# Experimental Study of the Supersonic Exhaust Diffuser Spray Cooling System

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**ABSTRACT:** A supersonic exhaust diffuser provides the required test cell vacuum conditions by self-pumping of nozzle exhaust gases to the atmosphere in the high-altitude simulator. However, the plume temperature is often much higher than the allowable temperature of the diffuser structure. In the present study, a spray cooling system design method is presented for a supersonic exhaust diffuser. The method is evaluated by performing several experimental tests. First, in order to identify the critical temperature region, the test of the motor with a chamber pressure of 60 bar and a chamber temperature of 3100 °C is performed with a non-cooled metal diffuser. The results indicate that the temperature of the diffuser body in the inlet and ramp regions reaches a temperature above 1500 °C, which leads to the melting and perforation of the diffuser in these regions. Two other tests are performed with average motor chamber pressures of 33 bar and 55 bar along with the spray cooling of the diffuser body. The results show that the designed cooling system keeps the maximum temperatures of the external surface of the diffuser at the values smaller than 200 and 400 °C in these tests. The achieved critical temperatures are well-matched with the respected ones in the design procedure.

## 1. INTRODUCTION

Orbital transfer systems are employed to place spacecraft and satellites into specific orbits around Earth. The nozzles of the utilized propulsion system can perform optimally in the low-pressure conditions of high altitudes due to their large expansion ratio. When these nozzles are tested at ground level, their performance cannot be evaluated accurately owing to the separation of flow inside the nozzle. Consequently, the altitude test equipment is used for simulating vacuum condition around the nozzle [1, 2].

Altitude test equipment consists of various subsystems the most important of which is the supersonic exhaust diffuser. In practice, the nozzle exhaust combustion gases which flow inside the diffuser have a temperature above 2200°C. This renders the thermal protection of the diffuser body a challenging issue. Therefore, it is imperative to design and analyze a cooling system for altitude tests such that the high exhaust temperatures do not damage the diffuser body. Water spray cooling has numerous applications in diverse industries including satellites and their carriers, medical equipment, steel industries, and petrochemical industries. As reviewed by Liang and Mudawar [3, 4] in 2017, despite the extensive research carried out, there are still numerous researchers active in this field. This cooling method is a highly complicated phenomenon with different parameters affecting its performance.

Farahani et al. [5] in 2019 presented a design method for spray cooling system of a vacuum test stand diffuser. The goal of the present research is the experimental evaluation of this design method. In the following, after presenting the test equipment, the results of small-scale tests which performed using a laboratory motor has been presented. Conducting these tests and analyzing the corresponding results have enabled the accurate assessment of the cooling system performance.

## 2. EXPERIMENTAL SETUP

The test stand built for the small-scale tests of the motor and the diffuser is shown in Fig. 1. This test stand consists of the cooling system, the laboratory motor, the second throat diffuser, and the data acquisition system. This research has
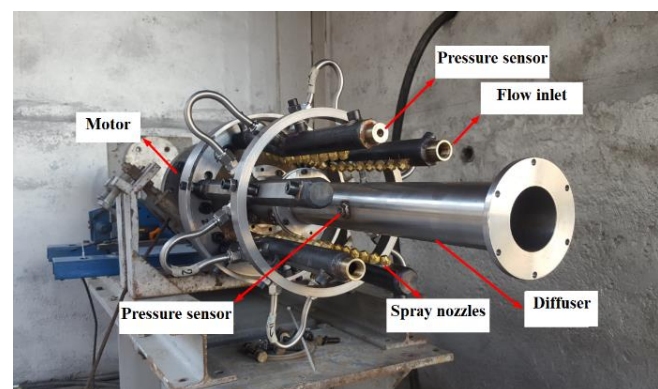
**Fig. 1. The test stand built for the small-scale tests**

used Kulite and Sensys pressure sensors in order to measure the pressure along the diffuser body and the motor chamber pressure, respectively. The diffuser made from stainless steel (SAE 309) with a thickness of 5 mm. The temperature of the external surface of the diffuser is measured at 6 points via a type K thermocouple. The water supply system is capable of providing water with pressures up to 20 bars. Spray nozzles from has been used for the cooling of inlet and convergent sections of the diffuser. Further details concerning the test equipment can be found in Ref. [6].

