# SYSTEM INFLUENCE ON THE SURGE BEHAVIOUR OF A CENTRIFUGAL COMPRESSOR

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## ABSTRACT

**Instabilities in turbomachinery operation may be originated by the intrinsic flow unsteadiness, sudden variations of operating conditions, and the interaction with the surrounding system. All impact both system stability and machine reliability.**

**The current investigations focus on the system influence, experimental method, test rig layout, and instrumentation when handling with reverse and pulsating flow. The evaluation of the system influence on compressor behaviour during surge and the best testing approach to describe the unsteady area without introducing further instabilities are specifically addressed. The main investigations, through experimental analyses, include the effect of discharge volume, location of flow-meter in the test loop for a prompt detection of flow reversal, and thermal stresses leading to overheating. The results, presented in time and frequency domains, show the evolution of the most relevant parameters during the surge and reverse flow phenomena and play a key role for the simulation of more complex dynamic scenarios.**

## KEYWORDS

Compressor test facility, unsteady flows, turbomachinery instabilities, surge cycles, flow visualization, system influence

## NOMENCLATURE

| | | |
|---|---|---|
| f | [Hz] | Frequency |
| m | [kg/s] | Mass Flow Rate |
| n | [rpm] | Rotational Speed |
| $p_i$ | [bar(a)] | Suction Pressure |
| Q | [m3/s] | Volumetric Flow Rate |
| q* | [%] | Relative Flow Rate (to nominal value) |
| LSV | | Large Surge Volume |
| SSV | | Small Surge Volume |

## INTRODUCTION

The flow unsteadiness in turbomachines, presenting a characteristic behaviour, requires a deep understanding of the underlying flow fundamentals, a careful analysis through advanced experimental methods and a clear distinction on how the surrounding system might lead to instabilities. These impact both system stability and machine reliability.

As presented in previous publications, this study is part of a broader research activity at the Norwegian University of Science and Technology – Energy and Process Engineering Department – comprising the study of the impeller stage capabilities, transient flow regimes, erosion, surge instabilities and the electric motor drive control and monitoring. The main application field of this specific design is subsea compression, in which process simplification and increased recovery from existing offshore gas and condensate fields yields a considerable value. However, a deeper understanding of surge development and system influence benefits many other compressors applications.

A critical literature review, with a particular focus on the system influence, experimental method, test rig layout, and instrumentation when handling with reverse and pulsating flow, is presented. This provides an overview of previous and similar approaches to accurately detect surge behaviour and on relevant correlations between flow oscillations and system characteristics; useful insights for the current research are highlighted.

In (Helvoirt, 2007), a centrifugal compressor is tested over a wide speed range (6000 - 16000 rpm) and suction pressure range (1-15 bar), operating $N_2$ gas. The authors report that, despite the uncommon, closed loop configuration, these last components should have effectively decoupled the suction and discharge sections. Mass-flow measurement is performed through an orifice meter with a diameter ratio 0,533 (in accordance with ISO 5167-2 (2003), accuracy ± 3.5 %), sample time of static measurements 5 s, while dynamic pressure measurements (sampling rate 1.28 kHz) by Kulite pressure transducers in suction and discharge pipes, and accuracy ± 5.8 %. Small fluctuations around the top of each surge cycle are possibly due to traveling waves in the suction piping and gas cooler. No unsteady mass flow measurements are available in the positive slope region.

In (Belardini et al., 2015-2016), a booster compressor is forcing the flow to be stable in reverse flow. The instrumentation (Kulite thermocouples and Kiel probes) has been rotated to properly detect reverse flow.

In (Baldanzini et al., 2018), different levels of surge intensity were induced on a full-scale centrifugal compressor (comprising 3 sections with independent closed gas loops, 2+3+2 impellers, recycle and bypass valves), thanks to the complex arrangement of the gas loops and several valves used to recycle the compressed gas. Dedicated instrumentation provides accurate measurement of axial displacements and thrust, and flow-rate measured by differential compressor section pressure transducers, using orifice plates installed reversed on each discharge.

In (White and Kurtz, 2006), the requirements of modern surge control systems, including algorithms, instrumentation, piping layout, sizing considerations for pipe volumes, and valves, are discussed. Surge is a particular issue in systems with low frequency pulsations.

Among the highlighted essential fields of action to avoid surge, the following ones are particularly relevant for the investigations of this paper: a precise surge limit model, proper instrumentation in terms of responsiveness, range and accuracy, a suitable recycle valve, capable both of large or small, rapid or slow opening and still presenting the dominant lag, and finally the right matching between valve response and piping characteristics. This same Author suggests, if possible, the flow-meter be capable of developing high differential pressure signals, while orifices, with their abrupt restrictions, might yield turbulence and high noise levels. A suction-to-eye method is deemed as preferred.

The evaluation of the system influence on compressor behaviour during surge and the best testing approach to describe the unsteady area without introducing further instabilities are specifically addressed: the experimental technique is employed and described in detail in this paper, while performance modeling validation, object of parallel studies, will be presented in future publications.

