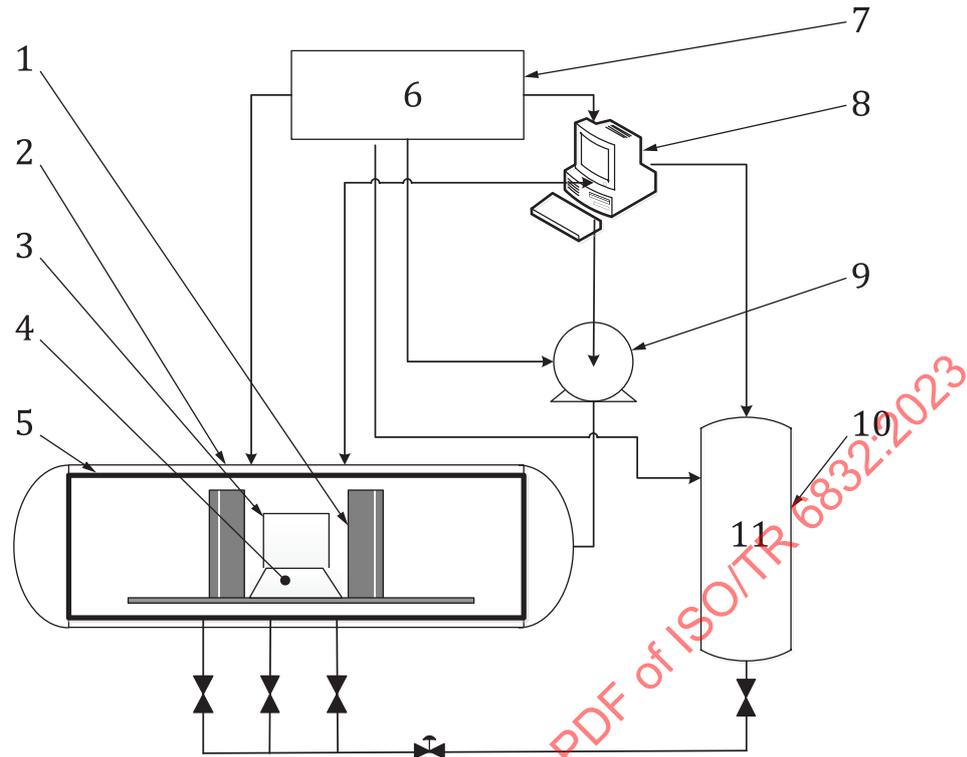
Key

1   vacuum vessel
2   shroud
3   test specimen
4   specimen support mechanism
5   heat flux simulator
6   cooling circulating water, equipment electricity, compressed air, liquid nitrogen
7   logistic support system
8   measurement and control system
9   vacuum system
10   nitrogen system
11   LN$_2$ tank

Figure 1 — Schematic diagram of a typical TVC

The simulation chamber composed of vacuum vessel and shroud is the main body of TVC, in which the specimen and its support mechanism are fixed during the test. The nitrogen system provides liquid nitrogen or gas nitrogen for the shroud to simulate cold black environment. The vacuum system provides the required vacuum environment for the simulation chamber. The heat flux simulation system provides the heat flux environment for the specimen. The measurement and control system realizes the operation control of the whole system and data acquisition.

6.2   General design

Firstly, the test requirements are analysed, including the maximum weight, the maximum structural dimensions, the attitude regulation, and the method of heat flux simulation of the test specimen, etc.

Secondly, the design standards are selected from the relevant international, national, industrial and enterprise standards.

Thirdly, the overall scheme is determined, including equipment configuration, the structural type of the simulation chamber, the way the specimen access to the simulation chamber, and the overall equipment layout, etc.

Then, technical specifications are determined, including the size of the simulation chamber, the maximum weight and the attitude regulation of the specimen, the vacuum degree with load and the pumping time, ways of heat flux simulation, the shroud temperature, the cleanliness requirement of simulation chamber, the measurement and control requirements, the reliability, safety and maintainability requirements. In order to diminish the simulation error brought by the limited volume of simulation chamber to be acceptable, the space between the specimen and the shroud is at least 1/3 of a characteristic dimension of the test specimen.

Finally, the executive plan of TVC is determined, including the development period, transportation, assembly, commissioning, and cost.

7 Vacuum vessel

7.1 Composition and function

The vacuum vessel is the main body of the TVC and provides a benchmark for other subsystem equipment installation. It houses the test specimen and the shroud. The vacuum vessel provides interfaces for nitrogen system, vacuum system, heat flux simulation system, specimen support mechanism, measurement and control system. The vacuum vessel is composed of cylinder, door, flanges, and support as shown in Figure 2.
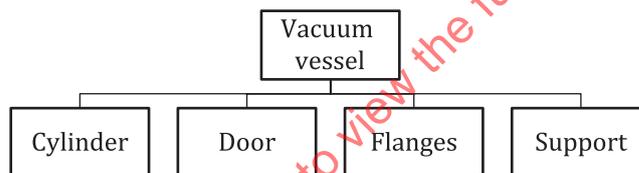
Figure 2 — Block diagram of vacuum vessel

7.2 Vessel design

7.2.1 Structure shape

The size of the vacuum vessel is determined together by the size of the test specimen, the room size and the other test requirements.

There are several structural shapes available for vacuum vessel, e.g. cylinder, sphere, and box. The most common shape of TVC is a cylinder vessel. Although its stress state is not as good as that of a spherical vessel, it has the advantages of simple structure and convenient manufacturing. Compared with the box-shaped vessel, its rigidity is much better. Table 1 shows structural shapes of vacuum vessel.

Table 1 — Structural shapes of vacuum vessel

Name		Diagram	Notes
Cylinder	Vertical type		This type vessel occupies small floor area and has high height. The sealing ring is compressed by the weight of the door itself, so no preload mechanism is required.
	Horizontal type		This type vessel is easy and safe access to the vessel for specimen. The self-weight of the vessel produces a bending moment.
	T type		This type vessel combines the features of vertical and horizontal type, but is complex and expensive to build. This type vessel is often used along with solar simulator and motion simulator.
Sphere			Under the same external pressure condition, the sphere type vessel has the best stress state and the minimum wall thickness required, which means saving the material. But it is complex to manufacture and expensive to build. It's not widely used due to the low effective space.

Key

1 door

2 cylinder

3 flange

4 support

Table 1 *(continued)*

Name		Diagram	Notes
Box	Cube		This type vessel is easy and safe access to the vessel for specimen, and high effective space. But it has poor stress state.
	Mailbox		This type vessel has similar features to the cube vessel with better stress state.
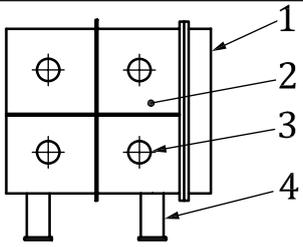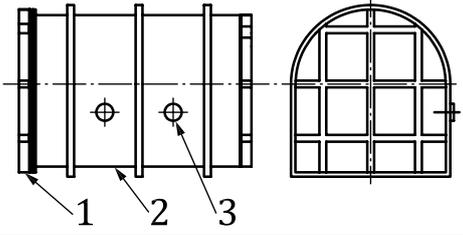
Key

1 door

2 cylinder

3 flange

4 support

7.2.2 Material

The vacuum vessel is placed indoor. Its external environment is ambient temperature and atmospheric pressure, and the internal environment is vacuum and cryogenic temperature. The material of the vacuum vessel not only bears low temperature and air corrosion, but also has low outgassing rate under vacuum environment.

The stainless steel is often used for the cylinder, dome ends, flanges, and inner parts of the vessel. Because it has many advantages, such as good rigidity, easy processing, easy welding, high chemical stability, oxidation resistance, corrosion resistance, cryogenic environment resistance, good air tightness, low outgassing rate, etc. Other components use in ambient environment, such as the support and stiffening ring etc. These components use carbon steel to reduce the consumption of stainless steel and reduce the manufacturing cost. The performance of the stainless steels commonly used in vacuum vessel are shown in Table 2.

Table 2 — Performance of stainless steel

No.	Performance	Name			
		SS 304	SS 304L	SS 316	SS 316L
1	Mass density/g·cm^{-3}	7,93	7,93	7,98	7,98
2	Yield strength/MPa (20 °C)	205	180	205	180
3	Allowable stress/MPa	137	120	137	120
4	Modulus of elasticity/10^3 MPa (20 °C)	195			
5	Outgassing rate/ × 133,3 Pa·L·s^{-1}·cm^{-2} (Pump 1 h to 25 h)	2,1 × 10^{-9} to 1,7 × 10^{-10}			

7.2.3 Structure design

7.2.3.1 Cylinder

The cylinder, the main body of the vacuum vessel, mainly includes the straight cylinder, the end, and the flanges. Refer to 7.2.1 for the structure shape of the cylinder.

The end shape is categorized into spherical, spherical crown, ellipse, disc, cone, flat etc. The spherical crown, ellipse and disc end are preferred for vacuum vessel because of their good stress state.

