Operational Conditions of P4.1 Altitude Simulation for VINCI® Upper Stage Engine

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Since February 2005 the new high altitude simulation test facility P4.1 for the VINCI ® upper stage engine is operational in Lampoldshausen, the European test centre for rocket propulsion. VINCI® is an expander cycle upper stage engine of 180 kN thrust developed by SNECMA Moteurs. The paper deals with the operational conditions of the altitude simulation especially the behavior of the super sonic center body diffuser. High nozzle expansion ratios, different test configurations and the re-ignition conditions drive the challenges of the high altitude simulation P4.1.

I. Introduction

FROM the very beginning in the 1960s, the DLR in Lampoldshausen has been involved in all European launcher programs and one of its special tasks has always been testing of rocket engines especially in space environmental conditions. The need to develop, qualify and accept propulsion systems under actual flight conditions in high altitude with fully expanded nozzle defines the essential operational criteria for the test facilities.

SNECMA is demonstrating a new Expander-Cycle-Technology with the rocket engine called VINCI®. For the VINCI® engine tests the test bench P4.1 (Figure 1) was adapted by a new altitude simulation. The P4.1 starts with test operation in 2005.

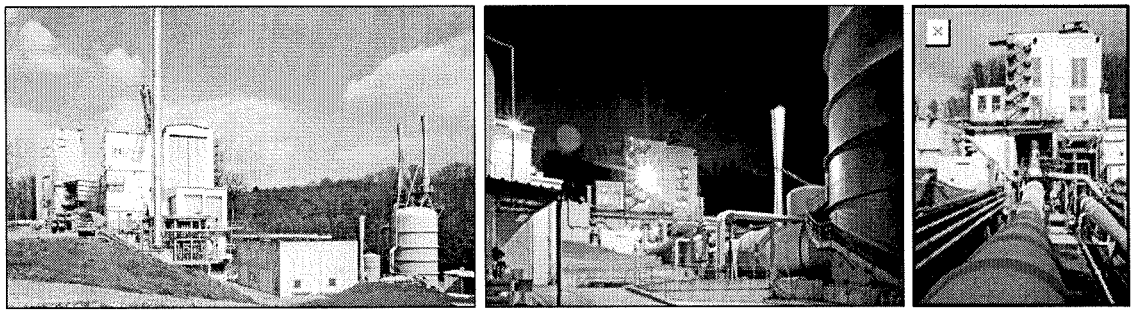

Figure 1: High Altitude Simulation P4.1

The task of altitude simulation consists of creating the test condition within a vacuum cell. This is primarily low ambient pressure of just few mbar. Special operational conditions are linked to the transients during Start-Up and Shut-Down of the engine with respect to the nozzle loads. Maintenance of the vacuum with running engine is

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achieved by using the energy of the exhaust jet. The supersonic gas flow is decelerated and compressed by a diffuser. Additional extraction of the exhaust gas by steam jet ejectors and condensation maintains the necessary pressure conditions. To provide the large quantities of steam, rocket steam generators with liquid Oxygen and Alcohol are used. The principle of rocket steam generators is to inject water into the hot gases of a rocket combustion chamber and to evaporate the water in a mixture chamber.

Using the test results the operational behavior especially of the super sonic center body diffuser is investigated. The objective is to verify the static and dynamic operational behavior of the system and to predict precisely the test conditions with respect to the test request and test configurations.

II. Test Requirements

The VINCI® engine with 180 kN thrust is tested in 3 test configurations, the combustion chamber up to expansion ration of ε= 22,3 (Figure 3), the chamber with fix nozzle up to ε= 93 (Figure 2) and the complete engine with the extendable nozzle up to ε= 243.