The main investigations include:

- Effect of discharge volume;
- Effect of the location of flow-meter in the test loop for a prompt detection of flow reversal;
- Thermal stresses on the machine, leading to overheating.

The results presented in time and frequency domains show the evolution of the most relevant parameters during the surge and reverse flow phenomena and play a key role for the simulation of more complex dynamic scenarios.

This wide collection of test data is of great value for a further understanding, the development of more reliable plant surge onset prediction models and control strategies.

## Unsteady flow and instabilities in turbomachines

A distinction between the inherent flow unsteadiness in the turbomachinery channels, related to variations in static pressure yielding stagnation enthalpy changes, and the machine instability with regards to the surrounding system, relating to the operating point, is needed. Stability of a system, instead, is related to the response to an external disturbation.

As the flow-rate is further reduced after the peak pressure ratio is reached, a significant change in flow pattern occurs. The compressor can either enter into rotating stall or surge, the former being a circumferentially rotating non-uniform pattern (with a single or multiple stall cell, involving up to the full-span blade height) with a machine performance impairment but constant overall mass-flow, while the latter (once fully developed) an axisymmetric phenomenon involving the whole machine, featuring mild or severe pulsations in the overall flow, up to reversal, affecting stability. At its inception, even surge may be circumferentially asymmetric, yielding intense radial load. The frequency of rotating stall is affected by the number of cells, while that of surge is related to the filling of the storage volume. The focus of this paper is on the surge phenomenon, which is a cyclic phenomenon featuring the following stages: initiation, blowdown, achievement of a minimum value, and final recovery.

## The phenomenon of Surge: characteristic parameters

The presence of a plenum or comparable piping volume between compressor outlet and throttle valve might lead to the establishment of a surge condition and different instability limits, owing to the faster variation of flow rate compared to the adaptation in pressure. In such case, the system instability inception is close to the pressure-flow characteristics peak.

For modeling purposes, the inertia of the flow and the volume of the plenum, hereafter depicted as surge volume, shall be distinguished.

(Greitzer, 1976) identified a key non-dimensional parameter, B, relating the natural frequency of the duct-plenum system, considering its length, cross-section, volume, the velocity of sound, and a characteristic value for the blade speed. It defines a threshold between surge and stall occurrence. Higher values of rotational speed make the system more prone to surge. This parameter compares the compressor pressure rise capability with the pressure rise required to induce mass flow oscillations: the conditions favouring surge are those reducing the pressure difference needed to oscillate the flow in the piping at the natural frequency of the system.

(Pampreen, 1993) observed that surge initiation can happen at different locations – inducer, impeller, diffuser, and its frequency and magnitude are related to the volumes of inlet and outlet ducting, with this trend: a reduction of system volume increases the frequency and reduces the amplitude, while its flow-rate at inception is independent from them.

The likelihood and magnitude of a surge event is based on key factors and mutual interactions:

- physical components, such as piping, flow volumes as vessels and exchangers, fittings, and recycle and check valves;
- compressor train inertias (fluid and compressor - driver inertias) and compressor performance characteristics;
- anti-surge system strategy, details, and timing.

An accurate surge margin definition is affected by uncertainties in prediction and transients during operation, as reported in (Cumpsty, 2004). A trade-off between safeguarding machine integrity and little impairment of performance is needed. Advances in aerodynamic and mechanical design help to restrict this limitation.

## EXPERIMENTAL TEST FACILITY

### General Test Facility Specifications

The experimental facility, presented in (Serena and Bakken, 2022) and installed at the Department of Energy and Process Engineering – Norwegian University of Science and Technology, has specifically been designed to perform local investigations as it provides optical access to the inlet and outlet sections. Different adjustments of the geometry and operating parameters are allowed by a flexible design which eases modifications of the system. This facility allows to rapidly test transient conditions too. A specific view of the compressor is on Figure 1.

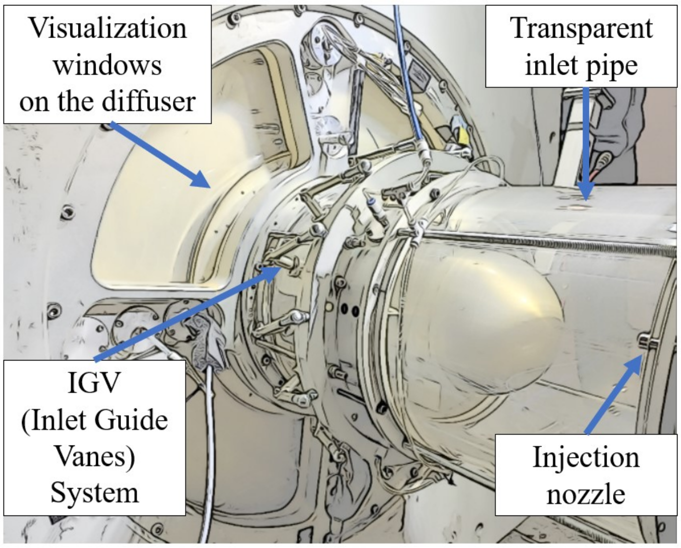

**Figure 1: View of the compressor: visible are the IGV system and visualization windows (both specifically subject of parallel studies)**

