The Morphology of Flash Boiling LN2 Sprays in High-Altitude Liquid Rocket Engines

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Abstract

This poster presents cryogenic flash boiling for high altitude conditions in liquid rocket engines. A new cryogenic test bench was built for investigating the flash boiling phenomenon of LN2 (liquid nitrogen) and later of the actual propellant LOX (liquid oxygen). With the temperature adjustment and injection system of that test bench variable injection temperatures and variable back pressures can be achieved. Those are the dominating parameters for flash boiling. The resulting sprays are visualized by means of high-speed shadowgraphy to investigate the characteristics and morphology of flash-atomizing LN2/LOX jets in dependence on the two injection parameters.

Introduction

Technology development for propulsion systems of upper stages like the cryogenic ESC-A engine HM-7B or the future Ariane 6 upper stage engine Vinci and for reaction control thrusters is driven by the invention of new 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. Due to the sudden pressure drop at injection the liquid is in a superheated thermodynamic state resulting in an eruptive evaporation, also called flashing boiling or flash evaporation. The evaporating gases raise the pressure inside the combustion chamber until the equivalence pressure shortly before ignition is reached. To know the composition related to phase, species and temperature distribution is important for both to determine the probability of a successful ignition and to avoid destructive pressure peaks.

The dominating parameters for the flash-evaporation phenomenon are the injection temperature and the back pressure. They both define the degree of superheat R_p or ΔT^* of the injected liquid, see figure 1:

$$R_\mathrm{p} = \frac{p_\mathrm{sat}(T_\mathrm{inj})}{p_\mathrm{c}}$$

$$\Delta T^* = \frac{T_\mathrm{inj} - T_\mathrm{sat}(p_\mathrm{c})}{T_\mathrm{sat}(p_\mathrm{inj}) - T_\mathrm{sat}(p_\mathrm{c})}$$

Further dimensionless numbers like the Weber number $\mathrm{We} = \frac{\rho_g u^2 d}{\sigma}$ and the Jakob number $\mathrm{Ja} = \frac{\rho_l c_{pl} \Delta T}{\rho_g h_\mathrm{vap}}$ can be used to determine the three regimes aerodynamical break-up, transition to flash boiling and fully flashing according to correlations developed in [1].

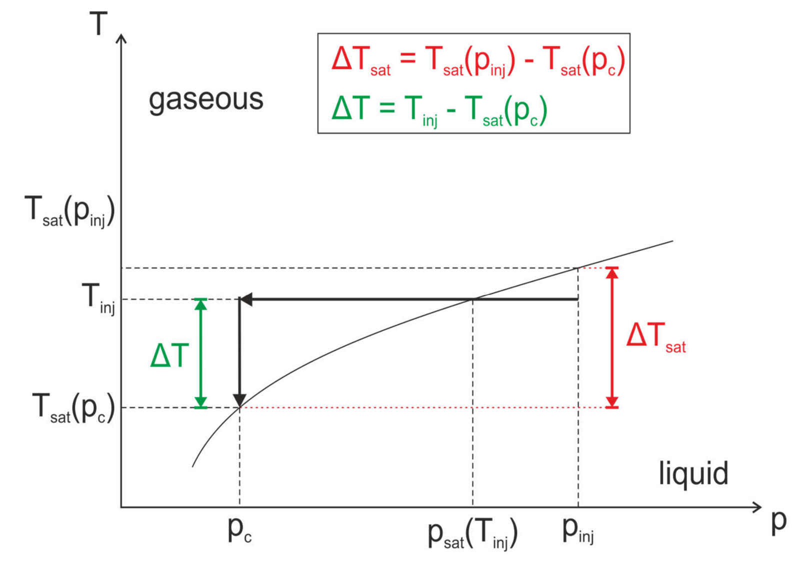


Figure 1. Definition of the degree of superheat.

Methods and Materials

The newly designed cryogenic test bench allows variable injection temperatures in the range of 70-120 K. It consists of three main systems: the supply and pressurization system, the cryogenic temperature adjustment and injection system and the vacuum system, as depicted in figure 2.

