Cryogenic test bench for the experimental investigation of cryogenic injection in rocket combustors under high-altitude conditions

Andreas Rees∗1, Michael Oschwald1,2
1 German Aerospace Center (DLR), Institute of Space Propulsion, Langer Grund, 74239 Hardthausen, Germany
2 RWTH Aachen University, Institute of Jet Propulsion and Turbomachinery, Templergraben 55, 52062 Aachen, Germany
E-mail: Andreas.Rees@dlr.de

Abstract. Due to current and future environmental and safety issues in space propulsion, typical propellants for upper stage or satellite rocket engines such as the toxic hydrazine are going to be replaced by green propellants like the combination of liquid oxygen and hydrogen or methane. The injection of that kind of cryogenic fluid into the vacuum atmosphere of space leads to a superheated state, which results in a sudden and eruptive atomization due to flash boiling. For a detailed experimental investigation of superheated cryogenic fluids the new cryogenic test bench M3.3 with a temperature controlled injection system at high-altitude conditions was built at DLR Lampoldshausen. First run-in tests as well as several measurement campaigns with liquid nitrogen as the test fluid showed the performance and suitability of the new test bench for the systematical investigation of cryogenic flash boiling. Besides new insights into the flash boiling process of cryogenic liquids, the experimental data of cryogenic flash boiling generated with this test bench provide a comprehensive database for the validation of numerical models and further numerical investigations.

1. Introduction
Technology development for propulsion systems of upper stages like the cryogenic Ariane 6 upper stage engine Vinci or for future cryogenic thrusters in reaction control or orbital and manoeuvering systems is driven by the invention of new, green propellants to substitute hydrazine, and by new ignition technologies like laser ignition. At high-altitude conditions prior to ignition the liquid propellants are injected into the combustor at near-vacuum conditions. This means that the ambient pressure $p_a$ is lower than the liquid’s saturation pressure $p_{sat}(T_{inj})$ at the injection temperature $T_{inj}$. The sudden pressure drop at injection leads to a superheated liquid in a metastable thermodynamic state. The injection of a liquid like that results in a fast expansion and eruptive evaporation, a process called flash boiling or flash evaporation. To know the composition of the propellants in the combustion chamber related to phase, species and temperature distribution is important for determining the parameters for a successful ignition and for avoiding destructive pressure peaks.

1.1. Flash Boiling
The dominating parameters for the flash boiling phenomenon in a given liquid are the injection temperature $T_{inj}$ and the back pressure $p_{ch}$ which can be a near-vacuum chamber pressure or atmospheric conditions. According to figure 1, they both define the dimensionless degree of superheat $R_p$ of the injected liquid in terms of the pressure ratio

$$R_p = \frac{p_{sat}(T_{inj})}{p_{ch}} \tag{1}$$
with the saturation pressure $p_{sat}(T_{inj})$ at the injection temperature $T_{inj}$ and the back pressure $p_{ch}$. A superheated liquid jet with a high degree of superheat is atomized close to or already in the injector nozzle due to vaporization and produces a fine spray with a big opening angle and small droplets. These non-equilibrium processes are quite complex and need experimental data for further modelling.

1.2. State of Research
Noteworthy studies about flash boiling processes can be found concerning the safety field in process technology or chemical and nuclear industry, where storable fluids like hydrocarbons, water, ethanol or refrigerants like R-134A were used [1, 2, 3]. In contrast to storable fluids, flash boiling of cryogenic liquids is much less investigated due to significantly harder experimental conditions, like e.g. the studies [4, 5, 6]. Especially adjusting and controlling the injection temperature in the range of 77–120 K was partly limited in the few studies with cryogenic flash boiling. This is why the new test bench M3.3 with a temperature-controlled injection system was built at DLR Lampoldshausen for a detailed experimental investigation of cryogenic flash boiling processes [7]-[12].

2. Requirements for Experimental Test Bench
Since the dominating parameters for flash boiling are the injection temperature $T_{inj}$ and the back pressure $p_{ch}$, it is important for an experimental investigation to make them adjustable, to keep them constant during the injection period and to make them reproducible. Besides controlling the temperature during the whole injection process, the injection pressure $p_{inj}$ as well as the back pressure $p_{ch}$ in the vacuum chamber have to be controlled and kept constant within the injection period. Furthermore, the injection conditions have to be measured as close as possible to the injector exit to provide defined boundary conditions for further analysis or numerical modelling. For spray visualization by different means of optical diagnostic techniques, the vacuum chamber needs appropriate accessibility.