This research is a parallel activity to the wet gas compressor project, as presented in (Hundseid and Bakken, 2015). Common investigations and purposes comprise the study of the impeller stage capabilities, transient flow regimes, erosion, surge instabilities and the electric motor drive control and monitoring capabilities. This provides very useful guidelines for a clear setting of test procedure and key parameters measurements to detect unsteady phenomena under transient conditions, with instrumentation available for field operation and separating compressor behaviour from system response.

The test facility, presented in Figure 2, allows the required responsive dynamic measurements; tests are performed covering a broad range of flow rates, over three different rotational speeds. The focus area is on the rapid cycles across the zero-flow axis.

The single-stage compressor features a shrouded centrifugal impeller with 18 blades, outer diameter 400 mm and a vaneless volute. The compressor is driven by a 450 kW electric motor with maximum rotational speed 11 000 rpm.

An open loop system provides the operating fluid, air in this case, through dedicated supply lines. After flowing into the compressor, the flow can be derived into a tank, simulating a much longer piping section.

A particular care has been given to tuning instrumentation, so as to properly handle with transient conditions. It shall be noted that, in real applications, surge control systems are implemented in plants with commonly available process control components, often favouring reliability and ruggedness, rather than response time. The main requirement for the flow transmitter, according to (White and Kurtz, 2006), is to be one order of magnitude faster than process variations.

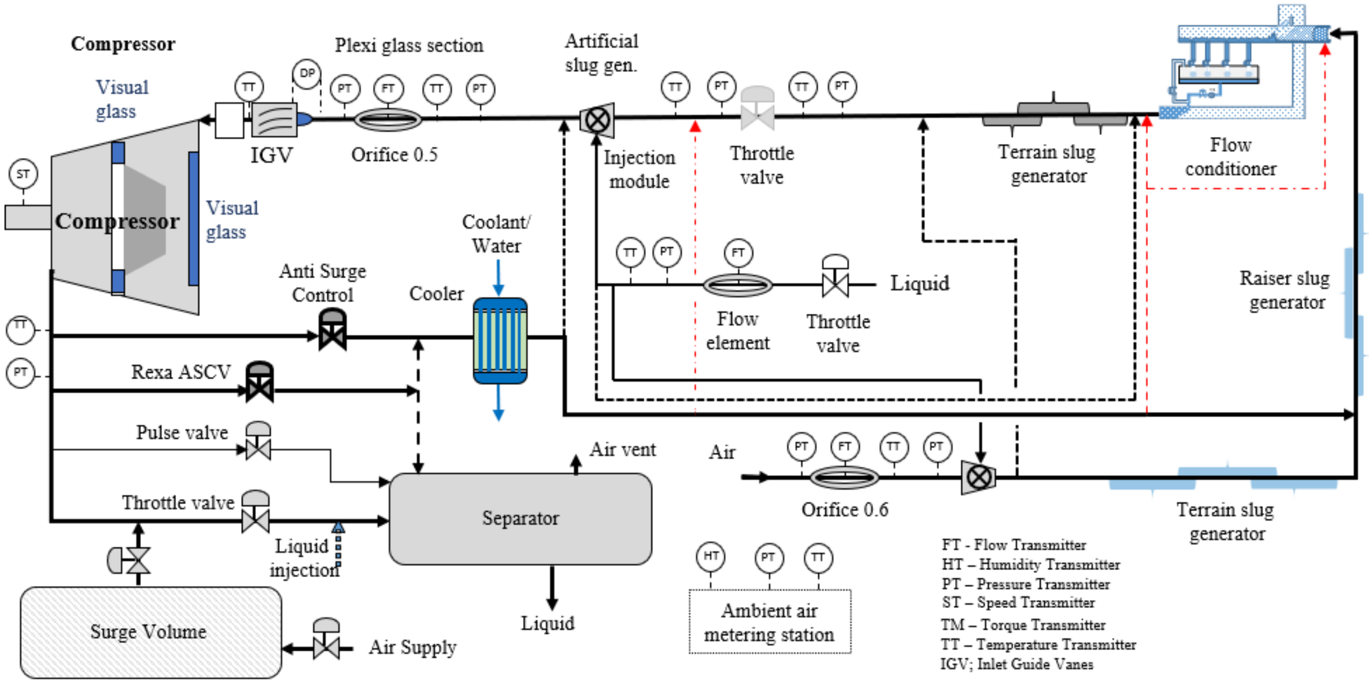

**Figure 2: Layout of the experimental setup**

### Instrumentation and data processing

A sensitivity study of the placement of the orifice flow-meters highlighting its effect on surging inception detection and study of the temperature effect is performed.