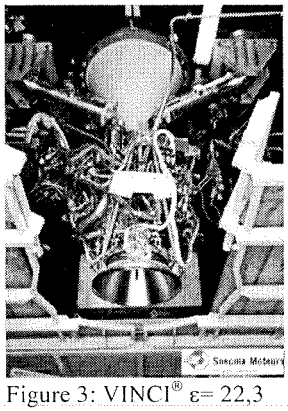


Figure 3: VINCI® ε= 22,3
In vacuum chamber P4.1

The required P4.1 test conditions are:

- Vertical test position with maximum test time of 770 s.
- Pressure at engine interfaces during chill down p < 200 mbar.
- Ignition at ambient pressure p < 60 mbar.
- Start up phase with simulation of in-flight engine start up conditions.
- Steady state phase with the operational envelope in vacuum conditions.
- Shut down phase with transients considering the maximum nozzle loads.
- Ballistic phase and re-ignition in vacuum conditions.

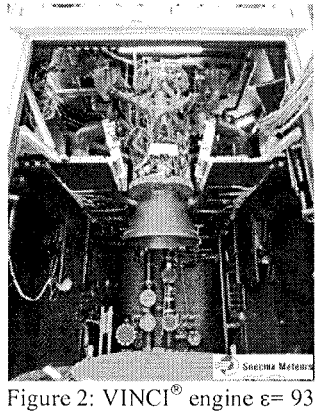


Figure 2: VINCI® engine ε= 93
In vacuum chamber P4.1

III. High Altitude Simulation Test Facility

The basic design of the altitude simulation P4.1 (Figure 4) includes the VINCI® engine inside a vacuum chamber, a center body diffuser, a two stage ejector system and a condenser between the ejectors stages.

Chill down ejectors maintains the vacuum at the engine interfaces during the pre cooling phase.

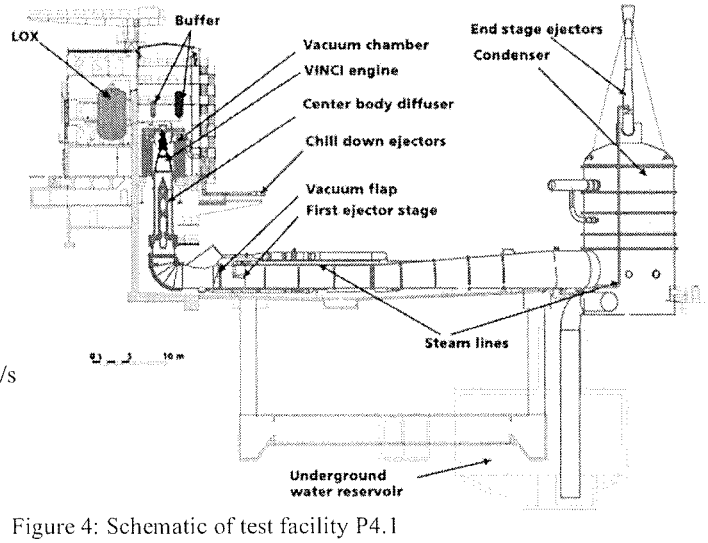


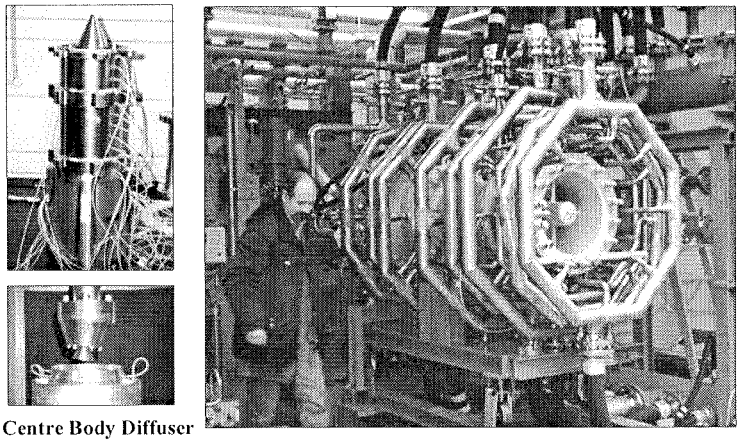
Figure 4: Schematic of test facility P4.1

