PERFORMANCE DIAGNOSTICS FOR NOZZLES FED WITH MULTIPHASE FLOW

D.M. Kirpalani* and T.W. McCracken
deepak.kirpalani@nrc.ca
National Research Council of Canada,
Institute for Chemical Process and Environmental Technology
Ottawa, ON, CANADA

Abstract
Multi-phase flow, consisting of gas and liquid, plays an important role in the atomization efficiency of feed systems used in coker and riser reactors for the petrochemical industry. For atomization of a mixture of gas (steam) and liquid (heavy oil) in these operations, the multi-phase feed to the nozzles injecting into the reactor is typically a complex mixture of bubbles in liquid. This flow is unsteady as evidenced by irregular pulsing with time. The extent of unsteady pulsing and the amplitude of the pulses depends upon the bubble density variation within the flow. In the present research, the flow pattern observed in a commercial coker nozzle, was complemented with development of an alternative flow characterization method using analysis of the dynamic pressure signal acquired for pipe flow just upstream of the nozzle inlet. The flow regime, being dispersed, bubbly or slug, was related to the downstream atomization efficiency for low gas to liquid ratios, typically less than 2% by weight. Pressure fluctuations were analyzed for flow fed to the nozzle. Dynamic pressure data were acquired and analyzed in real-time using wavelet functions to first obtain power spectra for the flow as it varied with time and then supplemental analysis was made using a semi-parametric wavelet variance estimator for tracking changes in the pressure fluctuations. This variance estimator approach allowed logging and comparison of the complex dynamic pressure signals acquired for various feed conditions and nozzle configurations. This estimator value correlated well with the observed flow regimes, recorded with high frame-rate digital video and the consequential nozzle droplet size measurements, determined with laser interferometry. Development of the dynamic pressure analysis method was made using air and water as the two-phase model system.
The key finding of this research was that the wavelet variance estimator can serve as a nozzle performance indicator since the multi-phase feed flow characteristics determine the resulting spray. The flow characterization method using analysis of the dynamic pressure signal described has potential for commercial application of monitoring multi-phase flow and estimating the performance of the spray system for the range of operation studied.

Introduction
Twin-fluid atomization has been the subject of numerous studies for a wide range of engineering applications. The goal of multiphase flow nozzles in coker and riser reactors is the equal distribution of droplets for the generation of large surface areas of the liquid phase in order to increase heat and mass transfer in the reactor. Typically, steam and bitumen are fed through piping and downstream nozzles as a two-phase flow mixture for the introduction of atomized bitumen into coker reactors. In the nozzles, the two-phase mixture is pre-mixed and delivered under pressure through a length of pipe to a nozzle where the fluid mixture is accelerated to critical mass flow conditions. This results in the expansion of the gas phase and the dispersion of the liquid phase into ligaments at the exit of the nozzle. Further decomposition of the ligaments into droplets depends on the fluid properties and operating conditions in the nozzle. Many investigators have examined the performance of multiphase flow nozzles. Lefebvre et al. [1] were amongst the first investigators to study pre-mixing of gas and liquid phases to feed a downstream atomizer. This approach of pre-mixing, identified commonly as effervescent atomization, altered the classical gas-assisted atomization approach of mixing the two fluids outside the nozzle. Chawla [2] studied the atomization of two-phase mixtures inside a nozzle at critical mass flow rates and reported a model for calculating critical two-phase mass flow density. Buckner and Sojka [3] measured droplet sizes in sprays of fluids with different viscosities and showed that mean droplet diameter was a strong function of air-liquid ratio and nearly independent of liquid viscosity. Luong and Sojka [4] discussed the unsteadiness of droplet size, velocity and arrival time in sprays and found that the unsteadiness is influenced by air-liquid ratio, liquid mass flow rate and physical properties of the liquid which alter the two-phase flow pattern inside the nozzle.
To monitor two-phase flow patterns, multiphase flow researchers have commonly relied on visual observations for investigating flow inside transparent pipes. The properties of the fluids combined with observations of flow