While calculations for steady-state performance points flow are made in accordance with ISO 5167, unsteady conditions make an accurate description of the instantaneous flow direction and module quite challenging. Flow is considered to be reverse when the pressure difference across the flow-meter becomes positive. The orifice 2, designated as 0.5 in the test rig scheme, is installed closer to the compressor inlet, to detect any inlet flow instabilities and reverse flow condition. The reverse flow accuracy has been validated against orifice 1, designated as 0.6, readings when the 0.5 orifice has been installed in reverse flow direction.

To detect pressure pulsations, piezoelectric fast-response pressure sensors, coupled with a high-sampling rate acquisition system, are installed at the impeller entrance and outlet.

The static pressure sensors signals are acquired at f = 10 Hz through an analog current signal, while the fast-response ones require a dedicated amplifier and are set at f = 20 kHz; the necessary frequency for a thorough analysis of the local oscillations. An overview of the instruments is presented in Table 1.

| Parameter | Sampling Rate | High Speed Sampling Rate | Uncertainty |
|---|---|---|---|
| Temperatures | 0.1 Hz – 2 Hz | | ± 0.005 ºC |
| Pressure | 1 – 10 Hz | Processing up to 20 kHz | ± 0.3 % |
| Air Flow | 1 - 10 Hz | Processing up to 20 kHz | ± 1.0 % |
| Pressure Fluctuations | 20 kHz | 20 kHz | |
| Motor Velocity | 1 – 10 Hz | Processing up to 20 kHz | |
| Torque | 9 Hz | | ± 0.05 % |

**Table 1: Logged parameters with sampling rate**

### Test Conditions

The focus of this paper is a thorough description of the machine and system behaviour, highlighting the influence of system layout and parameters.

The machine is tested over the full flow-rate, as in Table 2, with particular interest in the area between instability inception and second quadrant operation.

| Parameter | Range |
|---|---|
| Mass Flow Rate | 0 – 1.5 kg/s |
| Rotational Speed | 9 000 – 11 000 rpm |
| Inlet Pressure | 1 bar(a) |

**Table 2: Test Matrix**

### Test Procedure

Different approaches are employed to explore the specific parameters under investigation, as explained in (Serena and Bakken, 2022). The literature study revealed several methods too, as the procedure, layout, tuning of instrumentation, and especially approach of unsteady phenomena and instabilities sections are tuned to the specific need.

## TEST RESULTS

### Compressor characteristic

The test is performed at 9 000 rpm logging a sequence of steady-state points in the stable, negative slope area. After entering the surge zone, the transient path is recorded continuously logging the main parameters under investigation. The resulting characteristic curve is in Figure 3. The positive slope trajectory is presented and analyzed more in detail after Figure 6.

Detailed analysis of the positive slope operating “trajectory” shows a clear trend towards increased instability, pressure ration and inlet mass flow fluctuation as the operating point moves towards zero flow rate. At fully closed discharge throttle valve, zero net forward flowrate, the mass flow rate fluctuates between +0.15 to -0,15 kg/s. The operating point follows an “elliptical” trajectory with limited fluctuation in pressure ratio.

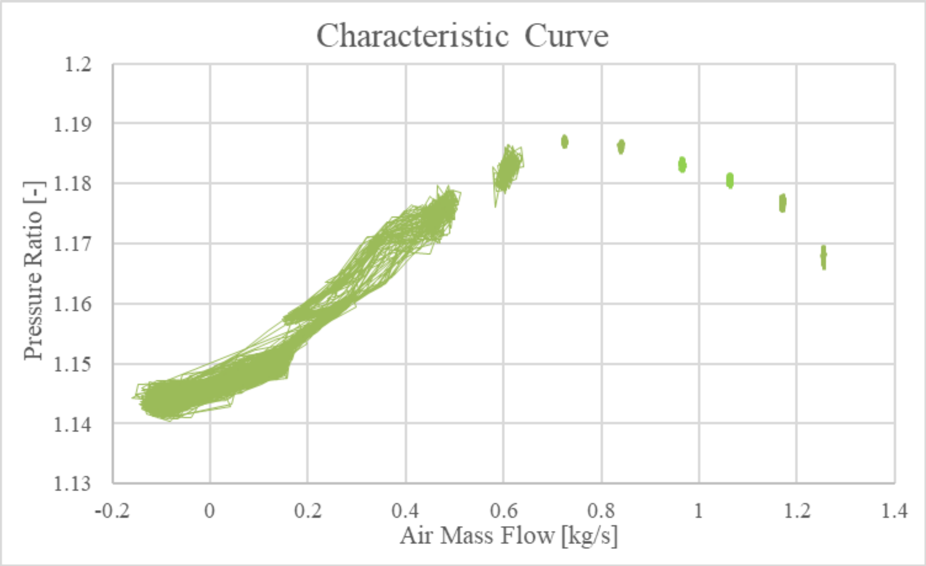

**Figure 3: Characteristic curve**

**Transient tests**

*Frequency Spectra of dynamic pressure pulsations*

The test is performed at 9 000 rpm and two relative flow rates values q* = 0 and q* = 60 %. For reference, the blade passing frequency is f = 2700 Hz. The location of the fast-response dynamic pressure sensors is 1133 mm from the compressor outlet. Figure 4 shows the FFT analysis of the dynamic pressure pulsations.

