Assessment of Slag Accumulation in Solid Rocket Boosters: Part II, Two-Phase Flow Experiments

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In solid propellant rocket motors incorporating a submerged nozzle, the entrapment of liquid residues of the combustion in the cavity formed in the surrounding of the nozzle integration part can lead to the accumulation of slag with a considerable mass.

The long-term goal of the present study is to characterise experimentally the driving parameters of the slag accumulation in a stagnant area modelling the nozzle cavity. The experimental database will be used for validation of a numerical tool.

In the present article measurements are shown in two-phase flow condition using a cold-gas simplified model to determine effectively the main parameters that are influencing the droplet entrapment. Furthermore, the deformation of the accumulated liquid surface is analysed and presented as well.

Nomenclature

\( x, y, z; X, Y, Z \) Cartesian body axes [mm]
\( U_0 \) Free-stream (reference) velocity [m/s]
\( h \) Inhibitor height [mm]
\( L_i \) Inhibitor location from the nozzle tip along the x axis [mm]
\( w \) Cavity width [mm]
\( o \) Nozzle throat opening [mm]
\( t \) Splitting plate thickness [mm]
\( O2NR \) Obstacle-to-nozzle ratio [-]
\( OT2NT \) Obstacle tip to nozzle tip distance [mm]
\( p_w \) Spray water supply pressure [bar]
\( p_{air} \) Spray air supply pressure [bar]
\( d_{32} \) Sauter diameter [\( \mu \)m]
\( Q_{V_d} \) Volumetric droplet flow-rate [l/s]
\( \alpha_p \) Volume fraction [-]
\( St \) Stokes number
\( f\# \) Focal number [-]
\( t_{exp} \) Exposure time [ms]
\( fps \) Frames-per-second [1/s]
\( P_{laser} \) Laser light power [W]
\( SobelY \) Sobel operator matrix [-]

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The first stage of spacecrafts (e.g. Ariane 5, Vega, Shuttle) generally consists of solid propellant rocket motors (SRM). These are typically operating during the first part of the lift-off providing most of the thrust to accelerate the vehicle. On one hand, to shorten the overall length, the nozzle is submerged in the last segment of solid propellant. That means that the convergent, the sonic throat and a part of the divergent are surrounded by solid propellant. This integration allows orientation of the nozzle to provide adaptation of the rocket trajectory during the launch. During the combustion, the regression of the solid propellant surrounding the nozzle integration part leads to the formation of a cavity around the nozzle lip. On the other hand, the propellant combustion generates liquefied alumina droplets coming from chemical reaction of the aluminum composing the propellant grain. The alumina droplets being carried away by the hot burnt gases are flowing towards the nozzle. Meanwhile the droplets interact with the vortices formed by the internal flow and thus may modify their properties. As a consequence, some of the droplets are entrapped in the cavity instead of being exhausted through the throat. The amount of entrapped droplets in the cavity depends most probably on their interaction with the vortices. The accumulation of the droplets in the cavity generates an alumina puddle, also called slag. This slag reduces the performances of the solid propellant motor due to its dead weight absence of impulse generation. In case of the two EAP of Ariane 5 the total mass of the accumulated particles can reach up to 4.8 tons by the end of the launch.\(^1\)

### A. Background

The presence of the slag can lead to control problems and possible vehicle instabilities (e.g. by sloshing of the slag or by slag ejection\(^2\)). As it is pointed out by Dupays et al.,\(^3,4\) the slag accumulation process and the instability of the internal flow-field of the motor are dependent on each-other.

These instabilities occurring in the motor during the launch have been investigated (using analytical, experimental and numerical tools) by several researchers, both in the USA\(^5\)\textsuperscript{–9} and in Europe,\(^4,10\)\textsuperscript{–17} within the frameworks of the ASSM (Aerodynamics of Segmented Solid Motors) and POP (Pressure Oscillation Program) for the Ariane 5 solid booster, MPS P230 (an overview of these studies can be found in Fabignon et al.\(^10\)) of CNES (Centre National d’Études Spatiales). Two-dimensional (axisymmetric and planar) numerical simulations were carried out to investigate the periodic vortex shedding and its effect on acoustic instabilities in a SRM.\(^11,12,18\) 2D-like cold-flow experiments using a 1/40 scale model of Ariane 5 SRM with Laser Doppler Anemometry (LDA) was used by Couton et al.\(^13\) to investigate the instabilities. The authors respect aeroacoustic similarities and reproduce the characteristic elements of the internal geometry including the wall injection of the flow. Within this campaign the particularity of the shear-layer in the wake of the obstacle is pointed out. The subject of Anthoine et al.\(^14,15\) is the investigation of acoustic instabilities in large SRMs incorporating submerged nozzle. The experimental work on different 1/30-scale cold-gas models of the Ariane 5 SRM is supported by numerical simulations as well.\(^16\) One of the conclusions of the authors is that the flow-acoustic coupling is dominated by the interaction between the vortical structures and the nozzle tip and by the volume and geometry of the cavity next to the nozzle.