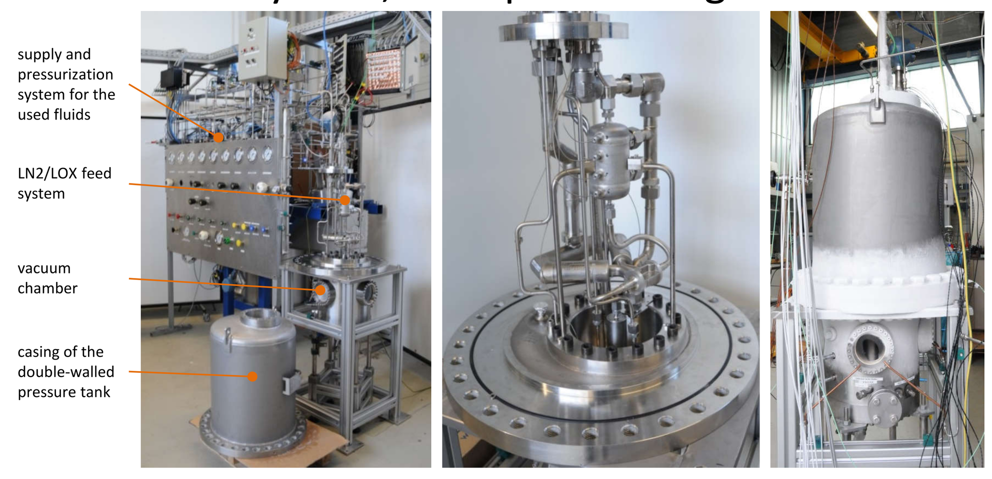


Figure 2. Cryogenic flash boiling test bench with main systems

In the second of the three systems mentioned above the temperature regulation is realized by a pressurized LN2/GN2 (gaseous nitrogen) tank surrounding the actual injection system. By evacuation or pressurization the GN2 phase in the pressure tank the fluid is cooled down or heated up, respectively. Inside this pressure tank is the complete LN2/LOX feed and injection system, which is a 0,5 l LN2/LOX run-tank, a mass flowmeter, a pneumatic run valve, the injector nozzle and piping in-between. That means that all these sub-systems are completely surrounded by the cooling medium nitrogen to provide a homogenous temperature distribution from the LOX run-tank to the injector nozzle, see figure 3.

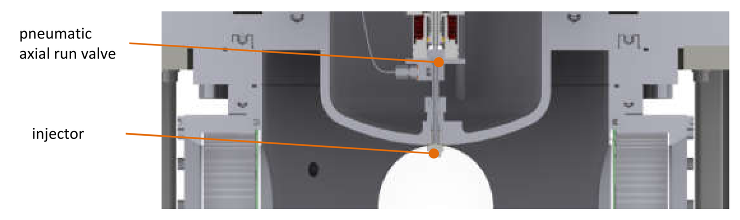


Figure 3. Injector position (CAD section)

Via two of the four windows in the vacuum chamber the sprays are visualized by high-speed shadowgraphy (Fastcam SA-X).

Results and Discussion

The evolution of the spray morphology with increasing degree of superheat R_p by variation of the back pressure p_c from 36 to 600 mbar at a constant injection temperature T_{inj} = 82,5 K (±0,6 K) and injection pressure p_{inj} = 4 bar (±0,2 bar) is shown for the injection of LN2 in figure 4. Each shadowgraph image was made 100 ms after start of the injection. The sprays with lower values of R_p show typical features of an aerodynamical break-up like long liquid cores in the spray center line, small opening angles and large liquid filaments. For increasing values of R_p the LN2 sprays become wider and more turbulent flow structures can be observed until the flash boiling process dominates the jet break-up for a degree of superheat R_p > 12.

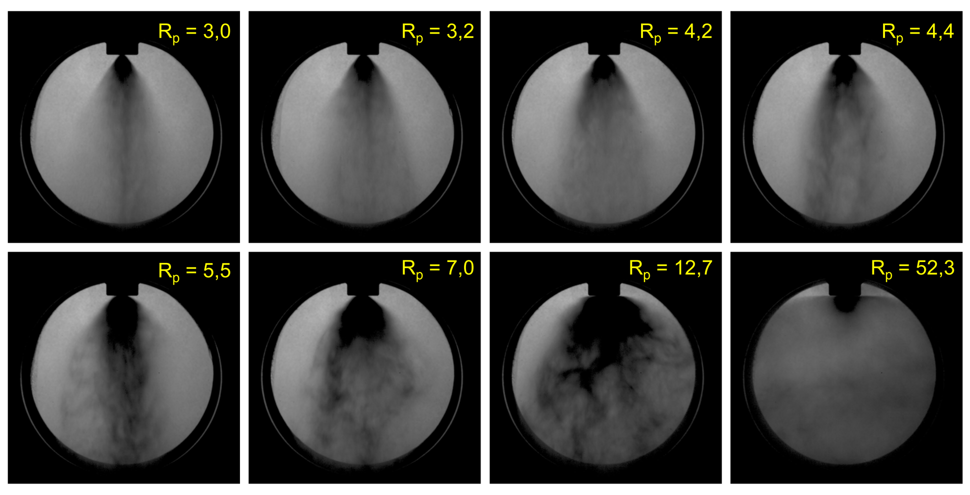


Figure 4. LN2 sprays at different degrees of superheat R_p at T_{inj} = 82,5 K, D_{inj} = 1,0 mm and p_{inj} = 4 bar

In these fully flashing sprays the remaining liquid core is quite small and exists only at the injector outlet while the remaining liquid structures are monodisperse droplet systems.

In figure 5 the influence of the injection pressure is shown, which was increased to p_{inj} = 8 bar (±0,3 bar) for the same injection temperature, injector geometry and back pressure range.