Main parameters are:
Vacuum chamber: ∅ = 5 m / h = 6,2 m
Diffuser: ∅ = 2,38 m / l = 10 m
Cooling Water: 2,0 m³/s
First Ejector Stage: Steam: 2 x 55 kg/s
Condenser: Water: 3,6 m³/s / 10°C
Second Ejector Stage: Steam: 2 x 59 kg/s
Chill down Ejectors: Steam: 2 x 8 kg/s
Steam generation plant: 600 MW power

Special developments were done concerning:

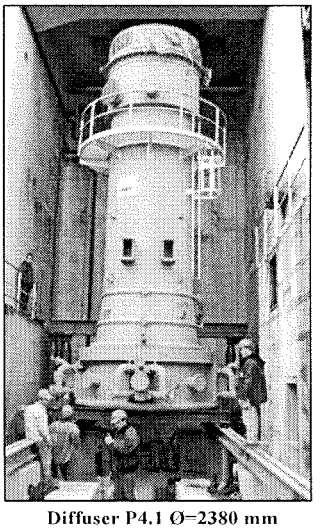
1. Centre Body Diffuser:

Due to the dimensions of the nozzle a center body diffuser were developed for the existing P4.1 test position. The centre body diffuser has a similar behavior like a second throat diffuser. The second throat is realized by a ring channel around a centre body. The length-to-diameter ratio of the diffuser is optimized to the diffuser efficiency and the intensively cooling. After Start of the supersonic flow the operation is stable down to lower pressures ratios (Hysteresis). Main design parameters are the characteristics of the engine, the extendable nozzle geometry and the suction system.



Centre Body Diffuser Cold Gas Model Ø = 130 mm ⇒ Scale 1:18

Centre Body Diffuser Hot Gas Model; Ø = 300 mm ⇒ Scale1:8



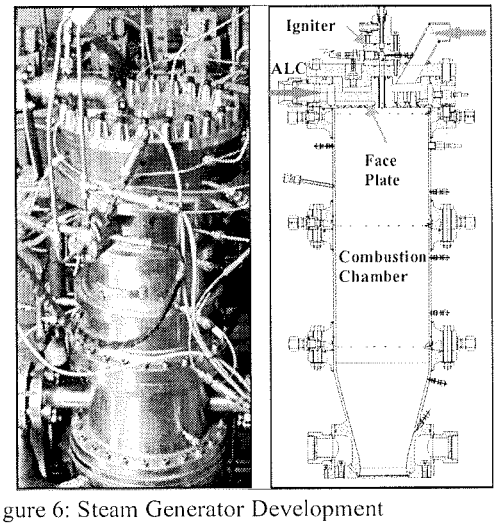
Diffuser P4.1 Ø=2380 mm

Figure 5: Development of the center body diffuser P4.1

2. Suction system:

The main parameters for the suction system were linked to the transient pressure conditions during Start-Up and Shut-Down of the engine. The trade-off was between powerful ejector system with high steam consumption for fast transients and a big condenser with high cooling water flow.

The development of the steam generator units for P4.1 (Figure 6), the cooling water supply and the maximum nozzle loads were the main drivers for the design of the suction system.



Development Focuses		
Focus	**Subject**	**Investigations**
HF stability	**Triggering**	**Bombing**
	Quarter wave tubes	**HF transducer inside cavity**
	Baffles	**HF transducer near faceplate**
Ignition	**Ignition shock**	**Vibration transducer at injector plate**
	Start Up conditions	**Water spray tests with high speed camera**
Wall cooling	**Wall temperature**	**Infrared camera**

