Experimental investigation and numerical simulation of heat transfer at walls in supersonic flows with induced condensation phenomena

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Abstract

Accurate prediction of wall heat transfer in thrust chambers is a major challenge for rocket engine designers. For actively cooled combustors, heat transfer computation can be even more complex when local saturation/solidification conditions are achieved on hot gas side by wall overcooling, inducing vapour condensation or even icing. A dedicated cold gas subscale 2D nozzle has been designed to gather an experimental database for condensation modelling validation, including quantitative evaluation of condensation influence on local wall heat transfer by accurate flush-mounted wall temperature sensors. The first two test campaigns provided test-cases currently being simulated by CPS CFD code.

1. Introduction

Generally speaking, H_2/O_2 expander cycle engines are particularly subject to condensation phenomena, because for such an engine cycle, the objective of maximization of heat extraction from thrust chamber regenerative circuit can lead to very low thrust chamber wall temperatures. The existence of thermodynamic conditions promoting water vapour condensation at several locations along the wall of a thrust chamber has been confirmed. Condensation or solidification have already been observed on cooled walls in the supersonic portion of subscale combustion chambers (cf. [1]) or even at the exit of some full-scale rocket engines, like the Cryogenic Deep Throttling Demonstrator Engine developed by Pratt & Whitney Rocketdyne (cf. [2]). In this context, European A5ME development project (ESA/CNES common team) decided to support the present work to gain experience on heat transfer understanding and modelling in the presence of condensed phase at the wall.

The first objective of this study was to experimentally investigate phenomena involved in wall heat transfer when local saturation conditions are achieved by supersonic expansion (low pressure, low temperature) and wall overcooling (further temperature decrease). This has been achieved by designing a dedicated cold gas subscale test hardware, consisting of an instrumented 2D nozzle cooled by nitrogen. This test hardware was designed and manufactured by ESTEC and installed in a test facility situated at TNO premises (The Netherlands). A monopropellant cold gas test configuration was chosen for simplification of test article design, manufacturing and mainly operation : this simplification enables parametric experimental studies with low cost and reasonable test planning.

Initially, three working fluids were identified as potential candidates for the main nozzle flow : Methane (CH4), Ethane (C2H6) and Ethylene (C2H4). Ethylene was found to be the best candidate, for the following reasons :

- it is gaseous at ambient temperature and moderate pressure, and remains in gaseous phase at thermodynamic conditions induced by moderate supersonic expansion (Mach 1.5 – 2)
- it condensates at relatively high temperature (150 K) when pressure reaches some hundreds of mbar in the supersonic section (cf. figure 1).
- it has a low specific heat capacity, and can thus be easily subcooled.
- it is also widely used in industry and has thus a low procurement cost.

