Strategy for Enhancing Fairing Air Conditioning Security Capacity in the On-Time Launch of Chinese Mars-1 Exploration

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Abstract: For the launch of Chinese Mars-1 exploration in a coastal spaceport at noon, summer, there are issues such as big fairing size, complex fairing layout and uncertain flow field of fairing. The author conducted analysis of fairing air conditioning security by thermodynamic modeling calculation and CFD simulation and proposed specific improvement measures to secure on-time launch according to the calculation analysis conclusions. Special test verification was conducted after the carrier rocket transfer. The improvement measures were proven to be effective. During mission launch, the fairing environment security is good. After fairing air conditioning decoupling, the fairing inside temperature rise is within the required scope, ensuring on-time launch of Mars exploration.

1. Introduction

Due to Earth-Mars mobility, there is only one Mars exploration launch window [¹] every 26 months according to the current capacity of carrier rocket. In 2020, the Mars exploration window opportunity was difficult to get. Therefore, the US, European Space Agency, Russia and UAE, etc. conducted Mars exploration missions [²][³]. Chinese Mars-1 exploration, China’s first planetary mission, represents a milestone event for China to access to deep space and emerge as a strong aerospace nation. As the event bears great significance and profound influence, there will be high launch test safety and reliability requirements. Besides, we must ensure on-time launch within the effective window.

The Mars Rover payload will achieve multiple scientific goals, use high-precision load equipment [⁴], and put forward specific requirements for key indicators such as temperature, relative humidity, gas flow speed, and cleanliness in the fairing during ground test launch. Especially in the pre-solar radiation procedure, the fairing air conditioning security is of utmost importance, as it relates to whether the rover work environment meets the requirements.

2. Fairing Air Conditioning Security Issues and Difficulties in Mars Exploration

2.1. Big security difficulty of the window at noon

According to mission ballistic planning and window calculation, China’s 2020 Mars exploration window was 12:00-13:00, late July to early August. Wenchang spaceport belongs to a typical tropical marine climate characterized by “high temperature, high humidity, high salt spray [¹]”. According to the spaceport’s history weather, at 12:00-13:00, from 2007 to 2019, the temperature was slightly higher,
minimum temperature 24.8°C, maximum temperature 34.9°C, average temperature 29.9°C; the minimum relative humidity is 53%, the maximum relative humidity 98%, and the average relative humidity 79.1%. According to the fairing environment temperature recording of earlier space mission, when the pre-launch work platform fully opens, the ambient temperature inside the fairing rises somewhat, or gets close to the upper limit under very rare conditions. Wenchang spaceport conducts space launch for the first time at summer noon and the large-sized fairing is used. Therefore, it's more difficult for fairing air conditioning security, and there is likelihood to surpass the indicator.

2.2. Security influence factors
The fairing air conditioning unit is set in the fixed service tower. The unit supplies air into the service tower pipe. The air goes to the rocket umbilical tower pipe via a hose, and then to air conditioning hose via the umbilical tower hose. The air conditioning hose end is the air conditioning connector to connect the fairing. The security pipeline is long and pipe diameter differs. Besides, the material heat leakage rate varies, as shown in Figure 1.

![Figure 1 Fairing air conditioning environment security system wiring](image)

Different parts of fairing have different key indicators. Air conditioning compressor output parameters include output power, air volume; fairing air conditioning pipeline parameters include pipe diameter, length; main air delivery parameters of fairing air conditioning connector include temperature and humidity. In terms of system design, the temperature and humidity inside the fairing and gas flow speed are artificially judged. Air conditioning compressor output power and air volume are manually regulated. There are no effective measurement methods on pipeline heat leakage and gas flow speed inside fairing. The feedback control has delay while security parameters such as temperature and humidity vary easily.

2.3. Few measurement points and inaccurate flow field description
Due to restrictions by fairing air conditioning mass, cleanliness inside fairing and air conditioning connector decoupling, there are usually few ambient temperature and humidity sensors inside the majority of fairing. Usually, some sensors are allocated along the perimeter of the fairing and the measurement points are close to the fairing wall, as shown in Figure 2. The present measurement points and positions are difficult to precisely reflect gas flow field inside the fairing. Especially, there are no main indicators for the rover positions. With only few inlet parameters and fairing wall measurement points, it’s very difficult to precisely describe the flow field inside the fairing.
3. Security process Thermodynamic Modeling and Simulation Analysis