In order to increase the rigidity and minimize the thickness of vessel, the stiffening ring is designed on the outer wall of the vessel. By this way, the consumption of stainless steel is reduced, saving manufacturing cost. Common shapes of stiffening rings include T type, H type and II type as shown in Figure 3.
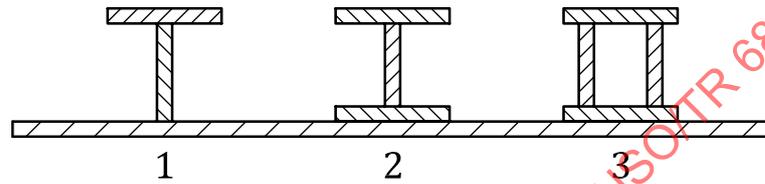
Key

1   T type
2   H type
3   II type

Figure 3 — Types of stiffening ring

7.2.3.2 Door mechanism

The door provides the access way for test specimen and personnel. The type of door mechanism depends on the vessel shape and the room layout. Table 3 shows the types of door mechanism.
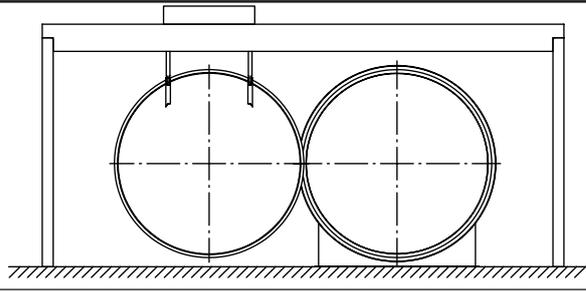
The door sealing ring is compressed before pumping. For vertical vessel, the sealing ring is compressed by the weight of the door itself. For horizontal vessel, p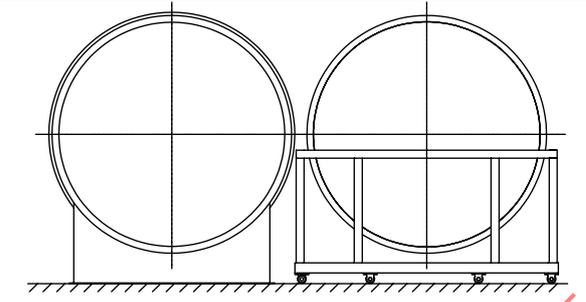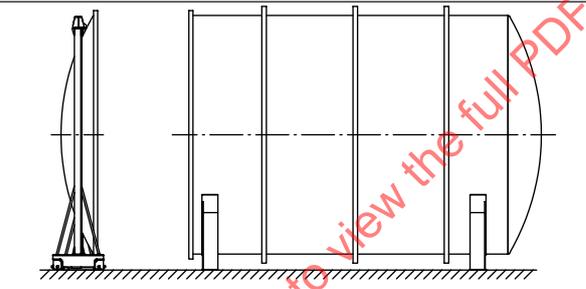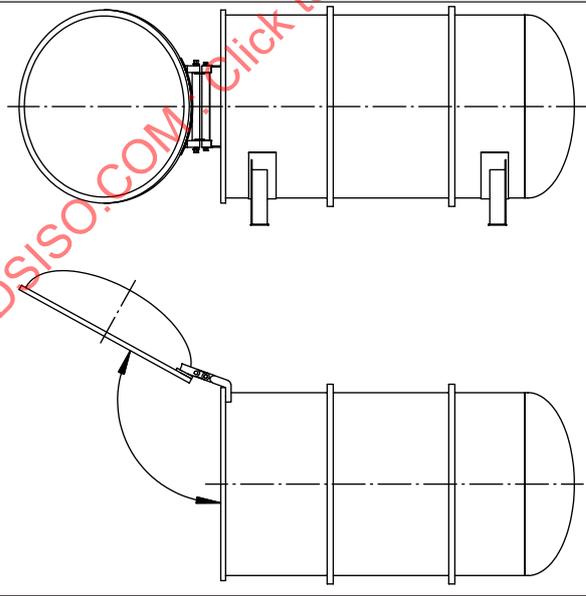reload mechanism is used to compress the door sealing ring. They are evenly and radially arranged on the door flange to ensure enough force for compressing the sealing ring.

7.2.3.3 Flanges

Flanges are used to connect other subsystems to the vessel. And the flanges can provide the feedthroughs for connecting the equipment inside and outside the vessel. In addition to meet the requirements of strength, rigidity and sealing, the flange is also easy to be installed and removed, and does not affect the sealing performance after repeated operation. Flanges on the vessel are mainly classified as non-knife edge flanges, quick-release flanges, knife-edge flanges. They are designed with reference to ISO 1609[1], ISO 2861[2] and ISO 3669[3].

7.2.3.4 Support

The support bears the weight of the vacuum vessel and all equipment mounted on it. The type of the support depends on the shape of vacuum vessel. Types of support commonly used in TVC are column type, skirt type, saddle type, as shown in Table 4.

Table 4 — Types of support

Name	Diagram	Notes
Column type		This type is used for horizontal, vertical, spherical and cube vessel.
Skirt type		This type is used for vertical and spherical vessel.
Saddle type		This type is used for horizontal vessel.
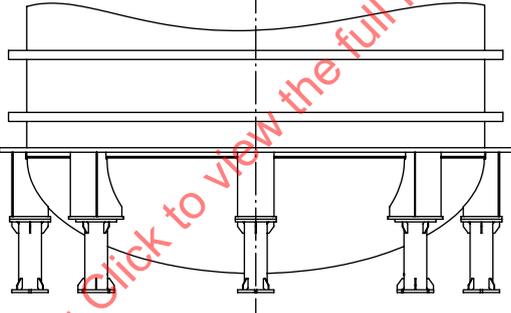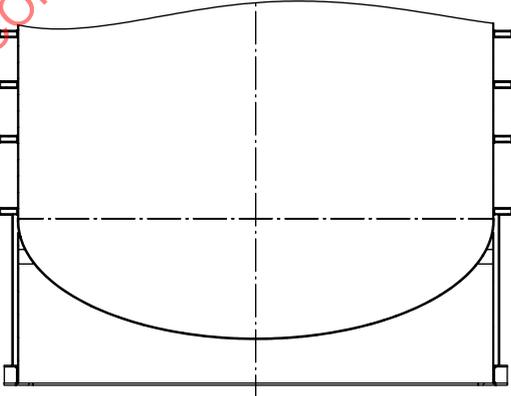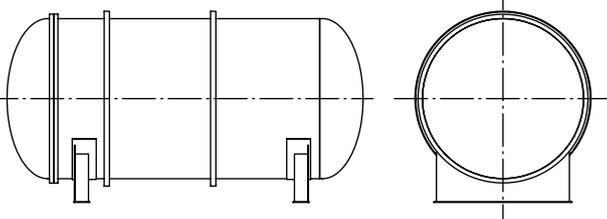
7.2.4 Design calculation

The design calculation of vacuum vessel includes stress and stability calculation. The calculation steps are as following.

a) The external pressure of the vacuum vessel is ambient pressure, while the internal pressure environment is vacuum. It means that the maximum differential pressure is 0,1 MPa. So, the design pressure is 0,1 MPa.

b) The design temperature of the vacuum vessel is ambient temperature.

c) The following loads are commonly considered in the design:

— the maximum differential pressure between the inside and outside of the vacuum vessel;

— the weight of the vacuum vessel;

— additional load, such as pipelines, platforms, test specimen, etc.;

— reaction force of the supports;

— seismic load, referring to the local seismic grade requirements.

d) The calculation includes wall thickness of cylinder, wall thickness of end, section size of door flange, section size of strengthening ring, and reinforcement of the openings, etc. Refer to ASME BPVC. VIII[4] for calculation method.

e) The finite element method is also used for the TVC stress analysis, deformation analysis, and buckling analysis, to check the strength and stability of the vessel.

7.2.5 Manufacturing

During the processing of vacuum vessel, these factors are considered, such as industrial manufacturing standards, flatness of door flange, the inner surface roughness, and leakage rate of the vessel.

Door flange is prone to deformation during processing to affect the sealing performance. Therefore, the flatness of the door flange is considered during the manufacture.

The inner surface of vessel outgases in vacuum environment. If it is rough, the amount of outgassing increases from the material. In addition, heat exchange between the vessel and the shroud is related to the surface roughness. The inner surface of the vacuum vessel is polished to obtain minimize roughness, to decrease the outgassing and heat radiation.

In order to ensure the high vacuum environment in the vacuum vessel, the leakage rate is detected by helium mass spectrometry. The total leakage rate of the vessel can meet the requirements of the test. The vacuum vessel is welded, and the removable parts are connected with flanges. So, leak detection objects are welding lines and flanges.

8 Shroud

8.1 Composition and function

The shroud is installed inside the vessel and covers the inner surfaces of the vessel as much as possible. It is a kind of structure made of large numbers of metal panels and pipes with good heat conductivity, to simulate cold black environment in space. At the same time, the shroud is coated with specific paints on the surfaces facing the test specimen, to meet the requirements of absorptivity and hemispherical emissivity. By flooding with LN_2/ GN_2, shroud temperature keeps below 100 K (LN_2 circulating) or 93 K to 423 K (GN_2 circulating) during the test.

8.2 Shroud design

8.2.1 Material of shroud

The shroud experiences high vacuum, cryogenic environment during the test of specimen. It is generally made of aluminium, SS or red copper, which has low outgassing rate in high vacuum environment, good mechanical performance at low temperature and better welding performance. The performances of all materials are shown in Table 5.

Table 5 — Performance of shroud materials

No.	Item	Material		
		Stainless steel SS 304	Red copper T4	Aluminium L4
1	Yield strength (MPa) (20 °C to -180 °C)	193 to 241 High	87 to 186 Moderate	31 to 39 Low
2	Impact toughness (MPa·m) (20 °C to -180 °C)	0 to 1,12 Good	0,771 to 0,892 Good	0,91 to 1,55 Excellent
3	Specific heat capacity (W·m^{-1}·K^{-1}) (20 °C to −180 °C)	490 to 251 High	386 to 254 Higher	902 to 376 Highest
4	Thermal conductivity coefficient (W·m^{-1}·K^{-1}) (20 °C to −180 °C)	15 to 8 Lower	395 to 609 High	152 to 351 High
5	Density (g·cm^{-3})	7,9	8,9	2,7
6	Elongation (%) (20 °C to −180 °C)	60 to 42 Excellent	30 to 31 Good	35 to 48 Good
7	Processing difficulty	High	Moderate	Low
8	Welding difficulty	Low	Moderate	High

8.2.2 Structure of shroud

The shroud structure is related to the materials. The aluminium shroud is generally welded by various pipes with wings on both sides. The red copper shroud is typically welded by a whole red cooper sheet and pipes. SS shrouds are of dimple type and flow channel type. The shroud panel are shown in Table 6.

The flow channels inside the dimple type shroud are interconnected. The dimpled shroud surface increases the heat convective surfaces with LN$_2$, thus enhances the heat convective effect. Laser automatic welding is used in the manufacturing, which improves the manufacturing efficiency and reliability. These properties make this type of shroud widely used.

Table 6 — Materials and panel forms of shroud

No.	Types	Diagram	Material
1	Pipe plate		Red copper
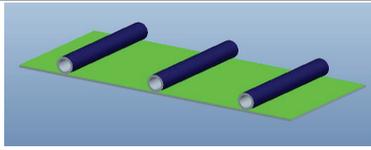
Table 6 *(continued)*

No.	Types	Diagram	Material
2	Pipe fin		SS pipe weld with red copper fin or both of the pipe and the fin is made of aluminium
3	Bump shroud		SS
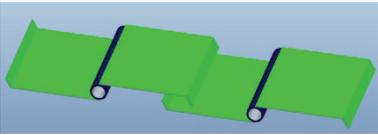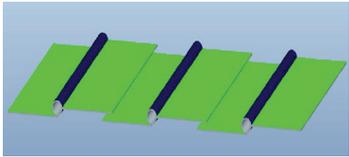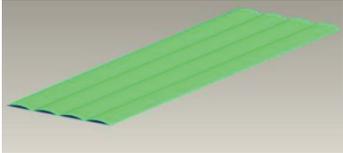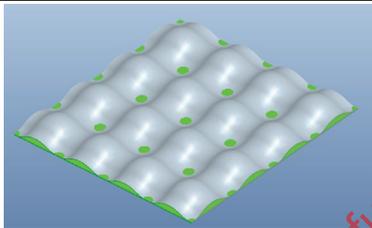
8.2.3 Shroud area division and thermal design

8.2.3.1 Shroud area division

As for the large size shroud, each part bears different thermal loads. To ensure the temperature and uniformity of the shroud, generally the shroud is divided into multiple areas, and the supply of LN_2 or GN_2 of each area is in parallel. Shroud is divided based on different heat load, the shroud structure form, and the calculation results of temperature uniformity.

