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## Experimental Evaluation of the Applicability of Capacitive and Optical Measurement Methods for the Determination of Liquid Hydrogen Volume Flow

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**Abstract:** This paper presents a capacitive and a vision-based method for measuring the velocity of cryogenic hydrogen flows. The capacitive sensing principle exploits the spatial frequency signature of perturbations moving through a multi-electrode structure. This setup increases the sensitivity to dielectric permittivity variations compared to a simple two-electrode structure while preserving the ability to detect small perturbations. The vision-based method relies on a high-speed camera system that monitors the liquid hydrogen flow through an optical window yielding the flow velocity by cross-correlating subsequent images of the flow. Although a comprehensive analysis of the obtainable measurement uncertainty was not performed yet, current measurement results show the applicability of both principles for the non-invasive measurement of the volume flow of cryogenic fuels inside conveyor pipes. *Copyright © 2009 IFSA.*

**Keywords:** Flow velocity measurement, Cryogenic media, Capacitive sensing, Optical sensing, Non-invasive measurement

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### 1. Introduction

Cryogenic fuels (e.g. liquid hydrogen, liquid natural gas) bear the potential of becoming an important energy source in the automotive field since the combustion of hydrogen and hydrocarbons with low

carbon rate results in a significant reduction of greenhouse gas emissions. Hence, in a mid-term and long-term view, cryogenic fuels can play an important role as a fuel for transportation due to the increasing environmental awareness and the foreseeable cutback in fossil fuels.

In order to operate both mobile and stationary tank systems for cryogenic fuels in a safe mode, appropriate sensor systems for state monitoring are required. Primarily, robust fill level and/or flow sensors are needed to perform real-time state monitoring of tank systems and to guarantee accurate billing at fuel stations. For fill level measurement, multiple approaches exist, but there is a lack in robust, accurate and cost-effective sensors for measuring the flow rates of cryogenic fluids.

Commercial cryogenic flow sensors have to fulfill the following requirements:

- Operation at the temperature predetermined by the boiling point of the conveyed fluid (for liquid hydrogen,  $T=20\text{ K}$ )
- Sufficiently low measurement uncertainty (below 1.5 % for billing purposes)
- Commercial demands (costs, lifetime)

Mobile tank systems are usually not actively cooled and therefore require high-quality thermal insulation. In order to maintain the thermal insulation properties, the additional heat input into the tank system due to the sensor has to be minimized.

In literature, both intrusive and non-intrusive measurement methods for cryogenic liquids are found: Particle image velocimetry (PIV) methods [1, 2] and capacitive or microwave cross-correlation principles [3, 4] are proposed for measuring the flow velocity of two-phase flows. Single-phase flows (no gaseous component) can be monitored by turbine flow meters [5] or differential pressure flow meters [6]. PIV principles are applicable to single-phase flows when gas bubbles are artificially created in the liquid flow [2]. Hot-wire anemometers can be used to determine the mass flow of cryogenic liquids [7].

The majority of measurement methods found in literature do not meet the demands posed on an automotive sensor since they either require complex sensor setups (PIV methods, turbine flow meter), can only be applied to single-phase flows (differential pressure flow meter, Coriolis flow meter) or are invasive and involve mechanically sensitive parts that limit the robustness of the sensor (hot-wire anemometer).

Both measurement principles proposed in this paper are non-contacting principles. The separation between cryogenic liquid and sensor front-end enables safe operation of the sensor. Moreover, the additional heat input due to the sensor system is reduced compared to contacting principles and the circuitry design is simplified due to less stringent thermal conditions at the place of the sensor head and electronics. For industrial use, the capacitive method seems more promising since the signal processing needed to obtain a measurement value is significantly lower than for the optical approach. Moreover, the fragile glass section of the tubing can easily be replaced by a different non-conducting material in order to increase the robustness of the setup.

## **2. Measurement Setup**

### **2.1. Test rig for LH2 Measurements**

For implementing the proposed measurement methods, a universal test rig for monitoring cryogenic flows was designed. The requirements on this test rig were derived from the fundamental demands posed by capacitive and optical sensors: For capacitive sensing, a non-conducting pipe section is needed in order to allow for the penetration of the applied electrical field into the pipe interior. For

optical sensors, at least a small section of the pipe has to be transparent for the specific wavelength of light used for measurement, and damp growth on this optical window has to be prevented. The test rig meets the concerns for both optical and capacitive measurement methods by using a pipe section of 230 mm length that is made of quartz glass (compare Fig. 1). The dimensions of the conveyor pipe resemble those of the tubing of current hydrogen gas stations (inner pipe diameter 10 mm), and standardized couplings are used for liquid hydrogen inlet and outlet.