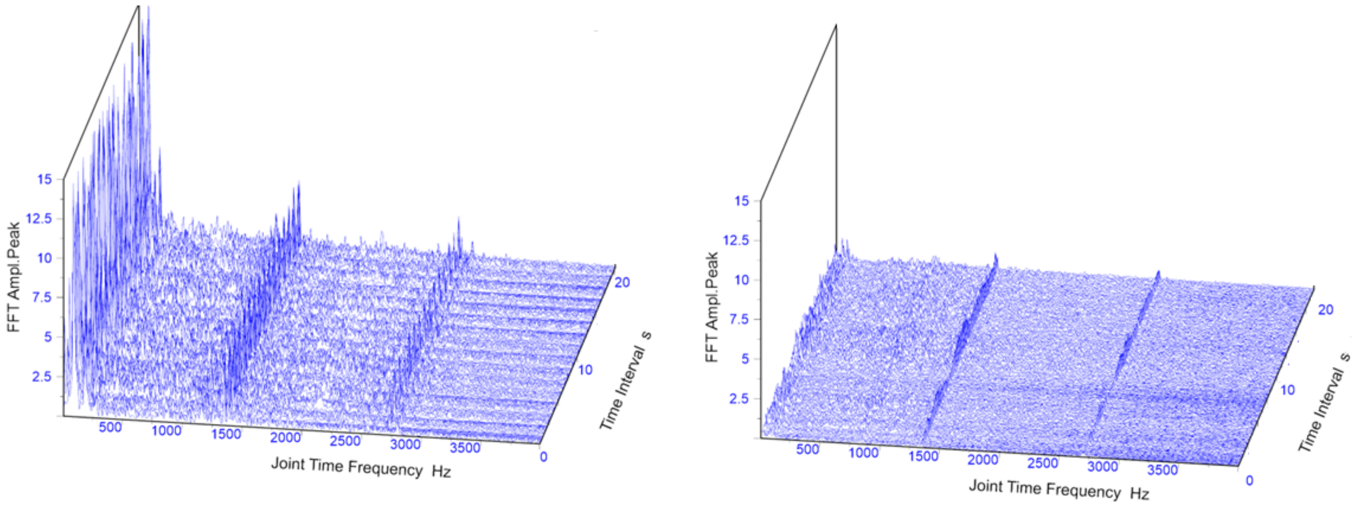

**Figure 4: Pressure oscillations frequency spectra at q* = 0 (left) vs q* = 60 % (right), please note the different amplitude scales**

At relative flow rate 60 % the FFT amplitudes are dampened with a certain peak at 2200 Hz. At relative flow rate 0 % the 2200 Hz peak remains, while the low frequency spectra is strongly intensified at full surge, across zero flow rate.

*Effect of the discharge volume section*

The compressor installation relative to the discharge pipework volume may directly affect the compressor system transient response. This especially relates to surge and surge approach operation. To validate the impact a test is performed at 11 000 rpm, and the discharge throttle valve is progressively closed and held in that position for 40 s, over 3 repeating cycles. Figure 5 shows the flow oscillations for the two surge volumes configurations. The large volume case shows the same transient while closing or opening the valve; the small volume, on the contrary, shows more intense fluctuations while recovering, more irregular and of higher frequency.