Within the CNES programs, during the instability study, the importance of the slag accumulation was also emphasised.\(^3,4\) Focusing on the slag accumulation, two-phase, quasi-steady, compressible numerical simulations were carried out by Cesco et al.\(^17\) using an Eulerian-Lagrangian method without simulating the combustion and the coupling between the phases. The authors found that the alumina droplet size and the turbulence play an important role on the rate of accumulation.
B. Objectives

The long-term goal of the present study is to characterise experimentally the driving parameters of the slag accumulation in a stagnant area modelling the nozzle cavity using a scaled 2D-like cold-gas model. To achieve this objective, the interaction of the droplets (modelling the alumina droplets of the SRM) with the vortices of the flow and the droplets entrapment process need to be investigated.

In the article of Tóth et al.\textsuperscript{19} the first step of the project is presented, where a single-phase 3D LES simulation and its validation are shown using detailed \textit{Particle Image Velocimetry} (PIV) measurements that were already performed in the 2D cold-gas model.

The objective of the current paper is to present the \textit{Level Detection and Recording} (LeDaR) measurement technique and the obtained experimental results in two-phase condition. The aim of this measurement campaign is to identify the main - primarily geometrical - parameters that are influential during the slag accumulation process.

II. The LeDaR technique

The \textit{Level Detection and Recording} (LeDaR) is a VKI home-made non-intrusive optical measurement technique that detects the liquid level in a plane of a tank. By choosing an optical method for the liquid surface detection, apart from the volume measurement, one has the possibility to investigate the shape of the surface as well.

Therefore, during the LeDaR measurement, one requires a transparent tank (to allow optical access) filled with some liquid (in the present case water) (see Fig. 1). The instantaneous position of this water surface is the subject of the investigation.

![General arrangement](image)

\textbf{Figure 1. General arrangement.}

By generating a laser sheet (using a continuous laser source), the plane of interest is illuminated. The surface detection is limited to the illuminated region.

When the investigated liquid does not diffuse effectively the light, as for water, one should mix some fluorescent dye (in the present case 0.1 g/l Fluoresceine) with the liquid.

From the illuminated plane, images are recorded with a camera. A typical image is shown in Fig. 2(a). Later, the captured images are analysed by the LeDaR algorithm.

The LeDaR algorithm is an image processing program. Its fundamental version relies on the so-called \textit{Sobel edge-detection transformation filter}. In practice, it scans the selected region of each image pixel column by pixel column from top to bottom. At each pixel location it computes the convolution of the local intensity distribution with the $3 \times 3$ Sobel operator matrix (See Eq. (1)).

\[
\text{SobelY} = \begin{bmatrix}
-1 & -2 & -1 \\
0 & 0 & 0 \\
1 & 2 & 1
\end{bmatrix}
\] (1)

As one can see, the filter is sensitive to vertical dark-to-bright gradients. At each location, the coefficient of the filter (Sobel coefficient) is determined and compared to a user-defined threshold. As soon as the value of the Sobel coefficient reaches the value of this threshold, the actual pixel position is considered to represent the liquid interface and the scanning of the lower positions of that pixel column is skipped.
The ensemble of the detected positions in all of the pixel columns draws the whole liquid surface corresponding to the plane of the laser sheet (similar to Fig. 2(b)).

