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Frequency and Time-Frequency-based Analysis of Pressure Drop Signals in Structured Packed Columns

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This study introduces a comprehensive novel analysis of pressure drop signals in both flooded and partially flooded packed beds. Pressure measurements were taken during column operation at various liquid loads and gas superficial velocities. Different liquid loads were investigated to enable a detailed study of the dynamic behavior of the structured packing during the onset of flooding. Two complementary methods were used for data analysis, a Fast Fourier Transform (FFT) was used to identify the dominant frequencies associated with the flooded stationary state. Then, a wavelet transform-based analysis enabled a novel high-resolution time-frequency representation, revealing the precise temporal evolution of flooding dynamics. This new method facilitates the characterization of the transition from incipient flooding to fully developed flooding, and its rapid propagation from the inter-packing zone. Understanding this dynamic behavior is crucial for online monitoring, prediction, and anticipation of flooding events, thereby enhancing operational control and efficiency of structured packed column systems.

1. Introduction

Thermal separation processes are the cornerstone of the chemical industry, serving as the primary method for separating and purifying mixtures. These processes are typically carried out in columns where liquid and gas phases flow counter-currently and interact, facilitated by internal elements that enhance phase contact. In recent years, structured packing has emerged as a key technological advancement, finding widespread application in newly constructed columns as well as in the retrofitting of tray and random dumped packed columns. The primary advantage of structured packings lies in their ability to provide large contact surfaces while maintaining low pressure drops, making them, for instance, especially well-suited for vacuum operations where pressure drop constraints are critical (Brunazzi and Paglianti, 1997).

For common processes packed columns are operated between the loading and flooding points (Riese and Gruenewald, 2018, Haushofer et al, 2023). These flow regimes require accurate methods for their detection and characterization. Pressure drops, a key parameter affected by these hydrodynamic transitions, provides a valuable diagnostic tool (Brunazzi et al., 2001, Flechsig et al., 2022). However, conventional time-domain analyses often fail to capture the complex dynamics underlying these phenomena due to the detrimental effects of field noise and external disturbances (Agachi P.S., 2024; Eyng E. 2010).

To address these limitations, the present study examines the application of frequency-based and time-frequency-based analysis techniques to pressure-drop signals. Fast Fourier Transform (FFT) based frequency analysis provides insight into the dominant frequencies associated with stationary and periodic hydrodynamic phenomena, while a time-frequency approach via wavelet transform enables a detailed examination of transient dynamics and regime shifts by combining both time and frequency resolution. To the best of the authors' knowledge, this is the first time a wavelet transform-based analysis has been applied to packed bed columns. Together, these two methods provide a comprehensive framework for identifying and understanding the flooding dynamics in structured packed columns. In addition to advancing the understanding of pressure drop behavior, this combined methodology offers significant potential for practical applications. By employing FFT and wavelet analysis, it becomes possible to detect the onset of flooding in real time, enabling the development of an early warning system for column operation. Such a system could form the basis of an advanced control strategy,

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where pressure drop signals are continuously analyzed to identify hydrodynamic transitions. This information could then be used to dynamically adjust operating parameters and manipulated variables, such as liquid and/or gas flow rates, to ensure stable and efficient column performance. By serving as a key component in a broader control framework, this approach holds promise for improving the reliability and automation of industrial separation processes.

2. Material and methods

2.1 Experimental setup

Figure 1 shows a simplified schematic of the experimental setup employed in this study. The main column (C) is made of transparent polymethyl methacrylate (PMMA) to allow visual inspection and has a diameter of 100 mm. It contains seven elements of Mellapak 252.Y structured packing made of AISI 316 stainless steel. Each packing element has a height of 220 mm, resulting in a total packing bed height of approximately 1500 mm. An orifice ladder liquid distributor, located approximately 50 mm above the packing bed, ensures uniform liquid distribution. The water used in the experiments is stored in tank D2 and recirculated in a closed loop by a centrifugal pump (G). Tank D2 has an inlet for liquid replenishment and an outlet for flushing. The gas flow is supplied by a rotary compressor (P) which compresses ambient air to approximately 7 bar and stores it in tank D1. A pressure-reduced valve between D1 and the column reduces the gas pressure to 2 bar. After the valve, an in-line rotameter measures the volumetric gas flow. The gas flow rate is adjusted by acting on another valve downstream of the rotameter to limit pressure fluctuations that could distort the reading. The setup allows the study of liquid flow rates up to 600 L/h and gas flow rates up to the point of total flooding of the column. Pressure drops across the packed bed are measured by a differential pressure transmitter through sampling points strategically located within the bed to eliminate end-effects. These sampling points include two symmetrically positioned sample plugs along the column diameter to average the pressure over the horizontal cross section and mitigate the effects of any liquid maldistribution within the packing on the pressure readings. The differential pressure transmitter uses a deformable diaphragm with a strain gauge bridge that converts pressure changes into resistance changes and then into an electrical signal. A photo of the test setup with the differential pressure sensor is shown in Figure 1 (right).