Figure 6: Steam Generator Development

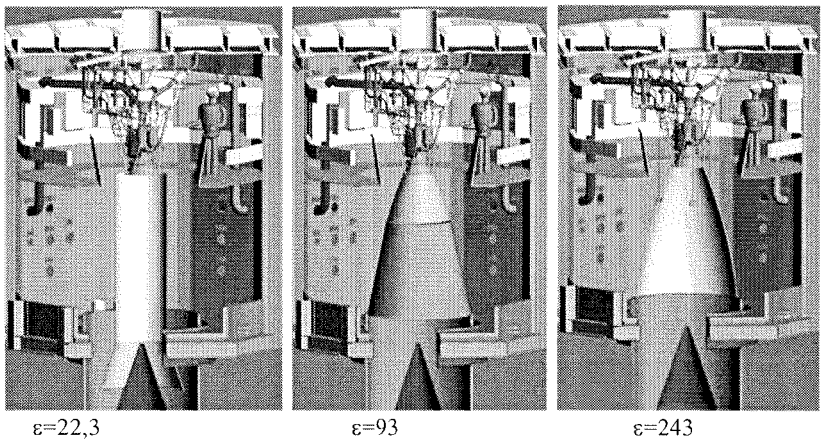
3. Modular System for the different test configurations:

Different adapters are used to test the VINCI® configurations (Figure 7).

The adapter for the ε = 22,3 configuration with the combustion chamber is designed like a tube diffuser. The centre body diffuser itself guides the exhaust gases to the first ejector stage.

The adapter for the ε = 93 configuration with the fix nozzle replace the extendable nozzle. The function of the altitude simulation is similar to the complete engine tests with the extendable nozzle.

The center body diffuser is designed to test the extendable nozzle.



ε=22,3 ε=93 ε=243

Figure 7: Test Configurations VINCI

IV. Operational Conditions

A. Test Phases:

There are different test phases with special operational conditions:

1. Test Preparation

During the test preparation the vacuum flap is closed and the vacuum chamber is evacuated by mechanical pumps.

2. Chill Down Phase

The chill down is performed at low ambient pressure. To maintain the vacuum < 200 mbar at the engine interfaces LH2 and LOX is extracted by steam ejectors. Conditioning systems and emergency purging prevents icing and the back flow of steam and air during operation and in case of emergency shut down of the ejectors.

3. Ignition

To maintain the conditions during ignition at low ambient pressure < 60 mbar the system is pre evacuated and the exhaust is extracted by the ejector system.

4. Start Up

During the transient start up phase the ambient conditions of the engine has to maintain:

- Sonic condition in the throat of the combustion chamber for the simulation of the chamber pressure gradient,
- Full flowing expansion part (chamber, fix nozzle, expandable nozzle) for the heat loads, pressure gradients and the verification of side loads.

During start up of the engine the super sonic flow of the diffuser starts. The starting of the diffuser depends of the VINCI® combustion chamber pressure gradient and the characteristic of the altitude simulation. The transient behaviour of the supersonic diffuser (START conditions) is essential parameters of the design. The smooth pressure evolution of the vacuum chamber during start up is supported by the reaction time to reach steady state conditions.

5. Steady State

For the altitude simulation there is a constant supersonic flow of the diffuser for all operational points of the engine. Another objective is the thermal balance of the engine. Heat is only emitted due to radiation. Part of the engine like the radiative cooled nozzle will be tested at maximum temperature reaching material limits. Important aspects include the simulation of environmental conditions for nozzle loads and the heat protection of sensitive parts. Additionally the gimballing has to be respected.

During the test campaigns the internal flow inside the vacuum chamber becoming more and more important. To verify the impact of the internal flow conditions CFD calculations with CFX were performed and adjusted by the test results.

6. Shut Down

Main objectives of the shut down conditions are the prevention of back flow of hot gases to the vacuum cell and the reduction of nozzle loads.

The nozzle loads occur by flow separation inside the nozzle and back flow of hot gases. The UN-Start conditions of the diffuser, the pressure gradients of the combustion chamber and suction system and at the nozzle flow conditions are essential parameters of the shut down.

For the verification of the shut down conditions CFD calculations with CFX were performed and adjusted by the test results.