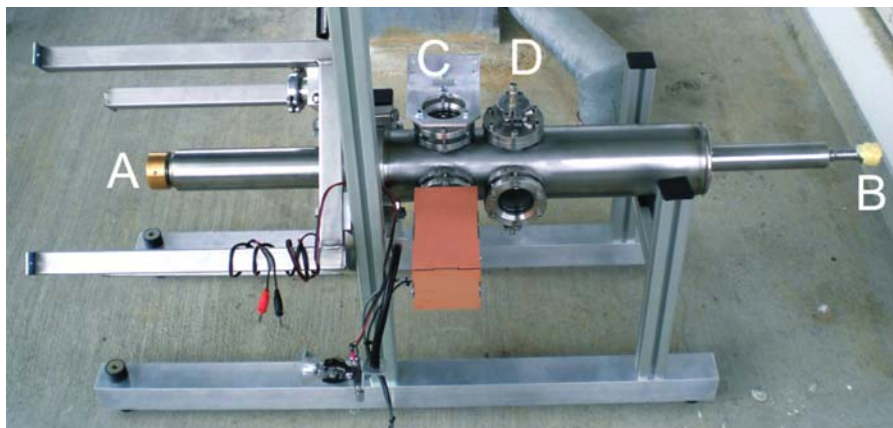


**Fig. 1.** Test rig for optical and capacitive measurements (prior to assembly): The conveyor pipe (bottom) comprises a quartz glass section of 230 mm length and two mechanical axial compensation modules to minimize the mechanical stress inside the glass section. For thermal insulation reasons, the conveyor pipe is inserted into stainless steel tubing (top) that is evacuated when operating the sensor. The outer tubing holds flanges for optical windows and electrical connectors.

In order to meet the stringent requirements concerning thermal insulation of the pipe system, the test rig is implemented as a double-walled system and the volume between inner and outer tubing is evacuated. At the position of the quartz glass pipe, eight circular openings in the stainless steel tube are arranged in two planes and are sealed with fixed flanges (Figs. 1 and 2). The flanges can be equipped with optical windows or vacuum-sealed electrical lead-through connectors. In addition to the thermal insulation, the evacuation of the setup prevents condensation of water droplets on the surface of the optical windows allowing the employment of cameras and other optical sensing components to monitor the cryogenic flow from outside the tubing.

## **2.2. Capacitive Velocity Measurement Principle**

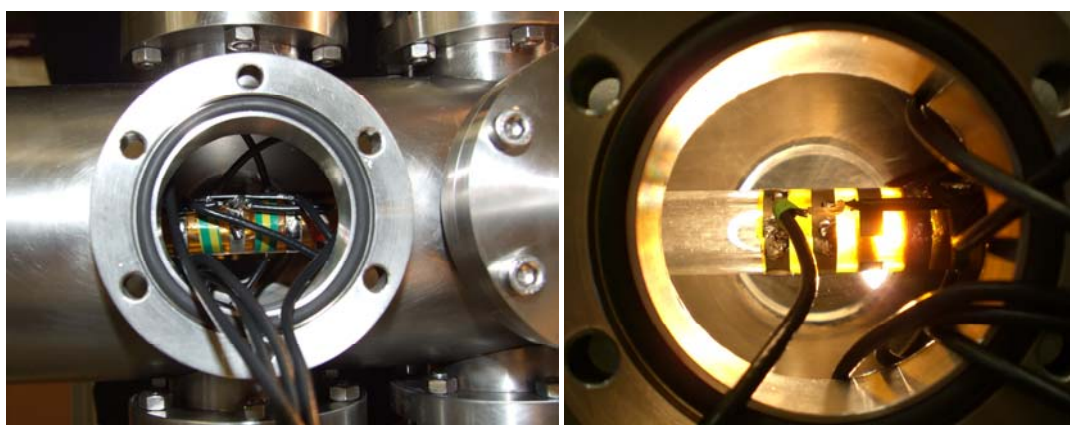
Capacitive flow velocity sensors rely on the existence of local variations of the dielectric permittivity (i.e. gas bubbles or liquid droplets) inside the flow and are commonly used in various applications [3, 8–10]. Typically, electrodes are mounted on the outer surface of the conveyor pipe in two measurement sections (“planes”) along the pipe. The primary sensor signals correspond to the coupling capacitances between electrodes in these planes that are affected by the varying permittivity value of the flow. The time delay between the sensor signals depends on the actual flow velocity and the geometric distance between the sensing sections, and is commonly computed by evaluating the cross-correlation function of the sensor signals.



**Fig. 2.** Test rig readily assembled for LH2 measurements: The conveyor pipe with the quartz glass section is inserted into the outer stainless steel tubing and can be connected via inlet (A) and outlet (B) couplings. The sensing components can be fitted to the pipe in two adjacent measurement sections (C, D). Both sections contain optical windows for measurement/surveillance purposes, while section D comprises the vacuum-sealed electrical connectors for the capacitive sensor head.