8.2.3.2 Shroud thermal design

The shroud thermal design focuses on heat load calculation, temperature distribution, LN_2 flowrate, etc.; it is checked whether the temperature and uniformity of the shroud meet the requirements, and whether the area division of shroud is reasonable, to provide the design basis for nitrogen system.

Heat load of shroud is calculated, including radiation heat transfer between shroud and inner surface of vessel, between shroud and surface of test specimen, between shroud and heat flux simulation equipment, and heat conduction leakage between shroud and vessel. Through the calculation of heat radiation and heat conduction transfer, the total heat load of the shroud and the heat load of each zone is obtained. In order to reduce the heat load of the shroud, a passive thermal radiation protection screen is added between the shroud and the vessel to reduce the radiant heat transfer.

8.2.4 Decontamination panel design

Generally, the decontamination panel is of the same structure as the shroud and is installed inside the simulation chamber. It is specifically designed as an individual cold panel or just choose one part of shroud. It is flooded with LN_2 separately during working. During the warming up process of shroud, the decontamination plate captures gaseous molecules that collide on their surface and turns them into crystalized solid particles, to avoid the specimen being contaminated because of the shroud temperature rise. The decontamination panel creates a low temperature area inside the simulation chamber, reducing the vapour pressure and capturing the molecules in suspension, allowing a clean

control of the process, obtaining different vacuum levels inside the chamber faster. This mechanism considerably reduces the pumping time.

8.2.5   Temperature measurement

The temperature measurement of the shroud is accomplished by temperature sensors installed on the shroud surfaces and the measurement system which collects data in real time. The commonly used temperature sensors are PT100 platinum resistance or T type copper constantan thermocouple. The measurement range of the sensor covers the shroud's working temperature, and the quantity of sensors can fully reflect the average temperature of shroud.

8.2.6   Inner surface painting

In order to simulate cold black environment in space, the surface of the shroud facing the test specimen is coated with a special kind of black paint of which has a solar absorptivity (α) of not less than 0,95, a hemispherical emissivity (ε) of not less than 0,90, a low outgassing rate, good cohesion performance, easy painting operation, and stable mechanical properties as no peeling or shedding phenomenon in the temperature range from 77 K to 423 K [5].

8.2.7   Leak testing

Shrouds are welded by large numbers of metal plates and pipes. Since the shroud works in high vacuum environment, leakage detection is carried out on each welding line and the whole shroud by leakage detector.

9   Nitrogen system

9.1   Composition and function

Nitrogen system is designed to supply GN_2/LN_2 to the shroud during TVT and TBT. It consists of LN_2 subsystem and GN_2 subsystem in general. LN_2 subsystem circulates LN_2 to keep the shroud's temperature below 100 K and GN_2 subsystem circulates GN_2 to keep the shroud's temperature in the required temperature range.

9.2   Design of LN_2 subsystem

9.2.1   Technical scheme

9.2.1.1   Open cooling scheme

Open cooling scheme consists of LN_2 tank, piping, valves, etc. as shown in Figure 4. LN_2 flow through the shroud driven by the pressure of LN_2 tank and absorbs heat load by evaporation, to keep the shroud's temperature below 100 K. This scheme is of simple composition, low cost, and high reliability. However, it can only withstand relatively low heat load. When the shroud bears high heat load, it is difficult to ensure its temperature below 100 K and temperature uniformity.
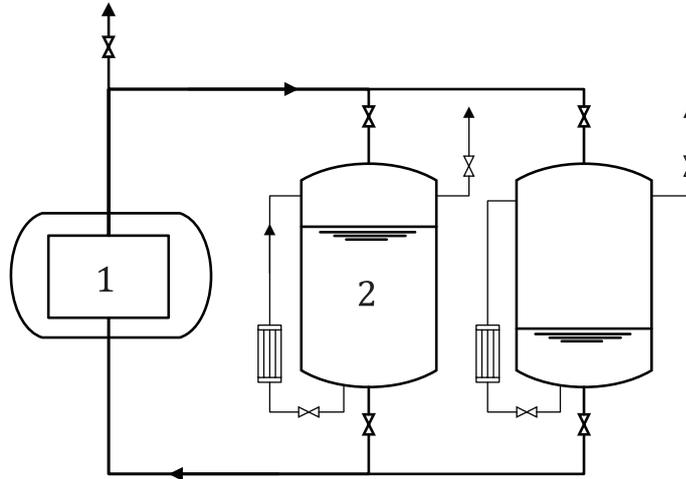
Key

1   shroud

2   LN$_2$ tank

Figure 4 — Flowchart of open cooling scheme

9.2.1.2   Single-phase closed loop scheme

The single-phase closed loop scheme mainly consists of LN$_2$ tank, LN$_2$ pump, subcooler, piping, etc. The flowchart is shown in Figure 5. When LN$_2$ subsystem is running, the piping, shroud, LN$_2$ pump and subcooler are fully pre-cooled and filled with LN$_2$, then LN$_2$ pump is started, and sends LN$_2$ in subcooled state to the shroud with a certain pressure and flow rate. The heat load absorbed by the shroud is taken away by circulated LN$_2$ so as to keep the shroud temperature lower than 100 K during the test. LN$_2$ flows out of the shroud, returns to the subcooler to reach subcooled state again. LN$_2$ in the subcooler tank is partially vaporized after absorbing heat load, and then vented to atmosphere. In this closed loop scheme, circulated LN$_2$ is single-phase liquid state all the time.

The single-phase closed loop scheme has the advantages of large circulating flowrate of LN$_2$, high differential head, high heat exchange efficiency between LN$_2$ and shroud. Therefore, it can withstand large heat load, and the shroud's temperature is more uniform, but with the disadvantage of slightly higher cost. This scheme has been widely used in large TVC.
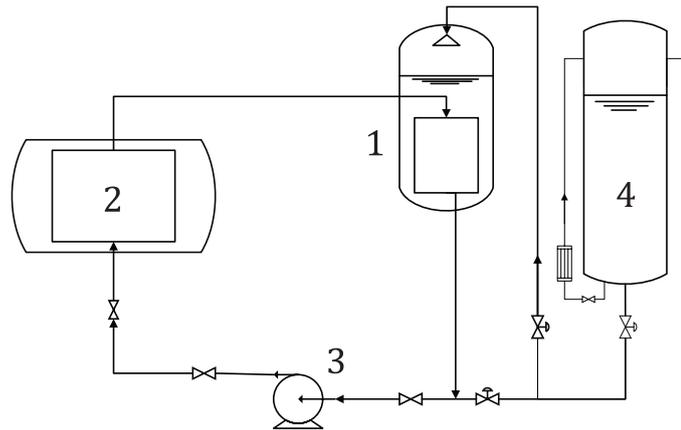
Key

1 subcooler
2 shroud
3 LN$_2$ pump
4 LN$_2$ tank

Figure 5 — Flowchart of single-phase closed loop scheme

9.2.1.3 Pressurized circulating scheme

Pressured circulating scheme is composed of LN$_2$ tank, LN$_2$ pump, valves, piping, etc. shown in Figure 6. LN$_2$ from LN$_2$ tank pressurized by LN$_2$ pump is sent to shroud, absorbs heat load of shroud, then returns to LN$_2$ tank. Evaporated LN$_2$ is separated in the tank and vented to atmosphere. The scheme has less equipment than single-phase closed loop scheme. Apart from the advantages, it is prone to cavitations on LN$_2$ pump. Hence, the suction pressure of LN$_2$ pump is provided enough higher than NPSH.

Key
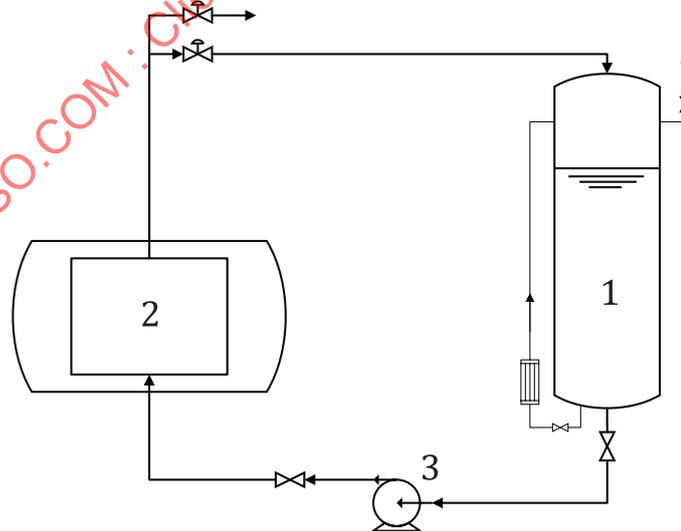
1 LN$_2$ tank
2 shroud
3 LN$_2$ pump

Figure 6 — Flowchart of pressurized circulating system

9.2.2 Equipment configuration

9.2.2.1 LN$_2$ tank

LN$_2$ tank is used to store LN$_2$ required by the test. Its parameters are volume, design pressure, rated supplying flowrate, and the type of structure. The choice of LN$_2$ tank's volume is related to factors such as LN$_2$ consumption per day during the test and local LN$_2$ supply condition. To avoid the test from being interrupted by lack of LN$_2$, enough large volume of LN$_2$ tank is chosen in the design. The design pressure of the LN$_2$ tank is not lower than LN$_2$ subsystem operating pressure. LN$_2$ tank has vertical type, horizontal type, and sphere type; and the type choice considers the on-site construction layout and transportation condition. LN$_2$ tank is also equipped with pressure and liquid level meters and sensors, so that the pressure and liquid level of the tank are monitored on site, and can also be transmitted to the control system.