types are then be mapped into a two-dimensional plot to define flow regimes in terms of physical properties of the fluids. A number of these maps appear in the literature [5,6], each having their own merits and application. An alternative approach, more recently applied by investigators [7,8], applies measurement of local pressure fluctuations with a dynamic pressure transducer and analyses of the data using signal analysis methods. The measurement of parametric variations has been limited due to the difficulty in extracting discriminatory features with the poor signal-to-noise ratio (SNR) from the pressure data. Moreover, analysis of the pressure-fluctuation signal has been typically made using fast Fourier transform (FFT) or similar signal analysis and statistical methods, to report and correlate the pressure fluctuation to observed flow phenomena but this technique was found to be limited in analysing subtle changes in the pressure fluctuation within the transition regime.
In our previous work [9,10], a model system with water and air fed to a commercial-scale coker nozzle, two phase flow conditions in the nozzle were mapped using the method of Dukler and Taitel [11] and the nozzle was found to operate in the transition region between dispersed bubble and intermittent flow patterns. Although, only two conditions of operation were examined, it was found that even small changes in ALR had a considerable effect on the resulting spray measurements. This provided a basis for correlating observed flow patterns to the resulting spray. Nozzle operation, near the intermittent or slug flow pattern, resulted in severe instability in the spray and the formation of large droplets in the spray. In contrast, if the flow was a dispersed bubbly flow, complete atomisation of the liquid occurred and the finer droplets formed indicating that atomisation efficiency was also improved. Also, wavelet analysis of pressure signals in the nozzle was introduced as a novel approach for correlating observed flow phenomena to spray characteristics qualitatively. In the current work, the qualitative flow pattern analysis was extended with the development of a wavelet variance estimator for the pressure fluctuations that can serve as a nozzle performance indicator for the nozzle system since the multi-phase feed flow characteristics determine the resulting spray performance. This internal flow characterization method has potential for commercial application of monitoring multi-phase flow in nozzles and estimating the performance of the spray system.

Wavelet analysis

Multi-resolution wavelet analysis has proved to be a mathematically clear and practical tool for analysing signals at multiple scales or frequencies, even in the presence of non-stationarities commonly found in pressure time series data. Practical applications in other fields of research have shown that wavelet statistics can be used to reveal scaling phenomena in natural systems in a more transparent way than other methods frequently used. The wavelet transform is defined on the basis of a family of analysing wavelets, $\psi_{a,b}(t)$, that are generated by varying the dilations or scales, a, and translations, b, from a mother wavelet, $\psi(t)$ (Kumar and Georgiou-Foufoula [12]), as:

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$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{1}$$

Where a> 0, -∞ < b <∞, and $\int_{-\infty}^{\infty}\psi(t)\,dt = 0$ (1.1)

$\psi_{a,b}(t)$ = Analysing wavelet function.
a = Wavelet scales
b = Translations of the wavelet
$\psi(t)$ = Mother wavelet function

The wavelet transform of a time series X (t) is defined as:

$$\overline{X}(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} X(t)\,\psi^*\left(\frac{t-b}{a}\right)dt \tag{2}$$

The asterisk superscript indicates the complex conjugate of the wavelet function. Hence, the wavelet transform takes a one-dimensional function of time and converts it into a two-dimensional function with variables for space or time and scale (or frequency).
In practical applications, wavelets can be conveniently discretized by setting $a=2^s$ and $b = t\,2^s$ in octaves where s and t are integers (Chui [6]). Then the wavelet transform for the time series X (t) becomes:

$$\overline{X}(s,\tau) = \frac{1}{\sqrt{2^s}}\int_{-\infty}^{\infty} X(t)\,\psi^*\left(\frac{t}{2^s}-\tau\right)dt \tag{3}$$

The variables s and t are integers that scale and dilate the mother function y (t) to generate wavelets. The scaling index, s, indicates the width of the wavelet and the local index, t, gives its position in space. From a huge

family of wavelet functions, the Morlet wavelet basis function was selected for this work due to its high resolution at low frequencies expected in the pressure data during slug flow. The Morlet wavelet function can be represented as:

$$\psi = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \tag{4}$$

Where w_0 is a dimensionless frequency, $w_0 = 6$ in this work and η represents a non-dimensional time parameter (Torrence and Compo [7]).