China’s understanding of fairing environment security gradually deepens during the space launch mission. Early literature [6] proposed a method of fairing environment adjustment by secondary return air PID control. Literature [7] discussed the cold energy control optimization method of temperature and humidity adjustment under summer and winter work conditions. Literature [8] proposed the enthalpy difference-based fairing air conditioning compressor control method. Literature [9] [10], et al. discussed fairing environment parameters measurement and sensor fault diagnosis. The domestic fairing air conditioning control method is effective to secure the launch mission. However, the current control circuit match should be strengthened; the fairing environment analysis method is limited to the sensor analysis and use. It’s mainly based on the classical thermodynamic modeling calculation fitting engineering experience formula, or focuses on external system measurement feedback control research. Without flow field simulation and verification research, it is difficult to effectively support the requirements for on-time launch window of Mars exploration. There are no simulation calculations. The Kennedy Space Center conducts flow field CFD simulation on fairing, air conditioning connector, etc., and continuously optimizes its flow field calculation model to improve simulation accuracy [11] [12]. Such practice is worth reference. In order to further accurately analyze the fairing air conditioning security of Mars exploration, the author will conduct analysis by thermodynamic modeling calculation plus CFD simulation analysis.

3.1. Thermodynamic modeling calculation

Considering fairing heat balance and based on heat exchange calculation of surface material

\[ Q = \Delta T \times k \times A \]  \hspace{2cm} (1)

Where, \( Q \) cooling amount. The new air mixes with fairing air, producing total heat exchange and reaching balance; \( \Delta T \) inside and outside temperature difference to sustain fairing balance. Solar radiation heat increases infiltration heat. During calculation, it’s deemed that the outside surface temperature has a certain increment in effect. Such increased temperature variation is related to wall direction, surface color and roughness, empirically determined at 5~10°C; \( A \) fairing surface area; \( K \) structure aggregate and heat transfer coefficient \((W/m^2 \cdot K)\); multi-layer structure heat transfer coefficient is calculated according to the formula:

\[ k = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \sum \delta_i / \lambda_i} \]  \hspace{2cm} (2)

Where, \( \alpha_1, \alpha_2 \) heat exchange coefficient \((W/m^2 \cdot K)\) of inside surface and outside surface of fairing; \( \lambda_i \) heat transfer coefficient of layer structure \((W/m \cdot K)\), \( \delta_i \) layer structure thickness.

Considering temperature variation after fairing inlet and inside balance,

\[ Q = (T_{out} - T_{in}) \times C_p \times m \]  \hspace{2cm} (3)

Where, \( T_{out} \) temperature after fairing balance, calculated at 25~30°C; \( T_{in} \) fairing air conditioning connector inlet temperature, calculated at 12-18°C; \( C_p \) air heat ratio, constant pressure specific heat
1.05 (kJ/kg·K), m air supply mass.  
According to Formula (1) (3), with the actual value of fairing temperature and inlet temperature, you can estimate effective air supply mass of the fairing at 0.538~0.837 kg/s. After conversion, the volume flow is 1498~2336 m³/h.

Due to few measurement points and position restriction, fairing temperature after balance T_{out} has poor measurement accuracy and there is inside and outside temperature variation estimation error. The estimation of heat transfer coefficient and inside and outside temperature variation adopt an experience approximation, and the calculation results show that there is a large difference in flow of air effectively entering the fairing and the design value. In order to accurately describe the flow field where the rover is located, and ensure on-time launch, CFD simulation analysis is conducted for full flow field of the fairing.

3.2. Simulation analysis
According to the fairing structure and position layout, CFD modeling is carried out. Main parameter settings include structural dimensions, connector caliber, wind panel form, exhaust hole settings, etc.

With influence of fairing air conditioning air supply pipe diameter change and bending, it’s estimated that the inlet pressure drops to ~750Pa, inlet temperature 15℃, maximum ambient temperature 35℃. When the work platform opens, the comprehensive air temperature of solar radiation after conversion 4℃, comprehensive heat exchange coefficient of fairing 5 (W/m²·K). Through simulation, fairing temperature field and speed field after heat exchange balance is shown in Figure 3 and Figure 4.

![Figure 3 Temperature field inside fairing under constant air supply mode](image1)

Figure 3 Temperature field inside fairing under constant air supply mode

![Figure 4 Speed field inside fairing under constant air supply mode](image2)

Figure 4 Speed field inside fairing under constant air supply mode

The temperature after balance is around 18℃ and the overall speed inside fairing is low, no more than 2m/s around the payload, complying with security requirements. The fairing wall temperature is the highest while the roller position temperature is the lowest. The fairing flow field temperature and speed are not uniformly distributed, showing the rule of “lower temperature higher than upper
temperature and fairing wall temperature higher than inside temperature. The air conditioning vent bottom temperature higher than temperature in other areas. The fairing inside temperature is the highest, with the lower part temperature higher than the higher part temperature, as shown in Figure 5.