This algorithm was modified using a new \((3 \times 21)\) operator matrix (see Eq. (2), which is detecting steps in the intensity distribution of the image. Furthermore, in each pixel-column the position of the maximal coefficient is identified being the liquid level to eliminate the ambiguity of the manual threshold. As a result, the new \textit{ForwardStep} filter is less sensitive to small illuminated droplets or image noise (see Fig. 2(b)), thus it is better accommodated with the current conditions.

\[
\begin{bmatrix}
-1 & -2 & -1 \\
\vdots & \vdots & \vdots \\
-1 & -2 & -1 \\
0 & -1 & 0 \\
0 & 0 & 0 \\
0 & 1 & 0 \\
1 & 2 & 1 \\
\vdots & \vdots & \vdots \\
1 & 2 & 1
\end{bmatrix}
\]

\text{(2)}

\section{III. The experimental facility and measurement conditions}

The experiments are carried out in the facility that was introduced in Tóth \textit{et al.}\cite{19} The 2D-like cold-gas model (see Fig. 3(a)) is supplied through the stagnation chamber of a wind tunnel and simulates the main characteristic features of the SRM of Ariane 5 (MPS P230). Thus, the symmetric test section models the emerging inhibitor, the nozzle geometry and the appearing neighbouring cavity (Fig. 3(b)).

The test section is designed in a way to allow the use of optical measurement techniques (e.g. PIV and LeDaR) to characterise the internal flow-field. Therefore, most of the walls are made of transparent material. Furthermore, different geometrical parameters \((h, L_i, o, w)\) can be varied. Due to the symmetric flow condition, the measurements are carried out using only one side of the test section.

The experiments are carried out at room temperature using air to model the gas-phase of the internal fluid of the SRM and using water droplets generated by a spray device to model the alumina droplets. The water spray is mounted in the middle of the stagnation chamber of the wind tunnel in order to allow a proper mixing of the water droplets with the air-phase before reaching the test section. The device itself and its supplying tube are located inside a cross-shaped tubing system that represents a constant, symmetric blockage in the stagnation chamber regardless the actual position of the spray system.

Furthermore, within the measurement condition, a considerable amount of water droplets is hitting the
inhibitor. As a result, this liquid is accumulating on the upstream side of the obstacle and as it reaches a critical amount, it is carried away by the airflow in the form of splashes or large (several millimeters in diameter) droplets. Due to gravity, the main part of this water is falling into the cavity and therefore biasing the accumulation measurement, where entrapment due to aerodynamic forces are to be investigated.

In order to overcome this uncontrolled accumulation, the depositing liquid is evacuated from the obstacle. Therefore, the inhibitor is inclined by 10° upstream (see Fig. 3(b)). Thus the liquid is pushed (by gravity and by the airflow) towards the base of the inhibitor. With the help of a pump (set to an adequate flow-rate) and a small tubing system (the airflow should not be modified) the excess water can be evacuated from the test section and it is not biasing anymore the accumulation measurement in the cavity.

The laser-sheet is generated in the mid-span of the test-section (cavity) with the help of a cylindrical lens (see Fig. 3(b)). The laser beam has a thickness of the order of 2 mm. Therefore, the laser sheet has the same thickness. On one hand, the most energetic part of the light plane is directed towards a mirror placed below the investigated cavity. This mirror reflects the sheet and illuminates the region of interest from below. On the other hand, the rest of the laser-sheet is entering through the sidewall of the cavity. Due to the construction of the set-up, from the side one can not illuminate the bottom 20 mm of the cavity. This is the main reason why the most energetic part of the light plane is directed towards the mirror.

The energy of the continuous laser is always adjusted according to the actual image quality. In most of the cases $P_{\text{laser}} = 0.4..0.6$ W are used.

The exposure time of the camera is chosen to be $t_{\text{exp}} = 0.5$ ms, which is sufficiently short to freeze the motion of the liquid surface.

However, the flow and thus the accumulated water do not have a strict two-dimensional behaviour inside the cavity. In order to ensure a clear view in the presence of three-dimensional waves, the camera is inclined by about 15° and the spray is working only until the accumulated water reaches roughly the middle of the recorded images.

In the presence of water droplets in the test section the image recording is not straightforward, because the droplets could deposit on the walls deteriorating the image recording quality (see Fig. 4(a)).

In order to overcome this effect, first of all a thin glass layer has been installed on the inner surface of the cavity wall through which the camera is recording the images. This glass surface could then be treated
to make it hydrophobic. Thus, no large droplets can stick to the wall; they would slide quickly down due to gravity. Furthermore, during the present experiments a Phantom v7.1 high-speed CMOS camera is used. The camera is equipped by a 35 mm Nikon lens. The advantage of the shorter focal length is the larger viewing angle. Therefore, the camera could be positioned closer to the window of the test section, at a given field of view (FoV). Thus, the images of the depositing droplets on the wall of the cavity are practically not visible in the images, when using the lowest available focal number ($f\# = 2.0$). The final image quality is shown in Fig. 4(b) (and in Fig. 2(a)).