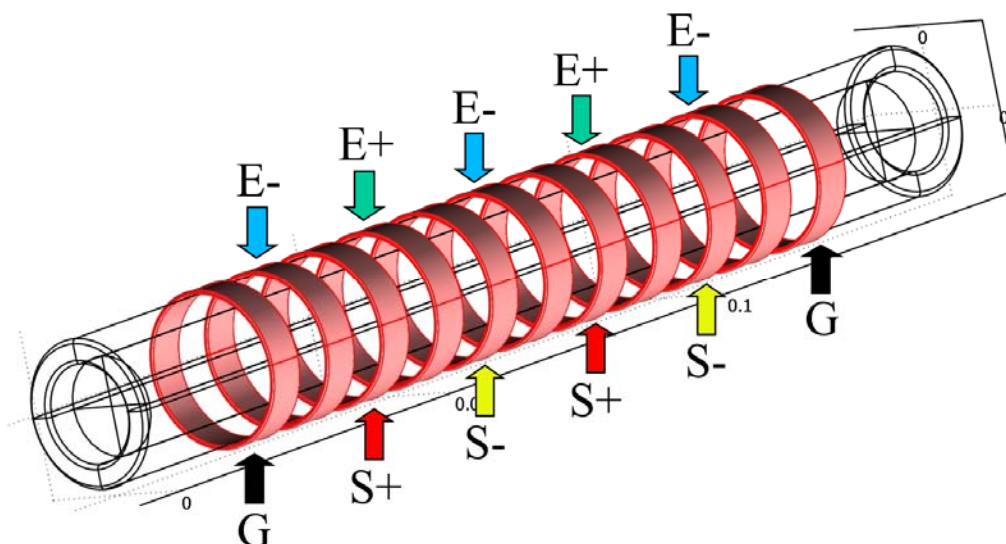
However, especially for low-permittivity fluids like liquid hydrogen the capacitance variations are rather small and the application of cross-correlation based capacitive principles is limited. Those principles yield a weak signal-to-noise ratio since the major part of the coupling capacitance originates from stray capacitances and from the high permittivity value of the pipe itself. Better results can be obtained by increasing the electrode dimensions or by using longer data sets when computing the cross-correlation function. However, this either reduces the capability of the sensor to detect small bubbles in the flow (due to spatial averaging) or prevents monitoring short-term variations of the flow velocity (due to increased correlation times).

Hence, the sensor principle presented in this paper uses a spatial filtering approach [11, 12] that allows an enhancement of the signal-to-noise ratio while maintaining the capability of detecting geometrically small permittivity variations. The sensor comprises a set of 11 ring-shaped electrodes located on a flexible printed circuit board that is wrapped around the transportation pipe (Fig. 3) and was first presented at the International Conference on Sensing Technology (ICST' 2008, [13]).



**Fig. 3.** The electrode structure on flexible printed circuit board is wrapped around the circumference of the quartz glass pipe: Left: Connection with RG174 coaxial cables before closing the tube opening; Right: Four electrode rings are visible when backlighting the quartz glass pipe.

The electrode topology is shown in Fig. 4: Four electrode rings are used as active (transmitter) electrodes. Five electrodes represent the measurement (receiver) electrode structure while the remaining two electrodes are grounded to obtain a well-defined measurement volume. Along the pipe axis, the transmitter and receiver electrodes are operated with alternating polarity yielding a nearly sinusoidal and offset-free sensor output signal (i.e. displacement current at the receiver) for a single particle passing through the electrode structure with constant velocity [12]. The amplitude of the measured signal depends on the size, position and permittivity value of the moving particle while the frequency of the signal is affected by flow velocity and distance between adjacent electrodes.