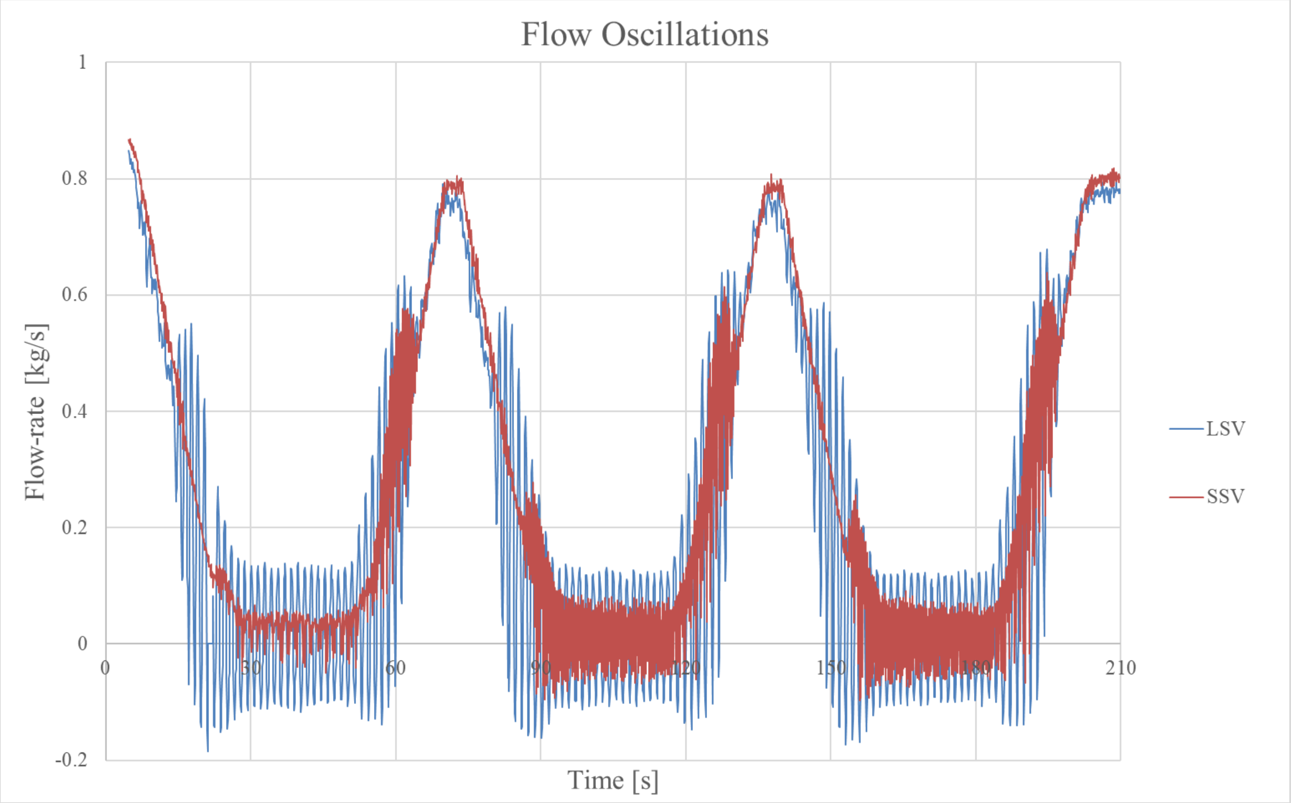

**Figure 5: Flow oscillations - small and large surge volume cases**

The small discharge surge volume is only 0.18 m$^3$, while the large one, comprising an additional manifold and tank, is 3.32 m$^3$.

With a suitable large surge volume, flow oscillations of consistent amplitude can be observed, both in the positive slope section and the full surge zero flow area. An insufficient small surge volume leads to more random flow oscillations with a scattered, less predictable positive slope trajectory due to the combined flow - pressure ratio fluctuation. The small surge volume osilations at full surge, zero flow are reduced due to the rapid discharge pressure loading and unloading.

In Figure 6, the trajectories in the positive slope area are compared. These are taken in the time interval t = 75 s to t = 90 s of Figure 5, corresponding to progressively closing the valve. It shall be noted that these trajectories vary when the valves are opened again, and the compressor recovers operation from deep surge.