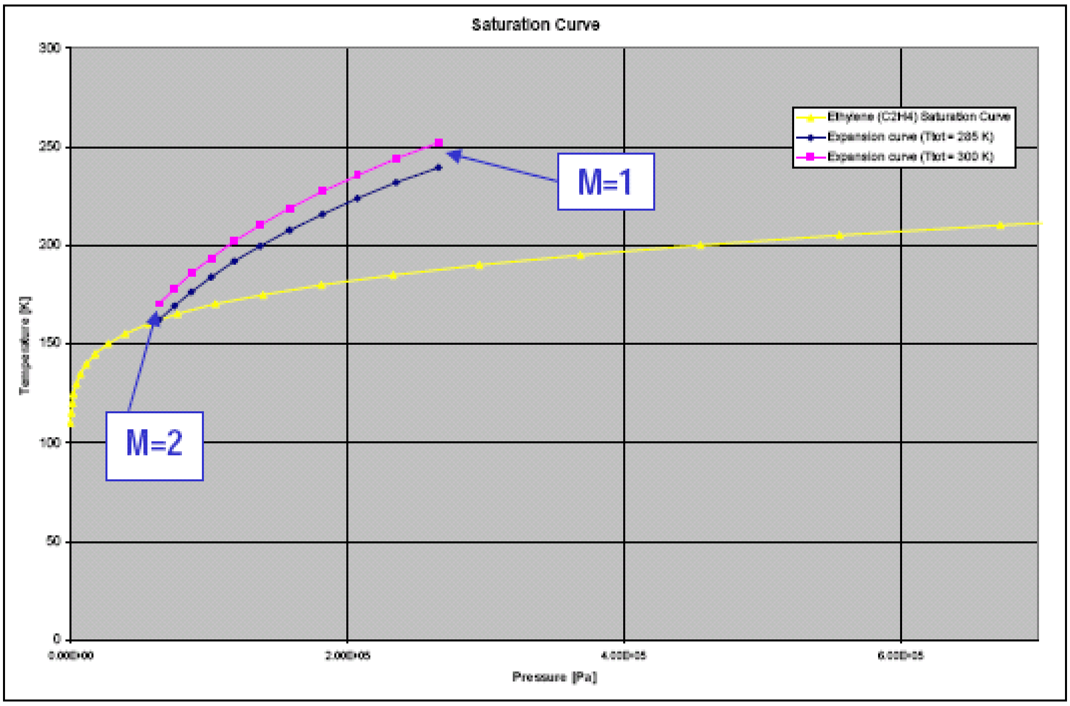

Figure 1 - Comparison between ethylene saturation curve and thermodynamic status along supersonic nozzle (1D computation)

On the other hand, ethylene has some drawbacks, which had to be handled by dedicated safety file and bench procedures :

- it is easily inflammable.
- it can form explosive mixture with air.
- it may decompose violently at high temperature and/or pressure or in presence of a catalyst.
- it may react violently in the presence of oxidants.

For example, the following safety countermeasures were applied : venting of ethylene storage area; ethylene burners installed downstream of the experimental set-up, …).
The experimental test set-up is presented in section 2 and some test results are discussed in section 3.

The second main objective of this study was to simulate the above mentioned tested configuration, using the CFD code CPS, developed by Bertin Technologies (France), as a first step towards validation of RANS condensation modelling, with the objective of further application to real hardware configurations for predictive calculations. A dedicated CPS condensation model was developed with the support of CNES Liquid Propulsion R&D project ; this model is based on a lagrangian description for the 2-phase flow in the region where condensation appears or disappears. Preliminary simulations were used to help designing the test hardware and chosing instrumentation location as well as some testing conditions.
CPS software condensation modelling strategy is presented in section 4, and some numerical simulation results are also discussed in this section.

2. Experimental set-up

2.1. Hardware design and instrumentation

The test hardware consists in a 2D nozzle (cf. figure 2), fed by an inlet manifold situated upstream the throat. The inlet manifold is fed by three separate flexible hoses, connected the test article by Swagelok SS-1210-1-12 connectors. The overall cross-section of the three connectors has been chosen large enough to reduce ethylene injection velocity, and a "T"-configuration has been chosen for connectors positions in order to promote ethylene mixing within the inlet manifold, and ensure homogeneous ethylene injection before throat section (cf. figure 3).