3. Test Bench M3.3
The newly developed cryogenic test bench M3.3 at DLR Lampoldshausen consists of the four main systems: supply and pressurization system, the cryogenic temperature adjustment and injection system (CTAIS), the vacuum system and the data acquisition system (DAQ). The first three systems are depicted in figure 2 and are presented in more detail within this study whereas information about the DAQ system can be found in reference [12].

3.1. Supply and Pressurization System
The supply and pressurization system consists of the pressure station and a LN2 supply tank. Within the pressure station, the needed fluids gaseous nitrogen (GN2), helium and later on
Figure 2. Schematic illustration of the cryogenic test bench M3.3 with the three main systems supply and pressurization system, the cryogenic temperature adjustment and injection system (CTAIS) and the vacuum system.

gaseous oxygen (GOX) for the test bench operation are set to the desired pressures for the respective subsystems of the test bench and are distributed to these systems. The LN2 supply tank contains 641 l LN2 which is used for the chill-down of the test bench, for the temperature adjustment of the injection system and currently also as test fluid instead of LOX.

3.2. Cryogenic Temperature Adjustment and Injection System
The CTAIS consists of a double-walled and vacuum-insulated pressure tank filled with LN2 and GN2, see figure 3 (a) and (b). By an evacuation or pressurization of the GN2 phase in the pressure tank, the fluid is cooled down or heated up, respectively. In the first case a new saturation state is reached due to vaporization of a certain amount of LN2. The latent heat of vaporization necessary for this phase change leads to a loss of heat of the liquid/gaseous nitrogen and consequently to a temperature decrease. In the second case, the saturation state after pressurization with GN2 is reached due to condensation of the vapor phase. In this process, the latent heat of condensation is released and heats up the nitrogen. Inside the pressure tank is the complete LN2/LOX feed and injection system, which consists of a 0.5 L LN2/LOX run tank, a mass flowmeter, the injector unit with a pneumatic run valve and the injector nozzle, and piping in-between, see figure 3 (c) and (d). That means that all these sub-systems are completely surrounded by the cooling medium nitrogen to provide a homogeneous temperature distribution from the run-tank to the injector nozzle. Several dynamic pressure and temperature sensors are installed at the nitrogen pressure tank as well as at the feed and injection system, in order to both control and adjust the temperature of the cooling medium and to measure the injection parameters of the jets. The latter is realized by a Pt100A temperature sensor and a dynamic pressure sensor 601A by Kistler each installed about 30 mm upstream of the injector nozzle exit. A hand hole at the top of the pressure tank provides the feedthroughs for the sensors and the supply pipes for LN2, GN2 and helium. The latter is used to pressurize the pneumatic axial run valve (Axius by Stöhr Armaturen) as well as the cable ducts for the sensor cables inside the pressure tank. The CTAIS allows variable injection conditions listed in table 1.
Figure 3. CAD model of closed (a) and open CTAIS (b), exploded-view drawing (c) and photo of open CTAIS (d) of test bench M3.3.

Table 1. Possible injection conditions of the CTAIS at test bench M3.3.

| parameter          | range | unit   |
|--------------------|-------|--------|
| injection temperature $T_{\text{inj}}$ | 77–100 K |
| injection pressure $p_{\text{inj}}$       | 1–20 $10^5$ Pa |
| back pressure $p_{\text{ch}}$            | 30–3000 $10^2$ Pa |
| injector diameter $D_{\text{inj}}$       | 1–2 $10^{-3}$ m |
| mass flow $\dot{m}$                      | 0.08–50 g/s   |

3.3. Vacuum System

Below the CTAIS, the vacuum system can be found which is a cylindrical chamber with an inner diameter of 300 mm, a height of 225 mm from the injector nozzle exit to the bottom of the chamber and four optical accesses with a diameter of 100 mm each. The four windows are positioned with an angle of 90° to each other. In order to prevent icing of the windows due to condensation and freezing of the humidity of the ambient atmosphere, we are running an external window heating system with warm GN2 during the test bench operation. Its copper pipes can be seen at the bottom of the optical access on the right-hand side of figure 4. An attached vacuum pump with a pumping speed of 87.5 m$^3$/h produces the near-vacuum atmosphere to simulate high-altitude conditions.

4. Diagnostics

Besides several temperature and pressure sensors as well as a mass flow sensor, optical measurement techniques like high-speed shadowgraphy or laser-based Phase Doppler anemometry (PDA) can be used at the test bench M3.3 for spray visualization. For further details about these diagnostics, there set-ups and the resulting data we refer to our studies [7]–[12].
5. Results

In the following subsections some results in terms of the general performance of the test bench M3.3 are presented.