## 3. RESULTS AND DISCUSSION
### 3.1. The hot test without cooling the diffuser body

In the first stage of the research, the motor was tested in the vacuum test stand without cooling the diffuser body. This test has been conducted in order to evaluate the performance of the diffuser and determine its surface temperature. For this test, the motor was burned for 13 seconds at a pressure of 60 bar. The maximum surface temperature recorded by the thermocouples at various points of the diffuser is displayed in Fig. 2. As shown in this figure, the diffuser surface temperature at the inlet ramp is beyond the allowable limit of the metallic body. The investigations carried out at the metallography laboratory have indicated that the inner surface of the diffuser has reached a temperature above 1500°C in this test.

### 3.2. The first cooling test

The next test was carried out on the diffuser with spray cooling system. For this test, the motor was burned for 33 seconds at a chamber pressure of 33 bar. The goal of this test was to assess the performance of the cooling system.

The diffuser temperature was measured at 6 points on its surface. The locations of the temperature measurement point relative to the diffuser inlet plane are displayed in Fig. 3. The thermocouples measuring temperatures *T3* and *T4* were installed at 90-degree angles (φ=90°) relative to the other
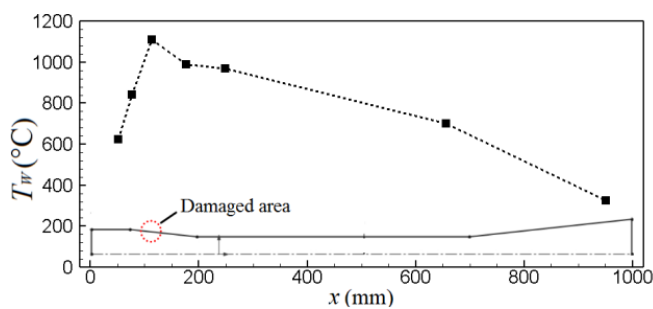
thermocouples. The diffuser inlet temperature at the first four points is shown in Fig. 4, and the temperature on the second throat at the two remaining points is shown in Fig. 5. The combustion pressure is shown in both figures for better comparison. According to these figures, the temperature of the external surface of the diffuser has not exceeded 200°C at any of these points.

### 3.3. The second cooling test

Subsequent to the first test, the second test was performed with an average combustion pressure of 55 bar. The temperature of the external surface of the diffuser for the inlet and ramp sections is shown in Fig. 6. As seen, the temperature has reached about 380°C at the inlet section. This value is in good agreement with the 400°C temperature predicted for the critical point during the design procedure. Moreover, the temperature has reached a steady-state in this test, which appears to be the result of the acceptable performance of the cooling system.

The maximum external surface temperature recorded at the most critical point was lower than 400°C. Using Fourier's law of heat conduction, we can prove that the maximum internal surface temperature of the diffuser has not exceeded 800°C. This is while the metal used in this research can withstand temperatures up to 1000°C. The post-testing observations have shown that the internal diffuser surface is completely undamaged. Therefore, the cooling system
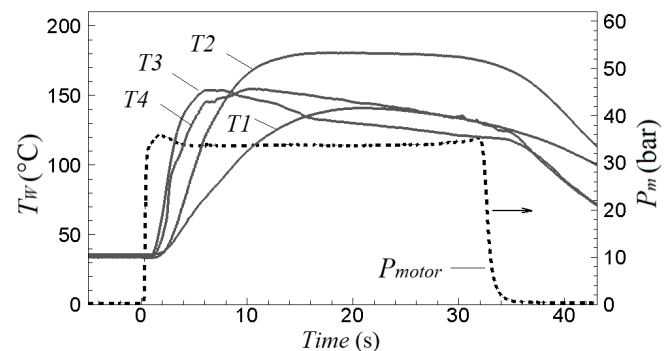
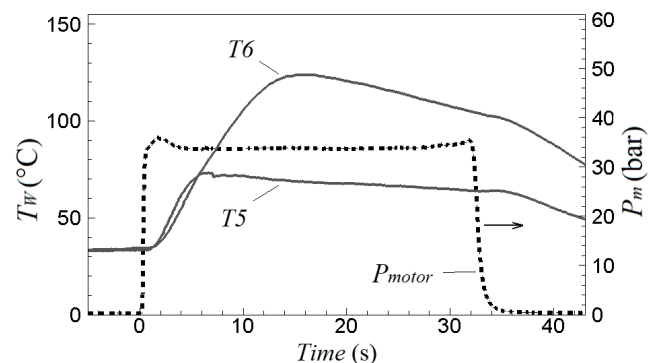**Fig. 4. Diffuser external surface temperature at the inlet ramp in the first test**