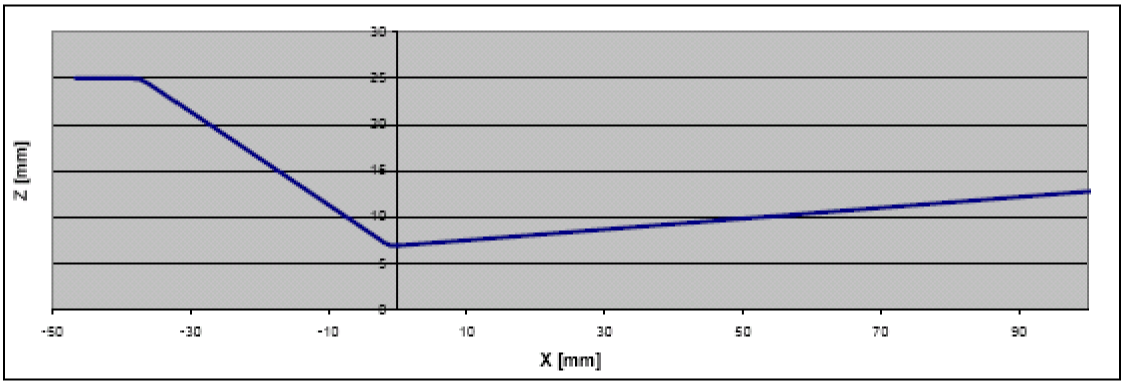

Figure 2 : Nozzle profile

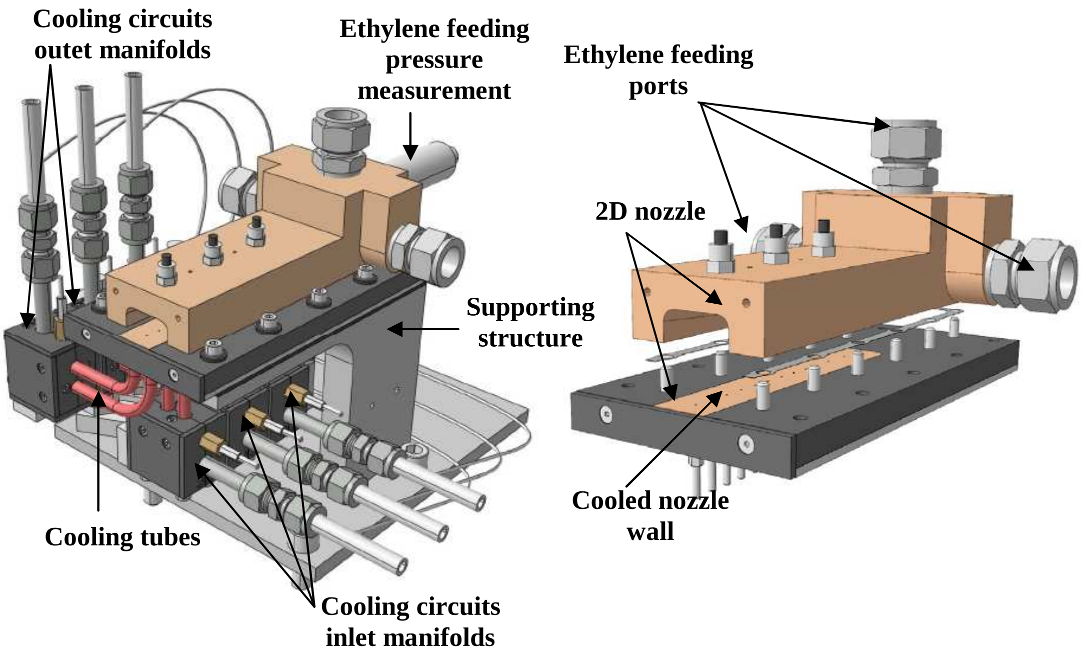

Figure 2 : Full hardware assembly overview and exploded view of chamber assembly

The lower nozzle wall is a copper (E-Cu57 F30) plate cooled by three successive cooling circuits sections. Each cooling circuit consists in two copper tubes, situated on both sides of the longitudinal central axis of the nozzle, and connected to one inlet manifold and one outlet manifold (cf. figure 4). Nozzle and cooling circuits have been designed so that condensation on the nozzle wall is only possible when cooling circuits are activated. Cooling tubes are embedded within the nozzle lower cooper wall ; a specific attention has been paid to ensure a correct bonding and proper thermal conduction between cooling tubes and nozzle wall, by using a specific glue (Eccobond 56C). Each manifold consists in two copper halves, sealed together with an indium gasket. Copper manifolds are thermally protected by thin UHMWPE plates, which are mechanically fixed on each side of each manifold.

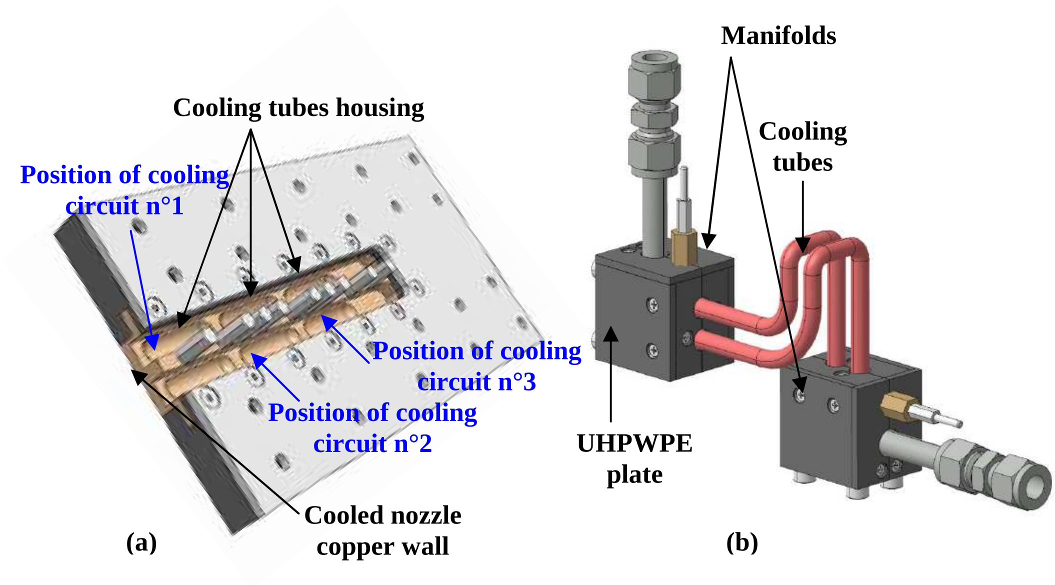

Figure 4 : Cooling plate view from below (a) – Cooling circuit assembly including manifolds (b)

Once the full hardware is installed on bench and instrumentation is connected to the acquisition system, cooling pipes are also insulated from the external environment by thermal protection foam (cf. figure 5). The overall hardware is also covered by the same kind of protection foam, in order to maintain hardware thermal boundary conditions as independent as possible from external environmental conditions (e.g. natural or forced convection inside the test cell, due to recirculation of cooling circuit exhaust gases).