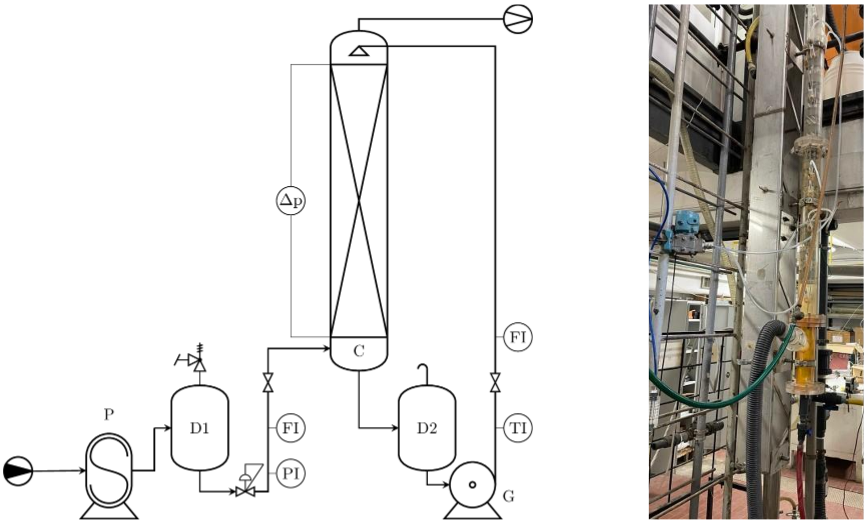

Figure 1: Experimental setup (left: schematic of the setup, right: picture of the setup)

2.2 Fast Fourier Transform, Wavelets transform and application on pressure signals

Fast Fourier Transform (FFT) analysis was selected as the primary tool for examining fluctuations in the pressure drop signals because of its efficiency in decomposing signals into their component frequencies. FFT is particularly well suited for analyzing stationary signals where the average of the signal does not vary with time. Steady-state pressure-drop signals from the column were sampled at a constant rate to ensure adequate resolution for frequency-domain analysis. The data were then processed by a custom Python script with the numpy.fft module, which provides robust and efficient algorithms for performing FFT calculations (Lee, 2019).

Continuous Wavelet Analysis was used to analyze non-stationary pressure signals where the mean of the signal changes over time. This method enables simultaneous time-frequency localization, making it ideal for characterizing transient phenomena in pressure signals (Brusco, 2022). It was used to study the evolution and dynamics of column flooding in response to a stepwise perturbation in the gas flow rate. The pressure data were processed using another custom Python script with the pywavelets package (Harris, 2020). Wavelet spectrograms were then used to examine the fluctuations by capturing local changes in frequency and amplitude over time. The choice of wavelet function and scale resolution was optimized to ensure an accurate representation of the signal characteristics.

3. Results

The obtained pressure drops per unit height of packed bed are shown in Figure 2 (left) as a function of the F-factor (defined as the product between the gas superficial velocity and the square root of the gas density, $F_V = u_{s,G}\sqrt{\rho_G}$). Three different liquid flow rates (L_V) were tested 100, 200, 400 L/h; corresponding to column liquid loads (B) of 12.7, 25.5 and 51.0 m^3/(m^{2}h), respectively.