In order to analyze signal at different resolutions, the analyzing wavelets are used in a scaling equation whose coefficients are obtained from solutions of higher order polynomials. It is helpful to think of these coefficients as filters. The coefficients are placed in a transformation matrix (cascade algorithm) and applied to the collected data. The coefficients are ordered using two dominant patterns, one that works as a smoothing filter (wavelet coefficients) and the other that brings out the detail (scaling coefficients). The scale parameter in the wavelet analysis is similar to that used in geographical maps. As in the case of maps, high scales correspond to a non-detailed global view (of the signal), while low scales correspond to a detailed view. Similarly, in terms of frequency, low frequencies (high scale values) correspond to a global description of a signal, usually spanning the entire signal, whereas high frequencies (low scale values) correspond to detailed information on a hidden pattern in the signal, usually lasting for a relatively short time. A time-scale plot of wavelet coefficients is obtained by a convolution the scaled and translated version of the mother wavelet with the original data.

Experimental Setup

The study was carried out on a full-scale multiphase flow coker nozzle assembly with a transparent mixing pipe for flow visualization as shown in Fig. 1. The nozzle was oriented horizontally and air and water were introduced into the nozzle through a mixing tee and delivered to the nozzle through the 1.86 m long transparent mixing pipe. The nozzle design was proprietary but it can be described as a configuration based on standard orifice nozzles. The experiments were performed at three different water flow rates and varying air-liquid ratios (< 2%) with the spray exiting to the ambient. Photographs of the flow patterns collected in the mixing pipe using a (REDLAKE PCI-8000S) high frame rate CCD camera. To illuminate the two-phase mixture and the spray, the camera was synchronized with a Flash Strobe (Photonics Analysis Ltd. – PALFLASH 501)) located opposite the camera as shown in Fig. 1, a DANTEC PDA (Particle Dynamics Analyzer) laser interferometer with 1200 mm transceiver and receiver optics located to make droplet size measurements at a distance of 0.92 m downstream of the nozzle exit. At that location, the spray was dispersed sufficiently for measurements were achievable with 85% validation or higher. Pressure fluctuations were recorded near the exit of the nozzle using a high-resolution pressure transducer (PCB Model No:482A with a 200 kHz frequency bandwidth at a gain K = 1). The transducer was installed to measure dynamic changes in wall pressure for flow inside the nozzle. The dynamic pressure data was acquired with a National Instruments DAQ board installed in a PC computer with LabVIEW data acquisition software. Pressure signal data was sampled at 512 Hz. Wavelet statistical procedures, written with MATLAB software, were developed using wavelet for characterizing the collected pressure fluctuations.

Results and Discussion

The two-phase nozzle system described above was operated over three (3) liquid mass flow rates and a range of air-liquid ratios (ALR), typically less than 2% by weight. In order to quantify the extent of variation in slug or dispersed flow with respect to time series analysis, the fluctuating component of pressure was recorded and analysed using wavelet functions for each operating condition. The signals were then studied using Morlet wavelet functions for developing time-frequency wavelet energy plots to differentiate spray performance in terms of the frequency and intensity for the irregular signals obtained. Sample wavelet spectral analyses, with respect to time and frequency, for two typical nozzle operating conditions at a water flow rate of 0.0023 m^3/s and ALR of 0.75% and 1.5% respectively are shown in Fig. 2. Large amplitude fluctuations in the spectral plot, represented as local maxima are visible between 2-4 Hz for ALR of 0.75%. By relating these plots to photographic records, we observe that the intermittence in peak pulses, corresponding to slugging behaviour, occurred between 2 to 4 Hz for ALR of 0.75 %. For an ALR of 1.50 %, pressure fluctuations occurred at higher frequency with lower intensity. In other words, high intensity pulses were detected for slug flow and not for dispersed bubbly flow. These fluctuations correspond to the effect of bubbles or slugs exchanging energy with the liquid phase in the mixture. Such exchanges of energy are displayed as coherent structures or wave bursts in specific frequency bands or wavelet scales as energy peaks as shown in Fig. 2.