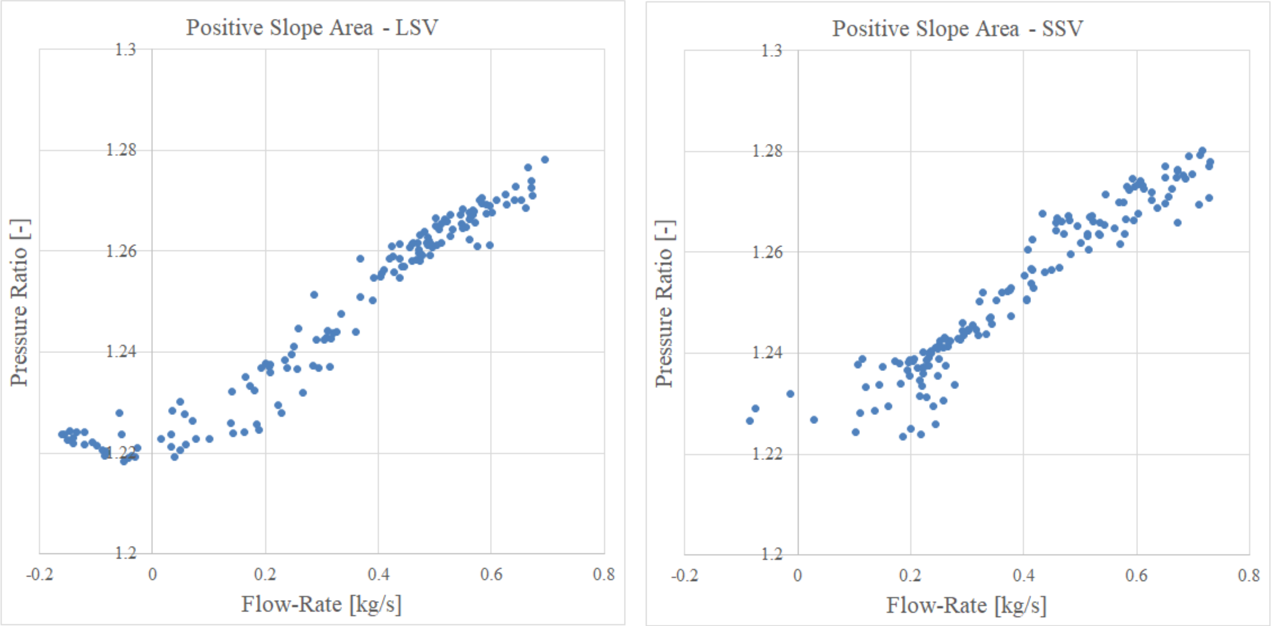

**Figure 6: Surge cycles and transient trajectories in the positive slope section in the two cases**

Detailed analysis of the positive slope operating trajectory shows a clear trend towards increased instability, accompanied by pressure ratio and inlet mass flow fluctuations, as the operating point moves towards zero flow rate. At fully closed discharge throttle valve, zero net forward flowrate, this oscillates between +0.15 and -0.15 kg/s, compared to the large volume oscillations in the range +/- 0.2. The operating point follows an elliptical trajectory with limited fluctuations in pressure ratio.

LSV shows larger, consistent pulsations over the whole trajectory, while the SSV case shows a more distinct line and larger fluctuations only after the recirculation operating area.

### *Effect of the location of the flow meter in the test loop for a prompt detection of flow reversal*

The installation of inlet flow measuring section relative to the compressor suction flange may affect the element capability to detect a representative transient response. This relates especially to surge and surge approach operation. To validate the impact a test is performed at 9 000 rpm, and surge cycles are recorded, at fully closed valve. Figure 7 shows the flow-meters signals in the two cases.

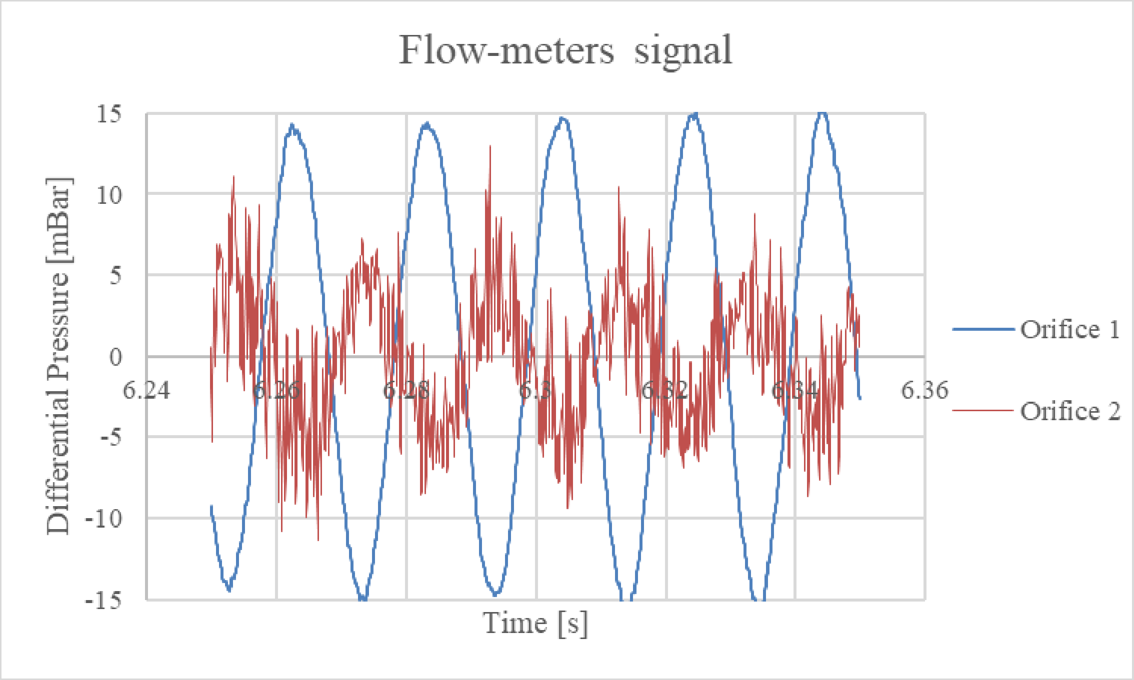

**Figure 7: Flow oscillations during surge cycles: signals measured at different locations**

Orifice 1 is installed 27.5 m upfront the compressor inlet, while Orifice 2 is 1.75 m upfront. Both elements are equipped with a similar pressure differential transducer. Figure 7 shows increased dampening the longer the piping between the sensor and the compressor inlet. It shall be noted that this type of flow meter, operating as flow restrictions, may significantly affect each other.