The high-speed camera has a maximal resolution of $800 \times 600$ pixels$^2$ and 1 GB on-board memory. The size of this memory determines the maximum number of recordable images and thus the length of the series of acquisitions. Therefore, the image size is reduced to $640 \times 480$ pixels$^2$, at which a maximum of 2289 acquisitions can be taken in each series.

The camera is capable of recording images with the maximum resolution even at 4000 frames-per-second (fps). However, during the LeDaR measurements this high frame-rate is not required. With the internal triggering of the camera, the lowest applicable recording speed is 100 fps. At this frame-rate 2289 images are recorded in 22.88 seconds.

With most of the parameters, a very low amount of accumulation is expected during 22.88 seconds, which could be measured only with a high uncertainty. In order to increase the length of the recordings in time, the overall frame-rate should be reduced, which can be realised by triggering the camera with an external signal.

For the LeDaR measurements the motion of the flow, or the liquid surface should not be followed in time. The only criterion from the point of the accumulation is that the images (samples) should be taken at known instants. Although currently it is not a goal to follow the deformation of the water surface in time during the accumulation, the chance should be kept for this investigation, as it might appear to be important in the future. Therefore, a burst recording (triggering signal) is designed (for easier understanding see Fig. 5). It is decided to acquire a sequence of 10 samples in each 4 seconds. These 10 images are recorded at a frame-rate of 100 Hz, which allows resolving locally the motion of the liquid interface. Furthermore, at the period time of 4 seconds it is still possible to follow the volume increase with sufficient resolution.

![Image of camera trigger signal](image-url)
Applying this image recording method, it takes about 908 seconds to record 2289 images and fill the on-board memory of the camera.

Although the LeDaR measurement technique was validated earlier, at the end of each experiment the water is drained from both of the cavities into a jug and the volumes are recorded to verify in-situ the LeDaR experiments. Furthermore, due to the fact that the spray device is not operating perfectly symmetrically, determining the difference of accumulated liquid in the two cavities, the non-symmetric behaviour of the spray can be corrected.

A. Measurement parameters

Within the present experiments the main objective is to study the effect of the available parameters with the facility. Altogether 23 configurations are chosen. The parameters are summarised in table 2. In the table already the measurement results are indicated as well. However they will be discussed only later.

In all the configurations the same spray device is used, which is working with pressurised water. Its flow-rate is measured with the help of a Venturi tube. Although the present tests are performed in a 2D-like facility in cold-gas condition, the dynamic characteristics of the droplets of the real booster is attempted to be modelled. By respecting the volume fraction \( \alpha_p \) of the liquid-phase and the Stokes number \( (St) \), the interaction between the two phases should be similar than in the real condition. The properties of the spray device and the corresponding similarity parameters of the real SRM can be found in table 1.

### Table 1. The main characteristics of the spray device

<table>
<thead>
<tr>
<th>Config.</th>
<th>( p_w ) [bar]</th>
<th>( d_{32} ) [( \mu )m]</th>
<th>( Q_{V_d} ) [l/min]</th>
<th>( St ) [-]</th>
<th>( \alpha_p \times 10^{-5} ) [-]</th>
</tr>
</thead>
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<tr>
<td>Spray</td>
<td>5</td>
<td>140</td>
<td>3.5</td>
<td>22.69</td>
<td>14.4</td>
</tr>
<tr>
<td>MPS P230</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.366..36.6</td>
</tr>
</tbody>
</table>

The configuration #1 (Meas.#1) is considered to be the nominal condition. The measurements with this configuration are taken twice (see Meas.#1’) in order to verify the repeatability of the tests.

In most of the configurations only one parameter is modified compared to this setting (in table 2 the modified parameters are shown with bold characters).

First, the effect of the free-stream velocity is studied. 6.06, 8, 12 and 14 m/s are chosen within Meas.#2 to #5 respectively.