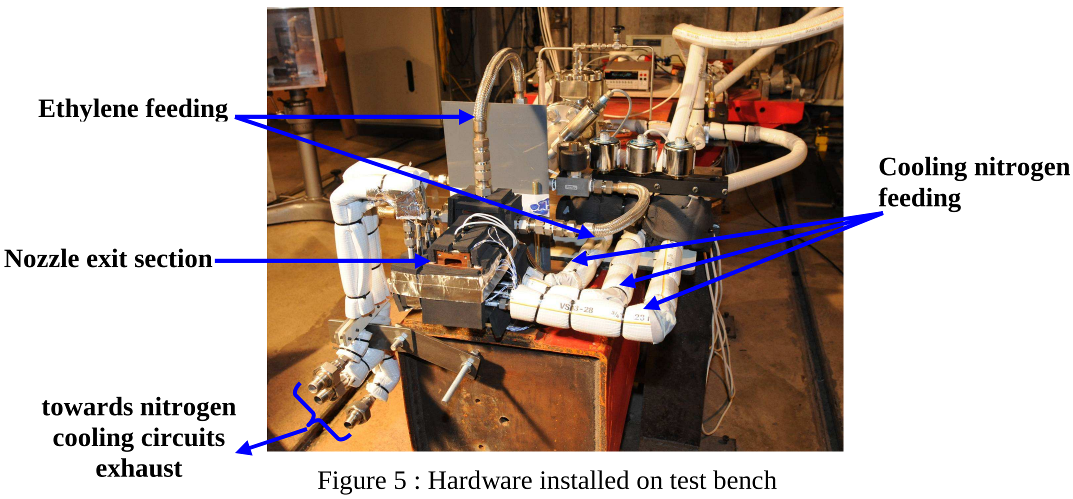

Figure 5 : Hardware installed on test bench

The upper part of the nozzle as well as the inlet manifold are also made of copper, but a sandwich configuration has been chosen in order to thermally insulate the cooled copper plate from the remaining parts of the test article (cf. figure 6). The insulating material is Ultra High Weight Molecular Polyethylene, suitable for cryogenic applications. The cooled copper part is bolted to the main insulator (UHWMPE) and thermally insulated from a steel support plate by a secondary insulator (UHWMPE). An indium gasket ensures the tightness between the main insulator and the cooled copper part.

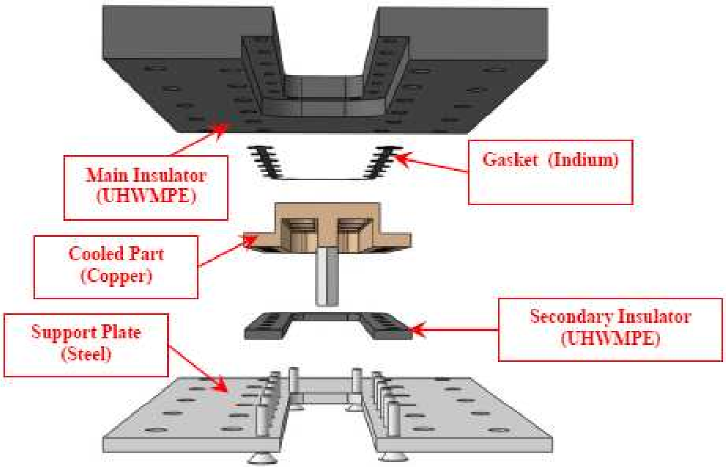

Figure 6 : Cooled nozzle plate assembly

The overall assembly is supported by a dedicated Aluminium alloy structure, directly mounted on the bench support. The complete mass of the test article is approximately 10kg, and its overall envelope fits in a box of approximately 200mm*200mm, which allow easy storage and transport. Test hardware design and manufacturing have been low-cost oriented ; standard interfaces have been used, enabling easy and quick mounting on several possible test benches.