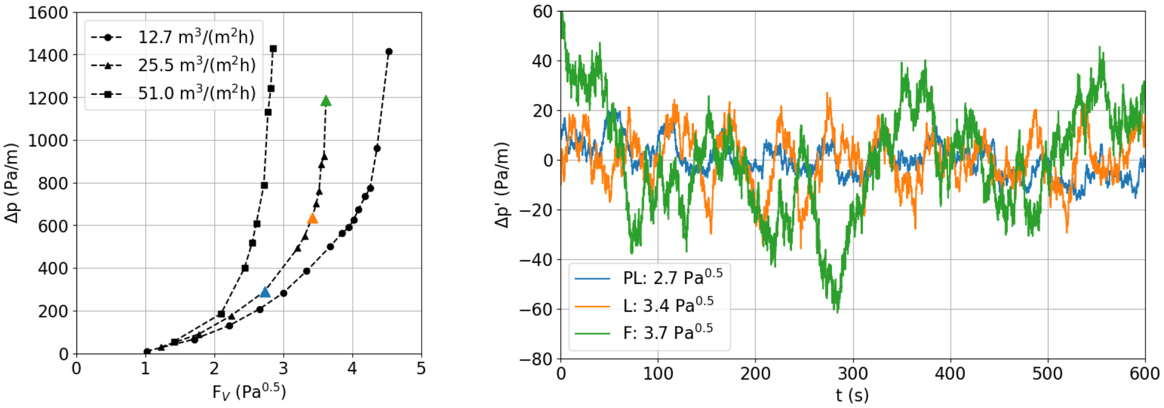

Figure 2: Pressure drop for different operating conditions (left: pressure drop curve vs F-factor for three liquid loads, right: temporal trends of pressure drop fluctuations [PL: Pre-Loading, L: Loading, F: Flooding])

The loading and flooding points identified for different liquid loads are summarized in Table 1. Interestingly, the distance between the loading and flooding conditions, expressed as the ratio of the F-factors at the respective conditions ($F_{V,L}/F_{V,F}$), decreases as the liquid load increases, indicating a less sensitive behavior of the system as the amount of liquid in the column increases.

Table 1: F-factors (Pa$^{0.5}$) for different operating points (LP: loading point, FP: flooding point)

B (m^3/(m^2/h)	LP	FP	$F_{V,L}/F_{V,F}$ (-)
12.7	4.1	4.6	0.89
25.5	3.2	3.7	0.87
51.0	2.1	2.8	0.76

Following the analysis of Haushofer et al. (2023), the time signals obtained from the pressure drop measurements were first centered by subtracting their mean values, thus obtaining the temporal fluctuations of the centered pressure drop, denoted by $\Delta p'$ in Figure 2 (right). This preprocessing step was essential to allow a meaningful comparison of the oscillatory behavior of the different signals, independent of baseline shifts. Figure 2 (right) shows the time evolution of the centered pressure drop for three acquisitions corresponding to the three different operating conditions of interest. The analyzed data-points are marked with different colors in Figure 2 (left) for clarity. These three conditions are defined by different F-factor values at a fixed liquid flow rate (corresponding to B = 25.5 m^3/(m^{2}h)): the minimum gas flow rate representing the preload condition (PL), an intermediate gas flow rate corresponding to the load condition (L), and the gas flow rate associated with the flooding of the packed bed (F).

Once centered, the pressure signals were processed to extract their frequency spectra. The data were acquired at a sampling rate of 50 ms (i.e., 20 Hz), resulting in a maximum resolvable frequency of 10 Hz for the one-sided Fourier spectrum. Figure 3 shows the calculated frequency spectra for the three liquid loads tested. While the spectra were computed for the full frequency range (0 to 10 Hz), only the results up to 1 Hz are shown because frequencies beyond this range have negligible amplitudes. The analyzed frequency spectra show that all signals display a hyperbolic trend with a prominent local maximum in the 0-0.25 Hz range, typically located near 0 Hz at low liquid loads, and shifting to 0.25 Hz as the liquid load increases. The transition between the PL and L conditions, and then between the L and F conditions, is characterized by a significant increase in the amplitude of the oscillations. Under low liquid loading conditions, as shown in Figure 3 (left), the oscillations exhibit the highest amplitudes, probably due to the huge gas flow rates required to induce flooding under these conditions. As the liquid load increases, a noticeable damping effect is observed: this effect is evident from the reduced differences in oscillation amplitudes between the different conditions (and F-factors). This phenomenon can be attributed to the increased liquid hold-up in the packed column, which acts as a damping medium. The increased liquid mass attenuates the propagation of pressure waves through the system, thereby reducing the amplitude of the oscillations. This damping effect highlights the interplay between liquid loading and gas flow rates in influencing the dynamics of pressure drop within packed bed systems.