7. Ballistic Phase and Re-ignition

The vacuum conditions during shut down, stand by phases and re-ignition have to be maintained to simulate the mission requirements of the ballistic phases and firing phases. The altitude simulation with running steam generators and ejectors is needed for the hot run; the vacuum of the ballistic phase is maintained by mechanical pumps. Re-ignition of the steam generators is one of the necessary functions for the simulation.

B. CFD- Calculations, Steady State

1. Test Configuration $\varepsilon = 22{,}3$ (combustion chamber and adapter):

The CFD calculation shows internal vortexes (Figure 10) inside the vacuum chamber triggered by the free jet between nozzle and adapter (Figure 9). The vortexes are influenced by the gap between nozzle and diffuser. The diffuser is designed for gimballing including an increased diameter. The impact of the jet to the wall of the diffuser is given by increased angel. This influences the pressure level (Figure 8). Actual the configuration will be optimized.

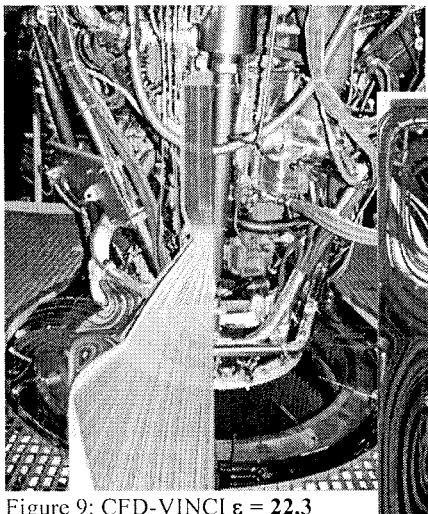


Figure 9: CFD-VINCI ε = **22,3**

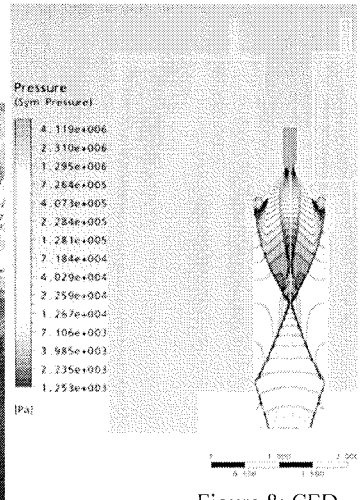


Figure 8: CFD – Pressure Level VINCI ε = **22,3**

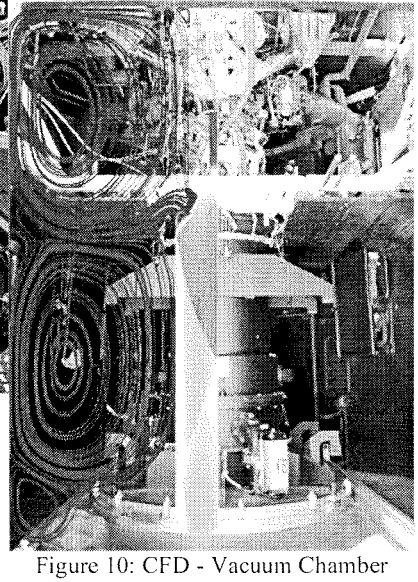


Figure 10: CFD - Vacuum Chamber VINCI ε = **22,3**

2. Test Configuration ε = 93 (combustion chamber, fix nozzle and adapter):

With the test configuration ε = 93 the center body diffuser and the adapter is in super sonic conditions. The CFD calculations were done to verify the flow conditions (Figure 11) and the heat loads (Figure 12) for the adapter and center body diffuser.