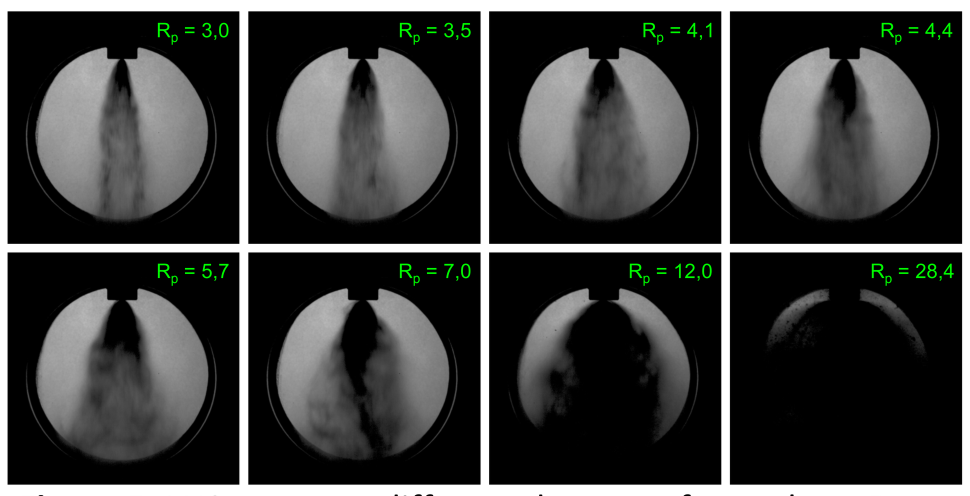
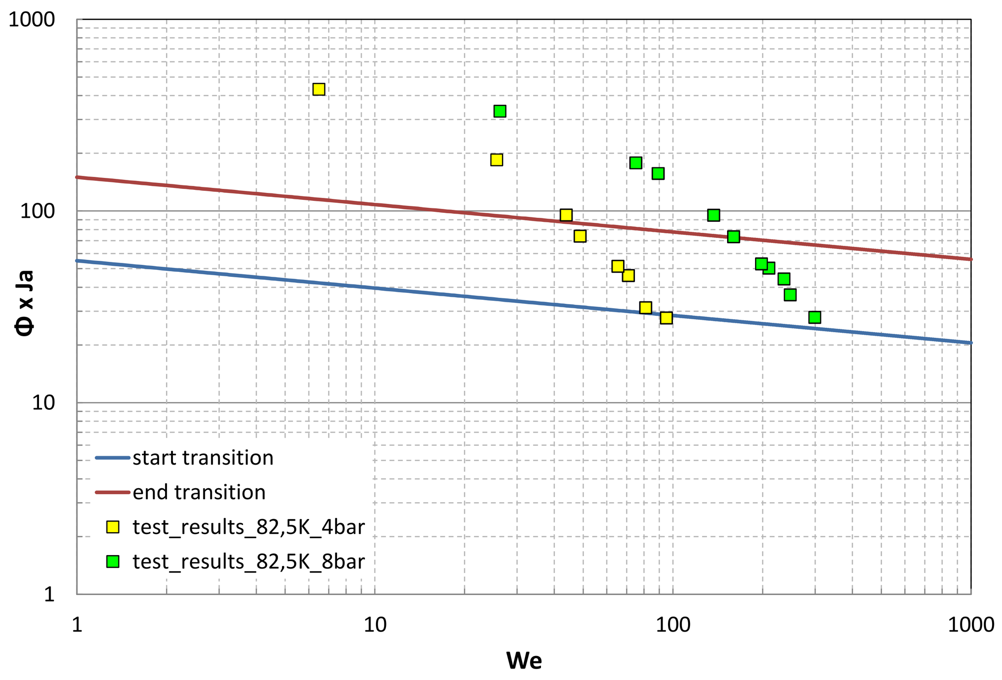


Figure 5. LN2 sprays at different degrees of superheat R_p at T_{inj} = 82,5 K, D_{inj} = 1,0 mm and p_{inj} = 8 bar

The opening angles of the resulting sprays are much smaller and larger liquid structures can be seen in the sprays compared to figure 4. For similar degrees of superheat R_p the influence of the flash boiling process onto the spray pattern seems to be smaller for the higher injection pressure.

All of the shown test cases fit into the transition correlations developed for storable fluids like water and ethanol [1] , see figure 6 (factor Φ describes the density ratio between liquid and gaseous phase, see [1] for exact definition).



Conclusions

With the temperature adjustment and injection system of the new cryogenic test bench LN2 sprays with a constant injection temperature T_{inj} and varying back pressures p_c can be produced. Decreasing the back pressure causes an increase of the degree of superheat R_p and changes the atomization process of the LN2 sprays from an aerodynamical mode into a fully flashing mode. Despite the difference in their physical properties all of the cryogenic LN2 sprays fit into transition correlations [1] developed for storable fluids. Increasing the injection pressure p_{inj} leads to a less dominant flash boiling process with narrower sprays at similar degrees of superheat R_p. That means this definition of the degree of superheat is not sufficient for a clear characterization of the resulting spray patterns. Apart from an exact determination of the spray angles droplet size and velocity measurements will be performed by means of phase doppler anemometry (PDA). Finally a test campaign with LOX is planned.

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References

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