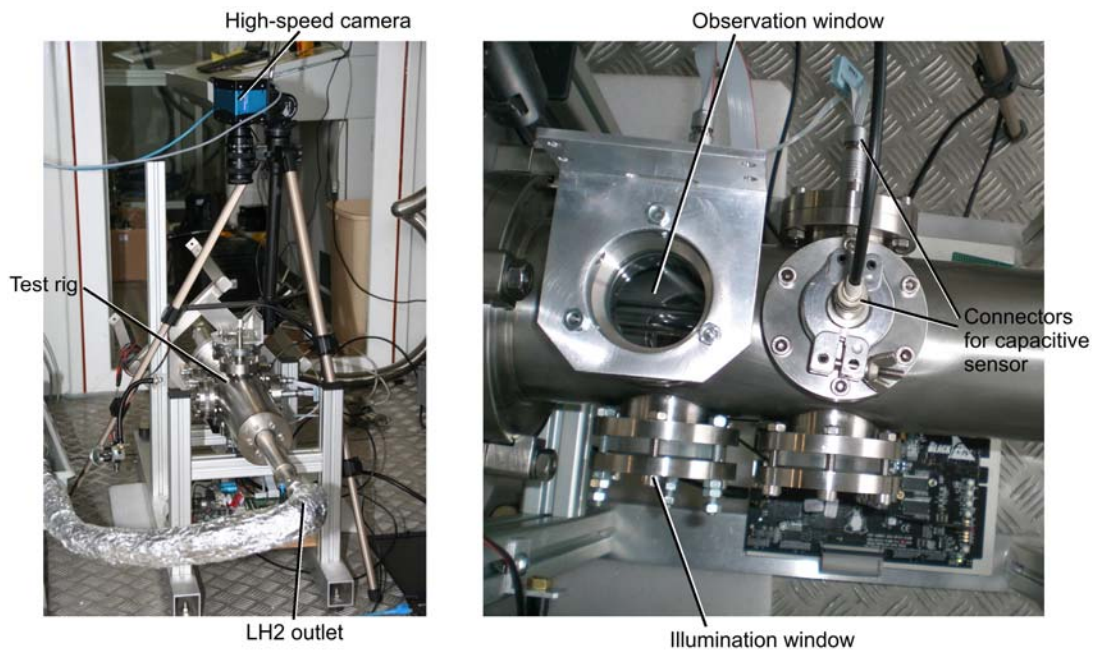


**Fig. 4.** Schematics of electrode structure and control: Active electrodes are excited with non-inverted (S+) and inverted (S-) AC signals; the receiver electrode structure (E+/E-) is built up fully differential; grounded electrodes (G) are located at both ends of the sensitive area.

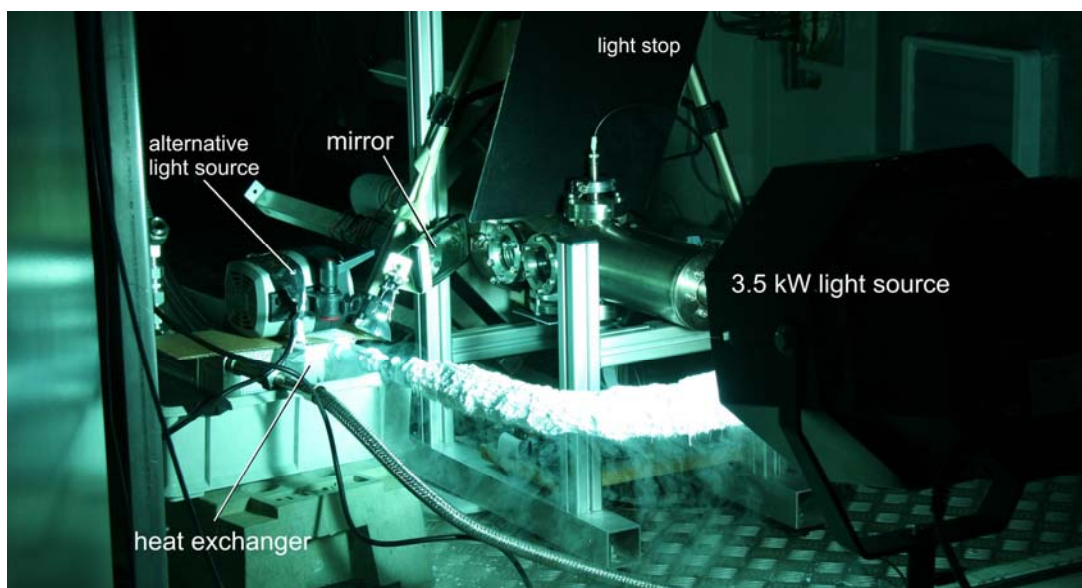
### 2.3 Optical Velocity Measurement Setup

The optical velocity measurement is performed by using a standard high-speed camera capable of recording full-frame video streams with up to 1000 frames per second. The camera system is located outside the evacuated test rig described in section 2.1 and monitors the flow from a distance of approximately 0.55 m (compare Fig. 5). Although the large distance between conveyor pipe and camera is impractical for industrial use it offers the possibility of neglecting the different perspective views of particles with varying distance from the camera system (the error due to the unknown distance is well below 1 %). Hence, standard lenses can be used instead of telecentric lens systems.

The pipe section that is covered by the camera system has a length of approximately 35 mm. In order to derive the flow velocity, the same particles have to be imaged on subsequent frames. Considering a maximum liquid hydrogen flow velocity in the range of 5 m/s, the observed structures are spatially shifted by 5 mm per millisecond. To operate the camera at the maximum frame rate (1000 fps) and to minimize smearing effects due to long exposure times, we use a 3.5 kW light source allowing exposure times of 167 microseconds (Fig. 6).



**Fig. 5.** Measurement setup with high-speed camera to track bubbles and droplets in the cryogenic flow (left); view from above (right) showing the optical windows for illuminating the flow and for monitoring the flow with the camera.



**Fig. 6.** High-speed camera measurement setup during experiments: Labeled are the 3.5 kW light source to illuminate the liquid hydrogen flow, the mirror to redirect the illumination into the conveyor pipe, the light stop to avoid artifacts due to direct illumination of the camera lens and the heat exchanger introduced for reference measurements of the mean volume flow by means of hot-wire flowmeters.