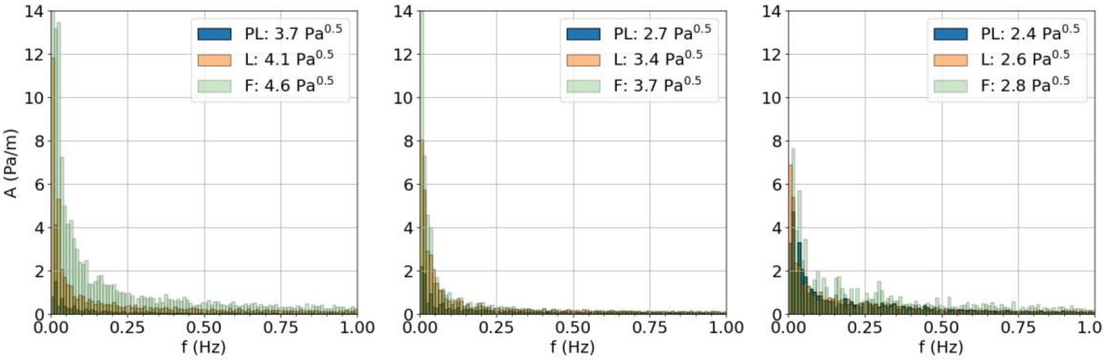

Figure 3: Frequency spectra at different column operating conditions. (left: B=12.7 $m^3/(m^2h)$, center: B=25.5 $m^3/(m^2h)$, right: B=51.0 $m^3/(m^2h)$)

Hyperbolic profiles are commonly observed in pressure drop signals from gas-liquid systems, such as in trickle beds (Prashant, 2005). Such profiles are consistent with typical patterns obtained from purely stochastic phenomena such as pink noise (1/f) and Brownian motion (1/f2) (Bak, 1987). Therefore, for these systems, the FFT analysis does not allow a robust diagnosis of the different regimes, as is obtained with similar analyses on other separation devices, such as reverse jet scrubbers, where the different regimes have truly distinct patterns (Giustacori and Brunazzi, 2025), justifying a more detailed analysis with the wavelet transform, as will be shown later. As further frequency-based analysis, the total signal power (P_{tot}) was computed as follows:

$$P_{tot} = \frac{1}{N}\sum_{i=0}^{N} A_i^2$$

where Ai is the i-th local amplitude and N is the number of frequencies. This parameter serves as a quantitative metric to distinguish between different column operating regimes. Figure 5 illustrates the total spectral power under the different conditions tested. It is clear that operating regions can be more effectively identified based on their total signal power rather than their frequency spectra. Under preload conditions, the signal power remains low, reflecting the small amplitudes observed in the corresponding frequency spectra. However, at the loading point, the signal power begins to increase for all tested fluid loads and becomes significantly higher than in the preload region. As the loading region progresses, the signal power continues to increase and peaks at the flooding point. In summary, the signal power calculation effectively distinguishes between different operating regions.

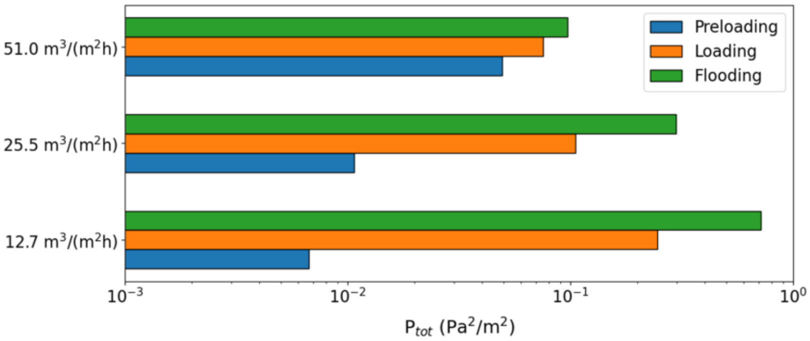

Figure 4: Total signal power histograms for different liquid loads (left: 12.7 $m^3/(m^2h)$, center: 25.5 $m^3/(m^2h)$, right: 51.0 $m^3/(m^2h)$)

To analyze the dynamics of packed bed flooding and investigate characteristic frequencies not resolved by FFT, the wavelet transform was applied to pressure drop. The signals were recorded under step changes in gas flow rate obtained by opening the control valve shown in Figure 1. Figure 5 (left) shows two example signals obtained at a liquid load of 12.7 $m^3/(m^2h)$ with two different gas flow rates varying from an initial F-factor of 4.1 (Data 1) and 4.4 (Data 2), respectively, to the same flooding condition (F-factor of 4.6). It is worth noting how the transient dynamics are highly dependent on the input variation; the settling time to reach the new steady state condition is higher as the initial distance to the flooding itself is smaller: 350 seconds for a 90% distance and 450 seconds for a 95% distance, distances expressed as a percentage of the flooding F-factor. The registered signal was processed to compute the wavelet spectrogram, with the results presented in Figure 5 (right) for the transient period between 50 and 500 seconds for both datasets.