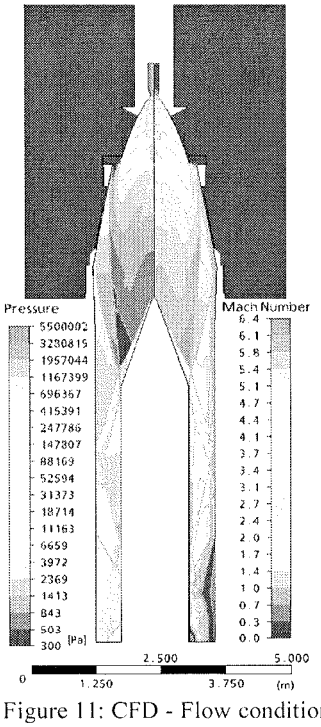


Figure 11: CFD - Flow conditions VINCI ε = 93

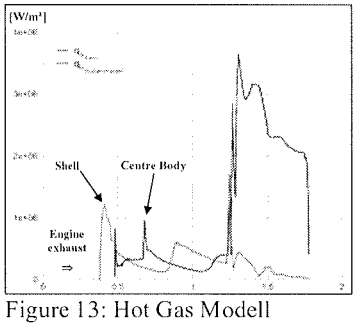


Figure 13: Hot Gas Modell

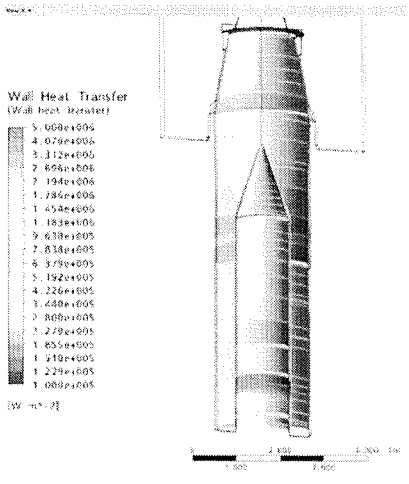


Figure 12: CFD-Heat Loads VINCI ε = 93

There is increasing heat loads (up to 5 MW/m²) compared to the CFD calculation of the hot gas model (Figure 13 up to 3,8 MW/m²). This phenomenon was already visible during the hot gas model tests. The CFD has to be adapted to the measured values of wall temperature and cooling water heating. Without adaptation to measurements the heat loads are under predicted.

3. Test Configuration ε = 243 (combustion chamber and extendable nozzle):

The CFD calculations for the extendable nozzle were done to predict the nozzle loads and the behavior of the center body diffuser. Actual the extendable nozzle is not tested. The flow conditions for the vacuum chamber (Figure 15) and the diffuser (Figure 14) were verified.