In planning and assessing the proper location of the flow meter, the main factors considered shall be: accessibility of installation, time delay, signal noise, frequency and amplitude, flow disturbance.

*Thermal stresses on machine: overheating*

The rotational speed is 9 000 rpm, and the fully closed valve held for 40 s, for 3 cycles.
Figure 8 shows the temperature profiles measured at the compressor inlet, diffuser and outlet, in the two small and large surge volume cases. Compressor discharge and diffuser transient temperatures remains similar for the two cases, while the large surge volume clearly affects the inlet temperature transients. Reference is given to the flow oscillations for the two surge volumes configurations, Figure 5.

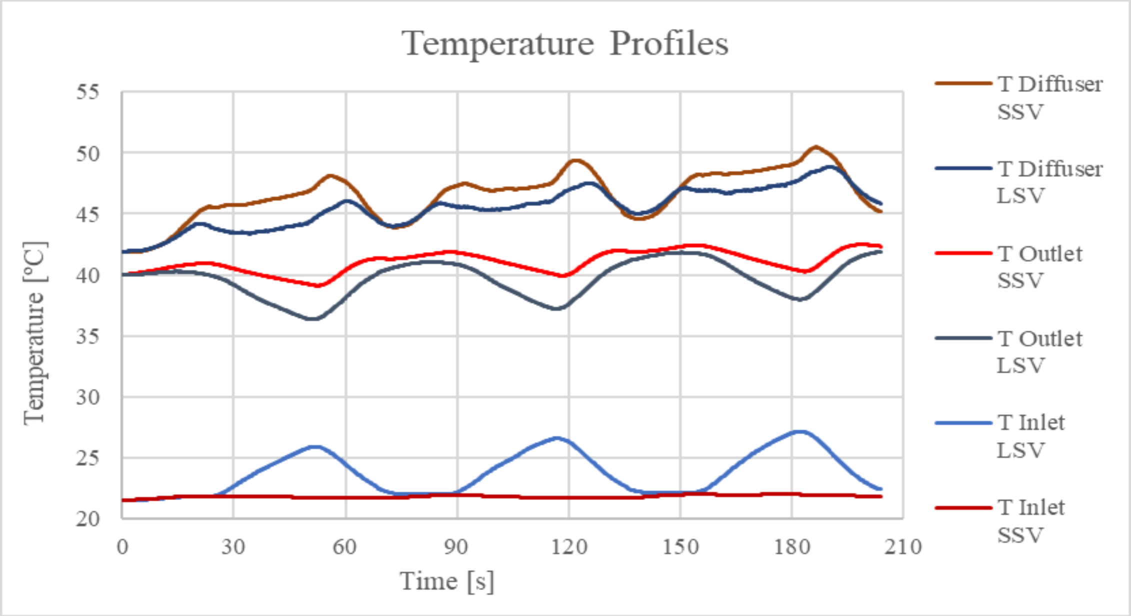

**Figure 8: Temperature difference across the compressor, with big and small surge volume**

## DISCUSSION AND CONCLUSIONS

As presented in (Serena and Bakken, 2022), surge oscillations at closed throttle featuring reversed flow, often named deep surge in other researches, are characterized by a cyclic process, starting from stall and involving a drop in mass flow rate at constant pressure ratio, then a discharge of the plenum, a change in mass flow at constant pressure ratio, and a final recovery of the system operating point.

The current research has experimentally investigated the characteristic behaviour of a centrifugal compressor operating under deep surge conditions. Useful insights on the necessary measurements for the definition of the safe operating boundaries are provided, of key importance to prevent shut-down events and failures and ensure an extended components life, yielding guidelines for measurement techniques and installations suitable to be implemented in a real-world context.

The occurrence of this and key aspects of its behaviour have been explored in this paper and are related to these main findings:

- the discharge setup plays a key influence on the occurrence and magnitude of the surge phenomenon, with a suitable plenum volume allowing the establishment of characteristic flow oscillations;
- subsynchronous pressure pulsations overall intensify as the flow-rate is further reduced away from the surge inception operating condition. Low-frequency, subsynchronous pulsations, characteristic of compressor-system interaction, present a much higher amplitude. Detailed frequency analysis will be performed at a later stage and supported by further tests;
- any measure safeguarding the system from deep surge operation benefits from a proper positioning of the flow meter detecting flow reversal, providing a clear and punctual signal;
- fluid oscillations and overheating may yield important, and potentially unbearable, stresses on the machine.

It should be remarked that the impact of unsteady flow may alter the response of the transducers, as the pulsating flow causes random pressure pulsations, making the identification of the instability onset more difficult. Therefore, the additional measurement of other parameters shall be considered in the future to overcome these uncertainties.

Further investigations comprise:

- a sensitivity study on the surge volume;
- a deeper understanding of the oscillation period with the main system characteristics and rotational speed.

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