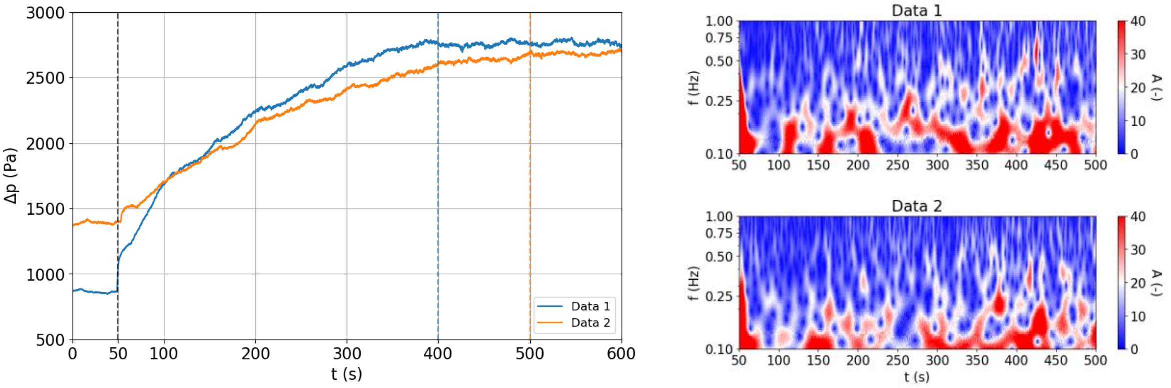

Figure 5: Wavelet analysis of pressure signal (left: analyzed stepwise signals, right: wavelet spectrograms)

The wavelet method proves to capture typical features in the pressure drop signal during incipient flooding events that are otherwise hidden in time-based or frequency-based analyses. This time-frequency analysis shows that the flooding transient is characterized by a dominant frequency of about 0.2 Hz that persists throughout the whole domain, as shown in both wavelet spectrograms in Figure 5 (right). Also, before the steady state, at around 300-350 seconds, a second higher frequency of about 0.5 Hz is visible on the spectrograms, indicating that the flooding condition is close to occur. It is important to note that these characteristic frequencies were not visible in the Fourier spectra, as shown in Figure 3.

As a matter of fact, the wavelet method can be successfully used in an online monitoring routine to anticipate the onset of flooding events. When these typical frequencies of incipient flooding are registered, automatic control strategies are applied by varying the available manipulated variables, such as for instance the liquid flow rate, thus avoiding inefficient operation under flooding conditions and returning the packed column to a safer scenario.

To sum up, the FFT analysis identified high amplitude pressure oscillations at very low frequencies, corresponding to a period of about 50 seconds. These dynamics, which were not resolved in previous studies such as that of Haushofer et al, (2023) can be attributed to the limited sample length used in their analysis (approximately 102 seconds). The results underscore the need to analyze signals with more samples to accurately capture these slow, large-scale fluctuations. Wavelet transform analysis enabled the identification of localized, transient features in the dynamic signals resulting from stepwise gas flow rate variations. In particular, a characteristic frequency was observed at approximately 0.5 Hz, marking the onset of flooding conditions within the column. This frequency, which is consistent across multiple experiments, suggests the existence of hydrodynamic behavior that serves as an indicator of the transition to flooding. Such an observation represents a significant advance over conventional steady-state approaches, providing real-time insight into the dynamics leading to inefficiencies.

4. Conclusions

In this study, frequency domain (FFT) and time-frequency (wavelet transform) analyses were used to investigate the dynamic behavior of pressure drop signals in a structured packed column under various operating conditions. The experimental setup allowed for a detailed characterization of the structured packing, providing insight into its dynamic response to changes in gas flow rates.

The results of this study have practical implications for the operation of packed columns. The identification of these characteristic frequencies paves the way for the development of advanced monitoring and control strategies. In particular, the 0.5 Hz marker could be incorporated into automated systems to predict and mitigate flooding, thereby reducing the duration of inefficient operation and improving column performance. Overall, this work highlights the utility of combining FFT and wavelet transform analyses for dynamic characterization of structured packings, providing both macroscopic and localized insights into system behavior. Future research will aim to expand the experimental data set and validate these methods under a broader range of operating conditions, with the ultimate goal of implementing adaptive control strategies in industrial-scale packed columns.

Nomenclature

A – pressure signal amplitude, Pa/m
B – liquid load, $m^3/(m^2h)$
f – frequency, Hz
F_V – F-factor, $Pa^{0.5}$
N – number of frequencies, -
P_{tot} – total signal power, Pa^2/m^2
$u_{s,G}$- gas superficial velocity, m/s
Δp – pressure drops, Pa/m
$\Delta p'$ - centered pressure drops, Pa/m
ρ_G – liquid mass density, kg/m3

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