The test article is equipped by a full set of pressure and temperature measurements, connected via a patch panel and multiplexer to a laptop PC on which test data can be visualized and stored. Test hardware measurements location have been chosen to enable a precise characterization of :

- main ethylene flow inlet conditions
- coolant flow inlet and outlet conditions on each cooling circuit
- external thermal boundary conditions
- cooled wall temperature and pressure evolution along the nozzle flow path.

A major part of the instrumentation effort was dedicated to the nozzle wall temperature instrumentation by flush-mounted Medtherm temperature sensors (cf. figure 7), which enable precise evaluation of nozzle wall temperature with regards to saturation temperature at each position along the nozzle.

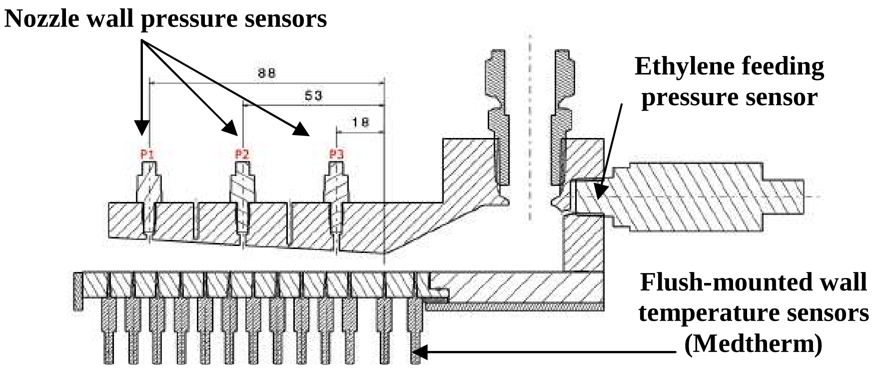

Figure 7 : Test hardware instrumentation

Further details on hardware design can be found in [3].

2.2. Test-bench set-up

Either gaseous and liquid nitrogen can be fed to the cooling circuits from a dedicated nitrogen bottle; the only constraint imposed for operation is to avoid phase change inside a cooling circuit.
Each of the three cooling circuits mass flow is calibrated by an orifice at the circuit outlet (cf. figure 5), which can be changed to vary the coolant mass flow. In the past test campaigns, orifices have always been chosen identical for the three cooling circuits, as the coolant feeding was provided by a single nitrogen storage. In the future, it could also be imagined to use different orifices on each cooling circuit, or to feed only one or two circuits over the three, for example in order to study the impact of the inertia of a condensed film created upstream and/or the impact of its evaporation on downstream wall heat transfer.
Nitrogen storage bottle mass is measured all along the test ; the temporal evolution of this mass gives an accurate estimation of the overall nitrogen cooling mass flow (measurement accuracy under 1g/s). The cooling mass flow for each cooling circuit has been considered as equal to one third of the overall measured mass flow. In the last test campaign, the liquid nitrogen cooling mass flow was varied in the range 50-200g/s.

Ethylene is supplied to the test hardware by a dedicated bottle. A splitter plate, equipped with pressure and temperature measurements, ensures the distribution of ethylene over the 3 test hardware inlets (cf figure 2). Helium can also be injected within the ethylene feeding line, through two dedicated injectors. Thanks to this possibility, the influence of the presence of a non-condensable gas at the wall on condensation and heat transfer at the wall can be analysed. The targeted mixture of helium in ethylene (from 10 to 20% in mass) is representative, in terms of partial pressure for ethylene, of the mixture of water vapour and non-condensable hydrogen in the combustion gases of a H2/O2 combustion chamber. The nominal ethylene mass flow is approximately 150g/s.

Two additional supply lines have also been assembled in order to purge or pre-cool the hardware :
- a pre-cooling circuit connected to the coolant feeding line, to ensure cooling circuits and nozzle wall pre-cooling before ethylene boost ; during this chill-down phase, nitrogen is provided by a separate nitrogen storage, different from the main cooling circuits storage .
- a nitrogen pre/post-purging circuit connected to the main ethylene feeding line, ensuring hardware purging during chill-down phase and after ethylene boost.

High speed video imaging has been used to visualize condensation on the nozzle wall ; in the last test campaign, two cameras were used : one for front view, looking at the nozzle inner wall exit from the top, and one for side view, looking at the nozzle exit (recording frequency : from 4 to 8kHz).