9.2.2.2 LN$_2$ pump

In LN$_2$ single-phase closed loop scheme and pressurized LN$_2$ circulation scheme, LN$_2$ pump provides differential head and makes LN$_2$ circulate in the system. LN$_2$ pump is generally a kind of centrifugal pump, and flowrate and differential head decide model of LN$_2$ pump. Moreover, to achieve high system reliability and avoid test interruption, backup of LN$_2$ pump is always considered in the design. LN$_2$ pump is also equipped with pressure and flowrate meters and sensors, so that the pressure and flowrate are monitored on site and can also be transmitted to the control system.

9.2.2.3 Subcooler

The subcooler is designed to utilize LN$_2$ under normal pressure to cool circulated LN$_2$ returned from shroud through heat exchanger. LN$_2$ under normal pressure absorbs heat and partially vaporizes and then is vented to atmosphere. The subcooler is mainly composed of a tank for storing LN$_2$ under normal pressure and a heat exchanger immersed in LN$_2$. During the design, the area of heat exchanger and LN$_2$ subcooling degree is determined by heat load, circulated LN$_2$ flowrate and pressure. The volume of the tank ensures that the heat exchanger is completely immersed in LN$_2$, and certain space and sufficient exhaust capacity is reserved at the upper part. The subcooler is equipped with pressure and liquid level meters and sensors, so that the pressure and liquid levels of the subcooler are monitored on site and are also transmitted to the control system.

9.2.3 Piping design

The design of LN$_2$ piping includes pipeline layout design, valve and sensor configuration, heat insulation design. SS pipe is chosen as pipeline material because of its excellent performance, reasonable price, and series of mature products. Secondly, pipeline layout design comes after LN$_2$ subsystem scheme design, to ensure that LN$_2$ piping is arranged reasonably. LN$_2$ piping is equipped with various valves including check valves, pneumatic valves, and safety valves, etc. Valve selection is mainly based on the operating temperature range, rated pressure, diameter, regulating performance of regulating valve, etc. In order to know the operating state of LN$_2$ subsystem, the pipeline is equipped with necessary meters and sensors to show pressure, temperature, and flowrate of the system. These parameters of the system are monitored not only on site but also remotely on HMI or remote computer. To reduce heat loss, the pipeline of LN$_2$ subsystem is heat insulated in two different ways of vacuum insulation or heat insulation material coating, so that outer surfaces of the pipeline is not dewed during the test. Compared with heat insulation material coating, vacuum insulation has less heat loss but higher cost.

9.3 Design of GN$_2$ subsystem

9.3.1 Technical scheme

9.3.1.1 GN$_2$ TCU scheme

By sending adjustable temperature GN$_2$ to the shroud, TCU keeps the shroud in the required temperature range during the test, which is equivalent to simulating the heat flux suffered by spacecrafts in-orbit. And it also has a function of warming up shroud. It mainly consists of blower, heater and spray vessel, as shown in Figure 7. In the low temperature condition, the blower conveys GN$_2$, which enters LN$_2$ spray vessel and mixes with the sprayed LN$_2$ to cool it down, and then enters the shroud after precise temperature control by electric heater.[6] Since the vaporization of sprayed LN$_2$ causes the pressure rise of system, automatic pressure relief equipment is designed to maintain the stability of the system operating pressure.
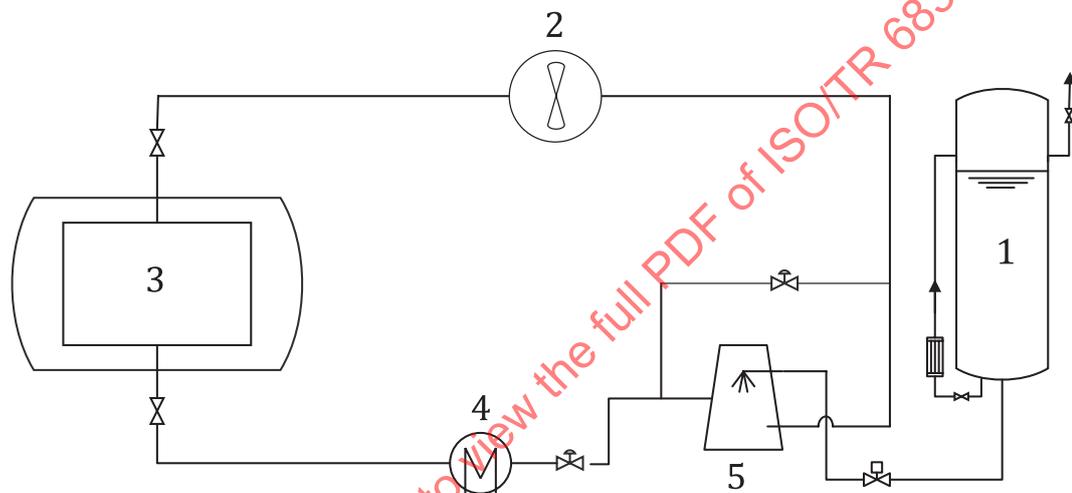
Key

1 LN$_2$ tank

2 blower

3 shroud

4 heater

5 spray vessel

Figure 7 — Working principle of GN$_2$ TCU scheme

9.3.1.2 GN$_2$ warming up scheme

After the test, GN$_2$ warming up scheme provides hot GN$_2$ to the shroud and warms it up to room temperature so that the door of vacuum vessel can be opened. GN$_2$ warming up scheme is mainly composed of the blower, electric heater and piping, as shown in Figure 8. During the system operation, after LN$_2$ is drained out of the shroud, GN$_2$ heated by the electric heater is sent to shroud by blower and warms up the shroud.

Key
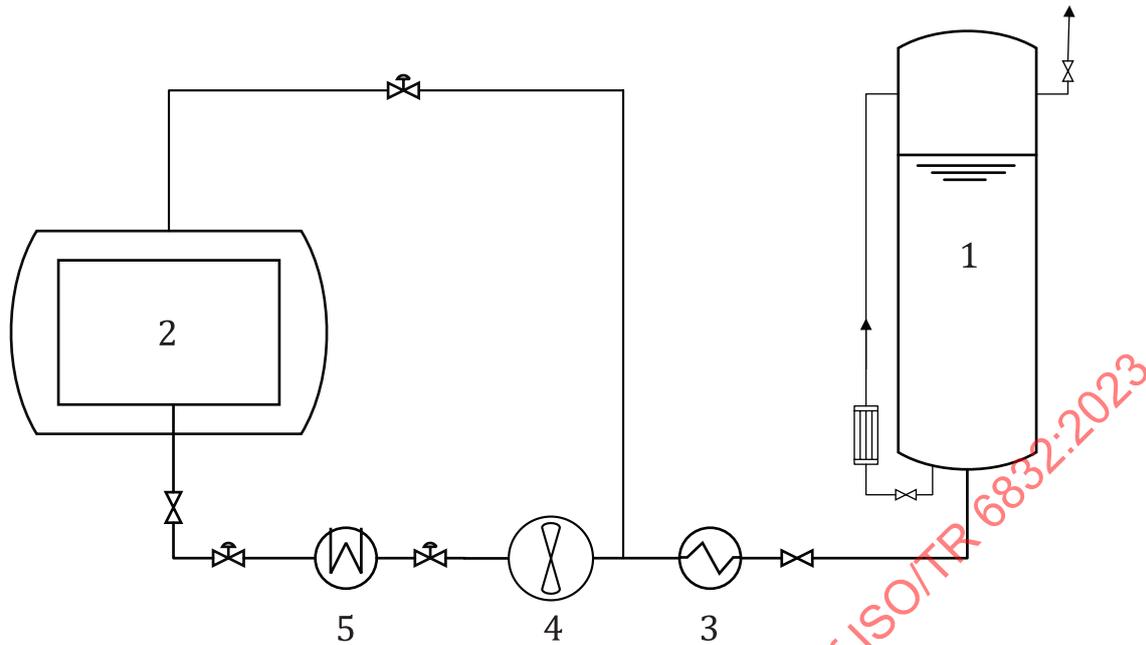
1 LN$_2$ tank

2 shroud

3 evaporator

4 blower

5 heater

Figure 8 — Working principle GN$_2$ warming up scheme

9.3.2   Equipment configuration

9.3.2.1   Blower

The blower provides differential head for circulated GN$_2$. Its parameters include flowrate, head and operating temperature. The required GN$_2$ flowrate and pressure drop is calculated in the design and is the basis of model selection. In order to improve the reliability of system operation and avoid test interruption, backup of blower is always considered in the design. The inlet and outlet of the blower are equipped with pressure meters and sensors, so that the pressure at the inlet and outlet of the blower are monitored on site and are also transmitted to the control system.

9.3.2.2   Electric heater

The function of the electric heater is to heat GN$_2$ to the required temperature. The technical parameters mainly include the structural type, heating power, working pressure, flowrate, temperature range, etc. In order to improve the reliability of the system operation and avoid the failure of the electric heater, the heating resistance of the heater selects multiple groups in parallel. The temperature sensors are equipped at the inlet and outlet and the temperature is transmitted to the control system.

9.3.2.3   LN$_2$ spray vessel

LN$_2$ spray vessel is used to mix circulating GN$_2$ with sprayed LN$_2$ through the nozzle, to decrease temperature of GN$_2$. Its technical parameters mainly include structure size, LN$_2$ injection amount, working pressure, gas flowrate, etc. The design and manufacture of LN$_2$ spray vessel is based on above parameters. The inlet and outlet of LN$_2$ spray vessel are equipped with temperature sensors to transmit

the signal to the control system, and automatically control the injection amount of LN_2 according to the set temperature.

10 Vacuum system

10.1 Composition and function

The vacuum system is used to establish the vacuum environment required for the test. A series of pumps are used in a vacuum system to pump the gas out of the simulation chamber. The system generally consists of vacuum pumps, vacuum pipelines and valves, vacuum gauges, repressurization subsystem, and residual gas analyser. See Figure 9.
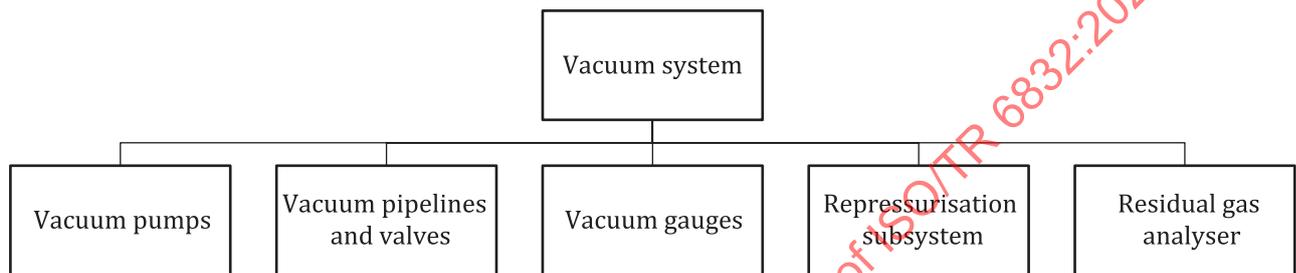
Figure 9 — Vacuum system diagram

10.2 Design of vacuum system

10.2.1 General

The pumping process scheme is determined firstly according to the test requirements. Secondly, the pumping speed of vacuum system is calculated according to the input conditions such as simulation chamber size, gas load, working vacuum pressure, ultimate vacuum pressure, pumping time, and cleanliness. According to the calculation results, the vacuum pumps, vacuum valves, vacuum gauges, repressurization equipment, residual gas analyser, etc. are selected.