In the followings the effect of the inhibitor is measured. First (Meas.#6 to #8), the nominal inhibitor is moved closer to the nozzle to realise smaller Obstacle-to-Nozzle Ratios \((O2NR, L_i/h)\). Furthermore, Meas.#8, #9, #10 and #12 represent roughly similar \(O2NRs\), where the inhibitor size and position are modified simultaneously. Finally, inhibitors with different sizes are installed to the nominal position (Meas.#11 to #13) to cover a wide range of \(O2NR\), but keeping the same physical location. Using Meas.#6 to #13 and Meas.#1, it is possible to change the effect of the inhibitors keeping constant either the height of the inhibitor, its position or the \(O2NR\), by modifying the two other parameters.

Additionally, two special arrangements are defined related to the obstacle. In Meas.#14 no inhibitor is installed in the test-section. In contrary, in case of Meas.#15 two inhibitors are mounted. The first inhibitor is the nominal one at its nominal position. The additional inhibitor is the smallest available obstacle, which is placed to the closest available position to the nozzle.

Within Meas.#16 to #18, different cavity widths \((w)\) are taken by which the volume of the cavity is controlled.

The final parameter is the size of the nozzle throat \((o)\) within Meas.#19 to #23. By keeping the volume of the cavity constant, the importance of the distance between the inhibitor tip and the nozzle tip along the \(y\) axis (please, refer to Fig. 3(b)) could be seen at a given \(O2NR\). In case of Meas.#18 \((o = 42 \text{ mm})\), the tip of the obstacle is aligned with the tip of the nozzle. Furthermore, \(o = 67 \text{ mm}\) is the largest dimension that could be set with the present facility.

B. The data processing

In order to determine the increase of the water volume in the cavity, the recorded series of images are processed first with LeDaR.
The liquid interface is detected only in a small zone of the images. This zone is defined in each series separately based on the mean image quality distribution. Since the acquisitions have occasionally some disturbances, while the spray is operating (e.g. splashes of droplets, reflections from the 3D waves, etc.) and the illumination is not ideally uniform (it is influenced by the liquid surface movement and the volume increase as well), choosing an optimal region of processing is necessary. However, one can always find a narrow (at least 100 pixels wide) zone, within which the intensity distribution does not change significantly and is not disturbed frequently by droplets or the waves (a sample is shown in Fig. 6(a)). In this way, the analysis is more reliable and the processing time can be reduced as well.

![Sample of the processed region.](image)

![Liquid accumulation of Meas.#1.](image)

**Figure 6. LeDaR data processing.**

Then, the instantaneous water volume is calculated from the floor area of the cavity and the mean actual water level. By investigating only a part of the images, the fluctuation of the volume in time would be artificially larger (due to the waves of long wavelength). However, having sufficiently large number of samples, the mean rate of entrapment remains unaffected.

The LeDaR output data containing the instantaneous liquid surface shapes are post-processed by an algorithm that is analysing and correcting the eventual discontinuities in the detected surface.

Finally, the instantaneous water volume is calculated knowing the position of the bottom of the cavity, the magnification of the images (the length corresponding to one pixel) and the inclination angle of the camera.

Plotting the liquid volume evolution in time, graphs similar to the one shown in Fig. 6(b) can be obtained. As one can see in Fig. 6(b) the raw volume increase shows increasing fluctuation as the volume of the liquid increases. However, by computing the moving average (averages of 25 local volume points) the evolution already shows a stable mean increase.

Focusing on the part of the plot, which corresponds to the time, while the spray is not operating, the mean final volume can be determined. The mean final volumes are compared to the values that are measured with the jug after each test. This comparison shows a good agreement in all the cases, which validates once again the applicability of LeDaR.

Focusing on the part of the plot, which corresponds to the time, while the spray is operating, in all of the cases a linear volume increase can be observed. In order to determine the rate of liquid accumulation, a first-order polynomial is fitted on the time-series in the corresponding range. The slope of this linear fitting (the corresponding relationship is shown in Fig. 6(b)) gives directly the rate of accumulation.

Finally, the portion of the accumulated droplets should be determined with respect to the total amount generated by the spray. However, from the post-experimental volume measurements performed with the jug, it is observed that the rate of entrapment in the left cavity (regarding the arrangement, please, refer to Fig. 3(b)) is not equal to the one measured in the right cavity. Since the flow inside the test section is verified to be symmetric, the entrapment should be equal as well if the spray was operating symmetrically.

Therefore, the water mass-flow injected into each half of the test section is defined by repartitioning the total mass-flow of the spray (measured with the Venturi tube) using the ratio of the accumulated liquid in the two cavities.
IV. Liquid accumulation results

First of all, in table 2 the accumulation corresponding to each configuration is summarised. In the followings, the rate of accumulation is plotted in function of the main parameters. In each plot, the nominal configurations (Meas.#1 and #1’) are highlighted.