The wavelet variance estimation is a statistical approach for analyzing the scaling behavior of wavelet coefficients at a particular scale of the signal and is calculated as the variance of wavelet coefficients at each scale. Logarithmic wavelet variances (σ_s), for the wavelet spectral data, shown in Fig. 2, are plotted for each frequency band in Fig. 3. The difference in variance values in the 2-4 Hz. frequency range is clearly seen in the plot. Logarithmic variance plots of the wavelet coefficients in the 2-4 Hz. frequency range, derived from the

pressure fluctuation data for the range of operating conditions are significantly influenced by ALR as shown in Fig. 4 (a). The increase in logarithmic wavelet variance with an increase in ALR indicates that the two-phase flow mixtures approaches uniform dispersion of bubbles and a decrease in intermittency or slugging in the flow.
For slug flow conditions in the nozzle, corresponding to low liquid mass flow rates at low ALR values, a central liquid core of large ligaments formed and did not atomise even at 3 m downstream of the nozzle exit. It appeared that only about 20% of the liquid was atomised. At higher liquid mass flow rates and higher ALR, where dispersed bubbly flow was observed in the feed pipe, the resulting spray consisted of fine droplets dispersed within the plume of a wide conical spray. At low ALR, slug flow is expected to occur causing the formation of large ligaments of liquid ligaments and large droplets downstream from the nozzle that decrease with an increase in liquid flow rate. The mean droplet sizes (D_{32}), measured by laser interferometry for two (2) liquid flow rates over the range of ALR values confirm that the mean droplet size decreases with an increase in liquid flow rate or ALR. Hence, it can be concluded that liquid mass flow rate and mass quality or ALR of the mixture influence atomisation efficiency of the spray nozzle significantly even at low ALR values. The wavelet variance estimator (σ_s) is shown to decrease with an increase in the mean droplet size (D_{32}) as shown in Fig. 4(b). Results from Figs. 4(a) and 4(b) indicate that the estimator can be extended to the prediction of internal two-phase flow of commercial nozzles and consequent spray characteristics.

Conclusions

Coker or riser rector multiphase nozzles were studied for the development of a commercial real-time performance indicator to track changes in spray characteristics. Slug flow formation in the nozzle was found to be responsible for intermittent pulsations and the formation of large droplets and poor atomization of the spray. An increase in ALR, produced a dispersed bubbly flow in the pipe and an improvement in atomization efficiency. Dynamic pressure data near the exit of the nozzle was acquired and analyzed in real-time using wavelet functions to generate wavelet spectral coefficients. Subsequent analysis made using a semi-parametric wavelet variance estimator has been introduced for tracking two-phase flow pattern and spray characteristics in coker nozzles. Development of the dynamic pressure analysis method was made using air and water as the two-phase model system. This estimator value correlated well with the observed flow regimes and resulting droplet size measurements.
The key finding of this research was that the wavelet variance estimator can be applied as a nozzle performance indicator for determining multi-phase feed flow patterns and resulting spray characteristics. Analysis of the dynamic pressure signal described has potential for commercial application in monitoring the performance of the spray system for the range of operation studied.