10.2.2 Scheme of the vacuum pumping process

TVC requires the working vacuum pressure with loads lower than $1,33×10^{-2}$ Pa. With current vacuum technology, it is not possible to pump directly from atmospheric pressure to high vacuum pressure by using a single type of vacuum pump. The vacuum pumping system is consisted of various vacuum pumps to meet the vacuum pressure requirements through multi-stage pumping.[7] Generally, the pumping process of vacuum system is divided into rough vacuum pumping process and high vacuum pumping process. The rough vacuum pumping process is achieved by combining roots pumps and dry pump to achieve the pressure range from atmospheric pressure to 10^{-1} Pa. The high vacuum pumping process is used to achieve pressure changes from 10^{-1} Pa to 10^{-5} Pa, which is realized by the cryopump as the main pump and the molecular pump as the auxiliary pump. The main pump determines the ultimate vacuum pressure and working pressure. See Figure 10.
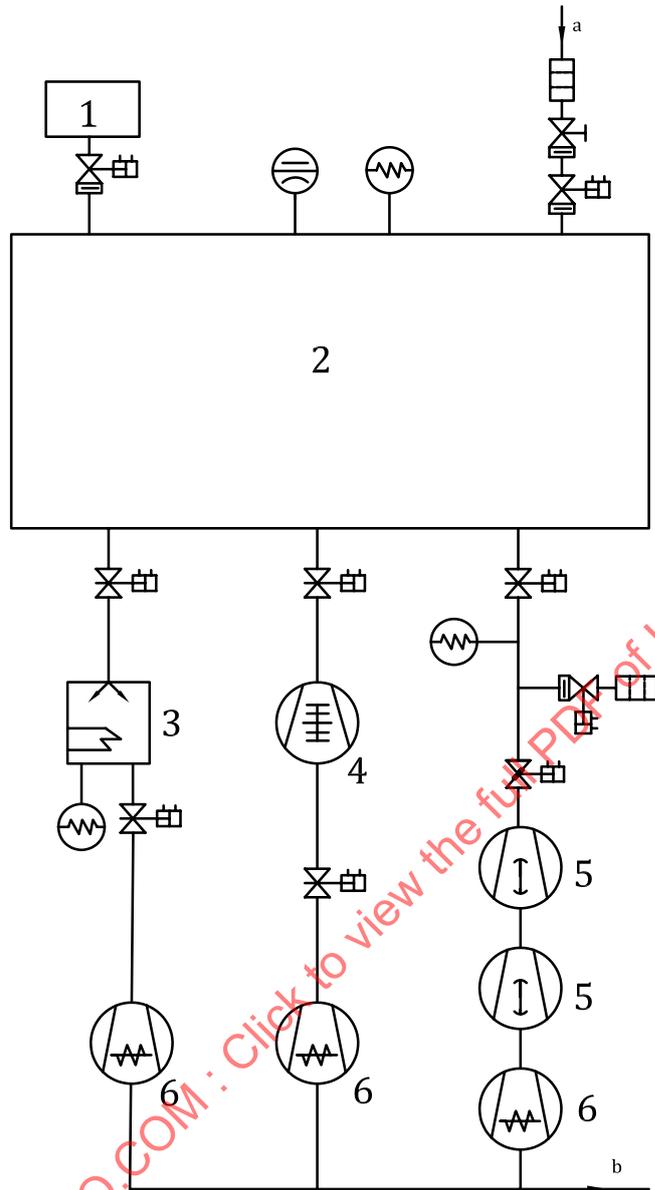
Key

1   residual gas analyser

2   simulation chamber

3   cryopump

4   molecular pump

5   roots pump

6   dry pump

[a]   Repressurized air.

[b]   Exhaust port.

Figure 10 — Working principle for vacuum system

10.2.3   System design calculations

After the vacuum pumping process scheme is determined, the following process parameters are calculated according to the test requirements as the basis for equipment selection. Firstly, the vacuum pumps of high vacuum pumping process are configured according to the technical specifications

of ultimate vacuum pressure and working vacuum pressure. Then vacuum pumps of rough vacuum pumping process are configured. The detail steps are as follows.

a) The high vacuum pumping process is calculated. Firstly, the gas load is calculated. The gas load of the system mainly refers to the gas generated inside the simulation chamber itself, including the surface outgassing of various materials under vacuum, the simulation chamber leakage, and the total amount of gas released from the specimen during the test. Secondly, the effective pumping speed required for high vacuum in the simulation chamber is calculated. The required effective pumping speed is calculated according to the parameters of no-load ultimate vacuum pressure, working vacuum pressure, gas load, pumping time, etc. Then, the high vacuum pump is preliminary selected according to the calculated effective pumping speed and the composition of the pumped gas. The ultimate pressure of the selected high vacuum pump is more than half an order of magnitude lower than the required ultimate pressure of the simulation chamber. And the working pressure of the simulation chamber is within the best pumping pressure range of the high vacuum pump. Finally, the practical effective pumping speed of selected pumps is double-checked to verify that the selected pumps meet the test requirements.

b) The rough vacuum pumping process is calculated. Firstly, the required limit pressure of rough pumping unit is determined. The limit pressure of rough pumping unit is mainly related to the starting pressure of high vacuum pumping unit, which is generally 1 order of magnitude lower than the starting pressure. Then, the required pumping speed of rough pumping unit is calculated. The rough pumping vacuum process mainly removes the free gas in the vessel. Outgassing from the inner surface of the equipment itself is negligible. The pumping speed of the rough pumping unit is calculated according to the volume of the vessel and rough pumping time. Finally, rough pumping unit is selected according to the calculation of required pumping speed. Based on the pumping speed curve of the selected vacuum pump and the dimension of vacuum pipeline, the practical effective pumping speed of selected pumps is double-checked to verify that the selected pumps meet the test requirements.

10.2.4 Equipment configuration

10.2.4.1 General

The selection of the main equipment of the vacuum system includes the selection of vacuum pumps, vacuum pipelines and valves, vacuum gauges, repressurization equipment, and residual gas analyser, etc.

10.2.4.2 Vacuum pump

a) High vacuum pump

The common high vacuum pumps used in TVC are cryopumps and molecular pumps. The cryopump condenses, captures and adsorbs the gas in the simulation room through the cryogenic surface. Therefore, the pressure in the simulation chamber is reduced and a vacuum environment is obtained and maintained. The cryopump is widely used as the main pump in TVC because of its ideal cleanliness, oil-free, and high pumping speed. Its pumping pressure ranges from 10^{-1} Pa to 10^{-8} Pa, and the pumping speed ranges from 1 500 l/s to 60 000 l/s (when the gas pumped is nitrogen). To make the cryopump work continuously, it is equipped with a roughing pump. The roughing pump is used to achieve the starting pressure required for the cryopump and for periodically regenerated for the cryopump.

The molecular pump is a kind of gas transfer pump, relying on the high-speed movement of the rigid surface to exclude gas molecules. Since the pumping speed of the molecular pump is much smaller than the pumping speed of the cryopump, it is usually used for transitional pumping or auxiliary pumping. In addition, the molecular pump has a higher pumping rate for lighter gases that are difficult to remove from other vacuum pumps such as helium and hydrogen. According to this characteristic, the molecular pump is commonly used as the main pump in the leak detection of vessel, shroud, specimen, etc. The molecular pump is usually equipped with backing pump to ensure proper operation.

According to the required effective pumping speed under high vacuum environment, the cryopump and molecular pump required by the TVC are selected. In addition, to improve the reliability of the high vacuum pump unit and prevent the single point of failure, the redundant design is to use at least one more set of cryopump and molecular pump set as a backup.

b) Roughing vacuum pump

The roughing pumping unit usually consists of a roots pump in series with a backing pump (choosing among dry pumps, rotary vane mechanical pumps, or rotary plunger vacuum pumps). The roughing pumping unit achieves a vacuum pressure better than 10^{-1} Pa in the simulation chamber. The roots pump is the main pump of the roughing pumping unit. In order to obtain a clean test environment, oil-free dry pump and roots pump (or multi-stage roots pump) are usually selected as the rough pumping unit. According to the required effective pumping speed under rough vacuum environment, the rough pumping unit required by the TVC is selected. In addition, in order to avoid single-point failure of the rough pumping unit, multiple rough pumping units are configured in parallel to improve system reliability.

10.2.4.3 Vacuum pipelines and vacuum valves

The vacuum pipeline is the component connecting the pumping port of the vacuum vessel with the air inlet of vacuum pumps. It usually takes the form of a circular cross section. The flow conductivity value is calculated according to the flow state and the layout of the pipeline. The selection of pipes follows the principle of short length and large diameter. Generally speaking, the diameter of the pipeline is not less than the diameter of vacuum pump inlet. The material of vacuum pipeline is low outgassing, clean surface and good welding performance. Stainless steel seamless pipe is usually used as the vacuum pipeline. Rubber is used as the sealing material for vacuum flanges. Leakage rate of the vacuum pipeline is determined by the vacuum pressure of the simulation chamber. Vacuum flange conforms to ISO 1609[1], ISO 2861[2] and ISO 3669[3].

The vacuum valve is the vacuum component used to cut off the gas flow, regulate gas flow and distribute gas flow, which is divided into gate valve, angle valve, butterfly valve, ball valve, etc. based on their structures. The diameter, leakage rate, response time and driving mode of the selected vacuum valve meet the requirements of test. The valves connected to the vessel are usually two-way sealed gate valve for high vacuum environment, while the valves used for backing pumps and pipes are angle valves or butterfly valves for high vacuum environment.