![Figure 5 Fairing inside temperature distribution under constant air supply mode](image)

After fairing air conditioning decoupling, the ground solar radiation is 700 W/m², the absorption rate of white paint of outside surface of fairing is taken as 0.13. The simulation results of variation of average temperature is given in Figure 6. 10min after air conditioning decoupling, the fairing average temperature is ~29.6℃, close to the upper limit of security requirement. The average increase rate is 0.36℃/min; after 30min, the fairing average temperature is 32.6℃, failing to comply with security requirements. The average temperature increase rate is 0.22℃/min. In the early period of air stop, the fairing temperature rises rapidly. The increase rate reduces over time.

![Figure 6 Average temperature predictions after air conditioning connector decoupling](image)

4. Security Strategy

During mission preparation and implementation, the security strategy below is formulated through modeling simulation analysis based on carrier rocket and spaceport system and relying on our previous fairing air security experience.

4.1. Fairing air conditioning interface connector timing adjustment

According to the simulation prediction, the fairing temperature rises fast after fairing air conditioning
connector decoupling. During the work program of launch day, the fairing air conditioning connector
decoupling should be adjusted close to the ignition moment, shortening temperature rise time. It’s
preferred to decouple the connector 10min before ignition. According to simulation result, 10min
temperature rise won’t exceed the security scope.

4.2. Fairing air conditioning interface inside baffle structure adjustment
In order to avoid direct impact of cold air on aircraft, the fairing air conditioning interface inside baffle
should be used. The baffle may not only change air flow direction, but also increase air resistance. In
order to expand the effective air volume entering the fairing for this mission, tap both sides of the fairing
baffle, as shown in Figure 7.

![Figure 7 Fairing baffle structure adjustment](image)

4.3. Fairing air conditioning parallel operation security
The launch bay fairing has 2 air conditioning units, one main/one standby. According to modeling
calculation and simulation results, when the fairing temperature rise is 11 ℃ over the air inlet, the
fairing air conditioning can meet temperature and humidity requirement. When the fairing temperature
rise is more than 11 ℃ over the air inlet, the relative humidity will be beyond the lower limit of 35%.
Therefore, when the ambient temperature continues to rise, and the fairing temperature rise is more than
11 ℃ over the air inlet, start the standby air conditioning. Both units will supply air to the fairing, thereby
reducing fairing temperature and cut temperature rise.

5. Test Results
According to measures above, fairing air conditioning simulation test was conducted in the launch bay.
Test fairing temperature and humidity variation under the conditioning of opening slewing platform,
disconnecting fairing air conditioning air supply and 25min launch delay (cumulative air stop time
35min). According to test results, when both air conditioning unit work, fairing temperature is around
20.5℃and humidity 43%. After air stop, the fairing temperature rises from 20.9℃ to 26.6℃ within
30min. In order to prevent further temperature rise, the fairing air supply starts again, as shown in Figure
8.
According to simulation results and test conditions, the ambient temperature doesn’t arrive at the peak value of 35°C during special test. Under the simulation condition, comparison of Manned Mars Exploration Mission for temperature rise rate is shown in Table 1.

| Regimen         | Ambient temperature °C | Inlet air pressure Pa | Fairing temperature after stable air supply °C | Temperature rise rate after air stop °C/min |
|-----------------|-------------------------|-----------------------|-----------------------------------------------|------------------------------------------|
| Simulation      | 35 (Peak historical value) | 750                   | 18                                            | 0.22                                      |
| Test results    | 29.1–31.0               | -                     | 20.5                                          | 0.19                                      |

When the ambient temperature is lower than the peak historical value, the average fairing temperature after balance is slightly higher than the simulation result. Main reasons include: it’s difficult to measure real inlet air pressure, possibly lower than analog 750Pa; test measurement point is fairing wall, with temperature slightly higher than average temperature inside fairing, namely the rover position temperature lower than 20.5°C. Because the ambient temperature is lower than the lowest historical value, the fairing temperature increase rate under test condition is lower than simulation calculation result. However, it’s still quick, consistent with the simulation result trend.

6. Conclusions
With respect to air conditioning securing issue of Chinese Mars-1 exploration, the author conducted thermodynamic modeling calculation and CFD simulation analysis and expand fairing air conditioning environment security analysis method of space launch mission. The author acquired fairing temperature field and speed field distribution under constant air supply balance condition and fairing temperature rise trend after air stop. A number of security measures are proposed, including adjustment of air conditioning interface inside baffle arrangement and fairing air conditioning connector launch program decoupling time and use of parallel air conditioning units. Special test has proven that the comprehensive
security measures taken are effective. During the actual operation, fairing environment security is good. After fairing air conditioning decoupling, the fairing temperature rise is within the required specification, ensuring on-time launch of Mars rover.

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