### **3. Data acquisition and Processing**

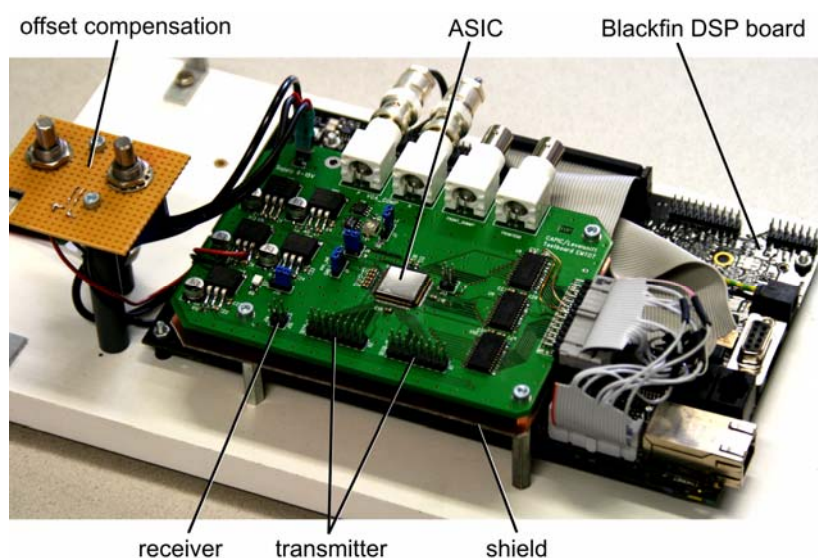
#### **3.1. Capacitive Method**

For the implementation of the capacitive prototype sensor, we use a rapid prototyping system for capacitive sensor design that was designed at the Institute [14]. The system consists of a capacitance-

to-digital ASIC [15, 16] in conjunction with a Blackfin digital signal processor (DSP) board running uCLinux (Fig. 7).

The ASIC generates the transmitter electrode signals and measures the displacement current at the receiving electrode. It also features an integrated 12 bit analog-to-digital converter for A/D conversion of the analogue measurement signal. The Blackfin digital signal processor provides the control signals for the ASIC and performs basic preprocessing before transferring the measurement data to a PC, where the signal processing of the sensor data is performed using MATLAB:

For each data record, the mean power spectral density (PSD) is computed by averaging the spectra of a given number of overlapping sub-intervals to reduce the noise level. A peak search algorithm is then used to extract the predominating peaks from the spectra. Considering the inter-electrode gaps, the frequencies of the peaks are used to compute the flow velocity. For the given sensor geometry, a frequency of 50 Hz corresponds to a flow velocity of 1 m/s. However, the carrier frequency measurement principle operated with low-bandwidth band pass filters in the MHz range prevents interference effects due to the power line frequency.



**Fig. 7.** Rapid prototyping system used for generation of transmitter electrode signals and measurement of displacement current: A capacitance-to-digital ASIC is controlled by a Blackfin DSP.

### 3.2 Optical Method

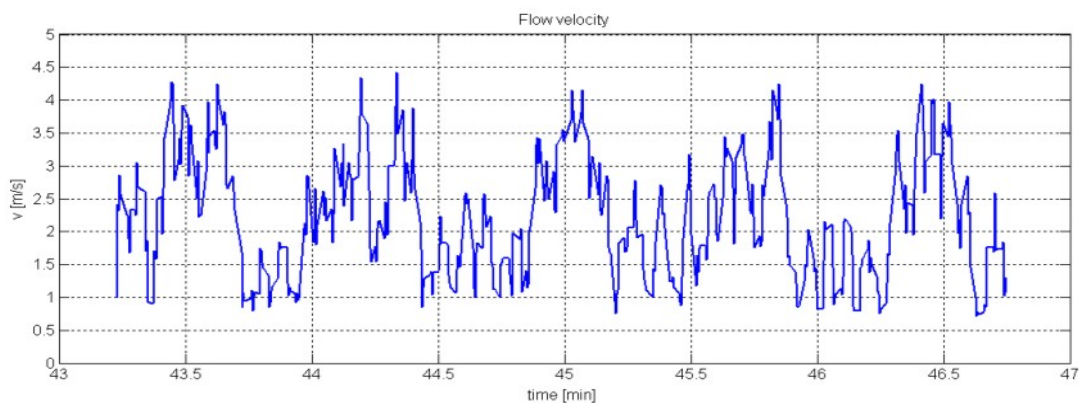
The camera used communicates with the control PC via local area network. The images are recorded as a video stream with a resolution of 1280x1024 pixels and a frame rate of 1000 fps resulting in an uncompressed data rate of 1.22 GB/s.

Signal processing is performed using MATLAB. We first compute mean intensity values for each pixel of the images by averaging a sequence of frames. The difference between each image and the averaged image yields the brightness variations due to moving particles while eliminating stationary features in the images (i.e. direct reflections of light on the surface of the glass pipe). In the last step, we compute the two-dimensional cross-correlation between two subsequent images to obtain a mean shift between these images. From the length of the shift vector and the known geometric dimensions of the setup, we deduce the mean flow velocity.