3. Experimental results

Two successive test campaigns were held at TNO premises : the first hardware acceptance test campaign ended in February 2010 and the second test campaign ended in February 2011 ; an extensive test database is now available, with different test-cases including different boundary conditions, both for the main ethylene flow and the nitrogen coolant flow. The following test-cases are available :
- tests with and without condensation
- tests with GN2 cooling or tests with LN2 cooling, for different cooling mass flows
- tests with supersonic or subsonic flow in the nozzle.

The test article is fed by a blow down ethylene feeding system. Consequently, better stabilised ethylene feeding conditions are obtained for subsonic test cases. Although not as representative as initially foreseen compared to the final application, these subsonic test-cases are nevertheless also fully relevant for validation of heat transfer and condensation modelling.

For all these tests, the thermal balance over each cooling circuit can be accurately calculated. Cooling circuit thermocouples accuracy has been verified on the full measurement range prior to installation on

hardware, and again after test campaign. Measurement uncertainty is estimated around 0,1K. Table 1 gives an example of heat balance calculation over cooling circuit number two for two test-cases with slightly different operating conditions on ethylene side, but very different operating conditions on coolant side (including a ratio of about two on cooling mass flows). Values in table 1 correspond to averaged values over a measurement time frame of 5s. No condensation was present on theses two test-cases.
Despite the very low absolute temperature increase measured between cooling circuit inlet and outlet in both test-cases, the measurement accuracy is high enough to capture the different total heat balance between the two test cases. This gives confidence for the evaluation of heat balance in the presence of condensation.

Table 1 : Heat balance evaluation over cooling circuit n°2 for two different test-cases

	Test-case n°1 @H0+412,5s	Test case n°9 @H0+655s
$\dot{m}_{cool}$	**47,5 g/s**	**24,1 g/s**
$p_{cool-inlet}$	5,26 bar	7,76 bar
$T_{cool-inlet}$	87,5 K	97,8 K
$p_{t-ethylene}$	2,26 bar	1,96 bar
$T_{t-ethylene}$	261 K	251 K
Δh_{cc2}	3283 J/kg	2963 J/kg
Q	156 W	71 W
ΔT_{cc2}	1,1 K	0,6 K

Condensation has been successfully triggered for several test-cases, as targeted by the hardware design ; this could be verified both by high-speed imaging of the flow at the nozzle exit (see figure 8) and by comparison of Medtherms wall temperature measurements to the local saturation temperature. Figure 9 gives an example of such a test-case. Corresponding operating conditions are summarized in table 2.

(a) Front view **(b) Side view**

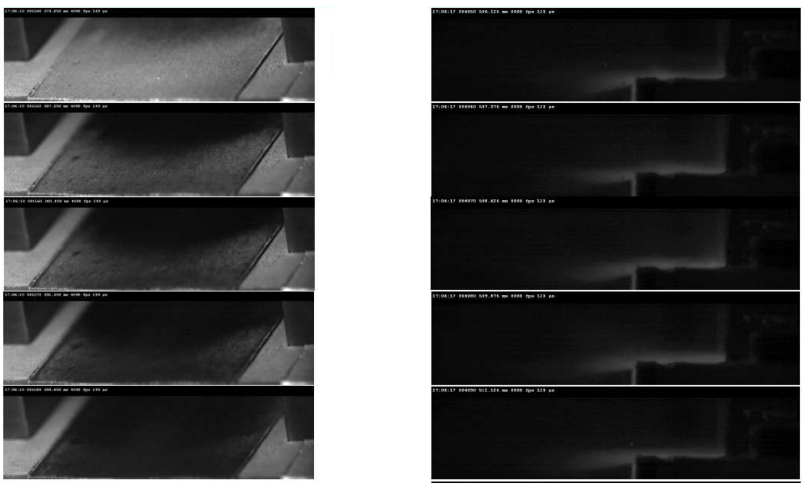

Figure 8 - Condensation front evolution visualized by high speed imaging (a) front view (b) side view

Table 2 : Operating conditions of test-case n°9 @ H0+566s

	Test case n°9 @H0+566s
$\dot{m}_{cool}$	32,1 g/s
$p_{cool-inlet}$	8,3 bar
$T_{cool-inlet}$	94,6 K
$p_{t-ethylene}$	1,14 bar
$T_{t-ethylene}$	238 K