10.2.4.4 Vacuum gauges

Vacuum gauges are usually chosen from thermal conduction vacuum gauge and ionization vacuum gauge. Thermal conduction vacuum gauge is used for low and medium vacuum environment measurement in the range of 10^5 Pa to 10^{-1} Pa. Ionization vacuum gauge is used for high vacuum measurement in the range of 10^{-1} Pa to 10^{-5} Pa. In order to ensure the reliability of vacuum gauges, the number of pressure-measuring points for the simulation chamber is not less than 2, and the installation position of the vacuum gauge cannot be close to the vacuum pump inlet.

10.2.4.5 Repressurization subsystem

The function of the repressurization subsystem is to inflate the simulation chamber after the test and gradually return the shroud temperature to room temperature. The repressurization gas is usually clean air in room. Repressurization equipment generally includes valves, gas source pipeline, filters, silencers, etc. The size of the inflatable aperture is calculated based on the volume size of the simulation chamber and the required recompression time. Then the selection and design of related repressurization equipment are completed.

10.2.4.6 Residual gas analyser

The function of residual gas analyser is to measure the type and partial pressure of residual gas in the simulation chamber. The most commonly used product is the quadruple mass spectrometer, which ionizes gas molecules and then separates them by mass using an electric or magnetic field for

measurement and analysis. It is used not only for gas partial and full pressure measurements, but also for vacuum leak detection. Its performance parameters include mass measurement range, resolution, maximum working pressure, minimum detectable pressure, scanning speed, etc.

11 Heat flux simulation system

11.1 Solar simulator

11.1.1 Composition and function

A solar simulator is mainly used to simulate solar irradiation environment of outer space. It can provide collimated and stable irradiation, which is similar to solar spectrum and uniformly distributed.

A solar simulator is usually composed of an optical-mechanical subsystem, a cooling subsystem, and a control subsystem. The optical-mechanical subsystem is composed of a lamp house assembly, an optical window and a collimation mirror assembly. The lamp house assembly provides uniform divergent light beams with the required energy, and is typically composed of xenon lamps, collecting mirrors, an optical integrator, a water-cooling baffle and a baffling tube. The optical window transmits the light beams and separates the vacuum from atmosphere. The collimation mirror assembly collimates the light beams emitted from the lamp house assembly and reflects them parallel to the test volume. The cooling subsystem is to cool the solar simulator, and it includes water cooling unit and air cooling unit. The control subsystem controls the xenon lamps and monitors the temperature of other components. The composition of the solar simulator is shown in Figure 11.
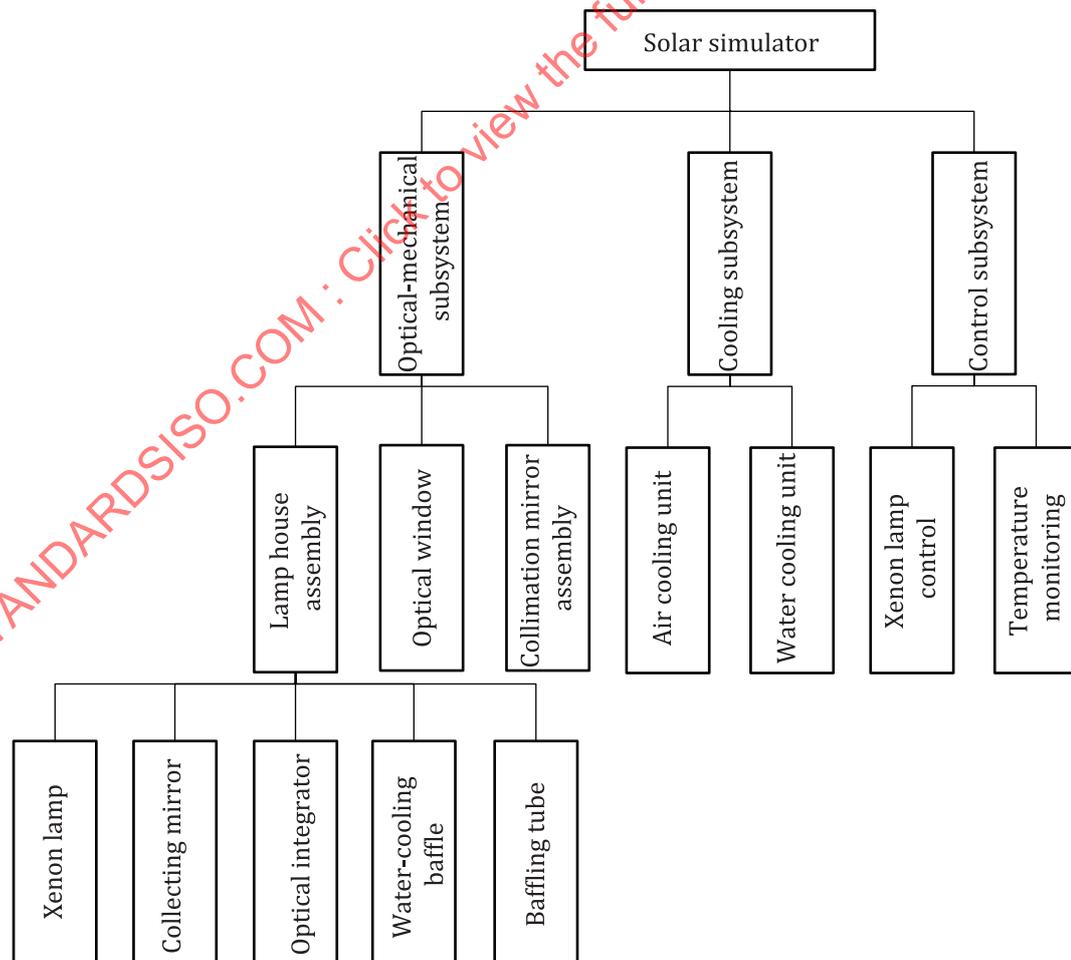

Figure 11 — Composition chart of solar simulator system

11.1.2 Solar simulator design

11.1.2.1 General design

In the general design of the solar simulator, the overall structure and optical system form of the solar simulator are determined by the vacuum vessel type and overall requirements, including the vertical or horizontal structure of the solar simulator, the coaxial or off-axis structure of the optical system, etc.

The coaxial or off-axis structure of the optical system is usually selected according to the aperture size of the exit spot of the solar simulator. For small solar simulators, coaxial collimating optical system is usually used, and the structure is shown in Figure 12.
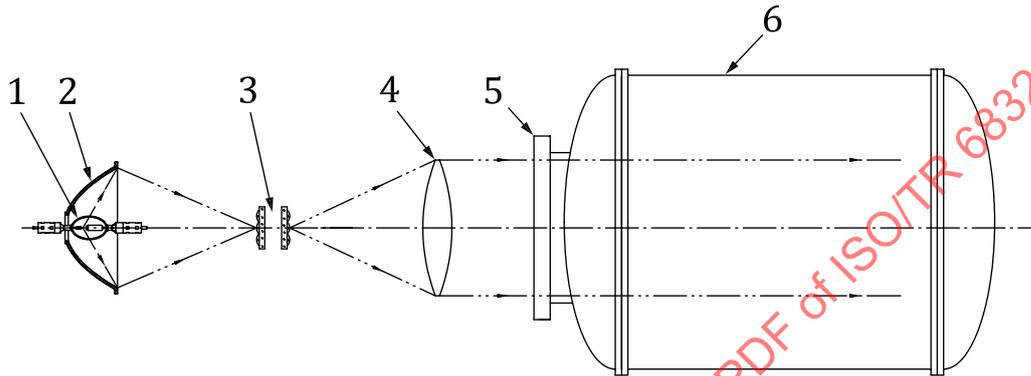
Key

1 xenon lamp
2 collecting mirror
3 optical integrator
4 collimation mirror assembly
5 optical window
6 vacuum vessel

Figure 12 — Structure diagram of coaxial collimating solar simulator

For large solar simulator, since the application of the first set of large coaxial collimating solar simulator in the world in the 1960s, the development of large solar simulator has experienced the transition of the optical system from coaxial collimating type to off-axis collimating type. At present, the off-axis collimating solar simulator is used worldwide (see Figure 13). The larger irradiation area and better irradiance uniformity are obtained.
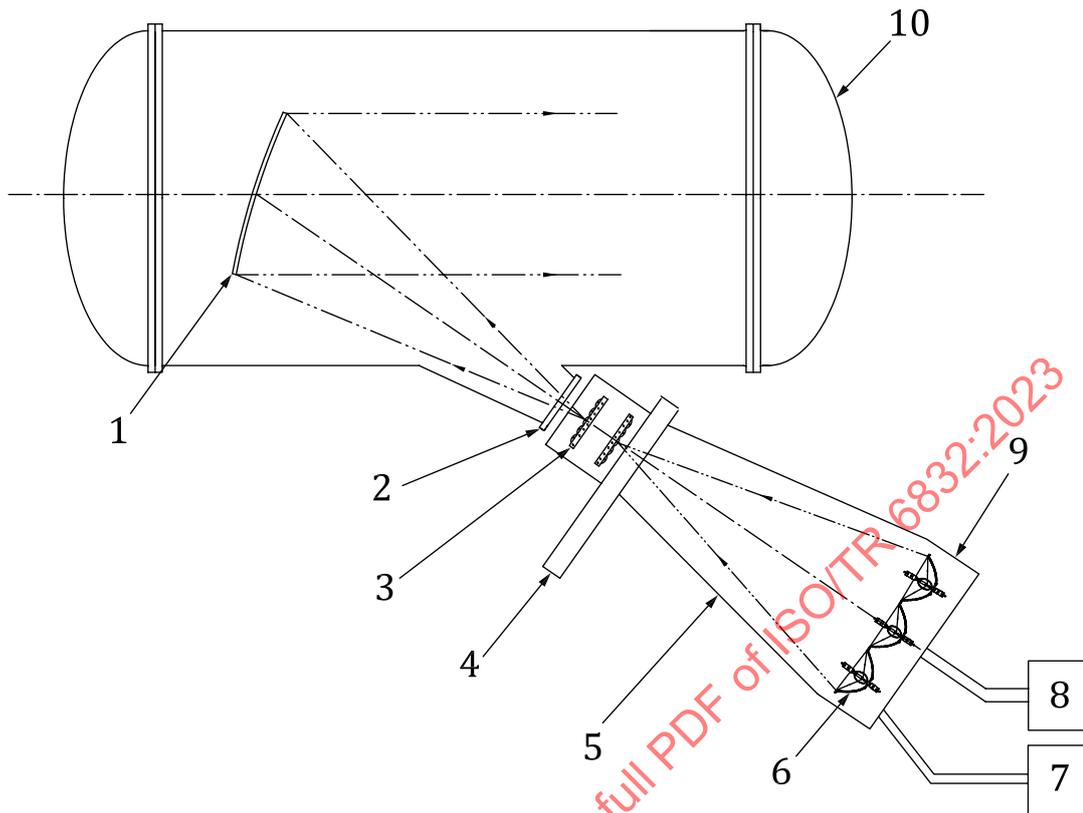
Key