## 4. Measurement Results

### 4.1. Results Using Capacitive Principle

For each measurement sequence, we acquire a data record with 1 s duration and apply the signal processing described in section 3.1. The variations of flow velocity over time are then obtained by repeating this procedure for many subsequent acquisition intervals. A typical velocity curve measured using the capacitive spatial filtering principle is plotted in Fig. 8.



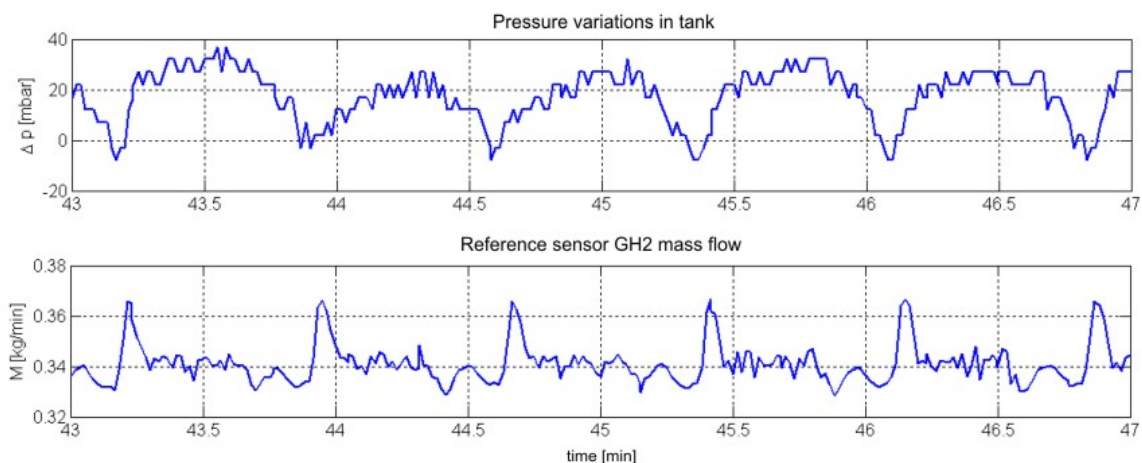
**Fig. 8.** Flow velocity over an interval of approx. 4 min measured using the capacitive measurement method.

The diagram shows rapid fluctuations of the actual flow velocity as well as a superimposed periodic variation with a period of approximately 50 s. These periodic variations are explained by the control mode for the liquid hydrogen flow: The mean volume flow is preselected by setting a nominal value of the pressure inside the liquid hydrogen tank. Due to the continuous extraction of LH2 from the tank, the pressure inside the tank decreases. When the measured pressure falls below the predefined value, gaseous hydrogen is blown into the tank to restore the nominal pressure. This causes periodic changes of the pressure with amplitude of approximately 40 mbar (see Fig. 9, top) that are strong enough to influence the liquid hydrogen flow. These pressure variations can also be observed in the readings of a hot-wire flowmeter used for reference measurements (Fig. 9, bottom).

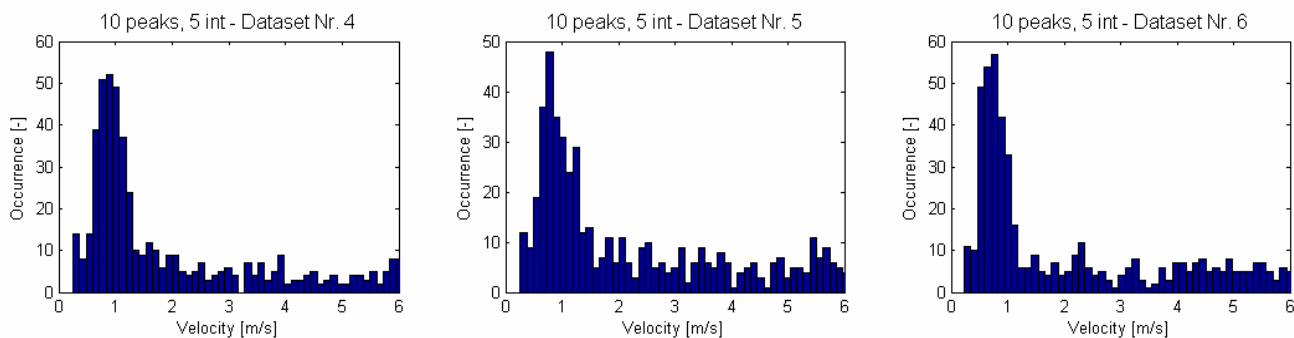
The random variations of the flow velocity are reasonable due to the highly sensitive equilibrium between gaseous and liquid phase of the hydrogen flow and the long conveyor pipe between the tank and the sensor (length approximately 10 m): The heat input along the conveyor pipe and the changing flow regime (e.g. formation and dissolution of plugs) cause variations in flow velocity that cannot be modeled in a simple way. Similar fluctuations are observed in various flows when a fast flow meter is used that does not average the measured flow over long time periods. The predominant flow velocity in such strongly fluctuating flows is usually visualized by plotting the frequency of occurrence of subsequent individual velocity measures over a given time period (i.e. plotting the velocity histogram). Three subsequent histograms for the measurement sequence plotted in Fig. 8 are shown in Fig. 10.