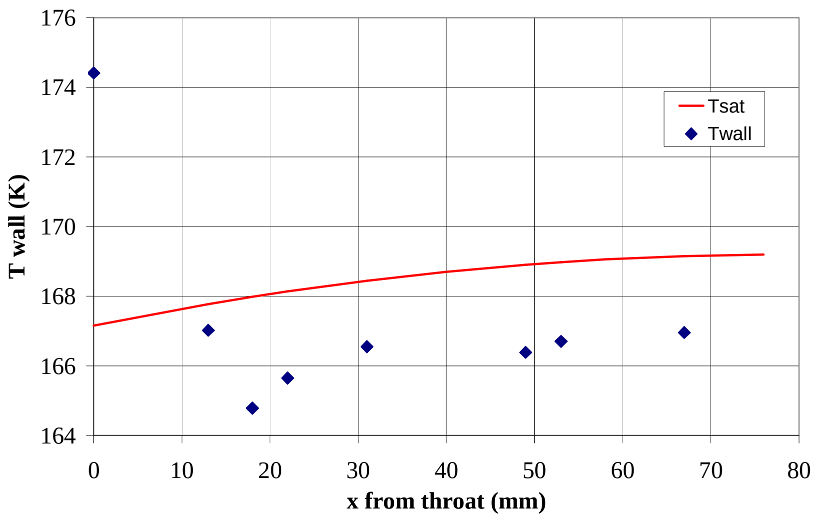

Figure 9 : Nozzle wall temperature (Medtherms) longitudinal evolution w.r.t saturation line – Test-case n°09 @ H0+566s

The detailed analysis of the complete test database is currently ongoing ; this analysis first aims at selecting operating points in steady-state conditions, both on ethylene side and on coolant side. Then, a systematic calculation of heat balance over each cooling circuit is made, as well a systematic comparison of nozzle wall temperature evolution and saturation temperature evolution along the nozzle axis. If possible, the high-speed imaging will be further analysed in order to get a rough estimation of the condensed ethylene flow height (at least an order of magnitude), see figure 8b). Amongst this database, 3 or 4 test-cases will be chosen for simulation and condensation/heat transfer modelling validation : one test-case without condensation, and two or three test-cases with condensation but different operating conditions, either on ethylene side or on coolant side.

4. Numerical simulation

4.1. CPS CFD code – Condensation/Evaporation modelling

CPS software, a CFD code developed by Bertin Technologies, has been used for several years as a support to CNES cross-check activities concerning propulsion in general, and thrust chambers in particular, for several projects : from R&D to new development projects like Ariane 5 Mid-Life Evolution, or Ariane 5 production follow-up.

CPS is a multiphysics software used for 2D and 3D configurations simulation, able to address various flow conditions :

- perfect or real gas, using a multi species approach, with varying thermodynamical properties
- compressible or uncompressible, turbulent, reactive flows,
- two-phase flows, using either a Lagrangian or an Eulerian approach.

CPS also offers the possibility to realize coupled heat transfer calculations in regenerative thrust chambers : both the coolant flow, the hot gas flow and the wall thermal behaviour can be simulated by using the same tool, which includes both a Navier-Stokes solver and a thermal solver.
In case of specific needs, dedicated models can be developed and implemented in CPS by Bertin Technologies under CNES support. This is the case of the condensation/evaporation model used in the simulations reported in the following paragraph. Model development was supported by CNES Liquid Propulsion R&D project .

The lagrangian two-phase flow model already implemented in CPS (Lasvegas) has been modified to be able to simulate the onset and the development of a condensated film on a cooled wall, and also its potential destruction by evaporation. Several interactions are taken into account in this model :
- thermal exchange between the main gas flow and the condensated film
- thermal exchange between the condensated film and the wall
- thermal exchange between the condensated film and the main gas flow during evaporation or condensation (due to release of latent heat of condensation or consumption of latent heat of evaporation).

All theses terms are taken into account in the conservation equations of mass, momentum and energy for both the gas phase and the dispersed phase in CPS Navier-Stokes solver. The first condensated droplets appear on the wall when 2 conditions are fulfilled : the condensating gas is present near the wall, and its temperature in the cell immediately adjacent to the wall is lower than the saturation temperature at the local gas partial pressure.

4.2. Ongoing simulations

The first simulation step consisted in simulating the thermal hardware status at the end of the chill-down phase, just before ethylene injection ; the idea behind this step was to get more confidence in the modelling assumptions made in the current nozzle model before stepping into the simulation of a test-case with ethylene injection, including or not condensation on the nozzle wall ; this simulation step led to the following main conclusion : boundary conditions between different materials have to be chosen carefully, and as representative as possible to the real hardware, in particular in case the hardware shows imperfections ; in the present case, as shown on figure 10, imperfect contact between copper lateral wall and UHMPWE insulator (effectively observed on real hardware after testing) has to be taken account in the model.