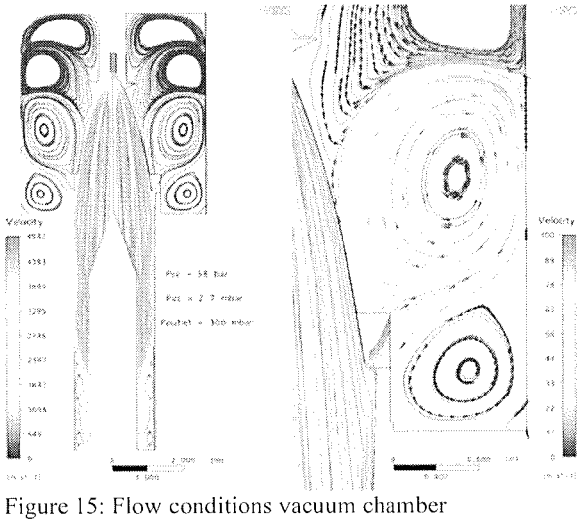


Figure 15: Flow conditions vacuum chamber VINCI ε = 243

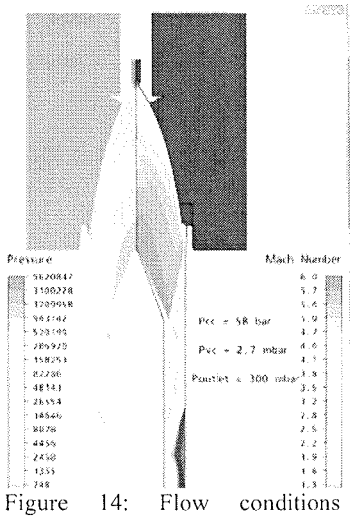


Figure 14: Flow conditions diffuser VINCI ε = 243

4. *CFD- Calculations Steady State, Shut Down*

To verify the shut down transients CFD calculations were performed for the test configuration $\varepsilon = 93$ (thrust chamber and fix nozzle). With decreasing combustion chamber pressure the super sonic flow field moves upwards to the conical adapter (Figure 16 picture 1 – 4). When the super sonic flow field arrives the inlet of the adapter (Figure 16 picture 5) backflow occurs and the ambient pressure increases. With higher ambient pressure the supersonic flow starts again (Figure 16 picture 7). Furthermore of decreasing the chamber pressure the super sonic flow field moves from the adapter to the nozzle (Figure 17 picture 7 – 8). It becomes flow separation inside the nozzle. Possible side loads has to be respected. Furthermore decreasing of the chamber pressure the super sonic flow field moves to the chamber throat (Figure 17 picture 8 – 10).

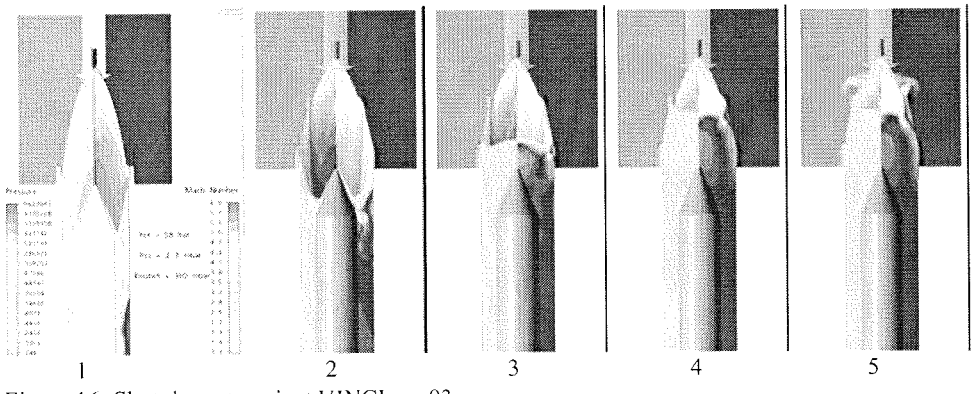


Figure 16: Shut down transient VINCI $\varepsilon = 93$

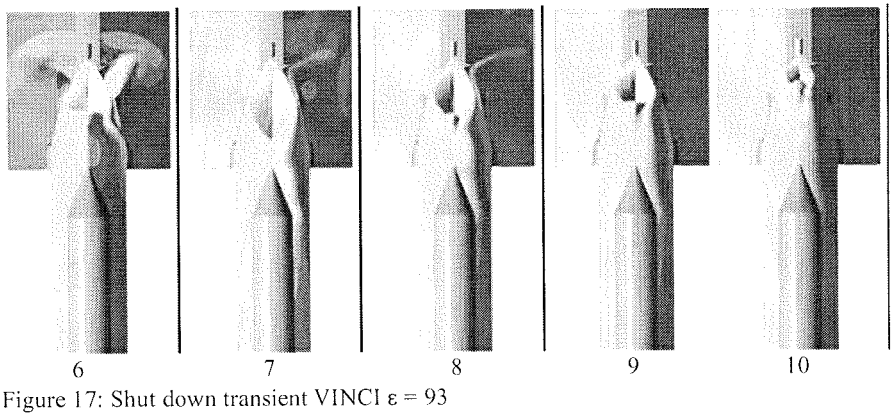


Figure 17: Shut down transient VINCI $\varepsilon = 93$

Conclusion

The reception of altitude simulation P4.1 with the VINCI® engine is successful performed. All the calculated parameters were reached within the expected limits. Nevertheless the ongoing testing of the VINCI® engine gives the chance to improve the understanding and to optimize the behavior of the test bench. The objective is to improve the operational model and to predict the test conditions precisely according the test requests. Additionally there is a need of ongoing improvement of the systems for the test conditions and the test operation.

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