<table>
<thead>
<tr>
<th>Meas#</th>
<th>U₀ [m/s]</th>
<th>h [mm]</th>
<th>L₁ [mm]</th>
<th>O2NR [-]</th>
<th>w [mm]</th>
<th>o [mm]</th>
<th>Accumulation [%]</th>
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<td>4.6</td>
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<tr>
<td>21</td>
<td>10</td>
<td>33.5</td>
<td>310</td>
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<td>107.2</td>
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1. The flow velocity

In Fig. 7(a) the accumulation rate is plotted in function of the free-stream air velocity (U₀). By increasing U₀ with a factor of 2.3, the accumulation decreases by a factor of 3.4. Therefore, the flow velocity is considered to be one of the influential parameters.

2. The inhibitor size

The liquid accumulation with respect to the height of the inhibitor (h) is shown in Fig. 7(b). By changing h between 0 and 50 mm, the rate of accumulation ranges from 25.0 % down to 5.5 % respectively with a relationship that appears to be close to linear. Therefore, h should be one of the most relevant parameters.

Focusing on the h = 33.5 mm inhibitor, in Fig. 7(b) below the nominal conditions the configuration with two inhibitors can be seen. Thus, by installing a small additional obstacle between the main inhibitor and the nozzle, the entrapment rate is reduced from an average of 8.2% to 4.9%.

Therefore, in order to reduce the amount of entrapped liquid, the size of the inhibitor should be increased or incorporating a second obstacle should be considered.
3. The inhibitor position

Fig. 8(a) shows the rate of accumulation in function of the physical distance between the nozzle tip and the inhibitor \((L_i)\). In the plot, the \(h = 0\) mm case (Meas.#14; without inhibitor), is indicated as \(L_i = 0\) mm.

Considering the ensemble of all the indicated measurement points, one can not define a tendency in function of \(L_i\).

Focusing on the data with constant inhibitor size (e.g. \(h = 33.5\) mm), the accumulation does not change considerably; between the minimum and maximum value one can find a factor of 1.5.

However, focusing on the points that represent a roughly constant Obstacle-to-Nozzle Ratio \((O2NR = 6.2..6.87)\), the accumulation shows a roughly linear decrease in function of increasing \(L_i\).

Furthermore, in Fig. 8(b) the accumulation in function of \(O2NR\) is shown. Focusing now on the measurements, where inhibitors with different heights are mounted to the same position \((L_i = 310\) mm), a clearly linear increase can be observed in the accumulation in function of increasing \(O2NR\).

Therefore, as the above-mentioned tendencies are visible, one could conclude that \(L_i\) or \(O2NR\) has an influence on the droplet entrapment rate. However, in reality it is always \(h\), which stands behind these observations. Thus, once again the primary importance of \(h\) can be seen.

4. The cavity width

The accumulation in function of the cavity width \((w)\) is shown in Fig. 9(a). By keeping the nozzle \((o)\) at a given position, the width of the cavity is modified. Within this range, a concave behaviour is discovered. The maximum droplet entrapment rate appears around \(w = 100\) mm (64\% of the height of the cavity).
Although the accumulation rate changes by a factor of two within the examined range, the width of the cavity does not appear to be the most influential parameter since the accumulation changes in a smaller range compared to $h$, for example.

5. The nozzle throat opening

The effect of the nozzle opening ($o$) on the droplet entrapment rate is shown in Fig. 9(b). According to the plot, one can conclude that in the investigated range, the nozzle throat opening does not have a direct impact on the liquid accumulation.

6. Obstacle tip to nozzle tip distance

The Obstacle tip to nozzle tip distance ($OT2NT$) is defined by the distance between the tip of the inhibitor and the tip of the nozzle along the $y$ (transversal) axis (see Fig. 10(b)). The component of the distance along the $x$ (longitudinal) axis is not taken into account. Therefore, the $OT2NT$ gives the distance by which a droplet - passing near the tip of the inhibitor - has to be deviated by the flow in order to escape through the nozzle and not to be trapped in the cavity.

In Fig. 10(a), the liquid accumulation rate is plotted in function of the $OT2NT$ distance. For the first sight, by increasing this distance, the accumulation is not affected up to about $OT2NT = 20$ mm. Further increasing $OT2NT$ the liquid entrapment increases gradually.