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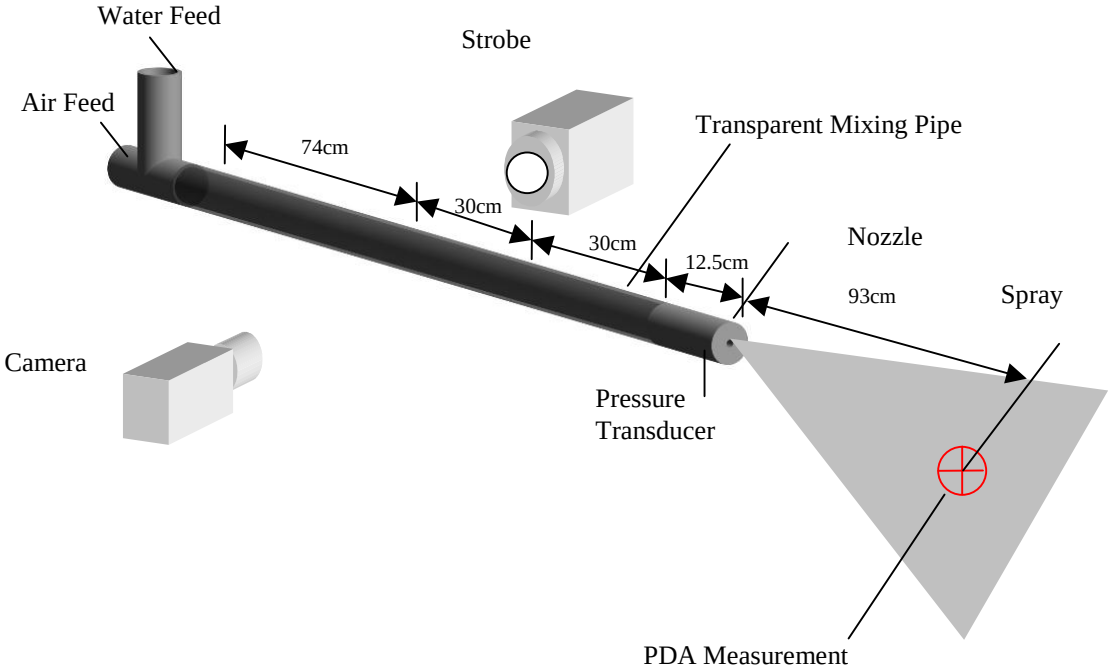

Figure 1. Schematic diagram of experimental arrangement for two-phase mixture and spray characterization.

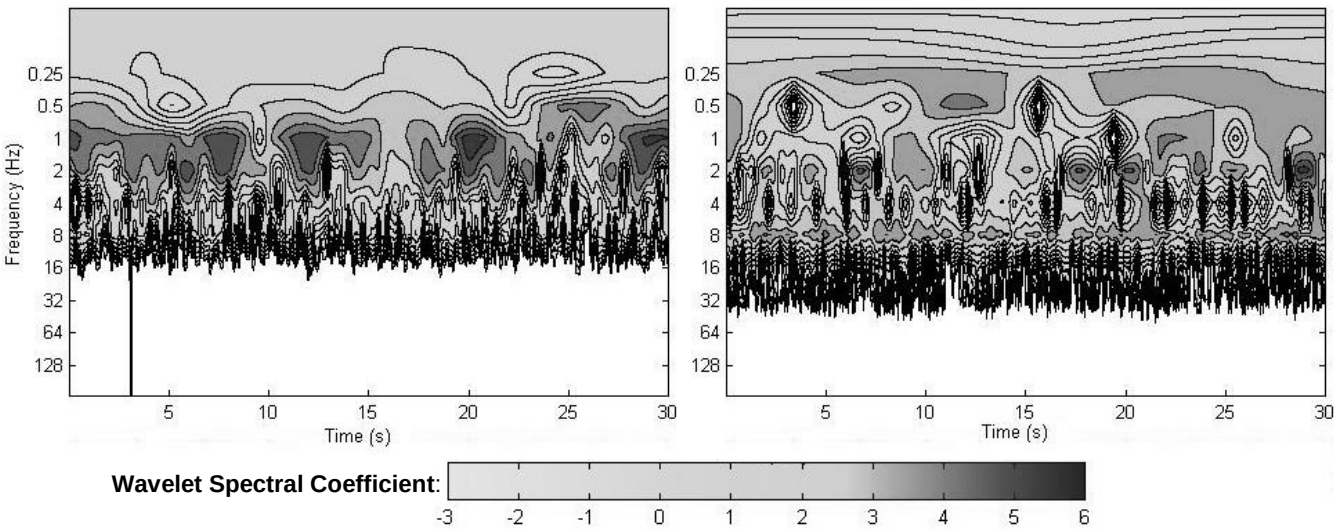

Figure 2. Wavelet spectral decomposition for water flow rate = 0.0023m^3/ s and ALR =0.75% (left) and 1.5% (right) by dynamic pressure signal analysis using Morlet wavelet function.