### 4.2. Results from High-Speed Camera Measurements

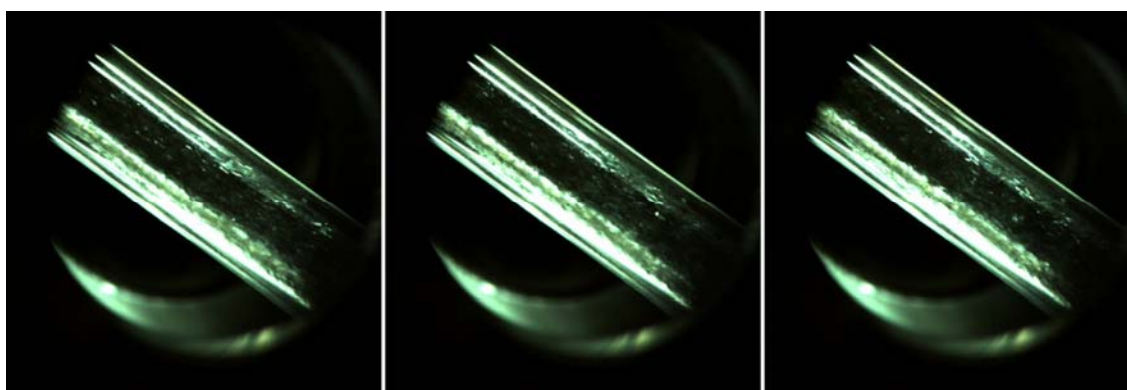
Fig. 11 shows a sequence of typical images taken by the high-speed camera at 1000 fps. As described in section 3.2, the video sequences are analyzed using MATLAB. Considering the video data rate of 1.22 GB/s, sequences of more than 500 ms duration were not recorded to keep the amount of recorded video data small enough to be easily handled. All data processing was performed offline. This yields the flow velocity over short time intervals as plotted in Fig. 12.



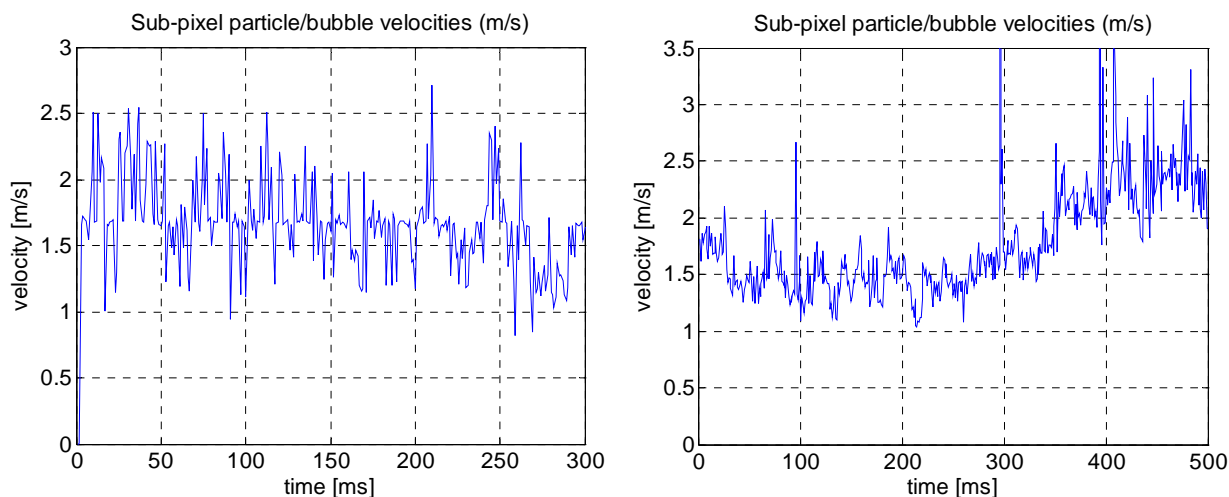
**Fig. 9.** Reference sensor readings showing the same periodicity as observed in the measurement signal of the capacitive prototype sensor. Top: Deviation of conditioning tank pressure from nominal value ( $p=3.4$  bar); Bottom: Mass flow of gaseous hydrogen obtained with a hot-wire flowmeter connected to a thermal heat exchanger on the outlet of the cryogenic flow test rig.



**Fig. 10.** Velocity histograms for three subsequent measurement intervals of 1.5 s duration each show a predominating velocity in a range of 0.9 m/s to 1 m/s.



**Fig. 11.** Three subsequent images of the liquid hydrogen flow obtained by the high-speed camera; exposure time for each frame is 0.167 microseconds, frame rate 1000 fps.