5.1. Functional Test Main Valve

Before the first complete chill-down of the test bench was performed, we did a functional test of the axial run valve with an opened CTAIS as depicted in figure 5. We filled the bottom part of the CTAIS with LN2 which surrounded the main valve entirely and chilled it down to a temperature of 77 K. After several opening and closing procedures we filled the run tank with GN2 at a pressure of $6 \times 10^5$ Pa. This pressure level stayed constant over a period of 30 minutes which proves the tightness of the run valve under cryogenic conditions.

5.2. High-Altitude Conditions

The pressure profiles in figure 6 show the pressure behavior in the vacuum chamber. A low pressure level of, e.g., $p_{ch} = 50 \times 10^2$ Pa stays approximately constant for about 200–220 ms after the start of the injection at an injection pressure of $p_{inj} = 8 \times 10^5$ Pa. After this period of steady-state the pressure increases slowly due to a higher mass flow of the injected test fluid compared to the evacuation rate of the used vacuum pump. With the help of an additional vacuum buffer tank with a volume of about 1.5 m$^3$ the period of steady-state conditions could be extended. This tank is available but was not tested so far within the vacuum system of the test bench M3.3.
5.3. Liquification and Pre-Cooling

The first chill-down operations of the test bench showed that the cooling capacity of the CTAIS is sufficient to cool down the warm helium needed for the pneumatic run valve without influencing the temperature distribution in the CTAIS. Otherwise, the LN2 temperature profiles at the five measuring points of the LN2 pressure tank in figure 7 would not be that constant over a test duration of $t_{\text{test}} = 4 \text{s}$. Furthermore, we learned that the CTAIS is able to liquify the test fluid within the run tank in about seven minutes. This means, the test bench allows a test run frequency of roughly once every ten minutes.

5.4. Chill-Down

Before each single chill-down of the CTAIS, several evacuation procedures are performed to get rid of any humidity in the system. At the beginning, the system was chilled down from room temperature to a target temperature of $T_{\text{inj}} = 90 \text{ K}$ in about five hours. To increase the duration for the actual test activities at a typical test day we modified the system slightly, as can be seen in figure 8 with the original CTAIS on the left-hand and the modified one at the right-hand side: We insulate the lower part of the pressure tank casing with Armaflex LTD foam to reduce the heat transfer, especially at the critical position around the massive bottom flange. Furthermore, we shield the bottom of that flange from the warm nitrogen flow of the window heating with temperatures of about 340 K by attaching large metal pipes around the windows. The third and most effective measure, however, is a change of the chill-down procedure itself in terms of increasing the feed pressure in the LN2 supply tank from $2 \times 10^5 \text{ Pa}$ to $4 \times 10^5 \text{ Pa}$. As a consequence, we reduce the chill-down time to the respective temperature to roughly 90 minutes as can be seen in figure 9.

5.5. Temperature Distribution in Feed Line

In figure 10 the temperature profiles of four different vertical positions in the run tank are shown. Obviously, all four profiles have a very constant trend and differ only little from each other during a time of 4 s. Hence, the temperature distribution of the test fluid in the run tank
Figure 8. Test bench M3.3 in operation mode before (left) and after (right) some minor modifications.

Figure 9. Chill-down rate to a target temperature of 90 K in the run tank of the modified CTAIS.

Figure 10. Temperature profiles in the run tank during a typical test run with the test fluid LN2.

Figure 11. Injection temperature $T_{\text{inj}}$ during a typical test run with the test fluid LN2.

is homogeneous with no thermal stratification. Figure 11 contains the profile of the injection temperature $T_{\text{inj}}$ over an extended test run duration of 4s. It can be seen that the injection temperature is at the same level as the temperature in the run tank and that it stays constant until close to the end of the injection event at about 3s. The subsequent temperature decay is caused by the closing process of the run valve which is initiated by the control sequence of the test bench 2s after the start of the injection. Consequently, the CTAIS is capable of keeping the injection temperature $T_{\text{inj}}$ constant during the whole injection time.
6. Conclusions
For a detailed experimental investigation of the flash boiling process of cryogenic liquids we developed the new test bench M3.3 with a cryogenic temperature adjustment and injection system which is in successful operation at DLR Lampoldshausen. This system is able to keep the injection temperature constant over the test run duration with a homogeneous temperature distribution in the whole test fluid line. We generated more than 400 LN2 sprays with this test bench so far. The limiting factor of a short steady-state period in terms of the back pressure in the vacuum chamber could be weakened by the usage of an additional vacuum buffer tank. With some minor modifications concerning oxygen safety the test bench is going to be operated with the actual rocket propellant LOX as test fluid in mid-term future.

7. References
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