According to Fig. 10(a), regardless to the position of the nozzle, a minimal accumulation rate is present.
This accumulation may represent on one hand the droplets, which are hitting the wall in the recirculation region downstream the inhibitor. As soon as a droplet hits the wall, most probably it is not entering the flow anymore, but it slides into the cavity.

On the other hand, droplets may be entrapped due to the vortex-nozzle interaction. This process is assumed to be quasi-periodic, controlled by the vortex shedding frequency downstream the inhibitor. Therefore, it could contribute by a constant amount of liquid.

However, by modifying the size (and the position) of the inhibitor, one may change considerably the instantaneous and mean topology of the internal flow-field. Therefore, this modification could have a considerable impact on the amount of accumulated liquid as well.

As a summary, the OT2NT distance - which comprises o and h as well - is found to be a relevant parameter in the droplet entrapment process.

However, one can identify w and U₀ being the secondary parameters driving the accumulation. As it was seen, they could modify the accumulation at least with a factor of two in the investigated ranges.

V. About the shape of the liquid surface

At the end of each accumulation measurement, after the inner walls of the test-section dried, one more sequence of images (2289 images at the same resolution) is recorded at a constant 100 fps, while the spray is not operating. These images have better qualities and can be entirely processed (similar to Fig. 2(b)) to analyse the properties of the liquid surface shape and its motion to see the impact of the air-phase.

A. About the mean surface

From the instantaneous liquid surfaces the mean shape of the interface is computed. An example of the mean surface can be seen in Fig. 11. Generally, about 10 % in the right hand side of the recordings (in the example: Position > 90 mm) is not correct due to image quality problems (see also Fig. 2(b)). Therefore, the scattering mean surface level should not be considered to be physical. In all the configurations the mean shape resulted to be similar. However, its amplitude is varying in function of the various parameters. Therefore, first of all the tendencies of the peak-to-peak deformation (see the definition in Fig. 11) are analysed, where two (three) parameters appeared to be important.

As it could be expected, by increasing the free-stream velocity (U₀), the surface deformation is increasing (Fig. 12(a)). Up to 12 m/s a linear tendency can be observed, which seems to break by 14 m/s, as the peak-to-peak amplitude does not increase noticeably. However, examining the actual images, it is visible that applying U₀ = 14 m/s, the aerodynamic disturbance of the surface is so intense that even bursts are occurring occasionally. Thus, analysing the surface by optical means is misleading at this level.

Concerning the inhibitor size (shown in Fig. 12(b)), in the presence of an obstacle, the surface deformation is proportional to h. However, installing an additional inhibitor just upstream the cavity, the flow disturbance appears to be damped, as the mean surface deformation is considerably smaller (see in Fig. 12(b) the point below the nominal configuration).

Concerning the nozzle opening parameter (see Fig. 13), it appears that by increasing o and keeping h constant, the mean surface deformation decreases. This can be explained by two different effects.

![Figure 11. The mean surface shape in the nominal condition.](image-url)
Figure 12. Mean surface deformation (the red "X" symbol shows the nominal configuration).

Figure 13. Mean surface deformation in function of \( o \) (the red "X" symbol shows the nominal configuration).

First, by increasing \( o \) and keeping the same reference velocity \( (U_0) \), the velocity amplitude at the nozzle exit is decreasing. Therefore, the momentum of the airphase in the nozzle region is smaller and the same decreasing effect can be observed, as by changing \( U_0 \).

However, one can compare the cases, where \( o = 25.4 \text{ mm} \) (Meas.#19), and the one, where \( U_0 = 6.06 \text{ m/s} \) (Meas.#2). Taking into account the continuity of the present non-compressible flow, the flow velocity at the nozzle opening should be the same. However, while with the first case, the deformation is 1.74 mm, in the latter configuration it resulted to be 0.96 mm. Thus, apart from the modified local velocity magnitude, the \( OT2NT \) parameter plays also role in the change of the interaction between the nozzle head and the airflow.

B. About the instantaneous surface

During the 100 Hz image recording, which serves as the basis of the surface shape study, the spray device is inactive. Thus, there is no accumulation and therefore, the liquid volume in the cavity should be constant in time. However, as it is indicated in Fig. 14(a), the volume evolution fluctuates in a 0.15 litres wide range. This is due to the three-dimensional waves that are present in the cavity. Since the measurements are performed in a plane, the waves are causing artificial volume oscillation. This effect is also contributing to the increasing volume fluctuation that was mentioned earlier during the accumulation measurements.