1   collimation mirror assembly
2   optical window
3   optical integrator
4   water-cooling baffle
5   baffling tube
6   collecting mirror
7   control subsystem
8   cooling subsystem
9   lamp house assembly
10 vacuum vessel

Figure 13 — Structural diagram of off-axis collimating solar simulator

11.1.2.2 Optical design

According to the overall requirements and the configuration of the solar simulator, the optical design mainly calculates the shape, overall dimension, relative distance, and xenon lamp power of each optical equipment of the solar simulator and optimizes the optical indexes such as irradiance and uniformity, to ensure that the optical performance meets the overall requirements. The optical system of the solar simulator is designed according to the lighting system. At the same time, the appropriate optical system and optical parameters are selected to improve the irradiation uniformity of the test space and the energy utilization of the solar simulator system. The specific steps are as follows.

a) Firstly, in the optical design of the solar simulator, the optical system follows theorem of Lagrange, that is, the Lagrange invariant of all optical surfaces in the optical system of the solar simulator is a constant. According to the overall requirements of the solar simulator, the irradiation surface diameter, collimation angle and focal length of the collimation system of the solar simulator are

determined firstly. Then the optical parameters of the collecting mirror, optical integrator and collimation mirror of the solar simulator are calculated according to theorem of Lagrange.

b) Secondly, after confirming the basic parameters of each optical equipment of the solar simulator, the optical design software is used to optimize the optical parameters. On the premise of meeting the irradiance, the optimization goal is to improve the irradiation uniformity and improve the energy utilization of the optical system. The optimization design is carried out with variables i.e. optical parameters and relevant position relationship of each optical equipment.

c) Finally, the optimized optical parameters that meet the overall technical specification are obtained, and the design of all optical equipment is completed.

11.1.2.3 Optical-mechanical subsystem

a) Lamp house assembly

The lamp house assembly is usually composed of xenon lamps, collecting mirrors, an optical integrator, a water-cooling baffle and a baffling tube, which is placed outside of the vacuum vessel. It is used to provide uniform divergent light beams with the required energy.

The light source is generally the short arc xenon lamp (see Figure 14), which has the characteristics of high luminous efficiency, highly concentrated luminous area, high brightness and close to the solar spectrum. The total power of the required xenon lamps is calculated according to the effective irradiation area and irradiance of the solar simulator in combination with the total energy utilization rate of the optical system. Based on the total power, the quantity of xenon lamps and the power of each single xenon lamp are determined. The layout of the light sources is reasonably designed according to the quantity of the light sources.
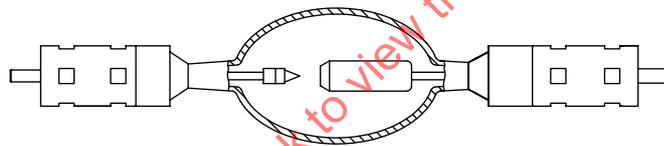
**Figure 14 — Short arc xenon lamp**

The collecting mirror is used to collect and reflect the light from xenon lamp to the entrance of optical integrator. Due to the axial symmetry of the beam emitted by short arc xenon lamp, ellipsoidal collecting mirror is usually used in order to obtain better condensation effect. When the xenon lamp is installed, the xenon lamp is overlapped with the optical axis of the collecting mirror along the length direction, and the xenon lamp cathode is adjusted to the first focus of the collecting mirror (see Figure 15). The first focal length of the ellipsoid collecting mirror is determined by the size of xenon lamp and the condition of the mechanical regulating mechanism. The paraxial imaging multiplying factor of the collecting mirror is determined comprehensively according to the collecting efficiency of the collecting mirror and the desired irradiance distribution on the second focal plane of the collecting mirror. In the design of collecting mirror array with multiple light sources, the main optical axis of each collecting mirror points to the centre of the field lens group of the optical integrator. A metal mirror is used as a collecting mirror, and its surface processing technology is aluminium substrate polishing or electroplating nickel, and finally coated with aluminium reflective film and SiO_2 protective film.

1

2
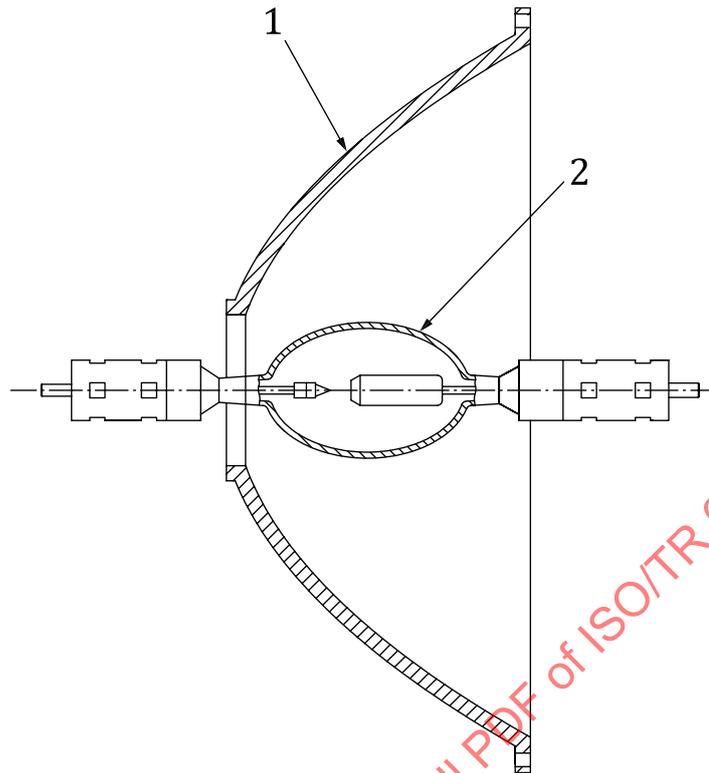
Key
1   collecting mirror
2   xenon lamp

Figure 15 — Collecting mirror

The optical integrator is composed of a field lens group and a projection lens group. The field lens group and the projection lens group are composed of multiple elemental lenses. Each corresponding element lens in the field lens group and the projection lens group form an optical path to form a lens array (see Figure 16). The field lens group of the optical integrator is placed at the second focal plane of the collecting mirror. The lens array of the optical integrator splits the irradiation distribution on the second focal plane of the collecting mirror. The irradiation distribution projected by the lens array is complemented and superimposed to obtain a uniform irradiation distribution. The quantity of the elemental lenses is determined by the specifications of the effective irradiation area and the irradiance uniformity. The elemental lenses of the filed lens group and the projection lens group are usually made of quartz glass. In the optical integrator, the elemental lenses are usually fixed on a flat glass substrate by photo resist technology. For a large optical integrator, the elemental lenses are fixed on a metal frame.
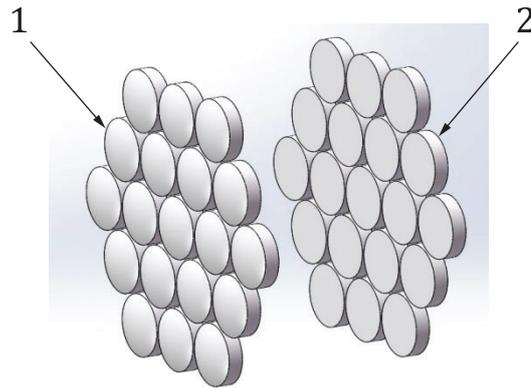
Key

1 field lens group
2 projection lens group

Figure 16 — Optical integrator

The water-cooling baffle is used to block the incident beam of the solar simulator. It is used to switch the state of test specimen between solar irradiation zone and the shadow zone. When the water-cooling baffle is closed, all the beams of the solar simulator irradiate on the water-cooling baffle, and the radiant energy is taken away by the cooling water.

The baffling tube is used to form the closed space of the lamp house assembly, eliminate the influence of external stray light on the light path, and ensure the overall sealing of the lamp house assembly to meet the cooling requirements. The baffling tube is usually made of aluminium alloy or SS. According to cooling requirements, the baffling tube is cooled by water.

b) Optical window

The optical window is installed on the vacuum vessel, which is mainly used for light transmission and vacuum sealing. The optical window bears the pressure difference inside and outside the vacuum vessel and the thermal radiation of xenon lamp. Because of its good heat resistance and high optical transmittance, circular quartz glass is selected. The material of sealing ring of optical window is usually O-type fluoro rubber.

c) Collimation mirror assembly

The collimation mirror assembly is mainly used to collimate the incident beam emitted from the lamp house assembly and passing through the optical integrator, and project or reflect it to the test space in parallel. The collimation mirror assembly does not need strict requirements for aberration, but controls the aberration within an appropriate range by selecting a reasonable relative aperture value. On the premise of meeting the irradiance, the relative aperture is selected according to the uniformity requirements. The diameter of the collimation mirror is determined by the distance from the collimation mirror to the effective irradiation surface, the collimation angle, and the diameter of the effective irradiation surface.

For the coaxial collimating solar simulator, the collimation mirror assembly usually adopts the lens of quartz glass, which is placed outside the vacuum vessel together with the lamp house assembly. For the off-axis collimating solar simulator, the collimation mirror assembly generally selects the spherical metal reflecting mirror, which is placed in the vacuum vessel. According to its size, it is either a single spherical metal reflecting mirror or to be formed by splicing multiple spherical metal reflecting mirrors. The surface processing technology of the metal collimation mirror is aluminium substrate polishing or electroplating nickel, and finally coated with aluminium reflective film and SiO_2 protective film. During the test, the collimation mirror's temperature is controlled in two ways. The first way is to embed cooling pipe inside the collimation mirror and adjustable temperature GN_2 flows through cooling pipe to control the temperature of collimation mirror. The second way is a combination of heating by thin

heat film pasted on the back of the collimation mirror and radiation cooling by shroud installed at the back of the collimation mirror.

11.1.2.4 Cooling subsystem

The cooling subsystem is composed of air cooling unit and water cooling unit, which is mainly used to take away the heat generated by xenon lamps and the heat radiated into the equipment during the operation of solar simulator. Firstly, the thermal load of each optical equipment of the solar simulator is determined by optical design, and then the cooling system is designed according to the thermal load of each optical equipment and its required operating temperature.