**Fig. 2. Maximum surface temperature along the diffuser**
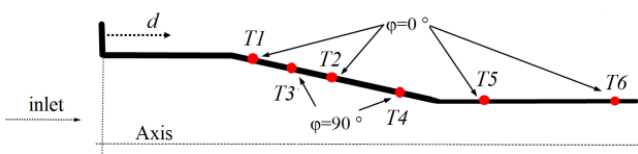
**Fig. 3. Thermocouple arrangement on the diffuser external surface**

**Fig. 5. Diffuser external surface temperature at the second throat in the first test**
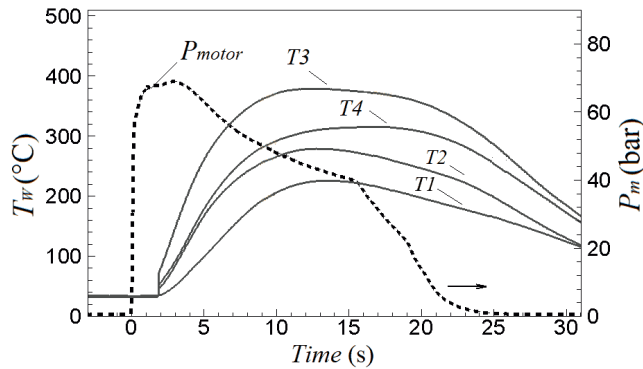
**Fig. 6. Diffuser external surface temperature at the inlet in the first test**

utilized in the present research is capable of protecting the metallic body of the diffuser up to a motor chamber pressure of 60 bar.

## 4. CONCLUSION

In the first stage, the test was conducted without a cooling system in order to identify the governing phenomena and the thermal behavior of the system. It was discovered that the temperature in the inlet and ramp sections of the diffuser were more critical than the other sections. A temperature above 1500°C was recorded in this section. Subsequently, two tests were conducted with motor chamber pressures of 33 and 55 bar with the cooling of the diffuser body. The temperature data and the post-testing inspection showed that the cooling system can protect the diffuser body and maintain its temperature at the safe value. The same diffuser body was used for both mentioned tests, and the highest temperature registered at the external surface of the diffuser was less than 400°C. In addition, the steady-state temperature at the critical point on the diffuser surface was in good agreement with the temperature expected from the designed system. Hence, these tests confirmed the adequate performance of the cooling system.

## REFERENCES

[1] K. Schäfer, H. Zimmermann, G. Kruhsel, Altitude simulation bench for VINCI Engine, In 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, (2003) p. 5043.

[2] R. Manikanda Kumaran, T. Sundararajan, D. Raja Manohar, Simulations of high altitude tests for large area ratio rocket motors, AIAA journal 51(2) (2012) 433-443.

[3] G. Liang, I. Mudawar, Review of spray cooling–Part 1: Single-phase and nucleate boiling regimes, and critical heat flux, International Journal of Heat and Mass Transfer, 115 (2017) 1174-1205.

[4] G. Liang, I. Mudawar, Review of spray cooling–Part 2: high temperature boiling regimes and quenching applications, International Journal of Heat and Mass Transfer 115 (2017) 1206-1222.

[5] M. Farahani, N. Fouladi, A.R. Mirbabaei, Design and analysis of a cooling system for a supersonic exhaust diffuser, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, (2019), in press. doi: 10.1177/0954410019840970.

[6] Propulsion research group, Thermal protection of diffuser metal body using a cooling system, Tehran, Space Transportation Research Institute, Report number: STRI-SSD9980-01-R, (2018) pp. 1-106.