However, thanks to this artifact, using the Fast Fourier Transformation (fft), the frequency of the out-of-plane liquid fluctuation can be determined. The result of the fft is shown in Fig.14(b), where frequency contents around a 4 Hz peak can be observed.

Going further, the goal is to determine the frequency content of the signal that represents the movement of the liquid surface within one given pixel column of the images. As one can see, the three-dimensional effect complicates its evaluation.

However, knowing already the variation of the mean surface level, its motion can be subtracted from the local (one pixel location) information. Focusing on the frequency content, the fft of the volume fluctuation
is therefore subtracted from the fft of the signal that represents the movement of the liquid surface within one pixel column. The original Power Spectral Density (PSD) and the one after the subtraction can be seen in Fig.15 corresponding to a pixel column, which is located 51 mm from the nozzle lip.

![Volume over time](image)

(a) The evolution of the liquid volume.

![Frequency content](image)

(b) The frequency content of the fluctuation.

**Figure 14.** Liquid volume, while the spray is off in the nominal configuration (Meas#1)).

**Figure 15.** The characteristic frequencies at 51 mm from the nozzle in the nominal configuration.

Using this method, the evolution of the frequency content of the surface movement around the maximal peak position of the mean surface (taken at Position = 51 mm in the nominal configuration; see Fig.11) is investigated in function of $U_0$ and $w$.

Due to the previously mentioned bursts in the surface, $U_0 = 14$ m/s is not taken into account during the analysis.

Fig. 16(a) shows the fundamental frequency (that represents the largest energy content) evolution in function of the reference velocity. According to the results, in the region of the maximum level of the mean surface, the fundamental frequency is monotonically decreasing with increasing flow velocities in the investigated range.

Concerning the cavity width (see Fig. 16(b)), by increasing this parameter, the fundamental frequency also decreases until reaching the nominal configuration ($w = 107.2$ mm). However, by increasing $w$ even more (up to $w = 139$ mm), the fundamental frequency does not show any change according to the present measurements.

Furthermore, in case of $w$, the frequency is changing in a wider range with respect to $U_0$, which proves that the cavity width is more influential on the fundamental frequency of the free surface movement in the center region of the cavity.
VI. Conclusion

The present paper describes the work performed with the help of the LeDaR measurement technique to investigate the driving parameters of the liquid accumulation in the model of the nozzle cavity of the Ariane 5 boosters. The current study is the continuation of the work presented by Tóth et al.19

First of all, the LeDaR technique had to be adapted to the current condition, especially to the presence of large quantity of water droplets.

During the experiments the effect of various geometrical parameters (inhibitor size and position, the width of the cavity and the opening of the nozzle throat) and the flow velocity, are taken into account.

After processing the recorded images, from the time evolution of the liquid volume, the rate of droplet entrapment is determined. Then, the rate of accumulation is plotted in function of each parameter. Investigating these graphs, the outstanding importance of the inhibitor height (\(h\)) is shown.

In addition, a new quantity is defined: the obstacle tip to nozzle tip (\(OT2NT\)) distance. In function of this parameter, after a constantly low accumulation rate, above about \(OT2NT = 20\) mm, the portion of the entrapped droplets is found to increase gradually.

Therefore, this parameter (\(OT2NT\)) is considered to play the primary role in the droplet accumulation process. Furthermore, the secondary role of the cavity width (\(w\)) and the reference flow velocity (\(U_0\)) are pointed out as well.

Taking the advantage of the optical measurement technique, the shape of the accumulated liquid surface is investigated as well. The influence of the flow velocity (\(U_0\)) and the \(OT2NT\) distance on the in-plane mean surface deformation are shown.

Finally, a short analysis is presented in order to give an idea about the motion of the free surface. Here, the relevance of the cavity width (\(w\)) is emphasized.

In the future, the two-phase flow-field should be studied with the help of two-phase PIV measurements using some relevant configurations in order to understand the physical forces that lead to the observed characteristics.

However, it is already visible that in case of a real SRM the rate of slag accumulation could be reduced most effectively by using inhibitors with smaller internal diameter and/or by placing an additional obstacle in the proximity of the nozzle. The present results show that installing a second inhibitor even with a smaller blockage ratio, the amount of the accumulated slag should already be lower.

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References