**Fig. 12.** Measurement results of liquid hydrogen (LH2) flow velocity over time intervals of 300 ms (left) and 500 ms (right) using the high-speed camera at 1000 fps. Velocity values were obtained by cross-correlating two subsequent images of the recorded video stream.

### 4.3. Discussion of Measurement Results

A direct comparison of the results of the capacitive principle and the velocities computed from high-speed camera images is not possible since the penetration depths of electrical field and visible light differ. The optical principle could not be operated continuously since the data processing was performed offline and the amount of video data is very high due to the required frame rate of 1000 fps. However, the flow velocities and velocity fluctuations obtained by means of the high-speed camera are well within the range of the values given by the capacitive principle.

For both principles, major simplifications have been made:

- The flow profile and the influence of penetration depth on the measurement results have been neglected (i.e. the predominating velocity component is assumed to correspond to the mean flow velocity).
- The flow velocities of the liquid and the gaseous component of the flow are assumed to be identical.
- For the optical principle, the lens has not been calibrated and the effect of perspective has been neglected although we do not use a telecentric optical system.

## 5. Conclusions and Outlook

The paper presents two approaches to determine the flow velocity of liquid hydrogen: The first method is based on a capacitive spatial frequency based flow measurement principle while the second method uses a high-speed camera to track structure inside the liquid hydrogen flow. The results are promising although major simplifications have been made for both approaches. As far as the results can be compared, no discrepancies can be found between the readings of the capacitive and the optical sensor. Moreover, the velocity readings of the capacitive sensor show a periodic behavior that originates from pressure variations in the conditioning tank used as LH2 source. This periodicity cannot be found in the results of the optical principle since the sequence lengths are too short to cover a complete cycle of the variations.

Both measurement principles proposed in the paper seem to be applicable for measuring volume flow of cryogenic fuels. However, for industrial use the capacitive principle has to be preferred for several reasons:

- The sensor front-end can be made up of a more robust material instead of the quartz glass pipe used in the experiments.
- The computing power required for real-time processing of the capacitance data is significantly lower than for the high-speed camera approach.
- Especially for measuring high flow velocities, a comparably expensive high-speed camera has to be used.
- A powerful light source has to be used to illuminate the cryogenic flow in order to realize the high frame rates; the light source itself must not be located in the vicinity of the conveyor pipe to avoid heating of the cryogenic fluid.

Future work should focus on deriving the volume and mass flow from the obtained sensor data. For this purpose, a flow model has to be established that yields the flow profile as well as the velocity difference between gaseous and liquid component. Mass flow can be obtained by measuring the liquid fraction of the cryogenic flow and combining the results of velocity and liquid fraction measurements. For sensors employed for billing purposes (e.g. at fuel stations) a calibration of the sensor for mass flow measurement is required. This is a challenging task since no commonly-used sensor system has been established on market that could be used as reference system.

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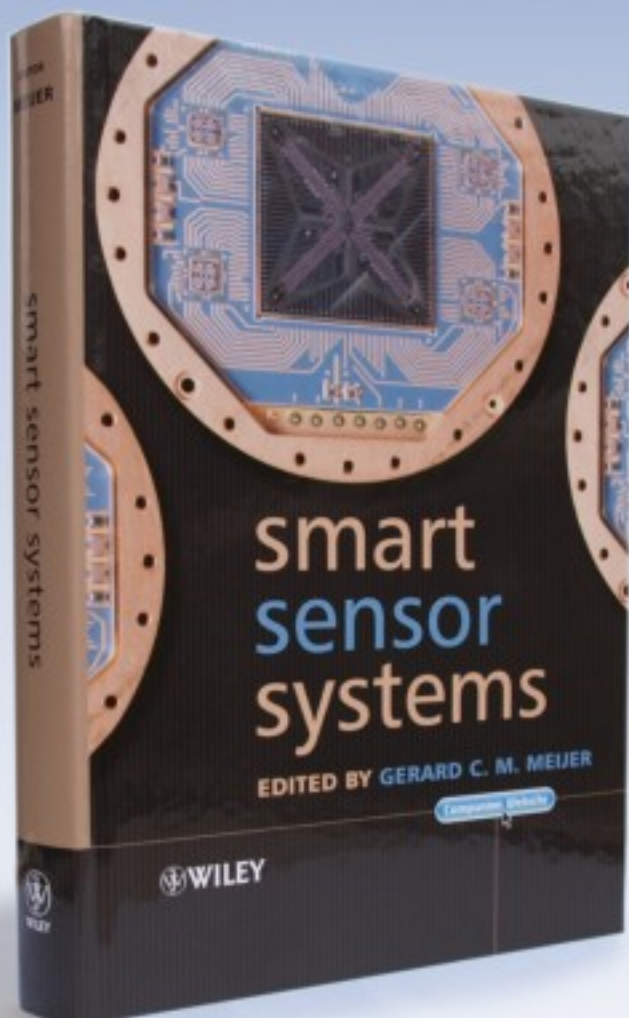
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