Once the experimental database will be analysed in details, simulations will be pursued for condensation modelling validation, first on a test-case without condensation and then on 2 or 3 test-cases with condensation for different operating conditions.

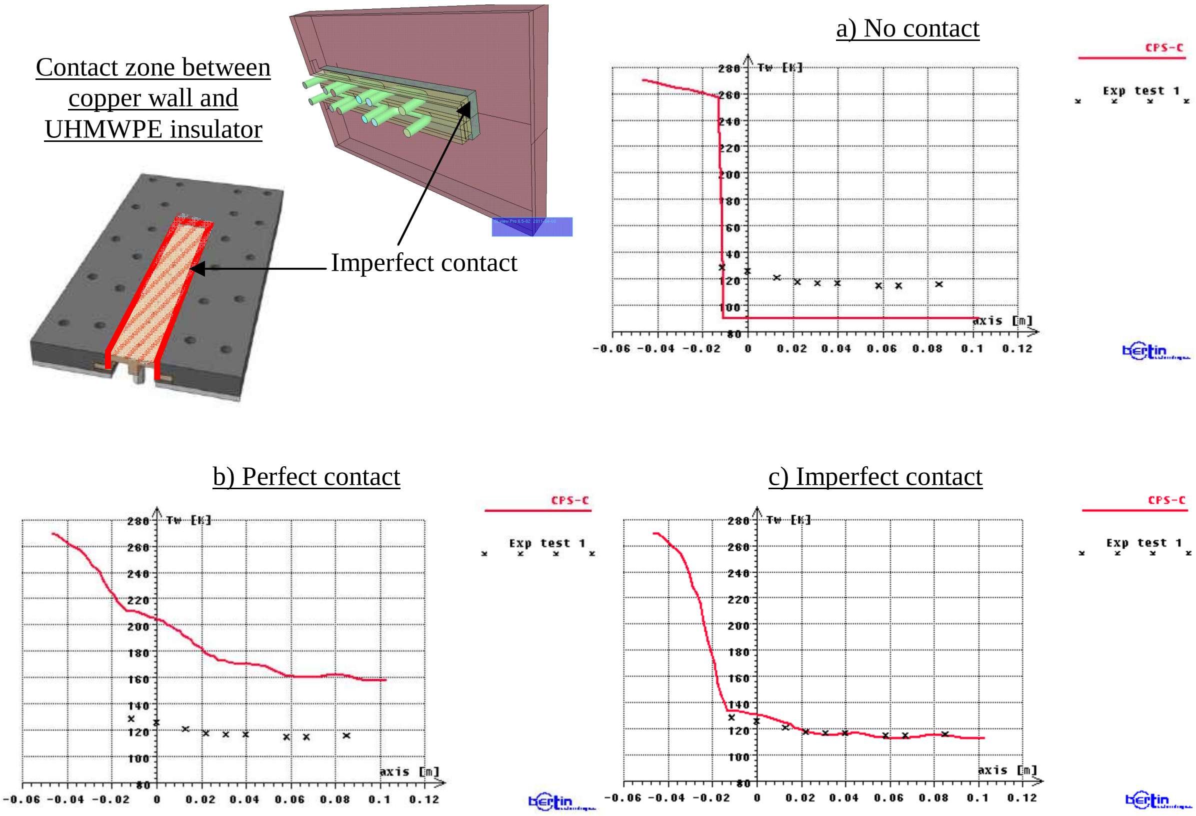

Figure 10 – Nozzle wall longitudinal thermal map at the end of chill-down phase for three different boundary conditions at the junction between copper wall and UHMWPE insulator

5. Conclusions.

A simple and low-cost experimental set-up has been designed and manufactured by ESTEC to study wall heat transfer in the presence of condensation obtained by wall overcooling in a non-reactive 2D nozzle test configuration ; the hardware has standard interfaces, allowing easy and quick transport and implementation on a test bench, as well as reliable instrumentation enabling accurate measurement of wall temperature evolution and cooling circuits inlet and outlet pressure and temperature, used for heat balance calculation over cooling circuits. Two test campaigns have been held at TNO and an extensive database including test-cases with and without condensation, for different operating conditions, is now available for condensation modelling validation. In parallel, a condensation model has been developed by Bertin Technologies under CNES R&D project support, and implemented in CPS CFD software. First simulations of the chill-down phase enabled a refinement of the nozzle model to take into account non-ideal contacts between different materials in the real hardware. The model is now ready for simulations of test-cases which will be issued from the experimental database, which will allow a first assessment of the status of CPS condensation modelling validation.

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