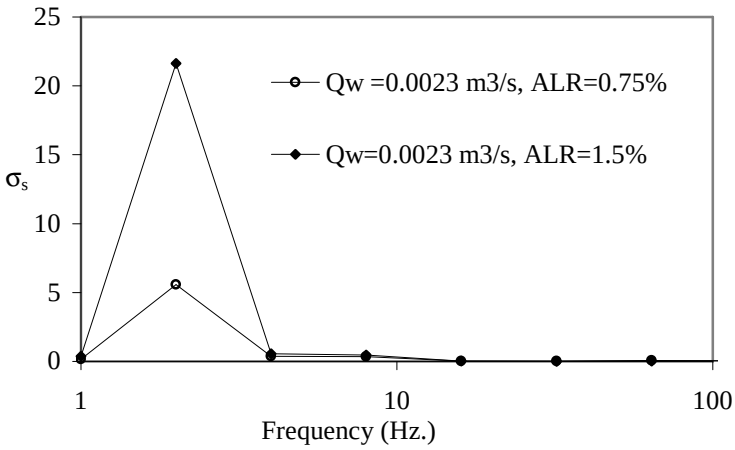

Figure 3. Wavelet variance estimator for water flow rate = 0.0023m^3/ s and ALR =0.75% and 1.5%.

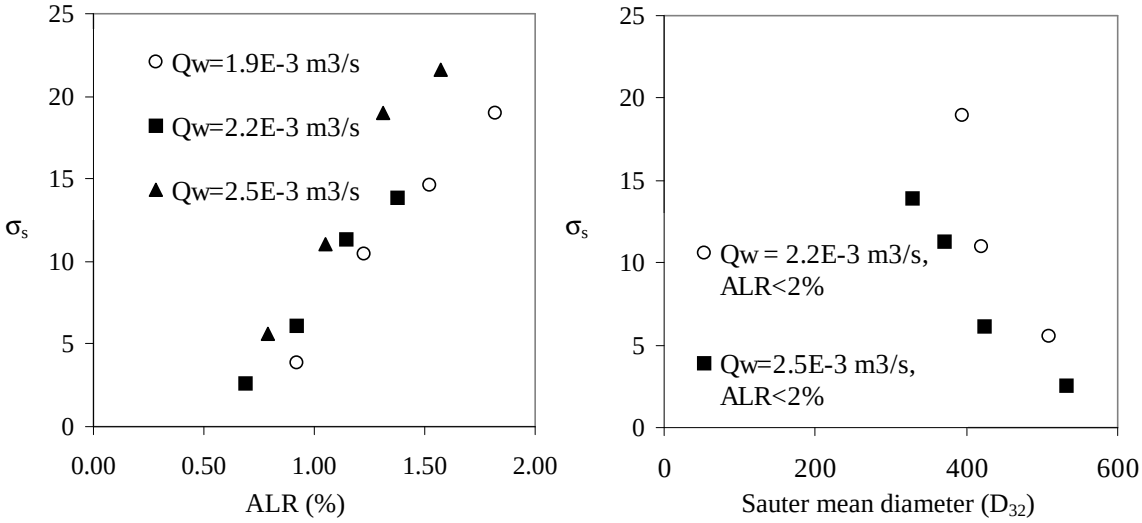

Figure 4. (a) Logarithmic wavelet variance estimation for coker nozzle operated at constant water flow rate and air-liquid ratio (ALR) up to 2% with respect to (a) air-liquid ratio (ALR) and (b) PDA measured Sauter mean diameter (D_{32}).