The air cooling unit is mainly used for the cooling of xenon lamps, collecting mirror, lens groups of the optical integrator, which is composed of fan, heat exchanger, filter, air flow adjusting valve and ventilation pipe. When the air cooling unit works, the fan sends the cooling air into the lamp house assembly, cools the internal optical equipment, and then returns to the fan to form a closed cycle. The flow rate and pressure of the cooling air are determined by the heat load and the required operating temperature of solar simulator components cooled by air.

The water cooling unit is mainly used for the cooling of water-cooling baffle, baffling tube and the frame of the optical integrator. The cooling water circulates in the cooling pipes and cools down solar simulator's components. The flow rate, pressure, and temperature of the circulating cooling water is determined by the required operating temperature of solar simulator components.

11.1.2.5 Control subsystem

The control subsystem is composed of xenon lamp control unit and temperature monitoring unit, which is mainly used for light source switch, irradiance adjustment of solar simulator, and temperature measurement and control of key components of solar simulator.

Xenon lamp control unit is composed of xenon lamp power supply, trigger, control module, etc. It mainly performs xenon lamp switch control and irradiance adjustment. The xenon lamp control unit uses the trigger to generate instantaneous high voltage to break down the inert gas between the anode and cathode of the xenon lamp to ignite the xenon lamp. By controlling the output current of the xenon lamp power supply through the control module, adjust the luminous flux of the xenon lamp to achieve stable and specified irradiance output. Xenon lamp power supply and trigger are selected according to xenon lamp performance parameters. Xenon lamp power supply usually adopts programmable power supply with wide voltage range and wide current range.

The temperature monitoring unit is mainly used to measure and record the temperature of xenon lamp anode, collecting mirror, water-cooling baffle, baffling tube, collimation mirror assembly and other components of solar simulator, and control the temperature of collimation mirror assembly during the operation as well.

11.2 Infrared heat flux simulator

11.2.1 Composition and function

The infrared heat flux simulator mainly includes the infrared lamp array, the infrared cage, the thermal control board, etc. It can simulate heat flux of the specimen's surface equals to the heat flux absorbed by the spacecraft working in-orbit. This simulation method neglects the spectral characteristics of radiation in space, only simulates equivalent thermal effect.

11.2.2 Infrared lamp array

An infrared lamp array is composed of infrared lamps and lamp array support, as shown in Figure 17. Typically, the lamp array is arranged towards the specimen to perform radiation heating. According to the real heat flux distribution on the specimen working in-orbit, the specimen surface is divided into several equivalent heat flux zones, which is simulated respectively by corresponding infrared

lamp arrays. By changing the input power of infrared lamps, the heat flux is adjusted to meet the test requirements.
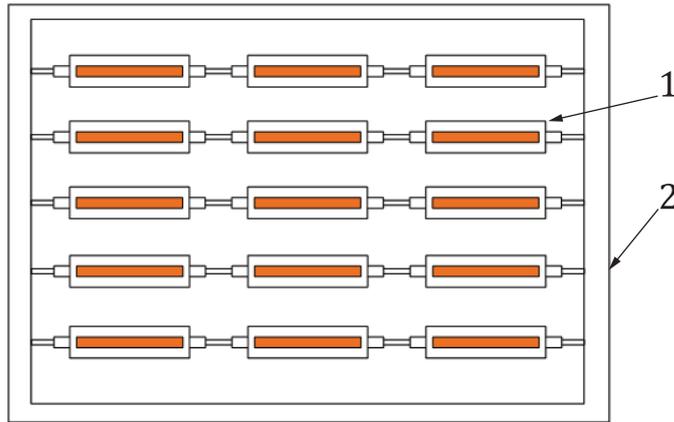
Key

1   infrared lamp
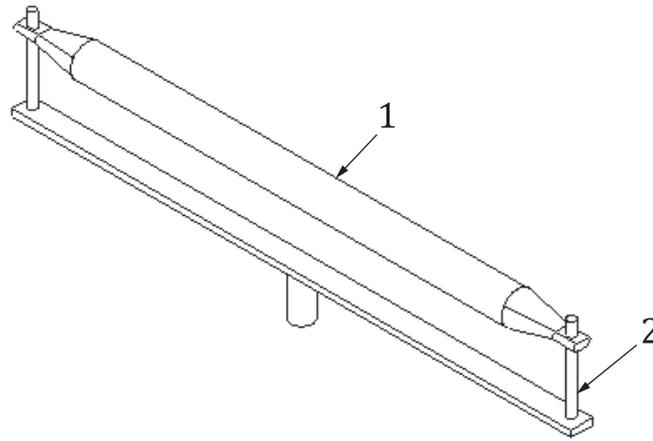2   lamp array support

Figure 17 — The infrared lamp array

Bases on the heat flux distribution of a single infrared lamp, the maximum heat flux and the uniformity of the heat flux distribution of the infrared lamp arrays are analysed and calculated. The power, quantity, and arrangement of the lamps are determined according to the heat flux, radiation area, radiation distance and radiation uniformity. There are two kinds of infrared lamps can be chosen. One kind of infrared lamp is composed of a quartz-tungsten-halogen lamp and a lamp holder mounted with reflector, as shown in Figure 18. The reflector is made of aluminium alloy as the base material, with gold plating on the inner surface. It is mounted on the back of the lamp to increase thermal efficiency and improve heat flux distribution of the lamp array. The lamp holder is used to hold the lamp and reflector, and they are assembled on the lamp array support. The other kind of infrared lamp is composed of a quartz-tungsten-halogen lamp with reflective film and a lamp holder, as shown in Figure 19. The reflective film is plated on the half side of the lamp. This kind of lamp array has relatively smaller shielding to shroud radiation.

Key
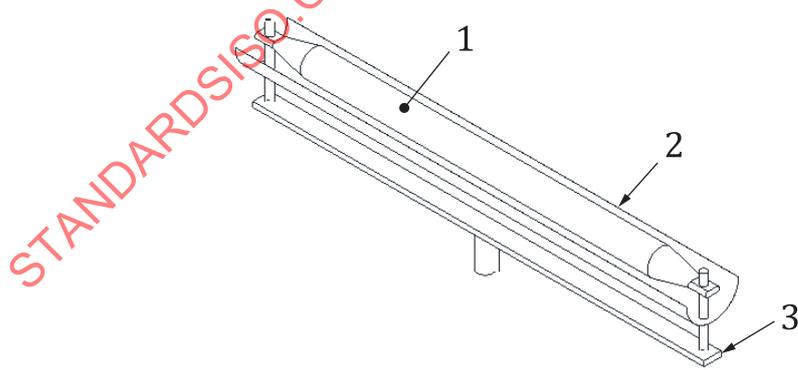
1   quartz-tungsten-halogen lamp
2   reflector
3   lamp holder

**Figure 18 — Infrared lamp with reflector**

Key

1   quartz-tungsten-halogen lamp with reflective film

2   lamp holder

Figure 19 — Infrared lamp without reflector

The lamp array support is made of aluminium or SS, which has the advantages of low outgassing under vacuum environment. It is surrounded by reflective panels to improve the uniformity of heat flux distribution. The surface of the reflective panels facing the lamps has high reflectivity, and the other side is blackened processed.

11.2.3   Infrared cage

An infrared cage is usually a cage shaped structure, arranging heating tapes or heating rods surrounded the specimen, as shown in Figure 20. The heat flux is adjusted by changing the input power of the infrared cage. The surfaces of heating tapes or heating rods facing specimen are coated with black paint. The other side is designed as a reflective surface to reduce heat radiation.
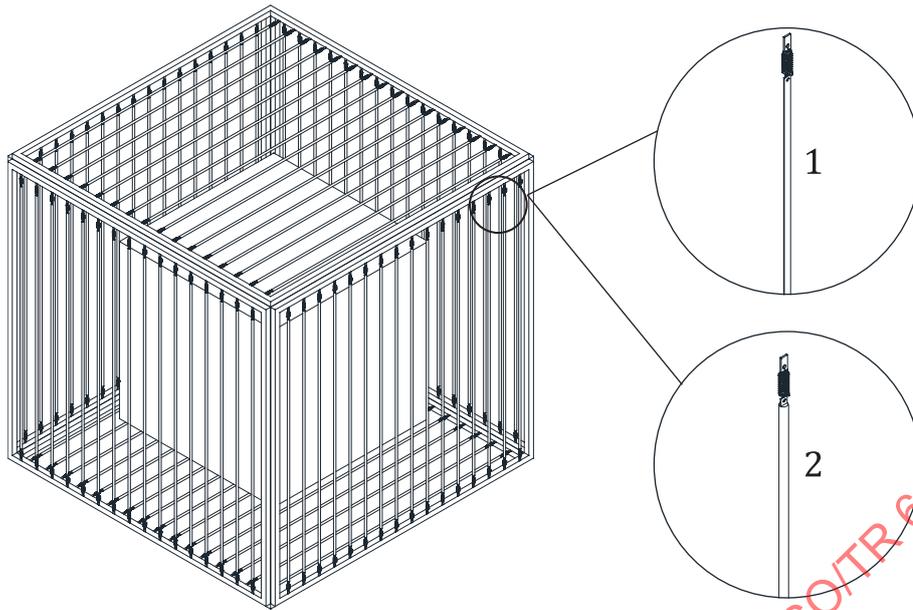
Key
1 heating tape
2 heating rod

Figure 20 — Infrared cage

The infrared cage is divided into several independent heating zones according to the test requirements. The radiation angular coefficient of the infrared cage to the corresponding area surface of the specimen is calculated by considering the requirements for high and low limits of heat flux. The maximum power required for each heating zone and resistance of heating tape or heating rod for each heating zone are calculated by considering the maximum safe applied current. According to the need of matching power and resistance, each heating zone is divided into several heating circuits. Then reasonable density of heating tapes or heating rods is arranged, and resistance of each heating circuit is determined.

11.2.4 Thermal controlled panel

The thermal controlled panel is installed close to surface of specimen, and used to simulate the thermal effect of infrared heat flux. According to the required heat flux, the temperature of thermal controlled panel can be controlled by fluid medium with certain temperature flowing in its internal tubes. The surface of the panel facing the specimen are coated with black paint to increase its emissivity.

12 Specimen support mechanism

12.1 General

The function of the specimen support system is to support, fix and control the attitude of the specimen inside TVC. According to different test requirements, the specimen support mechanism has three types: motion simulator, horizontal adjustment mechanism and test specimen support. Motion simulator is generally used together with solar simulator, which can realize the multi-dimensional attitude adjustment of the specimen in the test process. The horizontal adjustment mechanism can adjust the levelness of the specimen during the test. The test specimen support is used to support and fix the specimen; it has no adjustment function during the test.